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Mauro D'Onofrio
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From the Realm of the Nebulae to Populations of Galaxies

Dialogues on a Century of Research

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To our families with love and gratitude

The worth of that is that which it contains,
and that is this, and this with thee remains.
W. Shakespeare Sonet 74

Foreword

Fifty years ago, I was sitting on a couch by a window at my home in Baltimore, Maryland, watching television with my brothers, when, during a commercial break, I turned my head to look out the window and noticed a bright star. Not knowing what star it was, I got up and went out on the back porch to get a better view. I recall for a few moments just standing there, looking in awe up at a sky full of stars. The view was so remarkable that I went back into the house to look for an old constellation book I had, *Stars*, by Herbert S. Zim, with which I determined the bright star was Sirius. But more importantly, after identifying the star, I read the descriptions of celestial objects given in the book. On one page was a picture of the Andromeda Spiral, the caption of which stated that the galaxy was 750,000 light years away. I could not believe that anything could be so far away. Ironically, Zim's book was out of date; later estimates put Andromeda at more than 2.5 million light years.

I have recounted this story because it shows the draw galaxies can have on people. The minor experience I had, a turn of the head, a bright star, and a picture caption in a book, led me to a life-long interest in galaxies. Galaxies are islands of starlight spread across an almost unfathomable expanse of space and time. When I try and think of a single word that can describe them, I have to say "majestic," a term I might also use to characterize a beautiful, tall mountain.

How can we hope to know much about things so far away? The answer is provided in this book. *From the Realm of the Nebulae to Populations of Galaxies: Dialogues on a Century of Research* is a detailed compendium of the profound advances in the study of galaxies that have been made since the 1920s when Edwin Hubble discovered Cepheid variable stars in the Andromeda Galaxy. The book is a useful and admirable attempt to bring a century of progress into thoughtful perspective and to present the progress in the field through the outline of a logical chain of events largely involving advances in instrumentation and computing power. Extragalactic astronomy has gone from the domain of a few observers taking long exposure photographs at remote mountain-top observatories to large international collaborations involving space observatories and dozens, if not hundreds, of astronomers. Without a doubt, we are witnessing a golden age of discovery and exploration in extragalactic astronomy.

Why is the study of galaxies important? Hubble learned the value of such studies when he discovered the Hubble law, which first pointed to the idea of an expanding universe. Extragalactic studies have also led to the discovery of dark matter, stellar populations, and supermassive black holes. Such studies lead us to naturally ask what role our galaxy has played in our existence. Because we are on a planet in orbit around a star that was born in the Milky Way, we can ask how stars form and how the Milky Way provides the raw materials needed for star formation. In order to answer this, we have to know how stars evolve and the role that different kinds of stars and phenomena (like supernovae) play in enriching the interstellar medium with heavy chemical elements. We observe that the Milky Way is a rotating system with a highly flattened shape and can ask not only how it achieved this shape, but also what the mass of the Milky Way is and how that mass is distributed within it. We can observe or infer the kinds of orbits stars follow as they move around the galactic center and can link these orbits to other properties, such as metallicity. Our location in the Milky Way colors our view of the rest of the universe.

The study of other galaxies beyond the Milky Way is important because, on one hand, only such studies can provide a perspective on how the Milky Way fits into the grand scheme of galaxies. Multi-wavelength observations, measurement of parameters and scaling relations, recognition of structures, the distribution of galaxies, etc., are essential for understanding how galaxies form and evolve. Then there is the issue of cosmology, observing galaxies over a wide range of distances and lookback times, in order to probe not only the evolution of galaxies, but the evolution of the universe. A glance at the Table of Contents of this book shows that the study of galaxies is basically relevant to all fields of astronomy.

The charm of extragalactic astronomy lies not only in its progress over the last century, but in its history before people even knew such things as galaxies existed. Thousands of nebulous objects that were later shown to be galaxies had been catalogued during the 150 years before Hubble made his grand discovery. The mystique of the nebulae stemmed from a lack of knowledge of their distances, but the general suspicion throughout much of the nineteenth century was that most, if not all, nebulae were distant, unresolved star systems. Adding to the mystique was the discovery, in 1845, of spiral structure in some of the brightest catalogued nebulae. The old sketches made with the "Leviathan of Parsonstown," the home-built 72-in. reflector of William Parsons, the Third Earl of Rosse, are fascinating relics of a bygone era. When we combine these with the beautiful photographs of galaxies presented in, for example, the Hubble Atlas of Galaxies, we come to realize that there is an enormous and complex diversity in the morphology of galaxies. Physically explaining this diversity and the processes that led to it has been one of the major goals of extragalactic research.

Trying to summarize the breadth and scope of advances in such a broad field as extragalactic astronomy over a period of a century is a challenge. Rather than only writing a series of reviews themselves to present the stories and advances in galactic and extragalactic astronomy over this time, the authors of this book chose to interview a significant number of the most knowledgeable and dynamic contributors to the field, in order to provide a perspective that only such people could provide.

This has allowed the authors to effectively cover not only the scientific advances in galaxy research the past century, but how specific developments in instrumentation and technology helped to make those advances possible.

Given the sophisticated tools available for studying galaxies today: CCD cameras, the Sloan Digital Sky Survey, the Hubble and Spitzer Space Telescopes, etc., it is easy to lose sight of just how difficult it once was to obtain basic astrophysically useful information on even the nearest galaxies. One of the chapters in the book highlights the importance of galaxy surveys, which include catalogues and special databases. Astrophysically useful databases had humble beginnings, and one does not have to go back too far to see when the act of collecting data was a slow process. Only 40 years ago, for example, photoelectric photometry was still a standard technique for getting information on apparent brightnesses.

It was also not long ago when the distance scale was a topic of heated disagreement and discussion in the journals that left some astronomers in "camps." One camp favored a Hubble constant of 50 km/s/Mpc, while the other advocated a value of 100 km/s/Mpc. There were endless discussions of calibrations of "distance indicators," the effects of Malmquist bias and large-scale mass concentrations, and which methods provided the best distances for deriving H_0. The disagreement persisted for several decades until resolved in the 1990s by the Hubble Space Telescope Key Project on the Extragalactic Distance Scale.

These examples underscore how much the study of galaxies has changed even since the 1990s. CCDs effectively rendered photoelectric photometry obsolete in astronomy and took us off of the "photographic standard" used for decades into the realm of high quantum efficiency imaging. The Hubble Space Telescope gave us unprecedented views of galaxies, allowing the distance scale debate to be revolved. When we look at how extragalactic astronomy has been conducted the past century, the need for more photons and more resolution has always been keen.

I can imagine a time when we will have images of very high redshift galaxies at the same depth and resolution as a Sloan Digital Sky Survey image of a nearby galaxy. Our need to see high redshift galaxy structure in detail is one reason why we need bigger space telescopes; this is also the reason classical morphological analysis (i.e., Hubble-based visual classification) has survived into the modern era. Who would have thought that Hubble's old 1926 classification would still be used in one form or another, nearly a century later when other classifications fell into disuse more than 50 years ago? Although one of the book's conclusions is that there has been "progressive abandonment" of the classical Hubble view, I believe as improved imaging brings us more detail at high redshifts, the classical Hubble systems will continue to be relevant. The impending demise of classical morphological analysis was predicted 25 years ago but never really occurred. The James Webb Space Telescope should bring us closer than ever before to being able to see fine details in very high redshift galaxies.

The study of galaxies has led to some of the most important discoveries in the history of science. Virtually every field of astronomy is tied in some way to our understanding of how galaxies formed and have evolved since the time of the "Big Bang." This book effectively provides the background needed to understand how we came to our current understandings and lays the groundwork for what avenues of research will be productive in the coming decades.

University of Alabama, Tuscaloosa, AL, USA Ronald J. Buta
November 2015

Preface

In his preface to the 1958 reprint of the Edwin Hubble's *The Realm of the Nebulae* (Dover Publication, Inc.), Allan Sandage wrote "The complete change of perspective caused by the cosmological discoveries of the 1920s is now oftentimes forgotten. But just as the Copernican revolution unshackled man's mind from belief in the central position of the Earth, so the discovery of the true nature of extragalactic nebulæ as separate "Island Universes" opened the last frontier of the astronomical adventure into the vast regions of space."

This book wishes to witness the astronomers collective effort in trying to chisel away at the idea of "Island Universes" roughed out by the pioneers who started to debate the nature of spiral nebulae as individual astronomical objects similar to the Milky Way in the 1920s. This history is steeped in the profound passion for knowledge of many scientists in several countries.

Nearly 100 years ago even the use of the term *galaxy* was confuted. Hubble itself explained the parallel use of the terms *extragalactic nebulae* (as opposed to galactic nebulae) and *external galaxies* (considering the Galaxy, the Milky Way, as a prototype of the galaxies). He concluded that: "The term *nebulae* offers the values of tradition; the term *galaxies*, the glamour of romance," considering the use of the word *galaxy* provided at that time by the Oxford English Dictionary. Today the species of galaxies observed are so numerous that the concept of galaxy itself has profoundly changed. The so called "extragalactic astronomy" has become a mature and complex discipline of Astrophysics. New fascinating technological enterprises like the Hubble Space Telescope (HST) captured the public imagination. The roaring successes of extragalactic astronomers in improving observing facilities, at all wavelengths, and in taking profit of the explosive computing power to interpret and simulate observations of galaxies are building the modern scientific *Weltanschauung*. Nearby galaxies are often resolved into stars and observed with unconceivable detail, and far away objects are seen up to only 650 Myr after the Big Bang.

Our book wishes to present an organic collection of questions that we propose to specialists of different branches of extragalactic astronomy. The interviews aim at tracing the evolution of our understanding of galaxies across one century of research. The title of the book already hints at what happened to our idea of galaxies: they are no more the "Island Universes" imagined by Hubble, the courtiers of a realm; they are now "citizens" of a modern, eventful, and evolving population, the "cosmic web," made of companions, groups, clusters, filaments, sheets, etc. Their formation and evolution involve several physical processes, among which interactions play a significant role. From giants to dwarfs, galaxies are thought to coevolve, within and with their own environments, to so much an extent that *genetic algorithms* have been experimented for their classification. Once mapped, their *gene pools* should contain information about their ancestors and their evolving paths.

In each chapter we have asked contributors to emphasize the historical and the present vision of their research field, as well as to discuss the problems still unsolved and the future directions. We likely missed to mention some important project and to cite even more important works, we are sorry for that, but now extragalactic astronomy is a so wide discipline of astrophysics that is almost impossible to account of all things in a single publication.

Chapter 1 presents a short historical introduction of the pioneering years, from the *Great Debate* between Curtis and Shapley in 1920 to World War II, which represents the historical watershed between modern and old extragalactic astronomy. We ask contributors to sketch a panoramic view of the growth of their field of research, taking into account several geographic areas. The purpose is to emphasize the common efforts done for understanding galaxies all around the world. These led to the birth of several research teams and to the growth of international institutions. The chapter describes this *century of galaxies* characterized by the impressive impact of new technologies, by the exponential growth of computing power, and by new detectors which extended the observable wavelength range providing a panchromatic view of galaxies. Space missions, new ground-based optical/radio telescopes, and sky surveys brought us to the "Big Science" era. At this time the new astronomy is dominated by large scientific programs proposed by large teams of scientists. Everyday torrent of data feeds our modern computers both for reduction purposes and for numerical simulations. The romantic figure of the astronomer at his telescope is only a nice memory.

Chapter 2 is dedicated to the progresses in understanding our Galaxy, the Milky Way, and to the characterization of the Local Group of galaxies. A significant fraction of our knowledge of *external galaxies* is founded on what we know about our Galaxy: its size, its stellar, gas and dust structure, and its dynamics are basic fundamental information to explore the nature of other galaxies. Conversely, it is also true that we have learned a lot about our Galaxy from the studies of external systems. At the same time the present understanding of the Local Group provides the basis for a clear definition of the processes occurred during galaxy formation and evolution, as well as of the large scale structure of the Universe. The chapter also dedicates some space to the distance scale debate. This latter was particularly vivacious for many decades. The value of the Hubble constant, $H_0 = 72 \pm 7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, was only recently fixed through an `HST` key program.

Chapter 3 will touch the problem of the classification of galaxies. Extragalactic astronomers often refer to their work as "an archeology excavation conscious of the uniqueness of their subject of investigations." Notwithstanding, several systems of galaxy classification have been attempted. Well before nebulae were recognized to be *Island Universes*, the spiral structure of M51—described in 1845 by Lord Rosse—was used as classification class. The Hubble 1936 classification of galaxies is widely used and the concept of early vs. late type survives in the classification of distant galaxies. What makes the Hubble classification so long-lived? The descriptive classification of galaxies proposed by Reynolds or Vorontsov-Velyaminov has been rapidly abandoned although detailed morphological structures enjoy good health from the 1970s and 1990s and a revival is even present today when ring, ovals, lens, etc., are described. Is this the future of the classification of nearby galaxies? Or rather will *genetic algorithms* aiming at classifying galaxies according to their evolutionary path overwhelm Hubble's classification?

Chapter 4 is dedicated to the description of the galaxy structures and substructures, from the nuclear region to the outskirts. How these galaxy components did form? What is their role in the galaxy evolution? Is the idea of galaxy components still important in the currently accepted scenario of galaxy formation? Many of such questions will be discussed here. The chapter also investigates the origin of several scaling relations, such as the $M_{BH}-M_{bulge}$ relation, the fundamental plane, the Tully-Fisher relation, and other relations which provide us the footprints of galaxy evolution. Why are these scaling relations so important and to what extent current models are able to reproduce them?

Chapter 5 deals with the galaxy properties as they appear from multiwavelength surveys. The chapter focuses on the characteristics of poor and dense galaxy environments, with a special emphasis for the nearby Virgo and Fornax clusters, up the big superclusters and voids. Then we examine the results of the most important surveys in the various parts of the electromagnetic spectrum, from the far IR to the X-ray domain. In particular we discuss the HI surveys and the peculiar velocity field of galaxies, from which we have extracted the current picture of the cosmic web.

Chapter 6 is dedicated to the pursuit of high redshift galaxies. This saga dates back to the end of the 1950s. A letter to the *Astrophysical Journal* in 1960 by Rudolph Minkowski describes the photometric and spectroscopic problem in looking for distant galaxies, when distant mean $\Delta\lambda/\lambda \approx 0.2$. The chapter focuses on the history of the results of this hunt for high redshift galaxies, mainly coming from the combination of the `HST` deep images and the spectroscopy made using top class ground-based telescopes. Distant galaxies up to redshift $z = 3$ are now scrutinized in their morphology and star formation properties, while the frontier is set by sporadic identifications that reaches $z \sim 8$. A final section is dedicated to the formation of first galaxies and consequently to the problem of their detection with the coming observing facilities.

Chapter 7 attempts to mark the new boundaries of our idea of galaxies, as citizens of a complex society. The first part considers interactions, matter accretion, and merging phenomena as drivers of external galaxy evolutionary mechanisms. An other aspect considered is the role of environment. While substantial enhancements of the density of the nebulae in certain directions of the sky was noticed by Harlow Shapley itself, only much recently, as a direct consequence of redshift surveys of

1980s–1990s, the concept of cosmic web developed. Extreme environments are both inhabited by galaxies with different consequences for their evolution. The *century of galaxies* has also seen the change of the perspective of the energetic phenomena involved in galaxy evolution. AGN, GRB, and SNae as well as odd star formation histories are discussed in this chapter. Finally, we have accounted for the growing debate about the Dark Matter hypothesis and the most significant alternatives, like the modified Newtonian dynamics (MOND).

Chapter 8 shows how our understanding of galaxy formation and evolution developed since the first efforts in modeling them. We will see the main successes of theoretical models in interpreting the galaxy structures and characteristics, the evolution of the stellar populations, and the cosmological frameworks which are in better agreement with the current data. We will address the problems of the origin of the Hubble sequence, of the evolution of the star formation, and the role of energetic feedbacks, and we will compare the old monolithic scenario of galaxy formation with the hierarchical scheme that is in agreement with the modern cosmology.

Chapter 9 aims to associate the big open questions about galaxy formation and evolution to the forthcoming/proposed observing facilities. We start with the expected contribution from `Gaia`, the ESA satellite launched in December 2013, that will provide the new vision of our Galaxy and its companions. Then we examine the bulk of data for external galaxies coming from the next space missions, from the ground-based 30 m+ class optical telescopes, and from the new radio interferometers. The acquired data will be so large and complex that new *Virtual Observatories* are projected and organized to make these data available to the astronomical community.

Chapter 10, the final chapter, wishes to summarize the main successes obtained up to now in understanding the properties of galaxies and at the same time wants to focus the attention on the questions that are still unsolved. Remembering Hubble's words: "at the end the history of Astronomy is a history of expanding horizons," we will conclude the book with few considerations about the most promising missions of the near future.

Padova, Italy
September 30, 2015

Mauro D'Onofrio
Roberto Rampazzo
Simone Zaggia

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Acronyms

AAO	Anglo-Australian Observatory
AAT	Anglo-Australian Telescope
ACIS	Advanced CCD Imaging Spectrometer (Chandra)
ACS	Advanced Camera for Survey (HST)
ACSFCS	Advanced Camera for Surveys Fornax Cluster Survey
ACSVCS	Advanced Camera for Surveys Virgo Cluster Survey
AGB	Asymptotic Giant Branch
AIS	All-Sky Imaging Survey (GALEX)
ALFALFA	Arecibo Legacy Fast ALFA survey
ALMA	Atacama Large Millimeter Array
AMBER	Astronomical Multi-BEam combineR (ESO-VLTI)
AMIGA	Analysis of the interstellar Medium of Isolated GAlaxies
AMR	Adaptive Mesh Refinement
ASCA	Advanced Satellite for Cosmology and Astrophysics
ASI	Agenzia Spaziale Italiana
ASIAA	Academia Sinica Institute for Astronomy and Astrophysics, Taiwan
ASJ	Astronomical Society of Japan
BAO	Baryon acoustic oscillations
BM	Baryonic matter
BTA	Bolshoi Altazimuth Telescope
CANDELS	Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
CATA	Center for Excellence in Astrophysics and Associated Technologies
CCD	Charge-coupled device
CDM	Cold dark matter
CFHT	Canada-France-Hawaii Telescope
CGCG	Catalogue of Galaxies and Clusters of Galaxies
CMD	Color magnitude diagram
CMF	Core mass function

CIB	Cosmic infrared background
CIS	Commonwealth of Independent States
CMB	Cosmic microwave background
COBE	Cosmic Background Explorer
COS	Cosmic Origins Spectrograph (HST)
COSMOS	Cosmological Evolution Survey
CTIO	Cerro Tololo Inter-American Observatory
DENIS	Deep Near Infrared Survey of the Southern Sky
DIRBE	Diffuse Infrared Background Experiment (COBE)
DIS	Deep Imaging Survey (GALEX)
DLA	Damped Lyman-α
DM	Dark matter
EACOA	East Asian Core Observatories, NAOJ, ASIAA, NAOC, KASI
EAO	East Asian Observatory
ENO	European Northern Observatory
EROs	Extremely red objects
ESA	European Space Agency
ESO	European Southern Observatory
ESO-ELT	ESO Extremely Large Telescope
ESO-SERC	ESO Sky Survey and Atlas
ESO-VLT	ESO Very Large Telescope
ETG	Early-type galaxy
FIRAS	Far Infrared Absolute Spectrophotometer (COBE)
FORS	FOcal Reducer and low dispersion Spectrograph (ESO-VLT)
FUSE	Far Ultraviolet Spectroscopic Explorer
GALAH	The GALactic Archaeology with Hermes
GALEX	The Galaxy Evolution Explorer
GAMA	Galaxy And Mass Assembly
GMRT	Giant Metrewave Radio Telescope
GRB	Gamma ray burst
GTC	Gran Telescopio Canarias
HB	Horizontal branch
HDF	Hubble Deep Field
HMXB	High-mass X-ray binaries
HR	Hertzsprung-Russell (diagram)
HST	Hubble Space Telescope
HUDF	Hubble Ultra Deep Field
ICRF	Inertial Cosmic Reference Frame
IFU	Integral field unit
IGM	Intergalactic medium
ILR	Inner Lindblad resonance
IMF	Initial mass function
IPCS	Image Photon Counting System
IRA	Instantaneous recycling approximation
IRAC	Infrared Array Camera for Spitzer Space Telescope

IRAM	Institut de Radioastronomie Millimétrique
IRAS	Infrared Astronomical Satellite
IRS	Infrared Spectrograph for Spitzer Space Telescope
ISAAC	Infrared Spectrometer And Array Camera (VLT)
ISM	Insterstellar medium
ISO	Infrared Observatory Satellite
IUE	International Ultraviolet Explorer
JAXA	Japan Aerospace Exploration Agency
JCMT	James Clerk Maxwell Telescope
JVLA	Jansky Very Large Array
JWST	James Webb Space Telescope
KASI	Korea Astronomy and Space Science Institute
KPNO	Kitt Peak National Observatory
LBT	Large Binocular Telescope
LF	Luminosity function
LIRG	Luminous Infrared Galaxy
LMC	Large Magellanic Cloud
LMXB	Low-mass X-ray binary
LOFAR	Low-Frequency Array for Radio Astronomy
LSST	Large Synoptic Survey Telescope
MATISSE	Multi AperTure mid-Infrared SpectroScopic Experiment (ESO-VLTI)
MCs	Magellanic Clouds
MFD	Mean field dynamo
MHD	Magneto hydro dynamics
MIDI	MID-infrared Interferometric instrument (ESO-VLTI)
MIPS	Multiband Imaging Photometer for Spitzer Space Telescope
MIS	Medium Imaging Survey (GALEX)
MIT	Massachusetts Institute of Technology
MLT	Mixing-length theory
MOS	Multi-objects spectrographs
MW	Milky Way, The Galaxy
NAOC	National Astronomy Observatory of China
NAOJ	National Astronomical Observatory of Japan
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NFW	Navarro, Frank, & White
NGVS	Next Generation Virgo Cluster Survey
NICMOS	Near Infrared Camera and Multi-Object Spectrometer (HST)
NOAO	National Optical Astronomical Observatory
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
NSST	NOAO System Science Center
OAO	Orbiting Astronomical Observatory
OC	Open cluster

PAH	Polycyclic aromatic hydrocarbons
PISNe	Pair-instability SNae
PN	Planetary nebula
POSS	Palomar Observatory Sky Survey
RASS	ROSAT All Sky Survey
RAVE	RAdial Velocity Experiment
RC3	The Third Reference Catalogue of Bright Galaxies
ROSAT	Röntgensatellit
RSA	A Revised Shapley-Ames Catalogue of Bright Galaxies
SCJ	Science Council of Japan
SCUBA	Submillimeter common-user bolometer array
SDSS	Sloan Digital Sky Survey
SED	Spectral energy distribution
SEGUE	Sloan Extension for Galactic Understanding and Exploration
SFH	Star formation history
SFR	Star formation rate
SFRD	Star formation rate density
SKA	Square Kilometre Array
SINFONI	Spectrograph for INtegral Field Observations in the Near Infrared
SINGS	Spitzer Infrared Nearby Galaxy Survey
SMBH	Super massive black hole
SMC	Small Magellanic Cloud
SMEX	Small Explorer Mission
SNa	Supernova
SPH	Smoothed-particle hydrodynamics
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SPIRE	Spectral and Photometric Imaging Receiver (Herschel)
SSP	Single stellar population
SSS	Super soft X-ray sources
SVOM	Space-based multi-band astronomical Variable Objects Monitor
TAO	Tokyo Astronomical Observatory
TDG	Tidal dwarf galaxy
TRGB	Tip of the red giant branch
UCD	Ultra-compact dwarf
UFD	Ultra-faint dwarfs
UK	United Kingdom
UIT	Ultraviolet Imaging Telescope
UKIRT	United Kingdom InfraRed Telescope
ULIRG	Ultra Luminous InfraRed Galaxy
UVES	Ultraviolet and Visual Echelle Spectrograph (VLT)
UVOT	UltraViolet/Optical Telescope (Swift)
VCC	Virgo Cluster Catalogue
VERA	VLBI Experiments of Radio Astrometry
VIMOS	VIsible Multi-Object Spectrograph at VLT
VIPERS	VIMOS Public Extragalactic Redshift Survey

VLA	Very Large Array
VLBI	Very-long-baseline interferometry
VLT	see ESO-VLT
VLTI	Very Large Telescope Interferometer
VO	Virtual Observatory
VPHAS+	VST/Omegacam Photometric Hα Survey
VUDS	VIMOS Ultra-Deep Survey
VVDS	VIMOS-VLT Deep Survey
WD	White dwarf
WFPC2	Wide Field Planetary Camera 2 (HST)
WFPC3	Wide Field Planetary Camera 3 (HST)
WHT	William Herschel Telescope
WIMP	Weakly Interacting Massive Particle
WINGS	Wide Field Nearby Galaxy cluster Survey
WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe
WSRT	Westerbork Synthesis Radio Telescope
WUPPE	Wisconsin Ultraviolet Photo-Polarimeter Experiment (UIT)
WWII	Word War II
XMM-*Newton*	X-ray Multi-Mirror Mission–Newton Space Telescope
XRB	X-ray binaries
2MASS	Two Micron All Sky Survey
6dFGRS	Six-degree Field Galaxy Redshift Survey

Contents

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Chapter 1
Extragalactic Astronomy: From Pioneers to Big Science

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Le donne, i cavalier, l'arme, gli amori,
Le cortesie, l'audaci imprese io canto [. . .]
L. Ariosto *Orlando Furioso, canto 1, v 1*

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1.1 Outline of the Chapter

*At the beginning of the nineteenth century one of the scientific issues driving the research of astronomers, like the Herschels, was to test if all the nebulæ can be resolved into stars. This research continued uninterruptedly for many years surveying the nebulæ in the Charles Messier's "*Catalogue des nébuleuse et des amas d'étoiles*" published in 1781 and triggered the building of the* cosmological *telescopes of the time, among which the famous* Leviathan of Parsonstown*, a reflector with a mirror of 72 in. diameter (1.82 m) at Birr Castle in Ireland (Hoskins 1982). William Parsons, the Third Earl of Rosse, and other astronomers, such as Thomas Romney Robinson, re-observed with the* Leviathan *a large fraction of nebulæ already inspected by William Herschel. They revealed the spiral structure of the Whirlpool nebula M51 for the first time in 1845, (see e.g. Hoskins 1982), but they only sketched its shape in a notebook. They also wrote that "the nebulæ are resolved [into stars] without exception" (Hoskins 1982). However, the co-existence of stars and nebulosity was annotated by John Herschel describing the Magellanic Clouds in "*Outlines of Astronomy*", published in 1849. The stellar nature of nebulæ remained therefore unsolved.*

The first photographic experiments started with Louis Daguerre in 1824, but only in 1839 François Aragò presented this technique at the Académie des Sciences in Paris. In 1900 photographic cameras were already in use in the astronomical context and photographs by James E. Keeler at the Lick Observatory showed that thousands of nebulæ have a spiral structure similar to M51. The first descriptive classification of nebulæ was devised by Max Wolf in 1908 while the spectra of spiral nebulæ started to be obtained in around 1913 by Vesto Slipher, who obtained the first measure of redshift. Photography began to dissect the structure of spiral nebulæ and Heber Curtis (Curtis 1918) in 1918 showed that "a band of absorbing or occulting matter is crossing some spiral nebulæ".

At the beginning of the 1920s times were mature enough to tackle the fundamental question about their nature: are these nebulæ part of the Galaxy or are they separated Island Universes*? This non-trivial question was the core of the* Great Debate *that took place in 1920 at the Smithsonian Institute in Washington D.C.*

The first Chapter of this book briefly outline the history of astronomy of these years, introducing the work of the pioneers of extragalactic astronomy in the United States and in Europe (Sect. 1.2). Their different opinions about the nature of spiral nebulæ and about the impact of interstellar absorption are reviewed. This historical introduction brings us to the threshold of the Second World War (WWII). The war represented a watershed for the growth of extragalactic astronomy in several countries, whose effects are still present today. For a significant part of the twentieth century astronomers didn't know the scientific results of many colleagues affiliated to different institutes, because the world, and Europe in particular, was divided into blocks. For many years Journals publishing extra-galactic papers and even Catalogs were not easily accessible in many countries. Many authors used only their mother language, complicating the diffusion of scientific results. Only recently, the policy *of using English as the standard language for science communication and that of giving free access to scientific papers, has been widely encouraged by Journals.*

Section 1.3 reports the interviews to several astronomers, active in many areas of the world, about the most important developments of extragalactic research after WWII. Astronomy is a science that has seen in these years a true revolution. Several international institutions were founded together with consortia leading to the accomplishment of ground based and space telescopes equipped with sophisticated instrumentations. In parallel, big international research teams started to work on well defined projects. Astronomers entered in the so-called Big Science *era. Today they are no more alone at their telescopes working hard in the long cold winter nights, they are members of large teams and work on digital data that are stored in their computers. Quite often the youngest astronomers have never experienced a whole night at the telescope!*

Section 1.4 sketches the evolution of detectors and instruments. Their development at the focal planes of ground based telescopes and on board of space facilities determined an increase of spatial and spectral resolution, the widening of the electro-magnetic coverage from gamma-ray to radio, and the possibility of mapping the distant Universe providing the galaxy properties and distribution, and characterizing the different environments.

Section 1.5 deals with the jump to atmospheric free observations provided by space facilities. The growth of space missions provided the first panchromatic view of galaxies. Our interviews sketch the most relevant space missions in the ultraviolet, infrared and X-ray wavelength intervals together with their main achievements.

The explosion of computing power as well as the introduction of the World-Wide-Web network revolutionized our way of working and, as a consequence, also the extragalactic research field. The studies of galaxy evolution through computer simulations bore as soon as computers appeared. Semi-analytical and purely numerical approaches replaced the analytical ones. The interviews in Sect. 1.6 describe such a passage that has largely affected the present and future possibilities of understanding galaxies.

1.2 The Pioneering Time

Questions for James M. Lattis:

Nearly one century has passed since the "Great Debate" of 1920. As a historian of astronomy please sketch for us the physical and philosophical growth of the concept of "galaxy" during those tumultuous years.

Ninety years ago, just as Edwin Hubble was discovering Cepheid variable stars in spiral nebulae, the eminent George Ellery Hale discussed two interesting questions in a book intended for a popular audience: First, what is the distribution of stars through space? Second, what is the nature of spiral nebulae? "We may think of the galactic system as a flattened disk . . . having a diameter of perhaps 300,000 light-years, with the sun at a very considerable distance from the centre. . . . These great dimensions have been denied by Curtis, who argues in favor of a galactic system about one-tenth as large. But more and more evidence is accumulating in favor of the larger conception of Shapley, which has already found wide acceptance among astronomers." On the very question that Hubble was studying, Hale relates that "*The question has not been settled whether [spiral nebulae] are no farther from us than the more distant stars or whether they should be regarded as 'island universes,' isolated in the depths of space and comparable in size with the galactic system. . . Interesting arguments have been advanced on both sides, but these are too numerous to be presented here.*" (G.E. Hale, *The Depths of the Universe*, 1924, pp. 35–36.) Hale here alluded to the famous "Great Debate" of 1920–1921 between Heber Curtis and Harlow Shapley over the associated questions of the size of our own Galaxy (which Hale judged to be swinging in favor of Shapley) and our Galaxy's relationship to the innumerable spiral nebulæ which remained an issue too unsettled to summarize for his readers. In assessing these questions, Hale's summary captures for us a moment in a field of research that was changing very rapidly under the influence of new technologies, but also in response to provocative theories, new and controversial observations, and critical studies and reassessments.

Empirical approaches to these two questions go back to the work of William Herschel , who analysed his laboriously obtained samples of the number of stars per angular area on the sky and derived a rough three-dimensional model of stellar density as a function of direction and distance from the Sun. Herschel also studied and catalogued nebulae with a view to determining (though he never achieved definitive results) whether they were assemblages of stars too numerous and distant to resolve or were truly nebulous in nature.

By the late Nineteenth Century, more sophisticated results became possible through the application of statistical analysis to photographic plates of star fields. The two astronomers most closely associated with this method, Hugo von Seeliger of Munich Observatory and Jacobus Kapteyn of University of Groningen, who elaborated the model for many years, concluded that the Sun was near the center of a distribution of stars on the order of 30,000 light-years in diameter. Their star-counting methods assumed that the visibility of stars was limited by neither the power of their telescopes nor the transparency of space and that the stellar population in the neighborhood of the Sun was typical.

This view of our Galaxy, often labeled the "Kapteyn Universe", had little to say about the nature of the spiral nebulæ although the spiral nebulæ inspired searches for spiral structure in our Galaxy—a path that did not bear fruit until the 1950s. So the composition, size, distance, and relationship to us of the spirals remained a subject of debate, even by the time of Hale's account. Some viewed spirals as swirls of gaseous activity, possibly regions in which stars, perhaps entire star clusters, were forming. Observations of novæ in spirals (e.g. S. Andromedæ of 1885) in an era when the true luminosities of supernovæ were scarcely imaginable, led to rough distance calculations consistent with this view. In addition, the theoretical work of James Jeans in the years around 1920 on the dynamics of collapsing gas clouds seemed to produce results consistent with the observed morphologies of the spirals. So it could be judged reasonable to conclude that the spirals are relatively small, even compared to the Kapteyn-von Seeliger Galaxy, and not too far away.

But another view preferred to see the spirals as stellar in nature, yet at such great distances that individual stars could not be resolved. Evidence for this view could be found, for example, in the spectra of spirals, which showed absorption lines like stellar spectra, and in their large redshifts (first measured by Vesto Slipher ca. 1913), which suggested they could not be gravitationally bound to our local stellar system. This view would imply that the spirals are clouds of stars distinct from our own Galaxy, and the term "island universe" (as used by Hale, for example) became attached to this concept. Given that few limits could be placed on their distances, their sizes relative to the Kapteyn-von Seeliger Galaxy were open to speculation, so many considered them to be in fact "comparable galaxies," i.e. comparable to our own. Heber D. Curtis of Lick Observatory, whom Hale mentions as one of the parties in the "Great Debate", was of this view.

Curtis's opponent in the debate (which was in fact a series of exchanges both in person and in print) was Harlow Shapley, who had been on the staff at Mt. Wilson Observatory but soon moved on to become director of Harvard Observatory in 1921. Beginning about 1918, Shapley had constructed his own calibration of Henrietta Leavitt's Period-Luminosity relationship for Cepheid variable stars. Making the (incorrect) assumption that his calibration could be extended to the variable stars he was finding in globular clusters, he put together a three-dimensional distribution of the globular clusters by finding distances to them based on ultimately on the cluster variable stars. Assuming that the globular cluster distribution was co-extensive with the Galaxy, he could derive the Galaxy's overall size and the location of the Sun within it. He concluded that the Galaxy was about 300,000 light years in diameter (an order of magnitude greater than typical estimates based the Kapteyn-von Seeliger methods) and that the Sun was located far from the center of that distribution, again in contradiction to the Kapteyn Universe. In deriving distances to the globular clusters (Fig. 1.1), Shapley had also assumed that any absorption of starlight in its passage through interstellar space was negligible, despite the obvious presence of obscuring clouds of matter, dark nebulæ , which could be found and photographed in the Milky Way. But in the absence of evidence of more general and subtle effects, he dismissed those regions as local phenomena. Shapley, fully aware of the potential problem, offered a perfunctory argument based on the apparent lack of reddening of the starlight from selected stars of three globular clusters and concluded that the effect was negligible. But in fact the effects of interstellar extinction undermined his conclusions as much as the mistaken identification of the cluster variables with Cepheids.

This Big Galaxy concept, which Shapley sometimes called the Super Galaxy, was the concept that Hale said had "already gained wide acceptance" by 1924 (although Hale's impression of wide acceptance is debateable). Shapley would revise his conclusions in stages, but as late as 1930 he was still arguing that the Galaxy must be at least 200,000 or so light-years in diameter (very roughly twice the currently accepted value). How the two issues of the scale of our Galaxy and

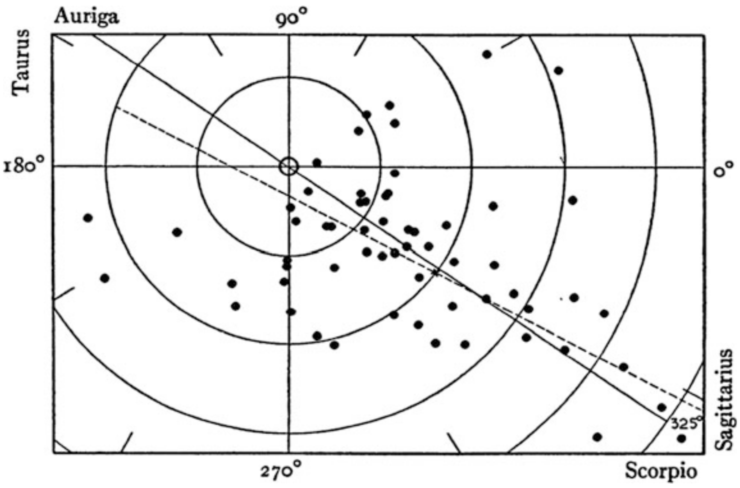

Fig. 1.1 Harlow Shapley's distribution of globular clusters in the plane of the Galaxy with the Sun at the origin. The radial scale is in units of 10,000 parsecs. *Credit*: Contributions from the Mount Wilson Solar Observatory, No. 157, p. 9

the nature of the spiral nebulae became entangled in the "Great Debate" has been much recounted in historical literature, so we can touch on it very briefly here [see for example (Smith 2006)]. The size of Shapley's Super Galaxy was awkward for the "comparable galaxy" view, because it would require "comparable" spiral nebulæ to be at uncomfortably vast distances in order to show their observed angular sizes. Moreover, Adriaan van Maanen, another Mt. Wilson astronomer, argued that he had found proper motions in the structures of several spiral nebulæ by astrometric measurements of photographic plates taken a few years apart. The speed of these motions would have been physically impossible if the nebulae were at island universe distances, so van Maanen's results convinced Shapley and others that the spirals must be relatively small and nearby.

The pivotal discovery of Cepheid variable stars in the Andromeda nebula by Mt. Wilson's Hubble in 1923 resolved almost at a stroke the debate over the nature of the spiral nebulæ. Although Cepheid calibration and the resulting distance was still very rough (and would remain so until Walter Baade's crucial recalibration in 1952), the Andromeda nebula had been shown to be undoubtedly stellar in nature. Hubble's work had demonstrated that its distance and size show it to be an association of stars roughly on the Kapteyn-von Seeliger model and not a small-scale phenomenon–not a nascent star or star cluster. Its status as a comparable galaxy was still questionable, but its island universe nature was not. And the same followed soon for other spirals in which Cepheids could be found. Yet Hubble's discovery did not resolve the other issue in the great debate, because Shapley's distances to globular clusters still implied that our own Galaxy is much larger in size than the Andromeda nebula (and presumably the other spirals). As Shapley himself wrote in 1930 in the wake of Hubble's discovery, "*Ours is a Continent Universe if the average spirals are considered Island Universes.*"

For the idea that spiral nebulæ were "comparable galaxies," the discrepancy in measured sizes between Shapley's Super Galaxy and the apparently smaller Andromeda nebula presented a problem: one or both of the sizes must be mistaken. Quite aside from his debateable identification of the cluster variables as Cepheids, Shapley's neglect of interstellar absorption was also a highly questionable move, so there was ample need to reassess Shapley's globular cluster distances. Furthermore, the other side of the discrepancy was the apparent size of the Andromeda nebula, which was derived from photographic images (known to be limited by such factors as sky brightness), so an independent check on this value might also help shed light on the problem. These important investigations were accomplished by astronomers of the University of Wisconsin's Washburn Observatory, under the leadership of Joel Stebbins, by applying the very new technology of photoelectric photometry. In two separate but coordinated programs, largely in 1933–1936, the Washburn astronomers (Fig. 1.2) calibrated interstellar absorption and derived new, much smaller distances to the globular clusters, thus showing that the Galaxy is much smaller than Shapley's Super Galaxy and arriving at dimensions that are effectively the modern values. They also used photoelectric photometry to show

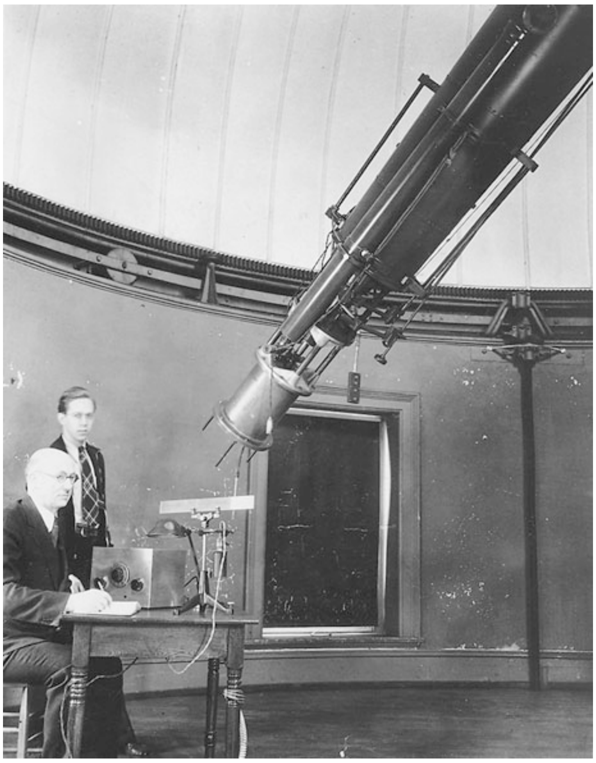

Fig. 1.2 Joel Stebbins (foreground) and Edward Burnett at Washburn Observatory in about 1935. The instrument on the telescope is a Whitford amplifier photometer. *Credit*: University of Wisconsin-Madison Department of Astronomy

that photography had underestimated the diameter of the Andromeda nebula thus showing that it was a comparable galaxy to our own. In the process, they also began to investigate not only the absorption effects but also the physical nature and distribution of interstellar matter and then showed it to contain a large fraction of the Galaxy's mass, thus initiating the modern study of the interstellar medium (Lattis 2014).

The new understanding of interstellar absorption was consistent with the studies of galactic rotation between about 1928 and 1930 by Bertil Lindblad (then of the University of Uppsala, Sweden), Jan Oort (of Leiden Observatory, Netherlands), and John Plaskett (Dominion Astrophysical Observatory, Canada). Their work indicated that the Sun must be relatively far from the galactic center and in about the same direction that Shapley had found, but the distance from the center must be much smaller than Shapley argued. Oort's calculations reduced Shapley's value by about one-third. Thus growing understanding of galactic rotation and interstellar matter had, in the years just before WWII, dramatically modified the Shapley Galaxy and strongly supported the view that the Andromeda nebula and other spiral nebulæ represented countless galaxies comparable to our own. Although the picture would not be substantially complete until the recalibration of the Cepheid variable method, the recognition of stellar populations, and the detection of spiral structure in our own Galaxy, all of which followed quickly after the war, the developments of the 1920s and 1930s had set galactic studies on a new course that left the Shapley Galaxy and Kapteyn Universe behind.

Who have been the most influential scientists in this area up to WWII? Does your historical research suggest the need for a reevaluation of the work of some of these scientists?

Kapteyn and von Seeliger were the authors of the older, established view early in the twentieth Century, and we should first understand that they recognized well the limitations of their statistical approaches to probing the galaxy, in particular that their assumptions about stellar populations, stellar motions, and transparency of space could lead to significant systematic errors. Compared to their statistical methods, Harlow Shapley's program, carried out mostly while he worked at Mt. Wilson Observatory, was as bold and innovative as his results. He assumed the globular clusters could be used as a reference frame, then developed innovative methods to measure their three-dimensional distribution and forged ahead without adequate testing of his assumptions (most notably the identification of cluster variables with Cepheids and the effective transparency of interstellar space). His boldly presented and novel results, that the Sun occupied a location far from the center of a vast Super Galaxy, propelled research in the field for many years.

The essential tension in the other direction, toward the idea that the spiral nebulæ were comparable galaxies, or at least island universes, came largely from the Lick Observatory "school", which included Heber Curtis, Robert Trumpler, and Joel Stebbins, among others, who would advance the debate and research. Trumpler showed in 1930, using photographic methods, that light experiences significant absorption effects in passage through interstellar space, and this result made inevitable the reassessment of Shapley's methods for determining distances to globular clusters. Trumpler's work also produced the very first empirical results on the nature of the interstellar matter responsible for the absorption effects. Curtis, of course, held forth in favor of island universes in the "Great Debate" with Shapley, and Stebbins would bring photoelectric photometry to bear on the problem of interstellar absorption .

A very important, but at first very puzzling result came from Vesto Slipher beginning about 1913. Working at Lowell Observatory, Slipher developed instruments and techniques that produced the first measured radial velocities of spiral nebulæ. The large velocities and predominance of redshifts among his results were interpreted by Shapley as evidence that the spirals were small, tenuous bodies being expelled from the Galaxy by repulsive forces or explosive processes. For advocates of the island universe concept, on the other hand, the radial velocities showed that the nebulae were not part of the galactic system at all. In the later 1920s, Slipher's results were essential in Hubble's formulation of his distance-redshift law.

Edwin Hubble (Fig. 1.3), as mentioned earlier, working also at Mt. Wilson, resolved the island universe debate with his discovery of Cepheid variables in the Andromeda "nebula" and other spirals, which demonstrated their stellar nature and put lower limits on their distances and hence sizes. That discovery left the

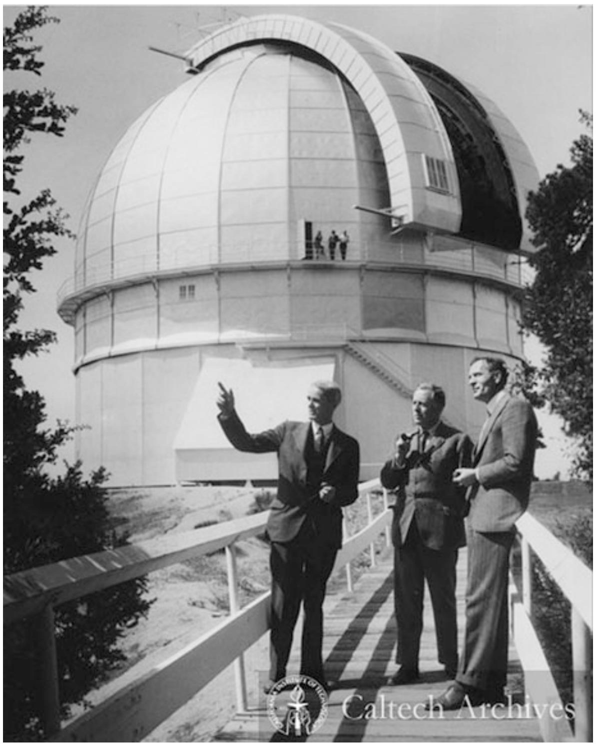

Fig. 1.3 Walter Adams, Sir James Jeans and Edwin Powell Hubble at the 100" dome of Mount Wilson. Courtesy of the Archives, California Institute of Technology

Shapley Super Galaxy intact, however, since the globular cluster distribution was not affected.

The results of Lindblad, Oort, and Plaskett on galactic rotation produced estimates of the distance of the Sun from the galactic dynamical center that were much less than Shapley's results, although they confirmed his determination of the general direction to the center. In contrast to all of the other observational results considered here, which depended on new technologies and very large telescopes, this contribution stands out in being an outgrowth of the European school of statistical astronomy that had produced the Kapteyn-Von Seeliger Galaxy, although applied in this case to stellar radial velocities.

Finally, it is important to note the program of photoelectric photometry led by Joel Stebbins, a member of the Lick school, director of the University of Illinois observatory, and later of the University of Wisconsin's Washburn Observatory. With his Wisconsin colleagues Albert Whitford and C.M. Huffer, Stebbins established a general quantitative model of selective absorption (reddening) of starlight in and near the plane of the Galaxy. Using reddening as an indicator of total absorption (Fig. 1.4), they showed the effect to be a significant, widely distributed factor affecting the apparent brightness and color of stars. Their unique expertise in the new technique made possible several important results in the mid-1930s: Distances to the globular clusters corrected for interstellar absorption; A general survey of interstellar absorption by measuring the colors of thousands of type B stars (a program carried out largely by Huffer); Photometric brightness profiles of the Andromeda nebula showing it to be more extensive than previously thought. Their B-star work demonstrated the extremely nonuniform distribution of absorption in the plane of the Galaxy and showed that a significantly larger fraction of the

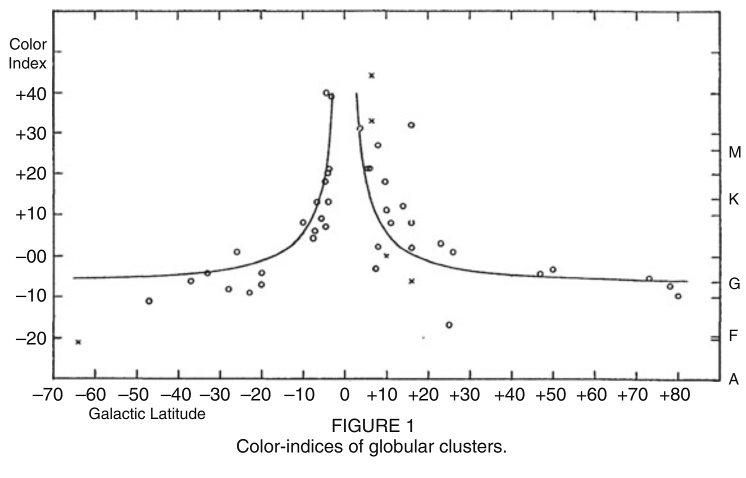

Fig. 1.4 Stebbins's photoelectric color indices, as a function of galactic latitude, of globular clusters showing stronger reddening nearer the plane of the Galaxy. *Credit*: Proc. of the National Academy of Science 19 (1933), p. 225

Galaxy's interstellar mass must be in the form of dust particles (compared to gas) and in a thin region coinciding with the galactic plane. This empirical result confirmed that the distribution of effectively opaque interstellar matter in our Galaxy is comparable to that seen in edge-on images of other spiral galaxies—a dramatic shift from the earlier transparent Galaxy models of both Kapteyn and Shapley. They went on to determine the wavelength dependence of optical interstellar absorption and provide a general method to correct for it.

May you provide us a short inventory of the main instruments available to the pioneers of the extragalactic research?

In early twentieth-century galactic research, typified by the Kapteyn-von Seeliger projects, photography played an essential role in the astrometric methods they employed. This technology made possible the qualitative advance over the methods used by Herschel roughly a century before. It can hardly be over emphasized that the ever more sensitive photographic emulsions being developed by industrial photographic research, often in close collaboration with astronomers, were at the root of most of the important work in galactic research well into the later twentieth century. The work of Shapley, Hubble, Baade, Slipher, and so many others could not have happened without this vital tool.

Also fundamental to most of the significant results in galactic astronomy were the large reflecting telescopes constructed in the western United States early in the century, most notably the Mt. Wilson Observatory 60-in. (completed 1908) and 100-in. (completed 1917). But other high altitude western observatories figure prominently in the scientific developments as well, including University of California's Lick Observatory (where Trumpler demonstrated the existence and significance of interstellar matter) and Lowell Observatory, in Arizona (where Slipher measured radial velocities). Neither of these had large reflectors in this period. The investments of both private and public funds in these observatories, not to mention relative political stability in the USA, helped make these institutions and instruments productive, but also important was their attractiveness to European astronomers (including among the many Baade and Trumpler).

In addition to photography, two other key technologies of modern astrophysics figured in the transformation of galactic astronomy in the early twentieth century. Early spectroscopy, certainly well employed by astronomers already, was not well adapted to analyze the light of dim, diffuse objects, such as the spiral nebulae. Slipher, at Lowell Observatory, had to develop methods much more efficient than the standard prism spectrometers and then learn to photograph the spectra for subsequent analysis in order to obtain his important results.

The newest of the new astrophysical technologies was photoelectric photometry, which had been developed in pre-WWI Germany, where Joel Stebbins first learned the techniques in 1912–1913. He developed them further at the University of Illinois observatory where he collaborated with University of Illinois physicist (and Swiss immigrant) Jakob Kunz to develop their own photoelectric detectors and measurement techniques suitable for astronomical applications. Their early instruments used electrometers to measure the weak photocurrents from the detectors, which were hand-made in Kunz's laboratory. Kunz and Stebbins experimented with photocathode composition (potassium was their favorite) and filler gases (usually argon), which provided some modest amplification. Stebbins moved his research to Washburn Observatory in 1922, but continued the collaboration with Kunz. There in Wisconsin he developed new techniques, such as photometric color-index measurement, and improved the detector technology. His student Albert Whitford developed a much more sensitive instrument, an amplified photometer, which he made by integrating the Kunz tube with a DC amplifier inside a brass vacuum chamber. The amplified output made it possible to read out the instrument with a galvanometer, which was vastly more effective than the electrometer method, and increased the sensitivity of the instrument by two magnitudes. They used this instrument on the large reflectors of Mt. Wilson from the early 1930s, but after WWII it was made obsolete by the availability of photomultiplier detectors.

This vivid view of the 1920–1940 years by James Lattis depicts the passage, still incomplete at that time, from the idea of Super-Galaxy, inherited by the nineteenth century to that of spiral nebulæ seen as Island Universes. None of the main actors of the Great Debate was totally right [see also (Trimble 1995)]. In the Curtis view the Milky Way has a size of 3 kpc with the Sun very near to the center. Shapley proposed a galaxy of 60 kpc diameter and a Sun location at about 20 kpc from the centre. The Galaxy is a normal galactic system, as Curtis suggested, while the Solar system is located at the periphery of the Galaxy, as supported by Shapley. The galactocentric distance of the Sun of 8.5 kpc, suggested by Baade in 1950s, was accepted in 1984 by the International Astronomical Union (Trimble 2001).

Some actors of Great Debate had access to the largest telescopes in the World, the reflectors at Mount Wilson. Others significantly contributed to the debate through the development of new instruments at smaller telescopes, like photometers as Joel Stebbins and collaborators or spectrographs as Vesto Splipher. The European astronomers continued the tradition of stellar statistics contributing significantly to the study of galactic properties like e.g. the Galaxy rotation.

Photoelectric measures by Stebbins, Whitford and Huffer emphasized the presence of an interstellar absorption on the plane of the Galaxy. Not only the interstellar absorption cannot be neglected, at odds with Shapley's suggestions, but it contributes to suggest that the Galaxy has strong analogies with edge-on spiral nebulæ noticed by Shapley in 1918.

The spiral structure of the Milky Way credited to Cornelius Easton (1900), "prediscovered" by Stephen Alexander (1852) (see Trimble 2001) was confirmed within 2 kpc from the Sun in 1951 by Morgan, Sharples and Osterbrock (see Morgan et al. 1951, 1953) making it really similar to other billion of spiral galaxies.

At the end of 1930s the European telescopes could not compete with those overseas. The largest reflector in Europe was the 1.22 m of the University of Padova (Italy) finished in 1942, in the middle of the WWII, 35 years later of the 60 in. (1.5 m) telescope at Mount Wilson and just 5 years before the 200 in. (5 m) Hale telescope at the Palomar Observatory was inaugurated.

1.3 From WWII to the *Big Science*: Some Geographic Angles

The overview of the daybreak of extragalactic astronomy in Sect. 1.2 bring us to the soil of WWII, which may be considered an historical watershed in many respects. If we exclude the North and Latin America continental territories, most of the countries, in particular Europe, the ex Soviet Union (USSR), the Far and Middle East, the North and West Africa, terribly suffered the consequences of WWII.

Europe already exhausted by World War I, both before and after the economic Great Depression of 1929, saw waves of migratory phenomena toward American countries. In particular the United States (USA) was the destination of scientists of many disciplines, including physics and astrophysics. James Lattis already mentioned Jakob Kunz and Walter Baade both German as well as Rudolph Minkowski that collaborated with Baade. In 1925 Fritz Zwicky emigrated from Switzerland. For German and Italian scientists, first the racial persecutions and finally the "racial laws" promulgated at the end of 1930s, were a compelling motivation to leave their countries. We mention Bruno Rossi, one of the fathers of the X-ray astrophysics, and Nobel laureates like Albert Einstein and Enrico Fermi among others.

After 1945, the terrible state of European economy left by WWII on one side and the bloom of scientific investments on the other, further motivated young and/or mature scientists to move towards USA. Foreign scientists found "fertile lands" for their studies in this vast country very attentive to the value of the scientific research. They contributed either to maintain or create the USA scientific leadership in many Science branches up today. In the following interviews of Martha Haynes and Riccardo Giovanelli the growth of the US extragalactic astronomy in the optical and radio domain just after WWII and the contribution of some distinguished migrants are reviewed.

1.3.1 USA: Preserving the Leadership

Questions for Martha P. Haynes:

The United States assumed the leadership in extragalactic research after the "Great Debate" with largely philanthropic support up to the inauguration of the Palomar 200 in. telescope with government support emerging in the 1950s and 1960s (i.e NRAO and KPNO). Is it possible to identify the dominant scientific currents (and scientists) in US extragalactic research after WWII?

Indeed, the second World War made obvious to the U.S. federal government the strategic national importance of scientific research as never before. Before the war, the U.S. government invested very little in research, but not long after the U.S. entered the conflict, Vannevar Bush, the president of the Carnegie Institution and a very influential person in Washington, convinced President Roosevelt to establish a new organization designed to stimulate and oversee research in support of the military effort. By the end of the war, Bush was even more firmly convinced of the critical need for government support for the research enterprise, and in 1945, published a highly influential article in which he called for the establishment of a "National Research Foundation" (Bush 1945). As a result, the U.S. National Science Foundation was established in 1950, and since then, federal investment has played a critical role in the development of astronomy in the U.S.

Also coincident with the World War was an important piece of U.S. federal legislation, the so-called "G.I. bill" (*Serviceman's Readjustment Act of 1944—General Records of the United States Government*), passed in 1944, which provided support for returning soldiers, among other things, to attend college. This financial aid program led directly to a huge influx of veterans into higher education and, bolstered by educational support from state governments, a significant growth in the capacity and strength of colleges and universities across the country. In addition to the importance of the expansion of peacetime federal investment in research, astronomy in the U.S. benefited hugely from the growth of the universities and the recognized importance of sustained investment in the research enterprise. There are current worries about whether this linkage, and the federal investment that arises from it, will be continued, but that is not the subject of our discussion here.

The war itself caused a delay in the construction of the 200 in. Hale telescope at the Palomar Observatory. While much of the telescope and dome was completed before the war, the mirror did not arrive at Palomar until 1947. On the other hand, Walter Baade, a German national, took advantage of the dark skies resulting from the wartime blackout to make seminal discoveries with the Mount Wilson 100-in. telescope. His understanding of the two types of Cepheids (Populations I and II) led to a revised measurement of the expansion factor ("Hubble's constant") and thus a doubling of the distance scale .

In the written version of a talk given in 1947 discussing the potential of the Hale telescope then under construction, Hubble (Hubble 1947) pointed out that the availability of new instrumentation, the telescope, led Galileo to innumerable discoveries unknown to humans beforehand. In his lecture, Hubble emphasized the scientific "problems" that might be solved once the new telescope, with its revolutionary new capabilities in angular and spectral resolution and in sensitivity, would be available. Curiously, his first example of the importance of new capability in high resolution imaging is directed at settling the controversy of whether on not there are canals on Mars. The other two big advances which Hubble predicts center on the importance of spectroscopy, for determining the sources of energy, for tracing the origin of cosmic abundances and for measuring redshifts. As soon as the telescope was completed a few years later, important results were delivered at a very fast pace. Indeed, as today, new instruments with new capabilities deliver new science.

The rapid rate of extragalactic discoveries in the next decade make a summary of them impossible. But a few important trends can be found.

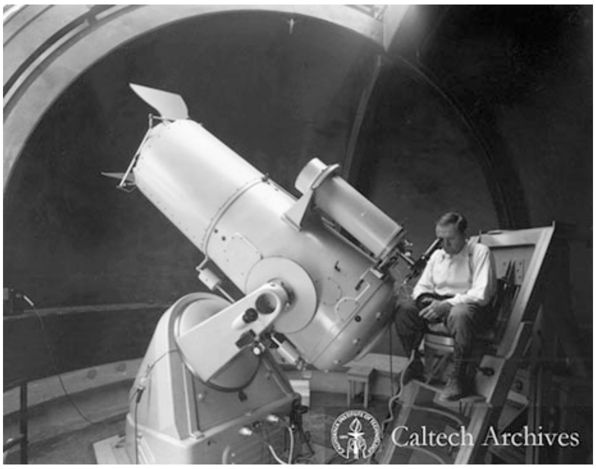

Fig. 1.5 Fritz Zwicky at the 18" Schmidt telescope of Palomar Observatory

- First, *the future importance of multiwavelength astronomy* is highlighted by Baade and Minkowski's identification and confirming spectroscopy (with both the 200-in. Palomar telescope and the 100-in. at Mount Wilson) of the optical counterpart galaxy of the radio source Cygnus A (Baade and Minkowski 1954), the first hint that radio emission could arise from mundane faint galaxies.
- Continuing Zwicky's (Fig. 1.5) speculations on the need for "dark matter" (Zwicky 1937), numerous others, including Burbidge and Burbidge (1959) reached the similar conclusion that additional mass was required to stabilize clusters of galaxies.
- The discovery by Schmidt (1963) of the large redshift of the star-like object associated with the strong radio source 3C 273 *expanded again our sense of the scale of the Universe*.
- Lastly, *the large scale structure in the galaxy distribution* became more evident for example, as advocated, in the case of the Local Supercluster, by de Vaucouleurs (1958); it is interesting to read that paper, as he claims to detect rotation of the "supersystem". The mapping of the number counts of galaxies in the Lick Observatory Survey by Shane and Wirtanen (1954) might even be considered a precursor to the modern "big science" surveys.

On a more personal front, 1951 brought the first detection of emission via the HI 21 cm line from diffuse atomic hydrogen in the Milky Way just a month before I was born. Their horn antenna is now displayed in front of the Jansky Lab at the NRAO site in Green Bank where I did much of my PhD research and served as site director in the 1980s. *While the detection experiment itself was not a great leap forward for extragalactic astronomy, the study of the HI line was quickly extended to extragalactic objects* first the Magellanic Clouds (Kerr53) and later other obvious nearby candidates like M 33 using existing small radio telescopes in the U.S. (Dieter 1957) and elsewhere (Raimond and Volders 1957). Eleven years later, Roberts (1962) who would become my PhD mentor published his first paper on neutral hydrogen in a sample of nine(!) galaxies, noting among other things the anti-correlation between continuum emission and line emission, setting up many future studies of the gas content and its variation among galaxies of different types including many of my own.

Martha Haynes in the last paragraph has introduced the progresses made in the observations of galaxies in the radio domain. We ask now Riccardo Giovanelli to provide an historical overview of the development of radio astronomy and its contribution to our understanding of galaxies.

1.3.1.1 The Progresses in Radio Astronomy

Questions for Riccardo Giovanelli:

developments in radio instrumentation have enabled very detailed radio imagery as well as wide field surveys of galaxies. Please give us an historical overview of developments in extragalactic research made possible from radio studies.

On 26 April 1920, Harlow Shapley and Heber Curtis debated on the nature of spiral nebulae and the size of the Universe. By 1925, the work of Hubble showed clearly that those nebulæ were "Island Universes", assemblages of stars like our Milky Way, as Immanuel Kant had postulated in the eighteenth century. It took 30 more years to demonstrate that the origin of heavy elements took place in the nuclear furnaces in the cores of those stars, Hoyle et al. (1956) and Burbidge et al. (1957), albeit a correction to that idea was needed in order (Hoyle and Tayler 1964) to explain the constancy of Helium abundance in all measured sources, i.e. as George Gamow had suspected, primordial nucleosynthesis played an important role too (Hoyle and Tayler 1964). In the meantime, understanding of the dynamics of galaxies through optical spectroscopy observations grew slowly: the review by Burbidge and Burbidge (published in 1975 but submitted in 1969) provides a useful compendium of the state of affairs at just about the time that radio spectroscopy was coming of age.

In 1933 Karl Jansky reported *Electrical Disturbances Apparently of Extraterrestrial Origin*. Electrical engineers of the epoch referred to what he called an "electrical disturbance" as *Jansky noise*, a nuisance which set a limit to the sensitivity of radio communications devices on Earth. The study of Jansky noise took two more decades and the end of World War II—freeing many a bright antenna engineer from defensive radar concerns—to bloom into a respectable field of cosmic research. In Leiden, Oort and Van de Hulst made good use of wartime by predicting the detectability of the 21 cm spectral line of atomic hydrogen (HI), which Ewen and Purcell first detected in 1951. Two years later, Kerr and Hindman observed the HI emission the Magellanic Clouds. The two decades that followed may well be the era of fastest development of astronomical facilities, particularly radio. Benefiting from the perceived challenge set by Sputnik and the ensuing race to the Moon, the establishment of major observatories took place in the US between the late 1950s and early 1960s. The 300 ft and the 140 ft[1] were built in Green Bank by the National Radio Astronomy Observatory. Both of them were important in my personal history, for I used them for my PhD thesis. I still keep a few samples of the 80-character cards used to input commands to the telescope by the on-line computer, which was able to read as many as 12 (yes, you read right: twelve) cards in a single load. Several US universities made important investments in radio astronomy in the 1960s, seeds that were to grow into a healthy and diverse community. I fear that phase of growth at academic institutions is now rapidly fading, starved and cornered by the avid appetites of large and costly international facilities. Unfortunately, the saying that "you can't have it all" applies conspicuously to the present historical period. Some of the radio telescopes built in that pioneering period still operate today. Among them are illustrious work horses in the history of HI astronomy like the Australian 64 m dish at Parkes, completed in 1961, the French antenna at Nancay, completed in 1965, and the 305 m stationary primary reflector in Arecibo, built by Cornell University and completed in 1963.

In his review on extragalactic HI radio astronomy, (Roberts 1975) summarized the results of work in the field during the decade of the 1960s. The number of sources surveyed was relatively small ($\sim$ 140) in comparison with more recent standards, but the scientific potential of the technique appeared to be substantial. Its advantages derived from several motives:

- Rapid improvement in receiver and back-end digital technology, yielding higher sensitivities, broader instantaneous bandwidths and higher spectral resolutions, took place, particularly in the 1960s and 1970s.
- The completion of large interferometric arrays in the 1970s, principally the one at Westerbork (`WSRT`) and `NRAO`'s Very Large Array (`VLA`) and, more recently, the Indian `GMRT` .
- The Arecibo telescope underwent two major upgrades after construction. The first, completed in 1974, replaced its primary surface with one of higher quality, making possible operation at 21 cm. The second, completed in the late 1990s,

[1]The 140 ft telescope was initially planned to be the first major instrument of NRAO. Because it was feared that computers would not be able to effectively point a large alt-az telescope, the 140 ft was designed to have a (very expensive) equatorial mounting. In late 1960, it was realized that parts of the mount design were vulnerable to brittle fracture. The redesign would impose a delay of years; hence it was decided that a large, but cheap 300 ft transit telescope with a surface of high enough quality for operation at a wavelength of 21 cm should be built, and built fast. Less than 2 years later, the 300 ft telescope designed by John Findlay was completed and NRAO's image, affected by the 140 ft delay, was restored. According to Findlay, a brilliant scientist/engineer with a sharp sense of humour, the 300 ft was built *"for the price of sugar: 68 cents per pound"* (Burke 2005). The 140 ft was eventually inaugurated in 1965. On the night of November 15, 1988, the 300 ft telescope collapsed, after one quarter of a century of fine service. On that day, in the course of the annual meeting of the Arecibo Observatory Board of Trustees, I was addressing the Board and representatives of the National Science Foundation on the need to allocate funds for an engineering inspection of the telescope's focal platform structural health. On the following day, after hearing news of the 300 ft collapse, the decision to inspect and the funds to do it were unanimously approved.

corrected the aberration of its spherical primary by the addition of secondary and tertiary subreflectors. This allowed for the telescope to have an extended field of view, making possible the operation of multiple feed detectors and thus increasing by nearly one order of magnitude its mapping speed and converting it into a powerful wide field survey machine.

- The nature of the 21 cm line and the distribution of HI in galaxies. The 21 cm line results from the transition between hyperfine energy levels of atomic hydrogen, so its natural width is extremely small. Much of the HI in a galaxy disk is found in a thermally stable, warm phase of 5000–8000 K, filling most of the disk volume. The galaxy disks are thus optically thin and the line flux can be safely converted to a gas column density and the integral flux to a gas mass. Moreover, the gas distribution in a galaxy disk is generally more radially extended than that of stars, allowing sampling of the gravitational potential well of a galaxy to greater radii than stars do.

Together with the National Radio Astronomy Observatory (NRAO) the USA founded national centers operating in the optical and, later, in IR band ground based astronomical facilities. One of these is the Kitt Peak National Observatory (KPNO), founded in 1958. Today KPNO is part of the National Optical Astronomy Observatory (NOAO) a system that operates in addition to the Cerro Tololo Inter-American Observatory (CTIO) and the NOAO System Science Center (NSSC) with a set of telescopes from 2-m to 10-m in both hemispheres. One of the future NOAO projects is the building of the Large Synoptic Survey Telescope (LSST) (see Chaps. 6 and 9) for deep galaxy surveys.

Since the eighteenth century one of the fundamental and systematic efforts made by astronomers was to catalog the properties of nebulæ. This work of inspection, galaxy–by–galaxy, either visual or automatic, was invaluable to test different hypotheses, but quite soon emerged the necessity of working with statistically significant samples. In 1950 the 48 in. Samuel Oschin Schmidt telescope started its operation at Mount Palomar producing the first sky surveys. This telescope recorded observations on photographic plates with sides of 14 in. corresponding to about $6^\circ \times 6^\circ$ *on the sky. The complete surveys made in blue and red filters covered all the Northern Hemisphere and extends up to* -20° *in declination. In 1971 a similar telescope with a Schmidt aperture of 1.0 m became operative for ESO at La Silla in Chile, starting the Southern sky survey.*

The Palomar Observatory Sky Surveys in the Northern Hemisphere and the ESO-SERC Southern Hemisphere survey played a unique role in exploring the manifold of galaxy morphologies, producing a detailed inventory of galaxy properties and numerous catalogues of galaxy associations.

This book will dedicate Chap. 5 to explore the impact of surveys on galaxies understanding. The next interviews will instead sketch the development of extragalactic astronomy in the rest of the world.

1.3.2 *The Extragalactic Research in the Ex Soviet Union*

Questions for Valentina Karachentseva:

Over more then five decades the USSR and eastern block countries competed in the scientific and technological arenas with the USA. The research in extragalactic astronomy continues today in Russia and CSI countries. Please, give us a brief overview of the first years of extragalactic research in this part of the world, together with your opinions on the main scientific achievements.

Contemporary young astronomers probably find it difficult to imagine the enormous role played by the photographic surveys of the sky—the Palomar Observatory Sky Survey, and then the `ESO-SERC` Survey in the study of galaxies. The scientists got to see the entire sky in a variety of objects up to the 21–22 stellar magnitude. Not to mention the purely aesthetic pleasure, the survey provided an opportunity to do a lot of fundamental work. Therefore, I believe that the acquisition by the astronomical institutions of the USSR of the prints from the photographic sky survey `POSS-1` and then the `ESO-SERC` was a very important event. I will try to make a brief description of the main, in my opinion, results, obtained from the 1960s and up to the early 1990s. As a rule, they refer to the studies that caused a great resonance and a vigorous observational and theoretical development.

Victor A. Ambartsumian (Fig. 1.6) has concluded in the fifties that supermassive bodies have to exist in the Universe and that in many cases these supermassive and superdense bodies are located in the galactic centers, representing the central cores. In 1961, at a regular congress of the International Astronomical Union (IAU) in Berkeley, Ambartsumian made an extensive report on the activity of galactic nuclei, which attracted great interest. Although later the nature and existence of the hypothetical "D-bodies" was not confirmed, the idea about the active processes in the nuclei of galaxies has proved to be very fruitful. At the IAU symposium 29 (Ambartsumian 1968) Ambartsumian analyzed the available observational data in support of his view that the activity of the nucleus is the main factor, determining the formation and evolution of galaxies. In his program speech, he made a description of different types of active galaxies, and showed that the nuclei of galaxies have a huge range of luminosities. In this regard, I believe it was very important that

Fig. 1.6 Armenian banknote with an image of Viktor Amazaspovich Ambartsumian. Courtesy of Valentina Karachentseva

Fig. 1.7 Armenian stamp dedicated to Beniamin Markarian. Courtesy of Valentina Karachentseva

Ambartsumian noticed the absence of the observed nuclei in the nearby galaxies of the Local Group—the Magellanic Clouds, as well as in the Sculptor and Fornax, which are characterized by very low surface brightness. Since the early 1960s to the present day a huge amount of observational and theoretical studies devoted to the galaxies with active galactic nuclei (AGN) has been accomplished.

Markarian (Fig. 1.7) in 1963, analyzing the literature data and the results of the surface photometry of galaxies, made in Byurakan, revealed the existence among the bright galaxies of a special category of objects with abnormal color and spectral characteristics. To explain the observed phenomenon he was the first to put forward the idea of the presence in the galactic nuclei of ultraviolet (UV) radiation having non-thermal nature. Markarian developed a special methodology and conducted a survey of the northern sky (at high Galactic latitudes) at the Byurakan 1-meter Schmidt telescope in combination with a set of objective prisms. The images of the survey revealed faint galaxies (13–17 magnitude) having intense ultraviolet continuum caused by excess UV radiation. "Blue Galaxies" (in the terminology of Ambartsumian) from the first three lists of Markarian were observed by E. Khachikian and D. Weedman on the 2.5-m telescope with a slit spectrograph of the Mt.Wilson Observatory. The spectra of these galaxies have demonstrated broad emission lines and it was found that a significant portion of galaxies discovered by Markarian are Seyfert galaxies. Ambartsumian suggested that the galaxies discovered in Byurakan were called the "Markarian galaxies". This term is now commonly used in the international literature. In parallel, work was carried out to produce new galaxy lists (there were 15 of them in the first Byurakan survey) and to obtain the spectra of Markarian galaxies at various telescopes with image-tubes in Byurakan (2.6-m), Crimea (2.6-m, 1.25-m), Alma-Ata (70-cm), and since 1976 at the 6-m telescope of the Special Astrophysical Observatory of the Academy of Sciences of the USSR.

The following scientists participated in this extensive work under the direction of Markarian: V.A. Lipovetsky (whose contribution to the work at all stages is difficult to overestimate), G.A. Stepanian, V.L. Afanasiev, E.A. Dibai, I.I. Pronik, V.I. Pronik, E.A. Denisuyk, A.R. Petrosyan, K.A. Sahakian, L.K. Yerastova, A.I. Shapovalova and other astronomers.

An extensive reference catalog of 959 Seyfert galaxies (245 of them are the Markarian galaxies) containing observational data obtained before 1987 was published by Lipovetsky and collaborators (1987). More than 900 references were cited in this catalog, including numerous studies carried out by the Soviet astronomers. The physical conditions in the nuclear and perinuclear regions of the Markarian galaxies were studied by V.L. Afanasiev, V.P. Arkhipova, E.A. Dibai and others. The catalog of galaxies with an ultraviolet excess, the First Byurakan Survey—FBS, was published in 1989 (Markarian et al. 1989). The updated version of the Catalog of Markarian Galaxies has been published by Petrosian and collaborators in 2007 (also see an enormous reference list therein). Selection principles established by Markarian were as well applied in the preparation of a deeper Second Byurakan Survey.

Based on the material of the First Palomar Sky Survey, B.A. Vorontsov-Velyaminov together with V.P. Arkhipova and A.A. Krasnogorskaya compiled and published five volumes of the Morphological Catalog of Galaxies (MCG), well-known internationally, which included about 35 thousand objects of the northern and a half of the southern sky (Vorontsov-Veliaminov et al. 1962). Vorontsov-Velyaminov paid particular attention to the search and classification of interacting galaxies. This term was coined to refer to the systems of two or more galaxies with signs of distortion in the structure. Vorontsov-Velyaminov irrespective to H. Arp has discovered about two thousand similar systems that were included in the catalog of interacting galaxies (published in two parts in 1959 and 1977 (Vorontsov-Veliaminov 1959, 1977)). He and the members of the Sternberg Astronomical Institute, A.V. Zasov, V.P. Arkhipova, R.I. Noskova, V.A. Dostal and others observed the spectra of the interacting galaxies at the 6-m BTA telescope. Studying the spectra of interacting galaxies, Vorontsov-Velyaminov and colleagues have detected rotation in nearly fifty such stellar systems and estimated their masses, discovered in most of them the abundance of gas and have proven that they are undergoing active star formation.

On the maps of the Palomar Atlas V.E. Karachentseva (1966, 1972, 1973) has discovered about 300 dwarf galaxies of low surface brightness, presumably Sculptor-type. It turned out that their distribution in the sky repeats the distribution of bright galaxies, showing strong concentrations in the Virgo cluster and in the nearby groups.

In 1966, I.D. Karachentsev showed that in systems of galaxies from pairs to superclusters, virial "mass-luminosity" ratio increases with the growth of the population in the system. In modern terminology, this means that in the groups and clusters of galaxies, the ratio of the dark (virial) mass to the stellar mass increases systematically with size and population of the given galactic system.

The Palomar Atlas along with the CGCG (Catalog of Galaxies and Clusters of Galaxies) by Zwicky et al. was also used in the preparation of three catalogs well-known to date: 603 isolated pairs of galaxies in the northern sky, CPG (Karachentsev 1972), the Catalog of 1050 isolated galaxies, CIG (Karachentseva 1973) and the Catalog of isolated triplets of galaxies, CTG (Karachentseva et al. 1979). From the spectra obtained with the 6-m telescope, the authors have determined radial velocities of more than 1000 galaxies of these catalogs.

Importantly, all three catalogs were compiled based on homogeneous photographic material to a uniform limiting magnitude (15.7 mag) and using the selection criteria specially developed for each catalog. This made it possible to use isolated galaxies as a control sample when comparing the properties of galaxies in pairs and triplets. It was shown for the first time, that in the CGCG catalog the fraction of isolated galaxies makes up less than 4 %, and over 75 % of isolated galaxies are spirals. In his book titled "Double Galaxies" Karachentsev (1987) gave a detailed description of the observed properties of galaxies in pairs and considered in detail the questions of the structure, kinematics and dynamics of these systems. Karachentsev has shown that the use of high-accuracy values of radial velocities and the elimination of optical members allows to estimate the average mass-luminosity ratio for the physical pairs of about 8–10 in solar units, i.e. corresponding to the normal values in the absence of massive coronas. Using direct photographs obtained with the 6 m telescope, many dwarf galaxies in the M81 group were first resolved into stars and the Atlas of dwarf galaxies in this group was published (Karachentseva et al. 1985).

At the beginning of the 1970s J. Einasto and his colleagues J. Yaaniste, M. Yyeveer, A. Kaazik, P. Kalamees, E. Saar, E.Tago, P. Trat, J. Vennik from the Tõravere Observatory, A. Chernin from the Leningrad Physico-Technical Institute identified a new class of aggregates of galaxies, which were called "hypergalaxies" (Einasto et al. 1974).

The center of hypergalaxies may host one or more massive galaxies or a compact group of galaxies. According to the view of the authors, the center is surrounded by a cloud of dwarf galaxies, and the whole system is immersed in a massive invisible crown (halo), having dimensions that significantly exceed the apparent size of the system. The heated debates have accompanied the emergence of this hypothesis. Now the existence of dark matter is well recognized, but its nature is still a mystery.

Based on the material of the three-dimensional distribution of galaxies and their systems, J. Einasto, M. Yyeveer, E. Saar and J. Yaaniste have revealed the large-scale structure of the Universe. The authors have found that the galaxies and clusters of galaxies tend to get grouped in the superclusters, which form cellular structures in the space, consisting of chains, clumps and voids between them (Einasto 1981). This observational material has united a group of Estonian astrophysicists with the group of Moscow cosmologists.

The principal place in the works of Ya.B. Zeldovich on the cosmology was occupied by the problem of formation of the large-scale structure of the Universe. Ya.B. Zeldovich with his co-workers (A.G. Doroshkevich, R.A. Sunyaev, I.D. Novikov, S.F. Shandarin and others) created the theory of increasing perturbations in the "hot" Universe during the cosmological expansion and considered some problems associated with the formation of galaxies as a result of gravitational instability of these disturbances. The authors showed that the resulting high-density formations, which are probably the proto-clusters of galaxies, are flat (Zeldovich

1978). Numerical calculations of the large-scale structure as a whole were in good agreement with the data of the Estonian group.

In collaboration with R.A. Sunyaev, Ya.B. Zeldovich created the theory of distorting of the cosmic microwave background radiation by the high energy electrons and predicted a physical phenomenon which is known now as the Sunyaev-Zeldovich effect (Sunyaev and Zeldovich 1972). Observed distortions of the CMB spectrum are used to detect the density perturbations of the Universe. A number of effects predicted by Zeldovich have been experimentally confirmed. In recent years, giant empty regions were discovered in the Universe, surrounded by the condensations of galaxies. Using the Sunyaev-Zeldovich effect, dense clusters of galaxies have been observed.

Before 1990 many research reports from the USSR were published in Russian journals and in Russian or Armenian languages. Please tell us what were the main journals (and observing facilities) for the study of galaxies.

Starting from the 1950s and into the late 1980s Soviet astronomers had the following journals and facilities in use.

Union-wide monthly journals, publishing the papers on the cosmology and extragalactic research: Astronomical Journal, Astrophysics (1965), Astronomy Letters (1975), Kinematics and Physics of Celestial Bodies (1985). These journals have been translated into English. In addition, the studies on the extragalactic topics were published in the editions of the observatories (such as the Tartu, Byurakan, Crimean Astrophysical, Special Astrophysical Observatory are further called the main editions). Certain studies were published in the Bulletins of the Moscow, Leningrad and Kiev universities. Of course, the research published in English helped the results to "penetrate" to the West much faster. To avoid the information gap, Soviet scientists prepared short surveys of extragalactic research in the USSR for the Transactions of the IAU. They were published every 3 years from 1961 until the 1980s. Starting from 1952, a monthly Abstract Journal (Referativnyj Zhurnal) of the VINITI of the Soviet Academy of Sciences was published—a periodic scientific and informational publication that printed the abstracts, annotations and bibliographic descriptions of the domestic and foreign publications, including the field of astronomy. Astronomical literature exchange between the Soviet and Western libraries was, unfortunately, incomplete and not always regular. Therefore the conferences, working groups, seminars, especially with the participation of foreign researchers were extremely important. I shall note the IAU Symposia held in Byurakan in 1966 was dedicated to the non-stationary processes in the galaxies (Ambartsumian 1968) and the large-scale structure of the Universe held in Tallinn, 1977 (Longair and Einasto 1978).

Referring to the observations of galaxies the most important facilities were the following.

- The Crimean Astrophysical Observatory: ZTSh (Shajn 2.6-m—1961).
- The Byurakan Astrophysical Observatory: the 1-m Schmidt telescope (since 1961). The telescope had three objective prisms with small angles, with the aid

of which the spectra of faint stars and galaxies were obtained; the 50-cm Schmidt telescope; the BAO 2.6-m telescope (a "twin" of the ZTSh);

- The observational station of the Sternberg Astronomical Institute (SAI) in the Crimea: the 125-, 60- and 48-cm reflectors.
- The Astrophysical Institute (Alma-Ata Observatory): the 70-cm telescope.
- The Special Astrophysical Observatory: the 6-m BTA telescope (since 1976); the 1-m Zeiss telescope; the 60-cm Zeiss telescope.

To obtain the spectra at the prime focus of the BTA, before the stationary spectrograph was mounted, the UAGS spectrograph was equipped with an image-tube by V.L. Afanasiev, V.A. Lipovetsky, A.A. Pimonov and others.

The contributions to extragalactic astronomy sketched by Valentina Karachentseva continue to have an enormous impact on our galaxy understanding (see Chap. 2). Unfortunately they were sometimes simply unknown to the western extragalactic researchers who were not used to read the Journals beyond the Iron Curtain, even if translated into English.

For many years the BTA-6 alt-azimuth telescope at Bolshoy Zelenchuk in North Caucasus (Russia) remained the only other Hale-class telescope in the World. Some 4 m class telescopes were operative at the end of 1970s. Preferred sites were in the Southern Hemisphere. UK and Australia in 1975 made operative the 3.8 m Anglo-Australian Telescope (AAT) at Coonabarabran (Australia) just before the 3.6 m of ESO that started its operation in 1977 at Cerro La Silla (Chile).

In the Northern Hemisphere, the United Kingdom (UK) started in 1987 the scientific observations with the 4.2 m William Herschel Telescope (WHT) in Canary Islands (Spain).

The next interview to Malcolm Longair is addressed to highlight the collaboration between United Kingdom and Commonwealth countries in this very fruitful period for extragalactic research.

1.3.3 UK and Commonwealth Countries

Questions for Malcolm Longair:

There has been a long lasting and fruitful collaboration between the UK, Canada, Australia, South Africa and other Commonwealth countries. Can you tell us what you think were the main scientific drivers, successes and leaders in the extragalactic field?

The origin of the United Kingdom's involvement with the countries of the British Empire, and subsequently the Commonwealth, stem from the UK's status as an island state, strongly dependent upon sea trade and naval defence. The Royal Observatories and the Observatory at the Cape of Good Hope in South Africa were set up principally to keep track of time and latitude and provide Nautical Almanacs for use at sea. What we would now regard as more purely astronomical activities were carried out by astronomers such as the Herschels. John Herschel built his observatory in South Africa to complete the Catalogue of Nebulae which was begun by his father for nebulae in the Northern Hemisphere. Most of the countries of the Commonwealth had their own Observatories which combined their astronomical and time-keeping roles.

In the post-World War II era, many countries sought to emulate the endeavours of the American pioneers who dominated astronomical and astrophysical research, largely thanks to the endowments of private benefactors with an interest in astronomy—Lick, Carnegie, Yerkes and so on. This philanthropy led to the construction of the large US optical telescopes, including instruments such as the Hooker 100-in. and the Palomar 200-in. telescopes of the Mount Wilson and Palomar Observatories. In the UK, funding on that scale could only be provided by the government. Plans for a Northern Hemisphere Observatory were drawn up in the 1950s, but these were very expensive instruments, even with the increasing investment in science after the War. Discussions were held about whether or not the UK should join the fledgling European Southern Observatory, the alternative being to join with the Australian astronomers in what became the Anglo-Australian Observatory. In the end, although the site on Siding Spring Mountain in New South Wales was not as good as the very best sites in the world, this option was adopted and it proved to be more than adequate for carrying out front-line astronomical research.

In my view, there were two key features of the development of the AAO from the UK perspective. Firstly, it gave all UK astronomers access to first rate contemporary observing facilities with which they could compete scientifically with the leading US observational astronomers. There had to be a strong element of ‘community training’ to bring the UK astronomers and astrophysicists up to speed in the area of advanced observational astrophysics.

The second feature was the piece of good fortune that Alec Boksenberg and his colleagues at University College London had developed the Image Photon Counting System (IPCS) and this was by far the most powerful optical spectrograph system available world-wide. In addition to his own IPCS, a common-user version was built for the AAT which gave UK astronomers access to the most powerful spectrographic observations available at that time. The particular feature of importance of the IPCS was that it recorded the arrival of individual photons on the phosphor of an image tube which was then scanned by a television camera. The software then identified the arrival of the individual photons. This meant that the system was ideal for the study of faint extragalactic objects such as quasars and distance galaxies. Because of the excellence of this ‘digital’ spectrograph, Alec and his collaborators had essentially unlimited access to the largest telescopes in the world. In addition many members of the UK community took full advantage of the opportunities offered by these remarkable instruments. As a result, extragalactic optical astronomy developed very rapidly in the UK, and also provided complementary support to the world-leading radio astronomy facilities which the UK had built up over the period 1945–1980. As the ambitions of the astronomers developed, plans for the Northern Hemisphere Observatory were revived and these led to the construction of the UK-led William Herschel Telescope on La Palma.

My own opinion is that clear highlights of the AAO programmes were extragalactic studies of the large-scale structure of the distribution of galaxies, the evolution of the population of radio loud and radio quiet quasars and the studies of quasar absorption line systems. I would couple this statement with the remark that strategically important decisions were made to develop instruments such as the AAT Two-Degree-Field multi-object spectrograph which, although expensive, complex and dedicated to one large and very important programme, more than repaid the investment through the outstanding contributions which were made to the definition of the large-scale structure of the distribution of galaxies, quasars and astrophysical cosmology.

The collaboration in millimetre astronomy was a legacy of the mutual radio astronomical interests of the UK and Canada in exploring the sub-millimetre wavebands with the James Clerk Maxwell Telescope (JCMT) in Hawaii. There, the emphasis was much more upon the use of sub-millimetre emission lines to study the processes of star formation. Perhaps the most significant advance made by the JCMT in extragalactic astronomy was the discovery made by the SCUBA submillimetre bolometer array of a population of intense sub-millimetre galaxies, which turned out to be among the most extreme starburst galaxies known.

In 2002 the United Kingdom associated to the European Southern Observatory (ESO). The ESO convention was signed in 1962 by five founding European members, Belgium, France, Germany, The Netherlands and Sweden. Today 16 countries are ESO members and its telescopes rivaled for size and kind of instrumentation with the best ones in the World. We ask now Per-Olof Lindblad about the motivations, especially those in the extragalactic area, that inspired the five co-founder countries.

1.3.4 The Dream of European Astronomers After WWII

Question for Per-Olof Lindblad:

In 1962 a few European countries including Sweden founded the European Southern Observatory. Please sketch the principal scientific achievements in extragalactic research that have come from this facility.

In the middle of the twentieth century European astronomers were badly equipped with observational facilities for extragalactic research. In many institutes the setup of astronomical instruments was old-fashioned, new instruments were of moderate size compared to competitors in other parts of the world, and placed in sites with poor weather and seeing conditions. In Northern Europe, furthermore, the bright summer nights would preclude any extragalactic observations during the summer season.

The main instruments driving the research in extragalactic astronomy in the first half of the century were the telescopes on the West coast of the United States: the relatively modest 36-in. (90 cm) Crossley reflector at Lick Observatory, the 100-in.

(2.5 m) Hooker telescope at Mt Wilson and, from 1948, the 200-in. (5 m) telescope at Palomar Mountain in California, as well as the 82-in. (2 m) Mc Donald reflector in Texas.

The possibilities for students of observational extragalactic astronomy in Europe to get access to these facilities were not excellent. An exceptional, and successful, case was Gustav Tammann who in 1995, discussing the situation in the 1950s, wrote: "There were top achievements [in Europe], but they came from single individuals. The average situation compared with the United States was desolate. Every young PhD student, particularly when he was interested in observations, had only one aim: to find at least a temporary position in the US."(Tammann 1995)

Furthermore, the asymmetric instrumental distribution with large telescopes in the Northern hemisphere, when there was no reflector larger than 74 in. (1.9-m) in the Southern, was a serious draw-back to the science of extragalactic research as a whole. A statement issued on January 26, 1954 by twelve eminent astronomers representing six European countries, mentioned below, notes:"that it is highly regrettable that the galactic centre in Sagittarius, the larger part of the globular clusters, the Magellanic Clouds, the extragalactic systems in Fornax and Sculptor, i.e. systems that do not have the equivalence in the Northern hemisphere, are almost inaccessible for the very large telescopes now in service". (Blaaw 1991)

The, arguably, most influential observational astronomer in the mid-twentieth century was Walter Baade. Educated in Germany he came to the US in 1931 and served as a staff member at the Mt Wilson and Palomar Observatories until 1959, when he returned to Europe at an age of 67. During World War II, when most of the Mt Wilson astronomers were working on military projects, Baade being a German citizen was confined to Los Angeles County but had almost unlimited use of the 100-in.—then the most powerful telescope in the world—with the lights from the Los Angeles area blacked out.

Baade (Fig. 1.8) was a divine story teller, about astronomy and astronomers, but he did not care very much about publishing. Thus, the best way to learn about his latest findings and ideas was to listen. With this in mind, the Dutch astronomer Jan Oort had invited him to spend 2 months at the Leiden Observatory in the spring of 1953. During that stay there arose in the discussions between Baade and Oort the idea of a joint European observatory with world class instrumentation, matching the Californian telescopes and placed in the Southern hemisphere. As the principal telescopes Baade suggested a 3-m reflector complemented with a 1.2-m Schmidt telescope.

Oort immediately got very enthusiastic about the idea and summoned a group of European astronomers on June 21, 1953, consisting of Baade, Bourgeois from Belgium, Danjon from France, Heckmann from Germany, B. Lindblad from Sweden, Oort, Oosterhoff and Blaauw from The Netherlands, and finally J.H. Bannier, director of the Dutch national science foundation and President of the CERN Council. The response was overwhelmingly positive, and on January 26, 1954, a somewhat extended group representing six countries (Great Britain had now joined represented by Redman) met again in Leiden signing a statement intended to

Fig. 1.8 Albert G. Wilson and Walter Baade. Courtesy of the Archives, California Institute of Technology

strengthen their efforts to obtain Government grants in their respective countries for the establishment of a joint observatory in the Southern hemisphere.

The idea to create a European observatory that could match the US telescopes in California, at a site with supreme astronomical conditions in the Southern hemisphere had a profound appeal to these Founding Fathers. Also, in these years after the World War II, international collaboration seemed desirable at all levels. On the other hand, most of the joining countries had suffered heavily from the war and Government budgets were tight. The igniting spark came from Ford Foundation. After negative reactions on an application by Oort, Oort and Lindblad went to the US to see the Ford President and the Director of Science and Engineering. A year later the Ford Foundation Board of Trustees approved an appropriation of one million dollars to be granted if four of the five nations, still positively involved at that time, signed the Convention to create ESO.

This made it possible to start site testing in South Africa and later in Chile (Fig. 1.9), where superior sites were found. The Convention was signed in 1962, infrastructure in Chile started, and a number of intermediate size telescopes were set up on La Silla. By 1972 the 1-m Schmidt telescope began operation. Finally, in November 1976 the 3.6-m telescope saw First light, and in October 1977 the telescope was open for visiting astronomers. As it happened, the Dutch astronomer Steven van Agt from Nijmegen and I had the privilege to be given the first visiting observing run with the 3.6-m, with the guidance of André Muller and Hans-Emil Schuster. Van Agt observed the Sculptor dwarf spheroidal galaxy, and I primarily

Fig. 1.9 Looking for an observing site in the Atacama desert in 1963. Among the others, Jan Oort, the fifth from left, one of the founding fathers of the European Southern Observatory (Photographic Archive of ESO)

the Southern supergiant barred galaxy NGC 1365. To sit in the quietness of the prime focus cage close to the open dome slit with the brilliant Southern sky overhead, and to see in the eyepiece this magnificent galaxy and its spiral structure in true colour with its extremely bright yellow nucleus (Seyfert nucleus as evident from subsequent spectral observations in the Cassegrain focus) was a supreme experience.

To answer your question: the driver of the founding fathers of ESO was the vision of a joint European observatory equipped with telescopes that would match those on the other side of the Atlantic. Further, this observatory should be placed in the underexplored Southern hemisphere with many unique galactic and extragalactic objects that could not be reached from the North, at a site with supreme astronomical conditions, and where observing time should only be awarded on the basis of merits of proposals.

The fantastic development of ESO, with the four 8-m telescopes with additional interferometric facilities on Paranal, exoplanet hunting instruments on la Silla, share in the giant millimetre radio interferometer ALMA on Chajnantor, and green light for starting the construction of the E-ELT 39-m telescope on Cerro Armazones, by far surpasses the wildest dreams of its Founding Fathers.

This vibrant contribution about ESO pioneering time by Per-Olof Lindblad also enlarge our view about the chiaroscuro of extragalactic astronomy in European countries after WWII. From one side we note the presence of extraordinary scientists and their schools, while from the other we see the lack of competitive telescopes and instruments to compete on the scene of the exploding extragalactic research led by *the USA. In 1979 European countries founded the European Northern Observatory (ENO) at Canary Islands, Spain. Today ENO, operated by Istituto de Astrofisica de Canarias, includes 17 member countries.*

The picture offered by Per-Olof Lindblad brings us to the present phase of development of ground-based telescopes and instruments. Two enterprises deserve a special mention: the `Keck` and the `VLT` . The multi-mirror `Keck` telescopes, made with the contribution of the M.W. Keck Foundation, are two 10 m class telescopes located at Mauna Kea (Hawaii, USA). The `Keck I` telescope began science observations in May 1993; `Keck II` saw first light in October 1996. The ESO Very Large Telescope (`VLT`), a battery of four monolithic 8 m telescopes inspired by ESO Director General Lodewijk Woltjer, initiated by Harry Van Der Laan was completed and put into operation during the directorship of the Nobel Laureate Riccardo Giacconi ESO Director General from 1992 to 1999.

The 10 m class telescopes today dominate the scene of ground based observations. Recently several telescopes of the 10 m class became fully operative. We remember the Gran Telescopio Canarias (`GTC`; La Palma, Spain) 10.4 m (2009) and the Large Binocular Telescope (`LBT`; 2×8.4 m equivalent to a single 11.8 m in light gathering power) at Mount Graham (Arizona, USA), operated by INAF, the LBT Beteiligungsgesellschaft in Germany, the Ohio State University, the University of Arizona, the Northern Arizona University Research Corporation in Tucson, and the University of Notre Dame.

These huge advances in the size of the telescopes, together with the types and flexibility of the instrumentations at the focal planes achieved during the last century, have greatly contributed to form our present understanding of galaxies, in particular continuing to expand our horizons as Edwin Hubble predicted many years ago.

We now interview Alvio Renzini about the contribution of the 8–10 m class telescopes and their instrumentations to propel the pursuit of distant galaxies (see also Chap. 5) and to increase our understanding of galaxies.

Questions for Alvio Renzini:

In your view, what have been the main scientific/technological achievements contributed by `Keck` and ESO `VLT` towards our understanding of galaxies?

The `VLT` of ESO started its scientific operations about 5 years after `Keck`, when `Keck` had already pioneered in this field with the discovery and characterization of redshift $\sim$ 3 galaxies by the Lyman break technique, a major breakthrough in galaxy evolution (Steidel et al. 1996). But the ESO community was quick to catch up, and then, in my opinion, took the lead in this field. This was achieved thanks to the variety of instruments installed on the `VLT`, notably offering efficient near-IR imaging and high multiplex optical spectroscopy. So, while at `Keck` they were still working on UV-selected samples of merely star forming galaxies, at ESO we could work on near-IR selected samples, close to be mass-selected, and including highly reddened star-forming galaxies and quenched galaxies at high redshifts, which were completely missed by UV-selected samples.

This has allowed European astronomers to make important discoveries, specifically in the field of galaxy evolution. One of them was the finding of high-redshift, very massive galaxies in which star formation had already been stopped, demonstrating that such virtually full grown, *quenched* galaxies were already in place in considerable numbers only a few billion years after the Big Bang (Cimatti et al. 2004). Then came the recognition that high redshift galaxies forming stars at hundreds of solar masses per year were not caught in a transient, *starburst* phase, but were actually the norm rather than the exception in the young Universe. This led to realize the existence of a tight correlation between the stellar mass of galaxies and their star-formation rate (SFR), now called the "Main Sequence" of star-forming galaxies and its strong evolution with redshift (Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007). This discovery then promoted the notion that most star-forming galaxies are in a quasi-steady state regime, in which a sort of equilibrium is maintained, for most of a galaxy active life, between gas accretion from the environment, star formation and gas ejection via galactic winds (Lilly et al. 2013).

Later, with the advent at the VLT of integral field spectroscopy assisted by adaptive optics, it became possible to uncover several internal properties of redshift ~ 2 star-forming galaxies, such as the predominance of large rotating disks, with massive clumps of star formation, much higher velocity dispersion compared to local disks and with already forming bulges.(Genzel et al. 2006; Schreiber et al. 2009). The majority among the most massive such galaxies are found to host an active galactic nucleus (AGN), powered by a central supermassive black hole, and even in cases in which the AGN is not caught in an active phase, the detection of nuclear high-velocity outflows indicates that an AGN had to be "on" in the recent past, even if it is dormant today (Genzel et al. 2014; Schreiber et al. 2014). Whether *AGN feedback* can be blamed for quenching star formation in massive galaxies is certainly a tantalizing option after these discoveries, yet remains unproven.

The technology that has allowed these achievements is represented by VLT instruments such as ISAAC for the near-IR imaging, FORS and VIMOS for the high-multiplex spectroscopy and SINFONI for the high-resolution integral field spectroscopy. Worth emphasizing is that these instruments have been developed and built in close cooperation between ESO and its community in the member states, focusing on the VLT human, intellectual and financial resources from the whole ESO community.

What about the contribution of other 8–10 m class telescopes?

The Gemini telescopes did some valuable contribution, e.g., finding quenched galaxies at high redshift (Glazebrook et al. 2004), but their instrument suit was never competitive with either Keck or VLT , at least in this field. I think that Subaru had a much stronger impact, having anticipated all other observatories with two crucial, unparalleled capabilities: wide-field optical imaging and high multiplex near-IR spectroscopy. While spectroscopic surveys have been able to deliver samples of several 10,000 high$-z$ galaxies, imaging can reach hundreds of times more galaxies. The Subaru Prime Focus Camera (Suprime Camera), with its half square degree field of view, has provided deep multiband optical imaging, allowing astronomers all around the world to derive *photometric redshifts* for huge galaxy samples, that we could barely afford via spectroscopy (Ilbert et al. 2013). Moreover, for quite a few years, Subaru had the only high-multiplex near-IR spectrographs in use (Onodera et al. 2012; Silverman et al. 2014), paving the way to those that have recently started to operate at the VLT and Keck.

Worth noting is that this complementarity between the ground-based telescopes was soon exploited by establishing planetary-wide collaborations, combining the capabilities of VLT, Subaru and Keck, on the ground, with those of a variety of telescopes in space. Thus, *opportunistic* international teams have been combining imaging data from several different telescopes to select targets to be fed to other telescopes and instrument for spectroscopic follow up, using the best facilities wherever they were located, and so on and so forth. It has been, and still is, a great time for galaxy evolution!

Along the lines of open collaborations sketched by Alvio Renzini, ESO facilities are now invaluable also for member countries in Latin America as Chile, hosting the ESO observing and administrative structures in South America, and Brazil which signed an accession agreement in 2010.

ESO is one of the Astronomical Consortia present in Chile. Providing among the best observing conditions in the World, Chilean deserts host observatories of different institutions. Since 1969, the Carnegie Institution of Washington cooperating with the University of Chile, has a battery of telescopes at Cerro Las Campanas. The 100-in. (2.5-m) Irènèe du Pont telescope started operation in 1979. Las Campanas site hosts the two 6.5-m Magellan telescopes fruit of a partnership between Carnegie Institution of Washington, Harvard University, MIT, University of Michigan and University of Arizona. The Walter Baade telescope first light occurred in 2000 followed by the twin Landon Clay telescope in 2002. In the Chilean territory, at Cerro Tololo is also located the CTIO that hosts the 4-m Victor Blanco Telescope a near twin of the Mayall 4-m telescope in Arizona.

With the next interview to Reinaldo de Carvalho we ask if these facilities are offering growing opportunities to Latin America astronomers, boosting extragalactic studies.

1.3.5 The Growth of Extragalactic Astronomy in Latin America

Questions for Reinaldo de Carvalho:

Central and South America have made significant contributions to the extragalactic research. What are the main drivers and who are some of the scientific leaders?

Despite the many cosmogony myths, primitive concepts, and vast array of observations in the eighteenth century, it is safe to say that modern extragalactic research truly began with Hubble's discovery of the expansion of the Universe. Since then, technology has played a decisive role in transforming our view of the world around us not only scientifically but also in human matters. Therefore, understanding of the current situation of this research in Latin America is intimately linked to the more general subject of how society developed in the last 400 years. This is a task far beyond the scope of this contribution and there is a veritable trove of historical accounts to which we can refer (Bynum et al. 1984; Merton 1979). We should bear in mind though that the role of examining the history of science is not only to put together facts and events in a certain order but also to reinterpret the past and redesign the world as we understand it. Science is part of the real world of war, politics, and business, and these elements deeply affect how scientific research is thought and organized. In turning our eyes to the specific question about extragalactic research in Latin America we have to take into account the simultaneous changes in society and science, considering the economic interests and the ambitious projects which ultimately globalized science.

The history of astronomy in Latin America traces back to the Mayan civilization (2000 BC). However, the development of extragalactic research in Latin America is relatively recent, which is not very different from the rest of the world if we consider Hubble's paper of 1926 on the expansion of the Universe as the starting point. Mexico and Argentina are the countries with the greatest tradition in this field, and Brazil has the fastest growing astronomical community in Latin America, especially in this arena. The list of astronomical observatories (en.wikipedia.org/wiki/List_of_astronomical_observatories) shows that most of those in Latin America are not competitive from an international perspective but they still serve to stimulate the growth of these small communities. A very nice source of information on all observational resources in Latin America can be found also in LANIC—Latin America Network Information Center (lanic.utexas.edu/la/region/astronomy/). There is great enthusiasm for extragalactic research in Latin America but unfortunately the astronomical societies from the individual countries are still much smaller than similar societies in European countries with comparable populations. For instance, the first Guatemalan School of Astrophysics occurred only in 2013. The presence of ESO (European Southern Observatory) and the American observatories in Chile (Tololo and Las Campanas) did not have an impact on the development of this research field in Latin America. The Arecibo Observatory in Puerto Rico, one of the largest Radio Observatories in the world, also does not represent an investment originally from Latin American countries. These facilities are much in demand by the international community and to be granted with observing time one needs to be already involved in very competitive projects, which in turn requires not only competence but also being immersed in an exciting and professional environment. Only in the last two decades or so have the extragalactic research groups in Latin America became consolidated. Much more investment is still needed to enlarge the participation of Latin American researchers in big projects.

It is challenging to determine when extragalactic research started in Latin America, but we may safely say that a few iconic names were responsible for boosting the interest in the area. In Mexico, two astronomers in particular were: Dr. Arcadio

Poveda, who in the 1960s made an important contribution by developing a method to calculate the masses of elliptical galaxies (Poveda et al. 1960). Dr. Arcadio received his PhD in Astronomy in 1956 from University of California, Berkeley, returned to Mexico and became a notorious figure of the Mexican astronomical community with important contributions to the development of extragalactic research there. Another fundamental figure in Mexican astronomy is Dr. Manuel Peimbert, who also obtained his PhD in Astronomy from University of California, Berkeley in 1967. His contribution to the study of chemical evolution of galaxies and a series of accurate determinations of the primordial helium abundance, are among his key contributions. His paper with Dr. James Lequeux on the chemical composition and evolution of irregular and blue compact galaxies is still one of the most cited in the field (Lequeux 1979). Another important researcher in Latin America was the Argentinian scientist Dr. José Luis Sérsic, who is well known for his empirical law describing the behavior of the surface brightness profiles of galaxies (Sérsic 1963). Dr. Sérsic (Fig. 1.10) created the extragalactic astronomy department at the Observatorio Astronómico de Córdoba, which is still active in research in this field in Argentina. A much younger researcher from Latin America, but with equally important work in the field is Dr. Gustavo Bruzual, from Venezuela. Dr. Bruzual obtained his PhD degree from University of California, Berkeley in 1981. Dr. Bruzual has made comprehensive studies in stellar population synthesis and is considered one of the most important researchers in the field. His papers with Dr. Stephane Charlot (Bruzual and Charlot 1993, 2003) are of paramount importance in the field. One of the fastest growing astronomical communities in Latin America

Fig. 1.10 The Extragalactic Group of the Cordoba Observatory (1966), Argentina. Dr. Sérsic was at that time head of the group. In the picture are from left to right: Dr. Horacio Dottori, Dr. Estela Aguero, Dr. Jose Luis Sérsic, Dr. Jorge Landi (Córdoba Observatory, Director), Mister McLeish (Astronomer), Dr. Gustavo Carranza, Dr. Miriani Pastoriza, Ms. Mary Pizarro (Secretary). Courtesy of Dr. Miriani Pastoriza

is in Brazil. However, the first PhD theses were completed as recently as the 1980s and the most important contribution was the Southern Sky Redshift Survey conducted by Dr. Luiz Alberto Nicolaci da Costa, who got his PhD degree from Harvard University in 1979. Recently, there has been a marked increase in the number of Latin American researchers actively participating in large collaborations and receiving recognition for their contributions. However, this increase reflects a greater number of individual achievements, leaving much room for improvement within our astronomical institutions and a need for cohesive strengthening of our community as a whole. Chile, as one of the most important astronomical communities in Latin America, has seen a steady increase not only in the number of people involved in astronomy but also grown organizationally. The creation of CATA (Center for Excellence in Astrophysics and Associated Technologies), the most important Chilean research and development (R&D) project in astronomy, may represent a new era for astronomy in the country that hosts $\sim$42 % of the world's astronomy infrastructure, but from which the astronomers do not fully benefit. Nevertheless, Chile is the country with the greatest potential for improving their astronomical community. Some prospective avenues for progress include increasing the 10 % of the observing time to which Chilean astronomers have access at facilities constructed there (low compared to Canary Islands, 20 %), or setting more stringent policies with foreign observatories for active participation by local universities and engineers in the development of astronomical instruments.

When we look at the history of extragalactic research in Latin America we see that it is marked by individual contributions which brings us to the question of new directions in the field. It is not surprising that we have not yet seen the institutionalization of scientific research in Latin America. The comparison of each country's expenditures for R&D is indicative of what is needed in the near future (data extracted from The World Bank—data.worldbank.org/indicator/ for the year of 2011). For instance, the USA spends 2.8 % of the GDP (Gross Domestic Product) in R&D. The numbers for European countries are similar or even larger: Sweden (3.4 %); Germany (2.5 %); and France (2.1 %), while Japan (3.4 %) and Israel (4.0 %) are also comparable. While the European Union in general spends 2.0 % of the GDP in R&D, in Latin America it is less than half of this value—only 0.8 %. Extragalactic research in Latin America is still in the process of consolidating their research groups and in order to achieve this goal it is imperative that a significant increase of the percentage of the GDP is invested in R&D in a consistent way.

Dr. Jim Gray, an American computer scientist who worked for Microsoft and received the Turing award in 1998, realized that the distinction between data-intensive science and computational science is so remarkable that we may be facing a fourth paradigm for scientific exploration. In brief, science in its early days was experimental, then came theoretical science (starting in the seventeenth century), and when theoretical modeling became too complex analytically, scientist started simulating the physical mechanisms. Today, simulations produce almost as much data as the new instruments in Astronomy. Astronomers do not look through telescopes anymore. Data is acquired by telescopes, processed through a very technical pipeline and the resulting information is stored in a way that a large community of researchers can utilize. An extraordinary example of this process is the recently completed Sloan Digital Sky Survey (SDSS) (Alam et al. 2015). It provides photometric and spectroscopic data over one-third of the Celestial sphere and it is publicly available. This may represent the first step in the direction envisioned by Jim Gray—all scientific data linked interoperatively to the scientific literature to enable researchers anywhere in the world to do science, even those with limited budgets. It seems that the current situation in extragalactic research, along with other areas of astrophysics, in Latin America can benefit from the idea of the fourth paradigm. Do we see already signs of this happening? Data from the SDSS has been used in 5800 papers published in refereed journals and most of them are written by scientists outside the SDSS collaboration. Interestingly, the third most cited paper among these 5800 was written by Dr. Gustavo Bruzual (Bruzual and Charlot 2003), a researcher based in Latin America. As an isolated example, this may not represent the whole story of what is needed to make extragalactic research grow in Latin America, but certainly leads us to reflect that investing in educating highly qualified and independent researchers, able to make use of the tsunami of data from the upcoming surveys, is perhaps an efficient avenue for development. The idea behind the fourth paradigm is very likely a path forward for developing countries in general, and Latin America in particular.

The extragalactic astronomy is rapidly developing in Asia. India, Japan, the People's Republic of China, South Korea and Taiwan are investing in both ground based and space astronomical facilities with remarkable repercussions on the extragalactic research. In 1999 Japan joined the club of countries with 8 m class telescopes with `Subaru` *8.4 m with important influence on the pursuit of distant galaxies mentioned above by Alvio Renzini. In the next section we focus our attention on the growth of extragalactic research in Japan with the help of Norio Kaifu.*

1.3.6 The Japan Rush to Extragalactic Astronomy

Questions for Norio Kaifu:

Japan has a growing tradition in many branches of extragalactic research and today is investing in astronomical research both on the ground and in space. You recently described the development of radio astronomy in Japan. Please sketch some important milestones in the development of extragalactic research in Japan.

I felt the above request difficult for me as I have been working for radio astronomy mainly for interstellar medium and star formation in our Milky Way Galaxy. I was interested in this proposal, on the other hand, as the exploration of distant universe has been a strong motivation for the most of astronomers (including me). It might also be useful to overview the evolution of astronomy which happened in a small Asian country, for Japanese young astronomers and for astronomers in

many countries still struggling for promotion of astronomy. So I will look back the growth history of Japan's astronomy concentrating in external galaxies and related fields, based on the developments of facilities and some related issues like Japan's unique basic research system, and international cooperation, etc., referring to some statistical points of view on astronomical research activity in Japan.
Modern astronomy has a long tradition of 400 years in Europe, and a little shorter in USA. In these "western" countries the astronomical research has evolved in parallel with the development of telescopes, and new discoveries made people recognize the existence of a vast world and unknown types of celestial objects, step by step.

The history of Japan's modern astronomy is considerably shorter, and its evolution was made in different manner. After the Meiji revolution (1867) the Japans new government started systematic program to quickly introduce the western science and technology into Japan. This was the first of such attempts made by eastern countries. The efforts were successful in many fields of sciences including astronomy: Tokyo Astronomical Observatory (TAO, a precursor of NAOJ) was founded in 1888 under the University of Tokyo. The Astronomical Society of Japan (ASJ) was established in 1908, and Japan joined the International Astronomical Union (IAU) in 1919, as one of the founder member countries. The main purpose of astronomy was, however, not for astrophysical research, but to secure the publication of ephemeris and calendar, measure and keep the time etc., which the new government needed to establish Japan as a modern country. This basic situation continued for more than half century, until the end of the Second World War (1945). The main reasons why Japan could not establish modern astrophysics for such a long time were the militarism and frequent wars, subsequent small funds for basic research, lack of instruments and scientific skills. In 1955, 10 years after the end of the tragic war, the number of papers presented in the ASJ meeting was 97 in total, about 10 papers among them were on stellar physics, 4 were on the Milky Way galaxy, and only one on external galaxies reporting studies in the western world.

The large telescopes for observations of distant and faint Galactic and extragalactic objects were far away, and without such large domestic telescopes provide new data and excitement, study of distant universe was just a drama being played in the far western world. Even now, this is the situation of astronomy in many developing countries. Meanwhile, however, the efforts to bring Japanese first modern telescope had started a few years before 1950, by Yusuke Hagihara (Fig. 1.11, 1897–1979), director of the TAO. The Japanese science community was still poor, but the whole nation was in positive atmosphere toward the construction of peaceful and democratic Japan.

Door was opened: The 1.88-m Okayama, and 1.05-m Kiso Schmidt Telescopes

Y. Hagihara was the eminent theoretician in the celestial mechanics and astrophysics, and he served as a vice president of the IAU from 1961 to 1964. His effort was fulfilled by foundation of the Okayama Astrophysical Observatory (OAO) under the TAO equipped with a 1.88-m equatorial mounting optical telescope, completed in 1960. This was the door to the Galactic and extragalactic astronomy in Japan. I like to emphasize here the fundamental importance for astronomy of

Fig. 1.11 (Left) Yusuke Hagihara (courtesy National Astronomical Observatory of Japan); (Center) Chushiro Hayashi in 1961 (courtesy of Fumitaka Sato); (Right) Minoru Oda (courtesy of Hajime Inoue)

working with high-level telescopes developed in the country. It is true even now, when international cooperation is frequent and easy, that the education of students and technology developments cannot be adequately made just by visiting foreign telescopes and/or using remote telescopes via internet. A small backyard telescope inspires and activates students by letting them touch the excitement of Universe directly, particularly when it has attractive forefront research purpose and/or new technological development.

The Okayama 188-cm telescope was fabricated by the UK industry Grubb-Parsons. It was the fifth or sixths largest in the world at the time of completion, and not a cutting-edge telescope with relatively poor observation instruments. Still it firmly opened the door to the Galactic and extragalactic astronomy for Japanese astronomers, especially of younger generation, by giving opportunities to touch the very distant objects and exciting mysteries waiting their challenges. In reality, for the first 10 years of the 1.88-m telescope the observations were mostly limited on stellar physics. The extragalactic observations actually started in 1969, when an Image Intensifier (I.I.) was given to the OAO through the wonderful project by the Carnegie Institution for Science. The I.I. spectrometer enabled the Okayama 1.88-m telescope to make the early-phase spectroscopic observations of external galaxies. Then in 1980s the era of CCD came, and observations of many faint and distant external galaxies were made possible even with the 1.88-m aperture telescope.

Among the Japanese optical astronomers which challenged the vast world of external galaxies during this early phase, Bunshiro Takase (1924–2015) started his systematic study of morphology of galaxies in 1950s, made early observations with the 1.88-m telescope. Then he constructed the 1.05-m aperture Schmidt Telescope of Kiso Astronomical Observatory (KAO, under the TAO), and conducted extensive surveys for galaxies since 1974 (Takase et al. 1977). The products from KAO includes the Photometric Atlas of Northern Bright Galaxies (1990) and the Kiso Survey for Ultraviolet Excess Galaxies (KUG Catalog, 1993). Sadanori Okamura, helped Takase at KAO, led the development of surface photometric analysis system for galaxies, and later extended those works to USA-Japan collaboration on the Sloan Digital Sky Survey (SDSS). He also extended efforts to the construction of the Suprime Cam, a wide-FOV camera for the prime focus of the `Subaru` telescope. A young astronomers group of University of Kyoto, Ken-ichi Wakamatsu, Kazushi Sakka and others, made spectroscopic observations and studies of active galactic nuclei like Arp215 with the 1.88-m telescope intensively. Although the telescope and instruments were not powerful enough for these targets, their works laid steps for the tradition of Japanese researches of AGNs and star forming galactic nuclei in the forthcoming `Subaru` Telescope era.

Synergies: Multi-Wavelength Observations and Theoretical Astrophysics

Figure 1.12 demonstrates the growth history of Japanese astronomy. Here are compiled the yearly number of orally-reported papers in the annual meetings of Astronomical Society of Japan (ASJ) which have been held twice a year since 1950–2014, by using the ASJ archived record. Shown are the changes of whole papers, papers on Milky Way Galaxy, papers on external galaxies, and the sum of Galactic and extragalactic papers.

A distinguished character in Fig. 1.12 is the rapid and accelerated increase of the total number of papers. Though the curve has been flattened after 2005, it counts 1400 in 2010s, more than 14 times larger than 97 in 1955. Such change could not be achieved without a considerable increase of number of astronomers. In fact, the number of Japanese individual members of the International Astronomical Union (IAU) was 18 in the 1961 General Assembly, and counted 626 in 2012, 35 times larger than in 1961 and the third largest among about 70 IAU member

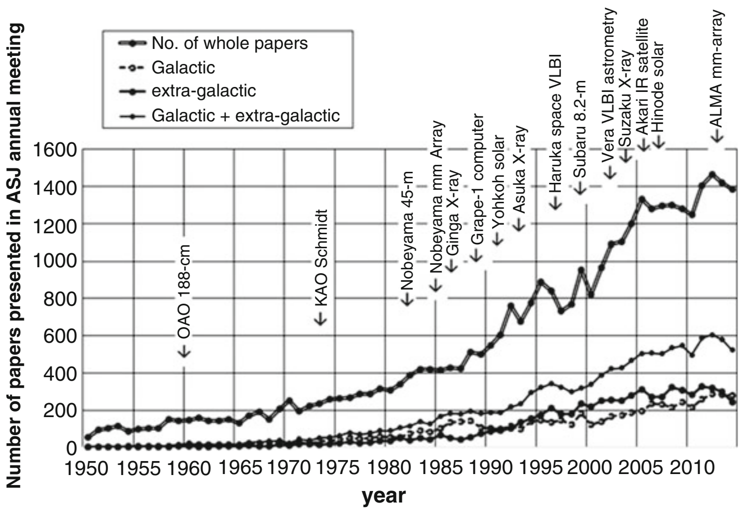

Fig. 1.12 Growth history of Japanese astronomy

countries. It was 14th among 37 member countries in 1961. Therefore, roughly speaking, Japanese astronomy had grown more than ten times larger during this half century. Now it is contributing significantly to the human understanding of external galaxies, and in all fields of astronomy. Such growth was achieved by successful constructions of cutting-edge telescopes in many fields of observations, starting from the Nobeyama mm-wave telescopes (1982/1986) and a series of space-borne X-ray telescopes since 1980s, then succeeded by `Yohkoh` (1991), `Subaru` Telescope (2000) , dedicated `VERA` (2003) , and so on.

Table 1.1 summarizes how the ground-based and space-born telescopes contributed to the building-up of Japanese astronomy, also indicated in Fig. 1.13 along the time axis. It is amazing that such a variety of telescopes covering almost the whole wavelength areas of electro-magnetic spectrum were realized in Japan within the short term, thanks to the Japan's economic growth in these days. We see the increase of total papers is parallel to the construction of those telescopes. The extragalactic researches slowly started with the Okayama 1.88-m and Kiso Schmidt telescopes, then accelerated by the `Nobeyama` mm-wave telescopes in 1980s. In the same time a series of X-ray telescopes joined. Those world-leading facilities in the two new wavelength regions brought very high activities to the Galactic and extragalactic astronomy in Japan. The 8.2-m optical/ IR telescope `Subaru` made the latest major contribution to the growth curve. Those multi-wavelength facilities attracted young students in many universities, because these telescopes were open to all Japanese astronomers (the "open-use" system, a Japanese important policy for basic sciences will be mentioned later). As the result, the number of professional members of the ASJ (a part of graduate students are included) increased from 480

Table 1.1 Japan's major observational facilities during half century

Year of completion	Telescope	Belonging institute
1960	Okayama 188-cm optical telescope	OAO (TAO/NAOJ)
1974	Kiso 105-cm Schmidt telescope	KAO (TAO/U-Tokyo)
1982	Nobeyama 45-m telescope, mm-wave	NRO (TAO/NAOJ)
1986	Nobetama Mm-wave array	NRO (TAO/NAOJ)
1987	Ginga, X-ray satellite	ISAS (JAXA)
1989	Grape-1 (U- Tokyo), now Grape-8&9	Various institutes
1991	Yohkoh, Solar X-ray satellite	ISAS
1993	Asuka, X-ray satellite	ISAS (JAXA)
1997	Haruka (VSOP), Space VLBI	ISAS (JAXA)
1999	Subaru, 8.2-m O/IR telescope	NAOJ
2003	VERA, VLBI for radio astrometry	NAOJ
2005	Suzaku, X-ray satellite	ISAS, (JAXA)
2006	Akari, IR satellite	ISAS (JAXA)
2006	Hinode, solar O and X-ray satellite	ISAS
2013	ALMA, large mm/sub-mm array	NOAJ/NRAO/ESO
2017	KAGRA, gravitational wave telescope	ICRR (U-Tokyo)

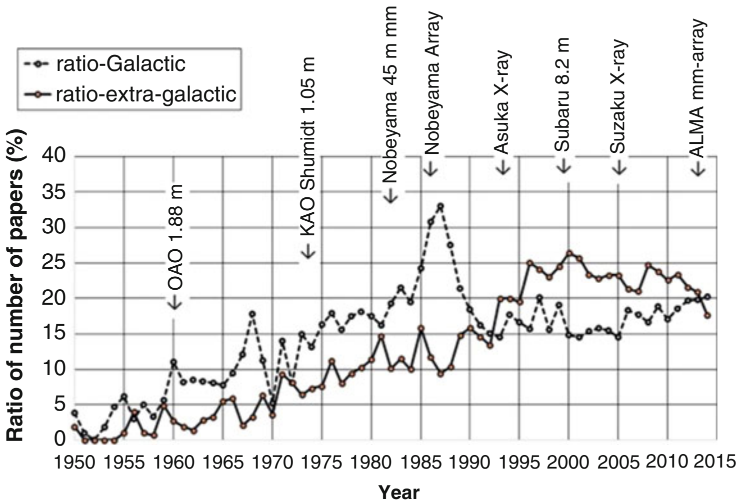

Fig. 1.13 Ratios of numbers of Galactic and extragalactic papers reported in the ASJ annual meetings

in 1979–1700 in 2009, 3.4 times larger in 30 years. The numbers of Galactic and extragalactic papers and the sum of these two fields in Fig. 1.13 shows similar curve with that of the total number. Such evolution seems to be a result of good synergies among observing facilities in various wavelength regions of the electro-magnetic spectrum. We will describe some more details of contribution by each of major telescopes later. Here I mention the great contribution of theoretical researches and its synergies.

Japan's natural sciences have a strong tradition of theory, as represented by Hideki Yukawa (1907–1981) and Shin-ichiro Tomonaga (1906–1979), early days Nobel Prize winners in the elementary particle physics.

A big stream in the theoretical astrophysics of Japan was created by Chushiro Hayashi (1920–2010, Fig. 1.11), Kyoto University. He is well known by theory of matter evolution in the big-bang universe, the stellar evolution, and the prediction of very luminous Hayashi-phase in the early stage of star-formation.

Together with other strong theoretical groups of the University of Tokyo lead by Wasaburo Unno, and of the Nagoya University lead by Sachio Hayakawa (1923–1992), etc., the powerful community of theoretical astrophysics was formed in Japan. Those leading theorists strongly supported the project to construct cutting-edge telescopes. The community of theoretical astrophysics was highly activated by high-level observations by using these telescopes too. This was another very positive synergy, and it was also true in the computing astronomy.

The GRAPE (GRAvity piPE), a dedicated super-fast pipeline computer for the gravitational N-body simulation was proposed by Yoshihiro Chikada in 1980s, and fastly built by D. Sugimoto, Jun-ichiro Makino and U-Tokyo group (Sugimoto et al. 1990). The simulation power of GRAPE, as well as that of the general purpose super computers, gave a huge impact to the theoretical study of astrophysics. The GRAPE has been developed step-by-step to the present models GRAPE-8 and -9, evolving into higher performance and capabilities. It made a great contribution to the theoretical astrophysics, especially to the understanding of the formation process of galaxies and large structures.

A "Big Jump": molecular line spectroscopy in mm-wave

The movements aiming at providing observations in new areas of the electromagnetic spectrum, such as the mm-wave (the short-wavelength radio wave), the shortest wavelength X-ray region and the mid-wavelength Infra-Red (IR), started worldwide in the 1960s. In Japan such efforts started also in 1960s, some small-scale telescopes were built in 1970s, and as summarized in Table 1.1 a number of advanced telescopes were constructed during the 1980s to the 2000s. The first of such cutting-edge telescopes was the 45-m aperture mm-wave telescope at Nobeyama, the 1300-m elevation plateau in the central Japan Island.

Japan's radio astronomy started in 1940s, just after the end of the war, almost in parallel with that of western countries (Ishiguro et al. 2012). However it was developed only for solar study, as the cosmic radio observations required larger and expensive radio telescope. This was different from the western world which aimed the distant Universe, Milky Way, radio stars and radio galaxies immediately. The efforts to establish the so called "non-solar" radio astronomy in Japan started in the Tokyo Astronomical Observatory under Takeo Hatanaka (1914–1963), a leading astrophysicist and one of the founder of the Institute of Space and Astronautical Science (ISAS), but unfortunately died young.

The first Japanese cosmic radio telescope was a 6-m aperture mm-wave telescope constructed by Kenji Akahane, Masaki Morimoto (1932–2010) and cosmic radio group in the TAO (1970). The author, Norio Kaifu, was among this group as a graduate student. He lead the mm-wave spectroscopic observations of interstellar molecules with the 6-m telescope a few years later than the first detection of multi-atoms molecules in the interstellar space (NH_3 and H_2O) by group of Charles Townes (1915–2015), a Nobel Prize winner for the invention of maser and laser, and William J. Welch in 1968. It was known in the molecular science that a tremendous number of molecular rotational lines existed in the mm-wave region, and it was immediately presumed that the mm-wave spectroscopy for various molecular lines would provide powerful new tool to explore the low temperature diffuse matter in the Galaxy, invisible with optical telescopes but assumed as the basic material of stars and planets. Therefore Akahane, Marimoto and Kaifu quickly planned the large mm-wave telescope to explore this low-temperature Universe.

The 45-m aperture mm-wave telescope was formally recommended to the government by the Science Council of Japan in 1970 under the strong support by leading physicists. It was, however, a really big jump from the 6-m to the 45-m, the top of the mm-wave observations in the world and we took 10 years to start the construction in Nobeyama (Kaifu 2013).

The 45-m Telescope for mm-wave was completed in 1982, as the first world-leading telescope of Japan. It achieved high surface accuracy of 0.12–0.15 mm rms. for full aperture, good enough to observe celestial objects at 2-mm to 3-mm wavelength (frequency of 150–100 GHz).

Equipped with superconducting receivers in several wavelength bands and with an extremely large new type of radio spectrometer applying the acousto-optical technology developed by Junji Inatani, and with an extremely large new type of radio spectrometer applying the acousto-optical technology developed by Kaifu, the 45-m telescope has been operated and used by many Japanese and foreign astronomers as the world largest mm-wave telescope for almost 30 years (Kaifu 2013). The early-phase observations with the 45-m telescope were focused in a variety of Galactic studies, especially interstellar molecular clouds, molecular line survey for dark clouds and various types of objects, and process of star formation form dark clouds. Figure 1.13 shows the percentage of yearly number of papers of the Galactic and extragalactic researches to the number of whole papers reported in the ASJ annual meetings. The years of completion of selected major observing facilities are indicated along with the horizontal axis too.

The important major discoveries by the 45-m Telescope in 1980s were, for example, the discovery of huge radio lobes in the Galactic center region (Sofue 1985, 1984), and successful detection of many new organic species in dark cloud (see e.g. Suzuki et al. 1986).

In 1990s, a big discovery of the extremely high velocity rotating disk in the core of the active galaxy NGC 4258 (Nakai et al. 1993) was made by the wide-band water maser observations with 45-m Telescope, and immediately followed by the confirmation of 36 million solar mass black hole by US-Japan joint VLBA observations (Miyoshi et al. 1995). This was the first observational confirmation of super-massive black hole in the center of galaxies, as engine of the AGN. Also the image of whole spiral galaxy (M51) with the spectral line of CO molecule (at the wavelength of 2.6 mm) shown the clear correlation of the cold CO gas with the spiral arms for the first time (Nakai et al. 1994). Such observations for external galaxies with the 45-telescope became active as the receiver sensitivities were improved and the pointing accuracy become higher.

The shift from Galactic researches to extragalactic researches was also accelerated by the completion of the Nobeyama mm-wave Array (NMA) with five (later six) 10-m dishes led by M. Ishiguro in 1886. The NMA was one of the first mm-wave interferometers in the world, providing several times higher spatial resolution than the 45-m telescope, which is also an important capability to observe compact and bright objects like distant AGNs. The NMA detected precise structure and motion in many central cores of active galaxies, like the central bar structure and motion in the IC 342 (Ishizuki et al. 1990). The NMA also detected the rotating and/or contracting motion in the protoplanetary disks for the first time (Hayashi et al. 1993; Kawabe et al. 1993).

Small is beautiful: X-Ray Satellites and High-Energy Universe

Another factor to accelerate the increase of Japanese extragalactic researches in the 1990s was the X-ray telescope `Asuka` , launched in 1993. The start of X-ray astronomy in Japan was also very soon after the discovery of cosmic X-ray sources by Riccardo Giacconi et al. (1962). Minoru Oda (1923–2001, Fig. 1.11), who worked with Giacconi in the Bruno Rossi's group, invented the famous modulation collimator to determine the position of X-ray source with high spatial resolution. He then identified one of the firstly detected X-ray sources Sco X1 to an extremely hot star by using the Okayama 1.88-m telescope by collaboration with Jun Jugaku (1927–2011).

Oda established his X-ray astronomy group at the University of Tokyo in 1966, and also S. Hayakawa, a well-known theoretical physicist created his X-ray astronomy group in Nagoya University. Oda and Hayakawa cooperated to establish and develop the X-ray astronomy in Japan, and successfully launched the Japanese first X-ray satellite `Hakucho` in 1979, 6 years later than the `Uhuru`, first X-ray astronomy satellite of USA. It was a small satellite with only 96 kg (the US X-ray satellite `Einstein`, launched in 1978 was 3.2 t!), still with its characteristic instruments, two sets of rotating modulator, it detected many X-ray bursts and X-ray pulsars. A series of Japan's X-ray astronomy satellites were launched successfully in about every 5–6 years, `Tenma` in 1983, `Ginga` in 1987, `Asuka` in 1993/2001 (the launch in 1993 failed, and recovered in 2001), and `Suzaku` in 2005.

The `Ginga` (1987–1991) reached the observations of active galactic nuclei for the first time as Japan's X-ray satellite, with its high-sensitivity X-ray counters provided by UK. It detected the spectrum features in nuclei of some active galaxies for the first time, which suggested the existence of a fine structure (Matsuoka et al. 1991). Rich data from `Ginga`, especially on high-energy phenomena of compact stars; pulsars and neutron stars, black hole binaries etc. highly activated Japanese physicists. The `Asuka` (1993–2001) conducted by Yasuro Tanaka extended X-ray observations further into extragalactic universe with high-sensitivity imaging in collaboration with the MIT (USA). The `Asuka` observations covered wide areas of high-energy phenomena in Galactic and extragalactic distance, including identification of X-ray flares from several proto-stars indicating high activities in early phase of star formation (Koyama et al. 1994), highly excited X-ray spectrum from jets from Galactic black hole objects and from disks around AGNs, structure of the high-temperature gas in clusters of galaxies (Makishima et al. 2001).

The number of papers on high-energy phenomena read in the ASJ meetings increased rapidly, as seen in Fig. 1.13. The "reverse" between the rates of Galactic and extragalactic papers happened in the early 1990s was very much accelerated by the `Asuka`, as well as the effect of Nobeyama mm-wave telescopes. A series of Japan's X-ray satellites highly contributed to astrophysics. They gradually grew in size through 20 years, still were much smaller compared with giant X-ray satellites of USA and Europe. To make unique observations they were equipped with characteristic instruments developed in-house, and also through the cooperation with USA and UK. Minoru Oda, the pioneer and leader of Japan's X-ray astronomy, always said "small is beautiful". This was Oda's firm confidence for the promotion of cutting-edge sciences in a small country like Japan. This was also a sort of "must" way for Oda and his colleagues, as the resources of space science in particular country is strictly limited by the policy of its government on space activity, and in the case of Japan the basic science from the space which was shouldered by the ISAS has been limited in relatively small budgetary scale, clearly separated from industry and application oriented developments by the National Space Development Agency of Japan (NASDA). This situation is essentially the same even after the merge of ISAS and NASDA into the Japan Aerospace Exploration Agency (JAXA) in 2003.

A slightly different strategy to catch-up with the forerunners in astronomy was taken in the case of radio astronomy, as mentioned above. The radio astronomy of Japan concentrated in the mm-wave, a novel and promising trend of astronomy which required new technological developments equally to the whole world. In the same time, radio astronomy of Japan made a big jump toward the largest telescope based on in-house technological developments and cooperation mainly with domestic industries. This was also the case for the 8.2-m Optical/IR telescope `Subaru` , and for new developments in the `VLBI` astronomy. Before we go to these recent developments, I would like to mention about Japan's unique "open use system" to promote basic sciences, which I regard as the fundamental element for successful evolution of the Japanese astronomy.

Evolution in the twentieth Century; `SUBARU` *and* `VERA`

In 1981, a long time after the construction of Okayama 1.88-m telescope, discussion by optical astronomers community started for Japan's national optical telescope. The discussions did not conclude for many years, as two groups insisted on different plans; one was to construct a medium-size (3 to 4-m aperture) telescope in Japan to succeed the Okayama telescope, and another was to build 5-m or larger telescope at the best overseas observing site. Japanese astronomy had no experience of building large facility in abroad, however. The point of argument was, in short, a cautious step, or a jump to the world level. The proposal finally submitted in 1985 from optical astronomer's community to the SCJ committee for astronomy and astrophysics was the former, plan to construct a 3.5-m telescope in Japan. I was among the committee members as a radio astronomer, and clearly remember the first words by Chushiro Hayashi to the presenter Keiichi Kodaira, "Are you really OK with this proposal?" Sachio Hayakawa and Minoru Oda immediately followed Hayashi, and the committee quickly agreed to adopt another plan to construct the world largest telescope at the best observing site. Yoshihide Kozai gave a spot answer to do his best efforts for the plan, as director of the TAO. I was so happy, and have kept this day in my memory as the day astronomy of Japan entered the new gate toward further evolution, by the powerful help of excellent leaders.

After this dramatic decision the optical astronomer's community got together for the JNLT (Japan Next-generation Large Telescope) plan, under the leadership of Kodaira. One important component for the JNLT was to combine near IR community to make the telescope excellent also for IR observations. The IR astronomy in Japan started in 1960s by Haruyuki Okuda, Toshio Matsumoto, Suji

Sato et al., starting from Nagoya University and then University of Kyoto. Okuda's group tried near-IR and far-IR observations with balloon-born small telescopes, and Sato led construction of Japan's first ground-based IR telescope with 1-m aperture at Agematsu, Kiso. A series of balloon born observations produced the Milky Way maps in near- and far-IR, and those achievements evolved to the IR satellite `Akari`, a 70-cm IR telescope launched by ISAS in 1996, which made all-sky mapping with much higher sensitivity than that made by IRAS in 1983. The ground-based IR observations were strongly enhanced by the very successful UK-Japan 10-years cooperation from 1984 (I was a representative of Japan-side), which combined the mm-wave observations in Nobeyama and the IR and sub-mm observations on Mauna Kea, Hawaii with the 3.9-m IR telescope `UKIRT` and the 15-m sub-mm wave telescope `JCMT`. One of the by-products of the cooperation was the introduction of two-dimensional IR detectors to the Okayama 1.88-m telescope. On these IR astronomy basis the `JNLT` was prepared as an O-IR telescope of the world level. Like in Nobeyama, various in-house and collaborative developments with domestic industries started by Masanori Iye, Takeshi Noguchi and colleagues, to overcome the technological difficulties to jump to the world-largest telescope. The construction of the `JNLT` started in 1991, and I moved from Nobeyama to the `JNLT` project to lead the construction. The `JNLT` was named as the `Subaru` Telescope. `Subaru` is an old Japanese name of the star association Pleiades, also means "make a group". Its aperture was fixed to be 8.2-m. The site was decided at the summit area of Mauna Kea with elevation of 4200-m, Hawaii. The situation very different from the case of the Nobeyama mm-wave telescopes was the international circumstances. The new technology telescopes of around 8-m aperture started construction in almost same time in Europe (the four 8.1-m telescope `VLT`, ESO) and in USA+UK (the two 8.0-m telescopes `Gemini`), as well as the fore-running two 10-m `Keck` telescopes. The thin-mirror and active optics technology were successfully developed in competing and cooperating atmosphere among those 8-m telescope groups (called as the "8-m club").

The `Subaru` Telescope started operation in 2000, with instruments as many as seven equipped on four foci; Primary, Cassegrain, and two Nasmyths. With its high-performance and rich instruments equipped, `Subaru` became Japan's first Optical/IR telescope which lead the observational cosmology and extragalactic astronomy. One of very successful `Subaru` instrument was the `Suprime Cam` on the prime focus, a powerful tool for observational cosmology with the field of view (FOV) as wide as 30 min arc, and CCD detectors of 80 million pixels. It was so successful and succeeded in 2014 by a 3-tons weight `HSC`, Hyper Suprime Cam, with 90 arcmin FOV and 870 million pixels CCDs, by collaboration with the Princeton University and lead by Satoshi Miyazaki, for further study of evolution of dark matter and dark energy, etc.

Apparently the `Subaru` Telescope brought considerable increase of papers as we see in Fig. 1.12, but no significant change of the ratio curves of Galactic and extragalactic papers in Fig. 1.13: in 2010s they show almost flat curves around 20 % of the total, respectively. We may interpret this as a saturation effect, and that

Japanese astronomy reached the similar condition with "western" leading countries in astronomy.

On the other hand, the Very Long Baseline radio Interferometer (VLBI), started in 1960s by Canada and USA, was a novel tool for astronomy which provided super-high spatial resolution of milli-arcsec for high brightness compact radio sources. It was first introduced to Japan for geodesy measurements in 1970s, and then in 1980s astrophysical observations were made by M. Morimoto and Nobeyama group, aiming detailed study of AGNs with shorter wavelengths. Morimoto, Hisashi Hitabayashi, Makoto Inoue and collaborators launched the first space-VLBI satellite `Haruka` (or `VSOP`), an 8-m diameter paraboloid in 1997 (Hirabayashi et al. 2000). With its 30,000 km orbit and close cooperation with ground-based large radio telescopes, the `Haruka` successfully imaged fine structure of jet in the very central region of M87 etc., also detected the acceleration of jet in the core of NGC 6251 (Sudou et al. 2000). The Japan's unique `VLBI` was developed as the `VERA`, VLBI Experiments of Radio Astrometry, started its full operation in 2003. This is a network of four identical and self-calibrated 20-m aperture antennas. Tetsuo Sasao proposed and led this project, and Hideyuki Kobayashi and Norio Kawaguchi et al. made this unique project realized (Kobayashi et al. 2005). The four antennas based in the 2300 km wide areas covering Japan Islands measure position of maser sources as precise as 10–100 arc-sec. The mission of `VERA` is to observe three dimensional position and kinematics of about 200 maser stars, and to make the three dimensional map of the whole Galaxy both in structure and dynamics by 20 years observations. Observations is under process together with astrophysical studies of star forming regions, late-type stars and AGNs, including the detection of 10 higher Galactic rotation velocity (Honma et al. 2012). Further new development is the East Asian `VLBI` network (EAV net) and KaVA (KVN and `VERA` Array) by cooperation with East Asian countries, particularly with Korea.

Norio Kaifu describing the development of extragalactic astronomy in Japan well introduced us to the impact played by new technologies in parallel with the growth of telescopes collecting area. We now examine this aspect more carefully with the next interviews.

1.4 The Impact of New Detectors and Instruments

Questions for Jonathan Bland-Hawthorn:

Please give us an overview of the current status of technological developments in astronomy with particular emphasis on those most likely to impact extragalactic research.

The most important advance is probably the development of spatially resolved imaging and spectroscopy across all wavebands, from the development of optical and imaging spectroscopy since the 1960s, the HI and radio continuum surveys of the 1970s, improvements in infrared imaging and spectroscopy in the 1980s, and the emergence of imaging mid-infrared, UV, X-ray and gamma-ray satellites in the 1990s to the present day. I believe these advances have come from a combination of detailed studies of individual objects and large surveys of global parameters. While we often credit the telescopes and instruments, we must not forget that instruments are designed backwards from the detector more often than not. Remarkable advances in detector technology has been the main driver; most of what remains is optical design and engineering. This is an overstatement, but it gets across how reliant we are on detector sensitivity and performance in almost any field of applied science. Astronomers cannot claim to have invented the bolometer or the CCD, but they have been instrumental in pushing their performance to new heights.

Over the past 20 years, imaging surveys from the Hubble Space Telescope (far field) and the Sloan Digital Sky Survey (near field) have been particularly effective in identifying evolution of galaxy parameters with cosmic time and with environment across large-scale structure. This has been matched by large galaxy surveys using multi-object spectroscopy, most notably at the AAT, SDSS, VLT, Magellan and Keck telescopes.

The new generation of detectors changed the design of the instruments and of the telescopes. Photographic plates have been the astronomical detectors for almost 60 years since the discovery of galaxies as extragalactic nebulæ. Today they have been substituted by charged coupled devices (CCD) detectors. The passage to these new detectors has not been neither sudden due to the low cost and versatility of photographic plates, nor without competitor devices, such as the electronographic cameras, the photometers, etc. The history of this passage, before CCDs reached the modern performances in terms of high quantum efficiency and spatial resolution, good cosmetics, field of view comparable or superior to that of photographic plates at Schmidt telescopes, and wavelength sensitivity, is fascinating. We ask George Djorgovski to review this for us.

Questions for George Djorgovski:

Please could you sketch the history of the period around 1982 when we made the transition from analogue (photographic) to digital (especially CCD) data recording?

Astronomers have always been good at adopting the latest detector technology to their needs, and have often contributed significantly towards the development and improvements of the relevant technologies. This is true over the entire wavelength regime, and CCDs are an excellent example.

In general, every time we used some novel detectors, we opened a new region of the observable parameter space, and discovered some previously unknown phenomena, or reached a better understanding of the known ones. This could be a new wavelength regime, a better angular resolution, an increased depth, etc. Progress in observational astronomy is driven largely, if not entirely, by the progress in technology. This has been argued convincingly, e.g., by Harwit (2009). CCDs opened new regions of the observable parameter space in several ways, which I will address below.

The transition from photographic plates to CCDs happened in the late 1970s to the early 1980s. Given their initially small formats, CCDs really represented a successor to the various types of photoelectric detectors, such as image intensifiers, TV cameras, and such. They really became dominant panoramic imaging detectors once their sizes and cosmetic quality increased substantially, and the progress in their manufacture improved the yield and thus lowered the cost per unit, so that we could "pave" the focal planes of telescopes with large detector mosaics. It is worth noting that telescope design, giving a particular physical size to the optically corrected focal plane (typically some tens of cm) was implicitly or explicitly driven by the choice of photographic plates as detectors.

The reason why the photographic plates held as long as they did was in their physical size advantage, allowing imaging of large areas that would not be practical with small CCD detectors. The era of astronomical photography really ended with the Second Palomar Observatory Sky Survey (POSS-II) some time in the mid-1990s. Even as that survey was starting in the mid/late 1980s, and its Southern counterparts were done at ESO and the UK Schmidt in Australia, it was clear to many of us in (then) younger generation that the future is going to be in the fully digital detectors. Even in the 1980s, it was clear that in order to do an actual science with photographic plates (aside from their use for finding charts to be eyeballed at the telescope) was to digitize them. Many astronomy departments had the PDS scanners, or built their own, and major sky survey plate scanning operations existed in the UK (the APM machine in Cambridge and the Cosmos machine in Edinburgh) and the US (notably at the Space Telescope Science Institute in Baltimore, but also on a more modest scale in other locations, such as the University of Minnesota). Digital versions of both the POSS-II [i.e., the Digital Palomar Observatory Sky Survey, or DPOSS; Djorgovski et al. (1992)] and its Southern counterparts, digitized and analyzed in the UK, produced some good science in the 1990s, but that was over once the CCD-based Sloan Digital Sky Survey (SDSS) really got into a full swing in the late 1990s. These plate scans are still widely used to produce digital finding charts through the Digital Sky Survey (DSS) servers. Today, Josh Grindlay and collaborators at Harvard are using a home-built scanner to digitize the historical Harvard plate collection, that contains unique archival material. That is probably the last hurrah of the photographic astronomy.

When the CCDs were just coming of age in the early 1980s, there was a lot of resistance among the older generation of astronomers, who believed that these new-fangled devices will "never replace" the venerable photographic plates or photomultiplier tubes. On a personal note, I was one of the generation of graduate students who had the (mis)fortune to tame the first astronomical CCDs and do some science with them. Thus, I got to talk about CCDs and how to deal with them at a workshop on improvements to photometry, organized by Bill Borucki (Djorgovski 1984). Borucki had what was then a crazy idea to look for extrasolar planets by using eclipses as they traverse the disks of their parent stars, which back then was almost a science fiction. I got a lot of, should we say, skeptical responses from the old pros of photoelectric photometry, to the effect of "CCDs will never be able to achieve that level of accuracy". Well, a few decades later, the Kepler satellite, Borucki's brain child, has revolutionized the field of exoplanets, using CCDs as its detectors.

The obvious reason why CCDs took over as the detectors of choice in the optical astronomy is their great quantum efficiency, approaching unity over the entire optical wavelength range, from the atmospheric cutoff in the UV, to the silicon transparency limit slightly longward of 10 μm (they also work fine in the far UV and soft X-rays above the atmosphere). Another reason is their great dynamical range (typically about four orders of magnitude in intensity, per pixel), and a good linearity over much of that range (unlike the highly non-linear detectors such as the photographic plates or the human eyes). A less obvious, but I think an important reason is the nature of their noise, which, to a good approximation, is Poissonian, i.e., the adjacent pixels are essentially uncorrelated, and it is the square root of the number of the detected or readout-generated photoelectrons that matters. This is unlike the photographic plates, where the adjacent pixels can be very correlated, due to the size of the grains in the emulsion. This makes image processing of the CCD data much more benevolent. And finally, they generate data that are already digital, as opposed to the plates that have to be sensitized (almost an alchemy in itself), exposed, developed, and then digitized.

As for the achievements of CCDs, it is essentially everything in the optical astronomy since about the mid 1980s. Probably the biggest gains were due to the increased depth of imaging, with the HST reaching to about 29th magnitude. This revolutionized our understanding of galaxy evolution and formation, among many other topics, exoplanets included. With CCDs, we could go deeper, faster (and thus have more sources covered), and better (dynamical range and the noise properties), whether in direct imaging or spectroscopy.

The digital detectors opened a new era for the panchromatic observations of galaxies. They were instrumental to space missions that knocked down the last barrier, the atmospheric absorption, towards full panchromatic observations.

1.5 Toward a Panchromatic View of Galaxies

Generations of platforms on board of balloons, rocket and air-borne experiments, and of space telescopes have greatly contributed to open a new era in the extragalactic research. Observations from space facilities are now often combined with ground based observations. These latter equipped with flexible multi-purpose instruments at focal planes of large telescopes complete the multi wavelength view of galaxies offered by space observations with kinematic measures and deep spectroscopic observations.

Prototypical of the space facilities is the 2.4-m Hubble Space Telescope (HST) lunched in 1990, built by National Aeronautics and Space Administration (NASA) with the contribution of the European Space Agency (ESA), and operated by the Space Telescope Science Institute in Baltimore (Maryland, USA). HST after various *refurbishing Space Shuttle missions, is still operative after 25 years. Its contribution to extragalactic astronomy is enormous and presented in different chapters over the entire book. With its high resolution optical imaging, ultraviolet and infrared instruments it represents a sort of paradigm for the multi-wavelength observations of galaxies. In the following section we focuses on the contribution of space missions that contributed in building the present panchromatic view of galaxies.*

1.5.1 The Ultraviolet Window

Questions for Luciana Bianchi:

Please describe the UV-optical space missions that have served as milestones in extragalactic research.

The nature of galaxies beyond our own Milky Way was first realized a little less than a century ago, but the story of UV-optical space observations begins much later. The first UltraViolet[2] space telescopes were launched in the 1970s, after pioneer rocket experiments. Earth's atmosphere blocks most UV radiation, therefore only space-borne instruments can provide sensitive observations of the sky at UV wavelengths. The first UV telescopes did not observe galaxies, but they indirectly helped our interpretation of them that was to begin.

After the first rocket free-flights (unstabilized) in the 1950s, 3-axes stabilized rockets in the early 1960s afforded a few minutes of observations (Morton and Spitzer 1966; Stecher and Milligan 1962). NASA OAO-2 (launched 1968) was one of the first "observatories": the Celescope cameras acquired photometry of 5068 stars (Code et al. 1970; Davis et al. 1973). The era of manned flights then began; hand-held cameras were used on Gemini flights, while ORION-2 on Soyuz-13 recorded UV spectra of ∼900 stars. Rocket flights also began to explore the UV sky background, with resolution of the order of ∼10° (Henry 1977). The European TD-1 S2-68 (1972), through apertures of $\sim 2' \times 17'$ and $12' \times 17'$, produced a catalog of 31,215 UV sources brighter than $\sim 10^{-12}$ ergs cm^{-2} s^{-1} Å^{-1}: only 3 are galaxies (Thompson et al. 1978). ANS yielded photometry of ∼5000 sources.[3]

Between 1972 and 1981 OAO-3 Copernicus (a collaboration between NASA and UK's SERC) collected UV high-resolution spectra of hundreds of bright, nearby stars. We were still far from the realm of galaxies, but we ought to mention Copernicus here for a discovery of paramount relevance for understanding stellar

[2]I will refer as Ultraviolet (UV) to the wavelength range shortwards of ∼3300 Å, which is often divided in far-UV (FUV) and near-UV (NUV) at ∼2000 Å. The range shortwards of Ly$_\alpha$ is usually termed Extreme-UV (EUV).

[3]There were other UV instruments: the USSR ASTRON station, GLAZAR on MIR, S201 on Apollo 16, FAUST on Spacelab, the GSFC camera, SCAP 2000, FOCA, FUVCAM, NUVIEWS,... Rocket and balloon experiments continue today, as an economical and fast way to test new technology.

and galaxy evolution: the strong supersonic outflows from massive stars[4] (Morton 1976) ($\dot{M} \sim 10^{-6-7} M_{\odot}$ year^{-1}, velocity $\sim 10^3$km s^{-1}), revealed by asymmetric ("P Cygni"-type) profiles in the resonance lines of the most abundant ions in the outer atmospheres. All these transitions fall in the EUV−FUV range.[5] Scores of works have since been devoted to measuring mass loss in hot massive stars, a most relevant factor and still a major source of uncertainty in modeling stellar evolution. Amazing progress was made thanks to `FUSE` data and increased modeling power. UV lines also allow us to constraining wind "clumping" which arises from instabilities in the wind acceleration mechanism (radiation pressure), and to reduce $\dot{M}$ uncertainties (e.g., Bianchi 2012; Bianchi et al. 2009 and references therein). Not only are FUV lines indispensable to constrain $\dot{M}$, they also led to a significant revision of canonical calibrations of $T_{\rm eff}$ and $L_{\rm bol}$ for massive stars (Bianchi 2002; Bianchi and Garcia 2014 and references therein), relevant for the ionization and energy balance of the ISM in galaxies. Massive stars play a major role in the chemical and dynamical evolution of the interstellar medium (ISM); they drive stellar feedback on galactic scales through supersonic outflows and supernova explosions. Massive stars are a powerful tool for tracing and precisely age-dating star-formation episodes, and they dominate the (redshifted) UV light from distant starburst galaxies. Understanding their evolution underpins our interpretation of deep cosmological surveys. EUV-FUV spectra have shaped our understanding of the physics of these fundamental players in galaxy evolution, as well as of the properties of ISM gas and dust, for which UV spectroscopy is also essential (see Fig. 9.3). All these are fundamental ingredients for modeling galaxy evolution.

Tracking UV milestones brings us finally to actual observations of galaxies. Early UV instruments[6] could observe only the brightest sources, mostly stars. Beginning in 1978, `IUE` (International Ultraviolet Explorer) collected UV spectra of bright extragalactic sources for 18 years. UV imaging of galaxies however was confined to limited-time flights, such as rockets and instruments flown on the `Space Shuttle`. `UIT` (Ultraviolet Imaging Telescope), (Stecher et al. 1992, 1997) yielded images of >70 nearby galaxies in ∼1500 and ∼2500 Å bands, with 3″ resolution, during the `Astro-1` and `Astro-2 Spacelab` missions (9 days in 1990, 16

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[4]The first discovery of broad absorptions in UV resonance lines of massive stars, with velocities of a few thousand km s^{-1}, from `Aerobee` rocket data of B stars in Orion, was reported by Morton and Spitzer (1966) who correctly interpreted them as evidence of mass loss.

[5]H_{α} and HeII 4686 are also wind diagnostics but only in high luminosity stars with high $\dot{M}$; instead, resonance lines in UV and EUV trace winds also at low $L_{\rm bol}$, low $\dot{M}$, high $T_{\rm eff}$ [even in the hottest evolved stars, when all other diagnostics fade Bianchi (2012)]. UV lines also allow us to measure wind velocity, and momentum injected by the stellar wind into the interstellar medium.

[6]The instruments mentioned so far had resolution of tens of arcminutes or worse, flux limit∼11–12 mag, except for balloons which can lift larger telescopes, but cannot access FUV due to the limited heights they can reach.

days in 1995)[7] and of portions of the Magellanic Clouds. Additional excitement came from the fact that an astronomer flew with the Shuttle crew, to perform the observations, overcoming the boundary between astronaut (a super-pilot) and scientist (payload specialist). Images from UIT and most earlier instruments were recorded on film. The exposed films returned to Earth with the Shuttle or rocket payload. The film medium posed serious challenges for flux calibration, often compounded by detector non-linearity. Different exposures of the same galaxy had to be combined to achieve a wider dynamic range. Overall, flux calibration of early data was no better than 20 % (Bohlin et al. 2014). Manned missions are also limited by the duration of the flight, and, during the flight, by pointing constraints as the telescope sits on the Shuttle's cargo bay (in relatively low orbit). Yet historical breakthroughs were achieved, showing the potential of UV observations, and driving new developments. UIT gave astronomers the first clear view of young stellar populations in nearby galaxies (Kuchinski et al. 2000; Marcum et al. 2001; Massey et al. 1996). It showed that galaxy morphology dramatically varies with wavelength. UV enhances the young hot massive stars, suppressing the longer-lived cool-star component: A new era had just began for the study of galaxies.

The quantum leap in extragalactic research (at UV wavelengths) was finally enabled by two recent, very different, complementary missions: the Hubble Space Telescope (HST) and the Galaxy Evolution Explorer (GALEX). The characteristics of these two space-borne facilities, offering the best spatial resolution and the widest surveys respectively, concurred to clarify the puzzle of how star formation works (modalities and causalities), and how it has evolved in the Universe. Of all UV observations collected prior to HST (launched 1990) only about 1–2 % were of extragalactic objects (O'Connell 1991). After Hubble and GALEX, it is impossible to even begin reviewing progress in this field. What follows is only a partial list of highlights.

Let's begin with the local Universe, the stepping stone for understanding galaxy formation and evolution throughout cosmic times. Nearby galaxies, the Local Group (LG) in particular, offer an ideal laboratory for resolved stellar population studies over a wide range of galaxy types, mass, gas content, metallicity, dynamics: differing environments which represent physical conditions typical of recent and earlier epochs of the Universe. Results from local galaxies calibrate global star-formation indicators, and inform population synthesis models used to interpret integrated light of distant galaxies.

GALEX provided the first comprehensive, deep view of UV morphology of extended nearby galaxies, and a UV *color*, FUV-NUV, extremely sensitive for age-dating young stellar populations (Bianchi 2011). With its wide-field capability and high sensitivity, GALEX yielded the long-missing road map for any observing UV

[7]With UIT, two other UV instruments were flown: the Hopkins Ultraviolet Telescope (HUT) performing spectrophotometry in the 425–1850 Å range, and the *Wisconsin Ultraviolet Photopolarimetry Experiment* (WUPPE spectrapolarimeter, covering the range from 1250 to 3200 Å).

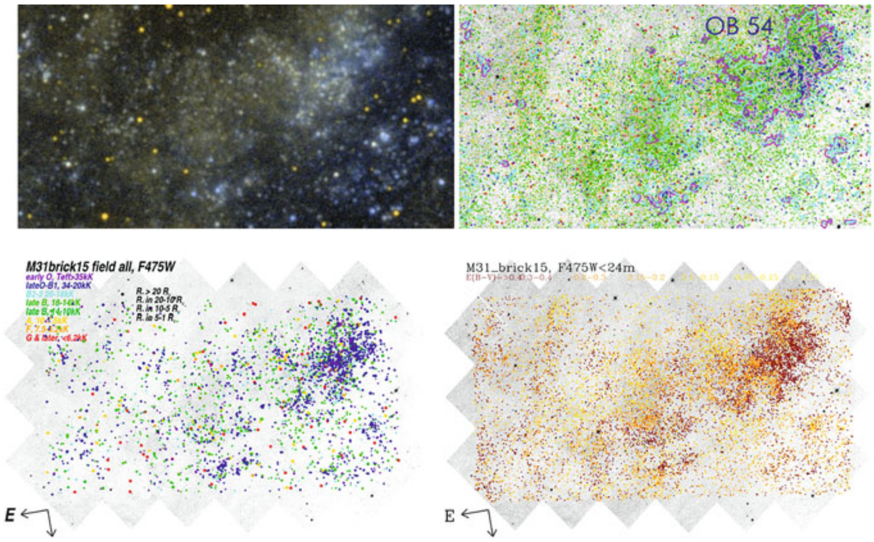

Fig. 1.14 *Top: Left:* A GALEX (FUV: *blue*, NUV: *yellow*) portion of M31 spiral arm including OB 54, and *Right:* a map of the stars in this region, color-coded by their $T_{\rm eff}$ derived from HST photometry (hot to cold: *purple to red*), with contours of GALEX-FUV flux [*magenta*, from Kang et al. (2009)] and of hot-star associations from clustering algorithm on scales comparable to GALEX resolution [*cyan*, (Bianchi et al. 2014)]. *Bottom:* the brightest stars in PHAT Brick15, color coded by $T_{\rm eff}$ (*left*) and by extinction (*right*, lighter to darker: *lower to higher* E_{B-V}) derived from HST photometry. The images illustrate the correlation between dust and SF, and the hierarchical structure of SF, with the hottest (youngest) stars clustered in tight groups, which are often arranged within larger complexes. From Bianchi et al. (2014)

program concerning star formation (SF) in galaxies, but it was launched almost 15 years after HST. GALEX highlights will be described in Chap. 5.5.1.

On the other hand, HST resolution of $\leq 0.1''$, or $\leq$ half pc projected on the sky within the Local Group ($\lesssim$1 Mpc), allows us to study the individual stellar constituents of local star-forming regions. Hot massive stars in particular, which trace young stellar populations and are prominent at UV wavelengths, are born in tight groups (Fig. 1.14) (Bianchi et al. 2012a, 2014), which then expand and dissolve as the radiation from the stars themselves dissipates part of the star-forming cloud, and the association is no longer gravitationally bound. Therefore, for the purpose of counting and characterizing massive stars, for studies of the initial mass function (IMF), ionization of ISM, cluster masses, and more, high resolution is critical. Not only may hot-star counts be underestimated at low resolution, but composite colors from photometry of unresolved stars yield incorrect physical parameters [see Fig. 3 in Bianchi et al. (2012b)].

HST studies of galaxies, in particular of resolved populations of nearby galaxies, amount perhaps to the most substantial investment of Hubble's time along its 25 years of operations so far. Many such studies include UV imaging, though few extend to FUV due to the demanding exposure times. A few examples out of many: LEGUS (selected fields in 50 galaxies within 12 Mpc, Calzetti et al. (2015), http://legus.stsci.edu), PHAT (Dalcanton et al. 2012) and TrImS (Bianchi et al. 2011b, 2012a,b, 2014), http://dolomiti.pha.jhu.edu/LocalGroup. The latter imaged 67 star-forming sites in six Local Group dwarfs and the two spirals, M31 and M33, with 6 filters from FUV to NIR, to study young stellar populations in different environments. Massive star content and extinction were characterized in a variety of OB associations; in M31 these cover galactocentric distances out to 22 kpc, and show large variations in number and density of massive stars. The cumulative mass distribution of OB associations follows a power law, with exponent similar to what is generally found for the bound stellar clusters ($\sim$2). Extinction is higher in SF sites in the inner disk, and tapers down to the foreground value in the outermost region imaged (Bianchi et al. 2012a). In the six TrImS dwarfs, young stellar populations range from a rather inconspicuous presence in Phoenix and Pegasus to vigorous SF in Sextans A and WLM; though SF is patchy in time and space, a broad correlation emerged between recent SF (as traced by the number of massive stars) and the integrated optical luminosity (a proxy for the galaxy's total stellar mass). HI gas emission does not always correlate with the distribution of UV-emitting massive stars, and in some cases it seems to have been even removed from the UV-bright stellar regions and main galaxy body (Bianchi et al. 2011b).

These and many other `HST` programs sampled small regions of nearby galaxies. The field of view of `HST`'s `WFPC2` and `WFC3` cameras (and `ACS` in optical filters) subtends the size of a typical OB association within the Local Group, yielding color-magnitude diagrams (CMD) of young coeval populations. Only one `HST` program so far covered a substantial contiguous portion of an extended LG galaxy: the Panchromatic Hubble Andromeda Treasury Survey (PHAT, Dalcanton et al. (2012)). Using 828 `HST` orbits over 3 years, PHAT mapped about one third of M31 in six filters from near-UV to IR. The resulting measurements of 117 million stars (Williams et al. 2014) at the same distance, in the same galaxy, are a unique template for studies of resolved stellar populations, and to inform models of stellar and galaxy evolution for years to come. PHAT early data has already enabled a quantum leap in the detection of stellar clusters (Johnson et al. 2012) and estimate of their ages and masses (Beerman et al. 2012; Fouesneau et al. 2014), improved constraints on AGB-manqué stars (Rosenfield et al. 2012) and thermally-pulsing AGB stars (Rosenfield et al. 2014), derivation of the inner halo stellar mass distribution (Williams et al. 2012), extinction (Dong et al. 2014) and the M31's dust disk (Dalcanton et al. 2014), and revealed the space- and time-tomography of the young stellar populations (Bianchi et al. 2014; Gouliermis et al. 2014).

Other `HST` highlights out of 25 years of relevant discoveries in extragalactic research are described elsewhere in this book, and highlights from `GALEX` in Chap. 5.5.1. Among other recent results from `HST` UV data, the `COS`-Halos survey showed that cold, diffuse haloes ($\sim$150 kpc) may harbour a total gas mass comparable to the galactic stellar mass (Tumlinson et al. 2013) and substantial heavy elements mass in the CGM of star-burst galaxies (Tumlinson et al. 2011). LARS and eLARS surveys use `ACS/SBC` imaging and `COS` spectroscopy to clarify Ly$_\alpha$ transport and leakage (Östlin et al. 2014). One of the primary objectives of `HST`, pursued with many programs, was to improve the cosmic distance scale; observations of supernovae showed that the expansion of the Universe is accelerating, important enough to earn Nobel prize recognition.

To the UV-optical- NIR vision of `HST` *NASA added two so called "Great Observatories",* `Spitzer` *Space Telescope, launched in 2003, exploring the Mid IR window and* `Chandra` *X-ray Observatory for high resolution X-ray observations, launched in 1999. Other two main ESA satellites contributed to the space exploration in the far infrared and sub-millimetre region to the X-ray:* `Herschel` *Space Observatory, with its 3.5 m single mirror, launched in 2009 and* `XMM-Newton` *launched in 1999. We ask Daniela Calzetti and Giuseppina Fabbiano to summarize the most important contributions of these satellites and their precursors respectively for the IR and X-ray extragalactic astronomy.*

1.5.2 The Infrared Window

Question for Daniela Calzetti:

Which IR space missions have been a milestone and what their most important achievements for the extragalactic research?

Starting in the 1980s, there are a number of IR space missions that have enabled progress in the field of extragalactic astronomy. Each subsequent mission usually included a few technical improvements over the previous one, in sensitivity, angular resolution, wavelength range, and/or field-of-view coverage that produced one or more milestones. For sake of clarity, I will refer to 'infrared' (IR) when discussing the entire wavelength region from $\sim$3 µm to $\sim$1 mm; the luminosity of a galaxy measured in this range will be defined as L(TIR) (total IR); sometimes the IR will be separated into two ranges: the mid-IR (3–40 µm) and the far-IR (40–1000 µm), where the separation point is purely historical.

`IRAS`, the InfraRed Astronomical Satellite, was launched in 1983 and run for 10 months. `IRAS` covered about 96 % of the sky in four bands centered at 12, 25, 60, and 100 µm. Its angular resolution was a few arc minutes, implying that most galaxies were point sources in the `IRAS` beam, and its limited sensitivity did not allow it to detect galaxies beyond a few hundreds Mpc, except for exceptional cases. Nevertheless, `IRAS` showed that there are galaxies that are at least 10 times, and more, brighter in the IR than they are in the optical, giving raise to the new terminology of LIRGs (Luminous InfraRed Galaxies) and ULIRGs (Ultra Luminous InfraRed Galaxies), impressive systems characterized by strong dust emission although relatively rare in the local Universe ($\sim$6 % of the total number of galaxies, Sanders and Mirabel (1996)). `IRAS` also revealed that our own Milky Way is pervaded with wisps of dust that emit strongly at the longer IR wavelengths, called 'cirrus' . The 'cirrus' would later turn out to be a common ingredient of galaxies, their cooler emission dust components, heated by stars like our Sun. In terms of global properties of galaxies, IRAS showed that about one–third of the bolometric luminosity from local galaxies is emitted in the IR (Soifer and Neugebauer 1991).

Although not specifically designed for the study of galaxies, the COsmic Background Explorer (COBE) contributed important advances in this field. Launched in 1989, COBE carried three instruments, two of which, DIRBE (Diffuse InfraRed Background Experiment) and FIRAS (Far–InfraRed Absolute Spectrophotometer) are of interest here. Together, they covered the wavelength range from 1.25 to 5 mm i.e., the region of dust emission. DIRBE produced the first measurements of the Cosmic Infrared Background (CIB) between 2 μm and 240 μm, i.e., of the integrated light in the IR from all galaxies at all redshifts [see review by Hauser and Dwek (2001), and references therein]. When combined with measurements of the extragalactic background light at UV–optical wavelengths, it became clear that the dust reprocessed about half of the bolometric output from galaxies into the IR. In addition, DIRBE and FIRAS produced detailed measurements of the infrared emission from our own Milky Way, which has enabled progress in understanding the physical nature of the interstellar dust (Draine 2003, and references therein).

ISO, the Infrared Space Observatory, operated between 1995 and 1998, and provided the first opportunity to account for the sources of the CIB. Indeed, a large fraction of the CIB at 15 μm was resolved by ISO deep surveys, revealing that at high redshift dust–obscured galaxies are more widespread than in the local Universe (Elbaz 2004; Lagache et al. 2005). ISO contributed major advances also to the understanding of local galaxies (Genzel and Cesaesky 2000). It showed that the mid-IR emission in galaxies is dominated by large molecules (Polycyclic Aromatic Hydrocarbons, PAHs) and small dust grains that are transiently heated by stellar radiation, and produce both emission continuum and broad emission features (Desert et al. 1990; Fig. 1.15). The features become generally fainter in active systems (AGNs, LINERs), suggesting destruction or processing of the carriers by hard radiation fields. The long–wavelength baseline of ISO, covering up to 200 μm, also revealed the presence of cold (T∼10–25 K) dust in galaxies, which reconciled the gas-to-dust ratios of external galaxies with that of the Milky Way (Genzel and Cesaesky 2000, and reference therein).

The Spitzer Space Telescope, launched in 2003, and with a cryogenic mission that ended in 2009, covered the wavelength range 3.6–160 μm with both imaging and spectroscopy. It is still operating as a 'warm telescope' at 3.6 and 4.5 μm. Thanks to its unprecedented angular resolution (2″ at the shortest wavelengths) and sensitivity, Spitzer opened new windows on both the local and the deep Universe (Soifer et al. 2008). It enabled the first detailed studies of the dust–enshrouded star formation in nearby galaxies. Major results include: demonstrating the dependency of the PAH emission on a galaxy's metal content, being stronger for higher metallicity; placing on a secure footing physically–motivated models of dust emission; and providing accurate tools for measuring the star formation rate of a galaxy, and of regions within galaxies, by accounting for both the dust–obscured and unobscured star formation (Calzetti et al. 2007). Spitzer has also resolved the

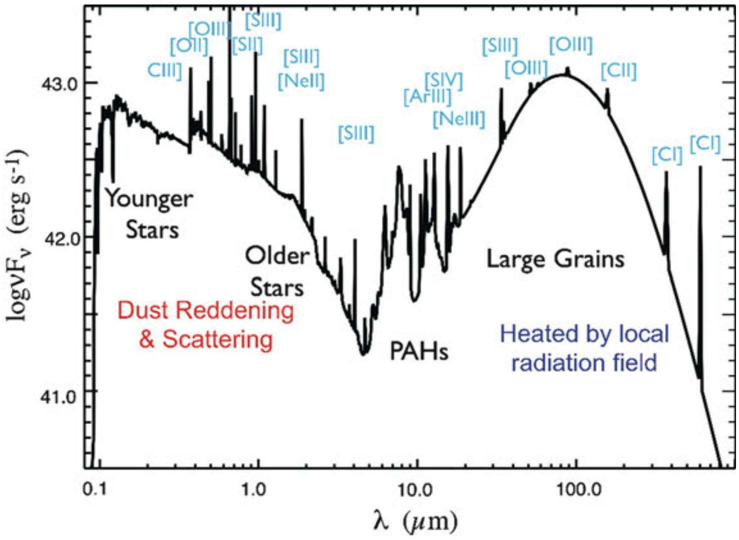

Fig. 1.15 A model galaxy spectral energy distribution (SED) from the UV (0.1 µm) to the far-IR (800 µm), from the models of (Groves et al. 2008). Both stellar and dust continuum are shown, the former in the 0.1–3 µm range and the latter in the 3–800 µm range. The stellar continuum is attenuated and reddened by dust, indicated in the Figure as 'Dust Reddening and Scattering'. The energy absorbed by dust is re–emitted in the IR, in the two regions indicated as 'PAHs' and 'Heated by local radiation field'. The wavelength region 3–40 µm has both continuum and emission features (PAHs) contributed by stochastically heated dust. The longer wavelength IR region emits radiation in thermal equilibrium. In addition to the continuum and broad PAH features, *narrow emission lines* from metals are shown and identified from the optical to the far-IR. The Hα emission line (not labelled) is located at 0.6563 µm. Figure produced by Brent Groves for this contribution

CIB by providing a full accounting of IR emission of galaxies at all redshifts (Dole et al. 2006), and has traced the dust–obscured portion of the cosmic star formation rate density up to redshift z>2.5, confirming earlier suggestions that galaxies as luminous as LIRGs and ULIRGs become major contributors of the cosmic SFR at high redshift (Murphy et al. 2011).

With a ∼3.5–m mirror, the `Herschel` Space Telescope, which operated between 2009 and 2013, is the largest infrared telescope ever launched in space so far. The wavelength range it covered, 70–500 µm, was uniquely suited to probe the thermal dust emission from galaxies. Among its unique results are the detection of an excess in the sub-mm emission tail of the cold dust from galaxies, the nature of which is still under investigation (Galametz et al. 2014). `Herschel` data also showed that metal–poor galaxies tend to have dust–to–gas ratios that are much lower, by about an order of magnitude, than what can be expected from a simple extrapolation of the metallicity trend (Remy-Ruyer et al. 2014); this result is also still being investigated. For metal–rich nearby galaxies, the high angular resolution of `Herschel` at and beyond the IR emission peak, ∼5″ at 70 µm, has provided unprecedented insights into the properties of the cold dust emission: its variations with galaxy location are tied to variations in the heating provided by the underlying stellar populations, rather than variations in the properties of the dust (Hunt et al. 2015). Moving away from the Local Universe, Herschel data have conclusively determined that the bright infrared galaxies at high redshift resemble in any other characteristic the low–redshift normal star-forming galaxies, rather than the local ULIRGs (Elbaz et al. 2011), thus confirming earlier suggestions based on smaller samples (Pope et al. 2006).

Thus, over the course of about 30 years, a few key missions have enabled us to progress from having just a sketchy description of how the infrared Universe looks like to entertaining a healthy debate on what are the physical mechanisms that drive the intensity, shape, and characteristics of the infrared emission from galaxies, and how these mechanisms respond to variations in the global and local properties of the galaxies themselves.

1.5.3 The X-ray Window

Question for Giuseppina Fabbiano:

Since the 1970s X-ray space missions have opened a new window on extragalactic research. Which X-ray space missions have been a milestone and what important discoveries and changes in our ideas about galaxies have resulted from X-ray observations?

In my view three NASA X-space missions should be considered as ground-breaking milestones for the field: Uhuru, the first X-ray satellite to survey the sky; the Einstein Observatory, the first imaging long-lived X-ray telescope; and the Chandra X-ray Observatory, the sub-arcsecond resolution, sensitive NASA great observatory for the X-ray band. I have been lucky to be closely involved with all three these missions, which were designed by collaborations led by Riccardo Giacconi.

Other X-ray missions, discussed below, have made (and are making) important scientific contributions. While their astrophysical impact in certain areas may be greater than that of the three milestone missions (e.g. the establishment of AGNs as X-ray sources by the ARIEL 5 group, (Elvis et al. 1978), they did not provide the same revolutionary opening of discovery space for the discipline and for astronomy in general.

Uhuru (1970–1973), was the first X-ray satellite to survey the sky [see reviews Giacconi and Gursky (1974), Pounds (2014)], and produce catalogs of X-ray sources, e.g., the 3U catalog of 161 sources (Giacconi et al. 1974), and the 4U final catalog including 339 sources (Forman et al. 1978). X-ray source positions were constrained by means of a collimator. Uhuru led to the establishment of X-ray binaries as the dominant class of X-ray sources in the Milky Way, to the discovery of X-ray emission from clusters of galaxies and to the first report of X-ray emission from nearby AGN and quasars (NGC 4151 and 3C 273). Together with subsequent observations with the UK survey satellite ARIEL 5, and the NASA SAS-3 and HEAO-1 missions—which were able to constrain significantly better the position of X-ray sources, thus aiding in the identification of optical and radio counterpart —, the basic picture of the different classes of luminous X-ray sky emerged:

- X-ray binaries (XRBs), both associated with the young high mass (HMXB) and the old low-mass (LMXB) stellar population, were discovered in the Milky Way and the Magellanic Clouds. XRBs are binary systems composed of a normal star and a compact stellar remnant. The compact counterparts of these sources were established to be black holes (BH), neutron stars (NS) and white dwarfs (WD) Subjects!White dwarfs (for the CV class). These sources were understood as resulting both from the evolution of native binary systems and—in the case of LMXBs—also from dynamical formation in globular clusters;
  - Supernova Remnants (SNR), both shells and Crab-like;
  - External galaxies: Magellanic Clouds, M31; M87;
  - Clusters of galaxies;
  - Seyfert galaxies (a class of AGNs).

Einstein, launched in 1978 and operating until 1981, was the first X-ray astronomy mission to include an imaging telescope (Giacconi et al. 1979). Although it operated in pointing mode, without surveying the whole sky, the increase in sensitivity and imaging capabilities opened up the study of the X-ray properties of virtually all classes of astronomical objects, not just the exceptional X-ray luminous sources that had been discovered by the previous class of non-imaging X-ray missions. Einstein detected the X-ray emission of normal stars, extending the study of coronal emission to stars other than the Sun, and establishing that all types of stars are low-luminosity X-ray emitters (Vaiana et al. 1981); allowed imaging studies of SNRs in both the Milky Way and the Magellanic Clouds (Long et al. 1981); studied distant quasars (Tananbaum et al. 1979) and galaxy clusters (Jones and Forman 1984); allowed the study of different types of normal galaxies and their X-ray components in X-rays, including the discovery of ULXs, which may super-Eddington accreting XRBs and in some case candidates for accreting intermediate mass BHs (Fabbiano 1989; Fabbiano et al. 1992); and produced a flux limited and homogeneous sample of 853 serendipitous sources in the high latitude sky (Gioia et al. 1990). The use of Einstein data obtained while the satellite was slewing between targets provided a complementary list of higher flux sources collected over a larger fraction of the sky with shallow exposure (Elvis et al. 1992).

The German -with NASA and UK participation- X-ray telescope ROSAT (Truemper 1983) was the most important follow-up mission to Einstein. Launched in 1990 and operating until 1999, ROSAT allowed the systematic exploration of the astrophysical properties of all the classes of X-ray sources discovered with Einstein, and produced an all-sky catalog of ∼120,000 X-ray sources (Voges 1992); being more sensitive than Einstein in the soft energy band, ROSAT was particularly important in furthering the study of the hot gaseous component of galaxies (Fabbiano 1996).

The Japanese-USA ASCA mission (1993–2000) had limited imaging capabilities, but pioneered the use of CCD detectors in X-ray astronomy, which then became the detector of choice for the next generation of X-ray telescopes (Chandra and XMM-Newton). ASCA's improvement in spectral resolution led to the first claim of gravitational redshift in the FeK emission line of AGNs (Tanaka et al. 1995), initiating the study of AGNs as potential probes of extreme gravity, which was then extended with XMM-Newton and more recently with NuSTAR.

Chandra, launched in 1999, is the NASA flagship X-ray observatory (Weisskopf et al. 2000). Thanks to its exquisite optics, Chandra provides unique sub-arcsecond imaging of complex X-ray emitting regions. This resolution also results in extremely low background levels in the source detection regions for point-like source, resulting in a factor of $\sim$10 better sensitivity for deep surveys at the lowest flux limits than any other X-ray observatory [XMM-Newton and ATHENA, the next ESA X-ray telescope, because of their poorer angular resolution are background limited in very long exposures.] Thanks to the moderate spectral resolution of the CCD detectors, the energy of the emitted photons can be mapped on a pixel base throughout the images of the X-ray emitting regions. It would take too long to describe the list of Chandra achievements here, because they touch virtually all areas of astronomy [see Tananbaum et al. (2014) for a review]. Chandra has opened X-ray astronomy, which has traditionally been a discipline of experts, to the general astronomical community worldwide. Chandra results are used in synergy with other wavelength high-resolution telescope data to gain a more complete understanding of the physical properties and astrophysical processes of virtually any kind of object in the sky. Examples include:

- Study of different types of stellar associations in the Galaxy;
- Detailed study of supernovae and their chemical composition;
- Discovery and study of populations of X-ray sources in all kinds of galaxies;
- Study of the physical and chemical evolution of hot gaseous halos in galaxies and galaxy clusters;
- Study of AGNs near and far, luminous and faint, and of their interaction with the host galaxy and surrounding gaseous medium;
- Detailed study of the merging evolution of galaxy clusters, galaxies, and their nuclear massive black holes;
- Constraining cosmological parameters with galaxy cluster observations.

XMM-Newton, also launched in 1999, is the ESA flagship X-ray telescope. It has three-times the collecting area of Chandra, but 30 times worse angular resolution (PSF). Similarly to Chandra, XMM-Newton is equipped with CCD detectors and gratings for high-resolution spectroscopy. These characteristics make XMM-Newton the telescope of choice for spectral and variability study of bright and moderately bright X-ray sources, when detailed knowledge of the spatial properties and contamination by nearby confused sources are not an issue. In particular, a recent joint XMM-Newton/NuSTAR spectra-variability study of the

AGN in NGC 1365 identify a reflection component arising from a region within 2.5 gravitational radii of the rapidly spinning black hole (Risaliti et al. 2013). A sample of ∼1000 extended sources found in the XMM-Newton database, selected as candidate clusters of galaxies, has been used as the bases of several studies of cosmic evolution (see Fassbender 2007). The Local Group galaxies M33 and M31, and M101 were mapped (Jenkins et al. 2005; Pietsch et al. 2003, 2005), resulting in catalogs of X-ray sources, and in the spectral and spatial characterization of these sources. In farther away galaxies, XMM-Newton observations have been instrumental for the study of the spectral variability of the most luminous X-ray sources, the ULXs (e.g. Soria et al. 2009).

In this context, it is necessary to stress that space missions have produced not only a new panchromatic view of galaxies, but also totally unexpected discoveries. Today the combination of space and ground-based observations is the widely preferred approach followed in extragalactic researches, as the following interview will demonstrate.

Questions for Alvio Renzini:

Which radio, sub-millimeter and space observations can help to construct an increasingly detailed panchromatic view of galaxies? And why this view is so important?

The combination of ground and space data has been both ubiquitous and essential to map galaxy evolution over most of the history of the Universe. Now we leave in the *multiwavelength era* of astronomy and especially so for galaxy evolution. We don't speak anymore of optical astronomers, radio-astronomers, X-ray astronomers and the like. *Monochromatic* astronomers have given way to multiwavelength astronomers, and Hubble, Spitzer, Herschel, Chandra, GALEX and XMM-Newton have provided us with data covering the full electromagnetic spectrum of galaxies at all distances from us. Radioastronomy has now emerged from its own *middle age*, in the last two decades having played only a marginal role in the advancement of our understanding of galaxy evolution. But with its extension to the submillimeter with IRAM and ALMA it is gaining the front raw again, and probably even more so in the future, with LOFAR and SKA.

Sub-millimeter observations of both the CO lines and the dust continuum have given us access to another fundamental quantity, the gas mass of galaxies. Optical and near-IR observations give us information on the stellar mass of galaxies, but say little about their gas mass content, out of which new stars form. This is where sub-millimeter observations are giving us this critical piece of the galaxy puzzle. So, IRAM and ALMA observations have shown us that the gas fraction of galaxies, their gas mass to stellar mass ratio, is much higher at high redshift. For example, this fraction is of order of $\sim 5\,\%$ in our Milky Way galaxy, but it is of order of $\sim 50\,\%$ in galaxies of similar mass at $z \sim 2$ (Daddi et al. 2010; Tacconi et al. 2010, 2013). It is then no surprise if such galaxies are forming stars so vigorously. Much more is coming from the sub-millimeter observations, which is perhaps the most rapidly advancing front, right now.

The panchromatic view of galaxies and the consequent jump in our observational knowledge of galaxies have been accompanied by an explosive growth in our computational resources and simulation capabilities. In his interview Reinaldo De Carvalho already noticed that "today simulations produce almost as much data as the new instruments in astronomy". In the following section we ask Françoise Combes and Cesare Chiosi to provide us their view of the revolution induced by the growth in computing power, highlighting the problems that are still open.

1.6 The Impact of Computing Power on Galaxy Modeling and Theoretical Understanding

Questions for Françoise Combes:

Modern computers provide a powerful resource for simulations. Through the last century, analytical approaches to galaxy formation and evolution made room to computational ones. What have been, in your view, the milestones in the simulation of galaxies? Are there possible hazards in the new approaches? What are the present limits of galaxy simulations?

The progress in computers has been stunning. It is not so long ago that the Swedish astronomer Erik Holmberg in the 1940s carried out analogic simulations of galaxy interactions with the help of light bulbs. Since the light intensity decreases as the square of the distance from any bulb, as the gravity forces decrease with the distance to the source mass, he could simulate the N-body problem, by computing the sum of forces in a particular location (i.e. the total light at this location). The interaction between two galaxies was simulated by two systems of 74 bulbs mobile on a table.

Note that he was tackling the true N-body problem, while the progress in this domain went through the very simplified restricted 3-body problem. To simulate the interactions between two galaxies, the main physical issue is to take into account the tidal forces exerted by each galaxy as a whole on all the stars of its companion, which can be considered as test particles. In a first approximation, the effects of the self-gravity of each galaxy can be neglected. This was the approach of several authors, like Pfleiderer and Siedentopf in the 1960s (Pfleiderer and Siedentopf 1961), but the main study, with a lot of insight and impact on future research, was the work of the Toomre brothers (Toomre and Toomre 1972). They showed how spiral structure could be triggered by the interaction, and also how bridges, filaments, long tails could be formed by tidal forces. Until this work, many other forces were proposed, like magnetic forces, to explain these very thin filaments, that were reminiscent of flux tubes. Simple numerical simulations were sufficient to convince that tidal interactions could reproduce the observations.

The essential milestones in galaxy simulations were first to include the full self-gravity with all the components, and in particular the dark matter halos, which in early works were approximated by rigid potentials. Then the account of the gas hydrodynamics, with all its complex physics, called "gastrophysics", which is not

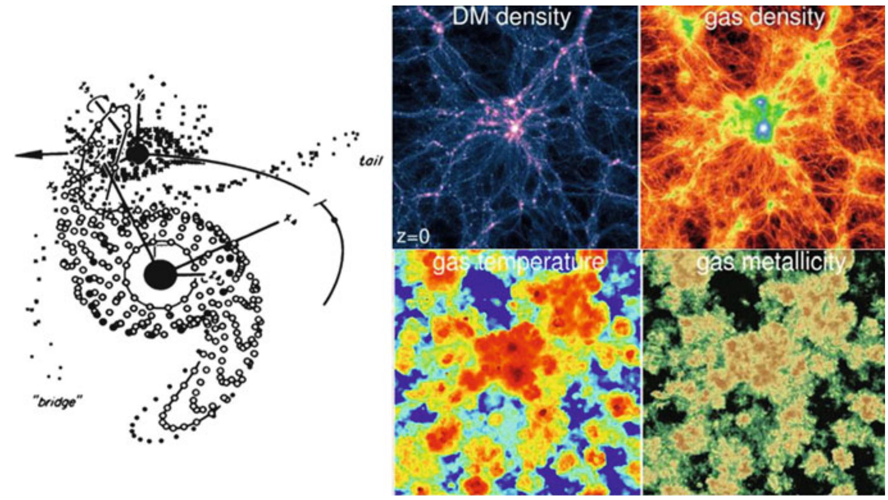

Fig. 1.16 Illustration of the huge progress in numerical simulations of galaxies, with *Left*: restricted 3-body simulation of the interaction between M51 and its companion, by Toomre and Toomre (1972) and *Right*: cosmological simulation of dark matter and baryons, with dark matter (DM) and gas density in the *top row*, and gas temperature and metallicity at the *bottom row*, as part of the Illustris project (Vogelsberger et al. 2014). The various milestones of the evolution are taken into account: self-gravity of all components, gas, stars and dark matter, to include all "gastrophysics" with cooling, heating, star formation and feedback, yield of heavy elements, and account for the widely different scales through zooming procedures, to involve the cosmological context in galaxy formation and evolution.

yet well understood: star formation and feedback, chemistry and cooling, multi-phase flows, and finally feeding of central black holes. Another milestone was to take into account the cosmological context: for a long time cosmological simulations of large-scale structures were done independently from galaxy-scale simulations, since they widely differed in spatial resolutions. At large-scales, galaxies were point like, and their physics was ignored.

Figure 1.16 is a striking summary of the evolution in less than half a century. There is no doubt that such a progress had a considerable impact on our understanding of galaxy formation. For example, the view of galaxies as isolated systems, exchanging matter or momentum only in galaxy interactions is now obsolete, and we know that most of the mass is assembled in galaxies through accretion from cosmic filaments; we know also that star formation and feedback have a crucial impact on galaxy evolution, and without feedback for example, much too many baryons end up in stars in galaxies, while less than 20 % of them are observed there. However, the simulations have reached such a complexity and the numbers of free parameters to vary in the simulations of physical phenomena is so large, that it is difficult to highlight the crucial points, and disentangle the actual important issues among the wide degeneracy. In spite of the huge progress in computing, the spatial resolution reached in cosmological simulations is not yet enough by orders of magnitude, to really account for the physics. All the phenomena (star formation, cooling, feedback) have to be added through sub-grid recipes, which make the whole endeavor still semi-analytical. This is even more exacerbated, when processes at very small scales, like the winds launched by active nuclei (AGN) around supermassive black holes have a wide impact in the whole galaxy. In the current paradigm, it is thought that AGN feedback is indeed the only solution to avoid the formation of too many massive galaxies.

Another caveat is that the tricks to simulate such a large range of scales and densities is that the computational effort is focused where the density is high. Lagrangian codes (like the widely used Tree-SPH) have effective size of particles much smaller in dense regions, and Eulerian codes have refined grids in those dense regions (AMR or Adaptive Mesh Refinement). This means that the spatial resolution is very poor in diffuse regions, for instance in cosmic filaments which continue to be poorly understood. Also, cosmological simulations are quite heavy to run, and the largest ones take months to be completed. It is therefore not possible to vary all parameters to experiment their impact on galaxy formation. In particular, the current standard paradigm of cold dark matter (ΛCDM) encounters some problems at galaxy-scales, such as the high concentration of dark matter in cusps which are not observed. This might prevent the right dynamical representation of galaxies, while it is not easy to test other models.

Fortunately, the simulations work is done in good symbiosis with the observational one. Observational diagnostics are computed from the simulations, and realistic images of galaxies, taking into account all specific colors and filters, are produced for the sake of a fruitful comparison. Simulations can help to probe selection biases in observations. Reciprocally, observations help to constrain the various unknown physical parameters in galaxy evolution. This continuous and tight interaction will hopefully lead to convergence, and to a strong progression of our knowledge in the near future.

Questions for Cesare Chiosi:

Our theoretical understanding of stellar evolution has greatly evolved and improved over the last decades, as one of the direct consequences of the exploding computational capabilities. This has been (and is) the basis of a better understanding of the stellar and chemical evolution of our MW and of the galaxies of different morphological types. May you sketch what have been, in your view, the milestones in this progress?

In the past three decades the theory of stellar evolution has gradually changed its focus from forefront research on the structure of stars (a few exceptions do however exist) to a sophisticated tool for predicting many properties of the stellar populations in galaxies. To this aim, the companion theories of stellar population synthesis and chemical enrichment have been developed.

Milestones of this progress are the huge data bases of stellar models, isochrones and single stellar populations (SSPs, coeval homogeneous assemblies of single stars with assigned initial mass function, IMF) at varying the initial chemical composition that have been recently made available to public access and are continuously maintained and updated. These data bases stand on stellar models calculated with state-of-the-art input physics and cover the entire HR Diagram. Together with extended libraries of both empirical and theoretical high resolution spectra at varying the effective temperature, gravity and chemical parameters and together with sophisticated codes of population synthesis, they allow us to generate synthetic spectral energy distributions (SEDs), color magnitude diagrams (CMDs), and luminosity functions (LFs) for an arbitrary large number of stars (Pasetto et al. 2012) in a large variety of photometric systems (Girardi et al. 2002, 2003, 2004). This allow us to study in great detail the stellar content of star clusters and field stars in general in nearby galaxies, where individual stars can be resolved. Using the concept of SSP, we can easily obtain the integral SED, magnitudes and colors of simple stellar aggregates (clusters) for which the singles stars cannot be resolved. Furthermore, introducing the law of star formation (number of stars generated per unit time and unit space with a certain IMF and chemical parameters), the law of chemical enrichment (the pattern of chemical parameters as functions of time and space), and the geometrical structure of the host galaxy, we obtain the integral SEDs, magnitudes, colors and other properties of complex stellar assemblies like galaxies of different morphological type, mean chemical enrichment, and mass as a function of time and hence redshift. The application of this goes from the field stars in nearby galaxies, where individual stars can be observed, to the stellar populations in distant galaxies for which only the integral properties are available. So thanks to the sophistication reached by stellar evolution and population synthesis, the study of the stellar populations is a powerful diagnostic to decipher the past history of galaxy formation and evolution for the local and the distant Universe.

If on one hand all this has provided modern tools for advanced research in other areas of astronomy and astrophysics, on the other hand it has carried on the feeling that all aspects of stellar structure were fully understood and known, which is not the case. There are many important questions that have not yet received a fully satisfactory answer. To mention a few, convection and mixing together with diffusion, sedimentation and levitation, detailed structure of the external envelopes of AGB stars and their transition to PN and WDs by mass loss, SNa progenitors and explosions, very low mass stars and their future evolution, very massive stars, primordial stars, last but not least rotation, and others. Below I will shortly comment only on two items of this long list.

Convection. In stellar interiors convection plays an important role: together with radiation and conduction, it transports energy throughout a star and chemically homogenizes the regions affected by convective instability. Therefore convection significantly affects the structure and evolutionary history of a star from the pre-main sequence stages to the very late ones [see for instance the classical textbooks by Cox and Giuli (1968), Kippenhahn and Weigert (1994)]. It may be present also in the pre-supernova stages of type I and II supernovae, and even during the collapse phase of type II supernovae, e.g. Meakin and Arnett (2007), Arnett and Meakin (2011), Arnett et al. (2014) and Smith and Arnett (2014).

In general, convection in the cores and inner shells does not pose serious difficulties because, thanks to the large thermal capacity of convective elements, the degree of "super-adiabaticity" is so small that for any practical purpose the temperature gradient of the medium in presence of convection is equal to the adiabatic value. However, when the velocities and distances traveled by convective elements are required, e.g. in presence of convective overshooting (Bressan et al. 1981; Maeder 1975a,b) a detailed theory of convection is needed. Convection in the outer layers of a star is by far more difficult and uncertain. Convective elements in this region have low thermal capacity, so that the super-adiabatic approximation can no longer be applied, and the temperature gradient of the elements and surrounding medium must be determined separately to exactly know the amount of energy carried by convection and radiation, e.g. Cox and Giuli (1968), Kippenhahn and Weigert (1994).

Convection is customarily described by the Mixing-Length Theory (Biermann 1951; Böhm-Vitense 1958), which is based on earlier works on the concept of convective motion by Prandtl (1925). In this standard approach, the motion of convective elements is related to the mean-free-path l_m that a generic element is supposed to travel at any given depth inside the convectively unstable regions of a star (Kippenhahn and Weigert 1994). The mean free path l_m is assumed to be proportional to the natural distance scale h_P given by the pressure stratification of the star. The proportionality factor is however poorly known and constrained. The mixing-length (ML) parameter Λ_m, defined by $l_m \equiv \Lambda_m h_P$, must be empirically determined by comparing the stellar models to some calibrator, usually the Sun. Nevertheless, the knowledge of this parameter is of paramount importance in correctly determining the convective energy transport, and hence the radius and effective temperature of a star. Furthermore, no strong arguments exist to suggest that the mixing-length parameter is the same in all stars and at all evolutionary phases.

This critical situation explains the many versions of the convection theory that can be found when investigated in different regions and evolutionary phases of a star such as the overshooting from core or envelopes zones (Bressan et al. 1981; Canuto and Mazzitelli 1991, 1992; Canuto et al. 1996; Claret 2007; Deng and Xiong 2008; Deng et al. 1996a,b), the helium semi-convection in low and intermediate mass stars, e.g., mass $M < 5M_{\odot}$ (Bressan et al. 1993; Castellani et al. 1985), the time dependent convection in the carbon deflagration process in Type I supernovæ (Nomoto et al. 1976), the studies on the efficiency of convective overshooting (Bressan et al. 2013, 2014), the sophisticated description of convection by Canuto (2011a,b,c,d,e), and finally the hydrodynamical simulations by Arnett and Meakin (2011); Meakin and Arnett (2007), Arnett et al. (2014), Smith and Arnett (2014), to mention just a few.

Looking at the classical formulation of the MLT, see for instance (Cox and Giuli 1968; Hofmeister et al. 1964; Kippenhahn and Weigert 1994), we note that the MLT reduces to the energy conservation principle supplemented by an estimate of the mean velocity of convective elements and that the complex fluid-dynamic situation is reduced to a crude estimate of the mean element velocity simply derived from the sole buoyancy force, neglecting other fluid-dynamic forces that all concur to shape the motion of convective elements as function of time and surrounding medium.

Very recently, Pasetto and collaborators (Pasetto et al. 2014) have proposed a new theory of convection in which the mixing-length parameter is no longer required. The new theory is formulated starting from a conventional solution of the NavierñStokes/Euler equations, i.e. the Bernoulli equation for a perfect fluid, but expressed in a non-inertial reference frame comoving with the convective elements. The motion of stellar convective cells inside convectively unstable layers is fully determined by a new system of equations for convection in a non-local and time-dependent formalism. They obtain an analytical, non-local, time-dependent subsonic solution for the convective energy transport that does not depend on any free parameter. The new theory applied to the outer convective zones of the Sun yields results that are fully consistent with those from the classical MLT once the ML parameter has been calibrated. Work is in progress to extend it to other stars with different mass, chemical composition and evolutionary stage and also to include the presence of convective overshoot.

Stellar Rotation. Perhaps the most striking advancement in the theory of stellar evolution is the systematic study of stellar rotation carried out over about 20 years by André Maeder, George Meynet and their collaborators (the Geneva Group). There is an impressive number of studies authored by this group in which the effect of rotation on the structure and evolution of stars all over the whole mass range, evolutionary phases and chemical compositions has been systematically investigated. Trying to summarize the results is nearly impossible. I limit myself to quote a few important review papers (Maeder 2009; Maeder and Meynet 2000, 2008, 2010, 2012; Maeder and Stahler 2009). Although the structure and evolution of stars has already reached an unprecedented level of accuracy and completeness (a few other areas of astrophysics parallel the achievements reached by stellar physics), still there are a number of serious discrepancies between current models and observations (e.g. the helium and nitrogen abundances in massive O- and B-type stars and in giants and super-giants, and the distribution of stars in the HR diagram at various metallicities). The observations clearly show that the role of rotation is largely overlooked. The work of the Geneva group has bridged the gap and clearly shown that neglecting rotation is no longer possible. The tracks in the HR diagram, lifetimes, actual masses, surface abundances, nucleo-synthetic yields, supernova precursors, etc. are greatly influenced by rotation. Quoting from Maeder and Meynet (2000), "the structure and evolution of the stars depend on the mass M, metallicity Z, and rotational angular velocity Ω".

The above interviews pointed out the enormous progresses achieved up to now, although many relevant aspects of galaxy simulations as well as of stellar structure/evolution are not yet fully under control and in some cases do not match observations. However, galaxy simulations and stellar evolution provide the clearer view of galaxies as evolving systems. We wish to discuss with James Lattis the impact of this vision on the present extragalactic Weltanshauung.

1.7 What Has Changed and What Is Changing in Galaxies Investigation?

Question for James M. Lattis:

Could you briefly comment the idea of an evolving Universe?

This question takes up some very broad issues and would demand much more discussion than is possible here. Moreover, not everything that might be important has received adequate attention from historians of science, suggesting that much further work in this area is possible. The evolving Universe might, for example, be contrasted with a deterministic "clockwork" Universe. The clockwork idea, to the extent that it means a deterministic Universe with an eternal, comprehensible order, although typically associated with Newtonianism through the mechanical connotations, is present, albeit less mechanically, in the Aristotelian-Ptolemaic cosmology, which has deep, ancient roots, of course. At the same time, cosmologies with very different characters conceivably including evolutionary concepts, such as a Stoic "fluid" cyclical cosmos, or the infinitely variable Universe of ancient atomists, were present and were debated in cosmological thinking into the Early Modern period. So the idea broadly construed might not be as recent as it seems at first. Beginning in the early 1600s, advocates of the Mechanical Philosophy, typified by Cartesian thinking (but broader than that, including alternative atomistic formulations), envisioned a cosmos governed by mathematical laws based in the nature of matter and motion. Newtonianism introduced mathematically described forces acting on matter and thereby initiated the age of modern physics. The result was a view that allowed the concept of dynamic equilibrium, so that a complex system, such as a star cluster, could be expected to change in minor detail yet look qualitatively the same over long periods of time. But other change, which might be the dramatic production of planets from a cloud of gas collapsing under gravity, as envisioned by Laplace, would be truly evolutionary, yet might be understood, in principle at least, as completely as the motions of the planets. William Herschel pursued observational investigations of nebulae, looking for evidence of change and expecting to see evolutionary processes, while most of his contemporary astronomers were concerned with star mapping, astrometry, solar system observations, and the like. Whether he had found evolutionary examples or not remained an open question for Herschel, but the development in the middle of the nineteenth Century of what we now call thermodynamics showed that such change was inevitable, even if the time scales over which such change might be observed had seldom been contemplated in scientific thinking. The idea of the conservation of energy, for example, demanded an answer to the source of the Sun's energy and led to estimates of how long such energy sources might be sustained. And the Second Law of Thermodynamics, to give another example, showed that whatever processes were at work in the universe had a limited capacity to drive change, assuring an eventual "heat death" of the cosmos. As in the biological sciences of the late nineteenth Century, evolution had entered astronomical thinking in a very serious way, although at that point the biological evolution was much more empirically grounded than its astronomical counterpart.

When did the idea of the evolving stars and galaxies become the new scientific paradigm?

The ability of astronomers to deduce masses, radii, and surface temperatures resulted in the recognition of the wide variety of stellar types by the early twentieth Century. And the extreme examples of red giants and white dwarfs, as well as the wide continuum of what would be termed the "main sequence" led to the compelling idea that the types represent stages of stellar evolution, although the general trends of that evolution, along with the obscure underlying mechanisms, took many years to work out. (And, of course, the details still occupy astronomers with a huge field of research, see above Sect. 1.6.) Nevertheless, the fact of stellar evolution brought that concept to the heart of practical astronomy in the way a very distant "heat death" could not. Much early astrophysical research focussed on questions of stellar evolution, and therein hinges part of the debate on the nature of the spiral nebulae we have discussed here (Sect. 1.2). Despite the growing understanding of stellar evolution, the assumption that at the cosmological scale the Universe was in dynamic (if not thermodynamic) equilibrium persisted into the early twentieth century. Hubble's work on Cepheids, showing spirals to be Island Universes, which he put together with Slipher's radial velocity measurements, produced the first, and quite surprising to many, evidence for the overall expansion of the Universe. But in fact, the Hubble Law, despite its great impact as a solid empirical construct, was far from a complete surprise for all. Hubble's data aligned well with the most innovative cosmological thinking of the day, notably theoretical work by George Lemaître (who anticipated Hubble's Law in some respects), Willem de Sitter, Alexander Friedmann, and of course Albert Einstein. This reminds us not to overlook the contributions of those theoretical researchers, the most important and successful of which were European scientists, whose contributions to the conception of expanding universe models were taking form at the same time as the spectacular observational achievements in North America. An expanding Universe is an evolving Universe. Although there were theoretical attempts to reconcile expansion with some kind of observational equilibrium, as in the so called "steady state" cosmologies, or a very long term average state, by long term oscillation, or cycles of expansion and contraction, the current formulation of Big Bang cosmology clearly implies unidirectional evolution on a vast scale. So in that sense the expectation of evolutionary processes does now permeate astronomical thinking at all scales, from the evolution of planets and planetary systems, to stars, galaxies and all their components, galaxy clusters, and the universe as a whole.

Several interviews in this chapter emphasized the contribution given by individual astronomers. This leads us to the problems of the development of ideas, sometimes novel and/or unconventional, and the need for debate during their testing. The Great Debate was organized by Hale in the spirit of a fair comparison between radically different ideas about the size of the known Universe. During the twentieth century there were many disputes. One, dragged on up to the twenty first century, concerned *the local value of the so called "Hubble constant",* H_0*, related to the determination of the extragalactic distance scale (see Chap. 2). The currently accepted value of the Hubble constant (*H_0*=72±7 km s*$^{-1}$ *Mpc*$^{-1}$*) is about 7 times less than the original value of 500–550 km s*$^{-1}$ *Mpc*$^{-1}$ *proposed by Hubble. Virginia Trimble (Trimble 2001) annotated that "Hubble was not the first to look for a distance dependent* $K - parameter$ *(later called the Hubble's constant,* H*) in the analysis of lines shifts of the nebulæ, nor even the first to find one, but he was the first to be widely believed". Before the* H_0 *value was set in 2001 to the above value by a* `HST` *Key Project on the extragalactic distance scale, in the 1980s there was a strong confrontation between two schools of thought, one lead by Allan Sandage (Fig. 1.17) and the other by Gérard de Vaucouleurs (Fig. 1.18) proposing values in the range 50–100 km s*$^{-1}$ *Mpc*$^{-1}$*, respectively. Not only the value but the nature itself of the velocity-distance relation,* $v = H_0 d$*, as expansion of the Universe was not so clear even to Hubble, that "veered between true expansion and something like tired light several times" according to Trimble (Trimble 2001).*

Fig. 1.17 The Astrophysics Faculty in 1966 at Caltech. Row 1: A.J. Deutsch between H. Swope and H.C. Arp, H. Babcock, J. Greenstein, E. W. Dennison, R. Kraft. Row 2: Rule, R. G. Wilson, F. Zwicky, I. S. Bowen, A. Sandage, R. Leighton, A. Vaughan, M. Schmidt, H. Zirin, G. Munch. Courtesy of the Archives, California Institute of Technology

Fig. 1.18 Gérard de Vaucouleurs with Jan Oort, Lucette Bottinelli, Lucienne Gouguenheim and Massimo Capaccioli (courtesy of Massimo Capaccioli)

Martha Haynes in her interview (Sect. 1.3.1) mentioned how the discovery of the 3C 273 "expanded again our sense of the scale of the Universe". After the discovery of 3C 273 by Maarten Schmidt in 1963, a dispute, called the "redshift controversy", about the nature the redshift arisen and maintained vivace for many years. We now interview Jack Sulentic about both controversies and/or unconventional ideas that have seen as opponents distinguished astronomers.

Questions for Jack W. Sulentic:

Have the USA been a cradle for unconventional ideas about galaxies? Please sketch the occasional rise and/or fall of some of these ideas during the twentieth century. Is there still a place for unconventional ideas in the era of "Big Science"?

Indeed there have been US astronomers involved in exploring unconventional ideas in astronomy but it has by no means been the only or major source of such ideas. In fact the ideological nature of the polity makes it a particularly hostile environment for new and, especially, unconventional ideas. Of course it also depends on what one means by "unconventional". Flat rotation curves in spiral galaxies (discovered by Vera Rubin) were certainly considered unconventional for a time. It is amazing that she (and a woman at only a semi-elite institution) could get observing time to complete her work, but Geoff Burbidge came to the rescue. He also helped Chip Arp and myself to get some observing time at Kitt Peak. Maybe thats why he was ousted as director.

I can only speak with some authority on the post-quasar period (the 1970s) when I entered the field. I spoke to Fritz Zwicky [Caltech: author of the *Catalog of Galaxies and Clusters of Galaxies* (Zwicky et al. 1961)] only once before he passed away but in some sense his entire approach was unconventional. During the 1930s he anticipated some of the concepts now inscribed into the paradigm. Also Boris Vorontsov-Velyaminov [Moscow State University: author of the *Morphological Catalog of Galaxies* (Vorontsov-Veliaminov et al. 1962)] another pioneer of extragalactic astronomy. I do not see any young Zwickies or V-Vs coming down the line. They could never get a job (Higgs has said pretty much the same thing). The discovery of quasars sparked much of the unconventional thinking that I am most aware of. Names like Geoff Burbidge [Geoffrey and Margaret Burbidge (Fig. 1.19) were British astronomers who made their astronomical reputations in the US] and Halton (Chip) Arp [author of the *Atlas of Peculiar Galaxies* and *A Catalogue of Southern Peculiar Galaxies and Associations* (Arp 1966)] come to mind. Lets face it both had a European turn-of-mind and were by no means typical US astronomers. They developed strong reputations in conventional areas before they stepped outside conventional boundaries. One could also mention Gerard de Vaucouleurs [author of the *Reference Catalog of Galaxies* (de Vaucouleurs et al. 1964)] who could be quite open minded to unusual ideas but he and his wife Antoinette were French. None of these three were true members of the US elite—as a litmus test—were any of them members of the US Academy of Sciences? I doubt it and I know of many NAS members who do not come up to their shoe laces as creative scientists. Many of the most creative and unconventional people were outside the US—India, Finland, France, Mexico, Russia. One may notice citations of catalogues attached to many of the above names. This is intended to make a point. These astronomer all looked at the sky and made as detailed as possible observations of galaxies. This

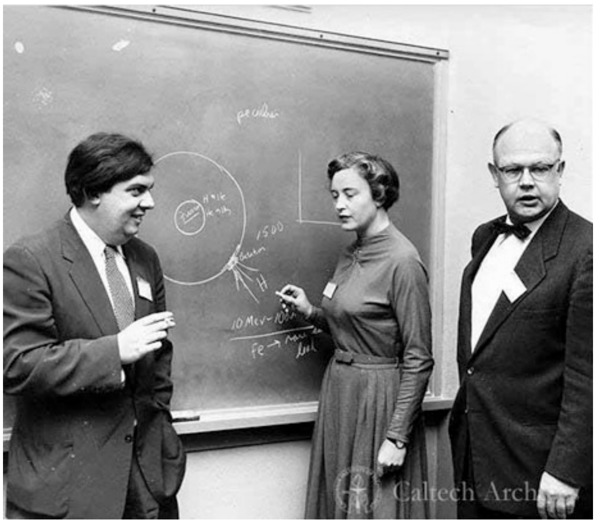

Fig. 1.19 Willam A. Fowler, Margaret and Geoffrey Burbidge. Courtesy of the Archives, California Institute of Technology

will tend to encourage one to think about the individual objects [as co-author of the *Revised New General Catalogue* (Sulentic and Tift 1973)], this author can speak from experience. This era is past and catalogues are now compiled digitally—not every author is inspired to actually scrutinize the catalogued objects. This is a great pity.

Returning to the discovery of quasars let us focus in on the period around 1967 and a paper by Arp et al. (1967). This was a time when people with access to 2 m class telescopes were rushing to obtain spectra of new quasar candidates. If a junior astronomer could see these photographic spectra recorded on glass plates they would not believe that we could learn anything from them. Well with a sharp eye and experience astronomers of that era could read a great deal. This particular quasar showed several different redshifts—we now know that broad and narrow emission and absorption lines in the same quasar spectrum can show a dispersion in redshifts $c\Delta\lambda/\lambda$=4–5000 km s^{-1}. At this volatile time, when everything was up for grabs, this may have motivated one of the authors to question the nature of the redshift. Again, he looked at the data without the encumbrance of a paradigm. There are three possible mechanisms for producing a redshift of spectral lines: gravity, scattering or the Doppler effect. Gravity was out of favor after 1964 and scattering was not promising. The velocity differences found in the new quasar were (at that time) quite large to be ascribed to motions (Doppler) so the idea of a forth mechanism–intrinsic non-Doppler redshifts arose. The debate over this possibility had a run but as more and better data accumulated the non-Doppler idea fell out of what little favor it had. It was not disproven—few things in extragalactic astronomy can be proven or disproven in any definite manner. It was however consistent with the vast majority of the observations.

At the same time, and at least partially motivated by the quasar results, the idea that some or many galaxies had a non-Doppler redshift component also had a run. Compact groups of galaxies had a particular appeal—think of (or Google photos of) Stephan's Quintet (SQ; Fig. 5.14 in Chap. 5) (Burbidge and Burbidge 1961) or Seyfert's Sextet (SS; see Fig. 1.20) . In fact many of the brightest and hence most famous compact groups contained one or more discordant redshift members. Of the 100 brightest Hickson compact groups (Hickson 1982) 43 contain at least one discordant redshift galaxy (well only 50–60 are actually compact groups using the stated definition in the Hickson's 1982 catalogue) (Sulentic 1997). At first glance this seemed to Arp, the Burbidges, Fred Hoyle and this author to be serious evidence for non-Doppler redshifts–there were just too many of them! A myriad of papers were published defending the Doppler interpretation–in many cases with weaker evidence than the non-Doppler advocates presented. But no matter the noble defenders of right were always favored. Most detailed arguments were too much focussed on the desire to prove or disprove their favored point of view that they missed the statistical one. It took this author until 1997 before it became clear why so many discordant groups were found. The discordant member(s) made the groups brighter than most real compact groups and compact group selection criteria (despite including an isolation criterion) favored their discovery. The final nail in this coffin came with publication of HST images of Stephan's Quintet (Gallagher et al. 2001)

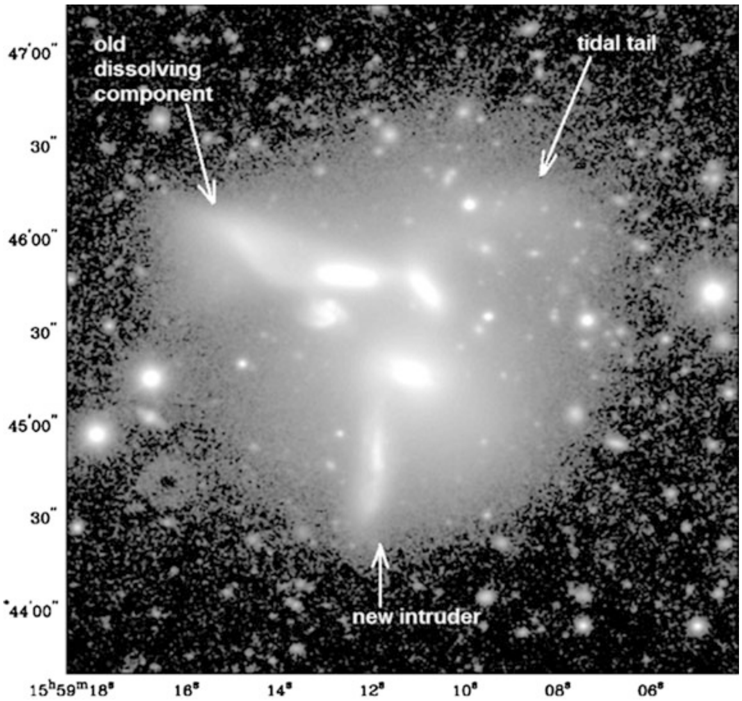

Fig. 1.20 An image of the famous compact Galaxy group known as Seyfert's Sextet. B + R band composite image (8 exposures from 2.5 m NOT) displayed to show the shape and extent of diffuse light in the group (50 % of total luminosity). Rather than merging the group has been slowly coalescing for at least 2 Gyr. All that remain of the galaxies are their central bulge components while disk debris contributes to the halo. One of the galaxies shows a discordant redshift and is assumed to be much more distant than the others

which showed resolution in the discordant redshift component NGC 7320. Given the extraordinary nature of the real Stephan's Quintet (there are after all 5 physical members if one adds accordant redshift NGC 7320c after rejecting discordant redshift NGC 7320 (see Moles et al. 1997; Sulentic et al. 2001) and the rarity of such systems (add NGC 7320c to make it again a quintet after rejecting NGC 7320) the a posteriori arguments are emotionally compelling. It is useful lesson for proto-astronomers to perhaps glance at the 158 adsabs entries with SQ in the title. Because of SQ and SS the compact groups became the "crack cocaine" of extragalactic astronomy. They have also been the bane of believers in the omnipresent role of mergers because they show little evidence for such dynamical coalescence—editorials in Nature notwithstanding.

Other galaxy associations involving discordant redshift objects were also likely motivated by the discovery of quasars. These included pairs and groups of galaxies whose apparent members did not show the same redshift. In my youthful naivety I actually proposed tests of the various claims for discordant redshifts in a birthday volume honouring Chip Arp (Bertola et al. 1987) . One of the first claims, involving galaxy-galaxy associations, mentioned in the volume actually appeared in Nature (Jaakkola 1971).

Rise and fall of such ideas? Well most of the tests in "New Ideas" were never carried out. It is certainly not the way to build a successful career in twenty first century astronomy. It is the way to make sure that you become a taxi driver with an astro PhD. If one is inclined towards exploring new ideas and controversial claims then one should do it after one has secured a tenured position. Unfortunately by that time such impulses have often been subdued and the path to full professorship is obstacle free. Do spiral galaxies have an extra intrinsic redshift component that is lacking in Ellipticals? I looked at this problem with the sample most likely to give a clear answer—the sample of isolated mixed E+S pairs collected by Igor Karachentsev in 1972 (Karachentsev 1972). This is a doubly controversial area (triply in US because until 1990—he was a citizen of the Soviet Union) to play in. What fun! Doubly because the experts who believe galaxy morphology is dictated by local conditions (nurture) said that E+S pairs cannot be physical binaries (random captures are just too unlikely). Yet Karachentsev found $\sim$ 150 such pairs and is it not wiser to favor the data over the experts? This kind of test requires a large and well defined sample. Many of the E+S pairs turned out to be disky pairs (S+S0): Rampazzo and Sulentic 1992). Others are early-type (E+S0) binaries. By the time a well defined sample of true E+S pairs is extracted the number falls below 100 and the significance of a $\pm 200\,\mathrm{km\,s^{-1}}$ difference between spiral and elliptical components is marginal at best (Sulentic 1982). The advent of SDSS offers a much better opportunity to test such claims—but who will do it?

Another fascinating test involves Holmberg's claim (Holmberg 1969) that satellites of massive spirals (e.g. LMC+SMC for Milky Way and M32+NGC 205 for Andromeda) cluster near the rotation axis of the spiral (an anisotropy) and that the companions possibly show slightly higher redshifts (Holmberg 1961). This is connected to the idea that massive galaxies eject proto-galaxies or compact bodies from their nuclei (possibly with an intrinsic redshift on top of their Doppler redshift) and/or generate spiral structure from (e.g. Ambartsumian 1958; Arp 1987; Pismis 1963; Sanders and Bania 1976; Saslow 1974; Valtonen 1975) nuclear outbursts. The former claim about anisotropy may turn out to not be so radical but the latter will scare away most curious people except the extremely naive (Arp and Sulentic 1985). These are the kinds of anomalies that surveys like SDSS was made to test. The anisotropy issue has been extensively explored with every possible conclusion and interpretation offered (see e.g. Wang et al. (Wang 2014) for a recent study or look at the many papers citing Holmberg's 1969 paper).

The figure of the astronomer looking at his sample galaxy-by-galaxy is today taxed by the brunt of the enormously large amount of data delivered by new instruments at increasingly larger telescope—terabyte/night. This flood of data not only contributed to change our view of galaxies, but also had a considerable impact on the methods of investigation.

Question for Martha P. Haynes:

In the last decades do the efforts done for big scientific enterprises (*Big Science*) have changed the working methods and approaches to the extragalactic research?

In looking through the early papers to answer the previous question (see Sect. 1.3.1), I noticed two very clear differences between searches of the literature back in the middle of the last century and today: in earlier years, both (1) papers and (2) author lists were short. Individual astronomers carrying out what seem today to be relatively small efforts made big contributions; and, we might suspect, too a lot more work than they would today. In this century/millenium, with such a body of knowledge behind us, advances often involve huge investments of telescope time, computational resources, software/algorithm/database development, and people in the undertaking of surveys or large projects which are far beyond the capabilities of small groups. We work much more in an environment where observers across the electromagnetic spectrum, theorists and numericists, regardless of their physical location, combine their expertise to tackle fundamental questions. Of course, without modern means of communications, the collaborations of today would not have been possible.

As a single but telling example, the Sloan Digital Sky Survey (SDSS), in its four distinct phases and multiple research projects, has involved hundreds of scientists at institutions around the world. And, at the same time, it has enabled many thousands of astronomers to conduct research using the datasets that SDSS makes public. The many on-going and future major surveys adopt this model of distributed engagement because it is entirely necessary given the ambitions and scope of their scientific programs. "*Big Science*" requires big investments including the intellectual resources that are available from the involvement of large teams of scientists. Today, this is simply the norm.

1.8 To Summarize

Beginning with the Great Debate this chapter sketches the way undertaken by astronomers to understand the nature of the nebulæ. The process was neither linear nor immune from errors, sometimes still today inexplicable, like the measure of the proper motion of stars in some spirals, claimed by Adrian van Maanen.

The efforts of the pioneers of extragalactic astronomy appear inextricably connected to the knowledges available at that time about our own galaxy, the Milky Way, as well as to the telescopes and instruments that were used. We have learned from the interview of Jim Lattis how the proper account of galactic absorption by Stebbins and collaborators undermined the Shapley's Super-Galaxy construction and restarted the recognition of the nebulæ as extragalactic objects. Only after the discovery of Cefeids in M31 by Hubble we have the definite assessment of the extragalactic nature of the nebulæ.

Later on, the discovery of the stellar populations introduced by Baade, the Galaxy rotation modeled by Oort, the identification of the galaxy associations sketched by Shapley, and the galaxy-galaxy tidal interactions brilliantly described by Zwicky started to characterize the development of extragalactic astronomy and to open the mind toward the modern view of galaxies.

Only after WWII we assist to the collective effort of astronomers in several countries for understanding the properties of nearby and distant galaxies through multiwavelength observations, both from ground and space telescopes. In that years also appeared the first models of stellar and galaxy evolution in a "crescendo" of comparisons with observations.

The growth of astronomical facilities, the impact of new instruments, the increase of computing power and the investigation strategies adopted by the pioneers have been beautifully described in our interviews. Here below we attempt to summarize, adding some personal recollection, the most interesting aspects of such discussion.

- **Astronomical ground based observing facilities**
  The WWII left the US Government with a more strong motivation for additional scientific investments. The extragalactic research needed to be boosted by the construction of large optical and radio telescopes. Along this line National Observatories as NOAO, NRAO were founded, but at odds with European countries, in the USA private institutions (like Carnegie, Keck, etc.) played a fundamental role in financing the research and building large telescopes.
  The post war economic problems and the division into blocks pushed few European Countries, Belgium, France, Germany, Holland and Sweden, in the first half 1960s to associate and to plan a collaboration that led to the foundation of the European Southern Observatory (ESO). The European Northern Observatory of the Canary Islands was founded only in 1979. The UK followed the road of the collaboration with Commonwealth countries, in particular Australia creating AAT, and joined ESO much later in 2002. Japan, basically from scratch implemented an autonomous development plan of the entire astrophysics. The expansion of the extragalactic studies was tremendously rapid compared to that of US and European countries. Latin American countries with few exceptions only recently started to develop this scientific sector. Here the growth was triggered by both National and International observing facilities located mostly in the Chilean deserts. In Asia, through regional collaborations (see Chap. 9), extragalactic studies are actually exploding especially in the Popular Republic of China and South Korea.
  For many years the 5 m Hale at Palomar (1942) and the 6 m BTA of the Special Astrophysical Observatory (1976) in the ex Soviet Union remained the largest telescopes in the World, but at the end of twentieth century many countries jumped to the 8–10 m class optical telescopes (and to the top class of radio telescopes). These are more or less spread out in the best observing sites around the world.
  Today the international collaborations have substituted the efforts of the single countries, because the budget of the modern scientific projects cannot be afforded

by a single state. Several major telescopes and radio telescopes are now open to the worldwide community of astronomers.

- **New detectors, instruments and observing strategies**
  The combination instrument/detector is as much important as the telescope. The new `CCD` *detectors appeared in the 1980s and in about a decade completely substituted the photographic plates. Their quantum efficiency and spatial resolution permitted the detection of fainter and fainter galaxies.* `CCDs` *also opened the road to panchromatic observations of galaxies and simplified the planning of multi-tasking instruments, performing e.g. both galaxy photometry and spectroscopy. New surveys required specific instruments, like MOS that permitted the mapping of galaxy associations and the definition of the large-scale structure of the Universe.*
  The development of National or International Observatories, with telescopes available through a proposal competition and mounting complex, multi-purpose instruments, triggered the production of ad hoc *software packages for the data reduction. The first data reduction packages were conceived about four decades ago. One of the beloved examples is* `IHAP` *(Image Handling Program), widely used by ESO observers (Middleburg 1977). It was conceived by Frank Middelburg for running on a HP 64kb computer equipped with the first graphic terminals in 1973. The more common data analysis packages for optical and infrared astronomy* `MIDAS`, `IRAF/STSDAS/PyRAF`, `XVISTA`, `MOPEX` *are still in use and together they represent "several million lines code and hundreds of person-years of development efforts" (see e.g. Ferguson et al. 2009). Similarly for radio observations commonly used packages are* `AIPS, MIRIAD, GIPSY` *and* `CASA`*.*
  Some packages have been specifically developed for some space mission and then upgraded for new missions and on board instruments e.g. for X-ray `CIAO` *and* `HEASOFT`*. A common format for stocking and transporting astronomical images* `FITS` *(Flexible Image Transport System) (Wells et al. 1981) was standardized and adopted for the new* `CCD` *images as well as photographic plates scanned using micro densitometers. It is interesting to notice that the more appreciated software packages are those built with the direct contribution of astronomers or starting from astronomers proprietary software.*
  The post war decades were characterized by the first Sky Surveys, such as the Palomar Observatory Sky Survey (POSS). They provided research material for extragalactic studies with a strong impact on the definition of galaxy associations, through the preparation of catalogues, and in expanding our view on the variety of galaxy morphologies. Surveys have completely changed the way of working in extragalactic astronomy. They opened the doors to the "Big Science" era.
- **Space facilities and the panchromatic view of galaxies**
  The 1960s and 1970s have been the years of the space experiments in the UV and X-ray windows. The IR window was open about a decade later, when the flagship space missions `HST` *was planned and realized.*

The synergy between `HST` *and the 8–10 m class telescopes had an immense impact on extragalactic astronomy. We mention here for example the introduction of the so called Key Programs, in the current astronomical terminology, indicating the complex set of observations addressed to solve key astronomical questions, e.g. the determination of the local value of the Hubble constant, H_0, that crosses the previous decades without a widely accepted solution.*
Today there is a fleet of space facilities covering almost all the electro-magnetic spectrum.

- **The Big Science era**
  In an intriguing paper titled "Astrophysics in 2049", published at the end of the millennium (Trimble and Sciatti 2000), Virginia Trimble explored "some things of which there are many and some of which there are few" in the astrophysical landscape 10 lustres ahead. She predicted in particular that 16 telescopes with diameters exceeding 8 m would be operative. Today their number is 15. Considering those under construction, we will equal the prophesied number and easily will exceed it in the next few years, since new countries are now entering in the club of 8 m owners. Fifteen years later that paper it is more easy "to prophesy" both a quantum leap in the size of telescopes diameter with respect to the 8–10 m class telescopes and that a wider use of this class of telescopes in interferometry and, on much larger scale, in the radio domain will occur (see Chap. 9).
  The construction of new "XXL telescopes", both ground based (30–40 m) and in space (8–10 m), is now entrusted to consortia composed of several associated countries. Chapter 9 reviews some of the ongoing and foreseen projects.
  We report, however, a radical change in planning not only the new enterprises but also the research programs. It is clear that the time when few astronomers building and calibrating their home made instruments for observations in house observatories is definitely over. The time of small research team, even those manipulating multi wavelength data set of hundreds of galaxies is running out. Teams of hundreds of researchers engineering telescopes, instruments and detectors, connecting hardware with software tools, performing remote observations on telescopes concentrated in few extraordinary sites or on board of space telescopes, stocking immense data set mined via net is "simply the norm" as Martha Haynes noticed. Amazingly, in "Astrophysics in 2049", Trimble predicted the "Largest number of authors on a single astronomical paper (Aaardvark et al. 2048, on dark matter candidates)": 1029. Extragalactic Surveys reached the rank of Big Science enterprises (see Chap. 5) so it is not uncommon to see papers signed by about 50 co-authors and some even by 100. Extragalactic research teams are not yet as numerous as those active in particle physics (e.g teams that use the Large Hadron Collider are of the order of magnitude indicated by Trimble) but the tendency is for good sketched out.
  The Big Science needs to assemble several different competencies along considerable amount of time, that is necessary to ideate, project an realize new big facilities. Since the large economic investments involved, these facilities should provide answers to different kind of problems. Complex molecules found in the

ISM, the dark matter and the dark energy problems impose continuous trespasses between chemistry, physics and astrophysics. New objectives are blurring the boundaries among "old disciplines" like astronomy, physics and chemistry (see Trimble 2012). This is particularly true in theoretical disciplines addressed to understanding the evolution of our and external galaxies.

Eric Hobsbawm (1917–2012) called the Twentieth Century "The Age of Extremes". This is also true from the astronomical point of view. During "The Cosmic Century", as Malcom Longair defined it (Longair 2006), astronomers definitely changed our place in the Cosmos, from the center of the Kapteyn Universe to the periphery of the Milky Way, a spiral galaxy among billions, at the mercy of a rude expanding stream in an evolving Universe. Astrophysics and Cosmology have risen to the rank of Big Sciences, observations and theory deeply interplay. The extragalactic astronomers, physicists and chemists interact in a growing number of areas of common interest.

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Chapter 2
The Milky Way and the Local Group

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Lo duca e io per quel cammino ascoso
intrammo a ritornar nel chiaro mondo;
e sanza cura aver d'alcun riposo
salimmo su, el primo e io secondo,
tanto ch'i' vidi de le cose belle
che porta 'l ciel, per pertugio tondo.

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E quindi uscimmo a riveder le stelle.
D. Alighieri *Commedia*, Inferno, Canto XXIV (1321)

Er starrte zu den Sternen empor, deren schicksalsbestimmt schicksalsbestmmender, zweitausendjähringer Umlauf sich nun bald runden musste…
und es grüßte ihn drüssen am südwestlichen Rande, vertraut und unheimlich, des Skorpionen Schicksalsbild, den gefährlich gekrümmten Leib von milden Strom del Milckstraße umfangen, es schmiegte Andromeda ihr Haupt an des Pegasus geflügelte Schulter…
H. Broch *Der Tod des Vergil* (1945)

2.1 Chapter Overview

The beauty and the charm of the Milky May (MW) have been celebrated by countless poets and writers of many Countries along the centuries (see e.g. the beautiful anthology of Piero Boitani 2012*). The stellar nature of the MW was firstly observed by Galileo. In 1610 in the* Sidereus Nuncius *(Galilei* 1993*) Galileo wrote that the MW is "nient'altro che una congerie di innumerevoli Stelle, disseminate a mucchi; chè in qualunque regione di essa si diriga il cannocchiale, subito una ingente folla di Stelle si presenta alla vista, delle quali parecchi si vedono abbastanza grandi e molto distinte; ma la moltitudine delle piccole è del tutto inesplorabile". In the same paragraph, Galileo remarked that observations with his telescope, for the first time, wipe out centuries of philosophical discussions about the nature of*

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the MW. Three more centuries have been necessary to complete a second radical Copernican Revolution that displaces the solar system from being roughly at the center of the MW and project this latter in the vast Universe populated by billions of similar spiral galaxies (see Chap. 1).

The first part of this Chapter is dedicated to the crescendo *of studies that have progressively contributed to our understanding of the MW. Section 2.2, by James Lattis, reviews the fundamental step in recognizing the Galaxy as a "normal" spiral, before the WWII. Piet van der Kruit in Sect. 2.3, goes into the evolution of our knowledge of the MW structure and of kinematics. This Section, starting from the achievements of Jaan Ort in the 1920s about the Galaxy differential rotation, brings us to the modern view of the MW and how this reverberates in general on the understanding of spiral galaxies.*

The Galaxy is made by stars of different families. The fundamental concepts of stellar populations is introduced in Sect. 2.4 by Antonella Vallenari with an historical evolution up to the use of stars in the definition of MW structure and the clock they provide to understand the MW evolutionary path. The dust properties in the MW are discussed in Sect. 2.5 by Daniela Calzetti.

The second part of the Chapter is dedicated to the problem of the extragalactic distance scale. As mentioned in Chap. 1 there was a long term debate on this issue that has seen two different schools of thought on opposite positions. Barry Madore introduces the debate about the determination of the distance scale and the use of adequate primary and secondary indicators for the purpose.

The third part of the Chapter is dedicated to the nearby galaxies of the MW and to the exploration from inside of a gravitationally bound group of galaxies in an evolving environment. It is worth to mention that the MW and the companions in the so-called Local Group (LG) are basically the only galaxies we can study resolving their stellar components. In this sense, the MW and the LG galaxies are a sort of Rosetta stone *for understanding extragalactic objects. They are of overwhelming importance even for understanding distant galaxies since among the recently discovered ultra faint dwarfs (UFD) might lurk the debris of first galaxies (see the contribution of Volker Bromm in Chap. 6. In Sect. 2.7 Valentina Karachentseva describes the population of galaxies members of the LG, their discovery along this century of research and their properties. A zoom on the Andromeda galaxy M31 is provided by Rodrigo Ibata in Sect. 2.7.1, while the dwarf galaxy populations, with the widest number of members in the LG is presented by Carme Gallart in Sect. 2.7.2. An overall view of the co-evolution of the galaxies members of the LG is presented in Sect. 2.8 by Rodrigo Ibata and Goerge Lake. In Sect. 2.9 Brent Tully brings us just outside the LG discussing the present view of the structure and motions in the nearby Universe.*

The Chapter closes with what we call the "lessons for the future" in Sect. 2.10. The road toward a modern vision of The Galaxy and a precise calibration of the galaxy distances was and remains hard.

2.2 Milky Way: One of Many

Questions for James M. Lattis:
we consider today the MW a quite common spiral galaxy. May you trace the historical evolution of our understanding of the MW properties up to 40s of the twentieth century?

There were several necessary steps along the way to seeing our Galaxy as typical rather than unique. One issue that had to be resolved was whether the Galaxy's dimensions could be determined by measuring the distribution of stars or star clusters. The success of such approaches depended on the transparency of interstellar space, which was, early on, debatable. It was not obvious whether dark voids in the Milky Way, like those photographically documented by E.E. Barnard of Yerkes Observatory, were gaps in the distribution of stars or effectively opaque clouds. Even as opinion settled on the existence of opaque clouds or "dark nebulae" it was not evident that interstellar transparency was significantly diminished beyond their boundaries. It took the efforts of first Trumpler in 1930, then Stebbins, and a few others, such as Peter van de Kamp (originally from the Netherlands and one of the Lick "school") to demonstrate and measure the effects, then take them into account for the globular cluster distances. Trumpler worked photographically on extinction in open clusters and Stebbins, as noted, on reddening by photometric colors. Van de Kamp, by contrast, continued in the European statistical track measuring extinction of nebulae as a function of latitude from photographic plates. By the mid-1930s it was not only clear that interstellar absorption was significant, thus invalidating both the Kapteyn-Von Seeliger and Shapley approaches, but methods for making the needed corrections were emerging.

From an understanding of the effects of interstellar matter grew the study of the matter itself, its amount, composition, and the like. And out of that study came the conclusion that such matter must constitute a significant fraction of the mass of the Galaxy. Stebbins estimated, for example, that the mass of interstellar matter was probably comparable to the combined stellar mass of the Galaxy. The work of Stebbins and Whitford shows the first stages of investigation of interstellar matter as an end in itself and not merely as a calibration issue. Their work moved galactic studies beyond discussions of structure and toward considerations of composition. This line of study also validated identification of extinction effects in our own Galaxy with photographs of others showing the strong effects of large amounts of obscuring dust—another clue pointing toward the typical nature of our Galaxy.

The structure that made the "spiral" nebulae a category very strongly suggested rotation, so it was natural to look for signs of rotation in our own Galaxy given a presumption of typicality. Rotation was convincingly found, as already mentioned, by Lindblad, Oort, & Plaskett. Spiral structure itself in our Galaxy was harder to demonstrate, although serious, if highly speculative, proposals about our Galaxy's spiral structure go back as far as Cornelius Easton ca. 1900. Good results for spiral structure occurred only after WWII and involved the post-war technology of radio astronomy. W. W. Morgan, (leading a group at Yerkes Observatory found evidence for spiral structure in the mapping of O-B associations, while Jan Oort (Leiden) and an Australian team including W. N. Christiansen and J. V. Hindman, mapped spiral structure in neutral hydrogen emissions, both results appearing just after 1951.

What has been the role of the interstellar absorption in the debate about the nature of the MW?
The role of interstellar absorption has been multifaceted. First it was a complicating factor in measurements of color and brightness of stars, globular clusters, and spiral nebulae. Its effects had to be, at first, acknowledged, then understood quantitatively before photometric distance determinations (most notoriously of the globular clusters) could begin to work. In this respect it was primarily a calibration issue.

Secondly, quantitative investigation of absorption effects at optical wavelengths (and soon after in the near infrared) were the first probes of the nature of what we now call the interstellar medium. The published results of Stebbins, Whitford, and Huffer as early as 1933 concluded that the preponderance of the mass of that matter was in the form of dust rather than gas and that the total mass distributed in the interstellar realm could be of the same order as the stellar mass of the Galaxy. Their work published in the early WWII years led to a formulation of a general "law of space reddening" that described the wavelength dependence of interstellar absorption and further refined ideas of the matter in the interstellar medium.

Thirdly, and more qualitatively, the extreme absorption evident in edge-on images of spiral nebulae was an influential point in discussions of whether they were comparable to our own Galaxy. Once the existence of interstellar absorption was proven and shown to amount to complete opacity (in the optical range) even between the Sun and the center of the Galaxy, the resemblance to the absorbing layers seen in external galaxies was compelling.

The fact that the MW has been recognized to be one among the plethora of visible spiral galaxies marked an era: it losts its singularity and the grade of Super-galaxy. At the same time this discovery makes the MW unique for the understanding of the properties of its distant counterparts by analogy. Being part of it, our view of the MW is, however, rather difficult. It takes decades to understand its kinematics, sub-structures and stellar composition. The contributions of Pieter van den Kruit highlight parts this still ongoing adventure.

2.3 The Milky Way Dynamics and the Connection with Spirals

Questions for Pieter C. van der Kruit:

the first studies about the galactic rotation date back to the second decade of the passed century with Bertil Lindblad in 1925, while the first parametrization of the MW rotation was formulated by Jan Oort in 1927. What progresses in the

definition of the MW kinematical properties have been done since then? Which astrophysical approaches have been developed to obtain the most reliable and recent measurements? What have we learned about external galaxies by studying the MW properties?

My answers come by discussing the following issues: Kapteyn's Universe, Oort and differential rotation, asymmetric drift, Schwarzschild velocity ellipsoid, secular evolution, disk stability, dark matter, global stability, flat rotation curves, maximum disk.

2.3.1 Background

The editors have asked me to give a general introduction to stellar kinematics and dynamics as I am using it in this chapter for the benefit of those unfamiliar with this field. I am happy to do so and take for this parts from lecture notes I have used throughout the years in connection with courses on structure and dynamics of galaxies.[1]

The notion of differential rotation led Oort in the 1920s to deduce that in the Solar Neighborhood there should be a systematic pattern of the motions of stars. Since the stars closer to the center 'overtake' the Sun and the stars further out lag behind, there is a pattern of a shear that manifests itself as a rotation of the stellar distribution in a co-rotating frame. The corresponding angular velocity of this local pattern is described by Oort constant B and is seen in the proper motions of stars as a function of Galactic longitude, which is a double sinus. Similarly the radial distribution of stars of the same distance r also display a double sine, the amplitude being governed by Oort constant A. The relevant equations are

$$V_{\rm rad} = Ar \sin 2l \cos^2 b \ , \ \ \frac{V_{\rm tan}}{r} = 4.74\ \mu = \{A \cos 2l + B\}\cos^2 b,$$

where l is Galactic longitude and b Galactic latitude. The Oort constants A and B relate to the local rotation velocity $V_{\rm rot}$ and the distance to the Galactic Center $R_\circ$ as

$$A = \frac{1}{2}\left(\frac{V_{\rm rot}}{R_\circ} - \frac{dV_{\rm rot}}{dR}\right) \ , \ \ B = -\frac{1}{2}\left(\frac{V_{\rm rot}}{R_\circ} + \frac{dV_{\rm rot}}{dR}\right).$$

Galactic dynamics started with the collisionless Boltzmann or Liouville continuity equation that simply states that the distribution function should in case of an equilibrium not change, so that the stars moving in and out of a volume element in 6-dimensional phase space according to the distribution of their motions and

[1]The lectures and notes are available on my Website at www.astro.rug.nl/~vdkruit; for the notes see van der Kruit (1991).

the acceleration arising from the potential gradient at the corresponding position in space, should be equal. The second equation is the Poisson equation that describes the potential as a function of position in space as resulting from the distribution of gravitating mass.

The continuity equation is usually replaced by hydrodynamic or Jeans equations, especially in the case of axisymmetric distributions as in disks of galaxies. These result from multiplying the continuity equation by a velocity component (e.g. radial velocity U) and then integrating over all velocities. If V is the tangential velocity, V_t the mean tangential velocity $\langle V\rangle$, and ν the space density corresponding to the distribution function, we get for the radial direction

$$-K_R = \frac{V_t^2}{R} - \langle U^2\rangle \left[\frac{d}{dR}(\ln\,\nu\langle U^2\rangle) + \frac{1}{R}\left\{1 - \frac{\langle (V-V_t)^2\rangle}{\langle U^2\rangle}\right\}\right] + \langle UW\rangle \frac{d}{dz}(\ln\,\nu\langle UW\rangle).$$

The last term reduces in the symmetry plane to

$$\langle UW\rangle \frac{d}{dz}(\ln\,\nu\langle UW\rangle) = \frac{d}{dz}\langle UW\rangle$$

and may then be assumed zero. Here it is assumed that the mean radial and vertical velocities $\langle U\rangle$ and $\langle W\rangle$ are zero.

Such a procedure in the tangential direction produces an equation with only cross terms of the velocity tensor and is not very helpful in almost all cases. For completeness:

$$\frac{2\nu}{R}\langle UV\rangle + \frac{d}{dR}(\nu\langle UV\rangle) + \frac{d}{dz}(\nu\langle VW\rangle) = 0.$$

In the vertical direction the moment equation becomes

$$\frac{d}{dz}(\nu\langle W^2\rangle) + \frac{\nu\langle UW\rangle}{R} + \frac{d}{dR}(\nu\langle UW\rangle) = \nu K_z.$$

Together with the Poisson equation for the axi-symmetric case,

$$\frac{dK_R}{dR} + \frac{K_R}{R} + \frac{dK_z}{dz} = -4\pi G\rho(R,z).$$

these form the basic equations to describe the dynamics of axisymmetric systems and define therefore the starting point of any discussion of disk dynamics.

Stars that deviate in their space velocities little from the local tangential velocity have orbits that can be described by epicycles (see Fig. 2.4). The properties of these epicycles depend on the local gravitational force field (and thus the local rotation velocity and its derivative) and therefore the Oort constants. If the maximum radial velocity is U_0, the semi axes of the epicycle will be U_0/κ in the radial direction and

$U_0/2B$ tangentially. The velocities as a function of time t in the epicycle are

$$U = U_0 \cos \kappa t \ , \ \ V - V_{\mathrm{rot},0} = \frac{U_0 \kappa}{-2B} \sin \kappa t.$$

The period in the epicycle equals $2\pi/\kappa$ and the epicyclic frequency is

$$\kappa = 2\{-B(A-B)\}^{1/2}.$$

The ratio of the velocity dispersions in the plane of the stars at any position follows from this as all stars do go through epicycles with the same shape defined by the local Oort constants.

$$\frac{\langle V^2 \rangle}{\langle U^2 \rangle} = \frac{-B}{A-B}.$$

If the circular velocity follows from $K_{\mathrm{R}} = V_{\mathrm{circ}}^2/R$, and if we ignore the cross term in the velocity tensor, the radial Jeans equation reduces to the asymmetric drift equation

$$V_{\mathrm{circ}}^2 - V_{\mathrm{t}}^2 = -\langle U^2 \rangle \left\{ R \frac{\mathrm{d}}{\mathrm{d}R} \ln \nu + R \frac{\mathrm{d}}{\mathrm{d}R} \ln \langle U^2 \rangle + \left[1 - \frac{B}{B-A} \right] \right\} .$$

A stellar component with a higher velocity dispersion $\langle U^2 \rangle^{1/2}$ with have a slower collective tangential velocity V_{t}, since the radial gradients on the right are in general negative.

The vertical Jeans equation can be used to derive the density distribution when for any component of stars the vertical density and velocity dispersion distributions are known.

For the vertical motion the approximation equivalent to the epicycles in the plane is that of a harmonic oscillator. For a constant density with z we have

$$K_{\mathrm{z}} = \frac{d^2 z}{dt^2} = -4\pi G \rho_0 z.$$

Integration gives

$$z = \frac{W_0}{\lambda} \sin \lambda t \ , \ \ W = W_0 \cos \lambda t.$$

The period equals $2\pi/\lambda$ and the vertical frequency is

$$\lambda = (4\pi G \rho_0)^{1/2}.$$

For the solar neighbourhood we have $V_{\mathrm{rot}} \approx 220\,\mathrm{km\ s^{-1}}$, $R \approx 8.5\,\mathrm{kpc}$ and $\rho_0 \approx 0.1\,\mathrm{M_\odot\ pc^{-3}}$. For a flat rotation curve (so that $\kappa = \sqrt{2} V_{\mathrm{rot}}/R$) the epicyclic period is about 1.7 $\times 10^8$ years and the vertical period is about 8.1 $\times 10^7$ years. The epicycle of the Sun measures roughly 0.35 kpc in the radial direction and 0.5 in the tangential one. The amplitude of the vertical oscillation is somewhat less than 100 pc.

2.3.2 Kapteyn's Universe

In 1922, Kapteyn (1922) published a paper with the title *'First attempt at a theory of the arrangement and motion of the Sidereal System'*. This paper can be seen as the start of the study of the dynamics of the Milky Way Galaxy. It discussed not only the distribution of stars in space, but in addition it showed how the system could be in equilibrium—in 'steady state' as Kapteyn called it—such that the motions compensated for the gravitational field at each position in the system (Fig. 2.1). I have discussed that recently in a detailed review (van der Kruit 2014) and in an extensive biography (van der Kruit 2015) (see also van der Kruit and van Berkel 2000). Kapteyn's results were partly wrong, partly right. His model of the system was a flattened ellipsoidal structure in which the stellar density fell off with radius, reaching a density of about 1.5 % of the central value at 8.5 kpc. The Sun was in this structure at 650 pc from the center and 38 pc out of the symmetry plane. It rotated as a whole with a velocity near the Sun of about 20 km s^{-1} in two streams that were going around the center in two opposite directions. This part was wrong. In the vertical direction the distribution fell off faster, reaching the same density at 1.6 kpc, and t his result is close to what we adopt today. This vertical structure was supported by a velocity dispersion of 12 km s^{-1} (more like 17 in modern estimates),

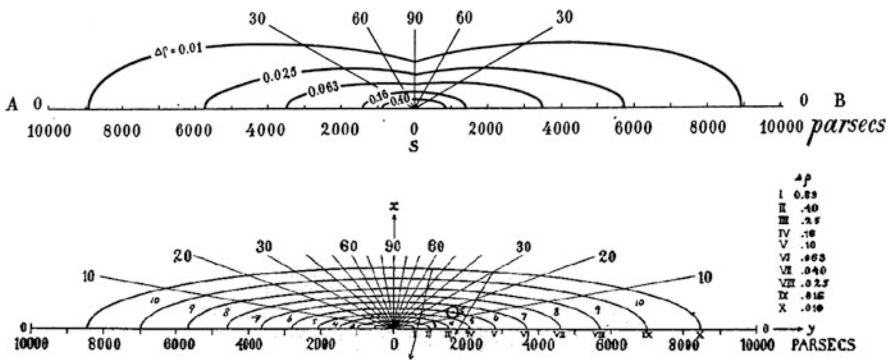

Fig. 2.1 On *top* the distributions of stars in space as determined by Kapteyn and van Rhijn (1920). The solution involves a dependence only with distance from the Sun at latitudes 0°, 30°, 60° and 90°. The *bottom* illustration is from Kapteyn (1922), where he fitted ellipsoids to the densities to facilitate computation of the gravitational potential. His interpretation of the Star Streams as two opposite rotations led him to adopt a position of the Sun 650 pc away from the center and on the basis of Ejnar Hertzsprung study of the distribution of Cepheids on the sky at 38 pc from the plane. The Sun is at the circle designated 'S', but is plotted at three times as large a radius from the center

leading to a mass surface density not very different from our current values. As Kapteyn expressed it, the equilibrium was sustained by thew known stars if each star had a mass between 1.4 and 2.2 times that of the Sun and that was at that time close to the total mass of the average binary star and therefore made sense. This part was substantially correct.

The flaws in the model were two-fold. In the first place, Kapteyn neglected absorption, even though he had argued for its presence on a number of occasions (Kapteyn 1904, 1909a,b, 1914) deducing that it would manifest itself by a reddening of stars with increasing distance from the Sun and deriving a somewhat low, but otherwise not at all unreasonable estimate of 0.3 or so magnitudes per kpc. He, and most of his contemporaries, were persuaded to neglect extinction by Shapley's observation (Shapley 1916) that there was essentially no absorption towards the globular cluster M13. Interstellar absorption was only established beyond doubt by Trumpler (1930a), when it also became clear that it was restricted very much to low Galactic latitudes. Secondly, Kapteyn's Star Streams, discovered by him in 1904, that he interpreted as two oppositely rotating stellar components, were really the manifestation of an asymmetry in the local distribution of stars, as first noted by Schwarzschild in 1907. Kapteyn rejected that notion on the basis of the very different compositions of stars in the two Streams. This viewpoint was also widely supported, by astronomers as Arthur Eddington, until this observation was shown to be incorrect in the 1920s.

2.3.3 Jan Hendrik Oort and Stellar Dynamics

Before discussing Oort's contributions to what he used to call Stellar Dynamics, I first look at developments leading up to his discovery of differential rotation. A very readable summary is Oort's chapter in Stars and Stellar Systems, 1965 (Oort 1965).

It did not take long after Kapteyn's demise that the flaws in his Universe were recognized. The situation is neatly summarized in Fig. 2.2, drawn by Oort. It shows that Kapteyn's system is much smaller and located asymmetrically with respect to Harlow Shapley's system of globular clusters (Shapley 1919). Although, as mentioned, the discovery of interstellar absorption is correctly credited to Trumpler (1930a), its existence was speculated on by others before then. In a lecture that Oort gave in 1926 on the occasion of his appointment of 'Privaat-docent' at Leiden University, entitled *'Non-light-emitting matter in the Stellar System'*, translated as appendix A in the Kapteyn Legacy proceedings (van der Kruit and van Berkel 2000), he concluded that for an explanation of what is known about the system *'for the moment* [. . .] *an absorption of light was the least contrived.'* What Oort envisaged has been summarized in Fig. 2.3, also drawn by him after Galactic rotation had been established.

As far as kinematics is concerned, two developments took place at about the same time. The picture of two Star Streams as Kapteyn had proposed was replaced by that

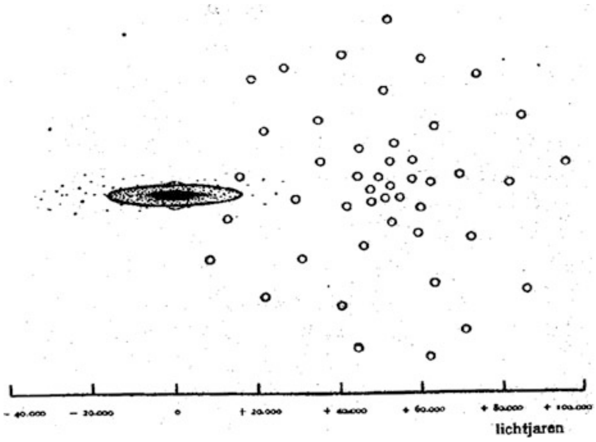

Fig. 2.2 The spatial distribution of stars in the Kapteyn Universe compared to that of globular clusters as determined by Shapley. The figure is from de Sitter's book *'Kosmos'*, published in 1934 and is credited to Jan Hendrik Oort. This is a Dutch translation of his *Kosmos: A course of six lectures on the development of our insight into the structure of the Universe, delivered for the Lowell Institute in Boston, in November 1931*

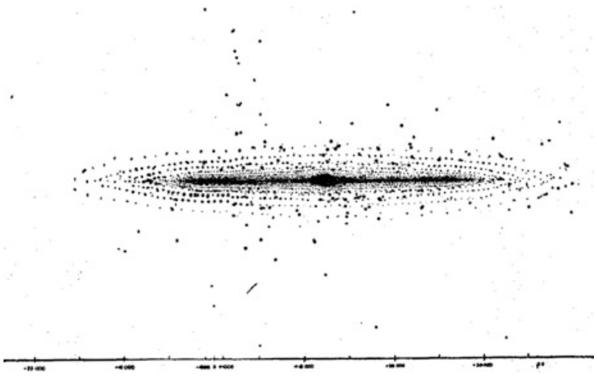

Fig. 2.3 This diagram shows a sketch of the Milky Way Galaxy's structure, also from de Sitter's book and credited to Oort. The disk is the flat structure, the halo is spherical and consists of many individual stars, but some of these are concentrated in so-called globular clusters. For further information see the caption of Fig. 2.2

of Schwarzschild's velocity ellipsoid, the streams being a reflection of the fact that this ellipsoid had a long axis. Secondly, the distribution of stellar motions was very asymmetric at high velocities. Oort had studied these high-velocity stars in his Ph.D. thesis. The discovery of the Strömberg asymmetric drift (see below) (Adams et al. 1921; Strömberg 1925), actually contributed to also by Kapteyn, Walter Adams, Alfred Joy and others, followed from studies of stellar motions. It was Oort, who in 1927 (Oort 1927), following work by Bertil Lindblad, showed that differential rotation would result in a systematic pattern of radial and tangential velocities with Galactic longitude, described by his 'Oort constants' A and B, which are related to the local rotation velocity and its first radial derivative and to the distance to the rotation center. He found that the direction of the center of rotation coincided with that of the globular cluster system. Oort assumed the two coincided, although this was in contradiction to the star densities of Kapteyn and van Rhijn (1920). He proposed that *'the most probable explanation is that the decrease of density in the galactic plane indicated for larger distances is mainly due to obscuration by dark matter'*. The rotation velocity of the stars near the Sun manifests itself as the mean of the velocities of the high-velocity stars and the globular clusters, some 200 km s^{-1}, if the globular cluster system is at rest. The situation has been summed up in Fig. 2.3, also due to Oort.

Oort next worked out a detailed theory of stellar dynamics, assuming a rotating disk and a Schwarzschild ellipsoidal velocity distribution with three different axes (Oort 1928). This theory had earlier been worked out in comparable forms by Arthur Eddington and James Jeans. The theory explained a number of observed facts. First there was a strong asymmetry in the velocities of high-velocity stars, starting at 63 km s^{-1}, and this would indicate that the escape velocity from the disk was that amount higher than the rotation velocity itself. The theory predicted that the ratio of the axes of the ellipsoid in the plane (the radial and tangential velocity dispersion) should be related to the Oort constants. And because a higher amount of random motion constitutes a sort of pressure and kinetic energy, the mean tangential velocity of any group of stars should decrease for higher random motions of the group; this corresponded to the Strömberg asymmetric drift. In detail, however, the theory seemed to demand too many fine-tunings, now understood as a result of the fact that the stellar motions are not so exactly Gaussian as the assumption of a precise Schwarzschild velocity ellipsoid demands. I will return to later determinations of the properties of the velocity ellipsoid, the Oort constants, etc. later on.

Oort's second important contribution was his analysis of the dynamics of the Galactic disk near the Sun in the vertical direction. His paper in 1932 (Oort 1932) can be seen as a major extension and improvement of the approximate analysis Kapteyn had done in 1922 (Kapteyn 1922). Remember that Kapteyn had performed no more than a basic exercise, concluding that with the given density distribution and average velocity of the stars, their gravity would be able to give rise to a 'steady state' if the average mass was some 1.5–2 solar masses. Since that was thought to be the mass of an average binary, there was no necessary to invoke much mass in 'dark matter'.

Oort's approach was much more detailed, using complete solutions to the equations of stellar dynamics, in particular allowing for the fact that different types of stars may have different velocity dispersions. The bulk of the paper concerns the collection of observational material and discussion of the results. It is summarized as a local space density of stars of 0.092 solar masses per cubic parsec, compared to an inferred value of 0.038 in the same units from stars down to absolute magnitude 13.5. Oort concluded: *'Extrapolating the mass of the faint stars the total mass gets dangerously near the value of 0.092 solar masses derived from $K(z)$. We may conclude that the total mass of nebulous or meteoric matter near the sun is [...] probably less than the total mass of visible stars, possibly much less.'*

2.3.4 Properties and Evolution of the Velocity Ellipsoid

During the 1930s the basic equilibrium dynamics of the Galactic disk seemed well described by the formalisms summarized. What remained was of course a precise determination of the constants of Galactic rotation: the distance $R_\circ$ of the Sun from the Galactic center, the rotation velocity $V_{\rm rot}$ at R, the Oort constants A and B and the local properties of the velocity ellipsoid. But then there would be the need to determine the full rotation curve and the gravitational field of the Galaxy as a whole to study stellar orbits. I will not trace the development in the adopted values of $R_\circ$, $V_{\rm rot}$, A and B, apart from stating that the astrometric studies from space have improved these and continue together with large, groundbased radial velocity surveys to do so. And of course, our understanding of the structure, kinematics and dynamics of the disk of our Galaxy could serve as a guide to that in external galaxies.

The properties of the velocity ellipsoid, once it was clear that Schwarzschild's description was applicable, turned out the be more complicated when studied in detail. The simple picture has the long axis pointing towards the Galactic center, and the axis ratio of the ellipsoid in the plane (the radial and tangential velocity dispersion) was simply related to the local Oort constants, while the vertical one was in principle independent upon these and could not be predicted from first principles. Also the radial dependence took a long time to be understood.

The first thing that became clear was that the local velocity dispersion of stars depended on stellar spectral type, absolute magnitude and age, which really were manifestations of the same property. The first hints of this came from studies of stellar velocities obtained primarily by Adams with the then new 60-in. telescope at Mount Wilson, but also by William Campbell at Lick Observatory. The situation around this is complicated by the poor personal relationship between Adams and Kapteyn. Initially Edwin Frost at Yerkes Observatory and Adams had found that the motions of the 'Helium stars' (type B roughly) were exceptionally small. But it really started out with a paper by Kapteyn and Adams (1915), in which they found that the average radial velocities and proper motions of stars increased with spectral types F, G, K though M (and with absolute magnitude). Eventually it was realized that the correlation was really with stellar age. A landmark paper in this respect form the observational side is one by Roland Wielen of Heidelberg in 1977 (Wielen 1977), which showed that stellar orbits diffuse in such a way that a star near the sun in the Galactic disk *'changes its space velocity at random by more than 10 km s^{-1} per galactic revolution'*. Stars appear to be born with an average velocity dispersion of about 10 km s^{-1}, which is more or less that measured in the neutral hydrogen in the disk. It matter is further complicated by the observation that for stars of most spectral types, the long axis of the velocity ellipsoid does not point as expected towards the center of the Galaxy, by amounts of 15° or more. This is a local phenomenon that appears related to the presence of spiral arms (Oort 1940, 1965), but is also now known to depend on metallicity and might be connected to the presence of a bar in the center of the Galaxy (e.g. Soto et al. 2007 for a recent discussion).

As early as 1953, Spitzer et al. (1951, 1953) attributed the correlation of stellar age with velocity dispersion to scattering of stars in their orbits by interstellar cloud complexes (the later identified as Giant Molecular Clouds), such that their velocity dispersions initially would resemble those prevalent in the clouds stars originated from but after that would steadily increase and eventually level off. Not much later Barbanis and Woltjer (1967) pointed out that the spiral structure could also explain the observed trend of increasing random motions with age. The Spitzer-Schwarzschild mechanism seems incapable of explaining the ratio of the radial to vertical velocity dispersions, so both mechanisms are likely to operate. The subject has recently been treated by Binney (2013).

2.3.5 Stellar Orbits

It is well known that to an excellent approximation the orbit of a star whose random velocity is small with respect to Galactic rotation can be described by that of an epicycle whose center rotates around the center of the Galaxy (see Fig. 2.4). The direction of motion in the epicycle is opposite to that of Galactic rotation and the axis ratio of the epicycle depends on the radial gradient of the gravitational force (assumed axisymmetric) and can be expressed therefore in terms of the Oort constants (see the Introduction for the form of the relevant expression). The period in the epicycle (the epicyclic frequency κ) can likewise be expressed in terms of the Oort constants. For small deviations from the rotation, the motion in the direction perpendicular to the Galactic plane can be considered independent of that and the frequency of this depends only on the vertical force field.

For orbits with larger random velocities the orbits can only be calculated in general from numerical integration of the equations of motion. In theory each orbit has six integrals of motion, resulting from double integration in three coordinates. Most of this goes back to the work by James Jeans, beginning with his treatment of Kapteyn's Star Streams (Jeans 1915), who formulated his famous theorem that any function of integrals of motion is a solution to the dynamics (formally the collisionless Boltzmann equation) in a steady state. Some of these are called isolating, since they restrict the orbits to a particular volume in phase space. Lynden-Bell (1962) showed in 1962 that *'Only isolating integrals should be used in Jeans' Theorem'*. In the axisymmetric case of the Galactic disk, there are at least two isolating integrals: the total energy and the angular momentum. These two restrict the orbits to a tube around the center, bounded by the 'zero-velocity surface', for which the star is not moving in a co-rotating frame. A longstanding problem concerned the question whether or not the orbits of stars in the Galactic disk that have substantial vertical

Fig. 2.4 The well-known principle of epicyclic orbits for stars with small random motions with respect to Galactic rotation

motion do have a third integral. Numerical integration showed [by Alex Ollengren, see his contribution to Oort (1965)] that the orbits are further restricted than the 'zero-velocity curve', so that there must be a third isolating integral [see van de Hulst (1962) for an analytical treatment, foreshadowing Stäckel potentials]. In the case of low velocity orbits the vertical oscillation is decoupled from the epicyclic motion and the energy in the vertical direction is the third integral.

A very important step forward in our understanding of the structure of the Galaxy using stellar kinematics is contained in a seminal paper by Eggen et al. (1962) in 1962 on *'Evidence from the motions of the old stars that the Galaxy collapsed'*. Using an crude model galaxy and the observed space velocities of stars, they estimated the eccentricity of the orbits and the angular momenta. From various correlations they concluded that the Galaxy must have collapsed, especially in the vertical direction. This analysis showed that orbits of stars of different ages are very different.

2.3.6 Stability

The properties of the general rotation of the disk and the random motions in it, did not address the issues of stability, star formation and spiral structure. Of course much effort went into a better determination of the distance to the Galactic center, the rotation curve of the Galaxy and the local Oort constants. The matter of stability of the stellar distribution in the Galactic disk, the apparent lack of major instability in spite of the formation of (spiral) structure, clouds of gas and dust and the birth of stars, was not part of these studies.

The theory of stellar dynamics and its application to the Sidereal System, as set up by Eddington, Jeans, Kapteyn, Oort and others, took as a starting point that systems were in equilibrium. In a broader context this concept is expressed in the 'Virial Theorem', defined in the course of the nineteenth century first in thermodynamics and later in mechanics by Jacobi, Poincaré and others, based on earlier work by Lagrange. The theorem states that in an equilibrium situation (on average) the kinetic energy equals half that of the potential energy. However, the question of stability of the distribution of stars in the Sidereal System has a much longer history, going back to the correspondence between Dr. Bentley and Isaac Newton on the consequences of the latter's theory of gravity. Dr. Bentley wondered how the system of stars could be stable when each star attracted every other one. Newton's suggested that the even distribution of stars in space assured that all forces on each star exactly compensated one another, but this provided only a very unstable equilibrium in a very finely tuned distribution, such that any minute disturbance would result in the collapse of the system. Newton had, however, difficulty in even showing that stars were distributed evenly in space (Hoskin 1977).

It became understood that the collapse is prevented by random motions, which is reflected in the virial theorem. In 1902, James Jeans had studied *'The stability of a spherical nebula'*, which provided the basis for what we now know as the 'Jeans

Mass' (Jeans 1902). In a medium of constant density and temperature (or kinetic energy per unit mass) there is always a maximum spherical volume in which the virial theorem can provide stability and prevent contraction, because as the volume taken is larger the potential energy grows faster (goes with R^5) than the kinetic one (with R^3). The largest mass that can be stable is called the 'Jeans-mass', which scales with the density as $\rho^{-1/2}$ and temperature as $T^{3/2}$ (or velocity dispersion $\langle V^2 \rangle^3$). Extensions of this and application to disks in galaxies came with the papers of Toomre (1964) in 1964 and by Goldreich and Lynden-Bell (1965) in 1965. The first of these led to the Toomre Q criterion for local stability. In his paper, Toomre first derived the equivalent of the Jeans criterion in an infinitely thin disk. Within the radius derived the disk would be stabilized by its random motions. Next he looked at large scales and investigated to what extent the shear resulting from differential rotation could provide stability and derived a minimum mass or radius for that. The Toomre stability criterion corresponds to those disks in which the maximum radius for Jeans-like stability and the minimum radius for stability by differential rotation are equal, so that the disk is just stable on all scales. The parameter Q, which is the ratio between the stellar velocity dispersion observed and that required for stability should exceed unity for stability. It is proportional to the observed stellar velocity dispersion and the epicyclic frequency, and inversely to the surface density σ:

$$Q = \frac{\kappa \langle V^2 \rangle^{1/2}}{3.36 G \sigma}$$

The proportionality constant in practice needs correction for finite thickness. In the solar neighborhood the determination of Q should be straightforward, but unfortunately the parameters involved are not known very accurately. Toomre himself estimated 1.2–2.0 (Toomre 1974) and that has not improved very much in more recent determinations.

Related to the matter of stability is that of resonances. For example one can look for a rotating coordinate frame in which a star goes through two of its epicycles in the same time as it goes once around the center. In such a rotating frame the star describes a closed elongated orbit. This is called the 'inner Lindblad resonance', named after Bertil Lindblad. It was noted early on that in the inner Galaxy the corresponding angular velocity of the frame was more or less constant with radius, so that a 'pattern speed' could be defined in which over a large range of radius stars described such closed orbits. The relation with spiral structure was suspected soon and indeed the density wave theory posed a spiral pattern that conserved its shape in a uniformly rotating frame. An excellent illustration of this has been provided by Kalnajs (1973). Further elaboration on the question of spiral structure carries too far; an outstanding discussion of the matter remains the 1977 review by Toomre (1977b).

2.3.7 Determinations of Kinematic Properties

The section above have described the progress in the definition of the kinematic properties of the disk of the Milky Way Galaxy. The astrophysical approaches that have been developed to obtain recent measurements of these properties are mostly in the areas of improved sample selection and measurement. Two examples to illustrate this are the following.

Oort's 1932 analysis of the vertical dynamics of the Galactic disk and the estimates of the local space and surface density culminated in the late 1980s in two studies that gave rather different results. Using samples of K-giants and various assumptions for the distribution of any unseen matter, John Bahcall arrived at surface densities near the Sun ranging from about 50 to 80 $M_\odot$ pc^{-2} (Bahcall 1984), while Konrad (or Koen) Kuijken and Gerry Gilmore (1989, 1991) found from K dwarfs a value of 46 ± 9 $M_\odot$ pc^{-2}. Recent very extensive samples such as from the (RAdial Velocity Experiment) and red-clump stars selected from various surveys such as 2MASS (two-Micron All Sky Survey) found a surface density of *baryonic* material of 44 ± 4 $M_\odot$ pc^{-2} (Bienaymé et al. 2014).

The determination of parameters like the distance to the Galactic center, the local rotation velocity of the Galactic disk and Oort constants (and through that the local epicyclic frequency) have been reviewed at various occasions since the 1920s, for example by Kerr and Lynden-Bell (1986), resulting in a set of IAU recommended values. The study of the properties of the velocity ellipsoid is now based on very large samples, as a direct result of huge surveys of radial velocities, proper motions and parallaxes. This has been crucially facilitated by astrometric satellites and dedicated survey telescopes. The status of the field is that now velocity dispersions, deviations of the vertex and asymmetrical drifts can be studied in the local disk of the Galaxy in a large variety of sub-samples, but a detailed discussion is well beyond the scope of this chapter (but see Binney et al. 2014).

2.3.8 Spiral Galaxies

Finally, what have we learned about external galaxies by studying the kinematic properties of the Galactic disk? Obviously it helps to understand local details in studying the kinematics and dynamics of disks in spiral galaxies, such for example the dependence of the characteristics of the velocity ellipsoid for the stellar component of the Galactic disk as a whole or as a function of age or metallicity, or the details of the local vertical space distribution or velocity structure of the stellar disk. Detailed understanding of local kinematics (asymmetric drift, velocity dispersions, epicyclic motions, stellar orbits) may serve as a guide in analyzing observations of disk galaxies. But I believe the effects the other way around have been much more enlightening. So more appropriately we may ask: what have we learned from external galaxies, or maybe more specifically, how have studies of the stellar kinematics in disks of other spiral galaxies helped further understanding our own system? I mention three examples and refer for a thorough discussion on galactic disks to a recent review paper by Ken Freeman and myself (van der Kruit and Freeman 2011).

The first concerns flat rotations curves. Although the rotation curve of the Galaxy could be determined quite accurately from HI 21-cm observations, starting in the 1950s, in the part interior to the solar circle, this has been much more problematic for the part beyond the sun. The reason for this has been that one needs independent distance information the turn observed HI distributions and radial velocities into a rotation curve. And determinations of the radial velocities of star clusters or other distance indicators suffered from uncertain absorption corrections and did not result in accurate rotation velocities at least not over interesting ranges of galactocentric distance. The property of rotation curves, that they remain flat out to large distances from the centers could only be established in external galaxies, especially when HI was mapped in extended outer parts. The story of who deserves the credit for the discovery of the flat rotation curves and from that for dark matter halos has been described by various authors, but the conclusions are not the same. In my own recollection the issue started with observations of HI, such as Ken Freeman's remark concerning NGC 300 (Freeman 1970) and about the same time the preliminary presentations by Morton Roberts on the HI rotation curve of M31, finally published in 1975 (Roberts and Whitehurst 1975). The matter has been described by e.g. Sanders (2010) and Bland-Hawthorn and Freeman (2014).

The other issue concerns the measurement of the stellar rotation curve and in particular velocity dispersion in external disks, starting in 1986 (van der Kruit and Freeman 1986). This gave rise to the discovery that the stellar velocity dispersions increase towards the centers of galaxies, implying in first approximation constant mass-to-light ratios and Toomre Qs. The first means that the stellar make-up in disks is in general terms very similar, so that a luminosity distribution can in good approximation be turned into a mass density distribution. The second, and the realization that Q is of order 2, showed that the old stellar disk is just stable according to local perturbations as described by that criterion. All of this (and what follows in the next paragraph) has been summarized in van der Kruit and Freeman (2011). Only after the radial variation in stellar velocity dispersion was established in external galaxies, has this same property been studied in our own Galaxy. It is true that estimates of Q in the Galactic disk at the solar radius were made, e.g. Toomre (1974), but only for the position of the sun.

A related point is the matter of whether external galaxies are 'maximum disk', and global stability. This is related to the realization that dark matter halos serve to stabilize the disks against global perturbations. This was first realized by Ostriker and Peebles (1973) who found that galaxy simulations produced strong bar-like perturbations unless it was stabilized be an inner component with large velocity dispersions. Since this could not be the stellar disk itself for the dispersions required they concluded that there had to be a spherical, unseen halo whose 'mass *interior* [their italics] the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.' Following this up, Ostriker et al. (1974) found that various arguments including the flat rotation curves, suggested that the mass of galaxies increases linearly with radius. Spiral galaxies like our own would have dark halos with masses up to $10^{12}\,M_{\odot}$.

The question remained how the flat rotation curves of our and external spirals had to be decomposed into baryonic matter (stars, gas, dust, stellar remnants, etc.) and the dark halo of unknown composition. A much used concept was that of 'maximum disk' (van Albada et al. 1985), in which the contribution of the disk to the rotation was scaled to the maximum value possible. Current observational work suggest that most if not all spirals are sub-maximal, except possibly the most massive disks.

It was only after in external galaxies the ubiquity of flat rotation curves was established and studies of radial variations of stellar velocity dispersion had become possible, and investigations into maximum or sub-maximal disks, dark matter halos, local and global stability were flourishing that more insight of such global kinematics and dynamics in our Galaxy has been forthcoming. Obviously the detail with which we can study the local neighborhood, starting with Kapteyn and Oort, have been important in guiding our minds when considering external galaxies. But in more recent years research on external spirals has helped understand our own Galaxy. It would seem that the advent of modern surveys of enormous samples of stars in the Galaxy will again turn this around.

The stellar population concept is the turning point of our understanding of the history of formation and evolution of the MW. Antonella Vallenari, introduces us with the birth of this idea , thanks to Baade, up to its modern ramification given by the discovery of multiple population.

2.4 Milky Way: Stellar Population and the Interstellar Medium

Questions for Antonella Vallenari:

W. Baade in 1944 introduced the Population I and II concepts for the stars of the MW. May you discuss how Baade arrived to this conclusion and how the concept of stellar population has been useful for the study of our Galaxy?

Would you address the main progresses done in the definition of the stellar composition of the MW and how the stellar population concept has evolved?

What is the current picture about stellar population in the MW?

One of the most challenging questions in modern astrophysics is how disc galaxies form and evolve, and how their component stars and stellar populations form and evolve. This is the main aim of the stellar population studies. The modern extension of this concept has its roots in the initial discovery of two stellar populations made by Baade in 1944. Walter Baade (1893–1960) was one of the most influential scientists of the past century. He made a significant contribution to our understanding of the Universe, revising the Hubble's distance and age scales.

But probably the most far-reaching implication for astrophysics comes from the discovery of two distinct stellar populations. He identified stars in E galaxies and in bulges of spirals with stars in globular clusters and stars in spiral arms with those in open clusters and in the Magellanic Clouds, calling them Population II and I respectively. This concept has been largely revised since then, but it has paved the way to the development of the previously marginal field of the galactic evolution. Nowadays, the stellar population concept, following the recipes of the stellar evolution, embraces most of the stellar astronomy. Below we will discuss the main steps Baade followed to arrive to this inspiring discovery, in the framework of the astronomical culture of that epoch. More details can be found in several reviews, among which we mention Frogel 1988 presentation at the meeting *Towards Understanding Galaxies at Large Redshift*, the Sandage 1986 paper (Frogel 1988; Sandage 1986), and the biography *W. Baade: A life in Astrophysics* by Osterbrock (2001).

Wilhelm Heinrich Walter Baade was born in Schroettinghausen in Westphalia (Germany). His scientific education took place first at the University of Muenster and then in Goettingen, at that time one of the most famous Universities in Germany, with a tradition in Astronomy going back to Carl Friedrich Gauss. At the beginning of the World War I Baade was still a student. In 1919 he received a PhD with a thesis on the eclipsing binary β Lyrae, a few months after the end of the World War I.

It should be noted that the Göttingen Observatory astronomical equipment was quite obsolete. The largest operating telescopes in the world was the 2.5-m Mount Wilson that went into operation in 1919. Before that, the 1.5-m Mount Wilson telescope (in 1908) and the 1.8-m reflector at the Dominion Astrophysical Observatory (in 1917) were operational. As a result of the new large telescopes, the first decades of the twentieth-century were characterized by exciting discoveries both in the star and in galaxy domains, in a period that Sandage (1986) describes as *driven by a faith in the Baconian ideal of science progressing by induction without prior benefit of theory.* Astronomers were learning the properties of the stars and their compositions. It is worth adding that the stellar evolution models, and the source of stellar energy were largely unknown in the late 1940s. Practically nothing was known about the interstellar extinction (see James Lattis contribution in Chap. 1). Less than 1 year after the completion of the PhD of Baade, H. Shapley and H.D. Curtis held the Great Debate at the National Academy of Science in Washington about the nature of the spiral galaxies, called at that time nebulæ. Curtis argued that the Universe was composed of many galaxies like our own. Shapley had a completely different view: the nebulae were indeed gas clouds, and ours was the only existing galaxy. In the mid-1920 a partial solution aroused with the discovery of Cepheid variables in M31 by Edwin Hubble using the telescope of Mount Wilson. This allowed Hubble to estimate the distance of M31, finding out that its distance is larger than the expected dimension of our Galaxy in Shapley view: M31 was a galaxy like our own. In 1919 Baade got a job at the Hamburg Observatory, where the largest German telescope, a 1-m refractor was housed. It is interesting to note that the title of the inaugural lecture after his Habilitation, i.e. his authority to teach at the Hamburg faculty, was *The extragalactic Nebulae as Star Systems* . Since 1931 he was staff member of Mount Wilson Observatory. During his long and bright career he studied variable stars, globular clusters, the structure of the Milky Way, local group galaxies, and distant universe. Every step lead him closer to the population concept he conceived during the wartime years.

In 1947, he held an invited talk at the American Astronomical Society meeting at the Perkins Observatory where he reviewed all the observations *which lead to the recognition of two distinct types of stellar populations. What I want to show is that this concept emerged gradually during the last 25 years*, and specifically between 1910 and 1935. Baade was able to put together the various bits of evidence building a coherent picture. During the first decades of the past century, data on stellar radial velocities, parallaxes and proper motions were collected to built a picture of our own Galaxy. Along an independent line of research, studies of external galaxies were discussing their content. A relevant step was the discovery by Adams and Kohlschutter (1914) that the high velocity stars had negative velocities. Through the discussion of the components of the velocity ellipsoid, Strömberg (1924) divided the stars in different groups having presumably homogeneous kinematical properties. This paper defining kinematic subsystems was the precursors of the Oort theory (Oort 1927) of galactic rotation. Three of Ströemberg groups are of particular interest here, since they involved RR-Lyrae variables, Mira variables, and globular clusters, all showing high velocity. These objects were specially important to form Baade's picture. In particular RR-Lyrae were called *cluster type variables* and regarded as markers of globular clusters. Trumpler (1930b) observed the open clusters with the aim of deriving the dimension of the Milky Way. Comparing photometric distances with metric distances based on angular diameters, he came to the conclusion that the differences were due to interstellar absorption. The subsequent determination of the extinction become important for many problems. An indirect confirmation of this result arrived in 1931 when Hubble mapped the zone of avoidance of galaxies, already identified by Seares (1925) with the Galactic plane. When Baade found RR-Lyrae variables outside globulars in galactic-plane fields, in the direction of the center, he realized that the interstellar extinction was able to prevent deep explorations in that regions.

Along a parallel line of investigation, the study of nebulae pointed out that Elliptical and Spiral resolution into stars differed significantly. In the 1930s astronomers were puzzled by the fact that observations of external galaxies could not resolve into bright blue stars E galaxies and bulges of spirals, while the arms of spirals were shown to be composed by blue stars. During World War II, Baade, almost regarded as an enemy, could not serve in the military service, but confined to Los Angeles County, spent a lot of time and efforts to study globulars and external galaxies.

Shapley (1938) discovered a new type of stellar systems, the Sculptor and the Fornax stellar aggregated. Their observations, although quite challenging from Mount Wilson, allow Baade and Hubble to detect RR-Lyrae in Sculptor and globular clusters in Fornax (Baade and Hubble 1939). Due to his observational skills, Baade succeeded in resolving M 32, the bulge and the disk of M31 and NGC 205. NGC 147 and NGC 185 were classified as E peculiars by Hubble. Baade resolved them at the absolute magnitude expected if the stars are like those in globular clusters,

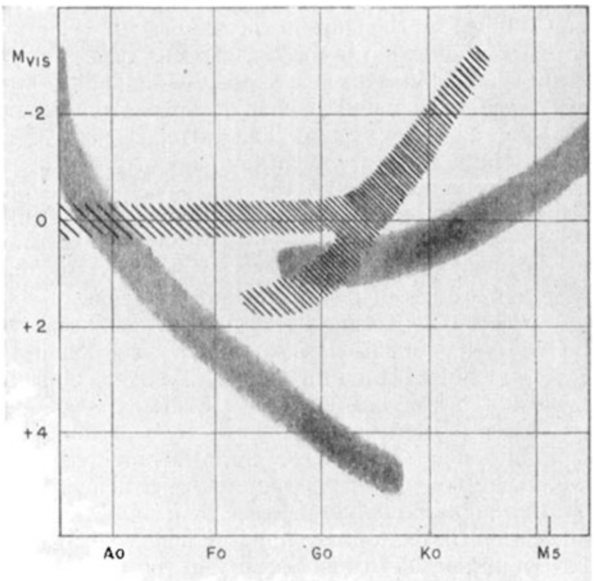

Fig. 2.5 Baade's Hertzsprung-Russell diagram, describing the spectral type against absolute magnitude. Population I distribution stars is represented by the *darker areas*, while Population II is represented by the *lighter hatched areas*

realizing that these galaxies were *the intermediate form between systems like NGC 205 and the Sculptor and Fornax systems*, defined as *globular systems of ..low concentration*. This established the link globulars-Ellipticals. In addition, he noted the strong concentration of hot stars, HII regions and dust in the spiral arms of M 31 as in our Galaxy, finally coming to the definition of Population I and II based on the properties of the stars on the Hetzprung-Russell diagram in two seminal papers, (Baade 1944a,b) (see Fig. 2.5 for the original diagram).

Baade was able to make the link between structural components of the Milky Way and the kinematic subsystems already identified within the Galaxy by Stroemberg, Oort, Lindblad (see the above contribution of Pieter van der Kruit). However, the physical explanation of these two populations was not clear to him. Only in 1948 Norris Russell published the idea that age was the real difference among these two populations. Population II was composed by old stars in which the most luminous and massive objects had moved away from the main sequence, while younger stars were part of Population I (Russell 1948). This was based on the understanding by Bethe and Marshak (1939) of the energy production through nuclear reactions in stellar interiors where H is transformed into He.

2.4.1 Early Revision of the Two Population Concept

After Baade's discovery, the field of stellar population had a very rapid development in the 1950s. Great theoretical and observational advances made possible including Galactic structure, kinematics, chemistry and age into an evolutionary context. In turn, all this added complication to the original picture of Baade, until the original definition become obsolete. However, the initial Baade definition was setting the stage for the understanding of the formation and evolution of our Galaxy, and of the galaxies in general.

The development of the stellar evolution theory was one of the main achievements of the period. This allowed to use the color-magnitude diagrams to date stellar clusters (Sandage and Schwarzschild 1952), and in turn to use them to calibrate the relative age of the field populations (Sandage and Walker 1955). In this way, the concept of age became fundamental in the definition of the populations, providing a wealth a new discoveries. In the 1940s, the astronomers were sharing the general opinion that all stars in the Galaxy had the same chemical composition of the Sun. Chamberlain and Aller (1951) analyzing the spectra of two stars found spectral differences they attributed to a different chemical composition. This was the beginning of a long way leading to the development of the chemical evolution. Through stellar evolution, it was possible to understand the process of nucleosynthesis and chemical enrichment. Since chemical abundances are written into star spectra, the classification of stars into chemical and age groups became feasible. The final association between structural-kinematics parameters of stellar populations and the age-metallicity groups arose when Roman (1954) discovered that metal deficient stars had high velocity. This connection allowed the development of an evolutionary picture of the Galaxy, able to explain the formation and the properties of the various stellar populations. In 1957, the Vatican Conference on stellar populations pointed out that the simple Baade picture of two stellar populations was not reproducing the reality (O'Connell 1958). One of the shocking evidence was found in Keenan and Keller (1953) study of a sample of high velocity stars showing an HR diagram of Population I, instead than a Population II, as expected on the basis of Baade model. This opened the Pandora's box of a revision of the Baade view. At the end of the Vatican Conference, the simple two discrete populations picture was replaced by the concept of various population subsystems having continuously changing properties (halo, intermediate population II, old disk population, old and extreme population I) (Blaauw 1965).

2.4.1.1 Towards a Galaxy Formation Picture

The relation between the different components and the intriguing complexity of our Galaxy were explored in the following decades. The majority of the progresses toward understanding the Galactic structure between 1960s and 1990s can be attributed to the success of observational surveys. Due to the instrumental limitations of that period, the surveys were basically limited to small samples of objects, previously identified either on the basis of assumed kinematic or chemical properties preferentially located in the solar vicinity. These kind of surveys were specially efficient in identifying stars with extreme properties concerning velocity, and metallicity. In alternative, tracer surveys, were using star clusters and/or various populations of luminous stars to probe the properties of the Galaxy at larger distances. The prototype of the selected survey is that of Eggen et al. (1962) (thereinafter ELS), that in 1962, provided a major break-through toward a global view of the Galaxy formation. ELS selected a sample of 221 nearby F/G turnoff stars showing large proper motions and discovered a smooth correlation between ultraviolet excess, orbital eccentricity, angular momentum and velocity. F/G stars were chosen since they are long-lived and represented in both population II and I. For this reason they can be used to trace all stages of the Galaxy evolution. ELS used the metallicity as a reliable proxy for age. They concluded that high velocity stars presenting an UV excess due to lower opacities, were metal poor and by inference old Population II. These stars were found at all heights above the plane while metal rich stars were assumed to be younger and detected closer to the Galactic plane. Taking into account the rapid chemical enrichment of the disk by recycling the products of the nucleosynthesis in the stars (Burbidge et al. 1957), ELS constructed a model in which the Galaxy formed by a collapse of a metal poor primordial density fluctuation. Reflecting the kinematics of the gas, the first stars had highly radial (i.e. with high eccentricity) orbits and low chemical abundances and were identified as the halo stars. The increase in the rotational velocity due to angular momentum conservation was able to halt the collapse in the Z direction. Eventually the gas settled into the disk. The age of the Galaxy formation was established in 10 Gyr, adopting as limit the age of the few globular clusters having accurate photometry at that time. Another piece of evidence was the small age spread among globular clusters believed to be coeval (Sandage 1962): this pointed in the direction of a rapid collapse of the proto-galaxy. The collapse time scale was found of the order of the freefall time, i.e. 200 Myr, based on the rotation period of the present Galaxy at the solar circle. ELS first used the analysis of the stellar populations in the MW to infer how the Galaxy formed. This seminal models was discussed and criticized in the following decades. Galaxy models become more sophisticated, introducing evolving gravitational potential, more realistic orbital parameters. New observations realized the presence of observational biases in ELS sample detecting groups of stars missing in the original data set. Larson (1969) interpreted the presence of retrograde orbits in the halo as due to a formation process in a clumpy and turbulent environment. The idea of turbulent galaxy formation was supported by observations of external galaxies, recognizing galaxy interactions and mergers as a common phenomenon (Toomre 1977a). The analysis of the properties of a sample of 44 globular clusters in our Galaxy, led Searle and Zinn (1978) to a revision of the ELS model. The discovery of low metallicity stars with low eccentricity, the absence of a radial metallicity gradient among the clusters in the external halo (R $>$ 8 kpc) and the chemical homogeneity of the stars inside the clusters were interpreted as the result of a slow collapse. It was pointed out that free falling gas could not have been so well mixed: clusters must have formed out of independent fragments that underwent completely independent evolution. The clusters in the inner halo were found to exhibit a correlation of the abundances with the HB morphology while the external halo objects presented a more complex behavior, with a spread in HB morphology at a given metallicity. This was interpreted as due to an age effect (Rood et al. 1968), resulting in the conclusion that the time for the halo collapse is the outer halo orbital time. In this scenario, the external halo clusters formed in a slower chaotic collapse lasting several Gyr, while the inner halo formed rapidly.

The scientific debate on these two different views took place for a long time, in spite of the observational evidences favoring a chaotic Galaxy formation (Majewski 1993). Clearly the effect of different selection functions, the use of small samples of data played a role in these interpretations. Due to the complexity of the Galaxy as we know now, using a small sample of different tracers gave only a partial view leading to opposite conclusions. Now we have realized that aspects of each picture were valid. The main value of these early studies is to have shown the importance of analyzing the joint distribution of age, metallicity, kinematics and spatial distribution of the stars defining a stellar population, to provide insight into the Galaxy formation and evolution process.

In other words, a detailed knowledge of the properties of the stars in our Galaxy and of the way in which they evolve holds the key for an understanding of how the Galaxy as a whole evolves. Observations drive the models. The large wide-field spectroscopic surveys of the current era mitigate the selection effects that critically hampered previous results and provide the basis for a new vision of the Galaxy evolution as we will discuss in the following. These are the basis of the modern *Galactic Archaeology*.

On the theoretical side, since the 1960s, to reproduce the properties of large samples of stars, models of chemical evolution of increasing sophistication were developed (van den Bergh 1962). Observations of metal poor Population I HII regions in external galaxies (Searle and Sargent 1972) led to the definition of the simple closed box model, with its natural extensions such as outflows and inflows (Chiosi 1980; Hartwick 1976; Mould 1984). These analytical and semi-analytical simplified models (not cosmological ab initio simulations) demonstrated how a broad range of stellar populations can be created at changing key parameters, explain large scale properties such as radial and vertical abundance gradients (Chiappini et al. 2001; Chiosi and Matteucci 1980; Matteucci and Francois 1989; Prantzos and Aubert 1995).

2.4.2 Population II Complexity: The Discovery of the Thick Disk

In its review of 1993, Steve Majewski, writes *"the partitioning (in separate stellar populations) may be semantic for evolution models that advocate a more continuous connection of populations."* Forty years after Baade's initial statement, the concept of stellar population was completely revised. Astronomers got to this conclusion discovering the complexity of our Milky Way. In 1983 Gilmore & Reid analyzing star counts of field populations, discovered an additional component of the Galaxy: the thick disk (Gilmore and Reid 1983). The stellar space-density distribution in the vertical direction was best fit by a double exponential, with scale heights of

∼300 pc and ∼1 kpc, identifying the oldest component of the thin disk and thick disk, respectively.

Mould and Kristian (1986) discovered that the mean metallicity in the halo of M31 is a factor of 10 higher than the metallicity of the field halo of the Milky Way. This had an unexpected consequence: Population II in the Milky Way and Population II in M31, cannot represent the same population, contrary to Baade's early definition. Gilmore and Wyse (1985) realized that the properties of M31 Population II were very similar to that of the Galactic thick disk, in terms of metallicity and kinematics. This led to the identification of the thick disk Galactic population with the intermediate population II, since its properties are intermediate between the halo and the (thin) disk Population II (Wyse and Gilmore 1988). This was a re-definition of the concept already expressed in the Vatican Conference of 1957, although the intermediate Population II as defined at that time, finds no counterpart in the modern Galactic populations. Nowadays, surface photometry has shown that thick disks are common features also in external late-type Spiral galaxies (Comerón et al. 2011; van der Kruit and Searle 1981). Recently the high quality of HST photometry has shown that they are also formed by old stars (Dalcanton et al. 2007; Mould 2005), as in the Milky Way.

Since then numerous models of thick disk formation were put forward, falling into two main categories, i.e. bottom up and top down scenarios. In the bottom up models, the disk formed as result of some action on or by a pre-exiting thin disk (heating by molecular clouds encounters, by a passing by satellite, accretion of disk debris). In 1988 Binney and Lacey proposed that the original thin disk was perturbed by a fast moving massive satellite. This idea stayed in place in various forms during the 1990s, and early 2000s.

In top down models the formation of the thick disk is simply a phase in the general contraction of the Galaxy, due to the product of dissipation during the contraction. The thin disk is the final product of the dissipative settling of the gas. These models produce different predictions concerning age distribution, chemical abundances, presence or absence of chemical gradients, kinematics and, in summary level of discreteness of thin, thick disk and halo. Gilmore (1984) proposed a model in which the star formation was largely suppressed after the free-fall formation of the halo, to allow the settling of the gas into the disk before the resumption of the star formation. Several mechanisms were proposed to substantially reduce the star formation rate after the halo formation, such as tidal shocks, supernovae explosions, intense bursts of star formation in the halo. In these models the halo and the thick disk would have discrete chemical distributions, with an age gap. Other models predict continuous age, metallicity and kinematics between thin and thick disk, as a result of the rapid decline in the star formation at early ages, followed by a more gradual decline at later phases (Burkert et al. 1992).

Testing these models on observational data gave rather controversial and inconclusive results. It is interesting to notice that this issue is not solved yet, in spite of all the progresses both on observational and theoretical side, as it will be discussed in the following sections.

2.4.3 *From Early Times to the Current View of the Milky Way*

Nowadays the galactic research is directed at the determination of the properties of the stellar populations as tracers of the formation process. The focus is not anymore on the cosmological aspects (i.e. to define the order of the formation of the stellar components in the Galaxy), but more on the cosmogonical point of view, to define the formation process.

Our current view of the Galaxy formation follows the hierarchical paradigm. White and Rees (1978) and Blumenthal and collaborators in 1984 investigated the dissipational formation of galaxies within dark-matter haloes where small scales, subgalactic mass, collapsed first, and larger systems built up by clustering and merging. Galaxies occupy only the central parts of dark haloes, enhancing their ability to survive the merging process. These works set the scene for a wealth of subsequent papers were the hierarchical paradigm was defined in more detail. The first simulation of a disk galaxy in cosmological context resulted in a not very realistic description (Katz and Gunn 1991). Since then, for more than 15 years, all simulations produced galaxies that were too bulge-dominated and whose stellar disks were too small in mass and/or dimensions. The solution of the problem arose when the stellar feedback from massive stars and supernovae was included in the simulations eventually leading to the formation of disks comparable to reality (Agertz et al. 2011; Guedes et al. 2011; Stinson et al. 2013). Recently, detailed chemical evolution models are included in cosmological N-body simulations (Minchev et al. 2014) (see Chap. 8 for a wider discussion).

From an observational point of view, our picture of the Galactic stellar population is still quite crude and fragmentary, with new observations basically opening new questions. In the following Section we will summarize our current understanding of the MW.

2.4.3.1 Setting the Clocks: Age Determination

To be able to infer the formation and evolution of our Galaxy from the properties of the stellar populations, we need to be able to assign ages to individual stars, and in particularly to long lived low mass stars. Unfortunately, this is a complex problem. It is relatively straightforward to derive information on the chemical composition of the stars through large spectroscopic surveys. However, that is definitely not the case when it comes to stellar masses, radii, distances and, in particular, ages. In practice while the ages of stars in clusters can be derived with reasonable uncertainties, the ages of field stars cannot be measured, but only estimated using model dependent or empirical age indicators suffering from a variety of limitations (Barnes 2007). None of the used methods can be safely applied to all mass ranges and spectral types. The widely used method of isochrone fitting depends critically on the completeness and accuracy of stellar models, and poorly understood processes lead to systematic errors. The main uncertainties are due to convection, mass loss, rotation, magnetic fields. In addition the stellar parameters such as T_{eff}, gravity, metallicity, and parallaxes, must be known with sufficient accuracy. However, even in that case, the ages derived from comparison of observational quantities with isochrones are still highly uncertain, and statistical techniques are required to avoid biases. For instance in Nordström et al. (2004), in spite of the high quality parameters of the stars, including parallaxes, only about 50 % of the stars have ages derived to better than 30 %. In addition, isochrone dating is meaningful only for stars in restricted regions of the HR diagram (Soderblom 2010). Reliable ages for red giant stars cannot be derived, since isochrones with largely different ages occupy the same loci in color-magnitude diagram within the errors of the observable parameters.

A very promising method relies on asteroseismology which allows us to derive fundamental physical quantities, masses and radii otherwise inaccessible in single field stars, and which can be used to obtain information on stellar distances and ages (Chaplin and Miglio 2013). In principle, radii can be derived from scaling relations with an accuracy of about 5 % in dwarfs and subgiants, and masses can be known with accuracy better than 10 % (at least around solar metallicity). This means that consequently ages can be derived with a median uncertainty of 34 % even without including parallax information. When [Fe/H] measurements are available, then the median age uncertainty decreases to 25–30 % for the vast majority of the stars.

Finally chemical abundances can be used as proxy for (relative) ages. The abundance ratio of different elements in stars provide cosmic clocks, since different elements are released to the interstellar medium by stars of different masses and therefore on different timescales. The classical example is the ratio of α-*elements* relative to iron. α-*Elements* form in core-collapse supernovae, i.e. on a short time scale, while iron is produced mainly in SNe Ia (McWilliam 1997). Other widely used clocks include the *s*- and *r*-neutron-capture process elements (e.g. $[Ba/Eu]$) or iron-peak elements. However differences among Galactic populations are of the order of 0.1–0.2 dex, requiring high precision chemical abundance determination (Nissen 2013). In addition, this widely used clock relies on the hypothesis that the majority of the stars in a population are formed in situ or at least that they share the same chemical evolution.

2.4.3.2 Thin and Thick Disks, or the Disk?

From a theoretical point of view the thick disk formation scenario is still unclear, with theories varying from direct accretion of gas or star rich material in merger(s) (Abadi et al. 2003; Brook et al. 2005; Micali et al. 2013) to dynamical heating by merger(s) (Martig et al. 2014; Villalobos et al. 2010). Finally, thin and thick disk formation can be related to secular processed models of stellar radial migration. The scattering of stars at the corotation radius of spiral arms changes the angular momentum of the orbit, changing the mean radius without increasing the orbital random energy (Sellwood and Binney 2002). Radial migration was proposed in literature among others (Minchev et al. 2014; Roškar et al. 2013) to explain for instance the observed lack of the age-metallicity relation in the thin disk (Nordström et al. 2004), and the radial metallicity gradient. However, at present the real role of the radial migration is very unclear. Present simulations suffer from several limitations and produce only a few specific observable predictions to be compared with the data. The situation will improve when data from next generation of Milky Way surveys will be available to quantify the importance of this process.

Many observational studies have tried to characterize thick disk stars in terms of metallicity, age and kinematics, especially discussing the differences relative to the thin disk (Edvardsson et al. 1993; Feltzing and Gustafsson 1998; Fuhrmann 2011; Gratton et al. 2000; Mikolaitis et al. 2014; Ruchti et al. 2011; Soubiran et al. 2003; Vallenari et al. 2000). In the classical description, the thick disk has a narrow age range, with the typical ages in the range 8–12 Gyr, and has a mean iron abundance around [Fe/H] ~ -0.6), while the thin disk metallicity distribution peaks at [Fe/H] ~ 0 (Casagrande et al. 2011). Estimates of the scale length and scale height of the thick disk are quite variable among authors, but in general lead to a stellar mass about 10–20 % of that of the thin stellar disk (Vallenari et al. 2000). The main question still open is whether thin and thick disk represent two distinct populations having different chemical and age properties, implying that they have different origins and have experimented different chemical histories. It is really unclear what are the boundaries between thin and thick disk, i.e. how metal poor the thin disk can be and how metal rich the thick disk is.

From one side, there are some evidence that at a given metallicity the thick disk stars show higher enhancement in the α-elements than the thin disk stars, while thin disk $[\alpha/Fe]$ abundance trends show a constant slow decline (Adibekyan et al. 2012; Haywood 2006; Mikolaitis et al. 2014). These findings give strong support to the classical view of a two-phase formation of the Galactic disks, where thin and thick disks formed in different processes (Haywood et al. 2013). On the other hand, applying a new approach to SDSS SEGUE G and K dwarf stellar sample, (Bovy et al. 2012) argue that the abundance pattern of the Galactic stellar disk can be represented by a continuous function of mono-abundance populations with increasing scale-heights, and hence no distinct thick disk should be claimed. The crucial role here is played by the reconstruction of the survey selection function and of observational uncertainties, which needs to be taken into account when analyzing stellar samples. Here a completely new definition of the stellar population is emerging. The central properties in the definition of a stellar population are not anymore age, metallicity and kinematics, as used in the past decades, but only chemical abundances. The reason behind this is that in the presence of significant radial migration, *chemical abundances are the only life-long properties that stars have, which can be used to isolate sub-groups independent of presuming a particular dynamical history* (Rix and Bovy 2013). However, is this sufficient to properly define a stellar population? The issue whether thin and thick disks represent two distinct population is very complex: for instance in the solar vicinity stars with typical thick disk kinematics can be found at high metallicities, even well above solar, suggesting the existence of stars with intermediate properties. More detail can be found in the reviews by Bensby (2014) and Rix and Bovy (2013).

2.4.3.3 The Open Clusters as Disk Tracers

Open clusters (OCs) are known to belong to the disk population. They span a large range of ages (from 10 Gyr till now) providing information about the disk formation and evolution, but also about the star formation process itself. One of the key questions of the Galactic astrophysics is related to the complex interplay between clusters and field stars. It is completely unclear if all stars form in clusters and then disperse in the field, or if the field population the result of a hierarchical process taking place on different scales (Lada and Lada 2003; Portegies Zwart et al. 2010). A vivid debate is taking place to understand how disruption processes and internal evaporation of the clusters populate the field, how they influence the thin/thick disk distribution, and in general how clusters interact with the rest of the MW.

If we want to study the history of the disk, and determine its evolution with time, we need to focus on intermediate age and old open clusters (Bragaglia and Tosi 2006; Carraro et al. 1999; Donati et al. 2014a; Friel et al. 2014; Sestito et al. 2006). The main advantage of OCs in comparison of field stars is that reliable ages can be derived with higher accuracy. The radial distribution of metallicity, as derived from OCs, has traditionally been described as a gradient with a slope of about -0.05 to -0.10 dex/ kpc (Friel et al. 2002). However, the idea of a single-slope gradient from the inner Galaxy to the external regions is presently disfavored by the measured abundances of outer disk clusters which seem to run flat (Friel et al. 2010). In addition, the only two tracers covering intermediate and old ages, i.e. the OCs themselves and the planetary nebulae, give at the moment contradictory results (Stanghellini and Haywood 2010). It is evident that at present still not enough OCs have been studied in the outer disk, and more reliable constraints on the global shape of the metallicity gradient are essential to confirm (or not) the change of slope at around 11–12 kpc from the Galactic centre. In addition OCs are expected to suffer from radial mixing and migration: the knowledge of OC orbits is an important to correctly derive the Galactic disk properties such as metallicity gradients, age distribution. A significant progress in the observational definition of the radial chemical gradient is expected as outcome of the on-going and planned high resolution spectroscopic surveys and Gaia (see Chaps. 5 and 9). The presence of a bimodal gradient has important implication on the possible scenarios of galaxy formation and evolution and is expected when radial migration is taken into account (Minchev et al. 2014). Semi-analytical models predict or not the flattening in the outer disk depending on the efficiency of the enrichment processes in the inner and outer regions of the Galactic disk (Portinari and Chiosi 1999; Tosi 1988).

2.4.3.4 The Halo

The halo contributes only a few percent to the total light, but includes the oldest, and most metal-poor stars in the Galaxy providing the opportunity to unravel the accretion history of our Galaxy. Many attempts were done to discover the first generation stars (Population III stars) in the halo, discovering a few very metal

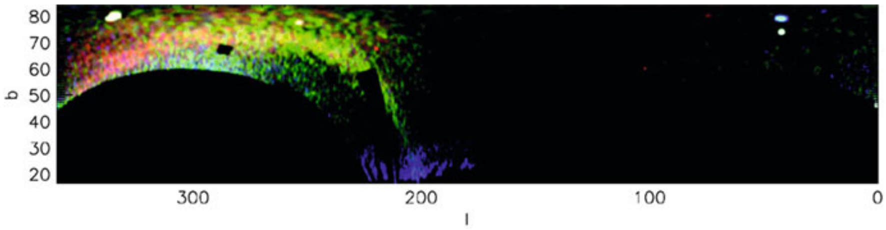

Fig. 2.6 Spatial distribution of SDSS stars around the North Galactic cap in Galactic coordinates. In addition to the Sgr stream, the monoceros ring is visible at low Galactic coordinates, and the orphan stream can be detected at b$\sim$ 50 and $180 < l < 230$. *Colors* indicate the density range in (100 stars /sq deg): *red* (102–330), *green* (107–304), *blue* (98–262). From Belokurov et al. (2006b)

poor objects (EMP) (Christlieb et al. 2008). EMPs are extremely important since they can constrain the high redshift conditions such as the initial mass function, the yields from Population III stars, the production of Li from Big Bang nucleosynthesis (Schlaufman and Casey 2014). Recently an handful of stars more metal poor than $-2.78 < [Fe/H] < -2.48$ were found in the bulge regions, where they could have been migrating from the initial location in the halo (Howes et al. 2014).

A major advance in our understanding of the halo came in 1955 when in a wide area survey of the bulge by Ibata et al. (1995) serendipitously discovered the Sagittarius dwarf spheroidal galaxy. Figure 2.6 shows spatial distribution of SDSS stars around the North Galactic cap where Sagittarius stream is visible, together with other structures (Belokurov et al. 2006b).

The existence of the Milky Way satellites falling in transformed our view of the halo and of the halo formation process, providing insight into the merging/accretion process. As a result, the past competing ideas of halo formation through monolithic collapse and through the accretion of protogalactic fragments have been largely replaced by a combination of the two scenarios within the theory of hierarchical structure formation (Freeman and Bland-Hawthorn 2002). Carollo and collaborators 2007 findings strongly supported the idea that the Galactic halo is not a single smoothly-distributed entity, but instead a superposition of many components (Carollo et al. 2007; Kinman et al. 2007), with an inner halo having distinct properties from the outer halo. However, recently different opinions are advanced in literature: taking into account the observational uncertainties and adopting a different distance scale, Schönrich et al. (2014) find that there is no strict evidence favoring a dual Galactic halo over a single halo full of streams. The situation is far from clear. In the hierarchical paradigm, streams and substructures are expected as relict of this process. After the initial discovery of the Sagittarius stream, recent studies have revealed a plethora of substructures in the Milky Way halo, many of which may be directly associated to accretion event (Kollmeier et al. 2009; Koposov et al. 2012; Newberg et al. 2002; Vivas et al. 2008). The nature of some of the known overdensities is not very clear and global asymmetries in the Galaxy can be responsible for them (Helmi 2008). These discoveries have confirmed the theoretical predictions from numerical simulations that the external stellar halo is built up from the accretion of satellite galaxies. But is really everything so clear? The number of structures found in the outer Galactic halo (galactocentric distances >15 kpc) has significantly increased in the past 10 years. However the hundreds of streams predicted by ΛCDM models of hierarchical structure formation (Bullock et al. 2001) are far from the observed numbers. This missing satellite problem is still important in our understanding of galaxy formation. In addition, recent hydrodynamic cosmological simulations find that some fraction of the inner stellar halo might be made up of stars formed in situ (Font et al. 2011; Zolotov et al. 2009). Indeed evidence of both in situ and accreted formation are detected in the local halo by Nissen and Schuster (2010, 2011). They find an high-α population consisting of stars probably formed in the inner Galaxy and then heated to halo kinematics by mergers, and a low-α population on retrograde orbits that may have been accreted at early times from satellite galaxies having lower star formation rates. Nowadays, it is completely unclear at which extent the halo is formed in situ or accreted.

2.4.3.5 The Globular Cluster Revolution

In the classical view, globular clusters (GCs) were thought to be the best example of simple stellar populations (coeval, mono-metallic systems), representing the main building blocks of the Galaxy formation. In the recent past, the unexpected discovery of multiple populations in globular clusters completely revolutionize the picture. The evidence comes from both photometric studies (Piotto 2009) and spectroscopy (Gratton et al. 2012). GC stars show large star-to-star variations in some light elements, like C, N, O, Na, Mg, and Al (Carretta et al. 2009). These variations occur also in unevolved, main-sequence stars that cannot have produced these chemical elements during their evolution. This implies that the chemical inhomogeneities were already present in the gas out of which these stars formed, i.e. GCs are made of at least two generations of stars, with the second generation formed from gas polluted by the material processed by the first. The multiple populations scenario for GCs requires that the clusters are massive enough to retain some of the primordial gas for subsequent star formation (D'Ercole et al. 2008). Details are really not completely understood, but cluster mass seems to play a determinant role in this process. Indeed multiple populations are found in massive GCs in the Magellanic Clouds, while lower mass OCs do not show any chemical inhomogeneity (Bragaglia et al. 2012; Cantat-Gaudin et al. 2014).

Present-day GCs are only a few percent of the mass of the halo. However, since they were probably more massive in the past, stars lost from the GCs might have significantly contributed to the field halo population, mainly in the inner regions (Carollo et al. 2013; Martell et al. 2011).

2.4.3.6 The Bulge

From the 1940s to the 1960s, the view of the bulge changed from a classical extremely metal poor population II similar to globular clusters to a slightly metal poor population. In the following 40 years the concept of bulge was further refined. The discussion focused on the metal content and age of the bulge as proxy of the formation process. Rich (1988) in one of the first spectroscopic study of the K giants in the Baade Window and later McWilliam and Rich (1994) find that the metallicity of the bulge is $-1 < [Fe/H] < 1$, with an average of $+0.3$, i.e. twice the solar value. The metallicity of the bulge was further explored and refined by a number of authors, but only with small sample of stars. Only in 2003, with the advent of a multiobject spectrograph at the VLT (Pasquini et al. 2003) it was possible to observe a large number of stars. Zoccali and collaborators (Zoccali et al. 2008) analysed 400 stars in the Baade Window, deriving a narrower metallicity distribution and a mean value of $[Fe/H] \sim +0.03$. In addition a sensible vertical metallicity gradient was detected at galactic latitudes higher than $b = -4$.

The general picture of old and passively evolved bulges in spirals resembling elliptical galaxies (Renzini 2006) was challenged by Kormendy et al. (2004) who notice that *some bulges are really disk* . These objects were called pseudo-bulges having in fact different characteristics than classical bulges: they are flatter, have peanut or boxy distribution, and present higher rotation velocity to velocity dispersion ratios. Since they are formed by secular evolution of the disk, via bar instability, they contain younger stars, and bars. The discussion about the nature of the Galactic bulge took place during long time. Near-infrared images of the Milky Way from COBE (Dwek et al. 1995) indeed show that when projected on the plane of the sky, the bulge appears peanut shaped, suggesting that it is indeed a pseudo-bulge. It is established that the MW hosts a bar, with the major axis in the plane of the Galaxy and inclined by 25° with respect to the $l = 0°$ direction (Gerhard 2002). One of the key parameter to ascertain the nature of our bulge, is the age of the stellar population. Classical bulges are expected to have a small age range, while pseudo-bulges formed by disk instability can present a large age spread. However, early determination of the age and of the age spread of the bulge were hampered by the stellar crowding, and by the disk star contamination (Ortolani et al. 1995). Statistical subtraction relying on a suitable disk model could not distinguish between ages of 10 and 12 Gyr. The desirable approach was a real star by star decontamination, able to tell which turnoff star is belonging to the bulge and which not. This was possible in 2002, when Kuijken and Rich derived relative proper motions from HST photometry (Kuijken and Rich 2002). The main result was that the bulk of the bulge population in the Baade Window is old, and that traces of intermediate age stars were expected just in the external regions.

The situation was rather confused, mainly because our understanding of the bulge was based on small windows. However, recently large photometric and spectroscopic surveys such as VVV (Minniti et al. 2010a), ARGOS (Freeman et al. 2013), BRAVA (Kunder et al. 2012) allow to map large areas of the bulge. It has become clear that it is impossible to consider the bulge as a single stellar population.

A growing evidence is pointing in favour of a mix population, with old metal poorer stars, and younger metal rich stars (Babusiaux 2012). Using infrared star counts of red clump stars, in a large area, McWilliam and Zoccali (2010) have revealed the existence of a bimodality in the red clump magnitude at lower Galactic latitudes which is consistent with the presence of a metal-rich boxy/peanut X-shaped component, with bar-like kinematics and an older metal poorer component (Babusiaux et al. 2010; Saito et al. 2011; Zoccali et al. 2014). Different formation scenarios are proposed in literature, namely, accretion of substructures, disk clumps or external building blocks in a CDM context (Kobayashi and Nakasato 2011). However, the properties of the bulge seem to be more consistent with a secular formation from disk material through bar formation, and instability, eventually producing a pseudo-bulge which can account for the existence of young stars (Athanassoula 2005, 2012; Ness et al. 2013, 2014). At the present stage, the presence of an additional classical bulge cannot be excluded. All the recent findings confirm that the bulge is a complex region we have not yet understood.

The dust is one of the components in the MW together with the atomic and molecular gas. Its extinction role and the serious consequences coming from neglecting this effect in the first galactic and extragalactic studies has been discussed in Chap. 1. The interview to Daniela Calzetti approaches the problem of its composition and distribution in the Galaxy.

2.5 Milky Way: The Dust Component

Questions for Daniela Calzetti:
How and when, across century, have we made progresses in mapping the dust distribution and understanding its general properties? When we start to understand where it is produced? Are the properties of the MW dust different from those observed in other galaxies?

The main effects of dust in the Milky Way and in other galaxies are to attenuate and redden astronomical sources. The attenuation is an overall dimming of the light at all wavelengths, while the reddening stems from the fact that dust preferentially dims blue wavelengths over red wavelengths. Both effects are generally present when dust is present, and are called extinction.

The stellar (or other source) energy that is absorbed by dust is re-emitted in the infrared, between $\sim$3 μm and 1–2 mm, with a peak around 60–150 μm which is due to re-radiation in thermal equilibrium regime. The thermal emission from dust, beyond 30–40 μm, cannot be observed from the ground, because of absorption by the water vapor in our atmosphere. Even the wavelength range between 3 and 30 μm, where PAHs and very small grains emit non-equilibrium radiation, only offers a few observing windows from the ground. In addition, the development of infrared detectors of quality and sensitivity sufficient for astronomical observations did not occur until the 1950s–1960s. Historically, this implies that observations of the emission from dust are fairly recent, with shallow and sparse observations done by instruments on rockets, balloons, and stratospheric flights in the 1960s and 1970s, until IRAS was launched and began the first systematic survey of the infrared sky, mapping both the Milky Way and other galaxies.

Thus, much of the earlier studies of the dust in the Milky Way were devoted to characterizing its extinction effects. Trumpler (1930a) was the first to recognize that the presence of both attenuation and reddening in stars was due to 'fine cosmic dust' concentrated in the plane of the Galaxy. Subsequent studies investigated the general properties of the extinction curve from the UV to the near-IR, and have attempted to relate these properties to the dust composition, which is likely to be dominated by carbonaceous grains and silicates (Aannestad and Purcell 1973; Savage and Mathis 1979), and to the grain size distribution (Draine 2003; Mathis et al. 1977). The general shape of the extinction curve in the Milky Way shows an increase from the near-IR to the UV, a broad 'bump' at 2175 Å, and a steepening of the raise in the UV (Fig. 2.7). The advent of the infrared observations have added more information that have helped constrain the physical and chemical composition of the dust and its grain size distribution; this includes the large molecules commonly identified as PAHs and that are responsible for the emission features in the mid-IR, between 3 and 20 µm, and extend the range of grain sizes from a few tens of Å to a few tenths of a µm (Desert et al. 1990; Draine 2003; Tielens 2008).

Even within our own Milky Way, there are large variations in the extinction curves observed along different lines of sight (Cardelli et al. 1989; Fig. 2.7), including more or less steep raises towards the UV, stronger or weaker features at 2175 Å, and higher or lower total-to-selective extinction R_V=A_V/E(B-V). Much of this variation has been linked to different physical conditions for the dust grains, which can lead to physical and chemical changes: for instance, in dense clouds dust grains can accrete ice mantles that increase the total opacity, while depressing the UV raise. However, in the diffuse interstellar medium, the characteristics of the extinction curve remain fairly constant from sightline to sightline (Draine 2003).

Studies of the effects of interstellar extinction on the colors of stars have provided the first rough maps of the distribution of the line-of-sight dust in the Milky Way (Fitzgerald 1968). These started to be subsequently replaced by maps of the atomic gas distribution (Burstein and Heiles 1982; Heiles and Jenkins 1976), since gas and dust are spatially correlated (Bohlin et al. 1978). Maps of the gas distribution, both atomic and molecular, still provide the best 3D representation of the dust distribution, as these maps also contain information on the distance of the gas along the line of sight via the Doppler shift. However, the most detailed maps of the *projected* dust distribution for the entire Milky Way have been produced by the infrared space missions, starting with IRAS, and progressing with COBE, WMAP (the Wilkinson Microwave Anisotropy Probe), and the Planck Telescope; a host of selected regions have been also imaged by Spitzer and Herschel. Recently, detailed maps of the line-of-sight extinction have been obtained using the homogeneously distributed distant quasars as 'background lights' (Wolf 2014).

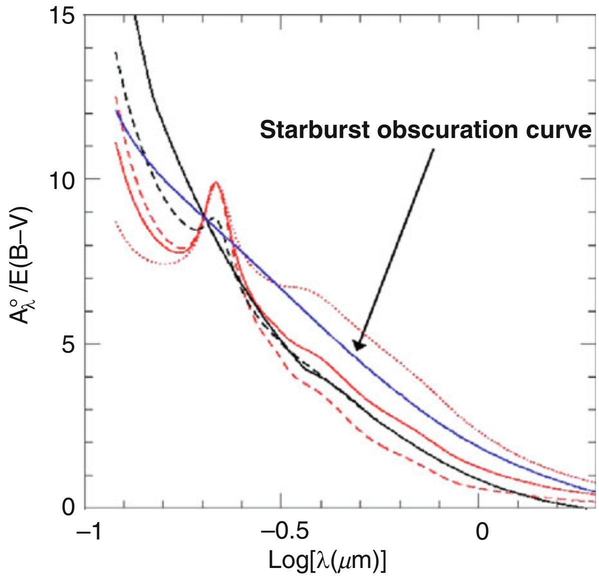

Fig. 2.7 Extinction curves for the Milky Way (*red lines*) and for the Magellanic Clouds (*black lines*) are shown together with the obscuration (also called attenuation) curve for starburst galaxies of Calzetti et al. (2000). The curves are used to recover the intrinsic luminosity of a source I_o from its observed luminosity I_{obs} via the relation: $I_o = I_{obs}\ 10^{0.4k(\lambda)E(B-V)}$, where $k(\lambda) = A^o_\lambda/E(B\text{-}V)$ is the extinction (or attenuation) curve and E(B-V) is the color excess, which is related to the amount of dust between the source and the observer (or an effective amount, in the case of obscuration). The three Milky Way extinction curves represent different environments: diffuse interstellar medium (*solid red*), dense clouds (*dotted red*), and low density regions (*dash red*), using the parametrization of Fitzpatrick (1999). The three Milky Way curves all show the 2175 Å 'bump' and a steep UV rise; however, the strength of the bump is larger and the UV raise less steep in denser environments. The Large Magellanic Cloud (*dash black*) and Small Magellanic Cloud (*solid black*) mean extinction curves are steeper in the UV than the mean extinction in the Milky Way, and show weaker or no 2175 Å bump. The starburst obscuration curve (*blue solid*) should not be confused with an extinction curve, although it is shown here for comparison

Despite the significant progress in characterizing the properties of the interstellar dust, where and how it forms is still matter of debate. In a generally accepted scenario, AGB stars are considered major contributors of carbonaceous interstellar dust, which is ejected into the surrounding medium during the mass-loss phase, while Type II supernovae tend to contribute mainly silicate dust (Dwek 2005), although more recent theories expect also carbon dust out of supernovae. The formation of ices in the interstellar medium was recognized already in the late 1930s, but it wasn't until the late 1950s that the idea of dust formation (especially carbon dust) in the atmospheres of stars was formulated. Later, Field (1974) showed that the depletion patterns of heavy elements were consistent with grain condensation in cool stellar atmospheres. An excellent timeline of this evolution can be found in the review of Li and Greenberg (2003). One important challenge to any formation scenario is the relatively high destruction rate of dust in the rather hostile interstellar environment, which is energized by shocks from supernova explosions, massive star winds and cloud–cloud collisions. Dust grains may be expected to survive for $\sim 10^7$–10^8 yrs, while their formation through the standard processes requires $\sim 10^9$ yrs (Jones 2001). Thus, a non-negligible fraction of the dust must be forming in-situ in the ISM, and this formation process is far more important than the simple coagulation of ice mantles on pre-existing dust grains (Draine 2009). Overall, the formation of interstellar dust is still an open and urgent question to address.

If some of the important characteristics of the dust in the Milky Way are still poorly known, things are even worse for external galaxies. In order to appreciate the complications of measuring dust extinction in external galaxies, it is enough to recall that extinction curves are generally derived with the 'pair' method, i.e., by comparing similar stars (as determined from spectroscopy), but with different amount of extinction along their lines of sight. The main difficulty in the case of external galaxies is to identify single, isolated stars (free of companions, neighbors, circum-stellar envelopes, etc.) to be paired for the extinction curve derivation. The high angular resolution of the HST has helped increase the samples of stars that had been originally collected with the `IUE` for the Magellanic Clouds, and confirm the differences between the MW, the LMC, and the SMC extinction curves. For instance, the SMC curve is characterized by a general absence of the 2175 Å bump and by a very steep UV rise, much larger than the UV raise of the MW, while the LMC curve lies in-between the SMC and MW ones (Gordon et al. 2003; Fig. 2.7). Whether the differences between the three galaxies are mainly due to variations in metal content or variations in the hardness of the local radiation field (Gordon et al. 2003), or a combination of the two, is still unclear. Andromeda, the 'twin' galaxy to the Milky Way, has similar dust properties and composition to our own Galaxy (Draine et al. 2014b), and shows, tentatively, also a similar extinction curve (Bianchi et al. 1996).

Several studies have attempted to extend the determinations of extinction curves to high-redshift galaxies, using quasars and/or gamma ray bursts as point-like sources to provide the lighting for the host galaxies. Results so far indicate that the extinction curves appear similar to that of the SMC, with a steep raise and a general lack of the 2175 Å bump, both at redshift ≈ 2 (Hopkins et al. 2004) and at redshift $z>4$ (Gallerani et al. 2010). There are at least two inherent difficulties in these studies: (1) they need to assume a specific shape for the SED of the quasar, and (2) the energetic environment surrounding quasars (and GRBs) may have processed the dust, thus changing the extinction curves.

Other attempts at deriving the extinction curve(s) in galaxies at redshifts ~ 1–2 have been relying upon fitting the galaxy SED, measured from multi-wavelength photometry, with models, and trying to disentangle the extinction curve from the dust geometry and the star formation history (SFH) of the galaxy. Different authors have obtained different results, some supporting an SMC—like extinction and some other an LMC—like extinction curve; while these differences may be real, the existence of a degeneracy between extinction, geometry, and SFH, coupled with often sparse sampling in wavelength and wavelength range, makes the interpretation of these results difficult.

The above contribution introduces the dust properties of Andromeda, SMC and LMC, companions of the MW. The science proceeds for comparisons. These galaxies are members of the Local Group, the environment of the MW is treated in Sects. 2.7 and 2.8. At the root of the determination of the galaxy environments there is the measure of a galaxy distance. Actually, only when the distance has been estimated, galaxy properties, acquire their full physical significance since comparison between galaxies is made possible. The problem of the evaluation of the galaxy distance, i.e. the selection and calibration of the more reliable distance indicators, has been at the basis a long debate. We asked to Barry Madore to review the historical and present problems as well as future solutions connected the determination of a galaxy distance.

2.6 Beyond the Milky Way

2.6.1 The Distance Scale Debate

Questions for Barry F. Madore:
The past century has seen several decades of a heated discussion about the build of the distance scale and the value of H_0.

Could you review the different scientific positions and comment the origin of the debated discrepancies?

Decoupling the discussion of the determination of distances to individual galaxies from a discussion of the calibration of the extragalactic distance scale, in general, and determining the numerical value of the Hubble constant, in specific, is problematic. Historically, conceptually, procedurally and technically the two problems are intertwined, hard to disentangle, and easily confused. Different challenges present themselves at progressively increasing distances. Many problems get worse with distance, but surprisingly some complications actually diminish with as we work ourselves further into the general systematic expansion of the Universe.

To illustrate the problem, suppose that we knew, to arbitrary precision and accuracy, what the value of the Hubble constant was. That is, we would know the expansion rate of the Universe at every point in space, where we could then use the easily-observed recession velocity (if it is assumed to be solely due to the cosmic expansion) to predict the distance to the object in question. After all the expansion velocity is simply the product of the Hubble constant times the distance. Knowing H_0 and the "recession velocity" automatically gives you the distance. This naive view of cosmology immediately fails in the nearby Universe, in a catastrophic way. For example, M 31, the Andromeda galaxy, the nearest sizable neighboring galaxy to our own Milky Way, has a radial velocity that is not "recessional" at all; it is negative. Even after being corrected for the motion of the Sun about the galactic center the residual, relative motion of M31 is towards the Milky (not away from it) at a closing velocity of $-122\,\mathrm{km\ s^{-1}}$. M31 and the Milky Way are falling towards each other, not expanding away, as would be the case if their motions were dominated by cosmology.

The lesson learned is that galaxies have three-dimensional components of their space velocities that are largely independent of cosmology to the degree that they are in addition to, and in some cases far larger than the cosmological expansion term. Indeed, nearby those "peculiar" motions may totally overwhelm any expansion terms. Locally the simple route to "distances from velocities" is ruled out. What can be done?

Here we are immediately confronted with the problems imposed by the enormous distances separating galaxies, making individual sources of light within them (mostly stars in our distance-related exercise) extremely faint, hard to detect, even harder to accurately measure, and often very crowded and confused by the myriads of other stars along the same line of sight through their parent galaxy. Indeed, had the nearest galaxies to our own Milky Way been ten times further away than they are, say, (that is 100 times fainter and 100 times as crowded) then it is probable that Edwin Hubble's program that detected and measured Cepheid variable stars in M 31 and other Local Group galaxies would have failed and we would have had to have waited another half-century or more for the same experiment to be run from space.

The impressive demonstration that stars familiar to observers of the Milky Way (the prototypical case being Cepheid variables discovered by Hubble in NGC 6822, M31, M33) could be found in nearby galaxies opened the door to distance determinations to specific types of galaxies (i.e., those that contain Cepheids); but it was not to be an easy opening and many complications, corrections and limitations still stood in the way of the application of any given distance indicator to extragalactic astronomy. A comprehensive overview of distance determinations in astronomy is given in a recent monograph by de Grijs (De Grijs 2011).

Alas, "*Desperate times call for desperate measures*" as the saying goes. And the earliest times for the determination of distances to nearby galaxies, especially in the race to determine the Hubble constant (and continuing to this day), resulted in a lot of desperate "measures". The NASA/IPAC Extragalactic Database (NED) has, without prejudice, been compiling distances measured to galaxies for about a decade now. In NED there are now over 60 different and identifiably unique methods of extragalactic distance determinations.[2] Most of these indicators rely on the inverse square law for light dimming with distance, tied to the hope or various levels of demonstration that these indicators are, by some means or another, standard candles (or even "standardizable" candles) with or without there necessarily being any theoretical understanding of the physical basis of these attributes of luminosity. The luminosities of Cepheids and RR Lyrae variables are fairly well understood

[2] http://ned.ipac.caltech.edu/Library/Distances/.

theoretically; the constancy of carbon stars luminosities and gamma-ray bursts are not. There are also so-called “standard rulers”. Using HII region diameters as standard rulers to gauge distances was pure fantasy; on the other hand, using masers orbiting nuclear black holes has proven to be extremely powerful. Having all of these methods available does not, of course, mean that they are all equally precise, or that they have been equally well calibrated. They all suffer from various systematics and they each have their own restricted ranges of application, be that a restriction on distance or a restriction on the type of galaxy that can or does host this type of indicator. As powerful as certain types of supernovae may be they impose their own special problems on determining distances to galaxies simply because one cannot go out and dial up a supernova in any given galaxy of interest. They occur when they occur; and you are lucky if someone notices and even luckier of others follow the supernova up with the necessary multiple observations over weeks and months before it disappears forever.

Of all of the non-explosive, stellar distance indicators, three stand out as particularly robust when it comes to determining distances to individual nearby (i.e., appropriately resolved) galaxies. Those three are the Classical (Population I) Cepheids, the (Population II) RR Lyrae variables, and the (Population II) tip of the red giant branch (TRGB) stars. These distance indicators really have no equals in the thirty or more other “standard candles” put forward over the years and as currently listed in NED. These three distance indicators however are sufficiently promising and well understood that they are worth discussing individually and in comparison with each other.

2.6.2 Primary Indicators

2.6.2.1 Cepheids

The Classical Cepheids are periodic variable stars whose charcteristic light-curve shapes in the optical (rapidly rising, by a factor of two or more in luminosity, and more slowly declining in the optical) make them easy to discover, to be relatively unambiguously classified, and have their periods determined. They are known to be brighter at longer periods. This Period-Luminosity relation (know as the Leavitt Law for Classical Cepheids) becomes progressively steeper at longer wavelengths, but more importantly it is also progressively more well defined (i.e., it has a smaller intrinsic dispersion) at longer and longer wavelengths (see Fig. 2.8 for the mid-infrared Cepheid Period-Luminosity relation). This decrease in the width of the period-luminosity relation has the same physical explanation as does the decrease in the observed luminosity width of the instability strip and the observed decrease in the amplitudes of individual Cepheids as a function of increased observing wavelength. That reason is the decreased sensitivity of surface brightness to temperature variations as a function of increasing wavelength of the emitted radiation. The same intrinsic temperature variations contribute to larger surface

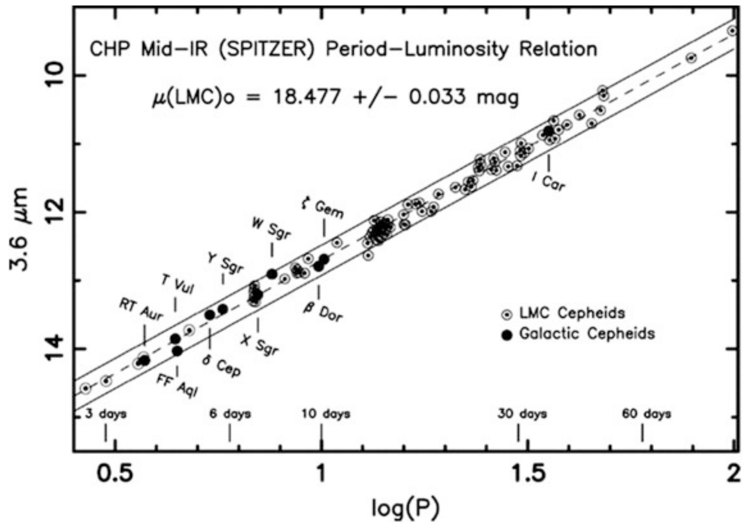

Fig. 2.8 The mid-infrared (3.6 μm) Period-Luminosity relation for Galactic Cepheids with independently determined trigonometric parallaxes (*filled circles*) overplotted on the PL relation for LMC Cepheids (*circled dots*) shifted to an apparent distance modulus of 18.477 mag. The total scatter in this PL relation is only ±0.1 mag (Freedman et al. 2012)

brightness variations in the optical that they do in the red and infrared portions of the spectrum. As a result cyclical variations in temperature for a given star result in smaller amplitudes in the infrared as compared to the optical, and the same temperature width across the instability strip and from the bright side to the faint side of the PL relation itself, results in a smaller luminosity difference (i.e. a smaller intrinsic dispersion) for stars of the same period. In the long-wavelength limit the small radius differences during a pulsation cycle or across the instability strip are the dominant contributors to the amplitude of the cyclical light variation and/or to the width/scatter in the observed PL relation. Find Cepheids in the optical where their amplitudes are largest. Measure their mean luminosities in the near or mid-infrared where their amplitudes are smallest and the dispersion in their PL relations are minimized.

Comprehensive reviews of Cepheids as distance indicators can be found in Freedman and Madore (2013); Madore and Freedman (1998). The advantages of moving to the infrared were all laid down, listed and explained in an early paper by McGonegal et al. (1982).

2.6.2.2 RR Lyrae Variables

The RR Lyrae variable are found in the hotter and fainter extension of the same instability strip that powers the Cepheids. The main difference are however that the stars populating this strip are highly evolved Population II stars of relative low mass and distinctly lower metallicity than their high-mass, high-metallicity Pop I Cepheid cousins. Confined to a narrow region in mass and evolutionary stage, the RR Lyrae variables are part of the horizontal branch population of stars after having evolved off of the red giant branch, presumably losing mass, and finally settling down onto the core helium-burning main sequence.

Because of the historical circumstance of plotting color-magnitude diagrams of globular cluster with the V magnitude as the bandpass of choice for the apparent luminosity the helium-burning main sequence is projected into the color-magnitude plane as a relatively narrow sequence that is almost constant in luminosity as a function of color resulting in that feature being called the "horizontal" branch. The fact that the horizontal branch is extended in color means that if any other bandpass is used to describe the luminosity then the very same helium-burning main sequence will not and cannot be "horizontal". This unfortunate historical accident had downstream consequences for the characterization of RR Lyrae variables. Specifically, while it was readily admitted that RR Lyrae variables showed a trend of color with period, the existence of a period-luminosity relation was denied because in the V band there was no trend of luminosity with period because those stars were "on the horizontal branch" and therefore had no range in luminosity to correlate with period. However, plotting any other bandpass would have revealed a PL relation. In fact, the existence of a period-color relation demands it. Nevertheless it was not until observers independently examined the properties of RR Lyrae variables in the infrared did the PL relation reveal itself. Nevertheless this revelation remained largely unmentioned and certainly under used for decades. It is purely a coincidence that plotting the V magnitudes of RR Lyrae variables versus period give no correlation, but it is still true that these stars nevertheless obey a PL relation, but the trend of that particular relation at that one wavelength is flat, the numerical value of the slope is zero.

Given that stellar evolution and the physics of the helium-burning main sequence confine their stars to a narrow region in the color-magnitude diagram and given the instability strip only intersects an even smaller sampling of the horizontal branch itself it comes to pass that RR Lyrae variables show small scatter in luminosity about their respective PL relations at all wavelengths but with ever decreasing dispersion as one moves to the red and infrared (see Fig. 2.9). For example, the dispersion in the K-band ($2.2\,\mu$m) PL relation may be as small as ± 0.03 mag.

The down side of using RR Lyrae variables for the determination of distances to individual galaxies is that they are the faintest of the three primary distance indicators that we are discussing here. From the ground, and then more impressively from space, using `HST`, RR Lyrae variables have been found in all of the Local Group galaxies in which searches have been undertaken. The method however reaches its limit at about 1 Mpc beyobd which the apparent magnitudes are too faint to be usefully measured by `HST` with its limited aperture and resolving power. However, RR Lyrae variables (unlike Cepheids) can in principle be found and used in any galaxies that has a Population II component that is rich enough and metal-

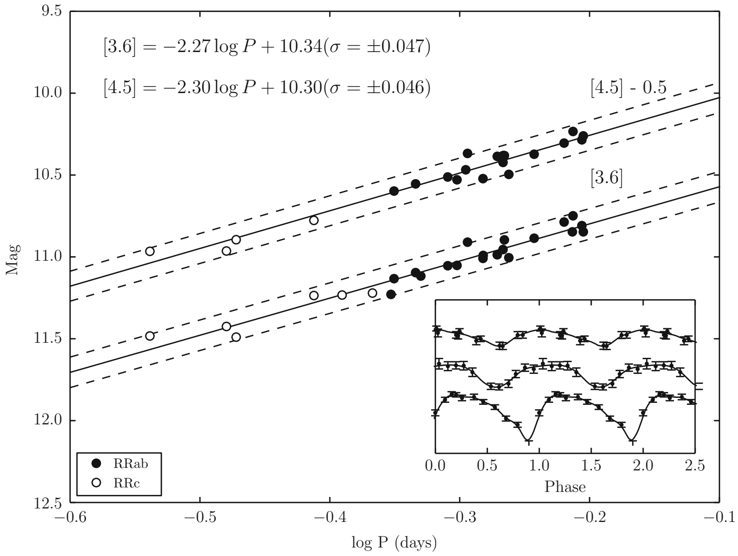

Fig. 2.9 An example of the small dispersion found in the infrared Period-Luminosity relations for RR Lyrae variables. In this case the data are for RR Lyrae variables in the Milky Way globular cluster M4. The observations were made at 3.6 and 4.5 μm using the Spitzer Space Telescope, and the observed scatter about the PL relation is less than ±0.05 mag in both cases

poor enough to form and populate a horizontal branch that crosses the Population II instability strip.

The monograph by Smith (2004) is certainly the best introduction to RR Lyrae variables available to date.

2.6.2.3 Tip of the Red Giant Branch Stars: The TRGB Method

The immediate progenitors to the RR Lyrae variables, are the stars at the tip of the red giant branch. The hydrogen-shell-burning stars have electron-degenerate helium cores and are completing that phase of their evolution up to and including the point at which as they undergo helium core ignition. This is followed by varying degrees of mass loss, after which they then eventually settle down on the helium-core-burning main sequence, discussed above. The rapid transition from shell to core helium burning rips stars from the giant branch and scatters them along the horizontal branch. The net effect is that there is a very sharp discontinuity in the RGB luminosity function that is distinctive and very easily measured (see Fig. 2.10). This "tip" magnitude of the ascending red giant branch is one of the best available stellar-based distance indicators. It is reasonably bright, being four magnitudes brighter than the RR Lyrae variables scattered along the horizontal branch, and it is comparable in brightness to a 5-day Classical Cepheid, both

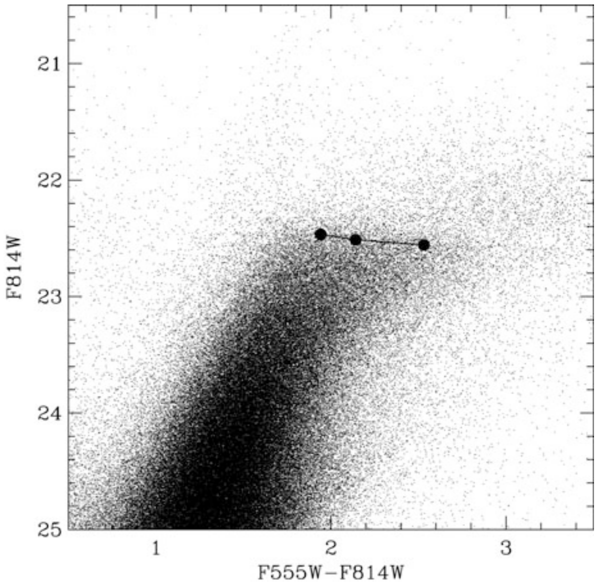

Fig. 2.10 The tip of the red giant branch in the nearby galaxy NGC 300 is clearly defined in this I vs (V-I) color-magnitude diagram for Population II stars in the halo of this galaxy. The very slight dependence of the tip magnitude on color (as delineated by the *line* between the *filled circles*) is due to the residual dependence of the I-band magnitude on metallicity, see Rizzi et al. (2007)

having $M_I = -4.0$ mag. But it is, admittedly, not as bright as the longer-period Cepheids falling in the 10–60 days range (which are typically used in extragalactic distance determinations) whose absolute magnitudes fall in the range $M_I = -4.9$ to -7.3 mag.

Da Costa and Armandroff (1990) were the first to demonstrate the constancy of the TRGB magnitude as a potential distance indicator. Lee et al. (1993) quantified the procedure and began applying the technique to extragalactic objects. Rizzi et al. (2007) give an up-to-date calibration of the method, updated by Mager et al. (2008) to fully account for metallicity variations.

2.6.2.4 Advantages, Disadvantages and Caveats

Of the three most trustworthy methods (discussed above) for determining distances to nearby galaxies the Cepheids, being the intrinsically brightest, have the furthest reach, with the RR Lyrae variables being the most restricted in the distances out to which they can be seen.

Line-of-sight reddening and extinction is a systematic effect that must be accounted for in all distance determination methods that use luminosity calibrations and the inverse-square law for the primary dimming of the measured light. The great advantage of going to Population II distance indicators such as the TRGB and the RR Lyrae variables is that they are to be found in the halos of galaxies which are generally gas and dust free. In those cases the only correction for extinction would be that due to foreground (Milky Way) extinction, for which all-sky catalogs (based on neutral hydrogen surveys and/or far-infrared dust maps) are available. Cepheids, on the other hand, are young, high-mass, Population I objects that have B stars as their progenitors and so they are, by their very nature, still embedded in the gas-rich (and dusty) regions of star formation in spiral and irregular galaxies. Every line of sight to each and every Cepheid will have a different amount of reddening and extinction. Two solutions suggest themselves: (1) Multi-color observations that allow for a direct fitting of an adopted dust extinction law, (2) Two-bandpass methods that judiciously combine colors and magnitudes to form Wesenheit magnitudes that are, by construction, independent of interstellar reddening (once a reddening law is adopted, which all methods for correcting for extinction must also do) and (3) moving as far into the infrared so as to minimize the effects of reddening. The latter does not solve the problem totally, but by going to mid-infrared wavelengths where the magnitude of the extinction correction is decreased by more an order of magnitude has its appeal.

Both Cepheids and RR Lyrae are variable stars and therefore, quite obvious, require multiple observations spread over time for their discovery, determination of individual periods, amplitudes, colors and mean magnitudes before their extinction-corrected distances can be derived. Cepheids require observing windows that are on the order of 100 or more in length; the RR Lyrae variables can be observed going through one or more complete cycles in just 1 day. Ten or more observations are required to secure the mean magnitudes for these stars that have amplitudes in excess of one magnitude and asymmetrical light curves that need to be delineated and averaged over. The TRGB stars however are not generally variable and so, despite their being fainter than Cepheids, their color-magnitude diagram need only be observed once in order to secure their distance.

After correcting for reddening the need to deal with the impact metallicity differences on each of these distance indicators is the next major systematic uncertainty. For Cepheids, theory has been unhelpful even to the degree that it is uncertain of the sign of the effect. Observations clearly show that the line blanketing due to varying amounts of metals in Cepheid atmospheres are detectable at short wavelengths but it is still being debated as to how much of an effect persists at longer/redder, infrared and mid-infrared wavelengths, or for that matter how much of the effect is parallel to the intrinsic reddening trajectory and thereof pre (coincidentally) cancels out when extinction effects are accounted for. This is still an active area of research and debate, where working in the infrared still holds a great deal of allure.

For the RR Lyrae variables a direct test for metallicity effects on their luminosities can be made, and, if needed, a calibration can be derived. The globular cluster Omega Centauri is both very rich in RR Lyrae variables and it is well know to exhibit a wide range of metallicities in its stellar populations. This metallicity spread manifests itself in the color width and luminosity structure of its red giant branch, which, in turn, feeds stars onto the horizontal branch, where we find the RR Lyrae variables. So within a single system at a fixed distance we can observe directly the effects of a metallicity spread on the apparent magnitudes of individual RR Lyrae variables at fixed period, say. Preliminary observations suggest that the metallicity effect (especially at the longer wavelengths) is small but those results preliminary and the studies are still on-going.

For the tip of the red giant branch, it is very well understood that the bolometric magnitude of the tip is extremely insensitive to metallicity and even age of the host population of red giant stars. The bolometric corrections required to map these total luminosities into observed bands are however affected by atmospheric line blanketting and therefore metallicity. Again, globular clusters, individually and as a class, provide us with the opportunity to observe and calibrate the effects of metallicity on the TRGB magnitude (and color). The wavelength-dependent effect of line blanketing on the ascending part of the red giant branch is such that at shorter wavelengths the stars are dimmed and differentially made redder than they are at longer wavelengths. But moreover, because the radiation must eventually escape at some wavelength the thermalization of the line-blanketed radiation eventually reappears at longer wavelengths (where there are coincidentally fewer line metallic line transitions) such that the stars then become more luminous that their unblanketed atmospheres would otherwise predict. Clearly there will be a transition bandpass that is neither brightened nor dimmed by metallicity. This circumstance happens to occur just short of one micron around the wavelength of the I-band filter, where it was indeed discovered that the TRGB is largely constant and only very slightly dependent on metallicity. And even that slight residual dependence has been measured and calibrated out (see Fig. 2.10).

2.6.2.5 Crowding and Confusion

Finally, it has to be mentioned that there is yet another factor that can seriously compromise the application of these three stellar distance indicators. That factor is crowding. The background population of stars that inevitably accompany any one of these distance indicators acts as an additional form of "sky"İ noise when it is not resolved, but for all stars of comparable brightness or greater than our distance indicators they can become damaging. This is especially true of the RR Lyrae variables which will be surrounded by at least 4 mag of brighter red giant stars and a host of non-variable horizontal branch stars of comparable brightness. In very dense (high-surface-brightness) regions TRGB stars themselves will be in danger of self-crowding, leading to a systematic brightening of the tip. However steps can be taken to mitigate these effects by targeting regions of low surface brightness, which are always available for pure halo populations.

For Cepheids the options are less clear. These young stars are always closely associated with their progenitor B stars in spiral arms and associations. And this is especially true for the longest-period Cepheids that are most commonly used for distance determinations, because they are the brightest; however, that also makes them the youngest and therefore the least likely to be separated from their crowded birth sites. It was once thought that an added advantage of going to the infrared would be to heighten the contrast between the cooler Cepheids and their hotter neighboring B stars thereby making crowding less of an issue. But what was not readily appreciated at the time is that there is an entirely new population of very bright red stars that dominate the crowding equation by the time one reaches the near infrared and are overwhelming in the mid-infrared. These dust-enshrouded , intermediate-aged, asymptotic giant branch (AGB) stars are ubiquitous throughout the disks of nearby spirals and they do severely compromise the photometry of even already-known Cepheids in those regions. catastrophic effect of these stars can be seen all of the PL relations derived from H-band (1.6 μm) photometry made using HST beyond its crowding/resolution limit (Riess et al. 2009). Despite a valiant effort to clean the data it is clear that the photometry is crowding dominated in as much as the observed PL relations have widths of at least 1.5 mag, which should be compared to the well-measured intrinsic dispersion of only ± 0.12 mag at 1.6 μm for the calibrating Cepheids in the uncrowded regions of the Large Magellanic Cloud (e.g., Persson et al. 2004) Indeed, this crowding effect is already dominant in the photometry of the Cepheids in the maser galaxy NGC 4258, but nevertheless it is still being used by some as an anchor for the calibration of the extragalactic distance scale. Moving this far into the infrared so as to avoid reddening issues may be premature given the significant crowding and confusion limits imposed on the photometry obtained by using a telescope in a domain beyond it reach. The systematic errors potentially embedded in that enormous scatter are still to be fully appreciated and quantified.

2.6.3 Secondary Distance Indicators

Moving beyond the reach of the TRGB and then not too much further and out of the reach of the Cepheids we enter a zone that can only be probed sparsely and even then with great imprecision by so-called "secondary distance indicators". These include the Tully-Fisher relation, the Faber-Jackson relations and various flavors of and/or projections of the "fundamental plane" of galaxies. Each of them attempts to use some kinematic measure of the host galaxy (its maximum rotation rate or central velocity dispersion, etc.) to predict the luminosity (within some appropriately chosen radius), which is implicitly linked to the total mass of the system (baryonic and dark) which control the measured velocities through a mass-to-light ratio of some deep cosmic significance.

2.6.3.1 The Tully-Fisher Relation

For Tully-Fisher the scatter is significant in the optical and seems to be irreducible below a value of $+/-0.5$ mag even in the near to mid-infrared wavelengths (Sorce et al. 2013), with or without color corrections or other attempts to significantly reduce the scatter. Cosmic variations in the relative contribution of dark to baryonic matter, variations in the mix of stellar populations (and their varying contributions to the light at various wavelengths), the presence of warps and non-axisymmetric perturbations on the radii and derived axial ratios and ultimately on the derived inclinations (kinematic or photometric) all seem to be conspiring to keeping the intrinsic dispersion of this method at the 25 % level.

2.6.3.2 Type Ia Supernovæ

Type Ia supernovae are not standard candles, but they are amazingly standardizable candles. The (Phillips 1993) relation between peak absolute magnitude and a characteristic decay time of the supernova light curve appears to provide a distance indicator having a scatter (at the longer wavelengths) of less than ± 0.1 mag (e.g., Freedman et al. 2009). Combined with the fact that these events reach an absolute magnitude of -19 mag means that Type Ia SNe have the greatest cosmological reach of any of the distance indicators so far discussed.

Despite their enormous appeal, Type Ia SNe have a few outstanding issues that should give one pause before declaring victory in unambiguously having obtained precision distances to host galaxies and/or establishing an accurate distance scale out to cosmologically significant distances. The first issue centers around "reddening". This is not just a matter of accounting for normal interstellar extinction in our Milky Way and then again in the line of sight penetrating the host galaxy, but also accounting for the possibility of anomalous dust in the immediate vicinity of the supernova event, strange radiative transfer effects in the expanding nebula itself and/or intrinsic color variations of the exploding star's rapidly expanding "atmosphere" which manifest themselves in a way that might be misinterpreted as being due to the effects of dust. The second point of concern is the possibility that there are two or more astrophysically distinct input channels apparently qualitatively similar phenomena.

Reason to suspect that there are two types of Type Ia SNe comes from the observed differences in the peak magnitudes of these supernovae arising in star-forming (gas-rich spiral and irregular) galaxies as compared to supernovae being found in gas-poor, elliptical and S0 galaxies. We might then speculate that there is a preferred channel for the production of prompt Type Ia SNe in star forming (Population I) galaxies and then another much more delayed, independent channel in the old, metal-poor, Population II dominated galaxies. If this is indeed true the situation is not hopeless, but it would at first blush at least, require two independent calibrations, and informed applications to distant events where the host galaxy type will be a necessary part of the process of determining the distance.

As powerful as Type Ia SNe are for cosmological applications they do have one... It cannot be predicted when and if a supernova event will take place in any given galaxy. Nor can the same supernova event be re-observed should new calibrations require different wavelengths or novel spectral data. Type Ia SNe simply cannot be ordered up for any given galaxy. And finally these events are still rare enough that obtaining a sufficient sample of them in very nearby galaxies, where primary distances can be or already have been obtained, is an unlikely event. Setting the zero point (or zero points, it there are indeed several flavors) of the absolute magnitude scale(s) for Type Ia SNe will remain in play for some years to come. All of that said, our theoretical understanding of Type Ia SNe is still in its formative stages, given that we really have no conclusive evidence for what the progenitors of these events are, let alone a comprehensive theory for their genesis and explosive evolution.

Next Sections will snapshot the galaxy populations in the Local Group. The variety of members both in luminosity and in morphology witnesses the complexity of the history and the evolution of the more nearby society of galaxies. We ask Valentina Karachentseva to provide a portrait of the Local Group across one century.

2.7 The Companions of the Milky Way: The Local Group

Questions for Valentina Karachentseva:
may you mention the main methodological steps in the determination of galaxy membership to the LG across the century?

In general, in order to determine that a certain galaxy belongs to the Local Group (LG) one needs to: (1) Detect an object by its brightness excess over the surrounding background: either the object as a whole, or by the contrast of its stellar density (number), and to estimate the apparent magnitude; (2) Determine the distance to it; (3) Measure its radial velocity by individual stars or globular clusters or observations in the neutral hydrogen HI 21 cm line. The knowledge of the distance and radial velocity of the objects is necessary to find the boundaries of the LG. Throughout the century, these problems are solved with the observational tools available at the moment: telescopes, photometric and spectral equipment and computer software.

It's hard to say exactly when the notion of the LG was formulated. Let us take as a starting point the list of the confirmed (although by the undervalued absolute distance scale) 13 members of the Local Group, compiled by Baade and Hubble (1939). According to W. Baade, the LG consists of galaxies, long-known from the Messier (1781) and Dreyer (1888a,b) catalogs: our Galaxy (=Milky Way), Andromeda (=M31, NGC 224), LMC, M33 (=NGC 598), SMC, M32 (=NGC 221), NGC 205, NGC 6822, IC 1613, NGC 185, NGC 147 and diluted stellar systems without gas and dust in the Sculptor and Fornax constellations, discovered by Harlow Shapley in 1938. The Sculptor and Fornax objects became the prototypes of the dwarf spheroidal galaxies of low and extremely low surface brightness, dSph. By numbers they dominate in the LG—their fraction among the dwarf galaxies exceeds 80 %.

Determination of the distance modulus is based on the knowledge of the apparent and adopted absolute magnitude of the resolved stars in the galaxy. The primary indicators of the distances are the short-period RRLyr and long-period Cepheids (period-luminosity dependence, PL). Apart from these, the Novæ, the brightest stars, as well as the position of the star at the level of the horizontal branch (HB) and fitting it with the main sequence are used. During the past 20 years, the main distance indicator in the Local Group is the estimate the apparent magnitude at the tip of the red giant branch (TRGB) on the "color-magnitude" dependence. The method has a clear physical reasoning, based on the reliable determination of the luminosity of red giants (Lee et al. 1993) and is applicable to virtually any type of galaxy (see the contribution of Barry Madore in Sect. 2.6.2.3). However, the Cepheids as distance indicators have not lost their importance. It was shown by comparison calibration of the Cepheid and red giant methods, made under the HST Key Project (Sakai et al. 2000).

Radial velocities of nearby galaxies are not suitable for their distance estimates using the Hubble law because of the peculiar motions in the Local Group. However, the knowledge of radial velocities is necessary for establishing the physical boundaries of the LG, i.e. the "zero velocity sphere radius", R_0 (Sandage 1986), which separates the group volume from the remaining surrounding medium that participates in the cosmological expansion. According to Karachentsev et al. (2013), the value of R_0 for the LG is (0.98 ± 0.03) Mpc.

What have been the instruments that mainly contributed to the modern view?

Until about 1960s the main sources of information about the LG galaxies were: the 100-in. telescope of the Mt Wilson observatory, the 120-in. reflector of the Lick observatory, and the 200-in. telescope of the Mt Palomar observatory. Using these telescopes the main discoveries have been done:the Cepheids; the stellar population of the II (old) and I (young) types; the nearest known galaxies of the LG were resolved into stars (100", 120", 200"—E. Hubble, W.Baade, H. Swope, P. Hodge); the distances modules of the galaxies and their most important structural parameters were determined.

The 48" Schmidt telescope of the Mt Palomar observatory was used to provide the all-sky photographic surveys: the first and second Palomar Observatory Sky Surveys. The POSS-I has visually detected spheroidal dwarfs in LG—Leo I, Leo II, U Minor, Draco, LGS-3, And I-III, and in the POSS-II, And V, Pegasus dSph (And VI) and Cassiopea dSph (And VII) were discovered. At the analogous 48" Schmidt telescope, mounted in the southern hemisphere, the ESO/SERC Quick Survey was done and the Phoenix dIr/dSph object was discovered.

Starting from 2000, a new epoch has emerged in the detection and study of dwarf galaxies of the Local Group. The Sloan Digital Sky Survey (SDSS) has the most detailed three-dimensional maps of the Universe ever made, with deep multi-color images of one third of the sky, and the spectra for more than three million astronomical objects. It uses the 2.5-m telescope in New Mexico. The SDSS now gives the major part of the newly discovered dwarfs in the LG. A continuation of the search for dwarf satellites of the Andromeda is the Pan-Andromeda Archaeological Survey (PAndAS) out to the distances of $\sim$150 kpc from the Andromeda. A new possibility to find the faintest objects is given by the SEGUE survey (Sloan Extension for Galactic Understanding and Exploration). The Panoramic Survey Telescope and Rapid Response System (PanSTARRS1) has final stacked data reaching slightly deeper than SDSS.

New discoveries of the dSph companions (including the Andromeda and Milky Way companions) were made as the overdensities of resolved stars within the certain magnitude and color range using a special algorithm. Really, this is a painstaking work …

The properties of dwarf galaxies are actively studied using large ground-based telescopes, such as the 3.6-m Canada-France-Hawaii Telescope with `Mega Cam` and `Mega Prism` devices, Cerro-Tololo 4-m Blanco telescope with DECam and many others. The great role in the outstanding the distance scale, star formation history and many other tasks is of course played by the `HST` with the Wide Field Planetary Camera 2 `WFPC2` and the Advanced Camera for Surveys `ACS`.

What is the actual member galaxies list? May you prepare a synoptic list of members as a function of time steps?

To create such a list, first we have to determine the boundaries of the LG. This is done either by defining the radius R_0 (see above), or by calculating the tidal index for each galaxy in the given volume, the distance and luminosity of which are known. The details are described in the UCNG by Karachentsev et al. (2013). For our purpose it is sufficient to know that the galaxy, physically associated with its "main" gravitationally dominant galaxy, must have a tidal index of ≤ 0. Comparing the McConnachie (2012b) and UCNG data, I made such a list. Several galaxies with slightly negative tidal indices (from -0.1 to -0.5) were included as the provisional members of the LG and marked in the list in italics.

Galaxies discovered and confirmed before 1950

Milky Way, LMC, SMC, NGC 6822, Andromeda (M31), M32, M33, NGC 185, NGC 205, NGC 147, WLM, Sculptor, Fornax, *Leo A*.

Note: These include the well-known members of the LG, whose status was confirmed decades and centuries later. The three latest galaxies mark the beginning of the "new era".

Galaxies detected and confirmed in the 1950–1999

Leo I, Leo II, Ursa Minor, Draco, Pegasus, And I, And II, And III, LGS-3, Phoenix, Carina, Sextans dSph, Sagittarius dSph, And V, Pegasus dSph (And VI), Cassiopea dSph (And VII), Cetus, *Aquarius (DDO 210), Sagittarius dIrr, Tucana*.

Note: these galaxies were discovered in the photographic surveys of the sky; their distances were determined and membership in the LG was confirmed a few years later.

Galaxies detected and confirmed in 2000–2013

2004—And IX; 2005—Ursa Ma I, Willman I; 2006—And XI, And XII, And XIII, Ursa Ma II, CVn I, CVn II, Bootes I; 2007—And X, And XIV, And XV, And XVI, Segue I, Leo T, Leo IV, Coma Beren., Bootes II, Hercules; 2008—And XVII, And XVIII, And XIX, And XX, Leo V; 2009—And XXI, And XXII, Segue II, Bootes III; 2010—Segue III, Pisces II; 2011—And XXIII, And XXIV, And XXV, And XXVI, And XXVII, And XXVIII, And XXIX; 2012—And XXX; 2013—Lacerta I (And XXXI), Cassiopea III (And XXXII), Perseus I (And XXXIII).

Note: the galaxies were detected within the modern digital sky surveys; the number of detections increases very rapidly; detection and confirmation of membership is already published almost simultaneously.

What is the range in mass?

A comparison of stellar masses of our Galaxy ($\log M_{Gal} \sim 10.7\,\mathrm{M}_{\odot}$) and the faintest dwarf spheroidal galaxy Segue I, located from it at a distance of 28 kpc, ($\log M_{SegI} \sim 3\,\mathrm{M}_{\odot}$) gives an impression of the vast range of masses in the LG, even with all the uncertainties in the estimation of masses.

Actually, the answer has already been given. But again, we can remember the classics. Assuming that the number of galaxies should increase monotonically with decreasing luminosity, F. Zwicky suggested that in addition to "normal" dwarf galaxies, there have to exist some "pygmy" galaxies with masses of about thousands of solar masses and "gnomes" with masses of around hundreds of solar masses. Faint and ultra-faint galaxies, recently discovered by the groups of V. Belokurov and S. Koposov fit these exotic definitions.

On the average, stellar masses of irregular dwarf galaxies are approximately the same as those of the dwarfs elliptical and much greater than the masses of the largest spheroidal dwarf galaxies. Stellar masses are usually estimated from the luminosity in the K_s band of the near-infrared range, in the assumption that the "mass-luminosity" ratio is equal to 1 in solar units. Then the characteristic masses of "normal" dSphs are approximately 10^6–$10^7\,\mathrm{M}_{\odot}$, faint $\sim 10^4$–$10^5\,\mathrm{M}_{\odot}$ and ultra-faint $\sim 10^2$–$10^3\,\mathrm{M}_{\odot}$. It is clear that due to the observational selection at the distance of the Andromeda not all the faintest dwarfs are found yet. The dynamical mass of the galaxy is determined by its internal motions: by the dispersion of stellar radial velocities, or the width of the neutral hydrogen line. According to the current (often uncertain) estimates, dynamical mass of dwarf galaxies exceeds their stellar mass by tens or even hundreds of times. This fact is known as the phenomenon of dark matter dominance in dwarf galaxies. Another topic of discussion is the terminology itself—to what extent by its mass can a stellar system be considered a "dwarf" galaxy, and whether it is necessary to introduce a new term for the most ultra-faint objects.

How the LG characterizes in density with respect to the field?

According to Jones et al. (2006), the average density of the stellar mass in the Universe is equal to $4.3 \times 10^8\mathrm{M}_{\odot}\,\mathrm{Mpc}^{-3}$. The sum mass of stars in the LG galaxies is $1.13 \times 10^{11}\,\mathrm{M}_{\odot}$ (Karachentsev and Kudrya 2014) which gives within R_0 the average stellar density of $2.9 \times 10^{10}\,\mathrm{M}_{\odot}\,\mathrm{Mpc}^{-3}$, i.e. 67 times larger than the average space density. Similarly, the total mass of the LG, $3.1 \times 10^{12}\,\mathrm{M}_{\odot}$, gives the average density of $7.9 \times 10^{11}\,\mathrm{M}_{\odot}\,\mathrm{Mpc}^{-3}$ within R_0 (Karachentsev and Kudrya 2014). In the standard Λ-CDM model with $\Omega_m = 0.28$ and $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ the average density amounts to $4.3 \times 10^{10}\,\mathrm{M}_{\odot}\,\mathrm{Mpc}^{-3}$, which creates a density contrast for the LG over the average background of 19:1. However, it should be taken into account here that the average local density of matter according to Makarov & Karachentsev Makarov and Karachentsev (2011), makes up only 1/3 of the average global density

$\Omega_m = 0.28$, taking this into account the local contrast of the dark matter density in the LG increases to 57.

What are the main sub-structures of the LG?

It is known that the two galaxies of the LG, MW and M31 are the most massive and bright. Their mutual distance is $\sim$780 kpc, and the approach velocity is $\sim$110 km s^{-1}. They are both surrounded by suites of gravitationally bound companions, so we can speak of two subsystems within the LG. Detailed data on individual galaxies—members of both subgroups, as well as about the authors and detection dates are given in the above mentioned survey of McConnachie (2012b). In a recent paper, Karachentsev and Kudrya (2014) give an ordered list of members of the MW and M31 subsystems, descending by the tidal index. Referring to these studies, I confine myself here to the minimal information. The corresponding subsystem lists give the names of the companion galaxies with positive tidal indices, their equatorial coordinates (J2000.0) and morphological types; below the dotted I list galaxies, discovered since 2000 (Table 2.1).

Is the morphology density relation valid for the LG?

Yes, almost all elliptical and spheroidal dwarf galaxies of the LG are found within a radius of 300 kpc around the MW and M31. The average projection distance of 60 early-type satellites around the MW and M31 is 120 kpc, whereas for 11 late-type satellites it amounts to 410 kpc. Partly this effect of morphological segregation is caused by the observational selection: the most low-mass dwarf systems were discovered near the MW, as they were resolved into stars, and the area of systematic search of ultra-faint dwarfs around the M31 did not exceed $\sim$200 kpc. However, a similar effect of morphological segregation has occurred in other neighboring groups (M81, Centaurus A, NGC 5236, NGC 4594), where the observational selection is not so great (Table 2.2).

For a better understanding of our Galaxy and spirals in general a deep survey of Andromeda is one of our best chance. The closeby spiral "twin" is perfectly placed for revealing the past accretion history of this class of galaxies and reveal its future in a possible merger with the MW. Rodrigo Ibata focus our the attention on the Andromeda galaxy and its plethora of satellites.

2.7.1 Andromeda

Questions for Rodrigo Ibata:
Andromeda is the best external galaxy for which we can study the disks, halo and dwarf companions properties in detail. Could you summarize the main properties of the M31 system?

The Andromeda galaxy (M31) is the best-known and best-studied of all galactic systems beyond the Milky Way. Indeed, as our view affords a full panorama of that galaxy, there are many aspects of its structure that we have a more complete picture

Table 2.1 The M 31 (00:42:44.3 +41:16:09, Sb) subgroup

Name	R. A.	Dec.	Type
WLM	00 01 58.1	−15 27 39	dIrr
IC 10	00 20 17.3	59 18 14	dIrr
NGC 147	00 33 12.1	48 30 32	dE/dSph
And III	00 35 33.8	36 29 52	dSph
NGC 185	00 38 58.0	48 20 15	dE/dSph
NGC 205	00 40 22.1	41 41 07	dE
M 32	00 42 41.8	40 51 55	cE
And I	00 45 39.8	38 02 28	dSph
LGS-3	01 03 55.0	21 53 06	dIrr/dSph
IC 1613	01 04 47.8	02 07 04	dIrr
And V	01 10 17.1	47 37 41	dSph
And II	01 16 29.8	33 25 09	dSph
M 33	01 33 50.9	30 39 37	Sc
Cassiopeia dSph	23 26 31.7	50 40 33	dSph
Pegasus dSph	23 51 46.3	24 34 57	dSph
And XVIII	00 02 14.5	45 05 20	dSph
And XX	00 07 30.7	35 07 56	dSph
And XIX	00 19 32.1	35 02 37	dSph
And XXVI	00 23 45.6	47 54 58	dSph
Cetus	00 26 11.0	−11 02 40	dSph
And XXV	00 30 08.9	46 51 07	dSph
And XXXII(Cas III)	00 35 59.4	51 33 35	dSph? (Martin et al. 2013c)
And XXX	00 36 34.9	49 38 48	dSph
And XVII	00 37 07.0	44 19 20	dSph
And XXVII	00 37 21.1	45 23 13	dSph
And XI	00 46 20.0	33 48 05	dSph
And XII	00 47 27.0	34 22 29	dSph
And XIV	00 51 35.0	29 41 49	dSph
And XIII	00 51 51.0	33 00 16	dSph
And IX	00 52 53.0	43 11 45	dSph
And XVI	00 59 29.8	32 22 36	dSph
And X	01 06 33.7	44 48 16	dSph
And XV	01 14 18.7	38 07 03	dSph
And XXIV	01 18 30.0	46 21 58	dSph
And XXII	01 27 40.0	28 05 25	dSph
And XXIII	01 29 21.8	38 43 08	dSph
And XXXIII(Perseus I)	03 01 23.6	40 59 18	dSph? (Martin et al. 2013b)
And XXVIII	22 32 41.2	31 12 58	dSph
And XXXI (Lacerta I)	22 58 16.3	41 17 28	dSph? (Martin et al. 2013c)
Pegasus dIrr	23 28 36.3	14 44 35	dIrr/dSph
And XXI	23 54 47.7	42 28 15	dSph
And XXIX	23 58 55.6	30 45 20	dSph

Table 2.2 The MW (17:45:40.0 -29:00:28, S(B)bc) subgroup

Name	R. A.	Dec.	Type
SMC	00 52 44.8	−72 49 43	dIrr pec
Sculptor	01 00 09.4	−33 42 33	dSph
Phoenix	01 51 06.3	−44 26 41	dIrr/dSph
Fornax	02 39 59.3	−34 26 57	dSph
LMC	05 23 34.5	−69 45 22	SB(s)m
Carina	06 41 36.7	−50 57 58	dSph
Leo I	10 08 28.1	12 18 23	dSph
Sextans dSph	10 13 03.0	−01 36 53	dSph
Leo II	11 13 28.8	22 09 06	dSph
Ursa Minor	15 09 08.5	67 13 21	dSph
Draco	17 20 12.4	57 54 55	dSph
Sagittarius dSph	18 55 19.5	−30 32 43	dSph
NGC 6822	19 44 56.6	−14 47 21	dIrr
SEGUE II	02 19 16.0	20 10 31	dSph
Ursa Major II	08 51 30.0	63 07 48	dSph
SEGUE I	10 07 04.0	16 04 55	dSph
Leo T	09 34 53.4	17 03 05	dIrr/dSph
Ursa Major I	10 34 52.8	51 55 12	dSph
Willman I	10 49 21.0	51 03 00	dSph
Leo V	11 31 09.6	02 13 12	dSph
Leo IV	11 32 57.0	−00 32 00	dSph
Coma I	12 26 59.0	23 54 15	dSph
Ca Vn II	12 57 10.0	34 19 15	dSph
Ca Vn I	13 28 03.5	33 33 21	dSph
Bootes III	13 57 12.0	26 48 00	dSph
Bootes II	13 58 00.0	12 51 00	dSph
Bootes I	14 00 06.0	14 30 00	dSph
Hercules	16 31 02.0	12 47 30	dSph
SEGUE III	21 21 31.0	19 07 02	dSph
Pisces II	22 58 31.0	05 57 09	dSph

of than in our own Galaxy. As the only other giant galaxy in the Local Group, located at a mere 785 ± 25 kpc from us (McConnachie et al. 2005), it is of prime importance in understanding the assembly history of the Local Group. It is probable that the proto-galaxies that were later to become the Milky Way and M31 formed in close proximity to each other in the primordial universe, and after initially traveling away from each other, turning around and then falling towards each other, they are now posed to collide for the first time. Given the inescapable effects of dynamical friction, it is fairly certain that the final fate of the Milky Way and Andromeda are also intertwined, as they will fully merge with each other within ~ 5 Gyr to form an elliptical galaxy (Cox and Loeb 2008). Some studies even suggest that M31 and the Milky Way have already interacted in the past via the ejection of satellites from one system to the other (Hammer et al. 2013).

Andromeda is seen almost edge-on, with an inclination of 77°, increasing to ∼80° at large radii (Chemin et al. 2009). This makes it somewhat challenging to study the precise structure of the disk populations, but provides an ideal view for studies of the stellar halo component of that galaxy.

The disk of M31 displays a rather irregular and asymmetric spiral pattern. Its most striking feature is a highly luminous ring of star-formation located at a radius of approximately 10 kpc from the galaxy's centre. The morphology of this ring measured from infrared images taken with the `Spitzer` space telescope, suggest that the ring-like structure is the aftermath of a collision with the dwarf satellite companion M32, which would have been responsible also for the presence of the inner ring situated at approximately 1.5 kpc (Block et al. 2006). The outer optical disk of M31 at ∼ 30 kpc displays a haggard appearance (Ferguson et al. 2002), and is most probably due to deformations of the disk or residues of the numerous accretions that the galaxy has suffered. Despite these intrusions, a remarkably extended disk component can still be detected from stellar kinematics in the distance interval 40–70 kpc (Ibata et al. 2005); this is presumably the ancient counterpart to the extended disks of young blue stars that were discovered with the `GALEX` satellite in several external galaxies (e.g., Thilker et al. 2005).

The stellar halo component of M31 has the best-studied global structure of any system examined to date. This structure is clearly detected both kinematically and photometrically in the inner galaxy (Chapman et al. 2006; Williams et al. 2012), and extends out to incredibly distant radii > 150 kpc (Gilbert et al. 2012; Ibata et al. 2014b). Over this immense range, there is evidence for the presence of a smooth and symmetric "underlying" stellar halo component, which declines approximately as r^{-3} (in 3-dimensional spatial density), although the metal-rich populations decrease faster than the metal-poor populations (Ibata et al. 2014b). In addition to this smooth component, there are numerous streams and shells (Ibata et al. 2007; McConnachie et al. 2009). These observations strongly suggest that the stellar halo was built up from the accretion of a large number of satellites arriving in an uncorrelated way from random directions at ancient times, with a small number having been deposited more recently (these are the ones whose tidal streams are still discernible).

Surrounding M31, one also finds a cohort of satellite galaxies that are still (relatively) intact, including M33, the compact elliptical M32, the three dwarf ellipticals NGC 147, NGC 185 and NGC 205, and a large number of dwarf spheroidal companions, of which 30 are now known (Martin et al. 2013b) (and > 100 further objects are plausible candidates, Martin et al. 2013a).

In what aspects is M31 different from the Milky Way?

The Andromeda galaxy can, in many ways, be thought of as the larger sister of our Milky Way. It possesses a substantially greater stellar mass, $1.0 - 1.5 \times 10^{11} M_{\odot}$ (Tamm et al. 2012), approximately twice the mass of the Milky Way $6.43 \pm 0.63 \times 10^{10} M_{\odot}$ (McMillan 2011). The scale length of the disk of M31, its major baryonic component, is 5.9 ± 0.3 kpc (Walterbos et al. 1988), which is more than twice the value of the scale length of the Galactic disk 2.3 ± 0.1 kpc (Ruphy et al. 1996). Likewise the bulge of M31 possesses approximately twice the mass of the Galactic bulge (Klypin et al. 2002). Recent dynamical studies also suggest a similar ratio in the total masses of the two galaxies, including their dark haloes (Diaz et al. 2014; Watkins et al. 2010).

Morphologically, these two spiral galaxies show differences and similarities. A recent analysis shows that the Milky Way possesses a four armed spiral pattern (Urquhart et al. 2014), in stark contrast to the quite irregular spiral density pattern of M31, discussed above. While both galaxies have a boxy inner bulge (Beaton et al. 2007), there is no counterpart in the Milky Way to the extended massive bulge component in M31.

However, it is perhaps in their stellar halo components that the two galaxies are most different. M31 possesses an extensive metal-rich component (with metallicity peaking at $[\mathrm{Fe/H}] = -0.7$) which is dominant throughout the inner galaxy up to a radius of $\sim$75 kpc (Ibata et al. 2014b). While nothing like this is present in the Milky Way, it is interesting to muse that this may well be what our Galaxy would look like if by chance the LMC were already tidally destroyed and its stars assimilated. There are also significant differences in the stellar halo profiles, with M31 exhibiting a smooth profile, whereas the Milky Way's becomes significantly steeper beyond 25 kpc; Deason et al. (2013) have argued that this points to a more gradual buildup of mass in M31.

In summary, M31 displays an abundance of signs of both ancient and recent merger activity (Block et al. 2006; Ibata et al. 2001, 2014b), justifying why that galaxy is often referred to as a "train wreck" in informal discussions, whereas the Milky Way appears to have led, until now, an unusually quiet existence (Hammer et al. 2007).

Why these studies are important for a global understanding of galaxies formation?

In order to study the formation and evolution of galaxies, we have essentially two options. One way is to use the light travel time to examine galaxies in their various stages of development through cosmic time. The advantage of adopting this approach is that it is direct and straightforward: the galaxies are as we see them. Of course, with current instrumentation, at interesting stages in their development, these structures subtend each only a handful of pixels on our best detectors. This means that we are forced to follow only global statistical trends that take place in galaxies on the largest of scales.

The alternative way is to realise that nearby galaxies have been built up by the same physical processes, so that the final state that we see them in today is the product of this formation history. The phase-space and chemical structure of the present-day galaxy is effectively like a rich geological deposit of many strata, due to the accumulation and processing of mass from outside and within the galaxy. Among these "strata" we can find preserved "fossils" in the form of stellar streams or other structures that provide evidence for individual accretion events in the galaxy's past (Freeman and Bland-Hawthorn 2002). While clearly indirect, this approach is able to utilise nearby galaxies, on which we have high spatial resolution information, and whose stellar populations can be studied to derive their detailed chemistry and ages. Furthermore, precisely because one is now sensitive to small-scale objects, the observations can be used to test cosmological theories on small scales where they face their greatest challenges (Springel et al. 2006).

While the substructures and satellites that inhabit the halos and outskirts of model galaxies are now readily detected in simulations, finding and studying the real fossil structures in nature is difficult, as they are generally small-scale features of very low mass and surface brightness. At present, the best way to study these structures is via their resolved stellar populations, due to the much richer information content that we can thereby obtain. Even in the ELT era, this probably constrains us to populations within 20 Mpc or so, and at present, to just a few Mpc with 10 m telescopes. Hence observations in nearby galaxies, and especially in the Local Group, are required to complement the samples at cosmological distances to answer many of the fundamental questions of galaxy formation.

What basic insight have we obtained about M31 and M33, the dominant members of the LG together with the MW, from the wide use of a multi-wavelength imaging approach?

Pan-chromatic imaging data has been essential for showing us how the stellar mass and the stellar populations are distributed across the giant galaxies of the Local Group (Barmby et al. 2006; Courteau et al. 2011; Groves et al. 2012). And such analyses are set to take a large step forward thanks to the giant HST Panchromatic Hubble Andromeda Treasury (PHAT) program (Dalcanton et al. 2012), which will provide an exquisitely high-resolution map of the stellar populations and the star-formation that is taking place over the disk of the Andromeda galaxy.

The stellar haloes of these galaxies only came to life after the wide-field imaging campaigns from the Sloan Digital Sky Survey (SDSS) and the Canada-France-Hawaii telescope gave us a first view of the complex network of small-scale accretions and interactions that they are built up of Belokurov et al. (2006a), McConnachie et al. (2009). For these analyses the colour information is essential for distinguishing the halo populations of interest from foreground contaminating populations.

We ask Carme Gallart to focus on the properties of the Local Group dwarf galaxy population introduced by the interview of Valentina Karachentseva.

2.7.2 The Dwarf Galaxy Population in the Local Group

Questions for Carme Gallart:
what are in your view the more relevant steps forward in understanding the LG dwarfs done in recent decades with respect to the past? What is the physical diversity between LG dwarf galaxies brought to evidence by deep, multi-wavelength imaging and spectroscopic observations?

The progress made on our understanding of the properties of LG dwarf galaxies since they were discovered about 75 years ago is impressive and makes up a fascinating story. A couple of what we call now dwarf irregular (dIrr) galaxies, NGC6822 and IC1613, were the first objects to be identified as being not part of our own Milky Way Galaxy. would like to cite the original sentence by Hubble (1925): "Familiar relations such as those connecting periods and luminosities of Cepheids, luminosities of brightest stars involved in diffuse nebulae, and frequencies of the most luminous stars in the systems are consistent when applied to NGC6822, *the first object definitely assigned to a region outside the galactic system"*. Thirteen years later, the first two among the lower surface brightness dwarf spheroidal (dSph) satellites of the Milky Way, Sculptor and Fornax, were discovered. They were "Two stellar systems of a new kind" (Shapley 1938), with "no irregular nebulosities, no clumpling of stellar images, no sharp or bright nuclei-only smooth and essentially symmetrical concentration to the centre". By 1955, four more 'Sculptor-type objects', as they were called for a while, had been found: Ursa Minor, Draco, Leo I and LeoII. Finally, Carina, Sextans and the Sagittarius dSph were discovered within 1977 and 1994 (McConnachie 2012a), completing the census of the so-called Classical Milky Way dSph satellites.

During the decade of 1960, the distribution of stars in these galaxies was characterized in a series of papers by Paul Hodge, and the first color-magnitude diagrams were obtained for Ursa Minor, Sculptor, Draco and Leo II (see the review paper on "Dwarf Galaxies" Hodge 1971). They were similar to those of the old Milky Way globular clusters. This, together with the fact that old RR Lyrae variable stars were discovered in them, led to the conclusion that dSph galaxies were basically old systems, much like globular clusters. However, in the decade of 1980, some hints on the existence of a range of metallicities and ages, and thus of a complex evolution in dSph started to accumulate (Buonanno et al. 1985; Mould and Aaronson 1983; Zinn 1980). At the same time, the first evidence of the large mass-to-light ratio of dSph were obtained with the measurement of radial velocities for just a handful of stars in Draco (Aaronson 1983) and Sculptor (Aaronson and Olszewski 1987; Armandroff and Da Costa 1986). This indicated a further important difference with respect to globular clusters.

Over the last 20 years, there has been enormous progress on the understanding of the star formation and chemical enrichment histories, as well as the chemodynamics, of dSph galaxies (Tolstoy et al. 2009). On the one hand, wide field cameras on 4-m class ground-based telescopes have allowed us to obtain color-magnitude diagrams of these galaxies that reach the oldest main sequence turnoffs over a large range of galactocentric radius. This kind of deep CMDs are the key for a reliable determination of the star formation history (see Fig. 2.11 and Fig. 2.12), that is, the rate at which a galaxy forms stars as a function of time, and how the gas is gradually

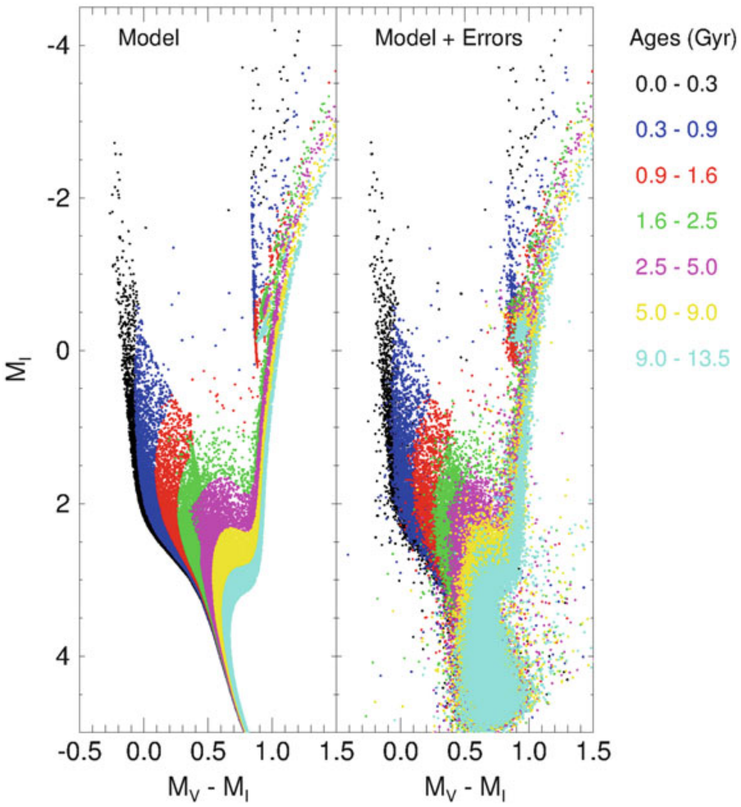

Fig. 2.11 Synthetic CMD computed using IAC-star (Aparicio and Gallart 2004) assuming a constant star formation rate and a single metallicity (Z=0.006) for all stars. The *right panel* shows the same synthetic CMD after simulation of observational errors typical of a Milky Way satellite observed with a ground-based telescope. Stars of different ages have been color-coded as indicated in the *right* labels. This figure illustrates the importance of obtaining color-magnitude diagrams reaching the oldest main sequence turnoffs (cyan stars located at $M_I \simeq 3.5$, M_V-$M_I \simeq 0.8$) in order to obtain precise star formation histories. The main reason is that, at magnitudes brighter than the oMSTO, stars along the main sequence are distributed in a sequence of age: short lived, young, massive stars are the bluest and brightest, and less massive, long lived stars are progressively fainter and redder. Metallicity affects mainly the color of a main sequence star in the CMD, and its magnitude only somewhat. In a shallower color-magnitude diagram, for example one reaching a few magnitudes of the red giant branch, or even down to the horizontal-branch, the position of the stars in a given evolutionary status is mainly determined by metallicity, and there is very little age sensitivity. Another important reason is that the main sequence is the best understood phase of stellar evolution (Gallart et al. 2005) and thus systematic errors are reduced in the resulting star formation histories

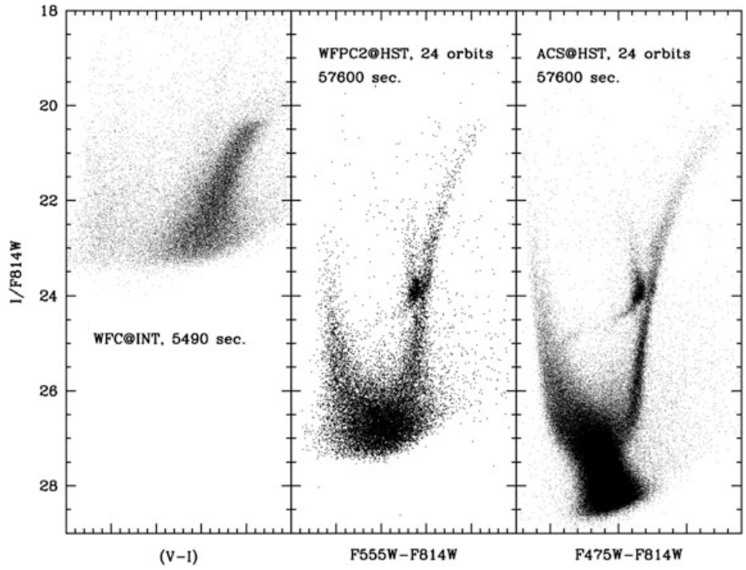

Fig. 2.12 This figure illustrates how the observed color-magnitude diagram of a Local Group dwarf galaxy has improved with better observing facilities. IC1613 (and particularly fields located at around 6 arc minutes from its center, and thus with similar stellar content) has been taken as an example of a typical Local Group galaxy located beyond the Milky Way satellite system. The *left panel* correspond to observations obtained using the Isaac Newton Telescope (Bernard et al. 2007)(INT), a 2.5 m telescope located at the Roque de los Muchachos Observatory. The two *right panels* correspond to observations obtained from space, using the WFPC2 and ACS cameras on board the Hubble Space Telescope (HST, 2.5 m), which provides a much better image resolution than ground based telescopes

enriched in the process.[3] On the other hand, the advent of multiobject, wide field spectrographs on 4 and 8 m-class telescopes (and particularly FLAMES on the VLT) has allowed us to obtain spectroscopy of representative samples (hundredths) of stars in each galaxy, from which abundances of a large number of chemical species and accurate kinematics have been derived, as a function of radius.

The photometric investigations have revealed that four out of the eight classical Milky Way dSph satellites, namely Ursa Minor, Draco, Sculptor and Sextans (these are the four closest to the Milky Way) formed stars over a relatively narrow age interval at old ages ($\simeq$ 13 to 10 Gyr ago, Aparicio et al. 2001; Carrera et al. 2002; de Boer et al. 2012a; Lee et al. 2009). The other four, more distant dSph, Carina, Fornax, Leo II and Leo I show a variety of star formation histories: all of them

[3]The wide field is important because these very nearby galaxies subtend a large area in the sky, and since substantial variations in the properties of their stellar populations as a function of galactocentric radius have been observed, in order to uncover the whole story it is important to sample them from the center out to their outskirts.

started forming stars as early as the other dSph, but most of their stars were born at intermediate ages (10–1 Gyr ago) and even young ages (in the last Gyr), either in a relatively continuous fashion, or in discrete events of star formation separated by a few Gyr, as is the case of Carina (de Boer et al. 2012b, 2014; del Pino et al. 2014). In all cases, a variation of the characteristics of the stellar populations as a function of radius has been noticed. While an old population is observed at all galactocentric radii, the central parts of the galaxies have hosted star formation for a longer period of time than the outer regions, and in some cases contain stars just a few hundred million years old.

The metallicities and kinematics derived from the new spectroscopic data, combined with information on the spatial location of a large number of individual red giant branch stars, has been fundamental information that has revealed even a larger degree of complexity in dSph. Regarding chemistry, it has been shown that each single dSph holds a very wide metallicity range in its stars, from extremely metal poor stars, [Fe/H]$\simeq -4$ (Tafelmeyer et al. 2010), to [Fe/H]$\gtrsim -1$, even in 'old' dSph such as Sculptor or Ursa Minor (Kirby et al. 2011; Tolstoy et al. 2004). They also show a range in the abundances of several chemical elements, e.g. Shetrone et al. (2001); Lemasle et al. (2014), some of which are known to originate in type Ia SNe. Both evidences indicate a substantial minimum duration of the star formation in dSph, which is at least the lifetime of the progenitors of SNIa, thought to be of a minimum of 0.1–1 Gyr (Maoz et al. 2014), and references therein. Furthermore, a metallicity gradient has been observed in a few of these galaxies, in the sense that stars are more metal poor on average towards the outer parts (Battaglia et al. 2006, 2011; Koch et al. 2006; Tolstoy et al. 2004). Kinematically (see Battaglia et al. (2013) for a review), the dozens of stars with radial velocities in small fields in the center of these galaxies that were available in the 90s (Hargreaves et al. 1994a,b, 1996; Mateo et al. 1991, 1998; Olszewski et al. 1996; Queloz et al. 1995) have turned into samples of hundreds (e.g. Battaglia et al. 2006, 2008; Mateo et al. 2008; Muñoz et al. 2005, 2006; Tolstoy et al. 2004; Walker et al. 2007, 2009; Westfall et al. 2006), and now cover the galaxies from the center to their outer parts. These new data have allowed us to detect variations of the mean line-of-sight velocity across several dSph, such as Sculptor, Carina, Fornax, Sextans, and Leo I. However, the origin of these velocity variations (e.g. rotation, tidal streaming, perspective effects) is still far from clear. In addition, there is general consensus on the fact that dSphs have flat line-of-sight velocity dispersion profiles, with only weak hints of a decline or a rise. Under the hypothesis of dynamical equilibrium, this is considered evidence that the dark matter is more extended than the stars. Finally, distinct chemodynamical components have been identified in a number of dSph, in the sense that the more metal rich stars are more centrally concentrated and have lower line-of-sight velocity dispersion (Amorisco and Evans 2012; Battaglia et al. 2006, 2011; Tolstoy et al. 2004). This, in turn, is in agreement with the results from the analysis of the color magnitude diagrams discussed above, which indicate that star formation has lasted longer in the inner part of these galaxies (and thus, it is reasonable to expect that subsequent generations of stars are more enriched.

And in the mid-2000, in the middle of all this frantik activity and exciting discoveries, many more, *fainter* dSph galaxies started to be discovered (Belokurov et al. 2006a; Willman et al. 2005; Zucker et al. 2006), both as Milky Way and as Andromeda satellites. They were generically named Ultra-Faint dwarfs (UFD),and their large numbers helped to alleviate (but not to extinguish Boylan-Kolchin et al. 2011), the tension on the so-called "missing satellites problem" (Klypin et al. 1999b; Moore et al. 1999).

UFd appear to be the least luminous, least chemically evolved and most dark-matter-dominated galaxies known. Their absolute magnitudes range from $M_V = -1.5$ (Segue I: this galaxy is less luminous than a single bright red giant branch star) to $M_V \simeq -8$ (e.g. Leo T and CVn I).In fact there is controversy on whether the faintest UFd are actual galaxies. Except for Leo T (Weisz et al. 2012), they don't show evidence for extended star formation histories, and appear to be at least as old as the old globular cluster M92 (Brown et al. 2012). Their metallicities, however, span a relatively wide range, [Fe/H]= -3.0– -1.0, including very metal poor stars which are comparatively less abundant in more massive dSph galaxies (Kirby et al. 2008). Additionally, their chemical patterns indicate that Type Ia SNe also contributed to their chemical enrichment (Vargas et al. 2013). Both evidences indicate that star formation in the UFd was not a single burst.

Until here, I discussed dSph and UFd galaxies, of which we have nearby samples. dIrr and the so-called 'transition' (dSph/dIrr or dT) dwarf galaxies are the other classes of dwarf galaxies in the Local Group. Except for the Magellanic Clouds, which are not quite dwarfs, all dIrr and dT are distant systems. This means, that their full life-time evolution has remained elusive till very recently and we still understand them in much less detail than the dSph satellites of the Milky Way.

Photometrically, the ACS on board of the HST has meant a crucial leap forward, since it has allowed us to obtain the first color magnitude diagrams reaching the oldest main sequence turnoffs for a sample, albeit still small, of dIrr galaxies: Leo A (Cole et al. 2007), IC1613 (Skillman et al. 2014), DDO210 (also called Aquarius dwarf Cole et al. (2014)), and Leo T (Clementini et al. 2012; Weisz et al. 2012). The same kind of data has allowed an accurate determination of the SFH of a couple of dT: LGS3 (Hidalgo et al. 2011) and Phoenix (Hidalgo et al. 2009); and two of the rare isolated dSph: Tucana (Monelli et al. 2010b) and Cetus Monelli et al. (2010c). These data has allowed us to show that: (1) the two isolated dSph have SFHs which are very much like those of old Milky Way satellite dSphs, like Sculptor or Ursa Minor, such that they formed their stars in just 1–2 Gyr around 12 Gyr ago; (2) the

SFH of the two dT galaxies are very much like those of the dSph, except for the fact that they continued forming stars at a very low level until almost the present time; (3) the SFH of the dIrrs is substantially different from the other two types, both because they have formed stars over their whole lifetime, and because they started forming stars at a low level, reaching their peak star formation rates at later times than dSph and dT, many Gyr later in the case of the smaller dIrr such as Leo A, DDO210 or LeoT.

These results have been, in my opinion, surprising and unexpected for all galaxy types: among Milky Way dSph satellites, a 'morphology-density' relation is observed, in the sense that the closest dwarfs have formed the bulk of their stars earlier than the more distant ones. The two old isolated dSph totally break this trend, since they are very old and more distant to the Milky Way or M31 than any of the dwarfs that are considered their satellites. The dT are galaxies that have been forming stars till very recently (if not the present time), and even have some small amount of HI associated to them. This would naturally lead to the expectation that their star formation rate would have been approximately constant as a function of time on average, or smoothly decreasing until almost the present time, when they seem to be just running out of gas. But instead, they formed 80 % of their stars in the first few Gyr. Finally, note for example the SFHs for dIrr galaxies compiled by Mateo et al. (1998) and Grebel (1998), based in most cases on qualitative estimates: they display high old and intermediate age star formation rates in most cases, unlike the recently measured SFHs.

These same data have also allowed us to understand the actual nature of radial variation of the stellar population characteristics in dwarf galaxies, first noted by Baade on IC1613 Sandage (1971), and that had been occasionally interpreted as the evidence of an 'halo-disk' configuration in dwarf galaxies e.g. Minniti and Zijlstra (1996); Minniti et al. (1999). Instead, Hidalgo et al. (2013); Meschin et al. (2014) and Noël et al. (2009) (for a sample of dSph and dT, and for the Large and Small Magellanic Clouds, respectively) have shown that the SFH changes smoothly as a function of radius, with stellar populations being younger on average toward the central parts.

Some works derive full lifetime star formation histories for dwarf galaxies from shallower color magnitude diagrams (extending below the horizontal branch or just down to a few magnitudes below the tip of the red giant branch). These star formation histories contain a very limited amount of detail and suffer of large uncertainties in the derived quantities at intermediate-age and, specially, old ages (e.g. Weisz et al. 2011). Weisz et al. (2014) do compare star formation histories obtained from shallow CMDs with those obtained from deep CMDs for a few dwarfs that have both, and show that the two are consistent within total errors (random and systematic combined, as defined in Dolphin (2012); Dolphin (2013)), which are, however, large, particularly for the SFHs derived from the shallow CMDs, and can accommodate a wide variety of SFHs. They "emphasize that the oMSTO is critical for precisely constraining the earliest epochs of star formation".

Individual old stars in distant Local Group dwarfs are challenging to observe spectroscopically, and in fact, until very recently, most of what we knew about their kinematics and chemical compositions was obtained from the observation of the gas component (typically the HI gas for kinematics and the HII regions for chemistry), or the young bright blue stars. These tracers represent only a current snapshot of the galaxy. From these observations, we learnt that the small and faint dIrr rotate very little if at all, and that the oxygen abundances are basically uniform in different HII regions across these galaxies. When spectrographs started to be available on 8–10 m class telescopes, it became possible to observe bright RGB stars in dwarfs beyond the MW immediate vicinity, that is, in isolated dIrr, dT and dSph galaxies, and in the system of M31 dSph. Being able to observe these stars is important mainly because they are present in all types of galaxies, including dSph with no gas, and are the ones that have already been observed in the nearby dSphs. This allows us to directly compare the results for the different galaxy types. Furthermore, they formed over most of the galaxy's lifetime (from very old ages to $\simeq$ 1 Gyr ago), they can inform us about the chemical evolution history of the galaxy, and their kinematics can be expected to trace the gravitational potential of the galaxy better than the gas, which is likely to be influenced by recent events.

Initially, samples of a few RGB stars started to be observed in them (e.g. Cook et al. 1999), much like what happened on the Milky Way dSph in the early days. But soon the samples started to grow, providing some exciting discoveries. Among the first studies, I would like to cite those of Lewis et al. (2007) and Fraternali et al. (2009), which obtained spectroscopy of a few dozen stars in Cetus and Tucana. They found indications of some rotation in these two galaxies, similar to the rotation observed in Sculptor (Battaglia et al. 2008). Worth highlighting is the work by Kirby et al. (2013), who derived spectroscopic metallicities in RGB stars in seven gas-rich dIrr and showed, contrary to previous studies using photometric metallicities for dIrr (Grebel et al. 2003), that dIrr obey a similar mass-metallicity relation as the dSph satellites of the Milky Way and M31. They also note that the shape of the metallicity distribution function does depend on galaxy type, such that the ones for dIrrs tend to agree with the predictions of simple, leaky box chemical evolution models, while those of dSph require an additional parameter, such as gas accretion, if they are to be reproduced by the models. This last result is probably to be taken with caution, since the spatial coverage of some galaxies by Kirby et al. (2013) is restricted to the central regions, while the metallicity distribution function of several dwarf galaxies is known to vary with galactocentric radius (e.g. Battaglia et al. 2006). Thus larger samples covering a more representative fraction of the galaxy may lead to somewhat different conclusions. Another thorough study, in this case of a single galaxy, is that of Leaman et al. (2012) on the very isolated dwarf WLM. They find rotation in the stellar component, the ratio of rotation to pressure support for the stars being V/sigma $\simeq$ 1, compared to a ratio of V/sigma $\simeq$ 6 for the gas. In Leaman et al. (2013) the metallicity distribution of stars in this galaxy is analyzed and compared with other well studied galaxies such as the Magellanic Clouds, and a number of Milky Way dSph satellites. The authors find an apparent dichotomy between the late type dwarfs (WLM plus the Magellanic Clouds) and the dSphs, in the sense that the first have statistically flatter radial [Fe/H]. These intriguing differences in the metallicity gradients in the two types of dwarfs are suggested to be related with their different amount of angular momentum, which is lower in the dSphs. Finally, Kalirai et al. (2010); Tollerud et al. (2012) and Collins et al. (2013) have presented impressive spectroscopic surveys of the M31 dSph satellite system. Overall, they agree on the finding that the mass-size-luminosity relations of M31 and Milky Way dSphs are fully consistent (see also Brasseur et al. 2011), despite some hints (McConnachie and Irwin 2006) that the brightest dSph on the first group may be systematically larger for the same luminosity.

How complete is the census of dwarfs in the LG?

In the case of bright dwarfs such as dIrr and classical dSph we are probably quite complete, except for a possible population of MW satellites at low Galactic latitude, which includes around 1/3 of the volume around the MW. But it seems that the current sample of known LG dwarf galaxies is just 'the tip of the iceberg' of the total expected population, even though the latter varies substantially depending on the models (see e.g. Hargis et al. 2014). Willman (2010) has written a nice summary of where we stand in the process of discovery of Local Group members, and of the expectations for forthcoming surveys that promise great advancements in this field. The Sloan Digital Sky Survey (SDSS) has meant an important leap forward, through the discovery of the new class of UFd galaxies, fainter by up to two orders of magnitude than the dwarfs previously known, and which existence had been predicted by some models (e.g. Benson et al. 2002). The current surveys have limitations at finding galaxies near the Galactic plane, due mainly to the obscuration by dust. Also, most of the south Galactic hemisphere is not covered by the SDSS and thus several faint dwarfs may remain undiscovered there. However, Laevens et al. (2013) report preliminary results using the first, single epoch data of the Pan-STARRS1 survey, which covers three quarters of the sky, and area which is about double of that of the SDSS data release used for DG searches. They don't find any new UFd candidate in the new are surveyed, thus questioning the isotropy of Milky Way dwarf satellite system.

Walsh et al. (2009) studied the limitations of the UFd census within the SDSS footprint, and they concluded that it is almost complete within 300 kpc to dwarfs brighter than $M_V = -6.5$. But note that 10 of the 14 UFd close to the Milky Way are fainter than this limit. Around M31, no dwarfs fainter than $M_V = -6.0$ have been discovered, while the population of brighter dwarfs is quite more numerous than in the Milky Way, meaning that a large population of UFd should also be expected in the vicinity of M31. This luminosity bias as a function of distance is a strong limitation on our understanding of the origin of these small systems, since we don't know whether small galaxies such as most UFd exist in less dense, quieter environments. Thus, it is difficult to answer the question of whether UFd have such low luminosities because they have been severely affected by the tidal field of the Milky Way, which may have removed an important fraction of their mass, or whether they have been born small, thus setting a limit for the smallest systems being able to form stars.

2.8 Tracing the Milky Way and the Local Group Co-evolution

Questions for Rodrigo Ibata:
what are the difficulties in understanding the structure and the kinematics of the galaxies member of the Local Group?

The main challenge confronting studies of the structure and kinematics of Local Group galaxies is the incomplete phase-space information on these objects. For instance, in the Milky Way we only have a very patchy view that is only fully representative (containing positions, distances, radial velocities and proper motions) for stars and other dynamical tracers in the immediate surroundings of the Sun. However, we are extremely fortunate that this situation is set to change dramatically in the near future with the arrival of astrometric data from the Gaia space survey. The parallax horizon of Gaia for K-giant stars (20 % distance errors) by the end of the mission will be approximately 11 kpc (Lindegren et al. 2008), meaning that we will obtain an extremely detailed view of the structure of more than half our Galaxy. Coupled with the Gaia proper motion measurements, and with complementary (probably ground-based) radial velocities, one can expect a true revolution in the understanding of our Galaxy by the mid-2020s.

Similar ground-breaking improvements in our knowledge of the phase-space structure of the Sagittarius dwarf and the Magellanic Clouds can be expected with Gaia. However, for the fainter dwarf galaxies and indeed for almost all of the more distant members of the Local Group, the present information will probably not be substantially ameliorated by Gaia, due to their lack of bright tracers that Gaia can survey. Thus some of the most pressing issues that we are interested in, such as determining the dark matter profile in small dwarf galaxies that have not been significantly perturbed by tidal forces, will probably still remain out of reach for some time.

In addition to the challenge of interpreting galaxies for which we have only partial phase-space information, there is the challenge of finding new objects with currently no phase-space measurements! The issue of course is to confront observations to the famous Λ Cold Dark Matter prediction that there are vast numbers of dark matter satellites around giant galaxies like M31 or the Milky Way (Klypin et al. 1999a). The upcoming sky survey with the Large Synoptic Survey Telescope (LSST) promises to give a full inventory of Local Group satellite members that are visible from Cerro Pachón in Chile, thanks to its extremely deep imaging capabilities ($r \sim 27.5$ in the final co-added images by 2032).

Thus we will be busy continuing to study the structure and dynamics of the Local Group, discovering its members and extent, revealing the distribution of dark matter for a couple of decades at least!

Recently it has been shown that M31 satellites lie in a disk (Ibata et al. 2013, Nature 493 ,6265; Tully 2013, Nature, 493, 32). What is the significance of such result and the possible consequences in understanding the LG evolution?

Since the discovery of the Sagittarius Dwarf Galaxy (Ibata et al. 1994), it has been crystal-clear that stellar haloes build up, at least partially, through the accretion of satellite galaxies. From observations of the kinematics and stellar populations of such satellite galaxies (Martin et al. 2007; Mateo 1998; Simon and Geha 2007), and from detailed modelling of the formation of CDM structures (Bullock et al. 2000; Gao et al. 2004; Moore et al. 1999), a consensus has built up that satellite galaxies are the remnants of a population of "building blocks" of the hierarchical formation of the stellar halos of their hosts (though the surviving objects are quite different to those that built the host galaxies). In this picture, each of the observed satellite galaxies is embedded in a dominant mini dark matter sub-halo. The vast majority of such sub-halos, however, are expected to be devoid of gas and stars (Kravtsov 2010), including many of higher mass than the sub-haloes that harbour faint satellites.

Simulations predict that the spatial distribution of luminous sub-haloes around a giant galaxy should be slightly anisotropic (Libeskind et al. 2007; Wang et al. 2013). This should produce apparent alignments of satellite galaxies, but these alignments should be transient structures, stemming from a combination of a mild intrinsic anisotropy, and small-number statistics, and possessing little or no kinematic coherence.

There have been hints of a possible alignment in the observed distribution of satellites around the Milky Way since the 1970s (Lynden-Bell 1976). The discovery of faint satellites in the SDSS strengthened this possibility, as the detected satellites lie in the same orbital plane (Kroupa et al. 2005). Several analyses of the satellite distribution in M31 tentatively came to similar conclusions (Koch and Grebel 2006; Metz et al. 2007), but the situation became much clearer once the M31 halo was fully surveyed out to 150 kpc and beyond thanks to the PAndAS survey (Ibata et al. 2013). With that panoramic survey, we found that 50 % of the dwarf satellite companions of M31 are confined to a very thin plane (12.6 kpc rms) that we observe almost edge-on and that extends $\sim$ 300 kpc in diameter. The satellites that belong to this structure possess coherent kinematics, with the satellites south of M31 moving towards us, and those to the north moving away from us, with respect to the mean radial velocity of M31. Such kinematics is of course suggestive of rotation. Similar coherent kinematics may be also be a feature of the population of Milky Way satellites (Metz et al. 2008; Pawlowski et al. 2013). Satellites of isolated field galaxies in the SDSS, picked to lie diametrically opposite each other across their host, appear to show a strong signature of co-rotation, consistent with the Local Group results (Ibata et al. 2014a).

That the satellites of both the Milky Way and M31 are preferentially distributed in thin planes with coherent kinematics is not expected given ΛCDM simulations, and this suggests that there may be a missing ingredient in galaxy formation simulations, possibly in the details of the baryonic physics that causes some satellites to light up with stars while most remain completely dark.

What are the future prospects?

The greatest single step forward in securing the integrity of the stellar distance scale to nearby galaxies will come when GAIA releases the parallaxes for the millions of galactic stars that it will be observing over the course of this space-based mission. This astrometric survey will include almost all known Milky Way Cepheids , scores of RR Lyrae variables and hundreds of TRGB stars. The distances will be secure, but it will still take time and ingenuity to secure the individual line-of-sight reddenings (especially for the Cepheids) and obtain an equally uniform database of metallicities for each of these stars if they are all to enter the intrinsic luminosity calibration. Fortunately, some measure of metallicity will be forthcoming from the `GAIA` mission itself. Individual reddenings will be more problematic.

Returning to the main topic of this essay, the distances to nearby galaxies, it is fair to say that without a concerted effort it is likely that many nearby galaxies will have ill-determined distances well into the foreseeable future unless some systematic survey is attempted now. The best course of action in order to build a uniformly determined, high-precision determination of distances to these galaxies would be to dedicate some of the remaining time on the Hubble Space Telescope to measuring the TRGB in the halos of as many galaxies as possible, while the telescope is still funded and functioning. The TRGB can and has reached out to systems as far away as the Virgo cluster at a distance of around 15 Mpc; it could easily be used to map out the inner 10 Mpc surrounding the Local Group.

Cosmologists believed that Local Group dwarf galaxies could be the answer to the hierarchical accretion of galaxies. The discovery that their chemical tagging is far from being compatible with the picture of dwarfs being building blocks of big galaxies have opened a lot of questions on the role of dwarfs that are still unanswered. George Lake will present our latest understanding of accretion events in the Local Group.

Questions for George Lake:

the dwarf galaxies of the Local Group are puzzling objects for several reasons. You proposed the possibility that the Magellanic Clouds were the largest members of a group of dwarf galaxies that entered the Milky Way (MW) halo at late times. Could you discuss why you did such hypothesis? What was the observational evidence at the basis of your idea? What is today the most accredited scenario for the formation of the Magellanic Clouds?

The lesson of Percival Lowell is that one should never underestimate the ability of astronomers to find patterns! Nonetheless, the distribution of dwarf galaxies around nearby galaxies has a lot of anomalies. In our galaxy, there seem to be two groupings/rings/planes of objects. The largest is a nearly polar ring where several dwarfs have distances similar to the Magellanic Clouds. Nearby, one often sees dwarfs in associations. Nobody doubts that the LMC and SMC are a pair. Abd al-Rahman al-Sufi even declared they were as early as 964AD. What else might you expect in such a group? Well, lots of things of lower mass since the basic theory of galaxy formation is scale-free. That theory relies on small objects being dark because they couldn't hold onto their gas. But, it does seem like dwarfs are strongly associated with one another. So, Elena D'Onghia and I (2008) suggested that most of the dwarfs in our galaxy might have come into the galaxy in a single group with the LMC and SMC as the most massive members.

As I said, nobody doubts that they are a pair. But, when we look at groups of galaxies, we find that the most massive satellite has a velocity of about 1/3rd of the parent, which fits the LMC/MW ratio. So, it's typical for isolated objects, masses scale as velocity cubed, so before the LMC fell in and was tidally limited, it's mass was ∼1/27th of the Milky Way (Reed et al. 2005). A massive object in a self gravitating system experiences dynamical friction (great process, it makes the dark disk!). The dynamical friction timescale is equal to the dynamical time when the mass of an object is roughly 1/20th of the total. So, an object like the LMC with 1/3rd of the velocity is barely safe, mostly because it's tidal limitation makes it closer to 1/100th of the Milky Way mass, so it's time scale to sink is 5–10 dynamical times. Indeed, in the cosmological simulations, a Milky Way mass object has three satellites the size of the LMC at a redshift of 1 (8 Gyr ago) and two of those spiral in and disrupt, with one of those often making the dark disk.

When we look at the SMC and LMC, their velocity ratio is a bit uncertain owing to proper motion. Some estimates put the ratio at 0.8. It's the cube that counts, which is then 0.5. That's compared with the norm of (1/3) cubed or 1/27. That's not a system that lasts long! Some propose that the SMC has lost a lot of mass which would make the system even crazier. They can only exist because of the tidal infall of the galaxy.

"First infall"İ models of the pair are very popular. This owed to a cascade of reasoning (originating in the anomalously low power spectrum normalization of WMAP3 which didn't last in the WMAP5 data). However, my suspicious is that you'll never get a first infall model to work as they spent too much time farther out without tidal influence and would have merged. This is not an issue that I've seen anyone else raise nor work on.

The kinematics and dynamics of groups of stars and/or galaxies could provide several important information for theoretical studies of galaxy formation and evolution. Could you discuss some examples?

The most famous is Zwicky's (Zwicky 1937) application of the virial theorem to Coma. Many are confused why this had so little impact. I think it's because the mass you measure depends on the square of the velocity times a radius, where the radius is a measure angle times the distance. The luminosity depends on the flux times the distance squared. At the time of Zwicky, the Hubble constant was 500 km s^{-1} Mpc^{-1}, so everything extragalactic looked 7 times darker than with a Hubble constant of $\sim$ 70 km s^{-1} Mpc^{-1}. The large Hubble constant was unbelievable for many reasons. For example, it made the Universe younger than even the Earth. There was one point in time where the Universe appears to be 1Billion years old, the Earth was 4.5 Billion and the Sun was a Trillion years.

That was one of the main reasons that Zwicky's work didn't have the impact expected when looking back through the lens of our modern knowledge.

By contrast in 1922 Jeans (1922) found large amounts of dark matter in the solar neighborhood, a result confirmed by Oort (1932, 1960). I had a paper describing how you could make a dark disk (Lake 1989). This was just about the time that several studies made local dark matter less popular. But, in work with Read et al.

(2008), we saw that my 1989 mechanism is generic in all the simulations, spiral galaxies always have a dark disk. This we considered impossible, anyone who looked for one in a simulation would have been considered a fool. Dark matter can't dissipate. But, the dark disk if formed by the dynamical interaction of lumps of dark matter with the baryonic disk. It can't be stopped and it happens well enough to make the dark disk generic. So, now all galaxy formation papers tell you how much a dark disk they see in their abstract.

Since 1980s Brent Tully is mapping galaxies in the nearby Universe according to their membership to a galaxy association, after having estimated distances with different methods. Catalogues, like the *Nearby Galaxy Catalogue published in (1988) ($V_{hel} \leq 3000\,km\ s^{-1}$), and maps have been produced up to the more recent Extragalactic Distance Data Base digital catalogue.*

2.9 Just Outside the Local Group

Questions for Brent Tully:
What is the picture of the Nearby Universe just outside our LG? May you describe the progresses made in understanding local galaxy motion? You evidence also the presence of a Local Void. May you describe this structure? What is the galaxy density in this Void? Have galaxies in it special characteristics?

Our increasing knowledge of the region just outside the Local Group has rather remained under the radar but cumulatively progress has been impressive. There have been two key ingredients that have advanced our knowledge. The first of these are the inventories that have been conducted to identify possible neighbors. Of particular note are the all-sky searches by Karachentseva and Karachentsev. This work has been complemented by more sensitive studies with large format cameras on large telescopes of specific regions like, for example, the study of the region around M81 by Chiboucas et al. The second ingredient is follow-up observations of suspected nearby galaxies with Hubble Space Telescope.

Imaging with Advanced Cameras for Surveys enables photometry of individual stars at least one magnitude below the tip of the red giant branch in galaxies within 10 Mpc with a single Hubble Space Telescope orbit. Almost 400 galaxies have now been observed; roughly 40 % of all galaxies brighter than $M_r = -12$ in this volume! Each of these observed galaxies now has a measured distance good to 5 % from the known luminosity of the tip of the red giant branch. A good distance gives an accurate measure of the line-of-sight peculiar velocity. The observation also gives information on young and intermediate age populations and metallicities.

We learn first that the galaxies within 10 Mpc are highly clumped. Major galaxies have entourages of dwarfs. It was a surprise to find, though, that most dwarfs that are *not* near a big galaxy find themselves in associations with other dwarfs. Very few galaxies lie alone.

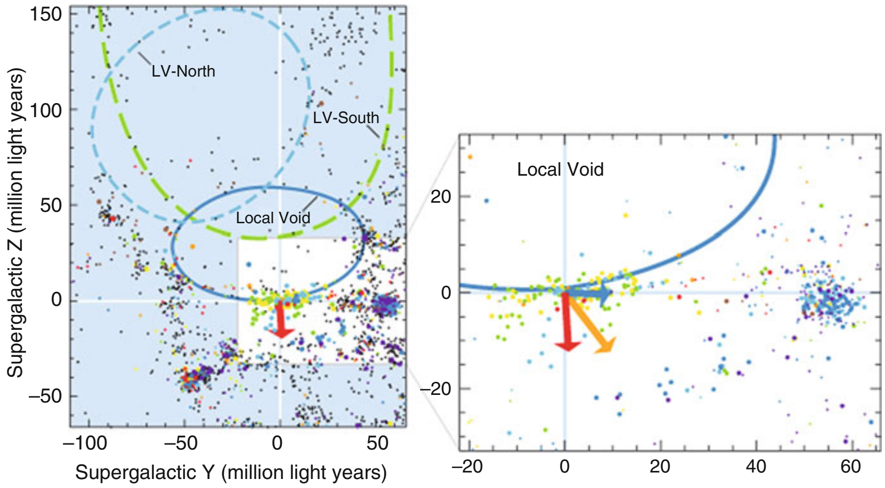

Fig. 2.13 The Milky Way lives in the Local Sheet, horizontal on these plots, among galaxies with similar velocities after subtraction of the cosmic expansion. Two local influences affect all these nearby galaxies: an attraction toward the Virgo Cluster, the *clump of blue* (representing negative peculiar velocities) at the right of each panel, and repulsion from the paucity of mass in the Local Void. These two motions represented by the *blue* and *red arrows* with respective amplitudes of 185 and 260 km s^{-1} add to explain our observed motion represented by the orange arrow. It is seen that in the Leo Spur, the feature that passes under the Local Sheet in the *right panel*, colors are *blue* representing negative peculiar velocities. As with the Virgo Cluster, these negative velocities are a reflex of our motion in their direction

The relative motions of galaxies in groups are responding to the underlying mass. The numerous dwarfs are test particles. They afford reasonable statistics for mass measurements, with the result that individual groups have been well probed over the mass range 10^{11} to $10^{15}\,M_{\odot}$. Mass to light variations with environment are now well documented. Groups dominated by spirals with masses $1-5\times10^{12}\,M_{\odot}$ generate the most light per unit mass. More massive groups tend to be more dynamically evolved, characterized by the membership of dominant early-types, and less light per unit mass. Less massive groups, those containing only dwarfs, also have less light per unit mass, sometimes dramatically so.

These groups are embedded in sheets and filaments (Fig. 2.13). We see in our own Local Sheet that peculiar velocities are remarkably small; of order 25 km s^{-1} in one dimension if the virial motions within groups are neglected. By contrast, there can be substantial large scale streaming. A dramatic example nearby is a consequence of the expansion of the Local Void. The Local Sheet is a part of a wall bounding the Local Void. The void lacks matter so is effectively repulsive. The Local Sheet has a component of motion directly away from the Local Void of 260 km s^{-1}. The next nearest filament on the opposite side from the void, a feature called the Leo Spur, does not experience this repulsion. There is a dramatic *velocity discontinuity* between the Local Sheet and the Leo Spur. Thanks to the emerging information on the motions of galaxies in the next nearest filaments we see that such kinematic signatures repeat. Motions within filaments are quiet but filaments as a whole can have large deviant velocities.

We are seeing that voids play an important role in dynamics on intermediate scales. Our own Local Void provides a great laboratory. It created the sheet-like structure that we live in and is probably responsible for the planar structures found among Local Group satellites. The void is sufficiently large and empty to generate that 260 km s^{-1} expansion motion. It begins on our doorstep at 1 Mpc so its contents, or emptiness, can be inspected. The Local Void is not entirely empty of galaxies; we have a few interesting cases to study.

2.10 How Far Did We Go in Understanding the Milky Way and Nearby Universe

Questions for James M. Lattis:
What should an extra-galactic researcher today learn from an epistemological point of view from the historical evolution in the interpretation of the MW?

Both the Kapteyn-Von Seeliger and Shapley programs were undermined by dismissal of the significance of the effects of interstellar extinction, despite the fact that the effects were obvious and dramatic in early photography of the Milky Way. Thinking of space as generally transparent aside from limited, local dark clouds, apparently seemed reasonable at the time. Certainly it was a working assumption that eased justification of certain research programs. A very diffuse, obscuring medium, the effects of which would become significant only across large distances, presumably did not seem a likely possibility. Shapley offered a weak argument justifying his neglect of interstellar absorption, but neither formulators of the Kapteyn-Von Seeliger galaxy nor Shapley saw the need to undertake a rigorous study as a prior condition to accepting the assumption of transparency. Both pursued their programs to logical conclusions, i.e. models, which could be tested against new observations. This is a cautionary example, showing that it can be hard to estimate the significance of seemingly simple assumptions; but it is not a bad example, because the consequences of the assumptions were testable.

Shapley's dramatic conclusions about the size of our Galaxy, the Sun's distance from the center, the nature of spiral nebulae, and his speculations about highly energetic processes and forces, all went well beyond what his evidence could support. They gained for him international notice, significant reactions both negative and positive, and almost surely advanced his career. They also spurred others to question his conclusions, scrutinize his methods, and re-evaluate his assumptions. The small and generally unheralded cadre of astronomers who undertook to detect and measure interstellar absorption ended up producing the more realistic model of typical spiral galaxies as we understand them today. The story is reminiscent of Karl Popper's observation that "the method of science is the method of bold conjectures and ingenious and severe attempts to refute them." (Popper 1972).

We can also think of Shapley's bold conjectures as occuring in the context of discovery, that is of the loosely constrained generation of novel ideas about nature. So long as the ideas are ultimately testable, scientists tend to allow each other wide latitude in this phase of investigation. But the "ingenious and severe attempts to refute" occurred in the context of justification. The evidence for the bold conjectures must eventually withstand rigorous and thorough testing or they must be rejected. Justification calls for careful examination of assumptions, control of experimental error, and preferably cross-checking for consistency between different approaches. This was the painstaking work undertaken by Stebbins, Hubble, and a few others in the growing understanding of galaxies.

A curious and interesting episode in the history of the understanding of the Galaxy, much studied by historians, was the quandary of Adriaan van Maanen's results that seemed to show proper motions within spiral nebulæ (Berendzen and Hart 1973). If true, these results almost guaranteed that the spirals could not be island universes and would more likely be relatively small, nearby systems. This conclusion was compatible with the Super Galaxy idea, but not at all reconcilable with the comparable galaxy idea of spiral nebulæ. It was easy to credit van Maanen's results because of his reputation for careful astrometry, but in the end they proved irreproducible by others, and were discounted. Once again only through the "ingenious and severe attempts to refute" did the correction to the bold conjecture emerge. The lesson is not that bold conjectures are always wrong, of course. But the justification must come about through assessment of underlying assumptions and evidence, independent reproduction of results, and the rest of the entire range of controls available to the astronomical community. The van Maanen example also illustrates the potential for confusion inherent in a unique instance, result, or method.

A further caution might be derived from the mutual support that emerged between van Maanen's spurious results and Jeans's theoretical studies of collapsing gas clouds that seemed to show they would take on forms resembling spiral nebulæ. The coincidental harmony of those results looks precisely like the consilience scientists hope and expect to find between theoretical predictions and empirical results when both are going in the right direction. In the absence of the strong preference for the comparable galaxy concept among many astronomers, the Jeans and van Maanen mutual "confirmations" would have seemed to make an even more compelling case that spirals were small and local. Again the process of open scientific inquiry worked because van Maanen's results proved irreproducible, but the intense scrutiny of them was driven to a great extent by the larger question of the nature of the spirals. Modern researchers can see this as a caution about potential pitfalls in computational simulations, for example as when a simulation's results apparently agree well with nature but in which the physical assumptions in the simulation can still be in error. The success of the simulation does not guarantee that the physics is correct.

Yet another aspect of the "ingenious and severe attempts to refute" in our case are the enormous and serendipitous returns resulting from Stebbins's 20-and-more years efforts developing photoelectric photometry as an astronomical tool. His earliest results, on eclipsing variable stars, held no hint of the applications that would emerge in the 1930s, but the color index measurements he could by then make on globular clusters provided an apt tool to check Shapley's assumptions about the transparency of interstellar space and then led to new and unexpected results. In general, we always move forward when we look in new directions or in new ways, and rarely if ever is such effort wasted: either new things emerge, or earlier views prevail in a new way, but both outcomes can justify the effort invested.

The development of the of the modern concept of a galaxy occasionally caused the proponents of one side or the other to invoke a philosophical principle, specifically the so called Copernican Principle. The Copernican Principle is generally understood to state that we should be skeptical of theories that place the observer in a unique or privileged situation. This is only one of several philosophical dicta occasionally invoked in scientific reasoning, especially when sorting out competing theories. Another such commonly called-upon principle is Occam's Razor. But such reasoning can be tricky to apply. In this case, both sides could claim the favor of the Copernican Principle. Shapley's model, for its part, removed the Sun from a "special" position near the center of the Kapteyn-Von Seeliger Galaxy. But at the same time critics could point out that it elevated our Galaxy, the Super Galaxy to a special structure among galaxies. As Arthur Eddington complained in 1933, at a time when the evidence could still be seen to favor the Super Galaxy, "I rather dislike the imputation that we belong to the aristocracy of the universe." (Eddington 1933). The Copernican Principle was presumably satisfied when our Galaxy was shown to be typical, but this vindication of the principle was post facto. Although philosophical generalizations like Occam's Razor and the Copernican Principle can be illuminating in retrospect, their utility in evaluating hypotheses and theories is open to considerable subjectivity; so it is unwise to place excessive emphasis on them, and perilous to value them over empirical evidence.

Questions for Gerald F. Gilmore:
did astronomers arrive at defining the characteristics of the bulge, the disk, the halo and the arms structure of the MW?

It is one of the curiosities of our developing understanding of the structure of our own Galaxy, the Milky Way, that we have taken so long to converge on a common view. Indeed, we are still very far from such a view. This largely follows from our inconvenient viewpoint, inside the mid-plane of the Galactic disk, and suffering inconveniently from the consequences of interstellar extinction. In consequence, most studies have been based on either extremely simple principles, or essentially on comparison with external galaxies, and an assumption that "we" are probably rather like "them".

Newton failed to develop a plausible model of the distribution of stars in space—the stellae fixae as they were known in those static universe days. He failed because of his simple assumption—that stars should be uniformly distributed, since that is what a sensible (i.e., in agreement with Newton's preconceptions) God-creator would have done. The first real progress was made by William Herschel (Phil Trans 75, 213–266, 1785 "On the construction of the Heavens"), who deduced a large scale structure from his own star counts, and a rather clever analysis. Herschel's result is broadly in agreement with modern observations. Interestingly, in that same article Herschel deduced that the Milky Way was just one among millions of galaxies, each made of millions of stars. In that latter deduction he was too far ahead of his times, so that idea did not get serious attention until well into the twentieth century.

The origins of the modern concept of stellar populations, with each characterised by both some observationally-based astrophysical distribution function and some spatial distribution, arose in the 1940s. Baade's 1944 paper (Baade 1944b) is often listed as seminal. As astrophysical understanding developed, we know the key astrophysical variable to be age and metallicity distributions characterising the population. Again observationally, it became clear there were correlations between these astrophysical parameters and the spatial distribution of the populations. Naively, old and metal-poor stars were found in the outer parts of galaxies in spheroidal distributions ("halo"), old metal-rich stars in a spheroidal compact "bulge" and younger stars in a clearly non-equilibrium disk-like structure, with complex spiral-like arms, bars, etc. This picture was expanded by discovery of the thick disk in the 1980s (Gilmore and Reid 1983), a discovery contentious at the time, but now well-understood to represent a common aspect of spiral galaxies, and indeed to hold crucial information on early Galaxy evolution. The thick disk is now a very major aspect of modern galaxy evolution studies.

More recently, astronomy has returned to its "galactic structure by analogy" phase, with careful recent studies showing that the "bulge" population mentioned above, which formed a crucial aspect of the Hubble-sequence, essentially is never found in Milky Way-like galaxies. Thus our bulge has vanished, being replaced by "pseudo-bulge", related to dynamical evolution of the inner disk. Hence the old bulge seems to be a later formation, albeit from old stars.

Excellent articles describing this recent history are available in Volume 5 of "Planets, Stars and Stellar Systems", edited by T. Oswalt and G. Gilmore. A 2-page summary, with a diagram, is available in "Allen's Astrophysical Quantities" (4th ed.), edited by A. Cox, in Sect. 19.3.

The census of the different structures in the MW is apparently not yet over. The case of the bar discovered only about 20 years ago and of the thick disk are emblematic. Which is the more current view about the structures composing the MW and what are their characteristics?

Not only the inner Galaxy bar! The real recent revolution has been the discovery of substructure in the outer galaxy. This really began with the discovery of the Sgr dwarf galaxy, a real independent galaxy deep inside the Galaxy's halo, currently being torn apart by Galactic tides, changing the nature of the Galactic halo from old and metal poor to young and metal rich (Ibata et al. 1995). This provided the direct evidence that the galaxy continues to form today by accretion. Since that discovery research into the outer galaxy has revealed a substantial population of small satellites and stellar streams. The numbers and properties of these sub-systems are quite opposite to what theory of the time had predicted, and they remain the most active set of targets to try to discern the nature of dark matter on small astrophysical scales.

The inner disk and bar, and associated pseudo-bulge, are fast becoming revealed from infrared surveys, so that picture is becoming more clear.

Questions for Barry F. Madore:
the road to build a solid distance scale has seen enormous progresses but also stark contrasts in this century. Which improvements could we expect in the near future?
The greatest single step forward in securing the integrity of the stellar distance scale to nearby galaxies will come when Gaia releases the parallaxes for the millions of galactic stars that it will be observing over the course of this space-based mission. This astrometric survey will include almost all known Milky Way Cepheids, scores of RR Lyrae variables and hundreds of TRGB stars. The distances will be secure, but it will still take time and ingenuity to secure the individual line-of-sight reddenings (especially for the Cepheids) and obtain an equally uniform database of metallicities for each of these stars if they are all to enter the intrinsic luminosity calibration. Fortunately, some measure of metallicity will be forthcoming from the Gaia mission itself. Individual reddenings will be more problematic.

Returning to the main topic of this essay, the distances to nearby galaxies, it is fair to say that without a concerted effort it is likely that many nearby galaxies will have ill-determined distances well into the foreseeable future unless some systematic survey is attempted now. The best course of action in order to build a uniformly determined, high-precision determination of distances to these galaxies would be to dedicate some of the remaining time on the Hubble Space Telescope to measuring the TRGB in the halos of as many galaxies as possible, while the telescope is still funded and functioning. The TRGB can and has reached out to systems as far away as the Virgo cluster at a distance of around 15 Mpc; it could easily be used to map out the inner 10 Mpc surrounding the Local Group.

2.11 To Summarize

After the Great Debate has ratified the birth of extragalactic astronomy, it tooks about two decades to recognize the MW as a normal spiral galaxy. Just after WWI a picture of the gas and stellar distribution of the MW has emerged. Our inconvenient position in the dusty MW thin disk hindered our comprehension of the nature of external galaxies and of the galaxy structure itself. Pieter van der Kruit pointed out how the studies of spiral galaxies and of the MW feed each other. The MW has been the natural laboratory to investigate in detail the stellar, gas and dust properties building a framework within which to interpret the integral properties of extragalactic objects. In this respect the contribution of Jan Oort to the stellar dynamics, with the discovery of the differential rotation and the description of the vertical equilibrium of the galactic disk, has been fundamental for a physical and mechanical description of the Galaxy and of galaxies in general. By converse studies of disks in external galaxies provided a better understanding of our own Galaxy. It *is noteworthy the discovery of the HI flat rotation curve in galaxies and the debate about dark matter in the MW. We address the reader to a recent synoptic view of the variety of approaches attempting to map dark matter in the MW (Pato and Iocco 2015).*

The stellar population concept with two main stellar populations, I and II, with distinct kinematic and chemical characteristics was developed by Walter Baade during 20 years of data collection. This concept was of enormous importance for extragalactic astronomy. The study of the stellar content of the MW improved over the years allowing for the identification of several stellar families and populating different galaxy structures. The idea envisaged by Baade remains and even the concept of a pristine Population III was postulated (see Chap. 6). However, new observations introduced significant modifications to the original Baade scheme. Famous in this context was the Vatican Conference in 1957 in which it was recognized that Population II and I properties smoothly vary in MW substructures. Our schematic view of the MW substructures has much evolved with the discovery of the presence of two disks, thin and thick, the identification of a central bar, the recent detection of several streams that line the external halo, to mention just a few of them.

Only in the 1960s the time was mature for a first formation model of The Galaxy. Based on a kinematic survey of just a couple of hundreds of F/G stars Eggen, Lyndel-Bell and Sandage, proposed a formation model. The MW should have formed via a collapse of metal poor density fluctuation in which first stars, today the halo stars, have highly eccentric orbit. The gas rapidly enriched of metals, may set in a disk, while the collapse in Z direction may be stopped by the increase in the angular momentum of the collapsing nebula. The Galaxy formation models have much evolved since then, as noted by Vallenari, the most important progresses being a direct filiation of the increasingly large stellar surveys.

The MW is today the gym where we test stellar evolutionary models, investigate the phenomenon of stellar migration, study the dust and gas composition (that we compare with that in distant galaxies), and measure the stellar and gas kinematics. Amazingly we still lack a comprehensive evolutionary model for the MW. Big progresses are anyway foreseen for the future, thanks to the number of planned surveys either from ground and space. We mention here in particular the `Gaia` *mission with its follow-up projects, that will provide a partial 3D view of the MW.*

The history of the pioneering years of extragalactic astronomy, sketched in Chap. 1, teaches how the correct determination of the amount of interstellar absorption is crucial for any luminosity measure within and outside the MW. The dust distribution, its properties and origin is consequently a key issue of many astrophysical studies. Daniela Calzetti pointed out how this issue is today pursued from combined multi-wavelength observational and theoretical approaches, e.g. the study of the late stellar evolutionary phases, like AGB and SNæ. In spite of the efforts, the characteristics of the dust in the MW are still poorly known. In addition, the extinction curves derived for the MW, the LMC and SMC are different. Only Andromeda has dust properties and extinction curve similar to the MW. If the different conditions, e.g. either metallicities or radiation field or both, *in these galaxies are at the origin of the observed differences is still not clear. With such premises it is quite difficult not only to produce extinction curves for distant galaxies—attempts have been done up to $z > 4$– but also to understand the underlying phenomena processing the dust.*

Moving from the MW to nearby galaxies the Chapter has touched also the key problem of the distance determination. The so called "distance scale" debate between Allan Sandage and Gerard de Vaucouleurs, supporting H_0=50 and 100 km s^{-1} Mpc^{-1} respectively, occupied for more than a couple of decades many research groups. Several primary stellar indicators as well as secondary indicators, including e.g. the size of rings in galaxies, have been investigated and their calibration attempted. Barry Madore provided here a description of the distance scale problem giving us the feeling of the difficulties encountered by astronomers in measuring galaxy distances. He focused on Cepheids, used by Hubble in his pioneering distance measure of M31 (see Chap. 1), and on Population II indicators like RR Lyræ and the TRGB method. Among secondary indicators, Madore mentioned the Tully-Fisher relation and the use of type Ia SNæ, raised to the altars by their use for the discovery of the accelerating universe and the Nobel prize assigned in 2011 to Saul Perlmutter, Brian Schmidt and Adam Riess. Doubts about the "reliability" of the different indicators as well as the errors connected in their calibration are still matter of animated debates.

Valentina Karachentseva provided us a panoramic view of the LG galaxies describing the steps that were necessary to build the modern view of the neighbors of our Galaxy. Digital sky surveys discovered between 2000 and 2013 more than half of the today known LG members and future `LSST` *surveys are even more promising in populating the LG with new members. Some of the dwarf recently discovered are really "Pygmys" and even "Gnomes" in mass with respect to MW and Andromeda as expected many years ago by Fritz Zwicky. The manifold of dwarf families are reviewed by Carme Gallart, highlighting the large variety of properties shown. The distribution of a recently discovered class of ultra faint dwarf, UFd, with respect to the MW and Andromeda raised the question if their evolution could be due to the strong influence of these giants. The co-evolution vs. nature hypotheses are still open for many kind of dwarfs (see also Chap. 3). The giants in the LG, MW and M31, are reviewed by Rodrigo Ibata. The two galaxies totally dominate the LG. They are not "twin" in most of their properties, including the arm morphology and the chemical composition of their halo. Andromeda has about two times the stellar mass, the disc scale length and the bulge mass of the MW and likely also its total mass including the dark matter component is twice as much as that of the MW. The halos of Andromeda and MW were built up, at least partially, via ingestion of satellites, reasonably in agreement with a hierarchical evolutionary framework. At the same time, the co-evolution of the two giant galaxies with their swarm of dwarfs is witnessed also by the accumulation of dwarfs in thin planes around both MW and Andromeda. This is not expected by ΛCDM models.*

The great progresses done in mapping galaxies properties and motions in the nearby Universe has been summarized by Brent Tully. Galaxies within 10 Mpc are highly clumped, forming groups, and very few are isolated. Groups are of different *nature and mass, some being dominated by late-type galaxies as our LG, others, more evolved, by massive early-type galaxies, others are composed only by dwarfs. Redshift surveys show that groups are embedded in filaments an sheets around Voids. Our Local Sheet and, at the opposite side, Leo Spur are part of a wall encircling the Local Void which is not totally empty of galaxies. The understanding of the co-evolution of these structures and of their inhabitant galaxies is the ongoing challenge.*

Quite interesting could be in this context the discussion about the future of the MW in consideration of its interaction with the LG companions. Cox and Loeb explored this question by simulating the encounters with a N-body/hydrodynamic code that considers the actual position, mass and dynamics of the LG members. The encounter between the MW and Andromeda ends up with their merging in less than 5 Gyrs. Milkomeda, as they call the merger remnant, will have the properties of a gas-rich major merger, i.e. it will resemble a low/moderate-luminosity elliptical galaxy. The half-mass radius of Milkomeda is 4.9 kpc, which is larger than the mean value found in the SDSS for galaxies of equivalent stellar mass (1.3×10^{12} $M_\odot$) or r-band absolute magnitude (-21.2). Cox and Loeb concluded that the comparison gives credit to the claim that present-day ellipticals cannot be formed from the merging of present-day spirals.

Finally, Cox and Loeb linger over the future of extragalactic astronomy. They wrote: "Finally, we note that the simulated views from the distribution of locations for the candidate Suns in the merger remnant...., which we have termed Milkomeda, represent the only views available for a future local astronomer. Extragalactic astronomy will come to an end within 100 billion years if the cosmological constant will not evolve with time. Owing to the accelerated expansion caused by a steady cosmological constant, all galaxies not bound to the Local Group will eventually recede away from the Local Group and exit our event horizon. At that point, the merger product of the MW and Andromeda (with its bound satellites) will constitute the entire visible Universe." We thank them for the optimistic prediction about the human race duration (and of astronomers in particular)!

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Chapter 3
Family Traits of Galaxies: From the Tuning Fork to a Physical Classification in a Multi-Wavelength Context

Contribution by: Roberto Rampazzo, Mauro D'Onofrio, Simone Zaggia, Debra M. Elmegreen, Eija Laurikainen, Pierre-Alain Duc, Carme Gallart, and Didier Fraix-Burnet

Aimable banditrix des hommes volupté
prend-moi par la main (disons) et montre-moi comme
au delà de coraux aux ambitions atolles
il vont faire l'amour les mignon nématodes
les némertiens gentil e les gais rotifères

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les lingules cornèes et le flustres spongieuses
e les annélides aux balades soyeuses
et les mollusques mous et les onychophores
et l'immortel tartigrade et papa trilobite…
R. Queneau *Petite cosmogonie portative [IV, 151–159]*

3.1 Chapter Overview

At the time of the *Great Debate* nebulæ where recognized to have different morphologies and first classifications, sometimes only descriptive, have been attempted. A review of these early classification systems are well documented by the Allan Sandage's review in 2005 (Sandage 2005). This review emphasized the debt, in term of continuity of forms of spiral galaxies, due by the Hubble's classification scheme to the Reynold's systems proposed in 1920 (Reynolds 1920).

In *The Realm of the Nebulæ* (Hubble 1936) Edwin Hubble was first of all convinced about the need of a classification scheme to properly understand the nature of galaxies. "The first step is obviously a study of the apparent features of the systems under investigations. The nebulæ might be members of a single family or they might represent a mixture of utterly different kinds of objects. The questions is very important for all investigations of a general nature. The nebulæ are so common that cannot all be studied individually. Therefore, it is necessary to know whether a fair sample can be assembled from the more conspicuous objects and, if so, the size of the sample required. The answer to this question, and to many others, is sought in the classification of nebulæ."

Hubble described his classification procedure as follows "sort out the nebulæ, by inspection of photographs, into groups of objects showing similar features. The more conspicuous members of each group can then be studied in detail and the results used for comparison of the groups themselves. The degree of success attained by the method depends largely upon the significance of the features selected as the basis of the classification. … The features must be significant– they must indicate physical properties of the nebulæ themselves and not a chance effect of orientation– and also they must conspicuously enough to be seen in a large numbers of nebulæ."

In the 1936 Hubble's classification scheme, nebulæ are divided into "two very unequal groups. The great majority are called *regular* nebulae, since they exhibit a common pattern, conspicuous evidence of rotational symmetry about dominating, central nuclei. The remaining objects, about 2 or 3 % of the total number, are called *irregular*, because they lack both rotational symmetry and, in general, dominating nuclei." The pillars of the classification of the regular nebulæ are "either *elliptical* or *spirals*. Objects in each group fall naturally into ordered sequences of structural forms … The progression throughout the complete sequence thus runs from the most compact of the elliptical nebulæ to the most open of the spirals. … The terms *early* and *late* are used to denote relative position in the empirical sequence without regard to their temporal implications."

Hubble concluded that his classification scheme, known today as the Hubble sequence (HS) and/or the tuning fork, is purely empirical in nature and emphasized that the above consideration "is important because the sequence closely resembles the line of development indicated by the current theory of nebular evolution as developed by Sir James Jeans." So an empirical approach is needed according to Hubble to build a robust classification system, although the morphologist has to keep an eye on the theory!

Since the HS definition, the galaxy morphological classification systems had an uninterrupted evolution whose main objective is to account for the plethora of substructures emerging from galaxy photographic observations. Up to the end of the 1980s astronomers concentrated on organizing such variety of morphologies (in the optical band) underlying the smooth continuity between classification bins (e.g. de Vaucouleurs 1959). At odds, classification systems taking into account the galaxy absolute magnitude, break the HS at high, where only cluster Dominators (cDs) are found, and at low luminosities [see e.g. the 3D classification system proposed by van den Bergh (1997)], where dwarf galaxies display their variety .

For decades the morphology has been considered the distinguishing feature of a galaxy and the classification process should be made by a "specialist". All galaxy catalogues report a classification, even if purely descriptive, we mention the Morphologicheskji Katalog Galaktik by Boris Vorontsov-Velyaminov (1962–1974), but very few have been considered a "must-see" catalog to refer in term of classification. We mention The Hubble Atlas of Galaxies by Sandage (1961), A Revised Shapley-Ames Catalog of Bright Galaxies, by Sandage and Gustav Tammann (1981–1989) and multiple versions of the Reference Catalogue of Bright Galaxies by Gerard de Vaucouleurs and collaborators (1964–1991).

Today the process of morphological classification of galaxies is going through the stress-tests of high-resolution, wide-field, deep imaging and multi wavelength observations through digital devices. Galaxies are today scrutinized with an unprecedented detail. The digital imaging provides the possibility to elaborate images, modeling galaxies, evidence asymmetries as well as identify sub-structures from the very center out to the extreme periphery of the galaxy. Different morphological structures can be investigated at several wavelengths and compared. Galaxies change, often dramatically, their morphology when observed at different wavelengths, still the basic HS is used to select galaxy samples over which to infer their global properties.

We may synthesize the question about galaxy classification using two sentences which express two opposite views. From one side, the sentence of Halton Arp in the Introduction to the Atlas of Peculiar Galaxies comes to mind "... But far from all galaxies fit the Hubble sequence of nebular forms. In fact, when looked at closely enough, every galaxy is peculiar." Peculiar features tell us a story, maybe of that "unique" galaxy. On the other side, Ron Buta, collaborator of Gérard and Antoinette de Vaucouleurs, resumed the need of a morphological classification in the following sentence "As long as only a few criteria define a system, and if image material of a similar quality to that which formed the basis of the system is used, then there will be a greater ease of applicability and reproducibility of that system by independent *observers. If one later finds correlations between fundamental observables and classifications, then the system could lead to physical insight . . . "*

This Chapter focuses on the evolution of the galaxy classification schemes throughout this century and wishes to introduce the debate about the power entrusted, since the introduction of the HS, to the morphology in disentangling the galaxy history, i.e. in identifying the formation/evolutionary mechanisms that are believed to be at the origin of the observed morphology. In this context, the debate today enumerates very different positions from those suggesting that the galaxy morphology is the basic parameter, sufficient to identify an evolutionary path, to those who believe necessary to "isolate few " additional galaxy physical parameters to that purpose, up to researchers that use sophisticated statistical approaches in which the morphology is simply one of the parameters that come into play.

In Sect. 3.2 Debra Elmegreen starts discussing the manifold of spiral galaxies that, since the daybreak of the extragalactic astronomy, charmed astronomers.

In Sect. 3.3 the class of S0s is considered. In the original Hubble's classification, S0s are viewed as transition objects between Spiral and ellipticals at odds with van den Berg, more recent classification, which considers them a sequence parallel to that of normal and barred spirals. Gary Welch in 1999 used colourful words to describe the S0 class "To span the abyss between the two main classes is the job of S0s or lenticular". Eija Laurikainen provides here an historical and modern interpretation of this class of galaxies. S0s are often considered part of the vast class of the so-called early-type *galaxies (ETGs) which also includes ellipticals.*

In Sect. 3.4 the classification of ETGs is considered by Pierre-Alain Duc, member of the ATLAS^{3D} team. This research group is trying to organize ETGs into more physical *classes, according to their bimodal, fast or slow, kinematic figures of rotation.*

Dwarfs, including irregular galaxies, were neglected by Hubble in The Realm of the Nebulae *and have been considered only in later more complex classification schemes. Carme Gallart and Debra Elmegreen deal with dwarfs in Sect. 3.5.*

"A good classification can drive the physics, but the physics must not be used to drive the classification. Otherwise the process becomes circular." (Sandage 2005). In Sect. 3.6 Didier Fraix-Burnet discusses the problem of galaxy classification and the use of multi-parametric approaches and genetic algorithms to provide a classification scheme independent from the HS. These techniques might potentially identify the evolutionary paths followed by galaxies in their evolution.

3.2 The Varieties of Spiral Galaxies

Questions for Debra M. Elmegreen:
Does the classical morphological classification scheme of galaxies, still have relevance today? May you provide us with an historical evolution in the classification of spiral galaxies? What are the lines for a physical categorization of spirals? What are the discriminant parameters in a multi-wavelength context?

The classical schemes for classifying galaxies certainly still have relevance today. Their elegance and importance is that they reflect underlying physical processes in galaxy disks, even though the classifications are made independent of theory. Galaxy classification has been around as long as astronomers have been observing galaxies, and different classification schemes often highlight different processes at work. I won't give a comprehensive history of the evolution of galaxy classification, but will provide some context. One recent review of the subject is by Buta (2013a), a present day morphologist whose PhD advisor was Gerard de Vaucouleurs. Sidney van den Bergh also has a book, "Galaxy Morphology and Classification," with a history and overview of the subject (van den Bergh 1998), and Allan Sandage summarized and compared different classification schemes and their development in the book "Galaxies and the Universe" (Sandage et al. 1975).

William and Caroline Herschel in the late 1700s and early 1800s catalogued thousands of nebulae and divided them into eight classes, including those with and without stars. William's son John extended this work and in 1864 published the first "General Catalogue of Nebulae and Clusters". Meanwhile, spiral nebulae were first explicitly noted by the 3rd Earl of Rosse, William Parsons, in 1845 with his drawings of M51 using his 6 foot telescope at Birr Castle in Ireland; he published a morphology atlas in 1880. At the request of the Royal Astronomical Society, John Dreyer expanded the Herschel catalogue to the New General Catalogue in 1888, and we still use the NGC numbers from that catalogue to identify some 15,000 nearby galaxies. This catalogue was updated in 1973 as the "Revised New General Catalogue of Nonstellar Objects" by Jack Sulentic and William Tifft, with further descriptions of objects (Sulentic and Tifft 1973). Dreyer produced a supplement as the Index Catalogue, from 1888–1908, so some galaxies are labeled by their IC numbers. (Of course there are many other catalogues that give galaxies other designations, such as the Messier catalogue.) As noted by Sandage et al. (1975), in 1908 the German astronomer Max Wolf published the first sketches of galaxies of different types, showing arm and bulge structures in edge-on and face-on spirals (see Fig. 3.1). Hubble (1922) commended Heber Curtis, a pioneer of astrophotography, for his significant leap forward in classification of nebulae with his divisions of planetaries, diffuse, and spirals; Curtis also was the first to note barred galaxies, which he referred to as phi-type spirals. In his paper, Hubble also commented on the distinction between galactic and non-galactic nebulae, by which were meant objects outside of the galactic plane, and began to speculate on further useful subdivisions of non-galactic classes.

By the 1920s, extragalactic nebulæ—galaxies—were confirmed to exist, thanks to Edwin Hubble's determination of the distance to M31 from Cepheid observations and Vesto Slipher's measurements of the rotation of spiral nebulae. Hubble was among the first to assemble a systematic classification system. He sorted elliptical galaxies according to the ratio of their axes, and spiral galaxies according to their bulge/disk ratio, pitch angle, and degree of resolution of arms into stars. Hubble (1926) noted that his visual classification was in concert with the theoretical work of Sir James Jeans. In a lively dinnertime talk at a conference on "Lessons from the Local Group" in Seychelles in May 2014, Block and Freeman (2015) provided some

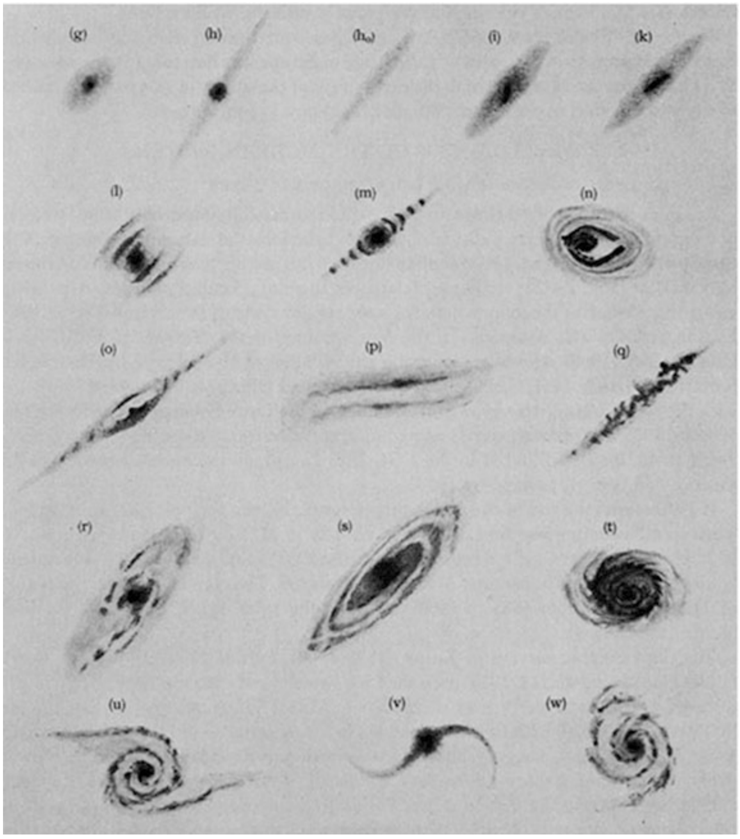

Fig. 3.1 Wolf's sketches of different nebulae (Wolf 1908), as reproduced by Sandage et al. (1975) without Wolf's top row of planetary nebulae

detective work and documents showing that the original Hubble classification had its roots in suggestions in 1920 by Reynolds (1920), with whom Hubble corresponded about classifications. Interestingly, Reynolds (1927) subsequently argued against the use of the classification scheme, because it oversimplified nebulæ. Hubble's (1927) rebuttal was that he had examined about 1000 spirals at that point (and several thousand nebulæ in total), and all but about a dozen were easily placed in his classification scheme. Block et al. (2004) also noted that the "tuning fork," first introduced by Hubble in a series of Yale lectures that became his 1936 book "The Realm of the Nebulae" (Hubble 1936), was preceded by a y-shaped tuning fork classification suggested by Jeans in 1929. Nonetheless, Hubble's book was the one that popularized the use, so he is most cited for it.

Allan Sandage inherited Hubble's plate collection and produced the "Hubble Atlas of Galaxies." Sandage, largely using the Palomar 200" telescope, extended the Hubble classification to thousands of galaxies, and produced several atlases that were the mainstay of galaxy researchers for decades (A Revised Shapley Ames Catalog (RSA), Sandage and Tammann 1981; "The Carnegie Atlas of Galaxies," Volumes I & II, Sandage and Bedke 1994).

As Sandage explains in a review article (Sandage et al. 1975), the Hubble classification scheme stands the test of time because it forms a linear sequence of fundamental physical properties. He notes that the system ultimately turns out to be tied to a galaxy's angular momentum and star formation history.

Gerard de Vaucouleurs and his wife Antoinette were also galaxy morphologists. Their Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991; following earlier versions) provided a repository of information on galaxy types as well as their sizes, axial ratios, velocities, colors, and brightnesses. de Vaucouleurs also made several important additions to the scheme followed by Hubble and Sandage. He extended the classification to include later types up to Sm (Shapley & Paraskevopoulos had introduced type Sd in 1940), and made finer gradations with intermediate types Sab, Sbc, and so on. He also recognized that some galaxies were not easily placed into S (non-barred) or SB (barred) categories, so he designated these galaxies with central oval distortions as type SAB, and designated the non-barred galaxies SA. In addition, de Vaucouleurs continued the work of Hubble in noting the way in which arms connected to the central regions, ending at the bulge, type (s), or in a circumnuclear ring, (r); Hubble applied this distinction to barred galaxies only, while de Vaucouleurs expanded this to include non-barred spirals too. These details are very useful in relation to what's happening in the central regions of galaxies and in understanding the impact of bars on the overall structure. Dynamically, SAB galaxies behave like SB galaxies in that bars can drive density waves and mix material radially, so it is important to distinguish between SA and SAB galaxies in this regard. Central rings can trap gas that might otherwise go to the center, which has implications for fueling central black holes. So adding finer details to the original classification highlights additional physical processes. The "classification volume" of de Vaucouleurs thus showed the sequence of classes (the Hubble types) with tuning fork "tines" for SA, SAB, and SB "families", and for (r), (rs), and (s) "varieties." (see Fig. 3.2). An atlas of the RC3 galaxies was compiled by Buta et al. (2002).

Holmberg was another pioneer in applying quantitative measures to galaxies, and his photographic photometry (along with work by de Vaucouleurs showed that the Hubble sequence is one of increasing blueness (Holmberg 1958), which suggested a tie to the star formation history. Morgan developed an alternative classification to the Hubble sequence based on a combination of central concentration and integrated spectral type to define galaxies, which became known as the Yerkes system (Morgan 1958). This system avoided ambiguities of arm structures. van den Bergh (1959b) developed the Luminosity Classification of galaxies, based on the apparent brightness of spiral arms. He noted that the intrinsically brightest galaxies have the best-developed arm structure.

In an effort to understand odd morphologies, Arp (1966) produced an Atlas of Peculiar Galaxies showing exceptional systems, many of which are mergers and interactions. This atlas, mostly containing photographs from the Palomar 200"

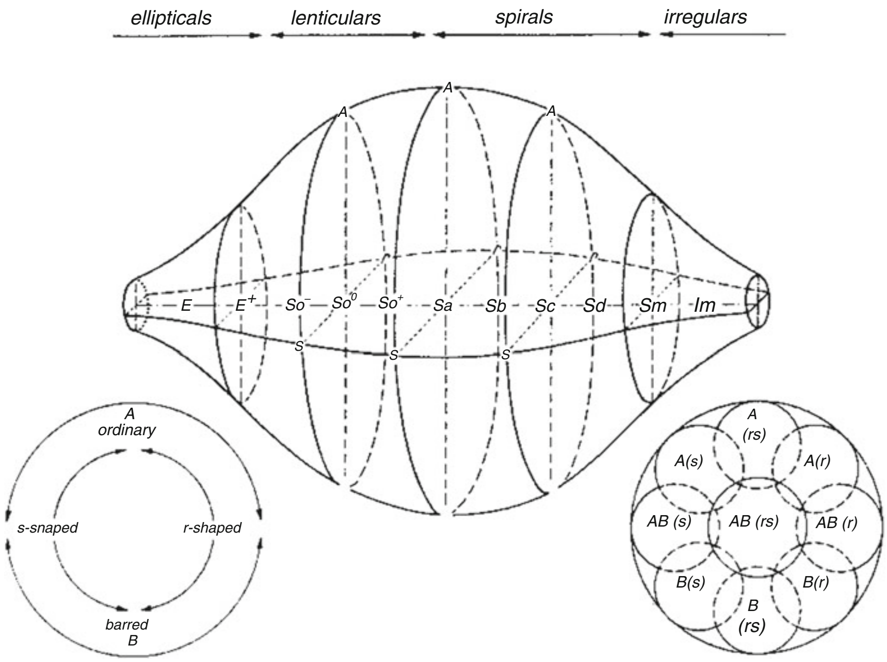

Fig. 3.2 de Vaucouleurs' (1959) adaptation of the Hubble tuning fork to include a wider variety of types (de Vaucouleurs 1959)

telescope, followed from Boris Vorontsov-Velyaminov's morphological catalog that contained many peculiar and interacting galaxies (Vorontsov-Vel'Yaminov and Arkhipova 1962); it was based on the then-new Palomar Observatory Sky Survey taken with the 48" Burrell Schmidt telescope. Arp and Barry Madore, another author of this volume, subsequently produced a catalogue of southern peculiar galaxies (Arp and Madore 1987). Madore is also the leader of the NASA/IPAC Extragalactic Database (NED), which provides a digital link to galaxy images, spectra, catalogues, and a wealth of galaxy parameters and references.

Modern-day surveys of thousands of galaxies, such as the Sloan Digital Sky Survey (Stoughton et al. 2002), have pressed efforts to automate classification processes. Computers can reasonably sort out early and late-type galaxies, using the Gini coefficient, which measures the distribution of a galaxy's light; this technique was pioneered by Abraham et al. (2003). A similarly useful parameter is M20, which measures the second-order moment of the brightest 20% of a galaxy's flux relative to the total flux (Lotz et al. 2004). The CAS system (measuring concentration, asymmetry, clumpiness) was developed by Conselice (2003) to help probe star formation histories and mergers in nearby galaxies, and can be applied to higher redshift galaxies too to the extent that they are resolved. All of these techniques are excellent in gathering statistics on large samples of galaxies, but the human eye is still unparalleled in initially identifying new categories of interesting features in galaxies.

3.2.1 Discriminant Parameters in a Multi-Wavelength Context

Although it was recognized early on that ellipticals tend to be red and spirals tend to be blue, it is indeed interesting to consider how galaxies may change appearance in different passbands. The original classifications were based on blue-sensitive photographic plates, which are dominated by light from billion-year-old A stars. Of course the Palomar Observatory Sky Survey in 1950 was done with blue and red-sensitive plates. The boundaries were pushed to I-band, 8800 Å, in the late 1970s and early 1980s, but it was only when `CCDs` became readily available that we could extend to JHK bands, out to 2.2 μm. With the `Spitzer` Space Telescope and other infrared detectors, the realm was extended to much longer wavelengths. At I and K bands and `Spitzer-IRAC` channel 1 at 3.6 μm, light is dominated by much older low mass stars. So it's reasonable to ask whether the spirals prominent in B band are still present at longer optical and near-infrared wavelengths.

One of the pioneers of examining structural details of galaxies in different colors was Fritz Zwicky, who in 1955 made composite photos of M51 from images taken in different filters (Zwicky 1955). Another important work was by Francois Schweizer in 1976 (Schweizer 1976), doing surface photometry on six prominent spiral galaxies from U through O band (6420 Å) or I band. He found that broad spiral patterns persist in the old light, and that arms are much bluer than disks. Wray's color atlas (Wray 1988) was a breakthrough in producing correctly color-balanced images; these provide much insight into the star formation history of a galaxy, showing at a glance the generally red bulges and bluer arms of spirals and the yellow-red colors of ellipticals. Zaritsky et al. (1993) were the first to obtain a K-band image of M51, which exhibits beautiful two-arm structure traceable over a larger radial range since this passband is relatively free from dust (the extinction at K band is less than one-tenth that in B). They showed that the stellar surface mass density is well traced at this wavelength (Rix and Rieke 1993). The `Spitzer` Survey of Stellar Structure in Galaxies ("S^4G"; Sheth et al. 2010) includes over 2300 galaxies in a volume-limited sample imaged in channels 1 and 2 (3.6 and 4.5 μm, respectively), in which Meidt et al. (2012, 2014) reconstruct the mass distributions. Buta did an extensive morphological classification of all of the S^4G galaxies (Buta et al. 2015) in the Comprehensive de Vaucouleurs revised Hubble-Sandage system (CVRHS); the majority have very similar classifications in both optical and infrared.

By the 1960s the density wave theory of C.C. Lin and Frank Shu, inspired by early work by Bertil Lindblad and Jan Oort, was gaining acceptance as the leading mechanism to explain "grand design" spiral patterns with symmetry on a galactic scale. Subsequent variations were suggested by Alar Toomre and others. Sandage's introduction to the Hubble Atlas discussed galaxies with two-arm and multi-arm patterns, as well as filamentary versus massive arms, which Hubble and

Reynolds (1924) had recognized. Sandage and later Woltjer (1965) discussed galaxies with "spiral-like" structure, followed by extensive related work by Kormendy and Norman (1979). While the latter identified massive arms with global patterns, Roberts et al. (1975) had a different description, referring to grand design arms as filamentary and less well-defined arms as massive (as did Reynolds initially).

I followed up these ideas by using the Palomar Schmidt and 200 in. telescopes to take B-band and I-band images of 54 spiral galaxies with different arm structures, and referred to these as grand design, multiple arm, and flocculent (Elmegreen 1981). My husband Bruce and I subsequently developed an Arm Classification system based on the symmetry and continuity of spirals arms (Elmegreen and Elmegreen 1984, 1987). Flocculent arms are the "spiral-like" structures, with short spiral pieces that lack global symmetry, whereas grand design galaxies have two main long symmetric arms and multiple arm galaxies have an inner two-arm symmetry and many long arms. From these images, it was clear that grand design and multiple arm galaxies showed their global symmetric structure in both bands, while flocculent galaxies had their most prominent structure in blue light. I had an office across the hall from Allan Sandage while I was a Carnegie postdoc, and was delighted that he stopped by when I had photographs spread all over the floor as I sorted various types. I should note here that John Bedke, who collaborated with Allan on the Carnegie Atlas of Galaxies, was the photographer extraordinaire at Carnegie in the days when we would carry our photographic plates from Palomar Mountain after an observing run; John would make contact prints for us. Surface photometry done from our plates (Elmegreen and Elmegreen 1984) revealed that the arms are about the same strength in blue and near-infrared light in grand design and multiple arm galaxies, whereas the arms in flocculent galaxies are weak in B band and even weaker in I band. Although the Arm Classification system is independent of van den Bergh's Luminosity Classes (van den Bergh 1959b), it turns out that within a given Hubble type, flocculent galaxies are fainter than grand design galaxies (and of course have less well-defined arms), so they have later Luminosity Classes.

The similarities across different bands for grand design and multiple arm galaxies are consistent with a global density wave origin, whereas the flocculent arm behavior does not require a density wave explanation. One popular alternative to explain flocculent galaxies was the stochastic self-propagating star formation theory of Gerola and Seiden (1978), whose models based on ideas of phase transition automatically generated short arcs of star formation in a differentially rotating disk. Following my Carnegie postdoc, I worked with Phil for a few years as a visiting scientist at IBM, as we compared his theories to our observations. (My husband Bruce would later leave his faculty position at Columbia to take up residence as a staff scientist—and astronomer—at IBM.) Current thought is that perhaps flocculent structure can be generated by, for example, overlapping wave modes too. In addition, there are a few spirals that appear flocculent at optical wavelengths, such as NGC 5055 and NGC 2841, but acquire a grand design at 2 μm wavelengths (Block and Wainscoatt 1991; Block et al. 1996; Thornley 1996). A review of spiral theory would take me too far afield of these observational reflections, but a recent paper by Sellwood and Carlberg (2014), who have popularized ideas of swing amplification in generating recurrent spiral patterns, contains an overview of some of these ideas. I'm sure that Giuseppe Bertin, another author in this volume and a longtime collaborator of C.C. Lin, will have interesting perspectives on his density wave work and that of Lin, Alar Toomre, and others.

After this overview about the origin and the physics behind the spiral galaxies classification, the discussion about spiral arm generation and maintenance will continue in Chap. 4. Now we turn our attention to S0s galaxies often called "lenticulars".

S0s have been postulated by Hubble as the missing link between Ellipticals and Spirals. What is the nature of S0s? Do S0s fill the abyss between Es and Spirals following the von Leibnitz's sentence tout va par degrés dans la nature, et rien par saut? Some astronomers suggest that S0s are not a primordial class, rather evolutionary aspects are predominant and possibly different paths lead to S0s. Perhaps, at least some S0s are the byproduct of the spiral evolution as suggested by Spitzer and Baade (1951). We interview Eija Laurikainen about the long lasting debate about the nature of S0s galaxies.

3.3 Filling the Abyss Between Ellipticals and Spirals: the S0 problem

Questions for Eija Laurikainen:
Although S0 (or lenticular) galaxies are often considered part of the vast family of early-type galaxies, their nature is still vivaciously debated. Their morphology is quite rich of features with respect to Ellipticals. What have been and what should be the lines for a physical categorization of S0s? What are the discriminant parameters in a multi-wavelength context?

S0s have been also considered as gas stripped Spirals by Spitzer and Baade in 1951 instead of primordial galaxies. What are, in your view, the most important questions to solve this long standing debate?

History of the S0 galaxies goes back to Knox-Shaw (1915) who recognized them as "lenticular" galaxies with no trace of spiral arms. In his galaxy classification published in *The Realm of the Nebulæ*, Hubble (1936) mentions the S0s only as hypothetical class of objects, but changed his mind before his death. Following Hubble's desire, largely based on unpublished notes, Sandage (1961) included the S0s into the Hubble tuning fork as transition types between the ellipticals and spirals. Sandage paid attention also to dust lanes and to structures called as lenses today (Kormendy and Norman 1979), seen in many S0s. He describes the lenses as "extended outer envelopes with subtle departures from smoothness in the luminosity profiles", giving the typical two or three zone structures. Dust lanes ended up to form part of Sandage's S0 sub-types, but lenses, although being the bases of the sub-types, were not coded in any particular fashion into his classification. de Vaucouleurs in

1959 (de Vaucouleurs 1959) further added the family (A, AB, B) and variety (s,sr,r) in his own classification, and replaced the S0 sub-types of Sandage with the stage ($S0^{-}$, S0°, $S0^{+}$). Currently the most complete de Vaucouleurs type classification, including also many characteristics to which Sandage paid attention, was made by Buta et al. (2015), at 3.6 μm wavelength. More recently kinematic classification has often been favored, based on the relative amount of rotation with respect to random velocities, but it cannot replace the detailed morphological classification, which illustrates the richness of the different structure components with different kinematic properties.

The lower luminosities of the S0s inspired Spitzer and Baade (1951) to suggest that they might be former spirals stripped out of gas, which thus prohibits maintenance of the spiral arms. When gas is removed star formation stops, which in principle can explain the lower luminosities of these galaxies. Spitzer and Baade even suggested that the S0s could form almost gas and dust free sequence that parallels the Sa-Sb-Sc line in the Hubble tuning fork. This idea was further developed by van den Bergh (1976), who proposed that there exists "anemic spirals" as intermediate between normal S0s and spirals, and also "anemic" S0s, having similar surface brightnesses distributions as observed in Sb and Sc spirals. However, no such "anemic" S0s were discovered by Sandage and Bedke (1994) in the Carnegie Atlas of Galaxies. Sandage confirms this in his review of galaxy classification as late as in 2005, reminding that "there does not exist any S0s that could have been like M33 or NGC 300 which have no large, bright central bulges characteristic to the S0s".

Although the idea of parallel sequence was abandoned soon after it was proposed, the S0s as stripped spirals was still thought to be a valid hypothesis. Actually, strong support for it came from the environmental studies. Dressler in 1980 found the morphology-density relation indicating that elliptical galaxies and S0s are more frequent in the highest galaxy densities. Dressler et al. in 1994 studied high surface brightness galaxies in rich clusters and showed that while the blue galaxies at high redshifts look normal late-type spirals, at low redshifts the flattened galaxies are mostly S0s. They concluded that spirals must have been transformed into S0s during the last 5–7 Gyr at z∼0.4. A possible role of the stripping mechanisms in the formative processes of S0s is still under an active debate. Also, it is under discussion whether the S0s are dominated by dark matter halos, and whether the halos are similar in S0s and spirals.

While answering to the questions made by the editors I try to defend, in the spirit of Sandage, the importance of the inclusion of detailed structure components in galaxy classification. In the workshop *Morphological and Physical Classification of Galaxies* held in Sant'Agata sui due Golfi in Italy in 1992, Djorgovsky, probably reflecting the general attitude in the meeting, stressed that "if one insists on purely morphological classification (which is not a good idea), it may be more profitable to classify galactic subsystems rather than entire galaxies." In fact, this has been the case for decades in morphological classification, and might be good to adopt more widely also in the kinematic classification scheme. My strongest critic goes to the interpretation of galactic bulges. Since the early studies at the beginning of the twentieth century bulges in the S0s have been generally assumed to be massive spheroidal systems, which to my view has been a misunderstanding.

The S0 galaxies show a large diversity of morphologies starting from almost elliptical like galaxies, and ending up to complex systems with multiple bars, rings and lenses. The obvious difference between the $S0^{-}$ galaxies and Sa spirals seems to be that the S0s have very little gas and dust and no spiral arms. In the classification by Sandage the only criterion for separating S0s from the elliptical galaxies is the fact that the S0s have large-scale disks. As simple as it sounds it is very difficult to do this separation unambiguously particularly at the higher mass end of the S0s.

It has been argued that in comparison to morphological classification kinematics would be a more physical approach for distinguishing the S0s and the elliptical galaxies. Already Bertola and Capaccioli in 1975 pointed out that although both the ellipticals and the disks of the S0s are flattened structures, the reason for the flattening is different: because giant ellipticals are slowly rotating systems their flattening cannot be due to galaxy rotation. But it also became clear soon that the level of rotation depends on galaxy mass, so that the lower luminosity ellipticals rotate as rapidly as the bulges of the early-type spirals (Kormendy 1982). Adding to this the found association of high galaxy masses with boxy-, and lower galaxy masses with disky isophotal shapes (Bender 1988; Dressler and Sandage 1983), many astronomers started to think that morphological classification is not critical, or is even misleading for characterizing the S0s.

A important step in kinematic characterization of galaxies was taken by the ATLAS^{3D}-group, using integral-field (IFU) spectroscopy for a volume-limited sample of ellipticals and S0s (see Cappellari et al. 2011b; Emsellem et al. 2011). More recently such an approach has been extended to z$\sim$0.03 by Falcon-Barroso et al. in 2014. Indeed, IFU spectroscopy allowing to make two-dimensional maps of kinematics, is one of the great achievements of this century. An important finding of the ATLAS^{3D}-group was that even 87 % of the galaxies classified as S0s or ellipticals are fast rotating, which means that they have rotationally supported disks. They also confirmed that kinematics is closely associated to galaxy mass and the isophotal shapes of the galaxies. Slow rotators are the most massive galaxies, have often boxy isophotes (70 % of them), and a lack of mass in the central galaxy regions ("core"). Fast rotators are less massive, typically have disky isophotes, and centrally peaked surface brightness profiles ("cuspy"). Different formative processes were suggested for the fast and slow rotators: fast rotators are presumably stripped spirals with some mass added by minor mergers, whereas only the slow rotators are formed in violent merger processes.

One limitation in the above approach is that kinematics is typically measured within one effective galaxy radius (R_e), which does not necessarily reflect the dominant kinematics of the galaxies. And even more importantly, S0s have complex morphologies, each of the components manifested in the kinematics in a different manner. Having this in mind it is difficult to see how any single kinematic parameter (like the often used λ_{R_e}[1]) would catch the nature of the S0s.

Another way to parametrize the early-type galaxies is to look at their outer structures. For the deficiency of gas, kinematics in the outer regions of these galaxies is difficult to measure. However, such efforts has been made using long-slit spectroscopy with very long integration times, or making spectroscopy of Planetary Nebulæ which appear even at large radial distances in galaxies. Based on the measurements of the Planetary Nebulae, Cortesi et al. in 2013 found that the random motions in the disks of the S0s are systematically higher than those in the disks of spirals. Stellar kinematics extending to 2–4 R_e have also shown that there exist early-type disk galaxies which have fast rotating inner regions and slowly rotating outer regions (see Arnold et al. 2014).

The angular momentum parameter λ_r (Emsellem et al. 2011), generally used to measure the level of rotational support in galaxies, is affected always when there is dynamical heating (decreases rotational support), or cool fresh material is accreted (increases rotational support). However, stripping of gas alone is not expected to considerably affect the λ_r-parameter. The efficiency of mass accretion to galaxies depends on the dark matter halos, because dynamically hot halos may prevent any major accretion event. Which part of the galaxy is dynamically heated also depends on the mass and gas fraction of the accreting satellites or gas in the tidal streams. Most probably kinematics in the outer regions of galaxies largely reflect fairly recent environmental effects, which cannot be directly associated to their formative processes. The environmentally induced morphological structures are largely discussed by Pierre-Alain Duc in this book.

A common way of distinguishing the S0s and elliptical galaxies is also to look at their surface brightness profiles: elliptical galaxies largely follow the Sérsic profile[2] with the shape parameter $n > 2$, in distinction to S0s which have bulges and nearly exponential disks. However, it has been shown by van Dokkum et al. in 2013 that at least for the Milky Way mass galaxies matter is accreted to galaxies at all radial distances, from z$\sim$2.5 until today. Similar mass growth at low redshifts was noticed by Caon et al. in 1993, and there are signs that in some S0s low level mass accretion might continue even until today (Ilyina et al. 2014; Moffet et al. 2012; Rampazzo et al. 2014). Fitting a single Sérsic function to the whole galaxy profiles at different

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[1]Editors Note: λ_r is a parameter describing the specific baryonic angular momentum defined as follows, $\lambda_r = \langle r|V|\rangle / \langle r\sqrt{V^2 + \sigma^2}\rangle$, where r is the galacto-centric distance, V and σ are luminosity weighted averages of the rotation velocity and velocity dispersion over a two-dimensional kinematical field.

[2]The "Sersic profile" is a photometric law empirically devised by Josè Luis Sersic in 1963 for fitting the luminosity profile of early-type galaxies:

$$I(r) = I_0\, exp(-(\frac{r}{\alpha})^{\frac{1}{n}})$$

where r is the radius, I the intensity, I_0 the intensity at the galaxy center, n the Sersic index, α the scale length.

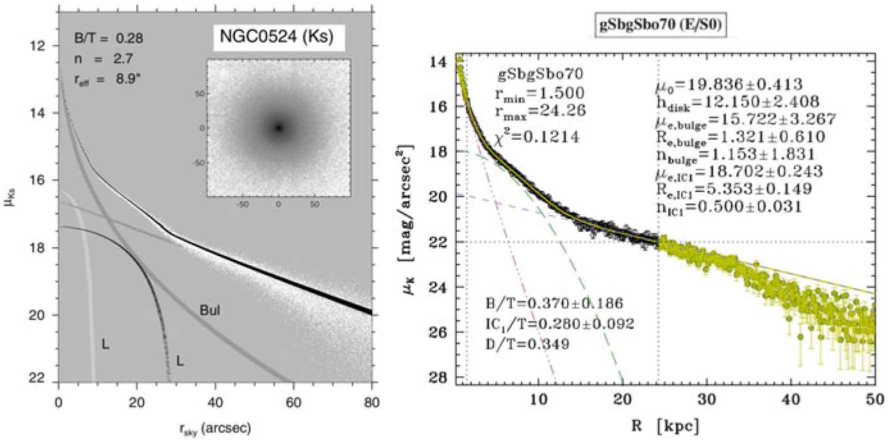

Fig. 3.3 Observed (*left panel*) and simulated (*right panel*) surface brightness profile of a typical non-barred S0 galaxy. The *dots* in both panels show all the pixel values of the galaxy. Shown are also two-dimensional multi-component decompositions, in which the bulge is fitted with a Sérsic function, the disk with an exponential function, and the lenses using either Sérsic or Ferrers functions. The observation is from Laurikainen et al. in 2009 and the model from Querejeta et al. in 2014. The small insert shows the observation of NGC 524 in the K_s-band. Notice how the total model makes a perfect fit to the surface brightness profile. The fitted components correspond to the structures visible in the images

redshifts van Dokkum et al. showed that, due to the accretion events, the Sérsic index *n* increases towards lower redshifts. This makes it challenging to identify the elliptical galaxies by their surface brightness profiles.

My approach to study the S0s has been to make multi-component structural decompositions for the S0s and early-type spirals, which I started a decade ago with Heikki Salo (Fig. 3.3). We have decomposed 2-dimensional surface brightness profiles, fitting with separate functions besides bulges and disks, also bars and multiple lenses which lenses appear as exponential sub-sections in the surface brightness profiles. A good example of a non-barred galaxy with multiple lenses is NGC 524 (Laurikainen et al. 2009), shown in Fig. 1 (left panel). This kind of exponential sub-sections has been successfully explained by cumulative minor merger events by Eliche-Moral et al. in 2012 (see Eliche-Moral et al. 2012, Fig. 1, right panel). The fitted lenses are flat structures in the plane of the galactic disk, as clearly shown for some S0s in the edge-on view already by Tsikoudi in 1980. It is easy to imagine that while lowering the resolution of the surface brightness profile of NGC 524, thus miming a similar profile at a higher redshift, it would look like a typical profile of an elliptical galaxy. For the interpretation of the E and S0 galaxies this resolution effect is of critical importance: it does matter whether we are talking about massive spheroidals or flat disk systems with some vertical heating of the disk.

In order to answer the question "what would be the physical categorization of the S0s", I would say that it should not be based on any single, or even a

few simple observational parameters. A challenge would rather be to associate the different structure components to the corresponding kinematics and stellar populations, and then try to understand those structures in terms of the dynamical models. To my view, although such automatically derived global galaxy parameters as the concentration parameter, can be used to derive useful information also of the early-type galaxies, they cannot be directly associated to the different structure components, or to specific physical processes in galaxies.
While considering the S0s as stripped spirals, an important question is what are the characteristics of their bulges compared to those of spirals. In particular, the differences between their masses should not be too large.

During the last century the concept of a bulge has been used in a wild manner, without necessarily associating them to any specific physical processes. A confusion comes when single parameters, like the Sérsic index, is directly associated to certain formative processes of bulges or galaxies, which approach is then routinely applied to large galaxy samples. The early photometric definition of a bulge was that it is flux above the underlying exponential disk. Today bulges are generally divided into classical and pseudobulges. Classical bulges are assumed to be highly relaxed structures (with n>2) formed either in galaxy mergers or by coalescence of giant clumps at high redshifts, whereas pseudobulges have more disk-like properties (n∼1). Pseudobulges are further divided into disky bulges, which are small inner disks, and boxy bulges, which are vertically thick inner parts of bars. The concept of a pseudobulge was originally suggested by Kormendy in 1982 (Kormendy and Illingworth 1982). Reviews of the different aspects of bulges have been recently collected to a book on *Galactic Bulges* by us (Eds. Laurikainen, Peletier & Gadotti, Springer, to appear in 2015).

The two-component bulge/disk decompositions by Simien and de Vaucouleurs (1986) have long been the leading standard to guide us to understand galactic bulges and the early-type galaxies in general. In these decompositions bulges of the S0s comprise more than half of the baryonic mass (bulge-to-total flux ratio $< B/T >$=0.6). Also, the surface brightness profiles of the bulges are similar to those of the elliptical galaxies ($n \sim$4). This led to the idea that the difference in B/T between spiral galaxies and S0s is very large. However, we thought that in these decompositions the flux of the bar or lens is erroneously attributed to the flux of the bulge (Laurikainen et al. 2005). Including bars and lenses into the decompositions leads to much lower B/T, which values are also very similar in the $S0^0$- $S0^-$ galaxies and in Sa spirals ($B/T = 0.25 - 0.29$) [Laurikainen et al. 2010; see also Weinzirl et al. in 2009 for barred galaxies). We found also some S0s having B/T flux-ratios as small as typically found in late-type spirals (Laurikainen et al. 2010, see also Barentine and Kormendy 2012).

However, the bulges of the S0s might be even more similar with those in the bright spiral galaxies than thought so far. In fact, there is no simple answer how the decompositions should be done. We started to think about this matter using a hypothesis that the bulges must be the same what ever our viewing angle is. And secondly, we used dynamical models to guide us to do the decompositions. It has been shown by Lütticke et al. (2000) that even half of the bulges in the

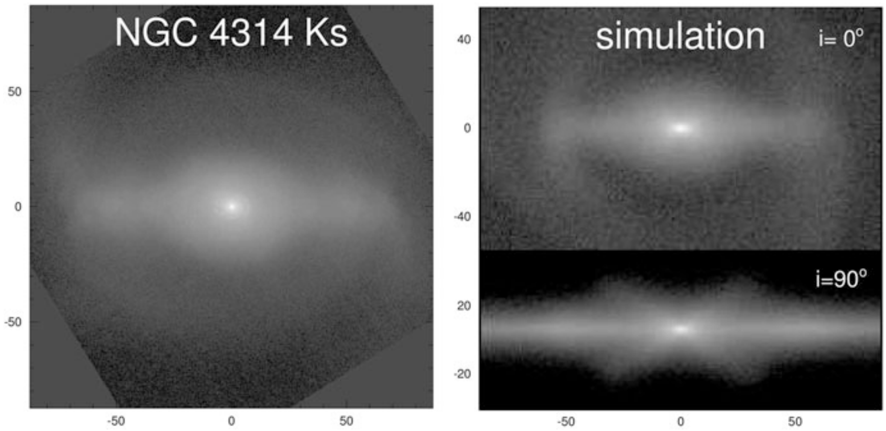

Fig. 3.4 *Left panel*: K_s-band observation for NGC 4314. *Right panel*: a simulation model by Athanassoula et al. (2014), shown in face-on and in edge-on views. The large bulge-like component in NGC 4314 is classified as a barlens. Notice the similarity of NGC 4314 with the simulation model when seen in the face-on view. The model has no classical bulge and it not particularly made for NGC 4314. This figure is from Laurikainen et al. (2014)

edge-on view have boxy/peanut isophotes. The most obvious explanation for such bulges is that they are vertically thick inner parts of bars, as first predicted by the simulation models of Combes and Sanders (1981). Our question then was: where are those boxy/peanut bulges in the galaxies seen nearly face-on? Our answer was that most probably they are the bright, fairly round components in strongly barred S0s and early-type spirals, which Sandage and others had interpreted as massive classical bulges (Laurikainen et al. 2011). We called them as 'barlenses'. One 'barlens' galaxy, NGC 4314, is shown in Fig. 3.4, which is compared with the simulation model by Athanassoula et al. (2014). What is shown here is that a boxy/peanut (X-shaped in strong bars) bulge in the model, when seen in the face-on view, has similar roundish appearance with a barlens. Using the model surface brightness profiles as guide for the decompositions of real galaxies, we found that the boxy/peanut/barlens bulges contain even $\sim$10–20 % of the baryonic mass, whereas the remaining classical bulges contain only $\sim$10 % of the galaxy mass. This is the case both for the S0s and spirals.

In summary, according to our decompositions the relative masses of bulges in the Milky Way mass S0s and spirals are fairly similar. It is possible that most of the bulge mass is confined to the vertically thick inner part of the bar. In that case the disk instabilities and subsequent secular evolution could be a central driving force in the morphology of the S0s and early-type spirals.

We can now try to answer the above question. The idea that the S0s might form a parallel sequence with spirals in the Hubble tuning fork has been renovated recently by us, together with two other groups independently. It is based on the detection of very small B/T mass ratios in some S0s (Kormendy and Bender 2012; Laurikainen et al. 2010), and also for the remarkable similarity of the ellipticities of the S0s and spirals in the edge-on view, the only difference being the lack of dust in the S0 galaxies (Cappellari et al. 2011b). Red and dead ("anemic") spirals have been found also at high redshifts (Szomoru et al. 2012). An alternative to the stripping scenario is that suggested by Sil'chenko in 2013, who speculated that all galaxies formed as S0s at high redshifts, and that only those living outside the cluster environment formed spiral arms later. Her reasoning is largely based on the measured old stellar populations (10 Gyr) of the disks in the S0s, and the fact that the S0s suddenly appear at z$\sim$0.4 in clusters.

How to evaluate these alternatives? If we look at the representative surface brightness profiles of the galaxies measured by van Dokkum et al. in 2013 (their Fig. 3), it seems that the disks were in place already at z$\sim$0.6, which is not far away from z$\sim$0.4 when the S0s appeared in clusters. It means that gas accretion has not been very strong after z$\sim$0.6, so that after that stripping mechanisms might have played an important role, possibly transforming spirals into S0s. In this picture disks are expected to have a mixture of stellar population ages, consisting mostly of old stars. It seems that the Milky Way mass S0s can be easily understood as former spirals stripped out of gas, without accreting any new mass. Morphologies of their disks within the optical galaxy radius are also very similar, manifested as inner and outer rings and lenses. The disks in the S0s are slightly hotter, which can be explained by gas stripping and internal dynamical heating. As discussed above, the bulges in the Milky Way mass S0s and spirals are also very similar.

The angular momentum parameter within one effective radius, λ_{Re}, has been measured by Falcon-Barroso et al. (2015) at redshifts 0.005<z<0.03. They found that in S0s and in Sa galaxies it is similar, but larger in Sb galaxies. Both high and low λ_{Re}-values were found in Sc-Scd galaxies. Based on the idea that the angular momentum, for a given galaxy mass and flattening, should not change much while transforming spirals into S0s by stripping mechanisms, they concluded that only Sa galaxies can transfer into S0s. However, λ_{Re} does not measure the original angular momentum of galaxies, being rather a measure of angular momentum in respect of the stellar velocity dispersion, which is high in bulges and perhaps also in lenses, and low in cool thin disks. Therefore, most probably the λ_{Re}-parameter in the different Hubble types reflects the relative mass of the bulge and lenses, which is similar in S0s and Sa galaxies, but drops in Sb galaxies (see Fig. 5 in Laurikainen et al. 2010).

My answer to the question whether the S0s could be gas stripped spirals instead of primordial galaxies, is that yes they can, at least if we restrict only to galaxies in a range of the Milky Way mass. Depending on the level of mass accretion during the Hubble time, and also on the environment where the galaxy is living, it is possible that such stripping, followed by quenching of star formation, might happen even more than once in the life of a galaxy.

Insights into the origin of S0s may come also from the side of Ellipticals. With the next interview to Pierre-Alain Duc we would like to enlarge the horizon considering the whole family of early-type galaxies (ETGs), which in the today's definition, includes Elliptical (Es) and S0s.

In the classification of Hubble "[Es] range from globular objects through ellipsoidal figures to a limiting, lenticular form with a ratio of axes about 3 to 1. It is probable that all regular nebulæ flatter than this limiting form are spirals" (Hubble 1936). Es "are highly concentrated and show no indications of resolutions into stars. The luminosity falls rapidly away from bright, semistellar nuclei to undefined boundaries" (Hubble 1936).

These apparently simple galaxies, from the morphological point of view, revealed, with the years the years, complex morphological characteristics, sometimes called fine structures for their intrinsic faintness. In addition, some Es have unexpected kinematic properties: their flattening is not connected to the galaxy rotation (Bertola and Capaccioli 1975).

Even the more complex classifications of ETGs developed up to the end of 1980s do not account for this complexity. It is hard today to consider either Es or S0s as homogeneous classes within ETGs, rather a set of families.

3.4 The Family of Early-Type Galaxies

Questions for Pierre-Alain Duc:
ETGs are considered a galaxy family, although inhomogeneous. They show a variety of peculiar kinematic features, like counter rotation of the stellar and gas components at different scales while deep, wide field imaging is unveiling faints features that may open a new view on their classification and understanding. A revision of ETGs classification, introducing the concept of fast (FR) and slow (SR) rotators has been proposed (see Emsellem et al. 2011 and reference therein). Why this classification may better describes the family of ETGs?

The SR vs. FR classification is up to now restricted to the central regions of early-type galaxies. How this kinematic view may account for the variety of features revealed, at larger radii [see e.g. Arnold et al. (2014) and Serra et al. (2014)], as those described above? What about a joint photometric and kinematic approach for robust bulge to disk decomposition?

I address here a critical view of galaxy classification based on our deep imaging survey. This part is closely related to the contributions of Debra Elmegreen (see Sect. 3.2), Didier Fraix-Burnet (see Sect. 3.6), George Lake (see Sect. 8.2). These questions indirectly address the morphological classification of galaxies, which traditionally relies on their appearance on optical images. The well known Hubble tuning fork, illustrated in Fig. 3.5, splits early-type galaxies (ETGs) which have a prominent bulge and late-type galaxies (LTGs) which are dominated by their disk. LTGs are themselves divided into barred and non-barred. How relevant is that classification nowadays?

First of all I have been always annoyed that the Hubble diagram ignores the numerous dwarf galaxies, which in fact have their own zoology and classifica-

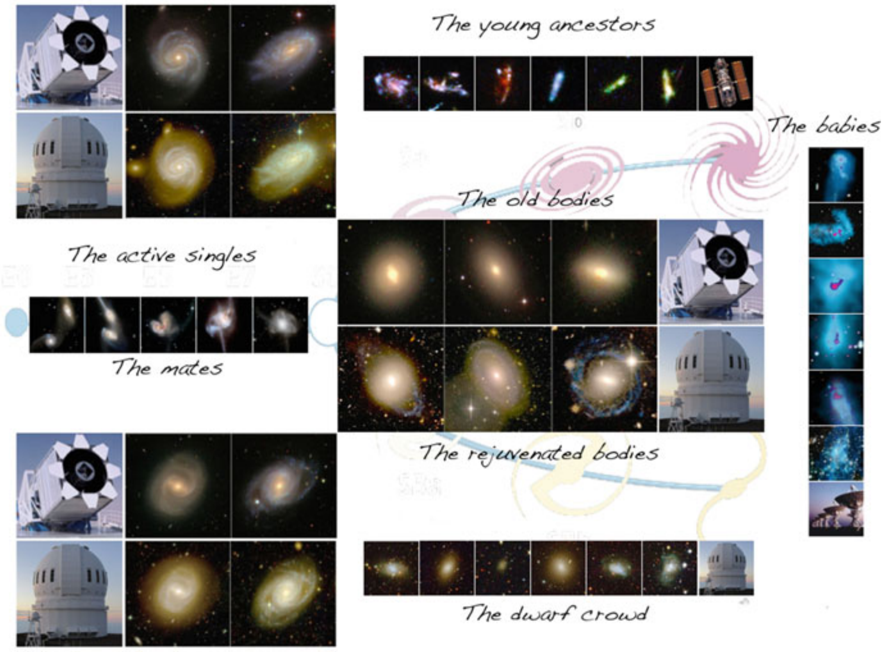

Fig. 3.5 *The blended family of galaxies*. The background sketches an old picture of it: *the Hubble tuning fork*. The *inverted diagram*, with optical images of *late-type galaxies* to the *left*, and *early-type galaxies* to the *right*, illustrates a more modern view of the sequence, in which mergers play a major role. Instances of interacting galaxies ordered as a time *Toomre sequence* are shown to the *right*. This tableau suffers a number of caveats. It misses important members: *the dwarfs*, though they are the most numerous in the family. Examples of various types of dwarfs portrayed by the Next Generation Virgo Cluster Survey are displayed to the *bottom*. Among the dwarfs, a sub-class has recently generated a lot of attention: the *tidal dwarf galaxies* that were born in the debris of galaxy collisions. The massive gaseous components of a few of them, as mapped in the radio with the Very Large Array, are shown to the *right*. This reminds us that studies of galaxies use multi-wavelength data, whereas galaxy classification is still made through the narrow optical window. To make the situation worse, the morphological appearance strongly depends on the depth of the images, as illustrated in the figure: each galaxy along the sequence of spirals and ellipticals is pictured with two images, a shallow one obtained as part of the Sloan Digital Sky Survey (*top*), and a ultra deep one from the Canada France Hawaii telescope (*bottom*). New structures show up on the latter images, in particular blue star-forming disks around ellipticals that were believed to be red and dead. Finally, another class of objects do not fit in the traditional Hubble diagram: the highly *perturbed/clumpy* distant galaxies detected by the Hubble Space Telescope in deep cosmological fields, such as the Ultra Deep field shown to the top. The exact link between these presumably ancestors and todays large spirals and ellipticals is strongly debated, and the imperious role of mergers in the galaxy transformation has been challenged. *Image credit*: SDSS, CFHT, NASA, NRAO, ESO

tion scheme: dwarf spheroidals, dwarf ellipticals, compact dwarf ellipticals, blue compact dwarf galaxies, ultra compact dwarf galaxies, dwarf irregular galaxies, Magellanic dwarfs, tidal dwarf galaxies. Besides, peculiar galaxies [see Arp (1966); Arp and Madore (1987)], as they were named when first discovered on photographic plates (and later on identified as interacting galaxies) are also missing though, as discussed later, they play a key role in galaxy evolution. Finally the Hubble classification cannot really be applied to the distant Universe. Above a redshift of 2, galaxies tend to be classified according to the selection criteria that were used to identify them—BzKs, LBGs, EROs, LAEs, i-band dropout, etc.—, and not based on their apparent morphology.

Even staying in the local Universe, the classification may change according to the wavelength domain. On the LTG sides, putting galaxies on the bar vs non-barred branch is not strait-forward. An unfavorable orientation may prevents its detection. The near-IR regime is actually much more adapted than the optical one to identify bars. More in general, one may wonder why one should give such a strong emphasis on the presence of a bar. Bars may indeed drive the secular evolution of galaxies, but other processes play even more major roles (not even mentioning external environmental effects), such as the inside-out migration of stars or the feedback by AGNs or starbursts (Eskridge et al. 2000). It is in fact believed that the majority of galaxies—60 %—host a bar. So the distinction should not be between barred and non-barred objects, but between weakly and strongly barred galaxies.

Turning to the ETG branch, the presence or absence of a disk is supposedly a fundamental criterion to distinguish lenticulars and ellipticals. On this branch, ETGs are ordered as a function of the bulge to disk ratio. There are numerous automatic methods to compute the B/D ratio, but eventually in many surveys the separation between ellipticals and lenticulars is done with the eye, and thus very subjective.

The availability of new types of images, obtained with surveys and data reduction pipelines optimized for the detection of low surface brightness (LSB) features, has recently blurred even more the Hubble classification (Duc et al. 2015). When galaxies are observed at limiting surface brightness of 28–29 mag arcsec^{-2}, new components show up: very extended sometimes distorted stellar halos, fine structures—tidal tails and shells—, or even LSB star-forming disks. Thus a number of galaxies become peculiar and should be banned from the Hubble diagram while the ETGs exhibiting in their outermost regions a faint spiral structure should in principle be considered as LTGs.

Given these issues, various alternative classification schemes have been proposed, with two opposite tendencies.

One method proposes to blur even more the Hubble diagram, forget about the presence of a bar or disk, and separate galaxies just based on their color. The Universe is then divided between the blue galaxies (i.e. forming stars) which inhabit a *blue cloud* and the red galaxies (passive, considered "dead") which live along a *red sequence*. This is how the million of galaxies from the Sloan Digital Sky Survey (SDSS), plotted on color-magnitude diagrams, are generally classified. To somehow mitigate such a Manichean view, astronomers have introduced the *green valley* inhabited by galaxies that are currently neither blue nor red (nor green!), either because they were blue and, being quenched, they suddenly lost their ability to form stars and are about to become red, or because they were red, are currently being rejuvenated with the accretion of fresh gas and become bluer, or because they are dusty hidden blue galaxies and are mistaken with red galaxies. To be provocative, this is the simplified Universe that cosmologists like: despite recent progress, their simulations have indeed a hard time to reproduce realistic galaxy morphologies whereas predicting colors is more strait-forward. More seriously, such a basic classification is instrumental when dealing with very large data sets [such as the SDSS: see Lintott et al. (2011)] for which a proper morphological classification becomes prohibitive (or requires the contributions of thousands of citizen scientists participating to the galaxy zoo project) and subject to strong biases. In contrast, determining the color of a galaxy with a good precision is child's or cosmologist's play. Besides, colors link galaxies and their star formation activity. The ability to form or not stars is a fundamental property which is likely more important than the galactic morphology.

Alternatively the galaxy classification (see the contribution of Debra Elmegreen in this volume) may be made more complex with the addition of extra morphological parameters: for instance the boxiness or the presence of a core in the central regions. This lead some authors to revise the Hubble tuning fork, adding new or parallel branches. Another approach is to add a third dimension, with the introduction of the internal kinematics. The world of galaxies is then divided into the *fast rotators* (including the spirals and most ex-lenticulars) and *slow rotators* (including most ex-ellipticals), depending on how fast their stars rotate (Cappellari et al. 2011a). Such a classification scheme supposedly better reflects the past mass assembly of galaxies. It is also more robust as the internal dynamics of galaxies evolve more slowly than their apparent morphology. A 3D classification is opportune in times when instruments with Integral Field Unit (`IFU`) spectroscopic capabilities have developed in all observatories. However, one major drawback of `IFU` cameras in their limited field of view, which hampers the study of the spatially extended nearby galaxies. As a result the kinematics is only known in the central regions, typically within 1 or 2 effective radius. Is the internal kinematics representative of the whole galaxy? Mapping the full galaxy with `IFU`s is extremely time consuming, especially because integration times have to be significantly increased towards the diffuse external stellar halos. Complementary surveys (Brodie et al. 2014) that use tracers other than stars, namely planetary nebulae or globular clusters, have recently provided amazing constrains on the very outer kinematics of massive nearby galaxies and revealed in a few cases discordant inner and outer kinematics.

Do such results imply that a classification based on the kinematics is also misleading and biased? A similar question was raised by the morphological revision induced by the use of deeper images. The answer is certainly NO . . . as long as the classification is based with a uniform set of data —same surface brightness limit, filter, field of view—, so that objects may be compared in a fair way.

In fact, before rating the merits of all these classification methods, one should wonder about our motivations to classify galaxies as they will eventually tell us how galaxies should be classified. Let us illustrate this with another field of research.

Fig. 3.6 *Left: Allium Ursinum* (wild garlic), family: Liliaceae; *Middle: Veratrum album* (false helleborine), family: Liliaceae; *Right: Gentiana lutea* (yellow gentian), family: Gentianaceae. The two first plants belong to the same family, but do not look each other, and moreover one is edible, the other toxic. The third plant (edible) resembles the middle one although they do not belong to the same family. In botanics contrary to astronomy, errors in the classification may be fatal. *Credit:* Prof Dr Otto Wilhelm Thromé, 1885, Gera, Germany. *Source:* www.biolib.deandwikipedia

I am rather ignorant about botanics and as such I have always been puzzled that plants like those shown on Fig. 3.6, which for me resemble each other have in fact been put in two different families. Plants assigned the same "type" have something in common that is more important than their visual aspect: similarities in the arrangements of their leaves, reproduction mode, chromosomes; such criteria may seem subtle or difficult to check, but are nevertheless considered fundamental. What is then fundamental for a galaxy? It is really its shape as seen by the eye-sensitive optical regime? The capability for a galaxy to continue growing with internal processes, to form stars, its "genetic" composition, e.g. the alpha over iron element ratio telling how star-formation proceeded in the past, the deviation of the galaxy from some standard scaling relations, e.g. the nowadays popular star formation rate—mass sequence, may be more discriminating criteria than the morphology or even internal kinematics.

Note that in the field of life sciences, taxonomy introduces a precise hierarchy in the classification scheme: Domain, Kingdom, Phylum, Class, Order, Family, Genus, and Species. The young astronomical extragalactic science only makes use of a few sub-divisions in its morphological classification of galaxies: basically a letter Sa–Sd or a number E1–E4 subdivides each class. Attempts to refine this were made, but no uniform scheme is used among astronomers. Astrocladistics (see a presentation of it at http://astrocladistics.org) is an effort to test on galaxies the taxonomy methods applied for a long time in botanics (see the contribution of Didier Fraix-Bournais in this volume).

Another difficulty arises when now considering the (morphological) evolution of galaxies. The hierarchical cosmological scenario implies that galaxies are not born spirals or ellipticals, but will become it at some time, i.e. redshift, during their evolution. Thus a morphological classification is time dependent. This is a major difference with plants or animals, which remain within the same species during all their life, although their aspect may dramatically change with time. Whereas the crawling monochromatic worm will unavoidably become a flying multicolored butterfly, most likely a given galaxy is not bound to end up as a big elliptical in a massive cluster of galaxies. Some of them will remain dwarfs for more than 13 Gyr; spirals may suddenly become an elliptical after a major merger, whereas an early type galaxy may gradually rebuild a disk. What is then irreversible in the world of galaxies, justifying their specific classification? In the life domain, species can also evolve.... but not at the time scale of an individual. Gradual adaptation to the environment, sudden chromosome anomalies, a disastrous meteorite falling or the intervention of man may cause an evolution, destruction or birth of species, but this occurs over multiple generations. This is a fundamental difference with galaxies that live in a Universe with a commensurable age. Just taking this into account, galaxy classification may appear meaningless.

3.4.1 Learning from (Deep) Imaging the Outskirts of Galaxies

Questions for Pierre-Alain Duc:
a wealth of structures emerges from deep images like rings, arcs, shells, arms, tails, plumes etc. Some of them are thought to be transient features created by interaction as well as by inner secular evolution. Once described in detail all the morphological characteristics displayed by galaxies, what are, in your view, the further steps to identify an evolutionary scheme?

Both photometric and kinematics studies have revealed the presence of disks, of different sizes, also in otherwise "bona fide" Es. What are the properties of such disks? Do they represent the link with S0 galaxies? What is the origin of such disks?

After a glorious period in the 1950s–1960s, when large field of view photographic plates of the whole sky were produced, deep optical imaging of the nearby Universe has until recently been neglected. The advent of sensitive `CCDs` in the 1980s, installed on large telescopes in the 1990s, triggered a prodigious step forward in the study of distant galaxies. Unfortunately the imaging surveys done with these devices which initially had small fields of view lacked sensitivity to extended low surface brightness features, and were thus improper to in depth studies of nearby objects. The development of large field of view cameras, coupled with optimized observing and data reduction techniques, and a growing interest for the so called galactic archeology, have recently changed the situation. Deep imaging surveys re-mapped nearby galaxies (Duc et al. 2015; Martinez-Delgado et al. 2010), disclosing around them sometimes prominent low surface brightness structures. They contribute to change the view we have on what we thought were familiar objects. There is an on-going competition between different teams to reach the lowest surface brightness limits. Radically different concepts of cameras are being developed and may eventually win the race (Van Dokkum et al. 2014). It is interesting to note that amateur astronomers are also valorous players: they obtain with their *simple* cameras,[3] amazing images (Martinez-Delgado et al. 2010) that are highly complementary to those produced by large costly facilities. For once in the astronomical world, the telescope's size does not necessarily matter.[4]

As argued above, the new structures found by these deep imaging efforts (see e.g. Fig. 3.7) may cause trouble in the traditional morphological classification. "Bona fide" ellipticals were initially classified as such because they did not show the presence of a disk... at the depth of the observations used to make the classification. This point of view may be changed with the discovery of a faint disk surrounding several nearby ellipticals (see examples on Fig. 3.5). However, the disks associated to lenticulars and later type galaxies and the low surface brightness disks disclosed by deep optical imaging are quite different.

It is striking that the newly found structures are particularly blue with, for several objects, no evidence of an underlying old stellar component. Located well outside the main stellar body, they show up in the UV (and for some of them were actually first found with the `GALEX` space observatory) and are associated with an extended gaseous disk of atomic hydrogen. They have likely recently been formed, perhaps out of gas that has been accreted from primordial flows, or more likely from nearby gas-rich companions or intergalactic debris of past collisions which is falling back (see also the contribution of Luciana Bianchi in Chaps. 1 and 7). This is in contrast to the disk of later type galaxies, including lenticulars, which contains an old stellar component, and has formed/grown long ago. However, one should recognize that only a few percent of bona fide ellipticals exhibit a star-forming disk or ring. So perhaps, much noise about little or nothing.

More frequent is the presence of collisional debris, such as *tidal streams* which emanate from tidally disrupted low mass companions, *tidal tails* which—according to my working nomenclature of fine structures—are the relics of major mergers from roughly equal mass parent galaxies, or *shells* which are typical of mergers between partners of intermediate mass ratio. How precisely frequent fine structures are remain to be determined. This depends on their survival time as they tend to evaporate with time, thus becoming more and more difficult to detect. According to simulations, the fading speed is different for streams, tails and shells, and varies as a function of the large scale environment. Collisional debris are more fragile in clusters than in groups. Rather than being a difficulty, the fact that fine structures

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[3]Simple being here an advantage over the complex cameras generally used by professional astronomers that are subject to a larger number of instrumental artifacts.

[4][Note of the Editors] These observations used small size (0.16–0.58 m) private telescopes with large field of view (20.4×30.6–73.7×110.6 arcmin) with a scale in the range 0.4–1.66 arsec px^{-1}.

Fig. 3.7 Deep image of NGC 474, classified S0, and the spiral companion NGC 470. The image has been obtained at the CFHT using MEGACAM

gradually disappear helps to set a time scale and to date past merging events. As an example, a prominent tidal tail pinpoints a major merger event that has most likely occurred less than 2–3 Gyr ago. Furthermore, the color, shape and gas content of the fine structures provide clues on the properties of the parent galaxies. The broader the tail is, the higher the velocity dispersion of its progenitor was. Its length, and even more its global shape, inform on the size and shape of the dark matter halo in which it expands. Its gas richness reflects that of its parent(s), while the broad-band color constrains the age and/or metallicity of the stellar populations in the parental disk. The frequency of fine structures may as well depend on the properties—morphological class, mass, dynamical status—of their host if they have, as predicted by cosmological simulations, different mass assembly histories (Cooper et al. 2013).

In the hierarchical CDM model, all galaxies should be surrounded by tidal structures which should be detectable…with instruments having an unlimited surface brightness. The systematic census of collisional debris, corrected for incompleteness issues, provides thus in principle a powerful test to the standard Cold Dark Matter model. This census has started in the Local Group, for which an exclusive high surface brightness sensitivity may be obtained thanks to individual stellar counts (see the contribution by Rodrigo Ibata in this volume, Chap. 2). Galactic archeology has already exhumed a wealth of filamentary structures around the Milky Way, and even more in the vicinity of the Andromeda galaxy which seems to have a more chaotic history than our Galaxy. The technique may be applied at larger distances, where the galaxies are no longer resolved into stars, exploiting the diffuse LSB stellar emission. The Universe has now been observed at all wavelengths, but the LSB sky remains a large virgin territory. Its exploration may become a source of key discoveries, even in the local Universe, provided that a proper instrumentation is developed.

3.4.2 The Depreciated Role of Mergers

Questions for Pierre-Alain Duc:
in the hierarchical evolutionary scheme galaxies tend to merge and to form larger and more massive systems. Alar Toomre and Juri Toomre in the 1970s proposed a merging sequence. What remains of that pioneering view? What are the best examples of nearby merging galaxies? What tell us the new multi-wavelength approach to the study of merger remnants? What are the signatures of a merging episode in early and late type galaxies?

The merger scenario for the formation of ellipticals has been for long very appealing, because it is consistent with the hierarchical CDM scenario, and also because models assuming a monolithic collapse have a rather hard time to produce pressure-supported systems. Thanks to the violent relaxation they induce, mergers make a good job at suppressing stellar disks. The already very convincing and realistic simulations of mergers pioneered by Toomre & Toomre in the 1970s have thus had an enormous impact on extragalactic science. In parallel the photometric analysis of nearby recent mergers, like the prototypical system NGC 7252, disclosed radial light profiles closer to the de Vaucouleurs profile that fit relatively well ETGs, than the exponential profile typical of disks (see contribution of Francoise Combes in this volume).

Mergers like NGC 7252 are very rare in the nearby Universe—just a few percent of galaxies show prominent tidal features—but have nevertheless been studied extensively. Indeed they can be used as a laboratory to study a number of physical processes, in particular the triggering of star formation or accretion onto the central massive black hole. Finally, these lucky galaxies provide us with very aesthetic images that flatter the annual calendars of observatories. It is remarkable that they

Fig. 3.8 The biased view of the nearby Universe as seen by telescopes/cameras during their first light. Interacting galaxies account for less than a few percent of the galaxy population, but for a large fraction of the first pointings. . . . At least mergers are good at producing nice-looking images!

nowadays emit the "first light" captured by most new telescopes around the world (see a portfolio in Fig. 3.8).

The multi-wavelength observations of nearby mergers revealed a number of specific properties for this class of objects, namely: (1) the presence of gas-rich debris, antennae, bridges, tails, etc. . . some hosting luminous compact condensations, the so called tidal dwarf galaxies (see below) (2) the presence of strong quantities of mostly molecular gas in their central regions, supplying nuclear star-formation or fueling an Active Galactic Nucleus (AGN) (3) a global star-formation enhancement, responsible for their usual strong mid-far infrared emission, followed for the most advanced mergers by a post-starburst episode which imprints a specific signature in their optical spectra (4) an internal kinematics which, despite the violent relaxation, does still show evidence of rotation. Are all these properties consistent with the hypothesis that massive ellipticals are old mergers?

Property (1) is OK as tidal debris tend to evaporate with time. The survival time of the prominent tidal tails is just a few Gyrs; very old mergers should look relaxed, especially if they are observed with shallow images. (2) may appear problematic since ellipticals are believed to be gas-poor (Young et al. 2011). However, an unexpected significant fraction of them exhibits molecular gas in their inner regions. The origin of this gas, found in spectroscopic line observations of CO and other species, is however debated. This gaseous component may not necessarily have been accreted, as evolved stars expel gas. The lack of gas in most ellipticals may be due to the presumably strong feedback by the central AGN causing the ejection of its gaseous surroundings (Feruglio et al. 2010). The discovery of molecular AGN driven outflows seems to indirectly support this scenario. Simulations however disagree on their real impact on the overall gas content of galaxies. (3) is a real issue since the bulk of the stellar populations of nearby ellipticals is confirmed to be old. This is not consistent with a merger induced starburst episode which should have a rather long-lived signature in their spectrophotometric properties. The *dry merger* hypothesis addresses this issue, since a starburst is only triggered if the merging galaxies were initially gas-rich. (4) is surely a difficulty: getting rid of angular momentum is not easy including through mergers (Bois et al. 2011). A rotating remnant is indeed expected even if the merging galaxies were initially non-rotating. The dance that precedes their mating, i.e. their orbital motion before the merger, generates an angular momentum, imprinting a rotation pattern in the merged body. To annihilate it, the galaxies should have very special orientations, with their internal rotation counter-balancing the orbital motion—a very unlikely configuration for the merger scenario. The good news is that most of ETGs do rotate. According to spectroscopic surveys of nearby ETGs, only about 15 % of them are slow rotators (Emsellem et al. 2011). These usually massive galaxies are a priori natural candidates for being the result of major mergers. In fact, simulations made in cosmological context state that their dynamics may be better reproduced if they are instead the product of multiple minor mergers that followed an initial founding dissipative event at high redshift, possibly involving a major merger.

Given all these stumbling blocks, the role of mergers in building ellipticals, after having been so much put forward at the end of the twentieth century, is currently being questioned. Besides alternative scenarios have emerged: the so called violent disk instabilities occurring in distant gas-rich galaxies generate massive clumps that migrate in the central regions and build a bulge without the need for an external merger (Bournaud et al. 2007). At the same time, there is a growing evidence that most of the star formation in the Universe occurred in a quiescent way and not in induced starbursting episodes, which contributes to further depreciate the role of mergers (Elbaz et al. 2011). We have entered in a merger skepticism times, not to say in a post-merger epoch. However, the large and debated uncertainties in the evolution of the merger rate as a function of redshift leaves large room for a still important role of mergers at least to drive the morphological evolution of galaxies. It remains undeniable that mergers do occur in the Universe—see the gorgeous images they produce. And thus post-merger objects necessarily exist and have to be identified. Even if it is claimed that the merger remnants do not quite look like "bona fide" ellipticals, they are surely more ETG-like, than LTG-like. I am thus totally convinced that a large fraction of ellipticals were primary made through merger events, some that likely have occurred at relatively low redshift.

I end this section by a question asked by Francois Schweizer in his contribution to the IAU Symposium 77 on "structure and properties of nearby galaxies" , which was held at a time where all galaxies were "nearby", in 1977! :

“*Let me be so rash to ask …provocative questions. Suppose that this meeting were held … in NGC 7252 at some 10 kpc from the nucleus …. What Hubble type would we give to the galaxy we would live in? S0, as NGC 7252 has been classified, or E, Sa, Sb or Sc.*”. The question is still topical.

The next interviews will deal with the lack of classification of irregulars and, in general, of dwarf galaxies in the Hubble’s sequence. Actually, Hubble did not neglect irregulars, indicate them as Ir, but considered them marginal. They simply represent a minority in his realm biased towards giants. In addition, irregulars “show no evidence of rotational symmetry and hence do not find a place in the sequence of classification” (Hubble 1936). At odds, the study of the Local Group, sketched in Chap. 2, evidences that Irregulars and dwarfs are the most frequent morphologies observed. Hubble has been puzzled about their nature compared to that of Es and Spirals. In The Realm of the Nebulæ” *stated “Their status, however, is speculative, and the absence of conspicuous nuclei may be of more fundamental significance than the absence of a rotational symmetry, which is a possible consequence”.*

Irregulars and dwarf galaxies were widely considered in the great Hubble’s sequence re-elaboration occurred during 1960–90s by Sandage and Tammann, from one side, and by the de Vaucouleurs classifications. Of particular interest is the dwarfs classification of Van den Berg in 1997 showing that in a limited range of absolute magnitudes their morphology mimic the entire classical Hubble sequence from disc-less, compact spheroidals to dwarf Spirals. In the society of the galaxies, *giants are a rare commodity and the manifold of faint galaxies includes quite “odd individuals”. Irregular galaxies emerge going towards faint absolute magnitudes. At the faintest galaxy absolute magnitudes the “tuning fork” disappears and only dwarf spheroidal and irregular galaxies systems remain.*

3.5 Extending the Hubble Sequence: The World of Dwarf Galaxies

Questions for Carme Gallart:
Deep imaging and spectroscopic observations revolutionized our view of dwarf galaxies. May you provide us with an historical evolution in the classification of dwarf galaxies?

Local Group dwarf galaxy, NGC 6822, was the first object to be recognized as being external to the Milky Way, and thus, dwarf galaxies were first identified and studied in the Local Group. Hodge in 1971 presented the first review paper on ‘Dwarf galaxies’, which was focused on Local Group dwarfs, the ones that had been studied in some detail till then, mostly by himself and a few others (such as the pioneers Swope, Baade, and van Agt). Hodge classified Local Group dwarfs in just two types: dwarf elliptical and dwarf irregular galaxies. The contemporary, pioneering searches for dwarf galaxies in nearby clusters (e.g. Hodge et al. 1965; Karachentsev 1965; Karachentseva 1967; Reaves 1962) classified them according to these two types. Later on, the Virgo dwarfs, observed using the 2.5 m DuPont telescope at Las Campanas, provided an ideal database for a wider morphological classification of dwarf galaxies (Sandage and Binggeli 1984). Sandage and Binggeli introduced dwarf galaxy types that are a progression from high luminosity to low luminosity galaxies: Sc and Sd into Sm and Im, with Blue Compact Dwarf (BCD) galaxies somehow related to these, E into dE and S0 into dS0. They highlight the lack of a sequence from Sa, Sb and Sc spiral galaxies into a class of very low luminosity spirals.

Using high-resolution surface photometry on excellent seeing images obtained at the Canada-France-Hawaii, Kormendy (1985) explored the observed correlations between core parameters of different galaxy types, finding correlations that have been since considered as probes of actual physical and evolutionary connections between different types of stellar systems (Kormendy and Bender 2012). Particularly telling are the correlations that can be observed between the central surface brightness and absolute magnitude of different stellar systems [see Figs. 3 and 1 in Kormendy (1985); Tolstoy et al. (2009) respectively]. Kormendy unexpectedly showed that large and dwarf elliptical galaxies do not form a continuous sequence: "Rather, bulges and ellipticals, dwarf spheroidals and globular clusters appear to be three very distinct kinds of stellar systems. Dwarf spheroidal galaxies are most closely related to dwarf irregular galaxies, and may have evolved from them".

The recent discoveries of very low surface brightness dwarf galaxies and ultra-compact, high surface brightness dwarfs provide a more complete picture of the variance in the properties of small stellar systems. Tolstoy et al. (2009) give the following list of dwarf galaxy types: "Early type dwarf spheroidals (dSphs); late-type star-forming dwarf irregulars (dIs); the recently discovered very-low surface brightness, UFD; and the centrally concentrated actively star-forming BCDs. The new class of even more extreme ultra-compact dwarfs (UCDs) are identified as dwarf galaxies from spectra but are of a similar compactness to globular clusters." I think after 5 years, this classification still holds (in their paper, these authors include the dT galaxies as particular cases of dIrr).

Purely morphological, or more physical, these classifications of dwarf galaxies all have in common that they are based on the current properties of dwarf galaxies, but they don't take into account their whole evolutionary history. It is quite possible that, if the ran the clock backwards by several Gyr, some galaxies now in different morphological types may have looked very similar. The star formation and chemical enrichment *histories*, covering the whole galaxy's lifetimes, obtained for Local Group galaxies, using color-magnitude diagrams reaching the oldest main sequence turnoffs and stellar spectroscopy, are starting to open the possibility to classify dwarf galaxies based on their own evolutionary history. Through the analysis of the lifetime star formation histories of a number of dSph, dT and dIrr, we are starting to glimpse that, at least for Local Group dwarfs, two basic *evolutionary types* of dwarf galaxies exist, which we are calling (these ideas have still not gone to press, except for a preliminary attempt in Gallart et al. 2014, in press) *slow dwarfs* and *fast dwarfs*: the SFH of UFd, *old* dSph and dT galaxies share the common characteristic of a strong early (age > 12 Gyr) and short ($\lesssim$1–2 Gyr) episode of star formation;

in contrast, dIrr galaxies started forming stars *slowly* (in the case of the smallest dwarfs with reliable SFHs, the main star formation activity started as late as 6–8 Gyr ago), are dominated by intermediate-age populations, and have kept forming stars in an approximately continuous way till the present time. The dSph galaxies satellites of the Milky Way that are dominated by intermediate-age populations (e.g. Fornax, Leo I and Carina) have SFHs that very much resemble those of dIrr: they are characterized, in particular, by a low (and/or delayed) initial star formation rate. We are currently analyzing this scenario, and trying to obtain some insight on the origin of the different dwarf galaxy types including the information on their full star formation histories.

Questions for Debra M. Elmegreen:
In a classification scheme, what is the location of Low Surface Brightness Galaxies?

Low Surface Brightness galaxies (LSBs) of course were not part of the original classification scheme since they were discovered more recently. Sidney van den Bergh was the first to discover LSBs during his development of the DDO Catalog of Galaxies (van den Bergh 1959a). Mike Disney was among the first to discuss the possibility of low surface brightness galaxies (Disney 1976), emphasizing that they are not just dwarf galaxies. He subsequently did a large study in the Fornax Cluster, which showed that LSB galaxies were common in the center (Phillipps et al. 1987). In an Annual Reviews article (Impey and Bothun 1997) on LSB galaxies, Chris Impey and Greg Bothun note that cluster LSB dwarfs have dIm and dE morphologies; they tend to be blue and gas-poor.

As for luminous giants, astronomers investigate about the origin of dwarf galaxies. Remarkable has been the debate about the existence of tidal dwarf galaxies. We interview Pierre-Alain Duc, one of the discoverers, about this subject.

Questions for Pierre-Alain Duc:
Galaxy-galaxy interaction may also generate new independent entities called tidal dwarf galaxies. May you explain evidence of such systems? Under what encounter conditions they are generated? What are their impact on galaxy populations in different environments? Do you believe that dwarf galaxies originate from the interaction of more massive galaxies?

Why dwarf galaxies are so important in the cosmological context if their total baryon mass is negligible? How can we extrapolate the frequency of galaxy interactions and their results to the high redshift epochs?

I will start with the last question…I work in a galaxy/cosmology group in which dwarf galaxies are barely discussed, for the very reason that they do not contribute much to the total baryonic mass: most of the stars in the Universe are in massive galaxies, and not dwarfish ones. Why should one then care about them? In the team meetings of my current collaborations, dwarfs deserve some attention mainly because they populate the low mass end of the galaxy mass function and allow to expand the x-axis, i.e. mass range, of global scaling relations. Dwarf ellipticals, dEs, are just dwarf …. (massive) ellipticals. However, my scruples to study these worthless objects vanish when I attend conferences focused on dwarf galaxies—there are several of them each year—: they suddenly become there the most useful laboratories in the extragalactic world. An inescapable fact to not leave them aside is that they are—by far—the most numerous objects in the extragalactic Universe, outnumbering the massive ones by at least a factor of 10 in our own Local Group. CDM model builders even say they are not numerous enough. They called this the *missing satellite* problem, a higher mass version of it being the *too big to fail* issue. The mismatch between the observed and predicted number of satellites may even be worse if not all the dwarf galaxies observed around us are these cosmological building blocks that for some reason escaped the merging process, but if part of them were made more recently, as second generation, recycled, galaxies.

This is the case for the so called Tidal Dwarf Galaxies (TDGs). The formation of dwarf-like objects in the collisional, tidal, debris of mergers, was first observed by Francois Schweitzer in the Antennæ galaxies and reported in the proceedings of the IAU S77 mentioned above. Quoting him "*although nothing is known as yet about its stability, we should envisage the possibility that tidal interactions may create dwarf galaxies and that these dwarfs may contain more metals than we would expect if we somehow think of primordial material there. This possible mechanisms for the formation of dwarfs was emphasized already long ago by Zwicky (1955)!*".

The name *Tidal Dwarf Galaxy* was first introduced by Mirabel et al. (1992) who re-observed the star-forming object near the end of the eponymous Antennæ. More than 20 years later, TDGs have been mentioned in about 700 articles (according to ADS) but their physical properties, stability and overall importance remain largely unknown. The subject has been revived recently with the publication of several papers claiming that they may make the bulk of dwarf galaxies, and, in particular, that in our own Local Group, the dEs lying along the so called *disks of satellites* are of tidal origin. After having devoted so much work to these baby galaxies born during the mating of their parent galaxies, including my PhD, and having promoted them to get my staff position, I should be pleased with these discoveries. Ironically, I feel uncomfortable with them and wrote papers denying the real importance of *my baby* galaxies.

What have we learned on the physics and distribution of TDGs since their discovery? The young ones, formed in recent mergers and for some of them currently located at more than 100 kpc from their progenitors, host star-forming regions. This property proves that the star-formation process may be extremely spatially extended in mergers and not necessarily concentrated in the central regions as often believed. Spectroscopic surveys have confirmed that the TDGs born in recent mergers are metal-rich: due to their specific genes—they are made out of pre-enriched material—, they are deviant points in the mass-metallicity relation followed by classical galaxies Duc et al. (2014).

Old-fashioned long-slit spectroscopy and more modern IFU spectroscopy have revealed that they are kinematically decoupled from their host tail: velocity gradients are observed in the ionized and HI components at the location of the star-forming regions. It is often assumed that they are gravitationally bound and virialized but this has not yet formally been proven. Besides, projection effects along a 3D bent tail may mimic a rotation pattern (Bournaud et al. 2007). The observed internal kinematics of TDGs has nevertheless been used to check that they lack "conventional" dark matter, to however claim the presence of dark hidden baryons or alternatively to support models of modified gravity. Indeed, the observed velocity curve of TDGs seems to match that predicted in the MONDian framework. Error bars however remain very large, and the lack of spatial resolution a serious issue to interpret the kinematics of TDGs.

The census of tidal dwarf galaxies has been made in a variety of environments: within the tidal tails of individual interacting systems of course, but also around massive galaxies that are possibly old mergers, in compact groups of galaxies where tidal interactions should be frequent, in clusters of galaxies, especially in their outskirts where actually the most well studied TDGs are located. For practical reasons, mostly star-forming and thus young TDGs have been searched. Their relative high metallicity could be confirmed from their emission lines, but most often not their stability. Hence it is noteworthy that papers generally provide list of TDG *candidates* and not genuine TDGs.

Efforts to count TDGs require in fact to agree on their identification criteria. Several definitions of TDGs have circulated in the literature. My own definition emphasizes the requirement to be a gravitationally bound, thus long lived, object. In that respect, identifying old TDGs that have broken the umbilical cord linking them to their parent galaxies, remains a critical task to derive their cosmological importance. Unfortunately very few such objects have yet unambiguously been found, i.e. objects that fulfill all the expected characteristics of TDGs: *specific genes*—a metallicity telling that they are recycled objects—, *specific history* —a past star formation that peaked at a specific time, soon after the mating of their parents—, *specific structural properties*—the absence of dark matter—, *specific environments*—given the way they were born, TDGs cannot be isolated, and should have a specific spatial distribution—.

The putative TDG candidates located along vast narrow planes around Andromeda or the Milky Way surely fulfill the last criterion. What about the others? Within conventional wisdom of galaxy dynamics, they are dark matter dominated, thus cannot be TDGs. However, some researchers, among them the group led by Pavel Kroupa, argue that because of tidal shaking, the velocity dispersion of their stars, thus their dynamical mass and mass-to-light ratio have been over-estimated. MOND advocates state that they host a phantom dark matter halo, which is compatible with a tidal origin. Turning to the first criterion, determining the genetic sequence of satellite galaxies with currently available large scale facilities has become much less expensive and time consuming. A parental test should give reliable results on their origins. But this requires that the genes have not been injured with time, or even have not mutated. If born several Gyrs ago, the dwarfs will have most likely faced a great deal of self-enrichment and gradually joined the mass-metallicity relation, erasing the signature of their deviant genes. Furthermore, the parents themselves were also chemically young when they gave birth and transmitted to their off-springs a metal-poor genetic heritage. In that respect, very old second-generation dwarfs might have a genetic legacy very close to that of first-generation primordial dwarfs. Last but not least, dwarfs born together are sisters and brothers: besides having a common genetic heritage, they inhabit the same house and should have experienced the same development and evolution. In particular they should have a similar star-formation history (SFH). This is clearly not the case for the Local Group dSphs. Stellar color-magnitude diagrams reveal a large variety in their SFH, and no strong evidence for a common peak of star-formation in the past. To be honest, parents know that members of the same family which presumably have received the same education may develop radically different identities. But statistically, it is undeniable that brothers and sisters look like each other. As long as one cannot prove that the dSphs along the plane of satellites have something in common besides their location, I will remain skeptical about their tidal origin.

Retrospectively, more than 20 years after they got promoted, I estimate that the most stringent progress on the physics of TDGs have come from numerical simulations. Idealized hydrodynamical simulations and chemo-dynamical models have taught us the physical mechanism driving their formation—instabilities in the gaseous component rather than in the stellar one—and the determining role of the shape of tidal fields. Simulations have shown that indeed objects formed in collisional debris may become gravitationally bound. Simulations have given clues on the local conditions pertaining the formation and survival of tidal objects against internal, i.e. stellar feedback, and external effects, i.e. ram pressure and tides. Simulations have warned us that, contrary to what is sometimes assumed, not all mergers are able to produce TDGs. Dry encounters, mating involving partners with unequal mass and speed dating, are infecund. Thus, until a proper TDG census is done in the real Universe—and I am afraid we are far from getting it—, simulations remain unavoidable to estimate their cosmological importance. Their predictions about the fraction of TDGs range between around 10 % for (what I consider) the most "realistic" ones to close to 100 %, an embarrassing number that forced a team to claim the pathetic failure of the CDM hierarchical model.

But how "realistic" are numerical models? The idealized simulations done so far (which have enough resolution, i.e. particles, mesh size or refinement level) do reproduce the observed properties of local mergers. But they may not be representative of the younger Universe when the bulk of TDGs might have been formed. At early epochs, galaxies had a larger gas fraction; their disk was instable, and more endowed to form massive TDG-like condensations. The mutual interaction between these clumps, further enhanced during galaxy-galaxy collisions, might have favored their proliferation and dissemination. The advent of simulations made in cosmological context, i.e. with self-consistent initial orbital conditions and properties of the merging galaxies congruous with their epoch, might in some nearby future give a more precise idea on the importance we should give to these objects.

I am not sure whether TDGs can really tell something about fundamental physics contrary to what is claimed in recent papers… or in my own observing proposals. The error bars are still too large for doing cosmology with TDGs. But for sure, they are the only genuine dynamically young objects present in the local Universe, and arguably the only dark-matter poor galaxies. As such, they are unique laboratories to study baryonic processes like star-formation and the large-scale recycling of matter.

Finally their very existence raises the question of the definition of galaxy which can no longer be based on its dark matter content, a criterion used to differentiate galaxies from globular clusters.

Tidal dwarf galaxies are among these oddities that do not fit in traditional classification schemes, but they contribute to the diversity and richness of the galaxy family portrayed in Fig. 3.5, together with all the recent new members, like the ultra faint dwarfs, and the ultra compact ones. As such, they deserve all our attention.

From the above interviews it clearly emerges the need to reflect upon the concept of galaxy classification itself and its purpose. The present morphology of galaxies may simply be a snapshot of the galaxy evolution movie. Does galaxy classification still make sense? What alternatives to the HS are possible and what have been attempted?

3.6 Going Beyond the Morphological Classification

Questions for Didier Fraix-Burnet:
You attempted a phylogenetic approach, called astro-cladistic, to galaxy classification. Would you express your opinion about the role of morphological studies in extragalactic astronomy?

It is interesting to recall that the debate about the usefulness of the morphological classification is a rather old one. There was a conference in 1990 (Longo et al. 1990) that confronted the morphological vs a physical classification of galaxies. The debate is still alive and Sandage in 2005 affirms his preference for the morphological classification and rightly noticed that the Hubble classification and the Hubble tuning fork have not yet been replaced by anything else some 15 years after this conference. So does the proponents for a physical classification have lost the battle? Is the morphological classification the unique and most powerful classification of galaxies?

To my point of view, all parties are right… and wrong. On one side, Sandage is perfectly correct when he says that classification should be driven by the data. Naturalists and biologists have known that for more than 250 years now. They have invented the science of classification (systematics) and have given birth to a branch of statistics that is so successful in several disciplines. On the other side, the proponents of a physical classification are right for fundamental reasons [see for instance Silk and Mamon (2012)]: would it be possible that one property alone could depict the diversity of billions of complex systems like galaxies that have evolved during billions of years? Could it be possible that the classification of galaxies, ensembles of billions of stars, could be simpler than the stellar classification? Would it be possible that one century of observations, technological developments, and so many discoveries about our Universe, have not yielded a modified view of the galaxy diversity? Why should we stick to the visible morphological parameter only while we have at our disposal morphologies from X-rays to radio wavelengths, spectra, chemical compositions, stellar populations, central black hole masses, kinematics of stars and gas. . . ? And if really the morphology is well correlated to other properties, why not use one of them that is quantitative, objective, simpler to observe even automatically, to build an equivalent classification?

So our modern physical understanding of galaxies clearly asks for a renewal of the classification of galaxies, a classification that is not based on morphology only and must be driven by the data.

I would add that a classification inevitably drives the physics, and not simply *can* as Sandage writes it. Indeed, there is not necessarily one unique immutable classification. There can be several classifications, each one having a particular purpose and changing according to the discoveries. In this sense a classification can be seen as "driven" (justified) by some physical question. For instance, you may want to classify the entire diversity of observed galaxies, or the different morphologies of galaxies in the visible or in the X-ray, or the different kinds of AGNs, like you want to classify supernovæ in the particular goal of probing the shape of our Universe. All of these classifications are perfectly legitimate provided that they are performed correctly and not used for other purposes. The morphological classification of galaxies will remain a classification of morphologies, nothing else. To classify morphologies, you have to use morphological parameters to build the classification. This will necessarily influence the physics you can do using this classification since everything will be related to the morphological parameters.

In conclusion, the physical goal drives the choice of the data, this choice drives the classification which in turn drives the physics you will infer from it. The most dangerous circularity is when you select your parameters from a priori arguments, like because you think they are the most important for instance. Then you end up with a classification that reflects you inputs, and you make no new physical inference.

So why despite after all these years and several attempts, the debate is still alive and no alternative to the Hubble classification and the Hubble sequence have yet emerged? To me, there are two reasons, apart from the simplicity and even the beauty of this traditional scheme.

The first reason is that I am convinced that the debate is based on a misunderstanding of the full classification process. I have noticed also that throughout the literature there is a frequent confusion between the Hubble classification and the Hubble tuning fork.

The second reason is the fantastic difficulty of the task. Each aspect of the classification process must be mastered and requires a great expertise. In addition, apart from a somewhat technical part present at each stage, a new global classification must prove its usefulness, pertinence, generality and completeness from an astrophysical point of view. The difficulty here is that physicists are not used to compare models to multivariate statistical results. So even if the technical difficulties were lifted, the way the astrophysical interpretation is made must evolve.

Let me clarify the full classification process, since this is an essential point in the debate. There are several distinct aspects to build a proper classification, each one being a different topic of statistics:

1. clustering (unsupervised classification): this is the statistical gathering of objects sharing some similarity (with the unique parameter of global morphology, this could be: elliptical, spiral, irregular);
2. taxonomy: this consists in characterising the classes with a full description, and giving them some name (the labels, which are obvious with one parameter like in the Hubble classification);
3. relationships: to understand the origin of the classes, one has to discover the relationships between the classes (this is the role of the Hubble tuning fork diagram);
4. classification (supervised classification): in statistics, this consists in putting new objects into previously established classes. But in more general language, this is the four aspects altogether, which adds some confusion.

The first aspect is the most important one, and depends much on the sample and the parameters. If you want to make a morphological classification, then select objectively the parameters that describe the morphology. When I say objectively, I mean three things: (1) all parameters, not only the easiest to obtain, (2) all of them and not the one you think are more important, (3) those that avoid redundancies and too much disturbance (use statistical tools to assess this). Then you must use some of the many clustering techniques developed in statistics. They all have their particularities and limitations, so that they should be seen as exploring tools to navigate inside a multidimensional parameter space.

The second aspect, taxonomy, is very important because there are some strict rules. In particular, when you are multivariate, the labels (names) of the classes should not be related to any particular parameters. For example, a class of galaxies which are blue and elliptical should not be called "blue" or "elliptical" or "blue elliptical". This rule has made the overwhelming success of the Linnaeus nomenclature in biology for about three centuries. Otherwise, you over-interpret the classification by putting forward a particular property and miss most of the physics. Let me take an example. The origin of lenticular galaxies (SOs) is not clear (Cecil and Rose 2007): are they formed as such or are they spiral galaxies stripped of their interstellar medium (see Eija Laurikainen in Sect. 3.3)? This formulation of the problem implicitly assumes that the SOs form an homologous class. This obviously cannot be true since at least two origins are physically plausible, making at least two theoretical classes. From a physical point of view, the good question is not about the origin of lenticular *galaxies*, but about the origin of the lenticular *morphology*. Other parameters are required to distinguish the two classes. The (multivariate) classification should give them two different names unrelated to any property, and unambiguously distinguish them in the data if they both exist in reality.

The third aspect, relationships, is useful to understand the origin of the classes. When Hubble established his classification, he tried to understand the physical drivers that generated the observed diversity. He proposed evolution (of the morphology) as the main factor and devised a scheme known as the Hubble tuning fork. This is not an observation, this is an interpretation at the origin of the terms "early-type" and "late-type" galaxies. This is an explanation of his morphological classification. In this approach (that I call clustering approach, see below), the relationships are outside the classification process, they are established afterwards, if required.

Phylogenetic approaches, the subject of astrocladistics, build the relationships directly from the data, and define classes based on the structure of these relationships, taxonomy coming next. Cladistics, also called Maximum Parsimony, is the most general of these approaches. For instance, with the two dichotomous parameters "elliptical" (yes or not) and "bar" (present or absent), a Maximum Parsimony analysis yields a tree that is exactly the Hubble tuning fork. This is obtained without any a priori classification or physical assumption, contrarily to what Hubble did. Not only the relationships are entirely integrated into the classification process, but it is the necessary first step. The only assumption behind Maximum Parsimony is that your objects can be related by some discrete or continuous link, that you will have to interpret at the end. I have demonstrated that this link is not necessarily real or physical, it simply shows the simplest path to follow if you could transform an object into another, even in a thought experiment.

I think that the proponents of a physical classification want to replace the Hubble tuning fork by a new diagram drawn in a space of physical parameters (Cappellari et al. 2011b; Conselice 2006). But these are not new classifications since the classification and the corresponding taxonomy are still those of Hubble. They are looking for the relationships between the Hubble classes (aspect 3), and are thus entirely driven by the morphological classification. This is perfectly correct if one is interested by the morphology of galaxies and its correlation or explanation with other properties. But in no case does it provide a general picture of the galaxy diversity and its origin.

At the end, the classification itself (aspect 4) is necessary to order new observations and to detect new kinds of objects when they cannot be put into the known classes. This is particularly crucial in the case of huge flows of data when the detection of deviant objects must be made automatically, if possible in real time (e.g. Andrae et al. 2011). You know that morphology is difficult to determine automatically. This is why some studies have tackled the problem from the start with multivariate data sets. However, since they want to recover the Hubble classification with clustering methods using multivariate objective and quantitative parameters (aspect 1), this results in a entangled process. Let me show why.

On Fig. 3.9, I depict the different approaches to classification: the Hubble method, the current multivariate studies and the complete process that I have been working on for the last 13 years.

Hubble proceeded correctly through a clustering method based on similarities, then devised the taxonomy to establish his classification (upper left panel of Fig. 3.9). It was based on the morphology only, and nowadays many studies propose a monovariate classification based on a particular property of galaxies, even though they are generally dichotomous: radio vs non-radio, infrared, ultraviolet or X-ray galaxies, field vs cluster objects, star-forming…Even if none of these monovariate classifications has the reputation of the Hubble one, it clearly shows that morphology is not enough to understand the physics of galaxies. At the end,

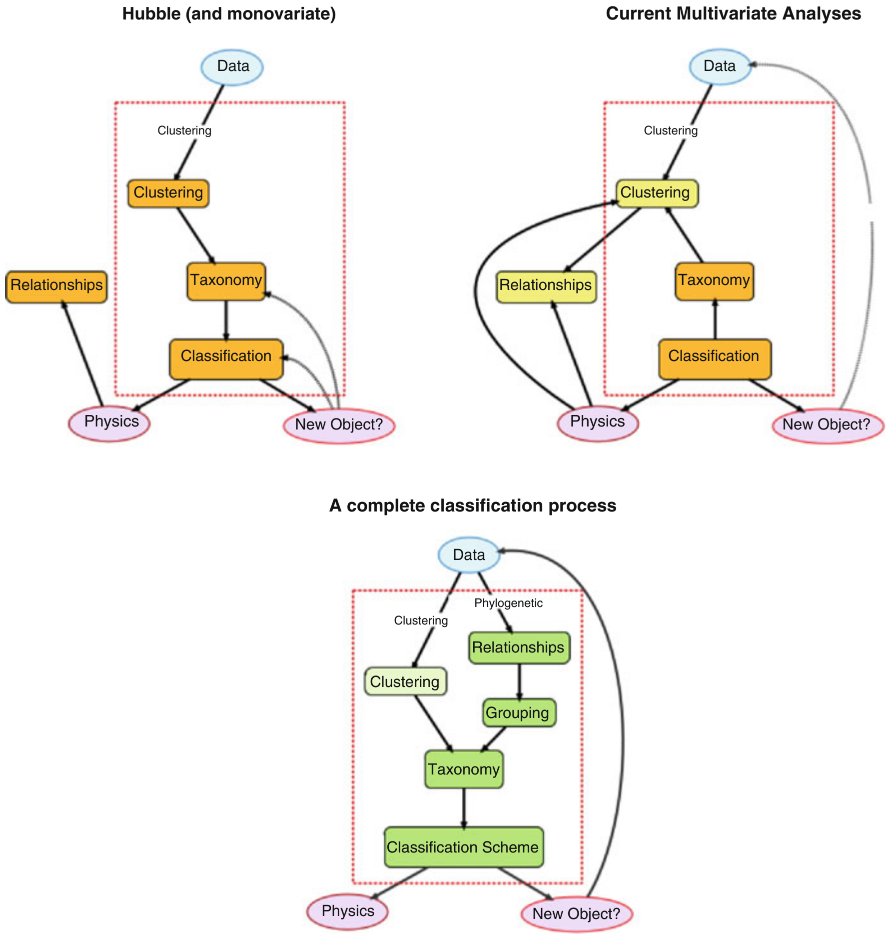

Fig. 3.9 Classification processes. *Upper left*: the Hubble classification. *Upper right*: most attempts to perform multivariate clustering analyses. *Bottom*: the correct and complete classification process that necessarily results in a new taxonomy and classification scheme

there are many monovariate classifications, not necessarily compatible with each other (a galaxy belongs to several classes, some classifications do not include some galaxies). This is startlingly similar to the situation of biology in the Middle Age, that fostered the invention of a new nomenclature by Linnaeus and of the multivariate analysis by Adanson in the eighteenth century.

How to make this classification method evolve in order to become multivariate and thus more representative of the real complexity of galaxies? The panel to the upper right of Fig. 3.9 shows my interpretation of the attempts done in this direction, mostly during the last 10 years or so, by most of the multivariate studies, and the proponents of a physical classification as well. Due to the enormous reputation of the Hubble classification, it occupies a central role in these studies. This leads to the paradox that the taxonomy and classification are still those from Hubble, even though the parameters and the clustering methods are different. Just recall the example of the lenticular morphology confused with a class. In this diagram, the circular process mentioned by Sandage is obvious! I personally do not see how a new classification scheme could emerge in these conditions, especially a scheme that could give new physical insights to the galaxy diversity and its evolution since the (visual) morphology remains so preponderant.

The bottom panel shows the correct way of doing multivariate classification. The branch called "clustering" is the same as the one followed by Hubble, but since we want to be multivariate, the taxonomy must be entirely reconsidered. The second branch, called "phylogenetic", is the one I have been following, because there are many kinds of links and relationships between different sorts of galaxies. Evolution is the most obvious one, like Hubble rightly thought. So why not begin by establishing these relationships from the data, right at the start? Anyhow, in both approaches, physics is a product of the classification process, so that there is no risk of circularity. But a new taxonomy must be invented.

Coming back to the role of morphological studies, I would say they are only one side of the diversification of galaxies. What is morphology after all? The distribution of the stellar orbits. This is neither less nor more important than the metallicities of the different populations of stars, or the presence of the black hole at the center of the galaxies, or the presence of molecular gas. So why concentrate exclusively on this feature? Probably because of the psychological effect of images that are always more artistic than, say, spectra! But we must do physics and understand the Universe as it is.

3.6.1 Multi-Parametric Classification Approaches

Questions for Didier Fraix-Burnet:
Multi-parametric approaches of a galaxy classification have been attempted in the past, may you describe what are their limits?

The first multivariate analyses performed with the purpose to renew the classification of galaxies are from Whitmore in 1984 and Watanabe et al. in 1985. There were only few similar studies until 2005, and then several papers are published yearly.

Indeed, most of the multivariate studies are intended to automatically classify observed objects into the Hubble morphological classification (Ball and Brunner 2010). The goal is not to build a new classification, but to use objective and quantitative observables obtained in large surveys (photometry and spectra) since one of the biggest problem with the Hubble classification is that the classes are determined with the eyes. Even the quantitative characteristics for morphology (e.g. Conselice 2003) are not easy to determine quickly and automatically and are subject to some caveats (Andrae et al. 2011).

So most of these multivariate studies have a specific goal which is not aimed at building a new classification system. I believe they are all based on the more or less advocated assumption that the morphology contains all the physics, so that using some physical observables should suffice to retrieve the morphological classification. Like Sandage warned in 2005, they end up into a circular process which is clearly visible on the upper right panel of Fig. 3.9. This is their limit. This is also true for other multivariate studies that pretend to build new classifications (Cappellari et al. 2011b; Conselice 2006).

This limit has a more fundamental cause: this is the absence of a nomenclature to design the new classes found in multivariate clustering studies. I am often disappointed when a very serious and often difficult analysis ends up with … the Hubble morphological classification to describe the results. For instance, a group of galaxies having a majority of elliptical shapes will be named the group of ellipticals for simplicity, throwing away all the methodological and the physical complexity! I know of only two studies that dare to give new names to new classes of galaxies: one by Sánchez Almeida et al. (2010) and my own work (Fraix-Burnet et al. 2010, 2012). These are only first steps toward a new taxonomy for galaxies, but this is really a key point.

It is clear that from the year 2005, there is a strong interest for multivariate analyses which proves the need for a new system to classify galaxies. There is a cultural revolution going on, but contrarily to the debate in the 1990s, a lot of groups have acquired advanced statistical expertise. This is related to the advent of astrostatistics, opening a new era for astrophysics. Regarding classification of galaxies, the bottleneck is the lack of an adapted taxonomy. This requires to get rid of a traditional usage.

May you explain your new astro-cladistic approach and its application to galaxy classification and evolution?

When you think over the problem of galaxies, three words come to mind: classification, diversity and evolution. These naturally points toward the evolutionary biology. So, in 2001, I discovered the phylogenetic tools, and especially the cladistics (or Maximum Parsimony) which is the most general, probably the simplest to implement, even though not the simplest to understand. Astrocladistics[5] was then born.

Astrocladistics is the introduction of phylogenetic methods in astrophysics. For instance, a big question is to find the progenitors of present day galaxies. This is typically a phylogenetic problem. Hence, using phylogenetic approaches to study the formation and evolution of galaxies, that I prefer to call the diversification of galaxies, looks a rather natural idea.

How does it work? Two objects are close not only because they are similar (like in clustering methods) but also because they share some relationship, like a common ancestor. The phylogenetic approach builds these relationships from the data, and

[5]http://astrocladistics.org/.

then classes are defined from the structure of these relationships (see right panel of Fig. 3.9). In the Maximum Parsimony technique, all possible arrangements of the galaxies on trees are built, and the one minimizing the total number of parameter changes is chosen. This represents the simplest evolutionary scenario.

The use of continuous parameters in Maximum Parsimony is widely debated in biology, yet there is a priori no argument preventing this practice. Indeed, we have demonstrated that it is mathematically justified. To my point of view, Maximum Parsimony can be used for any continuous distribution of points, the notion of "evolution" simply being the continuous variation of the parameters. In this case, one can see the relationships scheme as representing the relative costs to transform an object into another.

Maximum Parsimony is the most general and powerful technique to relate objects on a tree. It may be compared to the Minimum Spanning Tree method (also known by astronomers as the friends-of-friends algorithm) in the sense that it considers all possible arrangements between the objects and then select the most parsimonious one according to the weights attributed to the edges (branches). But Maximum Parsimony allows for unlabeled internal nodes (in other words unobserved "objects"). In this way, it considerably extends the range of possible tree structures at the expense of the computer time. It is a parameter-based approach, so it is relatively easy to implement accepting error bars and undocumented parameter values. Its main drawback is that it is NP-hard, preventing the analysis of thousands of objects at once. However, we are looking for relationships between classes (phylogeny), not between individuals (genealogy).

There are other phylogenetic techniques, but generally they are specific to the data or processes of biological evolution, so they cannot be applied directly to astrophysics. For instance, there is a class of probabilistic approaches that assume some laws for the gene mutations (usually under a brownian hypothesis). I am convinced that such probabilistic methods can be used for galaxies since we know rather well the transformation processes of galaxies. This is a direction I have not yet explored any further and would require the development of some statistical theory of galaxy diversification.

Galaxies tend to present continuous range of values for most properties. The advantage of phylogenetic approaches is that they treat continuous distribution of points more smoothly than clustering techniques. The latter are devised for distinct classes and generally yield rather sharp cuts in the multi-dimensional space of parameters, cuts which do not appear very realistic. For the same reason, phylogenetic approaches are suited to find evolutionary tracks, kinds of very elongated structures that clustering techniques cannot recover at all.

I am aware that reading phylogenetic trees needs some practice, but be happy since a more realistic representation of galaxy diversification might be a network (a split network also called reticulogram for cladists) because of "hybridisation" processes (mergers essentially) which, I think, may be as common among galaxies as among bacteria!

After nearly 15 years of development, where does astrocladistics stand? I must say that we spent a lot of efforts to learn, experiment, understand Maximum

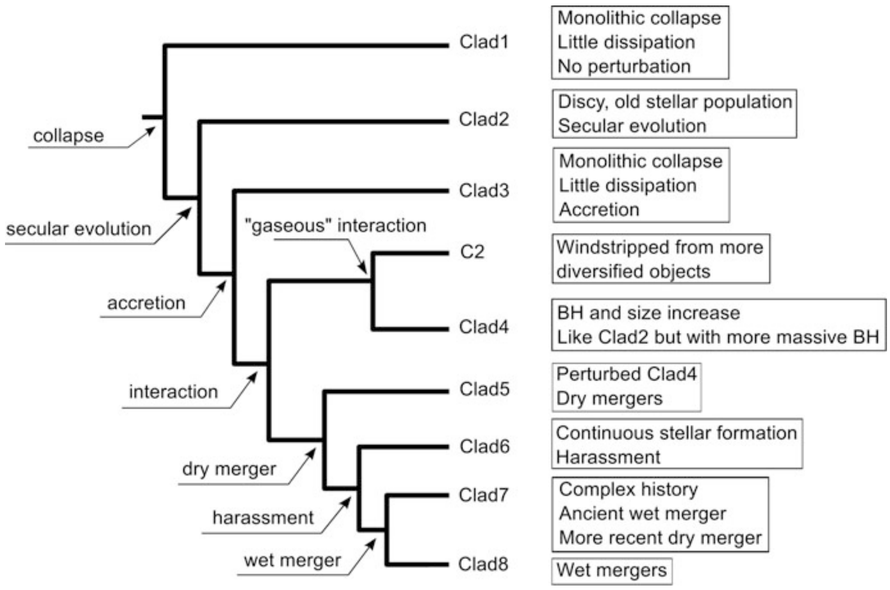

Fig. 3.10 A first step toward a global classification of galaxies based on their multivariate properties. From the properties of the classes, the history of the formation of the galaxies can be inferred. The internal nodes correspond to transformation events that are at the origin of the classes of galaxies emerging from these nodes (Fraix-Burnet et al. 2012)

Parsimony in the context of galaxies, and also for some other astrophysical objects like globular clusters, stars and gamma-ray bursts. We have compared this phylogenetic method with other clustering techniques. We have published papers in order to demonstrate the validity and usefulness of the approach. We have thus obtained a first instance of a true multivariate classification of galaxies (Fig. 3.10). It does not pretend to be global since only about a thousand galaxies have been considered, and these galaxies are not representative of the whole diversity we know. But this result shows that we are on the right track.

We have used correct taxonomic rules for this classification. The names of the classes are Clad1 to Clad8 and a class C2 coming from a previous study on a independent sample has been included. These classes are fully described using several parameters, and from these characterisation we analyzed the distribution of parameter values and correlations within each class, compared the classes, and used models and simulations from the literature to derive a possible history for the galaxies in each class. It is fundamental to understand that since our classes are characterized by many parameters, they are necessarily homogeneous, and very certainly homologous. As a consequence, they have a priori different formation histories which are easier to find thanks to the variety of the parameters.

From the diversification histories, we attempted to identify the events, represented by the internal nodes, that generated the new “species” of galaxies, which are the classes situated below the node in the ladderized representation of the tree given in Fig. 3.10. Here, the common ancestorship shared by some classes is a common transforming event that induced some new and durable property within a galaxy. This attempt is only tentative and illustrates the power of the tree-like representation that depicts the relationships between the classes.

To be clear, the tree representation results from an objective analysis of the data, it is not an interpretation like the Hubble tuning fork. The interpretation lies only in the inference of the formation histories and the transformation events indicated in Fig. 3.10.

This classification of a limited sample of the diversity of galaxies has already produced some major results. One of them is the possibility to compare in detail the properties of each class with numerical simulations of galaxy evolution. Why is this possible? Because our classes are homogeneous and built from many parameters, they represent more realistically the complexity of the transforming events that the simulations try to reproduce. This is impossible with a classification made from one parameter only since it is insufficient to constrain the many free parameters of the simulations

Another important result is that many correlations, or scaling relations, appear to be due to (co-)evolution, not to a causal physical process. It is striking that many correlations vary from one class to the other, and differ from the whole sample. This proves that there are different populations of galaxies, with quite different properties. Is this surprising? Not to me, but the difficulty was to correctly identify these populations.

This second result has strong implications for the fundamental plane of galaxies. This is discussed elsewhere in this book.

What's next for astrocladistics? Everything is now in place to extend the tree of Fig. 3.10 to cover most of the known diversity of galaxies and invent a new taxonomy. This goal is clearly within reach.

3.7 To Summarize

Cataloguing galaxies includes the art of the morphological classification. Well before the Great Debate, since first catalogues of nebulæ, the morphology has been considered one of their distinctive and fundamental characteristics. The galaxy morphology, before it is scrutinized, provokes a sort of fascination. Chip Arp and Barry Madore annotated in their "A Catalogue of Southern Peculiar Galaxies and Associations" (Arp and Madore 1987) "At it worst, cataloguing is a tedious and thankless pursuit; at its best it is simply tedious. However, for the two of us in the process of producing the seemingly endless listings of positions, types, sizes and descriptions that are contained in this Catalogue there was the pleasure of the discovery. Being the first to see a newly found galaxy, to be able to wonder, however briefly, at its place in a wider context and then to post notice of its existence, is an opportunity that few are privileged to share."

What does morphology tell us today when thousands of galaxies are under scrutiny in multi-band surveys? What classification criteria to adopt that can resist the stress-tests of the deep, high resolution, panchromatic images? Do we really can classify galaxy without pay duty on the impact of high resolution simulations?

The Hubble classification process was not straightforward. It required a good material (Hubble annotated "Millions of nebulae are within reach of existing telescopes, but relatively few are sufficiently large and bright for detailed investigation.") and the choice of definitely "good" criteria. Sandage synthesized the rules "A good classification can drive the physics, but the physics must not be used to drive the classification. Otherwise the process becomes circular. (Sandage 2005)" After "refinements/extension" between 1960 and 1990s the HS safely sailed for decades having a look at the Scylla of observations and avoiding the Charybdis of the theory, forte of the continuity between morphological classes, totally absent in the purely descriptive systems. Modifications of the tuning fork, of course, arisen but they do not change the spirit of the HS.

The flood of information about galaxies of each morphological class, panchromatic observations, the arrival in the scene of distant galaxies, are changing our view about galaxy classification and the Hubble system itself. Below are discussed some points of the chiaroscuro present in todays galaxy classification.

- **Refining the HS** *The HS extensions/revisions, mainly operated by de Vaucouleurs and Sandage between 1960–1990, integrated together with a detailed description of the Spirals and S0s substructures, Irregular, magellanic type dwarf galaxies. The goal of extended HS was to draw a very smooth transition between morphological classes. This systematic work obtained an unquestionable success for a purely morphological system. Moving along the extended HS, morphological types correlate, although with a certain dispersion, with some of the global properties of galaxies such as color, surface brightness and gas content. The morphology recovers relevant physical properties such as stellar populations, star formation properties, possibility of re-fuelling for star formation, etc.*
- **The panchromatic view** *The HS is based on photographic plates. Moving to e.g. far UV and/or far infrared windows morphological types inferred from optical imaging may radically change. Bars fade in UV and extended outer disk may appear; the elusive dust contribution to morphology emerges in FIR. The HS appears as* trompe l'œil *generated by a limited wavelength range. Morphological classes as in the tuning fork may exist, e.g. in Far UV, but they may result quite different, if not peculiar. There is no reason for which the B-band view may describe better a galaxy than any other band.*
- **The variety of dwarfs** *Dwarfs Ir of Magellanic type have been included in the extended HS. At the same time the variety of dwarfs displayed by deep observations is explosive disclosing a "parallel word" to the HS. Early-type dwarf spheroidals (dSphs), late-type dwarf irregulars (dIs), ultra-compact dwarf (UCDs)s, blue compact dwarfs (BDDs) etc. Even the nomenclature is not fully established yet. Dwarfs can have different origin. TDGs are supposed to be generated by tidal interactions. Genuine members of this class start to be*

analyzed in their characteristic. Low Surface Brightness Galaxies have been discovered at the end of 1950s by van den Bergh. LSBGs in cluster have dIrr and dE morphologies. This class includes very low surface brightness galaxies, called UDF. Classification is going-on!

- **The problem of ETGs** *The HS has been also thought to correlate with the maximum rotational velocity of the galaxy. This is reasonable on condition that the two sub-classes of fast (FR) and slow rotators (SR) are considered within the class of ETGs. SRs are "bona fide" bright (massive) ellipticals, typical clusters inhabitants, with very old stellar population. FRs (about 78 % of galaxies classified either E or S0, either barred or normal, in RSA and RC3) include S0s and many Es of intermediate/faint luminosity. FRs stellar populations appear younger than that of SRs.* α*-Enhancements measures suggest also a dichotomy between the two sub-classes: SRs have larger values suggesting a massive star formation event. A correlation is suggested between SRs and "core" nuclei in the luminosity profile at odds with FRs showing cuspy-core luminosity profiles. In this context, there is a growing tendency to view S0s, FRs, as a morphological sequence parallel to that of Spirals (see e.g. Cappellari et al. 2011a; Kormendy and Bender 2012 and reference therein) while SRs occupy the old space of Es in the HS. S0s are much gas poor than Spirals, although "anemic" spirals have been otherwise found in cluster: a classification scheme were proposed by van den Bergh taking it into account (van den Bergh 1976). The classification is closely tied to kinematics criteria: possible FR disk may only be inferred trough detailed surface brightness analysis. Consequences reverberated straight on the tuning fork.*
- **More on S0s** *The question if S0s are a sequence parallel to Spirals, recently revisited by the ATLAS*^{3D} *group, is one aspect of the S0s problem. In 1951 Spitzer & Baade posed the question: is it possible a transitions between Spirals and S0s? Although significant progresses have been done in defining the structural and kinematic properties of S0s, more than 50 years later the evolutionary path/s—at the end the primordial or the derivative nature of S0s—is not yet ascertained at least for all the range of masses. Some observations, discussed in next Chaps. 4 and 5 are indicating in the ram-pressure stripping of spirals, at least in cluster as suggested by simulation, the derivative nature of S0s. This fact is still stimulating their study.*
- **More about Es** *Es are not the amorphous galaxy class of increasing flattening supposed by the tuning fork. Inspected at different wavelength their morphology may radically change. They show a set of fine structures, shared with S0s, even if they are subdivided into FRs and SRs. Deep images may show shells, ripples, tails witnessing a recent although intense activity, that may become frantic in their nucleus with clear signatures in the optical. The simple addition of -pec- to their classification does not account for the variety of symptoms.*
- **Automatic classification** *One of the modern difficulties in the art of classification is that the volume of well-resolved galaxy images provided by modern multi-wavelengths surveys, is so large to make nearly impossible the by eye*

classification of individual astronomers. Although difficult, such work can be carried out by automatic image analysis systems studied to provide quantitative estimates of galaxy types. Machine classifications adopt different techniques and are efficient for statistical purposes, but often loose the variety and richness of morphological details as well as new possible categories of features in galaxies. They may reach anyway results comparable to by eye human classification. Odewahn et al. (see Odewahan et al. 2002 and references hereafter) remarked "However, it must be conceded that none of these classification systems are truly morphological in nature. In general, each method uses one or more two-dimensional parameter space based on global image properties and produces a type estimate via mean correlations .... using some multivariate pattern classification approach (e.g., linear parameter space divisions, principal-component analysis, decision tree, artificial neural network)."

Beyond doubt the HS offers a simple scheme *for classifying, by eye, a moderate amount of galaxies and galaxy vs. physical properties relations that can be used for machine classification. Initiative of crowd-sourcing classification, like that of the Galaxy Zoo project (Lintott et al. 2011), have been attempted with success.*

Didier Fraix-Burnet and collaborators experimented a new approach to galaxy classification abandoning the HS. The adopted approach is called astrocladistics. Being derived from phylogenetic algorithms, the multi parametric approach is suitable to understand the evolution of galaxies and to capture their formation mechanisms rather than to provide galaxy morphology. Galaxy simulations are widely used to infer/check evolutionary paths. There is an abyss with Sandage's view about classification.

Our interviews indicate that the morphological classification is still waiting a widely accepted scheme able to account of all galaxy properties, either for luminous and faint systems.

A detailed galaxy classification might be the herald of a better understanding of galaxies. The extended HS taxonomy, with its continuity among classes and the detail definition of substructures (rings, bars, etc.), demonstrated their invaluable role for statistical studies of galaxies, such as the categorization of their physical properties. Notably the extended HS can be also used to "instruct machines" for classifying the flood of galaxies from surveys.

The Hubble classification scheme had a fundamental role in triggering "key questions" about the nature of entire families of galaxies, like ETGs. Multi-wavelength observations may, however, return a galaxy morphology totally different from that in the optical band: all the local information reverberates on distant galaxy surveys.

Interviewers expressed also their doubts as well as their different points of view concerning the classification schemes, the criteria used for classification and even about the need of a galaxy classification. There is a growing tendency to emphasize that galaxy are not frozen but evolving individuals. In this framework the observed morphology represents just a snapshot in the "family album" of the entire galaxy life. This needs to be taken into account in galaxy taxonomy.

In the next Chap. 4 are presented and discussed galaxies substructures. Their use has been proposed instead of the global galaxy classification (see e.g. Djorgowski in the 1992 conference Morphology and Physical classification of galaxies) for understanding the main processes driving the evolution of galaxies. Most of them, however, change with time like their hosts.

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Chapter 4
The Anatomy of Galaxies

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Je puis bien concevoir un homme sans mains, pieds,
tête, car ce n'est que l'expérience que nous apprend
que la tête est plus necessaire que le pieds.
B. Pascal *Panseés* Fragment 102

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4.1 Chapter Overview

Just after WWII Astronomy started to live its "Golden Age", not differently to many other sciences and human activities, especially in the west side countries. The improved resolution of telescopes and the appearance of new efficient light detectors (e.g. CCDs in the middle eighty) greatly impacted the extragalactic researches. The first morphological analysis of galaxies were rapidly substituted by "anatomic" studies of their structural components, star and gas content, and in general by

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detailed investigations of their properties. As for the human anatomy, where the final goal was that of understanding the functionality of the organs that are essential for the life of the body, galaxies were dissected to discover their basic structural components and ultimately the mystery of their existence.

The first morphological studies and photometric analyses already identified many galaxy structures, that only later on stellar and gas kinematics were able to identify as separate and independent galaxy components. Despite these efforts many questions are still open today. What define a galaxy component? Does exist a structural component common to all galaxies? How much galaxy components are the product of nature and what can be attributed to nurture? What in synthesis define a galaxy system? And why some galaxies obey scaling relations and others do not?

In this chapter we interview several outstanding extragalactic astronomers to find an answer to the above questions. At the end we will have a much clear view of what astronomers actually mean when they speak of galaxy components.

We start in Sect. 4.2 with the central region of galaxies, often controlled by massive nuclei whose activity in terms of feeding and feedback might have important consequences for the evolution of the galaxy as a whole. Here we try to define the limits of the nuclear activity and the links that exist between the inner massive black hole, suspected to be the central engine of such activity, and the galaxy as a whole. Last but not least, we explore the connection between the nuclear activity and the galaxy environment.

Section 4.3 deals with one of the most debated issues about galaxy structure: the bulge component. What define it? how and when it was formed? to what extent bulges are naturally produced during the collapse of the protogalaxy and what can be attributed to secular evolution and merging events? In the same section we highlight the main properties of galaxy disks, briefly reviewing their structures and kinematics. Again, some underlying questions remain to be answered: how disks evolve with time? why galaxies disk exhibit different substructures (bars, lenses, rings, spiral arms) and different light profiles? in which way they chemically evolve? Why spiral arms are not equal in all galaxies?

Section 4.4 and 4.5 have been explicitly dedicated to the typical disk substructures. Although not present in all disk-like objects, these structures have an important role in galaxy evolution. Are they transient phenomena occurring on the disk components? How much they contribute to the general evolution of the galaxies and in which way? We will see what the current models are able to predict up to now.

Originally Sect. 4.6 had to address the properties of the less known galaxy component: the halo. Its structure and stellar/non-stellar content is indeed poorly known still today. The halo is the more difficult component to define and study, and would merit by itself an entire book. Actually a detailed analysis of this component is possible only in the MW and its neighborhoods. We therefore decided to focus our interviews on one important physical effect connected with halos: the gravitational lensing phenomenon. Why it is so important and what can we deduce about halos from this analysis? In the same section we also ask a question on the most typical stellar aggregate present in galaxy halos: the Globular Clusters. They are the oldest stellar systems and could therefore testify about the first epoch of galaxy formation.

In Sect. 4.7 we remind that galaxies often contain a non negligible amount of gas and dust. However in the whole Universe the percentage of cold gas represents a very small fraction of the global energy density. So, why should we care of it? Interestingly we will discover that this material can teach us a lot of things about galaxy evolution and the origin of the first galaxies. Following such discussion, Section 4.8, will introduce the theme of the hot baryon component of galaxies, mainly visible in the X-ray domain. What can we learn about galaxies from these studies?

Section 4.9 ends our discussion of the main galaxy components addressing the most neglected one: the magnetic field. This is not a classical component made of stars and gas and normally we cannot see it without measuring the polarization of light coming from galaxies; this has been always a very difficult job. However, today we are gaining more and more insights of the importance of magnetic fields in galaxies, in particular for their connection with the star formation process.

With Sect. 4.10 we review again the concept of stellar population and its connection with the structural components of galaxies. As it emerges from several parts of this book the various generations of stars do not reside everywhere in the galaxy body and can also migrate across it. Why then stars seems to know very well where they should reside? How the different populations of stars were chemically enriched? Why the Mass-to-Light ratio is so entangled with the galaxy Mass?

We finally discuss the main scaling relations that galaxies have shown to obey in Sect. 4.11. The physical origin of many of such relations is still not completely understood. We will address in particular the relations known as Fundamental Plane and Tully-Fisher. These relations tell us that galaxy form and evolve following well defined rules, but we miss some fundamental physics behind them. Their existence seems to indicate that a strong fine-tuning exists between the star formation history and the structures which host the stellar populations. We will also discuss the linearity of these scaling relations and their consequences for understanding the processes which gave origin to the present morphological classes of galaxies.

4.2 The Nuclear Region

Questions for Malcolm Longair:
the nuclear region of galaxies often host an active galactic nucleus (AGN) or are the site of an intense star formation activity (starburst). Could you briefly review the physical processes occurring at the center of galaxies? Which were the main steps which lead astronomers to formulate the standard model of AGN? What are the ionization mechanism dominating in the galaxy nuclei? Do all galaxies host an AGN, and if not why?

The simplest response to these questions is to refer the reader to my book *High Energy Astrophysics* which in its 888 pages provides reasonably detailed answers to many aspects of these questions (Longair 2011).

Looked at from the broadest perspective, the key features of active galactic nuclei which drove astrophysicists to invoke black holes as the prime cause of extreme high energy activity in active galactic nuclei were their extreme optical luminosities, up to 1000 times the luminosity of a galaxy such as our own, and their rapid time variability. An excellent survey of what was known soon after the discovery of quasars in 1963 is contained in the book *Quasi-stellar Sources and Gravitational Collapse* (Robinson et al. 1965). The observation of variability was the crucial piece of evidence since it necessitated coherent activity over time-scales of months to years. Concepts such as coordinated supernova explosions were considered, but rejected. The first suggestions that accretion onto black holes was an extremely powerful and compact source of energy were made by Salpeter (1964) and Zel'dovich (1964). The first serious attempt to construct such accretion models was carried out by Lynden-Bell in 1969 for spherically symmetric black holes (Lynden-Bell 1969) and by Bardeen in 1970 for rotating Kerr black holes (Bardeen 1970). The fact that these models could extract up to 42 % of the rest mass energy of the infalling matter in the case of a maximally-rotating Kerr black hole was a compelling argument and could account for even the most extreme cases of active galactic nuclei. By the early-to-mid 1970s, the black hole paradigm was the only viable model for active galactic nuclei on these rather general grounds. It is intriguing that it was the discovery of the quasars which stimulated a great deal of innovative research in General Relativity and established clearly the need for black holes, as they were named by Wheeler (1968), as the most powerful energy sources we have available to power them.

Once the black hole paradigm was established, the challenge was to convert this picture into a real physical model of the origin and evolution of black holes in active galactic nuclei, to understand the means of energy production and to understand the impact of their environments upon what we observe. On general grounds, it is not so surprising that black holes and active star formation take place in the central regions of galaxies. The deep central gravitational potential wells of galaxies mean that dissipative matter tends to accumulate in these regions. But at this point, the story becomes complicated. It is easy to write down a list of astrophysical process which must occur to a greater or lesser extent in these regions, but which are the most important and how they fit together to provide a self-consistent picture of what is observed are far from straightforward issues.

Most astrophysicists would probably agree with the following statements:

(1) The striking correlation between the masses of the central black holes and the masses of the spheroids of the galaxies within which they are located demonstrates that the growth and evolution of the central black holes cannot be dissociated from the evolution of the galaxy as a whole (Häring and Rix 2004). As the masses of the galaxies grow, so the masses of the central black holes must increase. The obvious ways in which this can take place is by the accretion of matter onto the black hole and/or by coalescence of lower mass black holes. The latter processes occurs rather naturally in the preferred picture of the hierarchical clustering and coalescence of galaxies as the means by which

they have evolved into their present forms. This is a 'bottom-up' scenario in which large galaxies are built up by the collision and coalescence of lower mass systems. Dynamical friction ensures that the black holes spiral into the central regions of the galaxy.

(2) There is a requirement for astrophysical processes which result in the formation and acceleration of relativistic plasmas in the nuclear regions of galaxies. The most direct evidence for these processes comes from the observation of superluminal motions of those radio jets observed in the nuclei of those quasars which are intense compact radio sources. In these cases, it is unambiguous that there are large fluxes of relativistic plasma in these jets and that these give rise to the non-thermal radiation observed in active nuclei. The problem is that the means by which the fluxes of non-thermal particles are produced are not fully established in the complex conditions in the nuclei of galaxies. While we can make a good case for the diffusive shock acceleration process being the means of accelerating the relativistic electrons, protons and nuclei in the shells of supernova remnants (Bell 1978), what are the corresponding sites in active galactic nuclei? This is a non-trivial question since it is those types of particles which would be responsible for the non-thermal ionising radiation which give rise to the continuum and emission-line spectra in extreme active galactic nuclei. It is also possible that quite different processes are responsible for the acceleration of particles close to rotating (Kerr) black holes. The electromagnetic acceleration process described by Blandford and Znajek (1977) is an example of this.

(3) It is unambiguous that in a number of well-studied cases, the strong emission lines seen in the spectra of active galactic nuclei are the result of photo-excitation of dense clouds close to the nucleus itself. I personally find the technique of reverberation mapping a remarkable way of disentangling the structure of the clouds in the vicinity of nuclei (Peterson et al. 1991). In this technique, the delay times between the emission of the exciting radiation and the response of the clouds in the vicinity of the nucleus are measured and result in a 'layered' ionisation structure, the densest clouds being closest to the nucleus and displaying the broadest lines. But this is a very demanding programme requiring a large amount of dedicated time on large telescopes.

(4) It seems probable that the means of probing as close to the event horizon of the black hole as is physically possible is provided by X-ray spectroscopy of the fluorescence lines of iron which quite plausibly originate from almost the last stable orbits about black holes (Fabian et al. 2002). This has proved to be more difficult to pin down than was originally expected, but the potential is there. The X-ray lines are broadened and asymmetric, just as expected if the reflected X-ray emission originated so close to the last stable orbit about the black hole that the combined gravitational and Doppler redshifts produce just such a distortion of the lines. If this interpretation is correct, the lowest energy photons from the fluorescent lines must have originated very close to the event horizon and so sample physical conditions there.

(5) It seems inevitable that the effects of obscuring tori about active galactic nuclei influence what is observed. The 'unification' industry attempts to account for what is observed in many different types of active galactic nuclei by either directional or spectral selection effects (Antonucci 1993). In some cases, this must be the case. For example, the superluminal phenomena observed in some of the extreme quasars require the observer to be looking close to the axis of the relativistic jet. The unification of bright radio galaxies and radio quasars as the same types of objects observed in the presence of an obscuring torus about their nuclei but at different angles of the jets to the line of sight seems to me very compelling (Barthel 1994). But it would be wrong, in my view, to regard this as an open and shut case.

Perhaps the most important conclusion of these considerations is that there is no single approach which is going to solve the issues involved in the physics of active galactic nuclei—it is a multi-wavelength problem and needs a generation of astrophysicists who are comfortable with making observations in all the available wavebands and of using the appropriate physical and interpretive tools to understand what they mean.

Among the massive galaxies, it is likely that all of them possess massive black holes in their nuclei, but it must be borne in mind that it is far from trivial to determine unambiguous black holes masses, as has been emphasised by Kormendy and Richstone—this is particularly the case for low mass galaxies (Kormendy and Richstone 1995). I find the correlation between mass of the bulge and the central black hole mass, for example that presented by Häring and Rix compelling evidence for the ubiquity of black holes in galactic nuclei (Häring and Rix 2004), the correlation including the $4 \times 10^6\, M_{\odot}$ black hole in the centre of our own Galaxy.

For a general review of the AGN characteristics and the astrophysical issues that are still open today, we suggest the reader to have a look not only at the fascinating book of Malcolm, but also at the book "Fifty years of Quasars" by Mauro D'Onofrio, Paola Marziani and Jack Sulentic, that has recently celebrated the discovery of quasars, the mysterious objects found by M. Schmidt D'Onofrio et al. (2012).

Now we will better define the demography of BHs in galaxies and the connection found between their masses and the bulge masses.

Questions for Laura Ferrarese:

HST has revolutionized the investigation of galactic nuclei and the search of central massive black holes (BHs). May you sketch the most important progresses coming from HST observations in this research area?

"Revolutionize" is a pretty strong word but, in this case, it is indeed justified: HST has entirely changed the nature of game when it comes to Supermassive Black Holes (SBH). This in spite of the fact that the best SBH detections do not come from HST; in fact, I will go as far as saying that none of the HST measurements has led to *conclusive* evidence of the existence of a singularity in a galactic nucleus. That proof comes from other data: Keck and VLT observations of the orbital motions of stars in the Galactic centre (Ghez et al. 2008; Gillessen et al. 2009) and the VLBA water maser study of NGC 4258 (Herrnstein et al. 2005; Miyoshi et al. 1995). However, such exquisite measurements are only possible in a handful of special cases. HST has allowed us to measure central masses in dozens of galaxies (e.g. Ferrarese and Ford 2005), many of them not showing signs of nuclear activity: of the ∼50 galaxies with a SBH mass measurements, 40 come from HST (e.g. Gultekin et al. 2009). It has led to the acceptance of SBH as a common component of galaxies, to the point that it has become noteworthy to find examples of galaxies that do *not* host one. An entirely new field—*SBH demographics*, namely how black hole masses correlate with the properties of the host galaxy—was born thanks to HST. And with that, the recognition that SBHs might play a very fundamental role in how galaxies evolve.

There are two reasons why HST has been so influential in this field. The first is spatial resolution: black holes can only be detected through the gravitational pull they exert on the surrounding material (be it stars or gas). As one moves away from the center, the gravitational pull of the black hole decreases, while the collective gravitational pull of the stellar body of the host galaxy increases. This implies that the region of space within which the gravitational potential of the SBHs dominates over that of the surrounding stars is rather small. On the plane of the sky, it projects to one second of arc or less for all but the most nearby or most massive galaxies: a region too small to be spatially resolved from the ground, due to blurring introduced by the Earth's atmosphere (there are notable exceptions, and the game will once more change with the advent of Adaptive Optics-assisted spectrographs on the next generation of ground-based 30m facilities, e.g. Do et al. 2014). Working above the atmosphere, HST could resolve details at the tenth of a second of arc level, and as such it could peer into the heart of black holes' sphere of influences.

The second reason is perhaps less widely appreciated. Allow me a bit of a detour: as a graduate student, I had the very good luck of working with Holland Ford, a key figure in the development (and then refurbishment) of HST. Holland and his collaborators had embarked in an HST program (with the very first generation Planetary Camera), to image the brightest 12 early-type galaxies in the nearby Virgo Cluster (I will point out here that even if the images were taken with the still unfurbished HST, they were spectacular by the then ground-based standards). Included in that sample (by mistake, I might add, since it was later realized the galaxy is not actually in the Virgo cluster, but part of a small group at about twice the distance) was NGC 4261. The HST images revealed a 1.6 arcseconds (230 parsecs) regular, thin disk of gas and dust surrounding the nucleus; immediately we realized that the regularity of the disk must reflect the signature of material in cold, circular rotation. This opened the possibility of using gas kinematics to probe the nuclear mass distribution. Indeed follow-up HST/FOS observations allowed to confirm the Keplerian nature of the gas kinematics, and constrained the mass of the central SBH to $(4.9 \pm 1.0) \times 10^8\ M_\odot$ (Ferrarese et al. 1996). As more nuclear dust disks were discovered (Tran & collaborators 2001 found that close to 20 % of early-type galaxies host NGC 4261-type disks) and kinematical studies performed, it became clear that gas dynamics can be a reliable (and, compared to stellar dynamical studies, relatively inexpensive in terms of observing time) method to measure SBH masses. This was a game changer: until then, gas dynamical studies had been summarily dismissed based on the (not unjustified) danger that gas (unlike stars) can easily be accelerated by non-gravitational forces (e.g. Kormendy and Richstone 1995). NGC 4261 helped change that frame of mind, and today over one-third of all SBH mass measurements come from gas dynamical studies.

The recent years have seen the discovery of a correlation between the mass of the spheroidal component of the galaxies and that of the inner massive BHs. How and when this relation set up?

The answer to this question would require its own book! In short, we do not yet know. From a theoretical prospective, the existence of such correlations is explained in terms of self-regulating processes. Galaxy merging is called into play, within a hierarchical scenario of galaxy formation, to trigger both star formation and black hole growth. Subsequently, this growth is self regulated by the black hole itself via AGN feedback, which acts not only to halt the accretion onto the black hole, but is also critical in shutting off the star formation (and therefore growth) of the host galaxy (e.g. Silk and Rees 1998; Kauffmann and Haehnelt 2000; Di Matteo et al. 2005; Sijacki et al. 2007; Somerville et al. 2008; Malbon et al. 2007; Hopkins et al. 2009; Booth and Schaye 2010).[1]

Observationally, tracing the cosmic evolution of SBH scaling relations is riddled with difficulties, mostly related to the fact that the different methods used (by necessity) to measure SBH masses at different redshifts imply complicated and often difficult to quantify selection effects, biases and systematics (e.g. Schulze and Wisotzki 2011). The emerging consensus is that the relation was already in place at redshifts of at least ~ 3, and that as the redshift increases, SBHs appear to be systematically more massive, relative to their host galaxies, than observed locally (Bennert et al. 2010; Decarli et al. 2010; Greene et al. 2010; McLure et al. 2006; Merloni et al. 2010; Peng et al. 2006a,b; Treu et al. 2007; Walter et al. 2004; Woo et al. 2006, 2008). The latter trend has recently been confirmed for two of the youngest known quasars, at redshifts ~ 6.4 (Willott et al. 2013).

BHs have been also discovered in bulge less galaxies. Their masses do not seem to be related to the structure of the disk or the extension of the halo. Would you discuss this observational evidence in the context of the supposed dependence of the BH mass to that of the bulge?

I am going to challenge the premise of that question. From my prospective, it was never clear that it is the bulge to drive the evolution of SBHs (and/or viceversa). The velocity dispersion in the $M_{SBH} - \sigma$ relation, for instance, does not isolate the bulge component: it includes everything that happens to fall within the fiber or slit used for the observations (incidentally, it also includes a rotational, not just a velocity dispersion, component, see Bellovary et al. (2014) for a related discussion). In the

[1] It must be pointed out that the possibility has also been raised that there might not be a causal connection between SBHs and galaxies, but that a tight linear relation between SBH and galaxy mass might arise naturally during the hierarchical merging of galaxies provided the galaxy mass function declines with increasing mass (Hirschmann et al. 2010; Jahnke and Macciò 2011; Peng 2007).

case of bulge-dominated galaxies, the bulge will of course carry most of the weight, but in late type galaxies with small bulges the disk contribution can be significant. So, the equivalence "$M_{SBH} - \sigma$ relation == SBH-bulge relation" is not immediate. Moreover, as pointed out in the question, there are black holes in bulgeless galaxies (e.g. Araya Salvo et al. 2012; Secrest et al. 2012; Simmons et al. 2013), so here we have a conundrum: are there two classes of black holes, those that form in (and then control the evolution of) bulges, and those that just don't? If that is the case, it's important to understand why; however I don't think we have go down that road quite yet.

In 2002 I published a paper claiming that in spiral galaxies as well as in ellipticals, the stellar velocity dispersion, which is typically measured within a radius of 0.5 kpc, is tightly correlated with the large scale circular velocity, v_{circ}, measured at radii which range from 10 to 50 kpc. This implies a relation (although not necessarily a *fundamental* relation) between black hole masses (through σ) and dark matter haloes (through v_{circ}). These findings have been challenged by Kormendy and Bender (2011), who claimed that the $v_{circ} - \sigma$ relation breaks down when including bulgeless galaxies, and that SBH masses do not correlate with disk properties. From this, the inference is made that it is the bulge to drive the evolution of black holes (and viceversa). I don't find these arguments compelling, for two reasons: 1) in bulgeless galaxies, the authors measured the velocity dispersion of the stellar nucleus. But in galaxies with a bulge (many of which also have a stellar nucleus) σ is inclusive of all galaxy components (nucleus, bulge, and anything else that might be present within the aperture). So, the only conclusion that can be drawn is that in bulgeless galaxies the velocity dispersion of the *nuclei* does not correlate with the large scale velocity of the disk in the same way as the velocity dispersion of the *bulge* (plus any additional component) correlates with the large scale velocity in galaxies with a bulge: hardly a surprise. 2) Whether SBH masses correlate or not with disks does not imply that they do not correlate with total (baryonic or not) mass. Add to this that completely independent lines of evidence (both observational, e.g. gravitational lensing, Bandara et al. (2009), and theoretical, e.g. Booth and Schaye (2010)) also support the existence of a relation between SBH masses and total gravitational mass, and the case is still very much open.

More recently Läsker and collaborators (Läsker et al. 2014a,b) unveiled an even more fundamental problem with the standard "bulge-SBH" connection. Based on 2D decompositions performed on deep $K-$band images of a sample of 35 galaxies with measured black hole masses, they found that of the 18 galaxies that could not be fitted with a single Sérsic component, only one could be well described by a standard Sérsic bulge plus exponential disk model. All others required additional components (nuclei, inner disks, bars, haloes). This raises some questions. In a galaxy with an inner bulge, a nucleus and an outer halo, what is the best definition of a spheroidal component? And indeed, is it possible to even define these components uniquely, given that the decomposition is dependent on the quality (depth, resolution) of the data as well as being inherently degenerate? Läsker et al. proceed to show that the relation between SBH masses and *total* $K-$band luminosities is as tight (and much less sensitive to the details of the photometric analysis) as the one with "bulge" luminosity (as much as one can define such a quantity).

In conclusion, bulgeless galaxies do not necessarily pose a problem. What they do is prove rather conclusively that the existence of a bulge is not a necessary condition for the formation of a black hole and, viceversa, that the existence of a black hole is not a sufficient condition for the formation of a bulge.

Nuclear star clusters have been found by `HST` in $\sim 75\%$ of late-type spirals. What do we know of these structures, are they primordial or a product of secular evolution?

Let me stress that it is not just late-type spirals that host stellar nuclei. In the early 2000s, I was part of a team that was awarded a significant allocation of time with the Hubble Space Telescope to carry out a large imaging survey of galaxies in the Virgo and Fornax Clusters (ACSVCS/FCS, Buta and Combes (2000); Einasto (1965)). I will describe these surveys in more detail in Chap. 5, but for now I will just mention that one of the big surprises from the ACSVCS/FCS was the discovery that most early-type galaxies—as many as 80 %—host stellar nuclei and indeed that the fraction of stellar nuclei is comparable in early- and late-type galaxies. An even bigger surprise was the discovery (Ferrarese et al. 2006b; Rossa et al. 2006; Wehner and Harris 2006, but see also Graham 2012; Leigh et al. 2012) that stellar nuclei comprise about 0.2 % of the total galaxy mass, the *same* fraction of the total mass that is enclosed in SBHs. This is shown in Fig. 4.1 (from Ferrarese et al. (2006b)), which plots the mass of "central massive objects" (on the vertical axis, stellar nuclei are in red and SBHs are in black) against a virial estimate of the mass of their host galaxy (on the horizontal axis). The solid line corresponds to a constant ratio, of approximately 0.2 %, between nuclei/SBH masses and galaxy mass. The fact that stellar nuclei and SBHs obey the same relation might be a (remarkable) coincidence or might imply a deeper link between the two. SBHs and stellar nuclei are not mutually exclusive: some galaxies host both a stellar nucleus and a SBH (Filippenko and Ho 2003; Graham and Spitler 2009; Seth et al. 2008; Shields et al. 2008); others only appear to host a stellar nucleus (e.g. M33 and NGC 205, Gebhardt et al. (2001); Valluri et al. (2005)), while others again, in particular the most massive ellipticals, have a SBH but lack a stellar nucleus (Côté et al. 2006; Ferrarese et al. 2006b). However, as a rule, different lines of evidence seem to indicate that the fraction of galaxies hosting SBHs decreases with decreasing galaxy mass (e.g. Baldassare et al. (2014); Gallo et al. (2008)), while the opposite is true for stellar nuclei (at least down to $M_B \sim -15$, Ferrarese et al. (2006b)). It is therefore tempting to conclude that the efficiency of formation of "central massive objects" is relatively constant across a large range in galaxy mass, but that while in more massive galaxies such central massive objects *preferentially* take the form of a SBH, in less massive galaxies the formation of a stellar nucleus is the most likely outcome.

How nuclear star clusters form, and how they relate (if at all) to SBHs is a very active field of research. Based on analysis of the ACSVCS/FCS data, Turner et al. (2012) conclude that "for the low-mass galaxies in our sample, the most important mechanism for nucleus growth is probably infall of star clusters

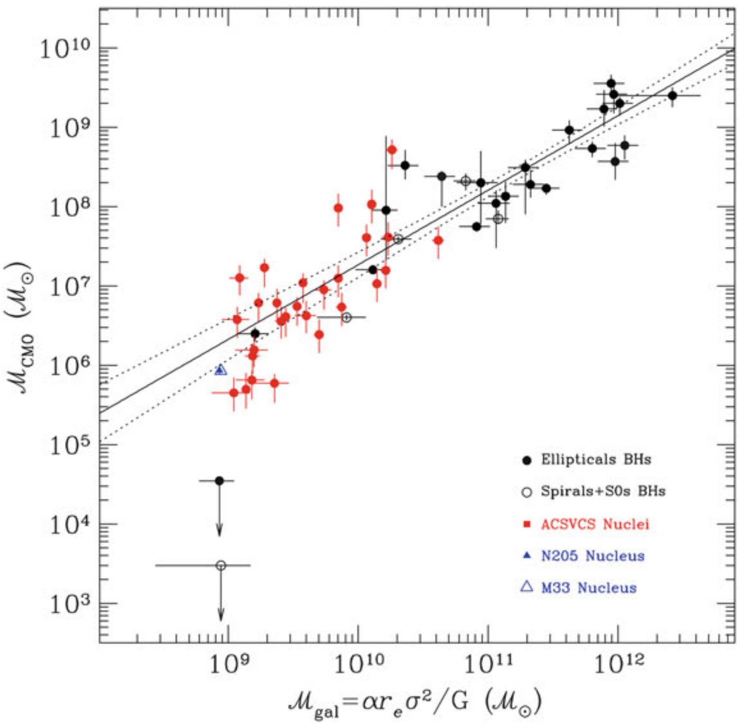

Fig. 4.1 Relation between "central massive objects" and their host galaxies, showing a common scaling between stellar nuclei (*red points*) and SBHs (*black points*)

through dynamical friction, while for higher mass galaxies, gas accretion triggered by mergers, accretions, and tidal torques is likely to dominate, with the relative importance of these two processes varying smoothly as a function of galaxy mass." The idea that globular clusters can sink towards the centre of the host galaxy through dynamical friction goes back to the work of Tremaine et al. (1975); in more recent work, Capuzzo-Dolcetta and Miocchi (2008a) and Arca-Sedda and Capuzzo-Dolcetta (2014) show that the subsequent merging of globular clusters leads to a nuclear star cluster whose properties and scaling relations are consistent with observational constraints. At the same time, the role of dissipation is also being confirmed observationally through detailed spectroscopic studies of individual galaxies. Such studies are challenging, due to the small angular size of stellar nuclei, but are painstakingly being assembled. Seth et al. (2008) suggest that the stellar nucleus in the edge-on spiral galaxy NGC 4244 was formed by episodic accretion of material from the galaxy disk, a mechanism that seems to be consistent with the observations of other late type galaxies (Neumayer and Walcher 2012; Seth et al. 2006; Walcher et al. 2006). Dissipation is also important in the formation of the stellar nucleus of the early-type galaxy NGC 404, although here the origin appears to be external, via multiple merging episodes, the most recent of which likely resulted from the accretion of a gas rich dwarf galaxy $\sim$1 Gyr ago (Seth et al. 2010).

Before concluding, it is worth mentioning that the lack of stellar nuclei in the most massive galaxies ($M > 10^{11} M_{\odot}$) is currently believed to be connected to the presence of a SBH. An existing stellar nucleus could evaporate as a consequence of the heating caused by the evolution of SBH binaries formed in galaxy mergers (Bekki and Graham 2010)—a process similar to the one that has been advocated to form galaxy cores (Milosavljević and Merritt 2003). Alternatively, nuclear star clusters could represent the seeds from which SBHs are formed (Capuzzo-Dolcetta 1993).

Overall, I would say that the last ten years have seen a profound change in the way we understand the structure of galaxies. We now know that SBHs likely play an important role in the evolution of galaxies, from shaping their nuclear structure to controlling the stellar population on a global scale. As I will describe in Chap. 5 we also know that there is a deep connection between nuclear and global structure, and that this connection extends to galaxies spanning a factor of almost a million in luminosity. These and other observational constraints will likely play a very fundamental role in guiding the next generation of cosmological simulations of galaxy formation.

The readers who are interested in the largely debated question posed by the $M_{SBH} - M_{bulge}$ and $M_{SBH} - \sigma$ relations can appreciate the recent review of this subject by Alister W. Graham (2015), who is also a contributed author of this book. His analysis seems to change the actual paradigm of a strict coevolution of SBHs and galaxy spheroids. From his data he conclude that the growth of SBHs has been much rapid than that of spheroids. The next future will see many new researches on this topic.

We continue now to explore the connection of the central massive BH with the host galaxies and their environment through the following interview to Paola Marziani.

Questions for Paola Marziani:
it is a widespread belief that nuclear activity is influenced by gravitational interaction between the host galaxies. Why?

There is long a standing belief that nuclear activity is indeed somehow “influenced” (we will discuss later which forms the influence may take) by gravitational interaction between the active nucleus host galaxy and one or more nearby galaxies. Figure 4.2 illustrates the case of an active galaxy—NGC 7469, whose nucleus appears bright and star-like in appearance—belonging to a strongly interacting system. This is just to give the reader a first glance of what we talk about when we talk about “interacting Seyfert galaxies” or interacting active galaxies. In this case the physical proximity of the companion galaxy (IC 5283) is supported by the small redshift difference between the two galaxies ($c\delta z \approx 88$ km s^{-1}), the presence of a tidal feature, as well as by regions of star formation on the side of NGC 7469 facing IC 5283.

Fig. 4.2 Multi-band image of the Seyfert 1 galaxy NGC 7469 and of its northern companion, extracted from the SDSS-DR10. Note the bright, stellar like nucleus, and several morphological features indicating mutual tidal effects related to a physical proximity of the two galaxies

Let me say first what we understand for nuclear activity. A very nice operational definition valid to this day is the one provided by Balick and Heckman (1982): an active galaxy is one in which signs of *qualitatively unusual* and quantitatively energetic activity originates from the nucleus, and the "qualitatively unusual" can not be associated with stars in any of their evolutionary state. Active galactic nuclei (AGN) came to attention not only because of being bright and star-like, but also because their spectra show a featureless continuum and strong and broad lines over a very wide range of ionization (Seyfert 1943). AGN spectra are different from the ones of HII regions, planetary nebulae, and supernovæ, and from the ones of non-active galaxies as well. Non-active (also referred to as "quiescent") galaxies show spectra which are, to a first approximation, the weighted average of the spectra of their constituent stellar population. Line emission from interstellar gas is very weak and does not affect the observed spectrum.

For nearby Seyfert galaxies, being bright translates into continuum luminosities that can be as high as 10^{44} erg s^{-1}. Being star-like translates into spatially unresolved emission. What makes AGN extraordinary is right the size of their line and continuum emitting regions. Broad emission lines respond with some delay to continuum changes. The light curve of the emission lines appears to be displaced by a relatively well defined time τ_{d} with respect to the continuum light curve. The delay τ_{d} can be retrieved by computing the cross correlation function of the light curves and by measuring its peak position. The size r of the emitting region is then simply

$\tau_d c$, where c is the speed of light. Emitting region sizes in nearby active galaxies are usually of the order of 1 light month for the Balmer line emitting regions (Peterson and Horne 2006). A very elegant way to gain a clue on the nature of the innermost region is to consider that τ_d changes systematically for different emission lines, and decreases with increasing ionization stage. For virial motion in the gravitational field of a "point-like" mass concentration M, the line width squared is $(\delta v)^2 \propto GM/r$, so that $(\delta v) \propto (c\tau_{d,line})^{-\frac{1}{2}}$. And indeed, line widths are found to be anti-correlated with $c\tau_d$ following a relation close to the one expected for virialized gas motions (Peterson and Wandel (1999); a simplified version is also shown by Marziani and Sulentic (2012)).

Therefore, there is convincing evidence—now considered overwhelming—of a large concentration of mass at the center of active galaxies. Is this mass in the form of a black hole? About this there is still no definitive proof: a proof would imply the detection of an event horizon (Doeleman et al. 2009), a feat not yet accomplished (and that may turn out to be intrinsically impossible, as theorists are nowadays unsure that an event horizon may even exist (Hawking 2014)!). A large concentration of mass—that we will assume to be a black hole in the following dialog—is of course not living alone as it will exert a strong gravitational pull on everything that may come close. The gaseous matter captured by the black hole may literally form a whirlpool, and will shed much of its gravitational energy by viscous attrition and much of its angular momentum trough a variety of mechanisms (Pringle 1981). A dense disk is expected to form very close to the black hole, leading to the accretion of matter onto the black hole.

Accretion is, in general, a very efficient process for emitting radiation: the total luminosity produced by the dissipation of gravitational energy is $L_{accr} \sim GM\dot{M}/r_{min}$, where r_{min} in the innermost edge of the accretion disk, very close to the central black hole, $1 - 3$ times the size of the black hole gravitational radius (the gravitational radius of a black hole corresponds to the event horizon, and is $r_g = 2GM/c^2$ for a non-rotating black hole, with G being the gravitational constant). It is easy to see that, if $r_{min} = 3r_g$, $L \approx 0.17\dot{M}c^2$. To explain the luminosity coming from typical Seyfert 1 nucleus, 10^{45} ergs s^{-1}, ≈ 0.1 $(L/10^{45})$ solar masses per years are needed. For the most luminous quasars, 10^{48} erg s^{-1}, 100 solar masses per year are needed.

This digression yields the basic elements needed to answer your question: an active nucleus, to sustain its luminosity needs to accrete a significant mass of gas. And the origin of the mass supply is an enigma of its own. The winds of stars in a dense nuclear star cluster as well as stellar mass loss in elliptical hosts may provide enough mass flow to explain fairly luminous AGN but not very luminous quasars. Such mass supply is however believed to be too short-lived to be consistent with the duty cycle of nuclear activity, and the central cluster stellar density needs to be too high to be consistent with observations (Norman and Scoville 1988; Padovani and Matteucci 1993). Stellar mass loss may play the dominant role in low-luminosity AGNs, but cannot explain the feeding history of AGN over cosmic time. An exogenous factor is expected to be at play.

Does observational evidence exists linking gravitational interaction to active nuclei?

The first observational attempts to study the connection between interaction and nuclear activity predate by just a few years the time when I, as an undergraduate astronomy student, started to work on my *laurea* thesis on interacting Seyfert galaxies. At the time, Seyfert galaxies were a hot subject, and interacting Seyfert galaxies a frontier topic of a hot subject. The idea that Seyferts were a local manifestation of accretion activity analogous to the one of the most distant quasars was already widespread (see Chapter 2 of D'Onofrio et al. (2012) for a first-hand account of the development of the AGN concept). The idea of cosmological redshift (i.e., that redshifted extragalactic sources were at the distance suggested by the Hubble law) for quasars was then already almost universally accepted, albeit not since long: not so many years earlier, a redshift—angular size relation for Seyfert galaxies was being hailed as a confirmation of the redshift cosmological interpretation (Khachikian and Weedman 1974). Instrumental capabilities were much poorer than today: the first CCDs were just coming into use. Images and spectra were still been collected on photographic plates, aided with image intensifiers that increased speed at the expense of higher noise level and often plate saturation.

The first systematic morphological survey focused on Seyfert galaxies and their environment and morphological disturbances appeared in Adams (1977), right on intensifier tube plates: the author noted that *there is apparently a surplus of Seyfert nuclei in disturbed and interacting galaxies.* A few years earlier A. Toomre and J. Toomre, in their seminal paper explaining galactic bridges and tails as due to tidal forces (Toomre and Toomre 1972) had put forward the possibility that *violent mechanical agitation of a close tidal encounter* would have led to *fresh fuel* in the form of interstellar matter deep into the potential well of a galaxy. The first systematic searches based on samples of nearby Seyfert galaxies were made possible by the Palomar Observatory Sky Survey (POSS) and its southern extension (not yet digitized!): wide-field $6° \times 6°$ plates covering the whole celestial sphere. A search for "companion galaxies" found that 15 % of Seyfert galaxies had a nearby galaxy within a search radius of 3 times each Seyfert galaxy diameter. This number was 5 times larger than what was found in a control sample of non-active galaxies from the Shapley-Ames catalog (Dahari 1984). These works were the backbone for discussing interacting Seyfert galaxies in the mid-1980s.

Some examples of interacting systems with an active nucleus are truly spectacular. Interaction can even produce cross-fueling, a large scale phenomenon occurring when an active galaxy is accenting gas from a donor galaxy. The examples associated with this mechanism are spectacular (Fig. 4.3), but are very rare, and require a restricted set of encounter parameters. In the case of Arp 194, a spectroscopic investigation proved that the gas clouds and stars associated with the blue blobs resolved in the HST image are falling toward the southern component (Marziani et al. 2003). The morphology of the system suggests a head-on encounter between the northern complex and the southern component, observed after the southern component has crossed the northern one. This type of encounters that gives

Fig. 4.3 The interacting system Arp 194, one of the rare examples of interacting galaxies where transfer of matter is occurring between galaxies. In the case of Arp 194, the bluish conglomerates are due to gas and recently-formed stars stripped from the northern component and falling toward the nucleus of the southern galaxy, as revealed by a spectroscopic investigation (Marziani et al. 2003). It is believed that the process of stripping accretion gas from one galaxy to another may ultimately yield accretion fuel to maintain an active nucleus. Credits: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

rise to ring galaxies has the additional advantage that the gas angular momentum may be minimised, leading to a nearly "free fall" of the gas captured by the intruder toward its center. Perturbed and interacting systems are detectable from poor data, stand out and catch attention. However, they may have biased the judgement of early workers in favour of a direct link between interaction and nuclear activity.

The basic result—an excess of interacting systems among Seyfert galaxies—was confirmed and extended to low-z quasars and radio galaxies by other studies carried out across the late 1980s and 1990s (Heckman et al. 1985; MacKenty 1989;

Moles et al. 1995; Rafanelli et al. 1995; Yee 1987). Interestingly, discordant results were also obtained (Dultzin-Hacyan et al. 1999a; Fuentes-Williams and Stocke 1988; Laurikainen and Salo 1995) in the same years: the prevalence of companions among Seyfert 2 galaxies was found higher than among Seyfert 1, and no difference was found between Seyfert 1s and non-active galaxies! This result was especially troubling. Not only the main observational support for the idea that gravitational perturbation as an initiator (a "trigger") of nuclear activity was starting to crumble, but also one of the basic interpretation scheme of AGN developed in the 1980s, the unification model, was being challenged. Unification meant that Seyfert 1s and Seyfert 2s were basically the same object observed at different viewing angles, with a "hidden" broad line region (HBLR) in Seyfert 2s. In the Seyfert 2 case, the innermost regions emitting the broad lines are obscured by a thick disk (a torus) of gas and dust (Antonucci 1993; Urry and Padovani 1995).

We leave aside AGNs for the moment. There is another, key element that we did not mention until now and that may help us understand the connection between gravitational interactions and nuclear activity. In this case, results on studies covering almost 40 years have been always consistent: gravitational interaction produces a significant enhancement of the star formation rate in the disk and in the nuclei of galaxies. Early studies detected bluer colours and enhanced radio-emission in interacting systems (indicative of recent star formation) than in field galaxies (Larson and Tinsley 1978; Sulentic 1976). A quantitative estimate of the star formation rate can also be obtained by measuring the far-IR luminosity of a galaxy that is related to the total thermal re-reprocessing of hot star radiation by dust, or the Hα line luminosity, which is a fixed fraction ($\approx \frac{1}{2}$) of the number of ionizing photons emitted by massive stars and absorbed by line emitting gas. Hence, the Hα and FIR luminosity can be easily connected to the number of hot stars being produced per unit time. Eventual studies unanimously confirmed that gravitational interactions can yield a strong enhancement in the star formation rate in the disk and nuclei of galaxies (e.g., Kennicutt et al. 1987; Lawrence et al. 1989; Owers et al. 2007; see Bournaud 2011 for a review). Observationally, the effect of a close neighbour galaxy is much clearer as far as star formation is concerned: Krongold et al. (2002b) noted that the enhancement in the FIR luminosity is strongly dependent on the galaxy pair separation. Figure 4.4 shows that there is a rather tight correlation between separation and FIR luminosity (proportional to the SFR rate) for the bright IRAS galaxy sample, i.e., for galaxies whose specific flux is $\geq$5.4 Jy at 60 μm. The bright IRAS galaxies are therefore, by definition, the brightest extragalactic objects in the sky at 60 μm. A set of control samples was selected by bootstrapping a nearby galaxy catalog matching isophotal diameter, redshift, Hubble morphological type distribution of the bright IRAS sample. An analogous result was recently obtained by the analysis of $2{\cdot}10^5$ star-forming galaxies from the SDSS, along with merger simulations (Patton et al. 2013): the strongest enhancement is observed at the smallest separations ($\lesssim$10 kpc), while no net effect is visible at separations larger than 150 kpc.

The first installments of the SDSS became available in the early 2000s. The SDSS and other major surveys (as well as the continuing availability of HST and

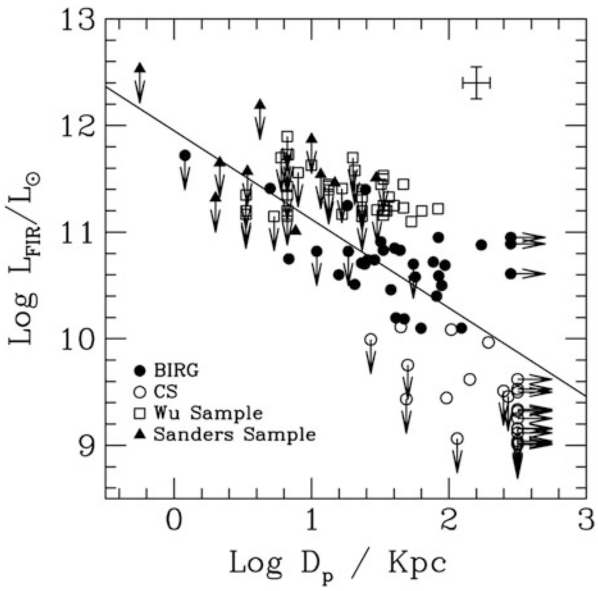

Fig. 4.4 Correlation between FIR luminosity (a measure of the galaxy star formation rate) and projected separation, for bright-IRAS galaxies (BIRGs) with companions and for a control sample. Samples including the most luminous IR sources show the smaller separations (*open squares* Wu et al. 1998; *filled triangles* Sanders et al. 1999). *Open circles* show one realisations of the control samples. The *solid line* corresponds to the lest-square best fit. From Krongold et al. (2002b)

increasing availability of ground based high resolution imaging associated with the development of adaptive and active optics) produced three major effects: (1) an increase in sample sizes, allowing for extraction of subsamples in terms of morphology and host luminosity; (2) the ability to detect nuclear activity at very low level, and (3) an extension toward higher redshift of approaches that were applicable only to nearby galaxies in the 1980s and 1990s.

Do these improvement provide a convincing solution of the disagreements among early studies?

I am tempted to answer yes, and no, at the same time. Generally speaking, all recent studies agree that interaction has "some" role in nuclear activity, most likely as a "trigger" (Hwang et al. 2012; Manzer 2014; Sabater et al. 2013; Villarroel and Korn 2014). Hosts of high luminosity quasars are by a large fraction perturbed and strongly interacting (Bahcall et al. 1997) (Fig. 4.5). Circumnuclear regions of Seyfert imaged with the `NICMOS` instrument on board `HST` reveal circumnuclear morphological perturbations for both Seyfert 1 and 2, with Seyfert 2 being more perturbed than Seyfert 1 (Hunt and Malkan 2004). AGN are associated with the development of a dynamically cold core of molecular gas, that constitutes a gas reservoir that is not apparent in non active galaxies (Hicks et al. 2013). Indeed, the AGN fraction is found to depend strongly on the morphology of and the distance

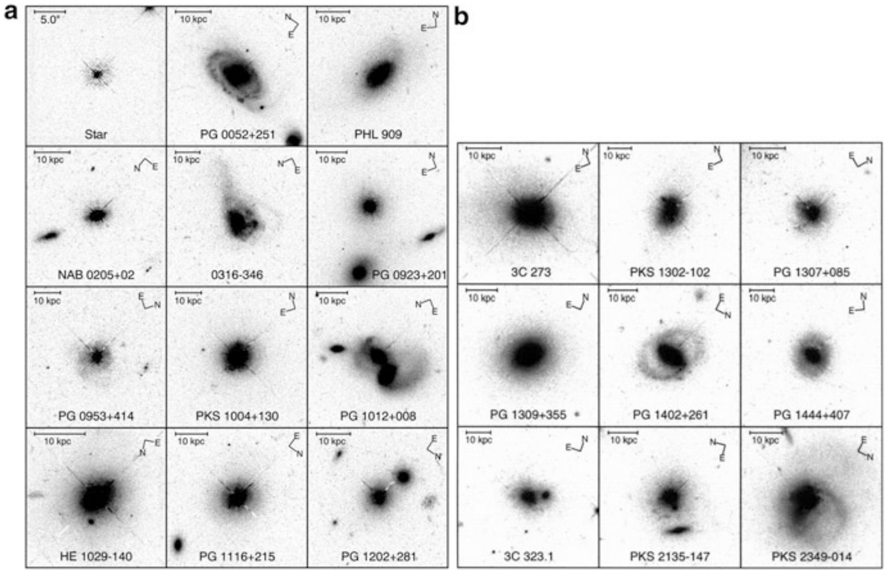

Fig. 4.5 Morphology of low redshift quasar hosts, after subtraction of a stellar PSF to the nucleus of the host galaxy. Note the large fraction of disturbed and interacting systems with companions. From Bahcall et al. (1997)

to the nearest neighbor galaxy when morphology and luminosity of host galaxy are fixed: basically, AGN are enhanced when there is a neighbour galaxy and when the AGN host has its own gas reservoir (Hwang et al. 2012; Sabater et al. 2013). The prevalence of optical AGN has been confirmed to be lower in the very dense environment provided by galaxy clusters, and increased in the case of strong one-on-one interaction (Sabater et al. 2013). Broad-line (i.e., Type 1) AGN are almost completely absent in compact groups of galaxies (Martínez et al. 2008). A convincing answer to the long-standing question of whether Seyfert 2s and 1s are surrounded by different environments may have been provided by the most recent analysis of SDSS DR7 and "galaxy zoo" data (Villarroel and Korn 2014). These authors considered AGN residing in spiral hosts, and showed that the fraction of Type 2 AGN with a companion within 100 kpc was between 55 % and 60 % (compared to $\approx$ 15 % for control), while no significant increase was found for Seyfert 1s. Interestingly enough, a very recent work separated non-hidden and hidden-BLR Seyfert 2s, the latter being essentially obscured Seyfert 1s. It is the non-hidden BLR sources that seem to show a significant excess of interacting companions (Koulouridis 2014). These works support a sort of evolutionary sequence (originally proposed by Dultzin-Hacyan et al. 2003; Krongold et al. 2003) between star forming systems, Seyfert 2s and Seyfert 1s:

$$\textit{Interaction} \Longrightarrow \textit{Starformation} \Longrightarrow \textit{Seyfert}\ 2s \Longrightarrow \textit{Seyfert}\ 1s \tag{4.1}$$

Interactions induces star formation and accumulation of a gas reservoir in the central region of a galaxy, yielding the formation of an obscured AGN. As obscuration decreases, the source appears as hidden-BLR Seyfert 2 or as Seyfert 1 depending on viewing angle. If we imagine to follow a gas parcel in its travel toward the central black hole, some non-negligible time will be needed before the parcel reaches its destination. The timescale for angular momentum loss by a stellar bar is of the order of the dynamical timescale at $\sim$ 10 kpc, $\sim 10^8$ yrs (Mouri and Taniguchi 2004; Shlosman et al. 1990). In a minor merger, the companion may have been literally swallowed by the Seyfert galaxies. In a transient encounter, the companion may have disappeared from the search radius, since the separation between the active galaxy and its companion $\delta d_{\mathrm{S-c}} \gtrsim v_{\mathrm{S-c}} \sim v_{\mathrm{S-c}}\tau_{\mathrm{del}}$, where the delay time is comparable to the dynamical timescale, yielding a separation $\delta d_{\mathrm{S-c}} \sim 3D_{\mathrm{S}}$ for an encounter velocity $v_{\mathrm{S-c}} \approx 300$ km s^{-1} after $\sim 10^8$ yrs. The delay needed for the AGN "ignition" may explain the results on the environment of Seyfert 1 galaxies. The evolutionary scheme can be seen as an extension to low luminosity of the scheme originally proposed for connecting ULIRGs and quasars (Sanders et al. 1988).

Of course proving an evolutionary sequence in astronomy is very hard, since we cannot follow galaxies in their evolution! However, the scheme is complementing and is not in contrast with the unification scheme for radio-quiet AGN. It adds an evolutionary dimension that is clearly missing on a scheme based only on orientation effects, a variable t that affects the probability and depth of AGN obscuration (Gaskell 2014). I am saying this because the idea of an evolution between AGN types was met with deep skepticism, but I do not think the unification scheme should be seen as a dogma not liable to improvements.

The third dimension of the issue is z i.e., cosmic epoch. Internal disk instabilities can arise as the disk becomes self gravitating. For sufficiently gas-rich, disc-dominated systems, gravitational instabilities can yield accretion rates sufficient to power luminous quasars at high-z (Hopkins and Quataert 2010). A celebrated success of the interaction scheme involving merging of galaxies is a straightforward explanation of quasar evolution (Cavaliere and Vittorini 2000). Both endogenous and exogenous gravitational instabilities are shown to be able to reproduce the quasar luminosity function up to relatively high-z, $\gtrsim 4$. However, luminous quasars radiating at high accretion rate should increase with luminosity in a merger-driven scenario, while disk instabilities yield the opposite trends (Menci et al. 2014). This prediction can be tested since highly accreting quasars show distinguishing UV properties that can be easily recognised in survey spectra (Marziani and Sulentic 2014).

Summing up, evidence that gravitational interaction between galaxies provides at least a trigger for high-accretion rate, luminous activity seems convincing if at least one of the galaxies involved is gas rich. Secular disk evolution seems to be, in part, a competing mechanism. Low luminosity AGN may be fueled by stellar mass loss. The last two mechanisms—along with the experimental difficulty at identifying interacting systems—help explain why, after all, not all AGN hosts appears interacting.

Which is the physics behind the belief of a link between interaction and activity?

Physically, forces that are relevant in affecting galactic morphology as well as the internal motions of gas and stars are of tidal nature i.e., they are due to different gravitational forces from an intruding or orbiting mass acting on different part of an extended object like a galaxy (not unlike tidal forces due to the moon on earth). Tidal forces scale as the inverse third power of the separation between the two gravitationally interacting body, $f_{\rm tide} \sim GM_1M_2/D^3$, hence the motivation for a search of nearby companions to active galaxies that should have a much larger effect that large scale environments. Indeed, works based on the SDSS found no difference in large scale environment ($\sim$ 1 Mpc) between active and non active galaxies (Sorrentino et al. 2006), nor a trend between fraction of AGN as a function of local surface density of galaxies as determined from the distance to the 10th nearest neighbour (Miller et al. 2003b).

Tidal forces from a nearby galaxy acting on a target galaxy destroy the axial symmetry of the target galaxy. Star and gas orbits become open and their ellipticity increases. These changes greatly enhance the possibility of collision between molecular clouds. Collisions lead to shock and compression and to eventual cooling of the shock-heated gas, ultimately yielding the formation of new stars. Cloud-cloud collision is also an efficient way to remove cloud angular momentum, leading to a significant infall of gas toward the center of the host galaxy (Barnes and Hernquist 1996). Numerical simulations of the galactic disk gas indicate a dramatic infall of gas toward the central region of the galaxy. The gas amassed in the nuclear region will form stars, but then? Will the gas, or perhaps the gas reprocessed through supernova events be able to reach the central black hole and provide its accretion fuel?

There is a new order of problems here. Viscous attrition operating within a dense accretion disk is efficient in removing angular momentum within 1 pc from the central black hole, but additional mechanisms are needed to let the gas reach the innermost parsec. Gaseous and stellar bars can provide sufficient torque to remove the gas angular momentum within the inner 1 kpc ("bars within bars," Shlosman et al. (1990)). Deep within the black hole sphere of influence, magnetic fields may be determinant, either through the Balbus-Hawley mechanism (Balbus and Hawley 1998) or through the Blandford-Payne torque exerted by magnetic field lines threading the outer accretion disk (Blandford and Payne 1982). On this spatial scale observational constraints are indirect.

Are prominence (i.e. luminosity) or type of an active nucleus in some way influenced by the environment of its host galaxy?

Let me consider first two extreme cases: galaxies in the densest environments i.e., in the core of clusters of galaxies, and "isolated galaxies". Clearly both of these environments are important if we wish to shed some light on the conditions that make possible nuclear activity.

Several studies found that, at the highest galaxy density, nuclear activity is inhibited: there are very few active nuclei in the inner region of clusters of galaxies

(Balick and Heckman 1982; Biviano et al. 1997; Hwang et al. 2012; Marziani et al. 2013). This may be related to the suppression of the host galaxy gas due to ram pressure of the hot intra-cluster medium: as the galaxy moves through the intra-cluster medium its pressure literally pulls away the gas of the galaxy, in some case even in a short timescale, comparable to the crossing time of the cluster (i.e., one passage through the cluster is sufficient to strip the galaxy of its gas and to give it a "jellyfish" appearance) (Ebeling et al. 2014). Central galaxies in clusters do show some emission line activity: they are so massive, and they host very massive black holes, that their active nucleus luminosity is significant even if the accretion rate is small. Their low accretion level implies an hard observational state with a flat X ray spectrum, and emission lines of LINER-type, and probably a particular accretion process associated with hot-phase gas (Bondi-type accretion, Fujita et al. 2014).

Now let us turn to isolated galaxies. A typical isolation criterion is that galaxies under scrutiny have no bright companion ($\delta m < 3$) within 20 times the companion diameter (Hernández-Ibarra et al. (2013), Argudo-Fernandez et al. (2013) provide a thorough discussion of various isolation criteria). Assuming a field velocity dispersion of 150 km s^{-1}, the galaxy may not have experienced major interactions during the past 3 Gyr (Hernández-Ibarra et al. 2013; Sabater et al. 2012). Recent studies found a rather high fraction of low-luminosity AGNs, increasing toward earlier morphological types and with host luminosity (Coziol et al. 2011). The low-luminosity of these AGNs makes it easy to explain their accretion fuel as due to endogenous secular processes (Hopkins and Quataert 2010) and mass lost by evolved stars.

As a final clue we may consider samples of interacting galaxies, i.e. we may ask: is there an enhancement of the AGN prevalence in samples of interacting or at least pairs of galaxies? This can be seen as the reverse question on prevalence of interacting systems among AGN. The answer is not immediately clear. Most earlier studies suggested a negative result, probably because of the small number of active galaxies involved. Activity in interacting and non-interacting Seyferts does not appear to be strongly different: differences in luminosity were found to be marginal (Dahari and De Robertis 1988). I think this early result has been confirmed by more recent studies: if there is an effect the effect is small and goes undetected or barely detected. Hence the notion that gravitational interactions or secular mechanisms are initial "triggers" of nuclear activity. Nuclear activity in compact group galaxies involving mostly early types may not be strong because of lack of gas supply even though they may experience frequent galaxy—galaxy interactions (Sohn et al. 2013). However, Ellison et al. (2011) (see also Sorrentino et al. 2006) found an increase in the AGN fraction in close pairs of galaxies within $< 40 - 70$ kpc by up to a factor of 2.5 relative to the control sample. The increase in AGN fraction is strongest in equal-mass galaxy pairings, and weakest in the lower mass component of an unequal-mass pairing. The increased AGN fraction at small separations is accompanied by an enhancement in the number of "composite" galaxies whose spectra are the result of photoionization by both AGN and stars. This does not mean that nuclear activity is also enhanced: Li et al. (2008) found that the AGN extinction-corrected [OIII]λ4959,5007 luminosity is the same in sources with and without a close companion.

If tidal forces ultimately lead to nuclear activity on one galaxy, some effects are expected also on its companion galaxy, especially if gas-rich and similarly sized (Koulouridis et al. 2013). In such case, a naïve expectation is that both galaxies show an active nucleus. Examples of double active galaxies (also known as AGN pairs) are however very rare, about 1 % of all AGN (Liu et al. 2012). Only in this context there seems to be a significant enhancement of luminosity and accretion, even dependent on pair separation as found for SFR.

The link between interaction and nuclear activity recursively come back in the astronomical literature with contrasting opinions. Could you explain us why it is so difficult to answer them definitively?

Some methodological considerations are in order. Works in the 1990s benefitted of the newly digitised `POSS`, since then known as the Digitized Sky Survey (DSS). Selection and measures were more easily made and also more accurate. However, these studies involved the study of the environment within a search radius of few diameters from a central active galaxy, typically corresponding to projected linear sizes of $\leq$ 100 kpc. For example, searches for companions to Seyferts considered physical companion galaxies the ones with $3D_{\mathrm{S}}$, $\Delta cz = 1000$ km s^{-1}, and $\delta m = 3$ (Rafanelli et al. 1995). The last criterion helped avoid the contamination from faint galaxies that appear proximate only because of a chance projection but that are distant in space. However, it also eliminated faint companion galaxies that may be gravitationally bound to the active galaxies. For example, the two satellite galaxies of the Andromeda galaxy, Messier 32 and Messier 110, would be missed since they are fainter than Andromeda by $\delta m \approx 5 - 6$. The nearest spiral to Andromeda, our own galaxy, even if gravitationally bound would be missed because at a distance larger than 3 diameters. These selection criteria clearly missed a part of the physical scenario.

Several of these studied also suffered of the absence of redshift information for the companion galaxies. The redshift and the properties of the companion galaxies remained largely unknown: once a companion galaxy was found close to the Seyfert, one could not be sure that the galaxy was actually proximate in space (a physical companion) or a background galaxy. Corrections were estimated from the counts of field galaxies, for example from the Shapley-Ames catalog, assimilating the detection of a background galaxy as a Poisson event (i.e., as a low-probability event giving the small search radius) but these corrections were large and increasing with search radius. This may in part account for the discordance in results. Other issues that limited the validity of these studies were small sample sizes, and often heterogeneous criteria for AGN selection. The selection of the AGN sample has to be done with extreme care—avoiding compilations and using only systematic surveys based on a physical criterion, let it be the UV excess, the X-ray emission of the IR color/luminosity. Not all of these requirements could be satisfied in full by the small samples (involving $\sim$ 100 sources) usually employed in early studies. The last work in the 1990s pre-SDSS era (Dultzin-Hacyan et al. 1999a) reached an apogee of refinement for the data available at the time. Seyferts were selected from a well-defined criterion UV excess (Lipovetsky et al. 1988). The determination of the surface number density that goes into the formula for the predicted number of background galaxies was made directly from the DSS plates. Galaxies were counted in regions of 1 square degree surrounding each active galaxy; the definition of a control sample matched the Seyert distribution in redshift and morphological types. The search for companions was done in circular areas around each galaxy, with radii equal to three times the diameter of the galaxy. This procedure reduced to a minimum the subjective bias present in all previous works, which were done counting galaxies from the POSS prints "by eye" (Dultzin-Hacyan et al. 2003). The final result obtained provided a confirmation of the difference between Seyfert 1 and 2 originally obtained by Petrosyan (1982); Laurikainen and Salo (1995): it is only Seyfert 2 galaxies that have excess companions, but not Seyfert 1 galaxies.

An important aspect to consider when comparing later studies to the early ones is the AGN luminosity. Recent surveys are able to detect very-low level activity (emission lines with just 1 Å equivalent width in Hβ) and AGN samples are dominated by dwarf AGNs. As a rule of thumb, dwarf AGN are a factor $\approx$ 3 more common than luminous Seyfert 1 and Seyfert 2. At this high sensitivity, the classification of emission line sources is a field of its own, and not safe from serious interpretation problems concerning the lowest equivalent width sources (retired galaxies?, "fake" AGN? Cid Fernandes et al. 2011). In addition, considering the well established morphology—density relation (Dressler 1980), samples have to be selected with known morphology, and with a control sample of matching morphological types (as done, for example, in Sabater et al. (2012)).

Unfortunately, even recent studies based on the SDSS may miss the faintest companions and tidal features. This is an unfortunate circumstance since minor mergers are expected to play an important role in driving perturbations on a galaxy disk gas. Seyfert 1 galaxies apparently do not show a different environment with respect to non-active galaxies on scales less than 100 kpc, and we do not know if this result is obtained because minor mergers go undetected, are already in their late stage, or are not occurring at all (Corbin 2000). There are two considerations in this respect. First, if a deep survey is carried out down to surface R-band brightness about 25—26.5 mag arcsec^{-2} then elongated tidal envelopes becomes detectable, indicating that a high fraction of Seyert galaxies underwent a merging $\lesssim$ 1 Gyr ago (Smirnova et al. 2010). The second consideration is that until now, I have spoken mainly from an optical perspective. The atomic hydrogen hyperfine transition line at 21 cm is a much better tracer of tidal effects. Spatially-unresolved, unperturbed disk galaxies, show an integrated profile consistent with an optically and geometrically thin disk, i.e., with a characteristic central dip surrounded by two symmetrically displaced peak. A recent study of nearby Seyfert galaxies found that the 94 % of the galaxies are disturbed in H I, spatially and kinematically, due to tidal interaction with a nearby companion galaxy. The relevant point here is that only 28 % showed signs of optical perturbations (Kuo et al. 2008).

There is then the complication that the early stages of the AGN development may be difficult to detect. As mentioned earlier, an active galaxy may appear isolated in the case of a minor merger or of a simple fly-by of an unbound nearby galaxy on an hyperbolic or parabolic orbit. We still do not have a complete observational assessment of the issue.

4.3 Spheroids and Disks: Their Structure and Kinematics

We start to discuss here the main visible galaxy components: the bulge and the disk. Already in this book we pointed out the main observational facts that led astronomers to broadly define these galaxy components in terms of stellar populations and kinematics. The interesting thing to note is that up to now does not exist an unambiguous measure of the consistency of both components. Many bulge-to-disk decompositions have been attempted, each one with its own advantages and disadvantages. It is also quite difficult to establish if a single star belongs to the bulge or to the disk.

Questions for Jack W. Sulentic:
the bulge and the disk are the primary structural components of late-type galaxies and the bulge-to-disk ratio B/D (or bulge-to-total= B/T) is one of the parameters driving the Hubble morphological classification. Is it possible to define unambiguously the physical properties of these stellar components? Could you trace a short review of the most important studies of the bulge component?

I am not the "proper" person to ask such questions or maybe it is better to avoid the proper persons? Or maybe it is better to ask two or more people in order to obtain a range of opinions? That is the special value of this type of book. My response will reflect upon two eras—around 1970 as a graduate student (alas I cannot at this point in the narrative mention that I was a student at Caltech) and after 1995 while supervising graduate students (U. Alabama) and, later, mentoring postdocs at IAA-Granada. The first period saw the advent of twin ideologies: (1) mergers as a major tool for constructing and evolving galaxies and, a bit later, (2) dark matter as the principal matter component in the Universe. Actually three because the supermassive black hole paradigm was adopted to account for the quasars (their high energies could be accommodated by gravitational accretion). At this point in time the champions of the merger ideology decided that all elliptical galaxies were formed by mergers. By 1989–1990 one heard stories of the rare dissenters (e.g. Stiavelli and Bertin 1985) not being invited to meetings on related topics. It all had the faint ring of the kind of shenanigans going on in Wall Street.

Returning from polemics to bulges. Until fairly recently any claims for a clear separation between bulge and disk components in spiral galaxies would have been accepted by the majority of astronomers. During the 60's-70's we were taught that the bulge was a dynamically "warm" component distinct from the disk—the bulge was likened to an elliptical galaxy inside the disk and the disk was thought to extend up to, but not necessarily into, the bulge. This idea of bulge and disk as distinct stellar components originated with the work of Walter Baade (the late Chip Arp's mentor by the way) during WWII (Baade 1944) who advanced the dual stellar population concept. The bulge + halo of a spiral galaxy involved older metal-poor Population II stars moving in non circular orbits (like the stars in an elliptical galaxy of pre-merger times). Younger and metal richer Population I stars were concentrated in the disk where star formation continued because gas and dust are found there. Of course an intermediate stellar population was also thought to exist with our Sun likely part of it. This was all regarded as consistent with the hypothesis that galaxies form by monolithic collapse of primordial gas clouds. Extreme Population I disk stars were richest in metals and their orbits were circular. They formed after the collapse process was completed. Keplerian motions were assumed but the aforementioned work of Vera Rubin (e.g. Rubin et al. 1980) failed to show the expected (Keplerian) velocity turnover in the outer parts of many spiral disks. Is it any wonder that the experts wanted to curtail her access to telescopes—she was wasting observing time! This is now taken as strong evidence that these galaxies are surrounded by dark matter halos whose masses can exceed that of the observed stars/gas/dust. An alternative model has been proposed that would slightly modify Newtonian dynamics (Milgrom (1983a,b,c) and later papers).

The idea of distinct bulge and disk components was reenforced as high resolution HI maps of spiral galaxies emerged from radio telescopes like Westerbork in the Netherlands. Such maps showed an HI disk (zero-age Population I material) component—spirals highly inclined to our line-of-sight showed characteristic double-horn 1D profiles. Those oriented near face-on showed very narrow 1D HI profiles (implying that the neutral hydrogen gas was concentrated in a disk dominated by orbital motions. 2D HI maps of these face-on spirals often showed a hole in the center (Bosma (1981a,b);—or zooming nearer the present—Walter et al. 2008) as would be expected if bulges were distinct components from disks.

Much has changed and the simple picture recounted above is now less clear despite the fact that we now have much more sophisticated linear detectors, CCDs, IFUs and much more software available for 2D galaxy modelling: (1) spiral galaxies often show bars, rings and lenses that complicate simple bulge-disk decomposition attempts, (2) not all HI maps of spiral galaxies show a hole in the center (interactions?); (3) dark matter haloes around galaxies make flat rotation curves more palatable(?), (4) Hubble Space telescope observations sometimes resolve a miniature spiral pattern in the central part of spiral galaxies where we had previously seen only a bulge (Carollo et al. (1997)—evidence for late formation of some bulges or mass acquisitions), (5) elliptical galaxies also show rotational motions sometimes along multiple axes (e.g. Benacchio and Galletta 1980). It is amusing to hear some argue (at least since 1992) that there is no longer a role for galaxy morphology studies because we have moved beyond to a physical understanding of galaxies. We cannot even agree on how to parametrize the structure in spiral galaxies. A bulge/disk (or bulge/total) measures is too primitive so move on to arguing the merits of Sérsic vs. Petrosian indices (Gadotti 2009)? Finally we can argue that most late-type spirals have no bulge at all but rather a "pseudo-bulge" (Kormendy and Kennicutt 2004). In real space we are influenced by both the empirical (the Hubble tuning-fork or deVaucouleurs wheel) and ideological (unconstrained dark matter distributions and arbitrary role for interactions/mergers. A naive outsider might get the impression we are moving backwards but there is a constant battle between empiricism and ideology in many branches of extragalactic astronomy—imperfect data vs. extraordinary models. I have long thought that we need to clarify the empiricism by exploring galaxy structure in the Fourier (i.e. linear spatial frequency) domain. A few people have tried this (my favorite was Iye et al. 1982–pre-CCD! Iye et al. 1982). Interpretation of direct images (non-linear domain) is too much affected by the past work of Hubble and followers. De Vaucoulers moved us toward a more sophisticated classification but still largely in non-linear space. In 2014 we still seem quite confused about basic structural issue—especially—is the bulge a distinct component or does the disk extend into the nuclear region in some or all spiral galaxies?

This imperfect overview of bulge studies can identify a few events that give historical flavor: (1) a review by Frogel (1988) covers the largely pre-CCD era from 1965–87, (2) Wagner et al. (1989) still found evidence in 1989 for two distinct (bulge+disk) components in a spiral galaxy; (3) 1990 finds the first ESO workshop on bulges (Schwarz 1990) as well as a paper (Prieto et al. 1990) with the words "bulge" and "CCD" in the same title; 4) 1997 sees a statistical study (Carollo et al. 1997) cited above involving `HST` imagery of 23 spirals. Anyone even peripherally involved in the field can remember these surprising results which played a role in emerging ideas that bulges might not even be primordial—back to square one? Indeed disks, at least sometimes, extend into galactic bulges. We see the appearance of several software packages: e.g. GASP (1985), GIM2D (1998), GALFIT (2002), BUDDA (2003), that facilitate bulge-disk decomposition—the results of which studies are now emerging.

What do we know about the most isolated galaxies? If they exist then what is the importance of such objects in this context?

The study of isolated galaxies is connected to a fundamental concept in science—that of "nature vs. nurture". What is the natural/primordial state of a galaxy and how much of what we see is due to environmental influences subsequent to formation? If some galaxies have spent most of their lives in isolation then they can give us clues about their primordial natural state—at least a state minimally affected by environment. If they can be found in significant numbers then they would represent an obvious and ideal control on all statistical studies of galaxies. In earlier times (1960's) there was a simple picture involving galaxy groups and clusters embedded in a homogeneous "field" population (all embedded in a smooth Hubble expansion). Gradually 3D surveys suggested that groups and clusters aggregated into superclusters connected by rather thin filaments (see Semenov 2013 for a recent review). In counterpoint to the rich clusters, voids were discovered—regions with very low galaxy density. This does not mean however that all void galaxies are isolated—interacting pairs and occasional compact groups are found in voids (e.g. Grogin and Geller 2000). In order to be truly isolated a galaxy should live in a region of low density but also should have no significant (less than $\sim$10% of the candidate isolated galaxy mass) neighbors within a few Gyr crossing-time—such requirements will keep the numbers down. Some early searches for isolated galaxies based on a local surface density selection criteria produced surprisingly small lists and replete with interacting pairs. These early attempts at pure digital compilation used source catalogues where binary galaxies were sometimes listed with a single catalogue number. Fail! As a graduate student I was two years too late to utilize new catalogues of isolated galaxy pairs (aka. KPG or CPG; Karachentsev 1972) and isolated single galaxies (aka. KIG or CIG; Karachentseva 1973) coming out of the USSR. They were compiled from visual searches on the original Palomar Sky Survey. These catalogues were both larger and less contaminated than the first digital attempts. They were published in the Soobshch of the Special Astrophysical Observatory (USSR) ensuring that they would receive minimal attention in the West. They had no equals until the advent of SDSS.

Having a primordial interest in the question of nurture, the CPG and CIG seemed as valuable at their time as the SDSS became after 2000. At the time several papers appeared claiming to find no effect of environment on galaxy properties (radio emission) which seemed surprising to this young naif. As a student I had read papers by Hrant Tovmassian about unusual radio properties of galaxies (Tovmassian (1972): 10 or 20 citations) motivating me to carry out a radio survey for my thesis using the NRAO 300foot telescope (later destroyed by aliens). I decided to survey a sample of interacting galaxies and being too late for the CPG, I surveyed galaxies in the Arp atlas (Arp 1966) (somehow presaging a later collaboration?) and compared results with contemporary samples of single galaxies as controls (Sulentic (1976)—ApJ kindly waived the page charges). The results suggested that interacting galaxies showed enhanced radio emission compared to similar galaxies alone. I thought this was rather cool but the results were not well received (100 citations) in that they contradicted at least two papers published the previous year. It is difficult in 2014 to believe that the prevailing wisdom in 1975 saw no role for interaction induced effects on galaxies beyond obvious structural deformations. Authors of the earlier papers told me that my conclusions were wrong. They even suggested tests which would enable me to "correct" my error. But the tests only confirmed my earlier conclusions. What to do? Well as a proletarian astronomer the only thing I could do was wait for confirmation from more "elite" sources. Fortunately I did not have to wait long. Just two years later Larson and Tinsley (1978) reported on a study of UBV colours of interacting/peculiar galaxies (also from the Arp Atlas). They found them to be unusual. Normal galaxies of a particular type show a very narrow dispersion in color (for a recent study e.g. Fernandez-Lorenzo et al. 2012). However L&T found that interacting galaxies showed a much larger dispersion and generally bluer colors presumably reflecting interaction enhanced star formation rates. The 1976 radio survey was twice confirmed within 4 years using different samples—one using the CPG with the CIG as control—good timing—(Stocke 1978). In one study the radio enhancement was ascribed to the disk (star formation/supernova remnants?) and in the other to the nucleus (nuclear star formation/ active nuclei?).

The Larson and Tinsley paper apparently (900 CITATIONS) opened a new era where nurture replaced nature as the driver of most galaxy properties—suddenly everything was caused by interactions and/or merger/accretion events. Only in the last 5 years do we (or at least in my imagination) begin to see the pendulum swing left—yes interactions are important but not as important as claimed in the twenty years after 1976. Of course today active nuclei are thought to be a product of interactions even though Seyfert 1 galaxies show no excess of companions (Dultzin-Hacyan et al. 1999b). Most active nuclei are radio-quiet so we do not necessarily expect a radio signature. The Seyfert companion statistics were perhaps the first movement of the pendulum. In some ways then the role of interactions has been overemphasized but it is important—despite this overemphasis some recent galaxy surveys have given little or no consideration to the environmental properties of the galaxies being studied. The reason for this contradictory reaction may be connected to confusion about the strength of the interaction signature. The lack of statistically useful control samples of isolated galaxies makes it difficult to establish what is normal and what is excessive (see e.g. Xu and Sulentic 1991). Many believe that the overwhelming majority of galaxies have lived active lives involving interactions with other galaxies and major or minor accretion events. The mergers were thought to produce ellipticals but as the need arose the idea of spirals as merger products also came into favor—where is the pendulum when you need it!

The merger mania might see all isolated single galaxies, paired galaxies and compact groups of galaxies as having created their isolated environment via mergers (they eat their neighbors). Isolated mixed E+S pairs of galaxies mentioned earlier (100+ examples in the CPG, Fig. 4.6) might somehow be an end product of this process, since established wisdom says they cannot be physical binaries. The elliptical would represent the merged/accreted galaxies from a 1-2Mpc group volume and the spiral representing the last intact original member of the group (Rampazzo and Sulentic 1992). We actually suggested this possibility (tongue in cheek) because we knew it would be attractive to ideologues—it was also proposed for compact groups like Stephan's Quintet (Governato et al. 1996) but few show a first-ranked elliptical. No problem, we can propose (tongue in cheek?) first ranked spirals as merger products? Mixed morphology pairs (like compact groups) are a kind of forbidden fruit and have been mentioned in various counter-culture contexts (e.g. Burbidge et al. 1963; Vorontsov-Velyaminov 1957). Do they breed active nuclei via cross-fueling from the S to the E (Domingue and Durbala 2005)? Denis Sciama mentioned them as evidence for continuous creation in support of the Steady State cosmology (the E represented the old pre-existing galaxy and the S represented new matter) although, for the life of me, I cannot find the reference—he even showed photos of one or more of the mixed pairs. Is it any wonder that they are a kind of taboo subject?

Returning back to isolated galaxies and the potential value of an isolated galaxy sample for controlling statistical studies. It must bring us back to the CIG of (Karachentseva 1973). The message is that enough of them exist to make them interesting and potentially useful. The reaction to a discussion of isolated galaxies will often be that they may be isolated now but a few billion years ago things might have been very different. Their statistical properties argue against this interpretation—see discussion of bulges below. Around 2000, near the dawn of the

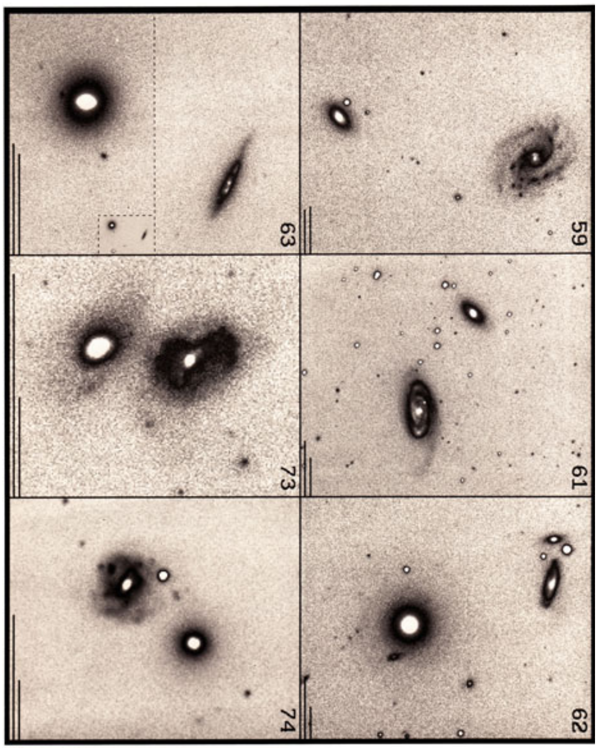

Fig. 4.6 Unpublished CCD images (from a 1m telescope at Kitt Peak) of six of the mixed E+S pairs from the CPG (Karachentsev 1972). Bulges of spirals in these isolated pairs tend to be larger than those in isolated single spirals from the CIG (Karachentseva 1973)

SDSS era, an attempt was begun to reanalyze the CIG using the 2nd Palomar Sky Survey. This led to the AMIGA project (Verdes-Montenegro et al. 2005) with the goal of a vetted CIG catalog of the most isolated galaxies in the local Universe (Fig. 4.7). The final chapter of the transition is now being written, where the POSS2 CIG results are compared to catalogues extracted from SDSS using (3D) isolation criteria similar to those employed (in 2D) for the CIG (Argudo-Fernandez et al. 2013, 2014).

What are the differences between bulges and pseudo-bulges? Is this distinction really necessary? You have analyzed the bulge component in one of the more isolated sample of galaxies ever built: the AMIGA galaxy sample. What can we learn about the formation of bulges from these studies?

Answering such questions must inevitably lead to the question of how galaxies form. In the 60's-70's we were taught that galaxies formed monolithically out of the collapse of primordial clouds. Issues of dissipation and star formation rate dictated the type of galaxy to emerge. In such a view the bulge/halo (globular clusters were a tracer of this extreme Population II component) experienced the first episodes

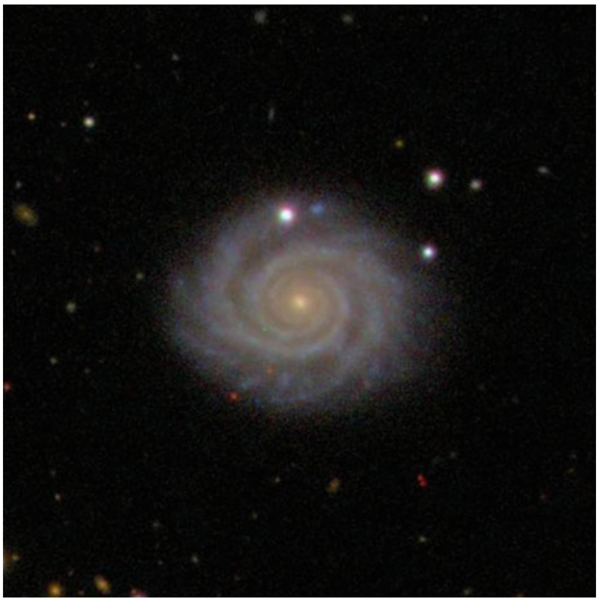

Fig. 4.7 A color composite SDSS image of CIG 281 (from the Karachentseva 1973 catalog). It is a typical isolated galaxy—a late-type spiral with large blue disk and considerably redder bulge

of star formation. Remaining gas and dust collapsed into a disk where extreme Population I stars continue to form. In this view the bulge was "classical" and shared the properties of elliptical galaxies (morphology, kinematics, stellar content). After 1970 new ideas crept into the field arguing that elliptical galaxies were not formed primordially but by major mergers. In that view it was logical to argue that interactions and mergers in spirals stimulated bulge growth. Small bulges (e.g. Sc) indicate spirals that experienced fewer interaction events while all Sa spirals presumably suffered many events. I detect no consensus on this interpretation.

As noted above the images from `HST` showed that disks extend into the bulge which is so-far-so-good. About the same time however deep `HST` images revealed object that some called sub-galactic clumps (Pascarelle et al. 1996). Coupled with the surprising `HST` images an idea began to grow that maybe some or all galaxies form by sequential accretion rather than monolithic collapse. I looked upon this suggestion as the equivalent of Wall Streeters suggesting that CDO's are a good investment. But it does not matter what I think—it only matters what the Universe tells us—if we are willing to listen. By 2004 we see papers (e.g. Fisher and Drory 2008) arguing that small bulges were not bulges at all but pseudo-bulges showing properties more like disks than like elliptical galaxies. Things are clearly confused if the disk extends into the bulge. The role of nurture also raises its head because interactions and minor mergers might also affect bulge properties. Is an old population classical bulge hiding in these galaxies? In the new scenario all early-type spirals showing large bulges have experienced many interactions/mergers although even the famous Sombrero galaxy (NGC 4594) has been argued to show pseudo-bulge properties (Gadotti and Sanchez-Janssen 2012). The pendulum is certain to move left before long.

I had never taken the sense that the sub-galactic shreds had shifted the paradigm against monolithic collapse. If real (refereed by Nature) it seemed like the kind of result that could do it. A paper from a non-elite institution with 138 citations cannot move a paradigm. If the paper had come from Princeton would it not have had 5000 citations by now and have changed the paradigm? Is it healthy for (US) science to have in place a self-styled elite that controls access to funding and to telescopes? Does the Universe recognize it and withold its secrets from all but the elite? In the face of an apparent pseudo-bulge revolution, I was motivated by 2009 to ask a theorist friend whom I trusted (and educated in the same era)—one who was speaking in favor of sequential galaxy formation—what observations had changed the paradigm? His reply was that no observation was responsible but rather the inability of CDM (cold-dark-matter) models to form galaxies monolithically. Is astronomical science driven by empiricism? Should it be?

The AMIGA survey and its sample of many isolated galaxies seems an ideal way to address the issue of whether bulges are classical or pseudo. A morphological reevaluation of the CIG within the AMIGA project (Sulentic 2006) found: (1) that 67% of the galaxies were small-bulge late-type (Sb-Sc) spirals and (2) that 14% of the sample involved early-type E/S0 galaxies of modest luminosity. The former was not a surprise—low density regions tend to be populated by late-types. The latter might be evidence for a primordial population of early-types if the morphology-density relation also applies to the lowest density regions of extragalactic space. More relevant here is the preponderance of small-bulge isolated spirals. One of my students studied 100 of the "typical" late-type spirals from the AMIGA sample as representative of the parent population of isolated galaxies (Durbala et al. 2008). She used the BUDDA software to accomplish a bulge-disk-bar decomposition and found a striking concentration of galaxies with bulge-to-total ratios $B/T<0.1$ and Sérsic indices $n<2.5$. The latter values, for believers in the Sérsic index as a meaningful parameterization has been adopted as the zone of pseudo-bulges. It would seem that the AMIGA sample is dominated by spirals hosting pseudo-bulges. Whatever they are, they are small and if B/T, or related measures, monitor dynamical history of a galaxy then the result confirms that AMIGA galaxies have lived very quiet lives—apparently little or no bulge growth has taken place via secular evolution. See also Durbala et al. (2009) for an initial attempt at Fourier analysis of the same sample.

If we assume that these galaxies have been isolated most of their lives then they may offer unique insights into the natural form of primordial spirals. If galaxies (somehow) form by monolithic collapse then we expect them to host classical bulges and if they form sequentially then the pseudo-bulge apparently grows slowly out of disk material. In the latter case the (pseudo) bulges should show rotational motion, younger (bluer colours) stellar populations and flatter morphology. If AMIGA galaxies are among the least nurtured galaxies in the local Universe then study of their bulges may offer a direct test of the relative merits of monolithic vs. sequential formation processes. A member of the AMIGA team set out to explore the properties of a significant samples of AMIGA spirals (using GALFIT and Sextractor software) where she has already found that spiral subtypes (the sample is large enough to permit discrimination at the level of basic subtypes e.g. Sb, Sbc, Sc…) show very small colour dispersion (Fernandez-Lorenzo et al. 2012) and larger disks (Fernandez-Lorenzo et al. 2013) than control samples involving galaxies from richer environments. The large SDSS imaging database provide 5 colour images for 60% of AMIGA galaxies (DR9) with sufficient resolution to permit estimation of bulge colours. The colours for most of the bulges turn out to be quite red (Fernandez-Lorenzo et al. 2014). Perhaps the best way to express this is to say that the bulges are considerably redder then the disks ((g-i)$_b$ $= 0.77$ for disks vs. 1.06 for bulges). Such colours imply predominance of an old ($\sim$7Gyr) (or very reddened) stellar population in the bulges. A recent analysis of SDSS fiber spectra for many of the same galaxies finds a model age near 10 Gyr for the majority of the bulges (Zhao 2012). Maybe pseudo-bulges formed quasi-primordially? If they show the same colours and stellar populations as expected for classical bulges formed (somehow) by monolithic collapse then the concept of pseudo-bulge loses its meaning and we are left with no clue about how galaxies formed.

The next interview deals with the disk component, historically the first structure that has been identified in galaxies, being our galaxy the MW of this type. Many are the questions that are still open. What we really know about this component? In which way the disk kinematics is connected with the star formation? Why many disks appears truncated? What produce the observed chemical gradients? What simulations tell us? Are these studies still important? Many of these questions will be tackled below by Pieter C. van der Kruit.

Questions for Pieter C. van der Kruit:
the disk component represents the most significant stellar structure of late-type galaxies. Could you trace the most significant achievements in our understanding of the disk component during one century of studies? Would you discuss the main physical properties of disks? Which is the spectrum of their masses and surface brightness properties?

The modern era of research on disks in galaxies started with the development of statistical astronomy, which aimed at determining the distribution of stars in the Sidereal System (Kapteyn 1922; Kapteyn and van Rhijn 1920; von Seeliger 1920). This took place before it was recognized that spiral galaxies are extragalactic systems, but it was soon realized that the Sidereal System was mainly a flattened structure. The history of Kapteyn's efforts have been described recently in my biography of him (van der Kruit 2015). When nebulae like Andromeda were shown to be external systems, it was obvious that our Galaxy had a similar disk structure. I pick the development up in the next section with the first optical surface photometry in the 1940s. A comprehensive discussion of our present knowledge of galactic disk has been presented in a chapter in Annual Reviews by Ken Freeman and myself (van der Kruit and Freeman 2011).

The exponential nature of the radial surface brightness profile in galactic disks was first noted in M33 by F.S. Patterson in 1940 (Patterson 1940), but it was

Gerard de Vaucouleurs who made the discovery more widely known (see e.g. de Vaucouleurs 1959). Mostly through the latter's efforts the number of galaxies with determined luminosity profiles increased and Ken Freeman collected in 1970 (Freeman 1970) information on 36 galaxies. This seminal study presented the rotation curve of an infinitesimally thin, self-gravitating exponential disk, expressed in the (to face-on corrected) central surface density $\rho_\circ$ and the e-folding scalelength h. Furthermore, he found that the values for the face-on central surface *brightness* $\mu_\circ$ clustered around a value of 21.65 B-magnitudes arcsec^{-2}, independent of morphological type.

Mike Disney (1976) showed that this 'Freeman's law' and its equivalent Fish's law in ellipticals could easily arise from selection effects. At any integrated magnitude the galaxies with bright central surface brightness have small scale-lengths and appear star-like, while the faint surface brightness, long scale-length systems cannot be seen above the sky background. The sky surface brightness of 22 or so B-magnitudes arcsec^{-2}, typical for dark observatory sites, ensures that the resulting visibility is restricted around values as Freeman observed. The bright cut-off has been confirmed as real in galaxies, but the detection of so-called Low Surface Brightness galaxies (LSBs) has shown that the effect does indeed operate. For a recent plot of the distribution of central surface brightness and further discussion see Fathi (2010).

Surface photometry was cumbersome from photographic plates, and it has been only with the advent of CCDs that it was done on a wholesale basis. Yet, with care it was possible to use photographic techniques to arrive at surface brightness profiles with excellent quality. For example the surface photometry in three colors of 16 galaxies in the Palomar-Westerbork Survey (published in 1986) took 42 dark nights on the Palomar 48-inch Schmidt telescope (Wevers et al. 1986). When not much later CCD photometry became available on some of the same galaxies (Kent 1987), a comparison of three of the galaxies showed that the luminosity profiles agreed excellently with deviations not exceeding 0.2 magnitudes (Fig. 1 of Chapter 2 in Begeman (1987)).

There is a large range in masses ranging from less than 10^9 $M_\odot$ to a few times 10^{11} $M_\odot$. The small mass disks tend to be in later type galaxies with more ongoing star formation. This feature is sometimes referred to as 'downsizing', the phenomenon that in the early universe star formation occurred mainly in high-mass systems, which subsequently shifted towards lower mass, smaller systems with cosmic time.

Color gradients are difficult to interpret uniquely as age gradients, as these are degenerate with dust absorption. However, this degeneracy can be broken when a set of colors in the optical and near infrared are used. de Jong (1996) showed that in his sample of moderately inclined galaxies the colors correlated with surface brightness, being bluer in areas of low surface brightness as in the outer parts of disks. Modeling then showed that the gradients could best be explained by combined age and metallicity gradients across the disks with the outer regions being somewhat younger and of lower metallicity. These age gradients are however, relatively shallow and not steep enough to think of galaxy disks as growing inside out over ten billion years or so.

The vertical distribution of stars can only be studied in edge-on systems. However, then we have to cope with the strong effects of dust absorption, limiting in particular in later type disks the available range in z to areas away from the central dust layer. When this was performed it turned out that to an excellent approximation the vertical scale parameter (an exponential scale-height or something equivalent) was independent of the distance from the center (van der Kruit and Searle 1981). This is surprising since it implies that the vertical velocity dispersion has to fall off with radius also as an exponential but with twice that of the light (assuming that the mass distribution follows that of the light, or that the mass-to-light ratio M/L is constant). This was indeed found by Ken Freeman and myself and confirmed by others (as documented in van der Kruit and Freeman (2011)). Although the original fits were performed with the distribution corresponding to the self-gravitating isothermal sheet (equal density planes all parallel and infinite, velocity dispersion constant with height), this should not be taken as an actual description of the detailed vertical dynamics of disks.

Another unexpected property was that of truncations, the observation that in edge-on disks the radial light profile after some 4 or 5 de-projected scale-lengths did quite suddenly start to fall off faster (van der Kruit 1979). This property has been found to occur in a large fraction of edge-on disks. It is remarkable that HI warps observed in such galaxies start quite abruptly just beyond the truncation radius (van der Kruit 2007). In some cases a corresponding feature in the HI rotation curve has been observed, suggesting that indeed the truncation occurs in the mass distribution and not just in that of the light (see van der Kruit and Freeman 2011). Although sometimes there are warps in the light distribution as well (NGC 4565 is a good example) these are of very small amplitude, although in the same direction as in the HI if present.

You proposed a 3D description of stars in galaxy disks and you got the first measurements of the velocity dispersion in galaxy disks. What have we learned from these studies? Could you describe the main differences in the vertical structure of disks in S0 and spiral galaxies? Why some disks appear warped?

When we combine surface photometry (and for sophisticated analyses supplemented with distributions of other baryonic components) with observed stellar kinematics we can address matters of the total mass distribution in disks, their dynamics and local stability. For what follows I again refer to the Annual Reviews paper (van der Kruit and Freeman 2011) for more details. All results found this way indicate that there is no major radial gradient in the mass-to-light ratios in galactic disks.

The fact that the vertical velocity dispersion decreases with radius in such a way that the vertical scaleheight parameter of the stellar disk is approximately constant, can probably be related to the disk stability. In my other contribution to this volume, I reviewed the progress in stellar dynamics of disks and the matter of local (and global) stability. The local stability has been characterized by the Toomre parameter Q (Toomre 1964) as arising from Jeans-like stability based on the virial theorem on small scales and shear resulting from differential galactic rotation on large scales. For an estimate of Q one needs to determine, in addition to the local radial velocity dispersion and epicyclic frequency from the rotation curve, also the surface density. This requires the measurement of the scale-height of the disk and its vertical velocity dispersion. The first two cannot both be measured in any galaxy so this involves statistical approaches. Also the axis ratio of the velocity ellipsoid is required to estimate both the radial and the vertical velocity dispersion. In broad description, analyses like these have provided a consistent result that in disks the stability is close to marginal at all radii. An approximately constant Q gives a velocity dispersion profile that would produce a stellar disk with approximately constant scaleheight. The corresponding mass-to-light ratios derived for disks are such that most or all disks are sub-maximal, that is to say are not massive enough to reproduce the amplitude of the observed rotation curves not even in the central parts of the galaxies.

An extensive program to study the kinematics and dynamics of relatively face-on disks is the so-called DiskMass Survey, led by Matthew Bershady and Marc Verheijen (see Westfall et al. 2014 and earlier papers in that series). The overall result is that disks are stable and sub-maximal, the level of stability apparently depending on the star formation rate in the sense that the star-formation activity and the gravitational stability are anti-correlated. This fits in with the notion that star formation is self-regulating in maintaining a balance between the heating, cooling and turbulence in the gas from which stars form and the vertical gravitational force field.

Is the origin of disks understood?

The radial distribution of matter in a disk depends on the force field (reflected in the rotation curve) and the distribution of specific (per unit mass) angular momentum. It was noted by Leon Mestel in 1964 (Mestel 1963) that the specific angular momentum distribution in the disk of the Galaxy is close to that of a uniformly rotating, uniform sphere. This was soon extended by others to external galaxies. Freeman (1970) showed the same for the self-gravitating exponential disk. This led to the notion of a collapse of the disk material in the force field provided by the dark matter halo with detailed conservation of angular momentum, as for example worked out in some detail by Fall and Efstathiou (1980).

Jim Gunn first showed that if you take a dark halo providing a flat rotation curve and let matter with the specific angular momentum distribution of the Mestel sphere settle with detailed momentum conservation into a flat disk, you will end up with a radial profile that is roughly exponential. Interestingly, if you then look at the matter with the highest specific angular momentum, it settles at about 4.5 scalelengths and since there is no matter with higher specific angular momentum this automatically produces a truncation at that radius (see van der Kruit 1987 and references therein).

This all is in general terms consistent with what we observe, so there may be some truth in this. However, the matter must be more complicated since there are very likely important redistribution of angular momentum during disk formation. Furthermore, the simple Mestel sphere fits into the notion of a monolithic collapse during disk formation, while the more recent picture of build-up by merging of smaller systems is strongly supported by theoretical and observational studies. The matter is currently very much evolving; a recent workshop at Lowell Observatory on exponential disks has much new and current information (Elmegreen and Hunter 2014).

The correlation of stellar disk truncations and HI layer warps (van der Kruit 2007; van der Kruit and Freeman 2011), where the extremely flat HI in the stellar disk abruptly becomes warped suggests that the truncation marks the discrete transition between the inner disk that formed quite early on and material that fell in later with different orientation of its angular momentum. Some galaxies have no extended HI (often in galaxy clusters such as Virgo), but it is also usually so that when a galaxy has HI beyond its optical disk, it almost invariably is warped.

It should also be noted that the inner disks are exceedingly flat over their full extent with deviations in the order of only a few percent, while often the spiral structure seen in the disk in HII regions, dust-lane and HI, continues in HI smoothly across the stellar disk truncation and onset of the warp (van der Kruit and Freeman 2011).

The picture of the structure and formation of the disk has been evolving significantly with the recognition of so-called thick disks, causing the traditional disk to be designated thin disk. These thick disks were first found in S0 galaxies by Vassiliki Tsikoudi and David Burstein around 1980 (Burstein 1979; Tsikoudi 1980), then detected a few years later in our Galaxy towards the Galactic South Pole by Gilmore and Reid (1983). Now thick disks are known to be present in all or almost all galaxies, that are seen edge-on. Current thinking is that the thick disks are metal poorer and older than the stars in the thin disks, and result from some secular evolution early on, maybe associated with merging and infall of small systems.

Although originally S0 galaxies were thought to be those systems in which the gas was all used up in star formation just after completion of the disk formation, the correlation of their relative occurrence with dense environments as galaxy clusters gave rise to the notion that they are spirals stripped from their gas content. Early measurements by John Kormendy suggested that S0 disks are hotter and the Q parameter higher than in normal spirals preventing the formation of small scale structure (Kormendy 1984). The heating up of the disk may also be affected by minor mergers. It is likely that both stripping of gas in S0 galaxies and internal mechanisms that cause the star formation to exhaust the gas content or prohibiting replenishment of gas, possibly related to strong bars, may both be operating in nature.

Why it is important to study the properties of disks today?

The study of disks in galaxies contributes much to our evolving insight into the matter of the formation and evolution of galaxies. It is vital for a better understanding to have more detailed and accurate determinations of radial gradients of the history of star formation (or at least average stellar ages) and metallicity in disks. This requires the study of resolved stellar populations, but that is feasible now for systems of to some Megaparsecs away and will soon be possible for larger distances as new observing facilities become available.

4.4 Rings, Bars and Lenses

Many disk galaxies host bars, rings and lenses, structures whose origin seems today quite well understood, at least in numerical simulations. Which is their importance as galaxy components? Why not all galaxies have such structures? Are these structures linked each other? What are the differences observed in the various morphological types? The next interviews to Eija Laurikainen, Debra M. Elmegreen and Françoise Combes will address these issues.

Questions for Eija Laurikainen:
S0 galaxies show a manifold of bar and ring structures. May you sketch their properties in a multi-wavelength context? May you explain the connection between bar and lens? The bar kinematics is often used to infer the DM halo of the host galaxy (fast and slow bars). May you explicit such method?

It has been suggested by Kormendy (1979) that bars dissolve into lenses. Outstanding examples of barred galaxies with lenses that end up to the radius of the bar indeed exist, of which NGC 1543 is a good example. However, there does not yet exist any theoretical grounds for this. It has also been suggested (Laurikainen et al. 2013) that only the main part of the bar (the thin bar outside the boxy bulge) dissolves into a surrounding ring. Observational support for this idea comes from the fact that inner lenses in the non-barred S0s have similar sizes as the boxy/peanut/barlens bulges in barred galaxies. Buta et al. (2015) also paid attention that galaxies with prominent boxy/peanuts or barlenses have weak bars. Indeed, it seems that the connection between the morphology of bars and the appearance of lenses is telling us something important of galaxy evolution which is not yet fully understood.

Bars respond to the total amount of mass in galaxies and resonance rings to the potential well of a bar. Therefore, imitating an observed galaxy with a simulation model can be used to estimate possible dark matter content in galaxies. One way of doing it is to measure the rotation curve and to evaluate the potential well of the baryonic mass using a near-infrared image, which best traces the stellar mass in galaxies. Galaxy morphology can then be looked at using an optical image, where the response of gas to the potential well is visible. In the simulation model a bar gradually grows and rings appear at the resonances of the bar. In the linear approximation the radial distances of the rings are determined by the bar pattern speed. Therefore the ratio $R=L_{CR}/L_{bar}$, where L_{CR} is the co-rotation radius of the bar, and L_{bar} barlength, is generally used as a measure of the bar pattern speed Ω_{bar}. The best fitting model can be found by adjusting the mass-to-luminosity ratio and Ω_{bar} in such a manner that it traces the ring locations and the overall morphology of the galaxy. The advantage of this "simulation method" is that it can be applied to all Hubble types and for a large number of galaxies at different redshifts.

It has been predicted by the N-body simulation models of Debattista and Sellwood (2000) that inside massive or centrally peaked dark matter halos bars should be slowly rotating. Conversely, a fast bar would imply a 'maximum disk' contributing most of the total force. One of the most detailed observational studies is the response-simulation study for IC 4214 (Salo et al. 1999), for which galaxy a fast bar was found (R$\sim$ 1.4). Moreover, the visible mass was found to dominate in the disk region, consistent with Debattista and Sellwood prediction. Indeed, so far all measurements for the S0s and early-type spirals in the nearby universe (Rautiainen et al. 2008), and even for galaxies until $z \sim 0.8$ (Pérez et al. 2012) imply fast rotating bars. Only some late-type spirals might have slower bars, but it is not yet clear whether these galaxies have more than one pattern speed (the measured pattern speeds could correspond to the outer spiral structure). These measurements are also in agreement with the direct Ω_{bar} measurements for the S0s, based on the Tremaine-Weinberg method using the stellar absorption line kinematics (see the review by Corsini (2011)).

Based on the above arguments we could simply adopt the view that in the galaxies with mass similar to Milky Way or larger, the dark matter content is not dominant in the visible disks. However, simulation models (Athanassoula 2002) have indicated that the bar slow-down is typically associated with the growth of bar length and strength. It is thus somewhat surprising that the longest bars appear in the S0^{-}-S0/a galaxies, whose bars are invariably fast, thus showing no signs of bar slow-down. This apparent controversy has recently cast doubts on whether the R-parameter is reliable for estimating whether the disks are dark matter dominated or not (Athanassoula et al. 2013). Nevertheless, it seems that the fast bar/maximum disk connection is still valid, if we look at the galaxy properties after the bar formation, and not the initial conditions of the simulations (see Sellwood and Debattista 2014).

In addition to the dark matter, there are also other factors like the stellar bulges or the spin of the halos, which can in principle affect the bar pattern speed and dark matter estimate. For example, small classical bulges embedded in bars can act in a similar manner as the centrally peaked dark matter halos, thus transferring angular momentum from the bar to the bulge (see Saha et al. 2012). However, taking into account that bars in the S0s are fast rotating, it is unlikely that the bulges would have any significant effect. Concerning halos, the cosmological simulations (Navarro et al. 1997) predict that halos of disk galaxies should have a certain amount of rotation. However, it has been shown by Saha and Naab (2014) that if halos are slightly flattened, bars form efficiently in rapidly spinning halos, but also those bars will be slowly rotating at the end. It has also been suggested that the dark matter halos not only absorb angular momentum from the bar, but may also emit angular momentum to the bar (Long and Shlosman 2014).

It seems that the answer to the question made by the editors is partly on the theoretical side: more simulation studies will be needed to thoroughly understand the evolution of bars in the presence of rotating triaxial halos. On the other hand it would be important to extend the number of measured bar pattern speeds which could then be connected to estimated dark-to-visible mass. Until proven contrary, it seems feasible that the disks of the massive galaxies (Milky Way mass and larger) are not dark matter dominated. In that case the fast bars frequently observed in galaxies would have a natural explanation. Indeed, massive disks would easily become unstable to bar formation, and via vertical buckling process, develop the boxy/peanut/barlens bulges in which most of the apparent bulge mass seems to reside in the nearby universe. Bars in the early-type disk galaxies could be longer simply because they were born stronger. Galaxies might have formed as almost bulgeless systems in the gas rich clumpy universe at high redshifts.

Questions for Debra M. Elmegreen:
Bars and rings are often detected in spiral galaxies. What are their frequency? Does exist a connection with the galaxy environment? Are the bar and ring properties of spiral galaxies different from those of S0s?

Françoise Combes, one of the contributors to this book, is an expert on this subject, so I will keep my remarks brief here. She wrote a review article with Ron Buta on rings (Buta and Combes 1996). They note that about 20 % of spiral disks have inner rings, which appear to be caused by bars or non-axisymmetric perturbations near the m=4 resonance. Outer rings, however, are dominant in S0 galaxies, as catalogued by de Vaucouleurs et al. (1980). Based on an examination of S0s from this and other catalogs, we find that most outer rings are in SB0 galaxies. About 2/3 of SB0 galaxies in the field have outer rings, while most SB0 galaxies in groups or binary systems do not (Elmegreen et al. 1992). Conversely, the fraction of SB0 galaxies with outer pseudo-rings increases with increasing density of the environment. These results suggest that tidal interactions by neighbors destroy or disrupt outer rings and enhance pseudo-rings. A recent examination of rings based on a catalog and atlas of 3.6 μm images of over 700 galaxies from the Spitzer S^4G sample finds that barred galaxies have outer rings 1.7 times more frequently, and have inner rings 1.3 times more frequently, than do non-barred galaxies (Comeron et al. 2014). In that study, outer rings are found in early type galaxies, whereas inner rings span the range of spiral types. The details of ring morphology are considered by Buta (Buta et al. 2007; Buta 2013).

Dressler (1980) studied the distributions of galaxy morphology in 55 rich clusters and found that the percentage of spirals decreases as the cluster density increases; since the bulge/disk ratio for S0s is systematically larger than for spirals, he argued that S0s do not form from stripped spirals. Both cold and hot gas are detected in S0s, even though they do not have current star formation (e.g., Ilyina et al. 2014). David Burstein, in his doctoral dissertation and subsequent papers, discovered a thick disk component of S0s (Burstein 1979). John Kormendy presented new observations and ideas on secular evolution, suggesting that "red and dead" S0 galaxies may be the result of ram pressure stripping by hot intracluster gas in addition to galaxy harassment by other cluster galaxies (Kormendy 2013; Kormendy and Bender 2012).

van den Bergh (1976) envisioned a revised tuning fork diagram that has parallel tines of S, A, and S0 galaxies (A is for "anemic," when the arms appear depleted

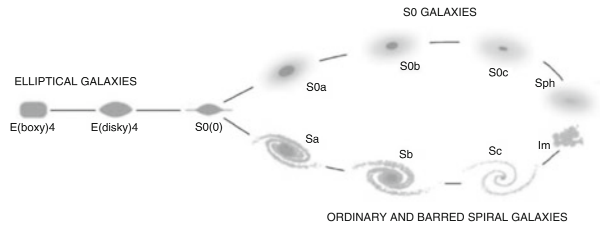

Fig. 4.8 Grayscale adaptation of Kormendy & Bender's revision to the tuning fork to include an S0 tine and endpoints at Sph and Im galaxies (Kormendy and Bender 2012)

in star formation for their Hubble type. Anemic spirals, primarily identified in the Virgo cluster of galaxies, turn out to have normal amounts of molecular gas but a depletion of atomic gas, presumably from tidal stripping). Kormendy and Bender (2012) further revised the tuning fork to extend from spiral galaxies to Im (irregular), and from S0 galaxies to Sph (spheroidal), noting that Sph galaxies are not merely dwarf ellipticals like M32 but evolve through a combination of processes; see Fig. 4.8. They provide a discussion of the implications and nuances of these classifications, including use of some quantitative measurements of parameters. An update and review is provided by Kormendy (2015).

The percentage of barred galaxies is about 25–30 % when considering just SB types, increasing to about 60–65 % when including SAB types (see summary in Sheth et al. (2008)). Buta et al. (2015), in studying `Spitzer` images of over 2400 galaxies, note that the percentage of barred galaxies increases from about 55 % to over 80 % going from early-type to late-type spirals. There is a quantitative difference between bars in early and late type spiral galaxies, with the former being longer and stronger ("flat" bars) than the latter ("exponential" bars) (Elmegreen and Elmegreen 1985). The overall percentage of barred galaxies decreases to about 20 % at redshift $z = 0.84$ based on galaxies in the `COSMOS` sample (Sheth et al. 2008). This decrease evidently is because disks were more turbulent then and therefore too hot for bars to form (Sheth et al. 2012). However, the fraction is about constant out to this redshift for massive galaxies with large bulges, which evolve more rapidly.

Questions for Françoise Combes:
simulations have been able to reproduce many properties of bars and rings. Would you summarize the main historical successes of these studies? Do simulations predict the whole range of physical characteristics of such structures? What is still lacking for a full understanding of these components?

Rings and bars were very early noticed in galaxy morphologies, as soon as external galaxies were recognized as such, at the beginning of the 20th century. The Hubble sequence contains two branches, one for barred and one for unbarred spiral galaxies. Rings are frequently the site of star formation, so they are bright and easily identified. The origin of these features remained a mystery for some time, and ejections of matter along the bar, related to nuclear explosions, were postulated (e.g. de Vaucouleurs and Freeman 1972). Numerical simulations were key in this domain.

Bars were not recognized interesting, and only the spiral structure was the focus of studies. In the 1960's the work of Lin and Shu was a breakthrough in setting robustly the theory of density waves for spiral arms (Lin and Shu 1964). The first N-body simulations, able to account for the self-gravity of the stars in a 2D disk were searching to confirm the theory. But after the development of a transient spiral structure, the stellar disks all ended up with a bar instability, spontaneously growing from their self-gravity (Hohl 1971). To get rid of these bars, initial stellar disks had to be built very hot, with a large velocity dispersion, much too large with respect to the observed cold galaxy disks. It was then discovered that bars are the main instabilities of a cold stellar disk. This nicely explained why about 2/3rds of the galaxies are classified as barred (1/3rd strongly barred, of type SB, the other 1/3rd mildly barred), type SAB. To obtain a much more realistic reproduction of galaxy morphologies, the interstellar gas had to be taken into account. Simulations of the behavior of the gas in a barred potential showed how a spiral structure could be generated (Athanassoula 1992; Sanders and Huntley 1976).

Much later, the inclusion of more physical phenomena, like star formation out of the gas, and supernovae feedback, with the account for completely self-consistent stars and gas component, together with live haloes, completed the picture, and now simulated galaxies resemble totally the true ones, especially when colors are also reproduced from the history of star formation, the dust content, etc. (cf. Fig. 4.9). However, this is only for idealized galaxy simulations, with a disk and bulge as initial conditions. When galaxy formation is involved, in cosmological

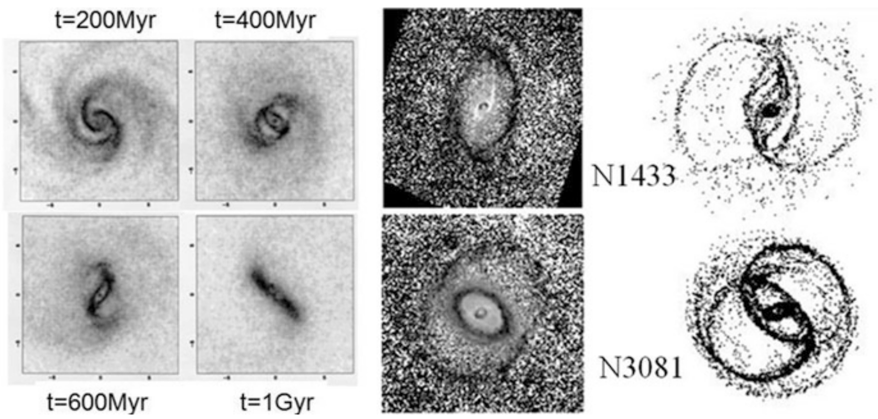

Fig. 4.9 Bar and ring formation in galaxy simulations: *Left*: bar formation in an N-body simulation with stars only. The different epochs reveal the transient spiral structure, transforming into a robust bar (from Buta and Combes (1996). *Right*: $B - I$ color index maps (blue features are dark, red features are light) of the two galaxies NGC 1433 and NGC 3081, compared to particle simulations, representing gas flows in the barred potential. The latter is derived from the corresponding H-band images, from Buta and Combes (2000)

simulations, the agreement with observations is much less satisfying. The dark matter haloes formed in the standard CDM model are too massive and too centrally concentrated in cusps, the baryons are not sufficiently self-gravitating, and spiral or bar instabilities are too weak. Barred galaxies are difficult to obtain in cosmological simulations, and it is not only because of lack of spatial resolution.

An important issue was to understand the observed frequency of bars and ovals in galaxies: if the main spontaneous gravitational instability in galaxy disks is a bar, why not all galaxies are barred? This issue is related to bar demographics and evolution. A bar might not be long-lived in a galaxy, but its strength may vary with time, especially when the disk is gas rich. Fully self-consistent simulations, able to follow the gravity torques of stellar bars on the gas, and the reciprocal torque of the gas on bars, showed that the bar are self-destructive. Their torques drive the gas from corotation inwards, and in the process they receive the angular momentum of the gas, which weakens their strength. A gas-rich spiral disk can then experience some strong bar episodes, and then enter in the unbarred galaxy classification, before being unstable to bar formation again (e.g. Bournaud and Combes 2002). This secular evolution occurs on time-scales of the order of 0.5–1 Gyr.

Bars have been recognized to be the main driver of secular evolution of galaxies, and through vertical resonances, elevate stars above the plane to form pseudo-bulges of peanut/box shapes (Combes and Sanders 1981). Combined with external gas accretion from cosmic filaments, this secular evolution competes with more violent events like galaxy interactions, minor or major mergers, to assemble mass in galaxies, and to the co-evolution of bulges and supermassive black holes, located in each galaxy centers.

Rings have been relatively easy to understand, as soon as bars have been clearly reproduced. In majority, rings are due to Lindblad resonances (named after the work of Bertil Lindblad in the 1940–50's). Since 3 or 4 rings can be observed in some galaxies, with characteristic shapes, the identification was easy. There could exist a nuclear ring at ILR (Inner Lindblad Resonance), an inner ring at corotation (in general just encircling the bar), and an outer ring at OLR (Outer Lindblad Resonance). These can be either parallel to the bar, or perpendicular to it, and both can exist, with some figure 8-shape, which correspond to the morphology of periodic orbit families, in the bar rotating frame. Details on observations, and the comparison with simulations have been described in Buta and Combes (1996).

Rings are the location of accumulation of gas, due to the gravity torques of the bar, which change sign at each resonance. They are therefore the locations of star formation, and the bright knotty rings in the nuclear regions of barred galaxies have been noticed for a long time (Sérsic and Pastoriza 1965). When several rings are observed in the same galaxy, it has been checked that they correspond to the resonances with the same pattern speed. The observation of rings are therefore precious tools to determine the pattern speeds of bar waves, that cannot be determined directly.

Now that bars and their resonant rings are rather well understood in the local universe, there remains to understand their cosmic evolution. It has been established from observations at high redshift that the Hubble sequence for spiral galaxies is not yet in place until $z \sim 1$, that the fraction of irregular galaxies is much higher early on, probably due to the large gas fractions, making disks violently unstable and clumpy. Also, when it was possible to resolve galaxy disks, the bar fraction has been observed to drop by a factor 3 at $z = 0.8$ (Sheth et al. 2008). Bars prefer to sit in massive galaxies with a stabilizing bulge. While the bar fraction in very massive spirals is about constant out to $z \sim 0.84$, it decreases from $z = 0.3$ already for the low-mass, blue spirals. Understanding this evolution is difficult, since it requires high spatial resolution in a cosmological context, to reproduce correctly the frequency of mergers, and the amount of cold gas accretion. It is however of prime importance to understand the link with the star formation history, and the black hole growth.

4.5 The Spiral Arms

The spiral arm pattern visible in several late type galaxies is one of the most beautiful sight in the Universe. What originate this patter has been one of the great challenges of modern astrophysics. Now Giuseppe Bertin and Françoise Combes will remember for us part of this story and will explain the most favorite interpretation of this phenomenon.

Questions for Giuseppe Bertin:
the spiral arms are a distinctive feature of this class of galaxies. Which observations have historically played a crucial role in defining their physical properties? May you describe the main progresses achieved in understanding the origin of spiral arms from the theoretical point of view? Which theories have been proposed and are now abandoned?

Historically, in the definition of the physical properties of spiral arms in galaxy disks and thus in the formulation of the problem of spiral structure in galaxies a major role was played by the scientists who addressed the issue of a proper morphological classification, starting with Hubble and his *tuning fork* diagram. Later improvements on the Hubble morphological classification scheme were performed by several astronomers, in particular by Sandage, de Vaucouleurs, and van den Bergh; this work is summarized in a set of Atlases, which generally include a deep discussion of the various astrophysical issues posed by the problem of classification. As well described by Sandage and Bedke in *The Carnegie Atlas of Galaxies* (1994), "the ultimate purpose of the classification is to understand galaxy formation and evolution." In other words, a good classification opens up problems that are ultimately relevant to the cosmological context.

The standard tuning fork diagram indicates that various, apparently unrelated properties, such as gas content, bulge size, inclination of spiral arms, structure and size of the HII regions of ionized gas, correlate along the SA sequence (from early-type to late-type non-barred spiral galaxies) and the SB sequence (from early-type to late-type barred spiral galaxies), with continuity among the Hubble types (*a*, *b*, *c*, and d) and between the two sequences. From the existence of these correlations, it is natural to expect that the possible evolution from one morphological type to another type should be rather slow and that the observed morphologies should be studied as quasi-stationary.

The luminosity classification proposed by van den Bergh brings further attention to the relation between observed morphology and the problem of star formation. Later studies focus on the observed regularity of spiral structure; within the same Hubble class, a spiral galaxy may exhibit a (generally, but not always, two-armed) grand-design structure (e.g., see the case of M81) or a less regular or even a flocculent structure (e.g., see the case of NGC 2841). With the advent of Near-Infrared (NIR) astronomy, attempts have then been made at new classifications based on the discovery that for a given galaxy near-infrared images reveal a morphological structure sometimes significantly different from that of the standard optical images.

In summary, studies of the morphology of spiral arms in galaxies make us realize that spiral structure occurs at different scales. On the small scale the structure can often be patchy, irregular, broken; this is generally associated with the interstellar medium and is likely to represent a rapidly evolving spiral activity, quite natural in a differentially rotating disk with cold interstellar gas subject to star formation. On the large scale, regular and generally (but not always) bisymmetric spiral structure is often observed, with arms that can be followed continuously over a large portion of the optical disk and beyond; the grand-design structure is often marked by star formation regions much like "beads on a string" or "white caps on ocean waves." These large-scale patterns are likely to be quasi-stationary. One important observational problem is to assess the frequency of the various morphologies and especially to establish to what extent such frequency (in particular, of bars and grand-design structures) changes from the optical to the NIR window.

The classical observations of the properties of spiral arms have been carried out in the optical wavebands and in the radio (21 cm and continuum), followed by studies in the millimetric range (especially probing the distribution of CO). Some wavebands require the use of telescopes from space. In the Ultra-Violet (UV) grand-design spirals often exhibit star formation events located symmetrically at opposite sides of a galaxy, sometimes at enormous distances from one another (e.g., for the galaxy UGC 2885 at locations separated by more than 100 kpc). Of course, even in wavebands accessible from the ground the imaging power of telescopes from space, especially the Hubble Space Telescope, has greatly helped to diagnose the fine details of spiral structure also in objects at relatively large distances. Spectroscopic studies have then diagnosed the presence of noncircular motions and their correlations with the imaged arms. In some cases (e.g., M51) radio continuum has revealed a corresponding structure in the interstellar magnetic fields.

In general, observations in different wavebands show that grand-design spiral structure tends to organize coherently a number of apparently unrelated physical processes. As we will briefly describe below, this was immediately interpreted (in the 1960s) as a natural signature of a large-scale shock scenario, in which the shock is expected to be due to the fast rotation of a standing density-wave pattern passing through the cold interstellar medium. To this purpose, the location and structure of dust lanes along the main arms was recognized to be a key marker of the pattern speed of spiral structure.

A decisive observational step has been made when NIR observations have become possible. These observations, especially those in the K and K' band (approximately at 2 μm), probe the underlying massive, old stellar disk and confirm that grand-design structure is associated mainly with the stars, that is, they show that grand-design structures are genuine density waves. In addition, they show that an underlying grand-design structure is very frequent (even in galaxies for which the optical picture is less regular) and is dominated by a small number of arms (i.e., by low-m structures), with a prominent $m = 2$ component. By comparing optical with NIR pictures it is possible to distinguish the separate dynamical roles of the cold dissipative interstellar medium and of the old, dynamically warmer collisionless stellar disk.

A fairly modern development in the observations of spiral structure in galaxies is the finding by 21 cm observations of prominent, frequently regular, spiral structure well outside the bright optical disk, where the disk is expected to be rather light and dominated by cold gas, within a gravitational field largely dominated by the dark halo. This is observed in a number of galaxies (among which, NGC 6946). This phenomenon has been interpreted as a kind of analogue of a galactic *tsunami* associated with the outgoing density wave signals produced by the galaxy spiral modes generated in the bright optical disk, and leaking out in the outer gaseous layer.

The properties of spiral arms captured by the early classical observations briefly described above immediately led to an apparent paradox, often known under the name of *the winding dilemma*. How should we reconcile the presence of a grand-design spiral structure, which would be naturally expected to be quasi-stationary, with the fact that the disk is subject to differential rotation? (Note that in other contexts, such as plasmas or fluids, large-scale regular patterns are generally quasi-stationary, whereas small-scale features tend to be fast-evolving; a well-known example comes from the study of hurricanes and small-scale weather phenomena in geophysics.) If spiral arms were *material arms*, that is, made of stars and gas remaining in the arm regions in the course of time, they would necessarily wrap up in a relatively short time. How should we then interpret the frequency of open grand-design spirals?

The problem of spiral structure was well formulated in an article by Oort in 1962 (Oort 1962), who gave a general discussion of the main issues and then moved to separate the problem into two questions: (a) How did spiral structure originate? (b) How does it persist once it has originated? The main merits of Oort's formulation of the problem are the focus on grand-design structures (dismissing the phenomenon of small-scale spiral features as a question of lesser interest), the decision to consider origin and persistence of spiral arms as separate issues, and the prediction that the question of whether the arms are to be seen as primarily gaseous or primarily stellar phenomena would soon be settled empirically by observations of spiral galaxies in different wavebands. In my opinion, one limitation of Oort's article is that he immediately leaves barred galaxies aside and focuses on non-barred structure as the primary concern, whereas the origin of bars and non-barred grand-design structures should (and eventually can) be explained within a unified dynamical framework.

On the theoretical side, the main step forward, pioneered by Bertil Lindblad (1963), was to recognize that the winding dilemma could be resolved if the motion of the material that cooperates in defining the spiral pattern is decoupled from the motion of the pattern itself: this is the concept of wave. A simple but instructive example of waves, as collective phenomena determined by the decoupling of the motion of the pattern from that of the constitutive elements is that of the so-called *olas* in a soccer stadium. In the 1960s it was proposed that spiral structure in galaxies should be recognized to be a collective phenomenon. As such, single-star orbital descriptions are not the best tool for their investigation; as is well known in other fields, such as hydrodynamics and plasma physics, better tools to approach such collective behavior are indeed available.

The concept of *density waves* as the basic element characterizing large-scale, grand-design spiral structure was best formulated and cast in mathematical form in the mid 1960s, starting with two pioneering papers by Lin and Shu (Lin and Shu 1964, 1966). That is to be considered as the beginning and the foundation of a theory, that is the formulation of a research program. The pivot of such program is the hypothesis that grand-design spiral structure is quasi-stationary, considered as a *working hypothesis*. It immediately led, as a natural consequence, to the formulation of the shock scenario and to a number of observational tests that are independent of the mechanisms that may be considered at the basis of the excitation and persistence of spiral structure, but rather characterize the density wave concept itself.

As briefly noted above, a large-scale shock is expected to result from the fast relative motion of a standing density-wave pattern sweeping through the cold interstellar medium, because in a differentially rotating disk corotation between pattern and disk motions is restricted to a thin annulus. Then the location of dust lanes and star formation regions marks the location of the grand-design shock much like "beads on a string" or "white caps on ocean waves."

In practice, at that time the key dynamical questions were left open as part of the research program, to be answered later, after the growth of the theory would receive encouragement from several decisive tests that the wave concept indeed had a firm empirical basis. Some of the key questions are the following: Why do some galaxies possess a significantly barred and others a non-barred grand-design structure? Why bisymmetry is most often present, but not always the rule and not always fully dominant? Why is grand-design spiral structure generally trailing? What is the reason of the observed frequency of grand-design spiral structure? What are the physical mechanisms at the basis of the origin of spiral structure? What are the separate roles of stars, gas, and dark matter in defining what we observe? Are external (tidal) interactions a necessary or rather an occasional ingredient in determining the properties of the observed large-scale morphology of galaxies? Why do some galaxies have only a flocculent structure? Can we ultimately propose a dynamical classification of the observed morphological categories corresponding to the main empirical classifications?

As noted above, a comprehensive dynamical theory able to provide answers to the above key questions in a coherent theoretical framework was not available in the 1960s. The theory started to grow and take shape in the second half of the 1970s, and was completed (at least to the stage of a satisfactory general framework, relying on also nonlinear processes such as self-regulation, but quantified mostly at the linear level only) by the end of the 1980s and beginning of the 1990s.

The observed quasi-stationary spiral structure is interpreted as the manifestation of one or few dominant *self-excited*, global spiral modes. These modes are similar to the dominant notes of a musical instrument. In mathematical terms, each mode is characterized by an eigenvalue, that is, a pattern frequency, and an eigenfunction, that is, a morphology. Each mode is a standing density wave, rotating rigidly around the galaxy center. In contrast to the notes of a musical instrument, the modes are self-excited, that is, they are produced spontaneously by the disk itself, without the need for an external (tidal) driving source; in a sense, this is reminiscent of the pulsation modes of Cepheid variables.

In a linear theory of small perturbations, it has been shown in quantitative detail how the modes are maintained and self-excited in realistic galaxy models. The standing wave is set up by means of a sort of resonant cavity. The inner parts of the disk (with the help of the bulge if present) act as a reflecting mirror, that is an inner barrier to density waves, thus guaranteeing a proper *feedback* of density-wave signals originating in the outer disk. (In passing, we note that this feedback resolves one criticism raised in the late 1960s, according to which density waves would be bound to quickly propagate away, with a speed determined by their group velocity, and thus quickly disappear.) The relatively thin corotation region acts as a partially reflecting mirror, allowing the transfer of angular momentum by some density-wave signal leaking toward the outermost regions. To satisfy the relevant boundary conditions, the inner barrier and corotation have to be located properly in the disk, as demonstrated by the requirement of a kind of Bohr-Sommerfeld quantum condition, which determines a discrete spectrum of global modes. The transfer of angular momentum to the outermost regions is made possible by trailing density waves. In the differentially rotating disk, such transfer has been shown to be associated with an internal source of amplification (*overreflection* at corotation; overreflection of leading into trailing waves is sometimes called *swing* amplification, although the term swing is often associated with a time-dependent process, whereas in the context of modes no *swinging* actually occurs), so that indeed trailing spiral structure is self-excited.

The key factor that limits the number of important modes to a few, with $m = 1$, 2, and sometimes 3, is the inner Lindblad resonance (ILR), which is fully active in the stellar disk and, if present, breaks the resonant cavity by acting as a perfect absorber of waves. In this respect, $m = 1$ waves with a given pattern speed are generally free from ILR and thus the $m = 1$ component in spiral structures should be ubiquitous. In the interstellar medium, ILR is only partially active, which is consistent with the existence of multiple-armed spiral structures in gas-rich galaxies.

The fact that the disk is thus expected to be dominated by one or few global spiral modes demonstrates that the hypothesis of quasi-stationary spiral structure adopted in the 1960s is indeed a good working hypothesis.

In a linear theory global self-excited modes are identified as exponentially growing solutions. In practice, when the amplitude of the structure becomes finite, phenomena such as shocks in the interstellar medium can counteract the growth and are expected to lead to a nonlinear saturation. If, as is often observed in the NIR, the azimuthal structure of the observed spiral arms is smooth and sinusoidal, then a linear theory may be reasonably accurate in determining the properties of the observed morphologies. In any case the linear theory should not be taken literally as an indication that we are observing exponentially growing structures; the theory is only a tool to identify what are the shapes of the energetically favored states realized in nature.

Relatively heavy disks (with respect to the bulge-halo component) are found to be prone to barred modes, with corotation located just outside the tip of the bar, whereas relatively light disks are prone to non-barred modes, with corotation located in the outer stellar disk, provided the disk is kept sufficiently cool. In this respect, non-barred spiral structure requires the existence of an efficient *self-regulation* mechanism, which is provided by the cold dissipative interstellar medium. The mechanism, based on the competition of different physical processes (cooling by dissipation and heating as a result of Jeans instability), is a sort of *dynamical thermostat*; this has also been demonstrated to operate efficiently by means of numerical simulations. From the theoretical point of view, the composite nature and the finite thickness of galaxy disks makes it possible for a given galaxy to host coexisting modes of different kinds (so that, under appropriate circumstances, we may expect even the coexistence of barred and non-barred modes), which is sometimes observed.

If the stellar disk is too warm and unable to produce a bar or other organized spiral structure, then the cold interstellar medium develops its own small-scale spiral activity, and the galaxy is expected to be flocculent.

In summary, by recognizing the separate important roles of the cold dissipative gas, the dynamically warmer collisionless stellar disk, and the presence of dark matter in different amounts, together with the three-dimensional structure of the basic state, the modal theory is capable of providing a relatively simple dynamical framework for the interpretation of the various observed morphologies and specific answers to the key dynamical questions raised above.

As indicated above, in the part devoted to observations, several photometric and kinematic tests were carried out in the 1960s and 1970s, providing convincing empirical evidence in favor of the point of view that indeed density waves are at the basis of the phenomenon of large-scale spiral structure. A detailed study of patterns and dust lanes and of the phase relation between density peaks and deviations from circular motions made the density-wave picture the successful picture and opened the way to tackle the more subtle issues related to origin and maintenance of spiral structure.

In practice, the decisive observational evidence for the density-wave theory as a *modal* theory came with the advent of NIR observations around the year 1990. These observations confirmed that grand-design spiral structures are very frequent, associated with the underlying massive stellar disk, with a morphology similar to that of the calculated spiral modes. Even when large amplitudes are present, NIR arms exhibit smooth and sinusoidal profiles. As anticipated already in the early asymptotic calculations of modes made in the late 1970s, the amplitude modulation observed along the spiral arms supports the picture that we are witnessing the interference of waves that compose the modes.

In the meantime, various methods have been proposed and devised to measure the location of the corotation radius for the dominant pattern in individual spiral galaxies. This has generally confirmed the specific expectations of the modal theory for barred and non-barred structures, sometimes with the detection of more than one pattern speed in a given galaxy. Here we should emphasize that any study of this kind adds strong support to the modal theory, because by definition a global mode is associated with a spiral pattern with a well-defined pattern speed.

The rather recent identification of color and age gradients as a test of the large-scale shock scenario, in line with some preliminary tests performed in the 1960s and 1970s, has provided further strength in favor of the overall astrophysical picture associated with the modal interpretation.

The identification of relatively light disks in spiral galaxies, coming from recent investigations such as the Disk Mass Project, has shown that light disks are rather common. Indeed, for our Galaxy the local mass discrepancy initially noted by the work of Oort and Bahcall has been resolved by the *Hipparcos* data, suggesting that we live in a relatively light disk embedded in a round dark halo. The existence of prominent spiral arms in the (rather light) gaseous outer disk is very natural in the modal theory of spiral structure. These findings are all against a previously proposed picture by which prominent low-*m* spiral structure should be associated only with heavy disks.

Of course, the variety of observed phenomena leaves a number of questions open and the theory should be improved and made more quantitative by detailed tests on individual galaxies, for which much work remains to be done. More work on the non-linear aspects of the theory and on the full global analysis of a disk made of gas and stars would also be desired; in particular, the shock scenario should be reanalyzed in the light of the theoretical developments in the study of global modes and in the light of the observational progress in our understanding of the structure and physics of the interstellar medium. Another interesting area of research that should be investigated further is the role of tidal interactions on a disk endowed with its own intrinsic global spiral modes.

The theory outlined above corresponds to the picture that grand-design spiral structure is generally *quasi-stationary* and of *internal* origin; as such, spiral structure reflects the intrinsic characteristics of individual galaxies or of the classes of galaxies that define the various morphological classification schemes that have been proposed as a framework for the observations.

Broadly speaking, there are three main alternative scenarios, all based on the concept of density waves, that might be considered and explored to explain grand-design spiral structure in galaxies. These scenarios are summarized in a table shown as Fig. 17.4 in Bertin (2014) the first book of the references given below. They correspond to different ways of answering the two questions posed by Oort in his formulation of the problem of spiral structure.

From the dynamical point of view, the scenario of quasi-stationary spiral structure of *external* origin would require that realistic models of galaxy disks are characterized by few *damped* spiral modes, which would become prominent if excited properly from the outside. The construction of models for which the disk is sufficiently cool to accept the driving, but free from self-excited modes, is a non-trivial task; furthermore, the morphologies and other properties of the presumed damped modes have not been studied in sufficient detail. In addition, if such external driving comes from an orbiting satellite, in general there would be a mismatch between the slow motion of the satellite and the expected fast rotation of the internal modes. If instead the driving comes from a fast close encounter, it would be hard to imagine that the induced spiral structure would survive long even if the parameters of the encounter and the structure of the disk were favorable to the driving.

Another line of reasoning might question the key hypothesis followed above, that is, it may be argued that large-scale spiral structure is *fast-evolving*. From the dynamical point of view, this would require that realistic models of galaxy disks are subject to a large number of modes or a continuous spectrum of modes. In this case, one option would be a recurrent organized spiral activity intrinsic to the disk. Another option would be that of a one-shot, fast tidal encounter, able to induce the observed large-scale pattern; several parameters characterizing both the encounter and the properties of the disk have to be tuned properly in order for the driving to be effective. However, the frequency of the observed grand-design structure in the NIR images is a strong empirical argument against the idea that spiral structure is of external origin. In addition, several empirical and theoretical arguments are in favor of the hypothesis of quasi-stationary spiral structure.

The three alternative scenarios sketched above should face the issues that we briefly described in these final comments and in the part devoted to the early steps in the theory of density waves and should provide sensible answers to them. In particular, the alternative scenarios all suffer from the fact that so far they have not been developed in a quantitative unified framework able to provide answers to the key questions raised by the observations. In any case, it would be important to explore these scenarios in further detail and to try to complete them to see to what extent they could stand successfully a comparison with the observations.

Of course, we should not ignore the fact that there is one dynamical ingredient that unfortunately still remains poorly known: the amount, distribution, geometry, and kinematics of the dark matter component. Triaxial halos with suitable properties (especially in relation to the rotation of their figure) might drive organized spiral patterns. The mechanisms involved might be similar to those studied in the 1970s under the name of bar-driving. But, even if we assumed the dark halos to be often triaxial, why should the halo figure rotate slowly in normal spirals and relatively fast in barred galaxies? In any case the reaction to the driving would depend on the properties of the disk. Until we have a proper demonstration of the actual mechanisms at work and of the viability of the picture to interpret the observed phenomena, the idea of attributing spiral structure to a suitable dark halo would be equivalent to invoking a *deus ex machina*.

Finally, I should recall that in the past some theories have been put forward to explain spiral structure that *are not* based on the concept of density waves. In particular, under the assumption that spiral arms are largely related to the interstellar medium and not to the stars, some scientists have explored the possibility that spiral structure be of magnetic origin. In the 1970s other scientists have explored the possibility that the large-scale spiral structure is due to a self-organized sequence of supernova-induced star formation events, occurring as a sort of phase transition under appropriate circumstances. These are two examples of scenarios that eventually had to be abandoned, not only because they were unable to face some important questions, but especially because NIR images finally proved that spiral arms are true density enhancements.

As the reader will certainly realize, the number of papers and authors dealing with and providing significant contributions to the topics that I tried to summarize above is enormously large. Therefore, I decided to refer to only two articles of the early 1960s that had a major impact. A rather complete list of references and a more detailed description of the astronomical and dynamical issues involved can be found in the two books (Bertin 2014; Bertin and Lin 1996).

Questions for Françoise Combes:
simulations have been able to reproduce several properties of spiral arms. To what extent simulations reproduce the great variety of spiral arms observed in real galaxies? In different wavebands spiral arms appear very different. Are simulations able to reproduce the color properties of spiral arms?

As we have just seen, some aspects of spiral structure have been reproduced in numerical simulations. However, for a long time, it was difficult to get rid of bars, which are the most stable feature in stellar disks. Several solutions were proposed: heating the disk with a large initial velocity dispersion, to stabilise it against bars, and in particular heating was more efficient in the central parts of galaxies, where bars develop. Also, a large fraction of dark matter was used as a stabilising agent, until it was understood that sometimes, a live dark matter halo can accept angular momentum and amplify the bar instead (e.g. Athanassoula 2002). A more realistic view is that the spiral structure develops in disks as recurrent features; that are triggered by gas accretion and star formation (e.g. Sellwood and Carlberg 1984). When a galaxy loses its gas, spiral structure fades away in the stellar disk, which could explain that early-type and lenticular galaxies are more barred or ringed but less spiral.

Galaxy tidal interactions trigger the formation of spiral arms, and the best spiral density wave galaxies are those with a companion, like M51 or M81 (cf. Fig. 4.10). Those have long been the prototypes of coherent grand design spirals, and much observational work has been developed to test the theory. For instance, in

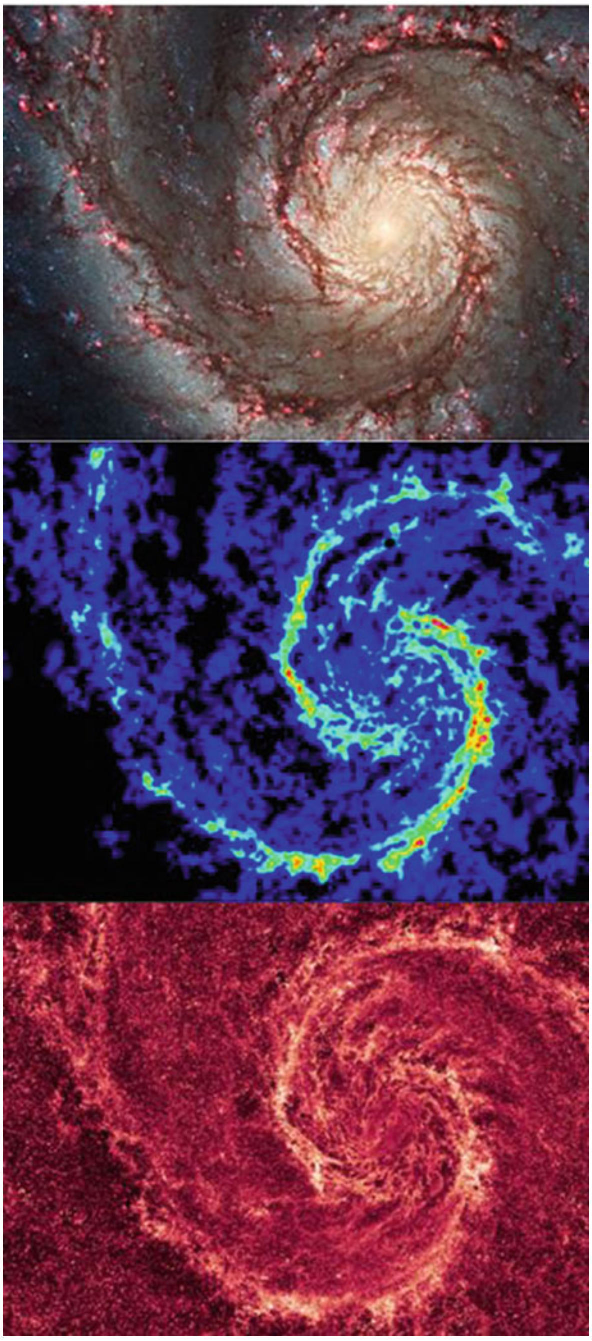

Fig. 4.10 Grand design spiral structure in M51, viewed at different wavelengths: *Top*: Composite image at the various optical wavelengths, showing the stars, and the sites of recent star formation (pink nebulae of ionised gas). *Dark lanes* indicate obscuration by dust (image HST-ACS, NASA/ESA). *Middle*: Molecular gas as seen with the CO emission at millimeter wavelength, with the IRAM interferometer, from Schinnerer et al. (2013). *Bottom*: Subtraction of the near-infrared HST-NICMOS image from the ACS optical image, emphasizing the dust structure, by removing the old stellar component (image HST, NASA/ESA)

the simplified theory, a regular succession of gas shock, star formation, streaming motions, is expected while crossing the arm, from the concave side inside corotation, and from the convex one outside. A series of observational diagnostics were then searched for: the gas shock will correspond to a dense layer, identified to the thin dust lane often seen associated to spiral arms. The magnetic field should be strongly enhanced there, and thus synchrotron radio emission. After the shock, star formation could be seen through the optical colors, but also the abundance of HII regions downstream. The potential of the density wave should be seen through characteristics streaming motions, and the old stars should follow the density wave with a much wider response than the newly formed massive stars, which live only 10 Myrs, and die while exiting the spiral arm.

All these diagnostics have been partly seen, and supported the density wave theory (e.g. Tilanus and Allen 1991. However, there were surprising exceptions, and sometimes in the same galaxy! In M51, the expected succession of gas shock and HII regions, with the right streaming motion was observed in the North, but not in the South of the galaxy. The atomic gas is sometimes widely observed across the arms, or only downstream the molecular gas: it is then interpreted as coming from the photo-dissociation of the molecular gas.

The fact that the predictions are sometimes not confirmed quantitatively is probably due to the influence of the stochasticity in the gas processes: star formation and feedback. Star formation can be self-propagating, and some chaos is introduced in the regular pattern. This feature has even been exploited to explain the case of flocculent spiral galaxies, where there does not appear to have any density wave, nor grand design (like the prototype of NGC 2841). Stochastic and self-propagating star formation have been successfully simulated to reproduce some aspects of flocculent spiral structure in galaxies (Gerola and Seiden 1978). Even in coherent grand design galaxies, such kind of processes can introduce some fraction of chaotic behaviour. Also, galaxies are not isolated, and minor interactions can leave their imprint in the spiral structure, blurring the picture. Several perturbations can superpose, like in our neighbour M31, where a ring wave superposes to a pre-existing spiral structure (Block et al. 2006).

Finally, while the density wave theory gained a lot of support in numerical simulations of idealized galaxies, the recent simulations of galaxy formation in a cosmological context appear to question the whole picture, claiming that only transient and material arms are observed (e.g. Guedes et al. 2011; Wada et al. 2011). Common to all these simulations is the existence of a CDM massive halo, with a radial profile developing a high central concentration, i.e. a cusp. This massive halo, with a large mass inside the central 10kpc, dominating the mass there, makes the baryonic disk less self-gravitating, and a flocculent multi-arm structure develops instead of a coherent density wave. These structures were thought before to be favored by the existence of a massive spheroidal bulge, in early-type galaxies, in which a light baryonic disk is dynamically evolving. Certainly, the problem of the high concentration of dark matter in ΛCDM halos has to be solved before being able to reproduce coherent density waves in cosmologically simulated galaxies.

4.6 The Halo and the Outskirt of Galaxies

We have seen in Chap. 2 that the MW is surrounded by a big halo component which hosts the oldest stars and the Globular Cluster system. What about the halo of external galaxies? When the telescope resolution increased it was soon clear that almost all galaxies are surrounded by this component. In the seventy, the first extended rotation curves provided the first indication that the halo component is likely dominated by non baryonic matter.

The study of halos is very difficult. In the MW the hunt of halo stars is still open. They are very metal poor and their kinematics is dominated by radial motions. Very deep photometric and spectroscopic surveys are required to discover stars belonging to this component. In external galaxies the studies of halos are hampered by the large telescope resolution required, so that in general only the most visible systems belonging to this component, GCs and Planetary Nebulae, have been observed.

Given the amplitude of this argument in the next interview we preferred to address one peculiar phenomenon that is deeply connected with the nature of the halo component and at the same time has powerful implications for cosmology: the gravitational lensing effect. The more massive galaxy halos can indeed deviate the light coming from background objects, and from the nature of the observed deviations we can deduce several properties of the halo component.

The gravitational lensing phenomenon is often associated to the famous Einstein' prediction of the space-time curvature and to the measurements of the light deflection by our Sun. Credits should however be given to Orest Chwolson (1924) and Frantisek Klin (1936) who also discussed this phenomenon and to Fritz Zwicky who first predicted that galaxy clusters can act as gravitational lenses.

Now Giuseppe Bertin will introduce this beautiful subject of modern astrophysics.

Questions for Giuseppe Bertin:
the strong lensing phenomenon has provided a way to measure the mass of the DM halo. Could you discuss the most important results obtained by the application of this technique? What are the main uncertainties related to this method? Up to which distance the method is able to work? Isolated strong lensing also offer the possibility of measuring cosmological parameters. Could you explain why and which are the assumptions behind the method?

The phenomenon of gravitational lensing (Schneider et al. 1992) has had a major impact on astrophysical research in the last three decades. The applications generally consist in deciphering the mass distribution of the intervening lens from the observed effects on the images of very distant sources (see also Chapter 26 in Bertin (2014)). In contrast to other dynamical methods of investigation used in the study of dark matter halos, lensing analyses have the advantage that their results do not depend on the assumption that the system being diagnosed be in a state of quasi-equilibrium. In this respect, some stellar dynamical or HI studies (generally relying on dynamical equilibrium conditions) and X-ray studies (often relying on hydrostatic equilibrium conditions) are at a disadvantage. In passing, we recall that in the context of elliptical galaxies X-ray diagnostics of the gravitational field has encountered a number of severe difficulties, so that it has often led to unreliable results (in spite of the optimistic expectations expressed in the 1970s).

Various types of gravitational lensing can be considered and various types of astrophysical objects can act as gravitational lenses. *Strong* lensing is generally seen as opposed to the case of *weak* lensing. In the case of strong lensing, the effect of the lens is to induce flashy effects on the images of distant sources, thus observed as arcs, arclets, rings, or multiple images. In turn, weak lensing studies rely on the patient acquisition of the slightly distorted images of many sources, properly analyzed by means of non-trivial statistical methods. For the lensing produced by clusters of galaxies, strong and weak lensing studies can be combined together so as to have a reliable measurement of the dark matter distribution from the inner regions (best diagnosed by strong lensing effects) to the outer regions (best studied by means of weak lensing).

In a typical case of strong lensing, that is, the study of a lens producing multiple images of one or more sources, the models generally do an excellent job in reproducing the observed positions of the multiple images and other features. However, it is often difficult to reproduce the flux ratios associated with the different images. This failure, and the violation of certain well-defined rules that the flux ratios should satisfy, are often ascribed to the existence of substructures in the mass distribution of the lensing object. Thus a potential weakness in the general method of investigation may be changed into the optimistic expectation that the method could also provide a powerful tool to identify the long-sought granularity of the gravitational field (*ab initio* cosmological simulations of structure formation generally lead to a large number of small objects, apparently at variance with the observations).

Probably the best and most popular applications of strong lensing are those to clusters of galaxies. However, many interesting applications to individual galaxies exist (Treu 2010). A long term project (the LSD survey, Ed.) in which the lenses considered are massive elliptical galaxies is the project conducted by Koopmans, Treu, and a number of collaborators, in which such strong lensing studies are accompanied by stellar dynamical measurements on the elliptical galaxies acting as lenses. (Recently, the project has been extended to the case in which the intervening lens is a spiral galaxy.) The best systems are those in which the lens is not too close to us, so that its lensing effects are most prominent, and not too far away, so that significant stellar dynamical data can be secured. Two of the most interesting and apparently clear-cut results of these investigations are the following. On the one hand, the combined use of lensing and stellar dynamics makes it possible to separate, at least inside the projected volume in which the data are available, the contributions of stellar mass and dark matter to the total density distribution; this is analogous to disk-halo decompositions of the rotation curves of spiral galaxies. On the other hand, if the *total* density distribution is modeled as a single power law, then strong indications have been found that the density declines as r^{-2}, which is the signature of the density distribution of an isothermal sphere and is associated with a perfectly flat circular velocity profile (reminiscent of the flat rotation curves of many spiral galaxies and of the related problem of the so-called conspiracy). The general conclusion is that, from the dynamical point of view, out to distances $z \approx 1$, massive ellipticals resemble massive elliptical galaxies observed in the nearby universe (see the case of NGC 4472).

One especially exciting case is the double Einstein ring (SDSSJ0946+1006), in which a lens at $z \approx 0.222$ is well aligned with two distant sources, one at $z \approx 0.609$ and the other at redshift somewhat below $z = 6.9$.

A more uncertain result on galaxies, in the direction of which attempts have been made in the last fifteen years, is the establishment of the spatial size of dark halos. Actually, this is a study that is mostly carried out by means of weak lensing analyses (galaxy-galaxy lensing). Other studies try to set limits on the shape of dark halos.

Since a prophetic article by Refsdal (1964), it has been realized that strong lenses may have a very interesting application to cosmology, in particular to measure the distance to the lens and, therefore to set important constraints on the relevant cosmological parameters. The general idea is that if the distant, multiply-imaged source is subject to some internal luminosity variation, then different images would exhibit variations at different times, because different optical paths are involved. In practice, the measurement of such time delays allows us to make an absolute measurement of a length scale in the lens configuration (which, otherwise, would only be a set of dimensionless relations among angles and thus would be distance-independent). Time-delay lenses are expected to be very effective in relation to the measurement of the Hubble constant and of the curvature of the universe. In a recent application to the gravitational lens RXJ1131-1231 and the gravitational lens B1608+656, it has been shown (Suyu et al. 2013) that the measurement of lens time-delays can lead to measuring the Hubble constant with ≈ 5 percent accuracy.

There are other ways of using gravitational lensing to measure the cosmological parameters. They follow from realizing that lensing analyses are based on three items, that is, the mass reconstruction of the lens, the redshifts of the distant sources, and the large-scale geometry of the universe. If we make assumptions or measure one of the three, we can then obtain significant constraints on the other two.

The most important stellar aggregate visible in galaxy halos are Globular Clusters (GCs). Their study has had profound implication for understanding the process of galaxy formation. Their stellar population and kinematics is still one of the most active field of today astrophysics.

In Chap. 1 we have seen the role of the GCs system in the solution of the MW structure. The next interview to Giuseppina Fabbiano will instead show us GCs under a different light, i.e. as one of the main contributors to the X-ray emission of galaxies linked to stellar sources: the low-mass X-ray binaries.

Questions for Giuseppina Fabbiano:
Globular Clusters (GCs) have had a key role in defining the properties of the MW and now are considered very important stellar systems for the studies of extragalactic galaxies. Could you briefly review this subject? Why are the properties of GCs so important? What are the major difficulties of these studies?

I discuss below two points relevant to GCs, both resulting from `Chandra` and correlated `HST` observations.

Firstly, GCs are seen as birthplace of low-mass X-ray binaries (LMXBs) Since the early days of X-ray astronomy, GCs were recognized as a likely site of LMXB formation (Clark 1975), because of the strong dynamical interactions to which their stars are subject. Since then the role of GCs on the evolution of LMXBs has been matter of debate: while production in GC is an efficient mechanism, these sources could also evolve from native stellar binaries outside of GCs (Verbunt and van den Heuvel 1995). With the detection of LMXB populations in early-type galaxies with `Chandra`, and the availability of `HST` coverage for at least some of these galaxies, the study of LMXB and associated GCs has gained new momentum (see review Fabbiano 2006 and refs. therein).

The emerging picture, supported by LMXB populations statistics, luminosity functions and spatial distribution (see below), is that (1) LMXBs form both from dynamical interactions in GCs and from the evolution of native stellar binaries in the field, and (2) that a fraction of the LMXBs detected in the field may have originated in GCs (e.g. Irwin 2005; Kim et al. 2009; Kundu et al. 2007). `Chandra` observations have also clearly demonstrated that LMXBs are more likely to be associated with the most luminous GCs, which is perhaps not surprising given the larger number of stars in these systems. A correlation with GC radius/compactness has also been observed, which is likely to be related to the increased chance of stellar encounters in denser GCs (Jordán et al. 2007), but an even stronger effect is with the color/metallicity of the GC. Red GCs are found to be $\sim$3 times more likely to be associated with LMXBs than blue GCs (see review Fabbiano 2006; Kim et al. 2013). The color effect has been discussed in terms of the effect of metallicity on the GC stellar population and its encounter probability (Ivanova et al. 2012).

Furthermore, GCs are seen as tracers of galaxy merging evolution The complete `HST` coverage of some of the elliptical galaxies observed with `Chandra` has also led to the discovery of two-dimensional inhomogeneities in the projected distribution of GC systems (Bonfini et al. 2012; D'Abrusco et al. 2013, 2014a,b). These features suggest GC streamers resulting from the disruption and accretion of satellite galaxies, similar to the GC and stellar streamers observed in the Milky Way and Local Group (Ibata et al. 1994; McConnachie et al. 2009; Salinas et al. 2012).

4.7 The Gas and Dust Content

In this section we leave the domain of the stellar components and we start to address several important questions connected to the cold gas and dust content of all galaxies. The next interviews by Riccardo Giovanelli, Françoise Combes and Daniela Calzetti will concern in particular the HI content, the emission from molecular clouds and the dust properties.

Questions for Riccardo Giovanelli:
HI observations have contributed to form the present idea we have today of galaxies. Could review the major steps in this research area across the century?

Why HI observations are so important? Is HI observed in all type of galaxies? And up to which redshift?

A couple of decades into the era called by some as that of "precision cosmology", we have become—if not comfortable with—aware of the fact that the stuff our Sun, our planet and our bodies are made of, what we call "baryonic matter", is nothing more than a piffling[2] fraction of the matter/energy density budget of the Universe. That fraction is a bit more than 4 %. Of that fraction, only 1.7 % is in the form of cold gas in galaxies; yet again less of half of that is in the form of atomic hydrogen (that would be about 0.0003 % of the total matter+energy density), capable of emission in the 21 cm line and available to keep some of us entertained with oodles of data to process.

Most of baryonic matter (close to 90 %) is unaccounted for by any observational census, and probably resides in hot circumgalactic coronas and the intergalactic medium. Dark matter (DM) and dark energy do of course make up 95+%. So, why is "HI astronomy" worth cultivating?

- Galaxy disks are optically thin at 21cm, and the detected HI line flux can be readily converted to gas mass.
- Because interstellar atomic gas is the first step in the process of forming stars, HI observations provide a good index of star formation fertility in a galaxy.
- The distribution of HI reaches radially much farther out than any baryonic component, in many cases its radial extent is several times larger than that of the stellar population. This makes HI an excellent tracer of its host dynamics. See Fig. 4.11.
- Because of their large radial extent, the outer regions of HI disks are more sensitive to disturbance by galaxy—galaxy interactions and mergers; kinematical and morphological properties of merger and tidal events are thus best provided by HI observations.
- HI gas is the dominant baryonic form in dwarf galaxies, a population which, as we'll see later, may hold the key to understanding mismatches between theory and observations.
- The interaction between the disk atomic gas and the hot intracluster gas in clusters of galaxies can be monitored to investigate the impact of cluster environment on galaxy evolution.
- The tight scaling relation between luminosity and rotational velocity of spiral galaxies provides an avenue for the measurement of the cosmic distance scale and of the peculiar velocity field, i.e. the deviations from smooth Hubble expansion flow produced by large-scale density inhomogenities.
- The ease of measuring redshifts via the 21cm line makes for large radio telescopes to be effective tools for the investigation of the large—scale structure of the Universe.

[2]I learned this obnoxious-sounding word from The Economist, a magazine that knows best how to put down an issue or a politician with supercilious superiority.

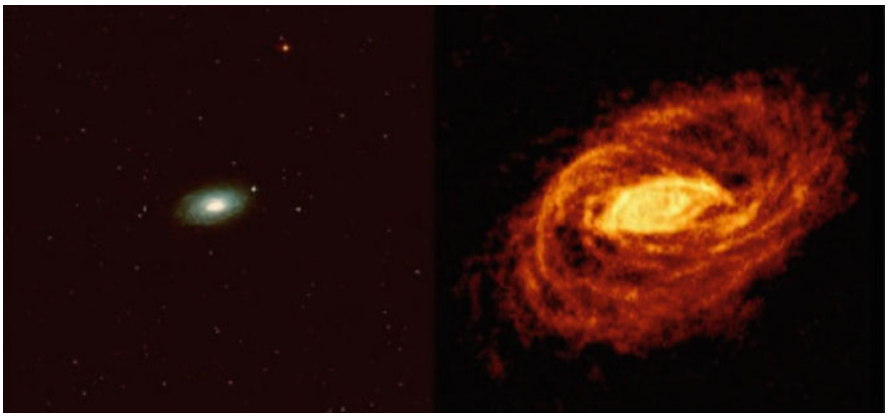

Fig. 4.11 Two images of the galaxy NGC 5055: on the left, an optical image, revealing the distribution of starlight in the source; on the right, and on the same scale, a WSRT image of the 21 cm line emission of HI (credit: Battaglia et al. 2006)

In 1973, Roberts and Rots (1973) wrote: *"Rotation curves extending to large radial distances are now available for 3 spiral galaxies [...] The shapes of the rotation curves at large radii indicate a significant amount of matter at these large distances and imply that spiral galaxies are larger than found from photometric measurements"*. It is often said that spectroscopy has turned Astronomy into Astrophysics. This is unfair, as there are many virtuous paths to converting broad band science to exquisite physical inquiry. It is however true that the distribution and kinematics of HI in galaxies made it possible to convert accurate kinematics into a powerful aid in the investigation of galaxies' dynamics.

The non-keplerian shape of their rotation curves has by now been observed in hundreds of galaxies, constituting one of the strongest elements of evidence we have for the existence of dark matter (Ostriker and Peebles 1973).

Questions for Françoise Combes:
the molecular gas observed in galaxies could provide a wealth of information on the star formation process. Which molecules are preferably detected in galaxies and in which morphological types? Up to which redshift could we detect this gaseous component? Why it is so important to understand the properties of the ISM? Why the study of the molecular content in galaxies is so important particularly for high redshift galaxies?

A large number of molecules were discovered in space in the 1970's thanks to millimeter and centimeter radio-astronomy. Before, only a few molecules (CN, CH) were known from optical spectroscopy. The atomic hydrogen in interstellar clouds, the most abundant element in space, was discovered only in 1951 with its 21cm line. The radical OH was discovered in 1962 and found far from thermal equilibrium, and sometimes with maser emission. The discovery of H_2CO in 1969 opened the Pandora box, and within 1 or 2 decades most of the $\sim$150 molecules known were discovered. The most abundant after H_2, the CO molecule, was discovered in external galaxies in 1975. Still today, the CO molecule is our main tool to map the morphology and the kinematics of molecular gas in galaxies, since the cold H_2 is not radiating. Being a symmetric molecule, it does not have any dipole, and the quadrupolar emission comes from a high-energy level, requiring gas at a temperature of 300 K at least, while the usual temperature of molecular clouds is 10–20 K.

Molecular gas is detected in most galaxies today, but preferentially in late-type galaxies, richer in gas (e.g. Young and Scoville 1991). While the HI content is regularly increasing from early-type to late-type and irregulars, this is not the same for molecular gas, since the tracer CO requires a sufficient metallicity, i.e. the presence of C and O in sufficient quantity. Galaxies are enriched in these elements during several cycles of star formation, and therefore metallicity increases with mass. Dwarf galaxies are deficient in metals, and very difficult to detect in CO. The more as they are deficient in dust, which normally absorbs UV radiation, while molecules are photo-dissociated by this radiation. Therefore, contrary to the atomic gas, the detection of the CO emission is less variable over the Hubble sequence.

Molecular gas is of prime importance to understand galaxy evolution, since it is the craddle of young stars. There is an empirical relation between gas density and star formation rate in galaxies, the Kennicutt-Schmidt relation (Kennicutt 1998), and it is remarkable that mainly molecular gas is following tightly the relation, much more than atomic gas, especially when the gas is resolved at kpc scales in galaxies (Bigiel et al. 2008). When the whole gas, atomic and molecular, is considered, the relation appears non-linear. However, it becomes linear with molecular gas: the star formation rate is directly proportional to the gas density (cf. Fig. 4.12). It is even tighter with dense gas tracers, such as HCN or HCO+ emission. The latter are much weaker signals than CO, but restricted to gas denser by 3 orders of magnitude. To form stars, the key step to understand is when and why dense gas is formed, or when molecular clouds collapse to dense clumps, the last step will automatically follow.

From the star formation rate and the gas density, it is possible to derive the star formation efficiency, which is their ratio, or the depletion time-scale, just the inverse quantity. In all the main sequence of star forming galaxies, the depletion time-scale is of the order of 2 Gyr, for local galaxies. There are however some rare galaxies experiencing a starburst, with a depletion time-scale of the order of 100 Myr. The star formation rate is boosted in them due to external perturbations, essentially galaxy interactions or mergers. Without external gas accretion, their star formation rate cannot be sustained longer. At the opposite, there exist "quenched" galaxies, mainly of early-type, or in group and cluster environments, which no longer form stars, and belong to the red sequence of galaxies. Their depletion time-scale can be as high as the Hubble time.

One of the main issue is to understand what quenches the star formation and why galaxies leave the main sequence to fall in the red sequence. Among the possibilities is the morphological quenching, i.e. the mass assembly builds a massive spheroidal bulge in the center, which stabilizes the disk against gas collapse, precursor to star formation. Others are the gas stripping in rich environment, like galaxy groups and

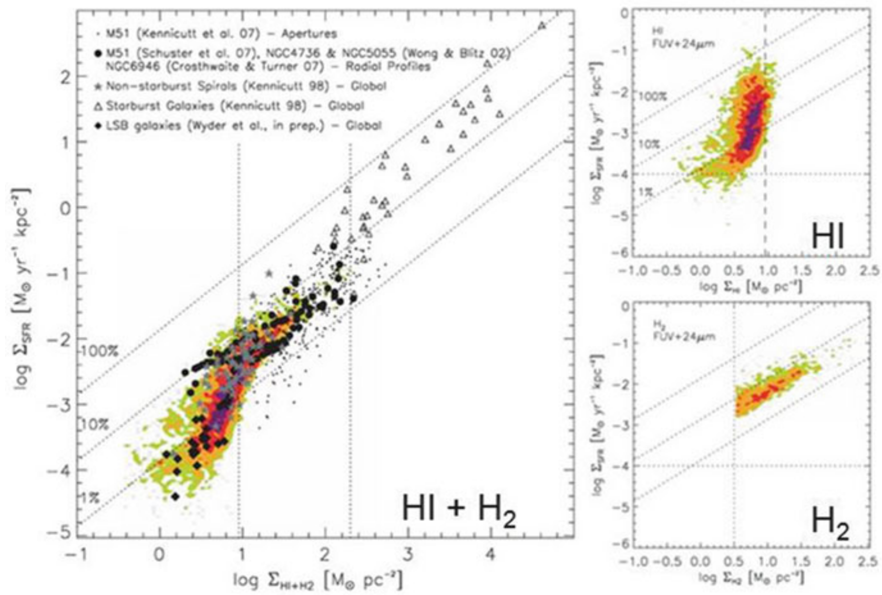

Fig. 4.12 Empirical relation between the gas surface density, and the star formation rate density *Left*: The gas surface density involves both HI and H_2. *Right*: The gas surface density is only HI (*top*) and only H_2 (*bottom*) (from Bigiel et al. 2008)

clusters, or some sort of feedback, from supernovae or black holes (AGN), which heat or remove the fuel for star formation.

All these processes must be understood as a function of cosmic time, in a cosmological context, and molecular gas is a crucial tool for these investigations. While the 21cm of the HI gas is not detectable beyond z$\sim$0.2 with present instruments, the CO molecule with its full rotational ladder, is detectable up to z=7 (e.g. Carilli and Walter 2013).

Questions for Daniela Calzetti:
dust grains of different sizes and composition are often distributed in thin disk structures. They represent a serious problem for every photometric observations of galaxies since most of the stellar light is absorbed and reddened. Could you trace the improvements obtained in these studies along the past century? Which observations are able to overcome the problem coming from the presence of dust? How the data coming from the new generation of IR telescopes have revolutionized this field of research? Going to large redshift, i.e. to earlier epochs, galaxies are younger and dominated by large amount of dust emission. What can we learn about galaxy formation from the analysis of the dust properties?

One of the interesting characteristics of external galaxies is that, despite the presence of significant amounts of dust, most of them do not appear either attenuated or

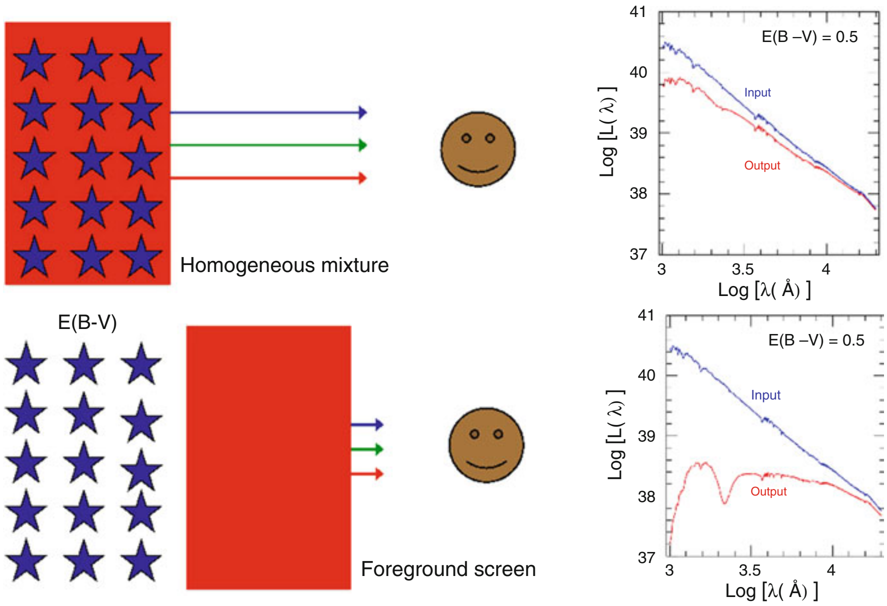

Fig. 4.13 The top and bottom panels show cartoon representations of the same extended distribution of stars and dust, but with a different geometrical relation between each other. In the top panel the dust and stars are homogeneously mixed, while in the bottom panel the dust is completely foreground to the stars. The properties of the stars are the same in the two panels. In both cases a Milky Way mean extinction curve has been assumed (red solid line in Fig. 2.7) with a dust thickness of $E(B - V) = 0.5$. The panels to the right show the input stellar SED, which is the same for the two cases (*blue*; 'Input' spectrum), and the emerging SED (*red*; 'Output' spectrum). All other characteristics being equal, the different geometric relation between dust and stars has considerable impact on the emerging spectrum. This explains why galaxies often appear 'blue' even when containing significant amounts of dust

reddened at UV and optical wavelengths, except for localized area along spiral arms, bars, in the centers, and in circumnuclear regions. This has considerably delayed the recognition that dust is, structurally, physically, and energetically, an important component of galaxies. The reason for the discrepancy between the presence of dust and its effects on the observed spectral energy distributions (SEDs) of galaxies is dust geometry. This can be easily seen in Fig. 4.13, where two identical distributions of stars and dust placed in different relation with each other (in one case the dust is entirely in front of the stars, while in the other case the dust and the stars are homogeneously mixed together) generate completely different UV—optical 'observed' SEDs. In particular, for the mixed dust—stars case, the emerging SED is almost as blue as the original one, owing to the contribution of the almost—unextincted stars located close to the surface of the dust layer and to the presence of dust scattering into the line of sight in complex dust distributions (as opposed to 'away' from the line of sight, which is typical of simple extinction). Although still resembling a virtually unextincted galaxy in terms of its SED, the dusty galaxy will be dimmer than its dust—free counterpart, implying that many of its physical properties, e.g., mass, SFR, etc,, will be underestimated.

Thus, when dust is mixed with a stellar population (the case of a galaxy), rather than being located in front of it (as in the case of a single star or quasar measurement), extinction, scattering, and geometry effects combine together to generate an effective attenuation or obscuration (‘attenuation’ for short) that is often dominated by the scattering and geometry. The first paper to describe in detail the importance of geometry in the determination of the attenuation of light in external galaxies is due to Witt et al. (1992). This pioneering paper coupled with the mounting evidence coming from the IRAS survey of a significant contribution from dust emission to the energy budget of galaxies have contributed to the increasing realization that accurate determinations of the physical parameters of galaxies require the inclusion of corrections for the effects of dust.

The most direct way to include these effects is to measure them, i.e., to measure the IR SED of dust. This has been enabled with increasing accuracy, sensitivity, and angular resolution by the series of IR space missions that started with IRAS, and continued with ISO, Spitzer, and Herschel. These missions have not only probed the dust emission with increasingly better sampling of its wavelength range in fainter and fainter systems, but also have detected galaxies at increasingly higher redshift. A new, major leap forward in terms of both angular resolution and sensitivity will be realized by the JWST.

However, attaining good IR wavelength coverage on a distant galaxy is usually not trivial: for instance, the two Herschel bands with the highest angular resolution and therefore highest sensitivity to point—sources, those at 70 μm and at 100 μm, probe only the rest—frame Wien side (up to ∼35 μm) of galaxies at redshift z=2–2.5. The long wavelength Herschel bands (250–500 μm) are particularly important because they probe the peak of the dust emission, i.e., the peak of the SFR, at high redshift, but they suffer from low angular resolution, which has limited their efficacy. The Rayleigh–Jeans side of the IR SED can be measured from ground based sub-mm and mm facilities (e.g., ALMA), but this part of the IR SED is sensitive to the dust mass, rather than the SFR, of a galaxy. In the absence of data from a far-IR space facility, two additional approaches are often employed to circumvent this limitation: (1) use of IR templates tied to galaxy properties measurable at shorter wavelengths (Kirkpatrick et al. 2012), and (2) use of rest frame UV-optical properties to infer the amount of dust attenuation (e.g., the UV slope, Calzetti et al. 1994, 2000). While neither approach is perfect, the use of both can offset some of their limitations.

The current state-of-the-art consists of IR-based, dust-corrected measurements of the cosmic SFR density of the Universe up to redshift z∼4, i.e., up to when the Universe was about 1.5 Gyr old (Madau and Dickinson 2014). Although only the brightest among the galaxies are measured at those distances, these results tell us that the Universe was already significantly enriched of metals (and dust). Dust has been clearly detected in galaxies at redshift as high as z∼5–6, and there are suggestions for presence of dust at even higher redshifts, as inferred from the reddening of the UV SEDs. This is telling us that dust formation is a much faster process than the $\sim 10^9$ yr timescale usually quoted, a timescale based on our understanding of the physics of the Milky Way dust. At the same time, the overall UV reddening of star-forming galaxies is decreasing, and is very low by z$\sim$7, i.e., when the Universe is barely 0.75 Gyr old (Bouwens et al. 2014).

4.8 The Hot Gaseous Component Around Galaxies

Thanks to the space missions we now have a quite detailed view of the sky in the X-ray domain. These observations through the years have enormously increased our knowledge of galaxies. Now Giuseppina Fabbiano will trace the most significant results obtained by some famous X-ray space missions.

Questions for Giuseppina Fabbiano:
from `Einstein` to the still flying `XMM-Newton` and `Chandra` X-ray missions opened a new window on galaxies. Would you tell us what have been the major successes of X-ray missions in tracing the X-ray properties of galaxies?

`Einstein` allowed the first systematic survey of nearby galaxies of all morphological types (see review Fabbiano 1989), resulting in the first X-ray Catalog and Atlas of Galaxies (Fabbiano et al. 1992), followed by a systematic study of the spectral properties of the X-ray emission (Kim et al. 1992). Major achievements include:

- multi-wavelength correlation studies of the `Einstein` galaxy samples (including non-detections) established the fundamental scaling laws, which have later been confirmed and further explored with `Chandra`;
- imaging and spectral studies of nearby galaxies first gave detailed information on the different emission components. In the spiral and irregular galaxies sample, the integrated emission of actively star-forming galaxies was discovered to be strongly correlated with star formation rate indicators, such as the far-IR emission, implying a dominant High Mass X-ray Binaries (HMXB) component to the emission. The emission of bulge-dominated spirals was instead found to correlate with the H-band emission, thus stellar mass, implying emission from Low Mass X-ray Binaries (LMXB) populations; possible nuclear and hot ISM contributions were also suggested for these galaxies (Fabbiano and Shapley 2002; Fabbiano et al. 1982; Shapley et al. 2001).
- The study of the XRB populations of M31 and M82 introduced luminosity functions for X-ray population studies (Trinchieri and Fabbiano 1991); this has now become an important tool with `Chandra`.
- Imaging and spectral evidence of gaseous halos and winds in interacting and starburst galaxies was first provided by the `Einstein` observations of the Antennae, NGC 253, and M82 (Fabbiano 1988a; Fabbiano and Trinchieri 1983; Watson et al. 1984).
- In the E and S0 sample, the $L_X - L_B$ correlation suggested the presence of hot gaseous emission in some, above the baseline, integrated emission of LMXBs

(Trinchieri and Fabbiano 1985). Further study reported a link between the ability of retaining a hot halo in these galaxies, their shape, depth of the potential well and metallicity (Eskridge et al. 1995).

- While the presence of hot halos in E and S0 galaxies may in principle provide a means to measure the amount of mass (baryonic and dark) in these systems, both the uncertainties connected with the contribution of LMXBs to the X-ray emission, and those resulting from the data quality, made these measurements unreliable with the `Einstein` data (Trinchieri et al. 1986). Comparison of the L_X/L_B diagram of E and S0s with halo evolution models suggested that a large number of them may be in a partial wind state (Ciotti et al. 1991). This hypothesis is consistent with the spectral differences found in the X-ray emission of E and S0 galaxies with different L_X/L_B ratios, showing harder emission in X-ray faint galaxies, which could be related to the integrated emission of LMXB populations (Kim et al. 1992).
- Super-Eddington X-ray sources with $L_X > 2 \times 10^{38} erg\, s^{-1}$ (the Eddington luminosity of a neutron star binary) were discovered in nearby galaxies with `Einstein`. For these sources, later dubbed ultra-luminous X-ray sources (ULX), it was then advanced the hypothesis that they may host very large BHs (see Fabbiano 1989 and refs. therein; Fabbiano et al. 1992).

`ROSAT` and `ASCA` overlapped in time and both contributed to the study of galaxies in X-rays. While it did not open the discovery space as `Einstein` had done, `ROSAT`'s similarly good imaging optics and long lifetime allowed to explore in depth some of the questions posed by the `Einstein` observations, as well as leading to new discoveries. `ASCA`'s CCD spectra contributed to the debate by providing new constraints to the X-ray emission components.

- `ROSAT` led to detailed studies of the XRB and SNR emission in Local Group galaxies; e.g., Supper et al. (2001) published a catalog of 560 X-ray sources detected in the field of M31 above a luminosity threshold of $\sim 4 \times 10^{35} erg\, s^{-1}$, and studied their properties. Comparison of `ROSAT` and `Einstein` data for this galaxy highlighted widespread source variability (Primini et al. 1993). `ASCA` spectra of ULXs in nearby galaxies (sources with $L_X > 10^{39} erg\, s^{-1}$) suggested the presence of accretion disks (Makishima et al. 2000), and spectral transitions similar to those of Galactic black binaries were observed in the ULXs of IC 342 (Kubota et al. 2001).
- The discovery of a low-luminosity Active Galactic Nucleus (AGN) in M81 with `Einstein` suggested a new facet of the AGN phenomenon (Elvis and van Speybroeck 1982; Fabbiano 1988b). An increasing number of low-luminosity AGNs were discovered with `ROSAT` (Fabbiano and Juda 1997; Koratkar et al. 1995).
- Gaseous emission, associated with winds out-flowing from starburst nuclei, was discovered with `Einstein` (see above). `ROSAT` provided several more cases and more in-depth studies of this phenomenon; it also discovered widespread soft emission, from a hot ISM, in face-on spirals (e.g. Bregman et al. 1993; see review, Fabbiano 1996).

- ROSAT and ASCA provided spectral evidence of a hard emission component in elliptical galaxies, both X-ray faint and X-ray loud, which could be related with the LMXB population in these galaxies (see review, Fabbiano 1995).
- ASCA spectra provided clear evidence of thermal emission from optical thin plasma in X-ray loud elliptical galaxies, confirming the presence of hot halos (Fabbiano et al. (1994); Matsushita et al. (1994); see Fabbiano 1989 and refs. therein, Kim et al. 1992 for the Einstein results).
- Central cooler cores were also detected with ROSAT in some of the large hot halos (e.g. Kim and Fabbiano 1995).
- ROSAT observation of young E (or post-merger galaxies) suggested that hot halos may be depleted at this evolutionary stage (Fabbiano and Schweizer 1995).
- The softer energy band of ROSAT, compared with Einstein, was instrumental in establishing the presence of a very soft thermal component of the emission (kT$\sim$0.2 KeV) in X-ray faint E and S0 (Fabbiano et al. 1994), in addition to the hard integrated LMXB emission. Modeling of these data suggested a component of the X-ray emission from the integrated output of stellar and active stellar sources, as well as some hot ISM (Pellegrini and Fabbiano 1994).

A new debate on the nature and evolution of the hot ISM of E and S0s arose with reports of very low sub-solar metallicity, based on spectral fitting of ROSAT and ASCA data. These low metallicities spurred the suggestion that strong winds expelled the Iron and other elements into the cluster medium (Loewenstein et al. 1994). Although the presence of the Fe 6.7 KeV line emission in clusters implied this enrichment mechanism, secular evolution of the hot halos, taking into account of SNII and SNI energy and Fe input, suggested that the Fe content in galaxy halos should be much higher than reported (Renzini et al. 1993). However, an observational data analysis bias may have accounted for the reported sub-solar metallicities: the use of simplistic emission models for the X-ray spectra. While complicated models were not needed to fit the data, still if the emission consisted of multi-temperature regions, the value of the metallicity would be artificially lowered by the assumption of single temperature emission (see Fabbiano 1995 for an extensive discussion) (Buote and Fabian 1998; Kim et al. 1996). Subsequent XMM-Newton observations also raised this point (Kim and Fabbiano 2004; Molendi and Gastaldello 2001). This data analysis bias is convincingly proved by the comparison of the ASCA and Chandra observations of the Antennae galaxies. Sub-solar metallicity was found with ASCA in this galaxy merger (Sansom et al. 1996). The deep high-resolution Chandra data, instead, revealed several emission regions with slightly different spectral parameters and super-solar metallicities. While the line emission may have been somewhat enhanced by charge exchange (see e.g. Zhang et al. 2014 for M82, based on XMM-Newton spectra), the line ratios in the Antennae and other star forming galaxies are consistent with SNII yields, as it would be expected for these young stellar populations (Baldi et al. 2006a; Fabbiano et al. 2004; Richings et al. 2010). When the spatial resolution of Chandra is disregarded, and the entire coadded spectrum is analyzed, the extreme sub-solar ASCA metallicities are reproduced, because the slight spectral differences observed in the different emission regions conspire in filling-in a higher continuum level (Baldi et al. 2006a).

`Chandra` has moved the study of galaxies in X-rays to a new, much deeper level. The sub-arcsecond imaging of `Chandra`'s mirror, together with the moderate spectral characterization of each resolution element, allowed by the CCD imager ACIS, has led to the detection and characterization of individual X-ray sources and hot gaseous X-ray emission regions in galaxies as distant as $\sim$ 100 Mpc. The almost zero background contained in the small `Chandra` source detection regions allows the detection of sources with X-ray luminosity comparable of those of Galactic XRBs in galaxies as far as $\sim$ 20 Mpc; it also allows to study the X-ray properties of galaxies at higher red-shift. The high spatial resolution of `Chandra` is also important for studying hot diffuse emission, allowing the exclusion of detected point sources (mostly XRBs) from the data; `Chandra`'s spectral capabilities also can be used to spectrally subtract the hard contribution of undetected fainter XRBs, effectively cleaning the hot ISM emission from contaminants.

`XMM-Newton` has been used for the study of Local Group Galaxies, and to study ULX spectra and variability, often together with `Chandra`. Also, spectral studies of the hot ISM have been conducted with `XMM-Newton`. While these studies have led to interesting results, `XMM-Newton` data do not provide the degree of detail and sensitivity offered by `Chandra`, which are important for the study of galaxies; I will discuss some of the `XMM-Newton` results below, as appropriate. To illustrate the importance of `Chandra`'s angular resolution in the study of galaxies, I compare in Fig. 4.14 X-ray images of the Antennae galaxies (the merging pair NGC 4038/39), of similar depth, obtained with `Chandra` (angular resolution $\sim$ 0.5") and `XMM-Newton` (res. $\sim$ 15").

Figure 4.15 shows the deep `Chandra` image of the Antennae (Fabbiano et al. (2004); $\sim$ 410 ks), which led to the detection of a population of 120 sources down to

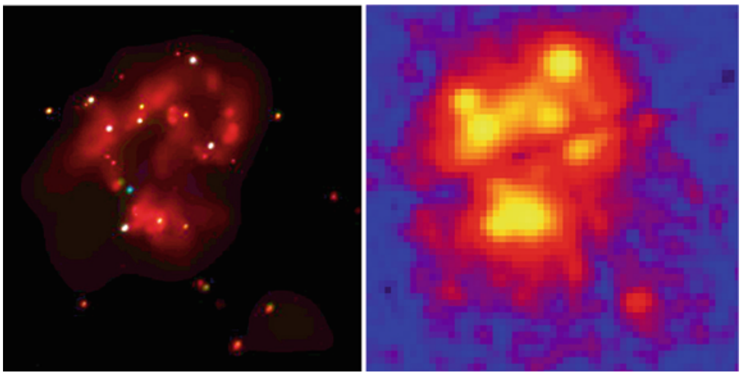

Fig. 4.14 *Left*, the first `Chandra` ACIS image of the Antennae galaxies Fabbiano et al. 2001; $\sim$ 70 ksec). *Right*, an example of an exposure of the Antennae from the `XMM-Newton` archive, same scale and comparable effective exposures (taking into account the different effective areas): `XMM-Newton` can only partially resolve the most luminous point sources

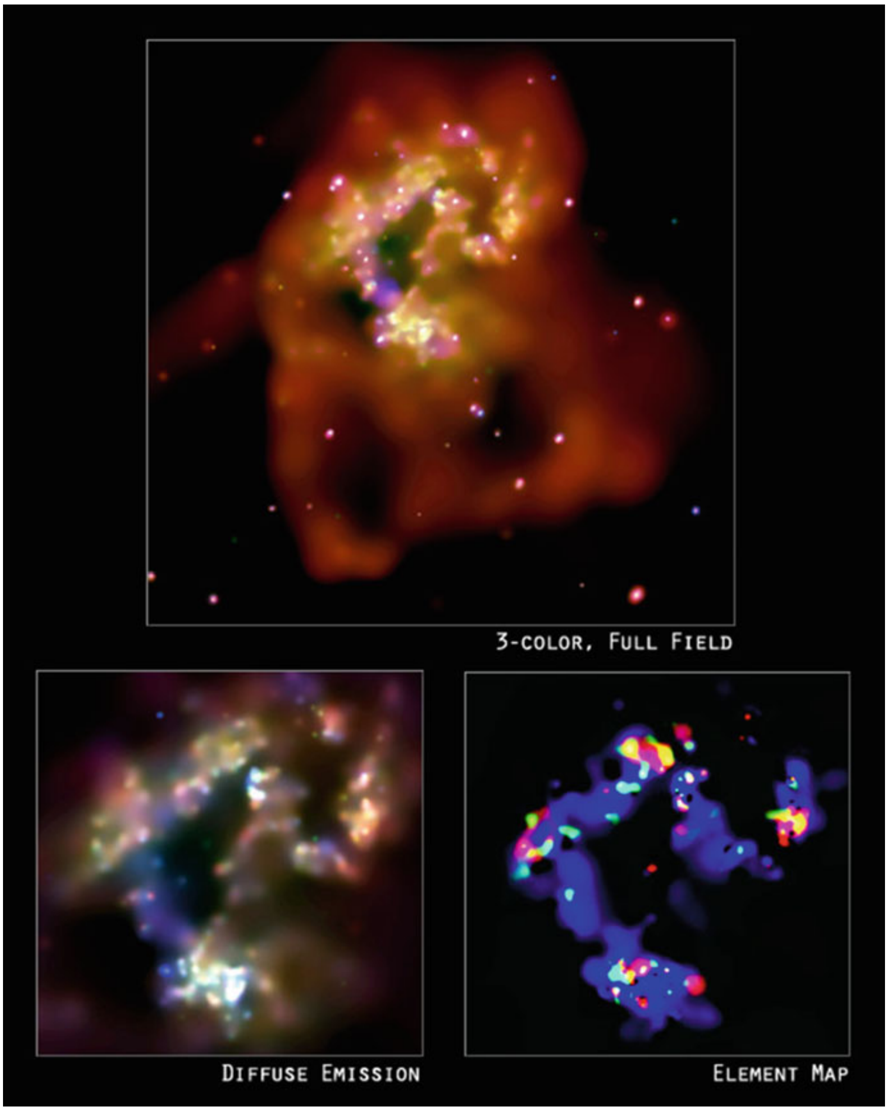

Fig. 4.15 *Top*: the deep ∼ 480 ks `Chandra` ACIS image of the Antennae galaxies Fabbiano et al. (2004), showing a population of 120 sources including 14 ULXs, and complex and extended hot gaseous emission, including ∼ 10 kpc size giant loops. *Left*: the hot ISM of the Antennae from `Chandra`, after subtraction of detected point sources, color-coded with the energy of the emission (blue is higher energy, red lower energy). *Right*: from the same data, metallicity map of the hot ISM of the Antennae, where *red, green, and blue* indicate emission by Fe, Si, and Mg, respectively (Baldi et al. 2006a,b; Fabbiano et al. 2004)

a luminosity of $(2-5)\times10^{37} erg\, s^{-1}$, depending on the local background. Fourteen of the point-like sources have luminosities above $10^{39} erg\, s^{-1}$, at least in one exposure, which qualifies them as ultra-luminous X-ray sources (ULXs; Zezas et al. 2006). We these data we could also resolve features of the hot ISM, and measure the metal abundance in these hot clouds (see Fig. 4.15; Baldi et al. 2006a,b; Fabbiano et al. 2004).

What are the main sources of X-ray photons in galaxies according to morphological types?

In Spiral and Irregular galaxies:

- (1) the X-ray binary (XRB) populations, with high mass X-ray binary (HMXB) contribution proportional to the star formation (SF) rate of the galaxy, and the low mass X-ray binary (LMXB) contribution proportional to stellar mass;
- (2) supernova remnants (SNRs);
- (3) Hot ISM;
- (4) accreting massive black holes (MBHs) at nucleus (if active or moderately active).

In Elliptical galaxies:

- (1) the LMXB populations, both in the stellar field and in GCs;
- (2) Hot ISM/halo;
- (3) accreting MBH at nucleus (if active or moderately active).

The detection and study of XRB populations in galaxies has made a quantum leap with Chandra (see Fabbiano 2006 for a review). XRB populations have been detected in galaxies of all types, including E and S0 galaxies, for which this detection was not possible with other X-ray telescopes. X-ray color-color diagrams have been used to determine the nature of individual sources, guided by the spectral properties exhibited by Galactic XRBs and SNRs. Multiple observations of individual galaxies uncovered widespread source variability, pointing to accreting X-ray binaries, with properties similar to those of the Galactic XRBs. Luminosity functions (XLF) were derived for the XRB populations, leading to their characterization; in particular, the shape of the XLF was found to differ for young and old stellar population, with the portion of most luminous sources clearly decaying with age. The normalizations of these XLFs, i.e. the total number of X-ray sources was linked to the star formation rate in young stellar populations, where the X-ray sources include significant components of luminous short-lived High Mass X-ray Binaries (HMXBs), and to the integrated stellar mass in older stellar populations, dominated in X-rays by Low Mass X-ray Binaries (LMXBs). These conclusions are in agreement with the results of the Einstein studies of the global X-ray properties of these galaxies (see Fabbiano 1989). X-ray population synthesis work was undertaken to explain the observed XLFs (e.g., Belczynski et al. 2004).

The XLF of these populations is well characterized by a relatively flat power-law, with cumulative slope of ~ -0.5 to -0.6, which is also consistent with the slope of the XLF of Galactic HMXBs (Grimm et al. 2002, 2003). The XLFs of the galaxies with the highest SFR observed with Chandra, such as the Antennae (Zezas et al. 2007; Zezas and Fabbiano 2002) extend to luminosities of a few $10^{40} erg\, s^{-1}$, including ULXs, without any detectable break. The similarity of HMXB XLFs associates ULXs strongly with the young stellar population (King et al. 2001). Observations of Local Group galaxies were instrumental in the study of the low-luminosity XLF. The Chandra and XMM-Newton survey of the SMC has pushed source detection to an even fainter limit, corresponding to $L_X \sim 10^{33} erg\, s^{-1}$. The XLF built with these data suggests a flattening below $5 \times 10^{34} erg\, s^{-1}$, consistent with low accretion rates and the onset of the propeller effect in NS binaries (Shtykovskiy and Gilfanov 2005). Using this survey, Antoniou et al. (2009, 2010) extended the relation between the number of accreting binaries and the SFR of the parent population to the very low luminosities of quiescent BeXRBs (a class of high-mass X-ray binaries that consist of a Be star and a neutron star, Ed.).

Detecting LMXB populations in E and S0 galaxies requires Chandra's angular resolution and sensitivity. The LMXB XLF is generally steeper than that of HMXB populations. While the number of LMXBs, in the galactic bulges of spiral galaxies and in E and S0 galaxies (the normalization of the XLF), is in first instance related to the stellar mass, there is also a correlation with the specific frequency of GCs in the galaxies (Kim and Fabbiano 2004). This correlation points to dynamical binary assembly in GCs for at least a portion of the LMXB population. Coordinated Chandra and HST coverage of early-type galaxies led to the extraction of LMXB samples associated with GCs and in the stellar field of the parent galaxy. The XLF of GC-LMXBs presents a low-luminosity break ($L_X \leq 5 \times 10^{37} erg\, s^{-1}$) that is not observed in the field-LMXB XLF (Kim et al. 2009). This difference suggests that a good fraction of field-LMXBs have evolved from native field binaries. A similar conclusion derives from the detailed study of NGC 4649, which showed that the radial distribution of GC-LMXBs is consistent with that of their parent red or blue GC population, while the radial distribution of field-LMXB is consistent with that of the stellar light (Mineo et al. 2014). In NGC 4649 and NGC 4278 inhomogeneities were discovered in the two-dimensional distribution of both GCs and LMXBs, suggesting that these sources could be used as beacons of satellite galaxy accretion and merging (D'Abrusco et al. 2014a,b). Comparison of XLFs of early-type galaxies with different stellar ages suggests that 'younger' LMXB population have an excess of higher luminosity sources (Kim and Fabbiano 2010).

Are the ULXs the elusive intermediate mass BHs, or are they highly accreting stellar BHs with masses possibly in the upper stellar BH range of $\sim 80 M_\odot$ (see e.g. Fabbiano 2005, 2006)? This is an area where both Chandra and XMM-Newton have contributed. The XLF studies suggest that ULXs are stellar BHs. This is confirmed by a more recent complete sample of $\sim$ 100 ULXs assembled from galaxies within 14.5 Mpc above the UGC and IRAS completeness limit: ULXs with L_X as high as $\sim 5 \times 10^{40} erg\, s^{-1}$ have XLF and spatial distributions consistent with those of the general HMXB and LMXB populations of the parent galaxies; a few ULXs reported in the literature with $L_X \sim 2 \times 10^{41} erg\, s^{-1}$ are not consistent with the general ULX luminosity function and could indeed be non-stellar BHs (Swartz et al. 2011). The study of ULX spectral and variability properties, both with Chandra and XMM-Newton have also contributed to the debate on their nature. Earlier interpretations of the low temperature ($kT \ll 1$ keV) disk component of ULX spectra were taken as strong indication of the presence of a BH with mass $> 100M_{\odot}$, in excess of those expected for stellar BHs (Miller et al. 2003a). However, more sophisticated models, including super or near-Eddington accretion, have since become the standard interpretation for an increasing fraction of these sources (King et al. 2001; Soria et al. 2007; Straub et al. 2013).

With Chandra we were able to detect (or set stringent limit to) faint nuclear emission in normal galaxies. This together with existing estimates of the mass of the nuclear super-massive black hole would set constraints on the accretion and emission state of these nuclei. For a sample of galaxies, Soria et al. (2006) show that a fraction of the total accretion power (mechanical plus radiative) would be sufficient to sustain a self-regulating, slow outflow that removes from the nuclear region all the gas that does not sink into the BH ("BH feedback"). The rest of the accretion power may be carried out in a jet or advected. We also discuss scenarios that would lead to an intermittent nuclear activity.

Hot ISM is detected with Chandra in all kinds of star-forming galaxies. Particularly intense is the hot ISM emission in galaxies with higher star-formation rates (Mineo et al. 2012), especially in interacting and merging galaxies. The deep Chandra observations of the Antennae first allowed an in depth study of the hot ISM, leading to the discovery of a complex hot ISM with several resolved large hot clouds with a variety of emission parameters. These data also led to measurement of metal abundances in these clouds, with line ratios consistent with SNII yields (Baldi et al. (2006a,b); see comparison with ASCA). Similar metal abundance results were derived in other star-forming and interacting galaxies (e.g. NGC 1365, Wang et al. 2009; NGC 4490, Richings et al. 2010; NGC 6240, Nardini et al. 2013). Large scale ($\sim$ 10 kpc or more) gaseous structures have been detected in merging galaxies, in regions disassociated with the galaxy stellar components, including the large loops of the Antennae (Fabbiano et al. 2004) and the structured extended halo of NGC 6240 (Nardini et al. 2013). The extended hot halo (radius $\sim$ 60 kpc) of NGC 6240 suggests the presence of a large dark matter halo. Hot coronae trapped in the dark matter potential of massive spiral galaxies have also been reported, based on Chandra and XMM-Newton observations (Bogdán et al. 2013a,b). All these structures need to be explained by detailed simulations to constrain the parameters of galaxy evolution. Hot coronae have also been detected with Chandra in late-type galaxies in clusters (Sun et al. 2007).

The ISM is an important component of galaxies. What have been in your opinion the main successes obtained in studying its X-ray properties?

The resolution of Chandra has allowed the detailed study of the hot ISM and halos of early type galaxies, including galaxies with relatively little hot ISM, by eliminating the 'contamination' of LMXB and nuclear source emission (e.g., Pellegrini et al. 2012). This resolution was also instrumental in the detection and characterization of circumnuclear cavities resulting from radio mode feedback (e.g. Finoguenov et al. 2008; Paggi et al. 2014), and the detection of sharp edges from the interaction of the galaxy hot ISM and the cluster hot medium (e.g. Kim et al. 2008). Elemental abundance ratios in the hot ISM demonstrate different enrichment history in galaxies with uniformly old stellar populations and galaxies showing symptoms of rejuvenations (Kim et al. 2012). XMM-Newton observations cannot detect sharp and small-scale features but have helped constraining the spectral parameters and abundance of large-scale features (e.g. Kim et al. 2008).

What are the most important scaling relations of galaxies at this wavelength?

The most important scaling relations are:

- (1) HMXB XLF scales with SF rate;
- (2) LMXB XLF scale first with stellar mass (L_K), and less strongly with GC specific frequency SGC;
- (3) Halo scaling relations for E/SO (Civano et al. 2014; Kim and Fabbiano 2013).

We have discussed the XLF dependencies in the previous pages; here we will concentrate on the scaling relations of the hot halo of E and S0 galaxies. With Chandra we were able to revisit the $L_X - L_B$ and other scaling laws of the gaseous component of E and S0s, by cleaning the hot ISM emission of contaminants (Boroson et al. 2011). This work, and the subsequent comparison of $L_{X,Gas}$ with the masses (M) of a sample of E galaxies obtained from kinematic measurements of globular clusters and planetary nebulae (Kim and Fabbiano 2013), established that $L_{X,Gas} \propto M^{\sim -3}$. This scaling relation together with the steep $L_{X,Gas} \propto T^{4.5}$ of Boroson et al. (2011) suggest that the hot gas is virialized, at least for $L_{X,Gas} > 10^{40} erg\, s^{-1}$.

The work on scaling relations was taken a step further by studying the sample of 69 X-ray detected passive early-type galaxies (ETGs) from the Chandra COSMOS survey in a range of redshift extending out to $z = 1.5$ (Civano et al. 2014). Using the relations from the study of the local universe (Boroson et al. 2011), together with the expected evolution of the X-ray emission, to subtract the contribution of LMXB populations from the X-ray luminosity, Civano et al. (2014) find that most of the galaxies with estimated $L_X < 10^{42} erg\, s^{-1}$ and $z < 0.55$ follow the $L_{X,Gas} - L_K$ relation of local universe ellipticals. For these galaxies, the gravitational mass can be estimated with a certain degree of confidence from the local virial relation. However, the more luminous ($10^{42} erg\, s^{-1} < L_X < 10^{43.5} erg\, s^{-1)}$ and distant galaxies present significantly larger scatter; these galaxies also tend to have younger stellar ages. The divergence from the local $L_{X,Gas} - L_K$ relation in these galaxies implies significantly enhanced X-ray emission up to a factor of 100 larger than predicted from the local relation. This could be ascribed either to the presence of hidden AGNs, or the evolution of hot halos, in nuclear and star formation feedback.

X-ray missions, in particular Chandra, have discovered new X-ray morphologies, like cavities, plumes etc. Why these studies are important to understand the galaxy evolution? May you present/discuss the more peculiar cases?

Many papers based on XMM-Newton observations reported that the hot halos of galaxies did not present the behavior expected from the standard cooling flow model, suggesting a multiphase gaseous medium, possibly linked to heating from the nuclear AGN and its associated radio sources (e.g., in M87, Matsushita et al. 2002). Chandra observations were instrumental in uncovering how the AGN–hot-ISM interaction operates (e.g., M87 Forman et al. 2007, NGC 1275 Fabian et al. 2006). Cavities were discovered with Chandra in Elliptical galaxies embracing the radio lobes of low-activity nuclei, but also associated with quiescent nuclei, attesting to past and present AGN activity and feedback (e.g., Finoguenov et al. 2008; Paggi et al. 2014). In NGC 4649, taking into account the effect of the AGN feedback on the gas in the pressure balance, X-ray mass estimates are in reasonable agreement with measurements from optical kinematics (Paggi et al. 2014).

What about circumnuclear regions of Seyfert galaxies?

Chandra observations of nearby Seyfert galaxies give us a view of the AGN interaction with the host galaxies in the scale of a few tens to hundreds parsec. In NGC 1365 and NGC 6240, both IR-bright galaxies with active star formation hosting Compton-thick obscured AGNs, the circumnuclear X-ray emission seems to be dominated by thermal starburst related phenomena. NGC 1365 presents a double-conical diffuse emission region, reminiscent of ionization cones, but the emission is instead well fitted with thermal models, has abundances consistent with SNII yields, and moreover, the X-ray and [OIII] clouds are spatially anti-correlated (Wang et al. 2009). In the double AGN NGC 6240, circumnuclear extended Fe XXV emission is spatially correlated with the large-scale morphology of H2(1-0) S(1) line emission and Hα filaments. Propagation of fast shocks originating in the starburst-driven wind into the ambient dense gas can account for this morphological correspondence (Wang et al. 2014). In other nearby Seyfert galaxies instead Chandra uncovers regions of direct AGN–galaxy interaction. In particular, a deep study of NGC 4151 (Wang et al. 2011a,b) uncovers cloud-based correspondence of optical forbidden line and X-ray emission, which can be explained with photoionization from the AGN. Clouds adjacent to the ends of the nuclear radio jet also show a thermal emission component, suggesting shock ionization; this is also seen in NGC 1068 (Wang et al. 2012). Using spatially resolved X-ray features, the estimated mass outflow rate in NGC 4151 is $\sim 2M_{\odot}yr^{-1}$ at 130 pc and the kinematic power of the ionized outflow is $1.7 \times 10^{41} erg\, s^{-1}$, approximately 0.3 % of the bolometric luminosity of the active nucleus in NGC 4151, and significantly less than the commonly assumed $\sim$ 5% AGN feedback value.

4.9 The Magnetic Fields of Galaxies

This often forgotten component of galaxies is currently providing very important insights about the star formation phenomenon. Now, magnetic fields studies will be reviewed by David L. Moss.

Questions for David L. Moss:
how has our knowledge of magnetic fields in galaxies developed?

Clues that there might be large-scale magnetic fields present in our galaxy, the Milky Way, were first seen in the late 1940s, following studies of optical polarization of starlight by interstellar grains aligned by a magnetic field (e.g. Hall and Mikesell 1949; Hiltner 1949). Measurements of polarized emission, at wavelengths from optical to radio, have been the basic tool for determining galactic magnetic fields. However, while continuing to be a useful method, optical polarization measurements can be contaminated by several effects and much of our knowledge comes from measurements at radio wavelengths. In the 1950s and 1960s radio synchroton observations began to indicate the presence of large-scale fields (e.g. Gardner and Davies 1966). By the early 1980s observations of linearly polarized radio emissions (PI) provided unambiguous evidence for the presence of *large-scale* ordered magnetic fields of microgauss strength in the Milky Way and nearby spiral galaxies—see e.g. Beck (2012); Beck et al. (1996). It is helpful straightaway to distinguish between small-scale ("random", "turbulent") fields, which appear to be universally present, and regular fields of kiloparsec or larger scale. The small-scale fields, which are detectable by their unpolarized synchrotron emission, often are stronger than the large-scale. However much of this article will be concerned with the regular large-scale fields.

Spiral galaxies have a well-developed disc, classically with conspicuous spiral arms traced by bright young stars and hot gas, and a more diffuse spheroidal halo. The strongest and best-observed fields are in the discs. Large- and small-scale fields are also present in the halos, but are more difficult to detect there.

Currently, there is detailed knowledge of magnetic field strengths and structure in a number of nearby spiral galaxies, and Local Group irregulars. M31 (the Andromeda nebula), M51, M81, NGC 6946 and NGC 1097 provide particularly striking examples, see e.g. Figs. 4.16, 4.17, 4.18. Total observed field strengths vary from a few microgauss (μG) in radio faint galaxies such as M31 and M33 through to $50 - 100\,\mu$G in starburst galaxies and those with nuclear starbursts.

Ordered magnetic fields seem to be universally present in well-observed spiral galaxies, and generally trace (maybe rather patchily) trailing spiral patterns. Sometimes regular magnetic fields are found predominantly *between* optical arms, with small-scale fields dominating within the arms (e.g. Beck and Wielebinski 2013; Fletcher et al. 2011). The pitch angles of the large-scale fields usually are not identical with those of the optical arms.

Studies of galactic magnetism have one marked advantage compared with those of solar and stellar magnetism—galaxies are comparatively transparent, and in favourable cases details of rotation and magnetic fields *within* galaxies can be determined. Nevertheless, the large-scale structure of the Milky Way field is quite uncertain—largely because of the location of the solar system in the disc plane and the confusion present along lines of sight lying within the disc ("can't see the wood because of the trees").

What are the methods used to detect and measure galactic magnetic fields?

Although measurements of the polarization of starlight have played and continue to have a role in magnetic field determinations, these measurements can be difficult to interpret, and the main tools now are measurements of polarization at radio wavelengths.

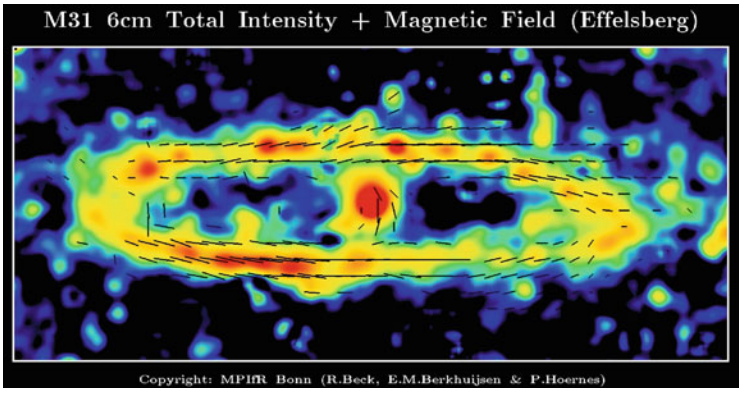

Fig. 4.16 Polarization vectors and total intensity contours for M31 at 4.8GHz; image courtesy of Rainer Beck, MPIfR, Bonn

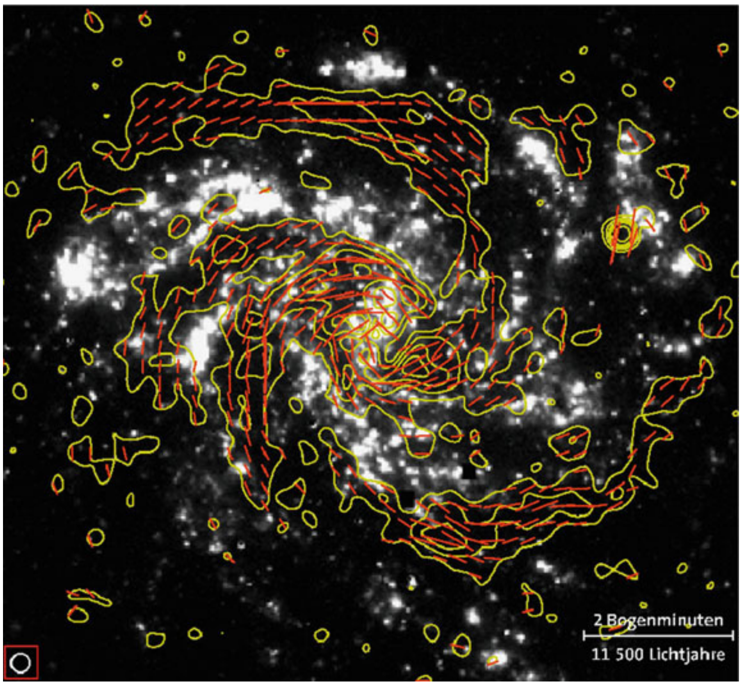

Fig. 4.17 Polarization vectors and polarized intensity contours overlaid on an optical image of NGC 6946. Note that the arms defined by the regular field (polarization vectors) lie between the material arms. Image courtesy of Rainer Beck, MPIfR, Bonn

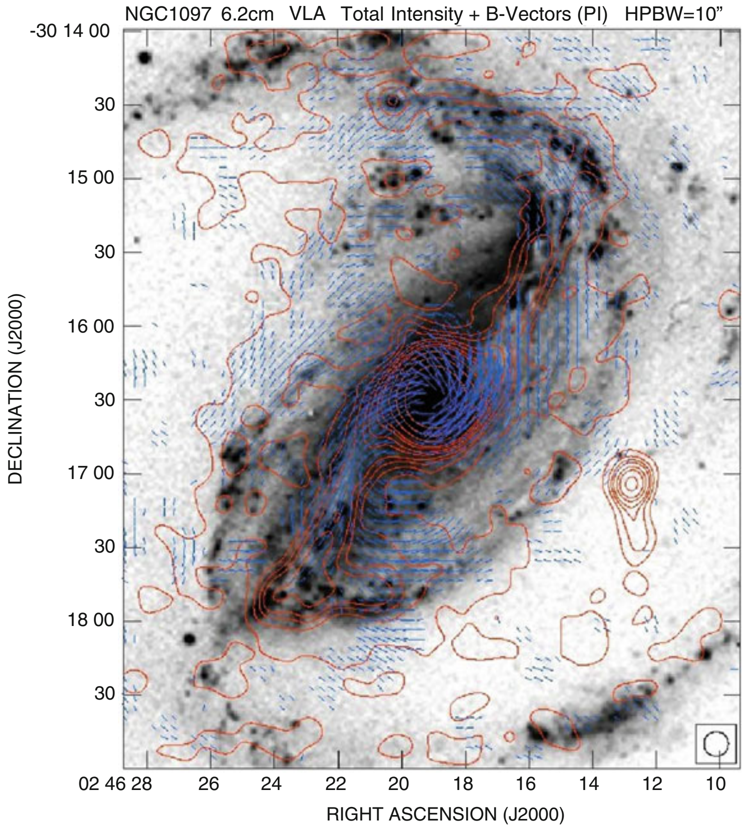

Fig. 4.18 Polarization vectors and total intensity contours at 4.8GHz overlaid on an optical image of the strongly barred NGC 1097; courtesy of Rainer Beck, MPIfR, Bonn

Synchrotron radiation is generated by the spiralling of cosmic ray electrons around magnetic field lines. This radiation is intrinsically highly polarized, and the polarization is widely observed. Measurements of linear polarization give a measure of large-scale field strength and morphology. Note also that polarization measurements do not unambiguously determine field direction—there is a $\pm 180°$ uncertainty. Linearly polarized emission traces *ordered* fields that can be *regular*/large-scale, or anisotropic with many reversals within the beam. (The latter typically arise from turbulent fields that have been sheared by gas flows.) To resolve the directional ambiguity, multiwavelength Faraday rotation measures (RM) are necessary, which is observationally much more demanding. Nevertheless, ingenious use of wide band receivers has enabled progress, notably but not exclusively in the Netherlands. It is also important to realize that linear polarization measures cannot distinguish regular fields (large-scale without reversal of direction within the telescope beam) from anisotropic fields (also of large scale but reversing within the beam). Regular field generation can be described by mean-field dynamo theory.

Turbulent (i.e. small-scale, also "random") fields give rise to unpolarized synchrotron emission—by Faraday depolarization. The observed degree of polarization can be decreased by a number of factors in addition to Faraday depolarization, including the presence of unpolarized thermal emission, and variation of the source across the telescope beam.

Faraday rotation is caused by the rotation of the plane of polarization of radiation when passing through a magnetized medium. The angle of rotation increases with plasma density, the strength and direction of the line of sight magnetic field and the square of the wavelength. Because it is sensitive to field direction, only regular fields generate measurable Faraday rotation. Multiwavelength measurements are required to determine *rotation measures* (RMs), and if these are known for a number of lines of sight through a galaxy then, together with linear polarization measurements, it may be possible to determine the magnetic configuration. If RMs are available at several wavelengths, then the strength and *direction* of the line of sight regular field can be determined.

Zeeman splitting of radio spectral lines can give a direct measurement of field strength in Milky Way gas clouds, and in some starburst galaxies.

There are some general considerations in making radio observations. High frequencies are needed to obtain higher angular resolution, and to avoid Faraday effects. Lower radio frequencies allow measurement of small Faraday rotation, and so determination of weak regular fields. Synchrotron radiation is generally stronger at low frequencies, but so is Faraday depolarization, so for given field strength there is an optimal frequency for measuring polarized emission. Higher frequencies give a smaller field of view for a given instrument, and *vice versa*. From the above it is clear that there are competing and conflicting factors that affect observations with different instruments and different objects.

The "big dish" (such as that at Jodrell Bank) is the iconic radio telescope, but radio interferometry has played a vital role in radio astronomy, uniting signals from two, and often many more, receivers (not all of which take the form of a classical dish) with large spatial separation (baseline). This enables much higher high angular resolution—the larger the separation the better. In terrestrial terms this process will approach a limit with the planned completion of the Square Kilometer Array (`SKA`), in its full realization being an assembly of several thousand receivers with total area approximately 1km^2, and baseline extending from South Africa to Western Australia.

What do we know about magnetic fields in the Milky Way and other galaxies?

Well-ordered fields are mostly observed in spiral galaxies. The *total* field strength increases with the star formation rate. In general, field strengths are weak for type S0 and Sa galaxies, and stronger for types Sb and Sc. For example, the radio-faint M31 and M33 have *total* fields of about 6 μG (e.g. Tabatabaei et al. 2008), whereas spirals with high star formation rates, such as NGC 6946 (see Fig. 4.17) have total field strengths of $20 - 30\mu$G in the arms. Field strengths in starburst galaxies may be stronger still. The irregular LMC has a weak ordered field of O(1) μG and a stronger small-scale field (Gaensler et al. 2005). There is a very tight correlation between total radio continuum emission at a few GHz and far infrared luminosity. In general total fields in dwarf and irregular galaxies follow this relationship, but regular fields are there weak or undetectable.

Although elliptical galaxies with active nuclei are extremely radio-bright, apart from the nuclei and jets there is no evidence for large-scale magnetic fields in elliptical or S0 galaxies (consistent with the absence of differential rotation in ellipticals—see discussion on dynamo theory in Sect. 8.8). Small-scale fields are present—e.g. Moss and Shukurov (1996), and but will not be discussed further here. Ring galaxies are rather unusual objects, with a ring of bright stars and ionized gas surrounding a central core (Ilyina et al. 2014), but at present magnetic fields have not been detected in the rings.

Fields in the discs of spiral galaxies are often predominantly axisymmetric, with only small contributions from higher modes, but the azimuthal symmetry cannot always be firmly established. However earlier beliefs that a significant proportion of fields were dominated by $m = 1$ azimuthal modes have now weakened considerably. It is difficult to determine clearly the symmetry of galactic fields with respect to the disc plane (suitable galaxies seen edge-on are rather scarce, and observations are difficult to interpret), but the data are generally consistent with even (quadrupolar) symmetry (see Sect. 8.8), in the very few cases where determination is feasible. In galaxies with massive bars and non-circular motions, field lines approximately follow the gas flow.

While our galaxy, the Milky Way (MW), might seem the most readily accessible for magnetic field determinations, in fact the position of the solar system within the obscuration of the galactic disc gives rise to substantial general difficulties—even the spiral structure marked by material arms is not known for certain. For example, it appears that the large-scale disc field may possess a reversal (several have even sometimes been claimed), whereas similar features have not been seen in well-observed external galaxies. Such uniqueness in our local system leaves an uncomfortable feeling, and it may be that we are seeing a local, rather than a global, feature.

Measurements of rotation measures (RM) for pulsars in the galactic halo and for even more distant extragalactic sources have the potential to provide information about the large-scale field structure away from the disc plane, importantly including the field direction. However our location within the disc plane means that only sources sufficiently far above or below the plane can be used. The number of such objects is limited (but growing).

Current data suggests, rather weakly, the conclusion that the MW field is of even parity with respect to the disc plane (i.e. "quadrupole-like"), which is in accordance with basic concepts of dynamo theory and with the very tentative information about the parity of fields of external spiral galaxies.

Signatures of large-scale magnetic fields are currently seen in galaxies with red shifts $z \lesssim 2$—i.e. by ~ 3 Gyr after time zero (Bernet et al. 2008): technological advantages may soon push this "first field" time back very considerably in favourable cases.

In what ways do galactic magnetic fields impact on other areas of astrophysics? Why is it important to know about them?

Magnetic fields are found almost universally in spiral galaxies, both at the near-global scale, and also at the scale of the turbulence (about 100 pc). Their energy density is of the same order as that of the turbulent motions in the ISM and of cosmic rays. They are thus a major component of the ISM (and also the inter-cluster medium) and affect dynamically the turbulent ISM and gas flows, e.g. in spiral arms. The realization of the role of magnetic fields in the outward transport of angular momentum resolved an number of important issues, This means that magnetic fields can directly influence the formation of stars and solar systems. *Inter alia*, they directly influence the mass at which gravitational instability occurs in gas clouds (e.g. Mestel 1965a,b). van Loo et al. (2012) is an accessible review. There is therefore an input into the stellar mass function. It follows that for a holistic understanding of the evolution of these galaxies, with subsequent formation of stars and planetary systems, it is essential that the generation and structure of galactic fields be understood. Direct dynamical effects in some galaxies, in driving mass inflows to the centre of barred galaxies, and also possibly modifying the rotation curves at large galactocentric radii also should not be ignored. For these and other reasons magnetic fields should be included as an intrinsic part of fully comprehensive studies of spiral galaxies.

What are the major developments of the 21st Century? And what are the outstanding problems?

Major advances, both observational and theoretical, have been made in the last few decades. However there are still many outstanding issues.

I have made little mention of magnetic fields in galactic halos. Outflows such as galactic fountains and winds may transport fields from disc to halo, and even into the intra-cluster medium. Independent dynamo action may also take place in the halo (e.g. Sokoloff and Shukurov 1990). Moss et al. (2010) made a preliminary numerical study which suggested that dynamo action in galactic halos could be significant. The outcome depended critically on the particular galaxy environment, and could include halo fields with parity different from that of the disc fields. Observations of halo fields are difficult—in galaxies with small inclination to the line of sight halo fields are confused by the disc, and there are currently few suitable observations.

In the Milky Way, filaments of strong field perpendicular to the disc plane are seen at the very center of the Galaxy. It is thought that these filaments are not directly connected with the large-scale dynamo action, but are associated with the central black hole. Nevertheless the mechanism of formation of these filaments is uncertain. More generally, our lack of detailed knowledge of the global structure of the MW magnetic field remains an embarrassment.

With these provisos, we now seem to have a basic *generic* understanding of the mechanisms involved in generating the fields observed in spiral galaxies. Dynamo theory, even in reduced mean field form, seems generally satisfactory in reproducing gross features. But it is clear that a better understanding of the feedback from small-scale fields into the dynamo is needed, in particular the role of helicity transport. Increased understanding of this problem may lead to resolution of another outstanding problem: why, in certain galaxies do the magnetic arms, as defined by the large-scale field, appear *between* the material arms, while small-scale fields are stronger in the material arms (see, e.g., Chamandy et al. 2013, 2015; Moss et al. 2013, Moss et al. in preparation).

Large scale flows can also strongly influence dynamo action. These include galactic fountain flows, outflows in the halo ("winds"), and non-circular flows such as seen in barred galaxies and in galaxies that interact strongly with a neighbour, or are affected by passage through a surrounding medium. Some progress has been made on all these issues (e.g. Chamandy et al. 2015; Kulpa-Dybel et al. 2015; Moss et al. 2014), but a comprehensive understanding is still lacking.

Exact details of magnetic field generation and maintenance can be expected to vary with galaxy type and history. However, there are only a few models that reproduce the fields of any specific galaxy in a comprehensive manner (but see Moss et al. 1998; Vollmer et al. 2006 for examples). Correspondingly, at best only a very broad brush predictive power exists. This is particularly unsatisfactory when account is taken of the vast amounts of data that will be available when the Square Kilometer Array is fully operational. The fundamental issue is the difficulty of modelling sufficiently detailed physics, requiring consideration of very short time and spatial scales into global galaxy models extending over much larger scales. Also we are still ignorant of some essential physics relevant to the local models. As suggested earlier, in the short to medium term the most promising approach may be to develop local "in a box" models using Direct Numerical Simulation (DNS), of regions of the disc with different parameters—energy input, differential rotation, disc thickness, etc—and to use these to calculate reliable mean field tensors α and η to insert into global models. (Indeed, Ferrière (1998) and Ferrière and Schmitt (2000) are pioneering papers in this area.) Alternatively, shell models of MHD turbulence could be used to calculate systematically the mean field coefficients locally as the computation proceeds. (Shell models of MHD turbulence follow, in a computationally efficient manner, the evolution of representative Fourier modes of physical quantities, whilst conserving magnetic helicity, energy, etc.—see e.g. Frick and Sokoloff 1998). Of course, a good knowledge of the large-scale motions (circular and non-circular) will also be necessary. In such ways, if relevant properties can be determined for selected galaxies, the prospect of realistic predictive modeling may be approached. Needless to say, any such program will be distinctly ambitious.

4.10 Stellar Generations and Their Interplay with the Interstellar Medium

After having discussed the main properties of galaxy components, we now address the problem of the connection between stellar population and morphology. Behind this relationship there is some fundamental physics that is not completely understood yet. Francesca Matteucci will introduce this complex subject that will be deeper touched in Chaps. 7 and 8.

Questions for Francesca Matteucci:
the first systematic investigations of the stellar content of galaxies trace back to the studies of resolved stellar populations by Hubble and Baade and the analyses of galaxy colors and spectra by e.g. Stebbins, Whitford, Holmberg, Humason, Mayall, Sandage, Morgan, and de Vaucouleurs. May you trace the progresses that led to the current knowledge of stellar populations in galaxies trying to emphasize the crucial phases of our understanding?

Edwin Hubble marked the first fundamental step in the knowledge of stellar populations when in the late 1920's and early 1930's confirmed that the "nebulae" are stellar systems like our Milky Way galaxy containing billions of stars. This discovery changed the view of perceiving the Universe and started a new era in Astronomy where many scientific discoveries followed at the fastest rate in the whole of astronomical history. Hubble classified the galaxies into different types according to morphology and structure and ordered them into a sequence, known as the *Hubble Sequence*. The galactic types are basically three: ellipticals (E), spirals (S) and irregulars (I), and are determined by their morphological structure and apparent shape.

Walter Baade in 1944 marked the second fundamental step in the knowledge of stellar populations. Baade discovered the existence of two main stellar populations in galaxies, thus opening other fundamental fields such as stellar and galactic evolution. In particular, he resolved the stellar populations in the bulge and disk of M31, in M32, NGC 205, NGC 147, and NGC 185. The two main stellar populations inhabiting galaxies were called by Baade, Population I and Population II. The two populations show different colors and different chemical composition, with the Population II stars being red, metal poor and lying well above the Galactic plane relative to Population I stars which are blue, more metal rich and belonging to the disk. Henry Norris Russell in 1948 first interpreted the stars of Population II as old and Population I as young. Now we know that because of Galactic chemical evolution the first stars that formed (Population II) have a lower metal content than younger stars, which formed out of gas enriched by the previous stellar generations.

In the following years, integrated galaxy colors and spectra were measured in galaxies showing that elliptical galaxies are dominated by red stars, whereas in the spirals the central bulges are red and the disks are blue like irregular galaxies. The red light is typical of low mass giants stars, whereas the blue light is typical of massive stars (M$>10M_{\odot}$). This fact immediately indicated that in disks of spirals and in irregulars there is evidence of recent star formation, so that the integrated light is dominated by young and blue massive stars. On the other hand, the bulges of spirals and elliptical galaxies have an integrated light dominated by low mass stars, a sign of absence of star formation. This information immediately suggested that ellipticals and bulges must have exhausted most of their gas content whereas spiral disks and irregulars still have gas to form stars.

In the following years a great step in the knowledge of stellar population was made by the derivation of the chemical abundances and kinematics of the stars of our Galaxy. In particular, a milestone is represented by the work of Eggen, Eggen et al. (1962), who suggested for the first time that the motions of old stars (Population II) was evidence that the Galaxy collapsed. They observed 221 dwarf stars and showed that the eccentricity of the stellar orbits is correlated with the stellar metallicity (Z), measured by means of the ultraviolet excess which is related to the Fe abundance; in particular, the stars with the largest excess (lowest Fe abundance) are always moving in highly elliptical orbits, whereas stars with low excess (high Fe abundance) move in nearly circular orbits. They also found a correlation between the velocity component perpendicular to the Galactic plane and the ultraviolet excess. These two fundamental findings indicated that stars older and more metal poor are on orbits with high eccentricity and lie well above the Galactic plane, while the younger more metal rich stars have circular orbits and lie on the disk. They interpreted these two correlations in term of collapsing Galaxy and suggested that the old stars formed out of a gas collapsing from the halo onto the disk. They also concluded that the collapse was very fast and lasted only a few 10^8 years. We know now that this time-scale is too short for describing the formation of the disk even locally, but the basic idea of the stellar halo forming by gas collapse is still valid.

In the last decade, a very important step in understanding stellar populations was represented by the accurate high resolution spectra obtained for stars in the Milky Way and some of the local galaxies. In particular, abundances in the halo, thick and thin-disk and bulge of the Milky Way have allowed us to better understand the history of the formation of our Galaxy by means of the astro-archaeological approach. This was possible thanks to a generation of highly efficient spectrographs, such as `UVES` on the Very Large Telescope (`VLT`), and to large ground telescopes that have allowed us to measure with unprecedented accuracy the abundances of several chemical elements in stars in a large range of metallicities. An example of the large variety of accurate abundances available now for the bulge of the Milky Way is shown in Fig. 4.19. The abundances are expressed as [X/Fe] $= log(X/Fe)_{*} - log(X/Fe)_{\odot}$: in this notation $[X/H]_{\odot} = 0$ and $[X/Fe]_{\odot} = 0$.

In which way the morphological class is connected to the stellar populations?

The morphological classes, namely ellipticals, spirals and irregulars are strictly related to their stellar populations. In fact, elliptical galaxies contain mainly old low mass stars and their integrated spectra are dominated by K- and M-giants. This fact, together with the absence of cold gas and ongoing star formation, indicates that most of the stars in these galaxies formed several billion years ago. Moreover, the chemical abundances deduced from their spectra indicate the chemical composition of the stellar population dominating in the visual light and suggest metallicities

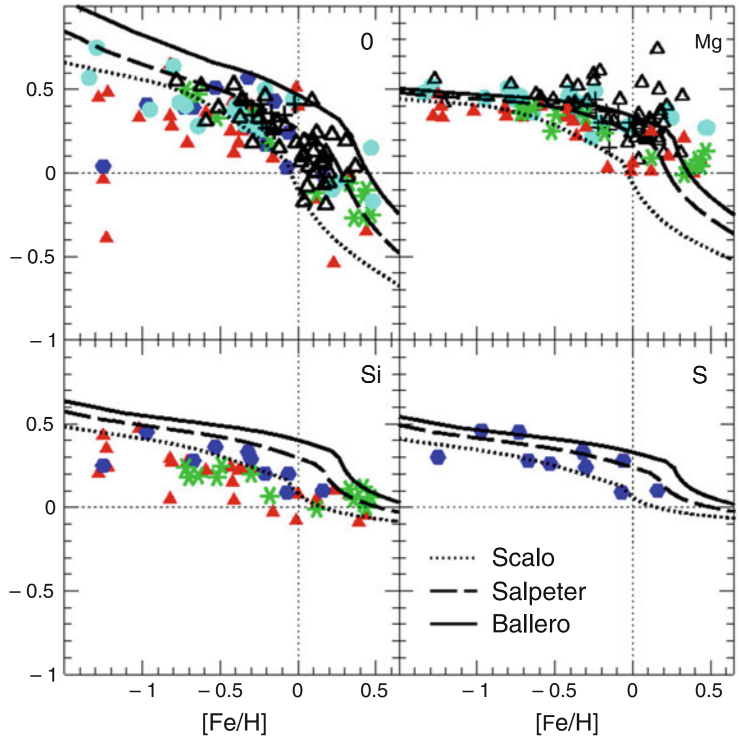

Fig. 4.19 In the Y-axis are reported the [O,Mg,Si,S/Fe] ratios versus [Fe/H] in the X-axis. The Figure shows a comparison between high resolution abundances measured in Galactic bulge stars with chemical evolution models adopting three different IMFs: Scalo (1986); Salpeter (1955) and Ballero et al. (2007). The references to the observational data can be found in Cescutti and Matteucci (2011). Figure from Cescutti and Matteucci (2011)

which can be higher than the solar one as well as having oversolar abundance ratios, such as those of α-elements (e.g. O, Mg, Si, S) to iron, with a trend with galactic stellar mass. In particular, more massive ellipticals show higher [α/Fe] ratios than less massive ones. This fact has been interpreted as being due to faster star formation in more massive galaxies favoring a fast gas consumption and preventing supernovae (SNe) Ia (the main Fe producers) to pollute substantially the gas with Fe. On the other hand, in spiral galaxies like the Milky Way there are several different populations including the two identified by Baade but with a finer subdivision. In fact, in the Milky Way bulge there are old stars with halo kinematics but also high metallicity, whereas in the halo the stars are all metal poor (Population II stars). Then the disk stars belong to two distinct populations: the thin-disk and the thick-disk population. The thin-disk population is the Population I, whereas the thick-disk one has kinematics and chemical characteristics which are intermediate between Population II and Population I. The presence of young stars in the thin disk and old stars everywhere in the Milky Way together with oversolar [α/Fe] ratios in the halo, and solar [α/Fe] ratios in the thin disk indicate that our Galaxy formed on a longer timescale than elliptical galaxies and that the thin-disk assembled by accretion of cold gas on timescales of several billion years. Finally, irregular galaxies contain a lot of gas and active ongoing star formation together with a few old stars; this indicates that the star formation in these galaxies has been slower than in ellipticals and spirals. The slow process of star formation in these objects is confirmed by the low average [α/Fe] ratios (solar and subsolar) in their stars. In fact, in a low star formation regime the abundance of Fe in the interstellar medium (ISM) increases slowly and when Type Ia SNe start to be important in restoring Fe, the Fe abundance is still low. This is related to what we call *time-delay model*, namely to the fact that α-elements are mostly produced by massive stars whereas Fe is produced by Type Ia SNe (white dwarfs in binary systems) on much longer timescales. This fact, coupled with the different histories of star formation, can explain the abundance patterns observed in galaxies of all morphological types. Therefore, from the characteristics of the stellar populations we can reconstruct the history of star formation in galaxies, which seems to be the main parameter to explain the Hubble sequence. In Fig. 4.20 we show an illustration of the effects of the time-delay model in different galaxies.

Do we fully understand the mechanisms driving the stars-ISM ecosystem in the different morphological types?

What we understand is that the star formation history should have been different in galaxies of different morphological type. By star formation history we intend the convolution of the star formation rate (SFR) and the initial mass function (IMF). Clearly, a different star formation history influences the feedback between stars and ISM: supernovae of different type explode at different times and deposit in the ISM a given amount of energy. This energy increases the temperature of the ISM and this increase in temperature can have several different effects. First of all, an increase in temperature would prevent star formation in the heated region and also trigger an outflow from the galaxy, which can result in a galactic fountain or in a real galactic wind. We do not know how much energy can be deposited into the ISM by each supernova, since the stars-ISM ecosystem depends on the environmental conditions. For example, the energy deposited by a supernova exploding in isolation can easily be lost by means of gas cooling: roughly 3 % of the initial blast wave energy ($\sim 10^{51}$ erg) can be deposited into the ISM after the cooling (Bradamante et al. 1998). On the other hand, almost all the energy deposited by several supernovae exploding in the same region can be stored in the ISM, owing to the large filling factor of the supernova remnants. Another important point is whether a SN explodes in a cold medium or in an already heated medium: in the second case there is no loss of energy (see Recchi et al. 2001).

Galaxies of different morphological type experience different histories of star formation and therefore different SN (Type Ia and core-collapse) rates: small galaxies must have experienced galactic winds whereas more massive galaxies such as spirals like the Milky Way are more likely to have suffered galactic fountains. Concerning ellipticals and spheroids, their star formation must have been very intense and lasted for a relatively short period. The large energy transferred by SNe

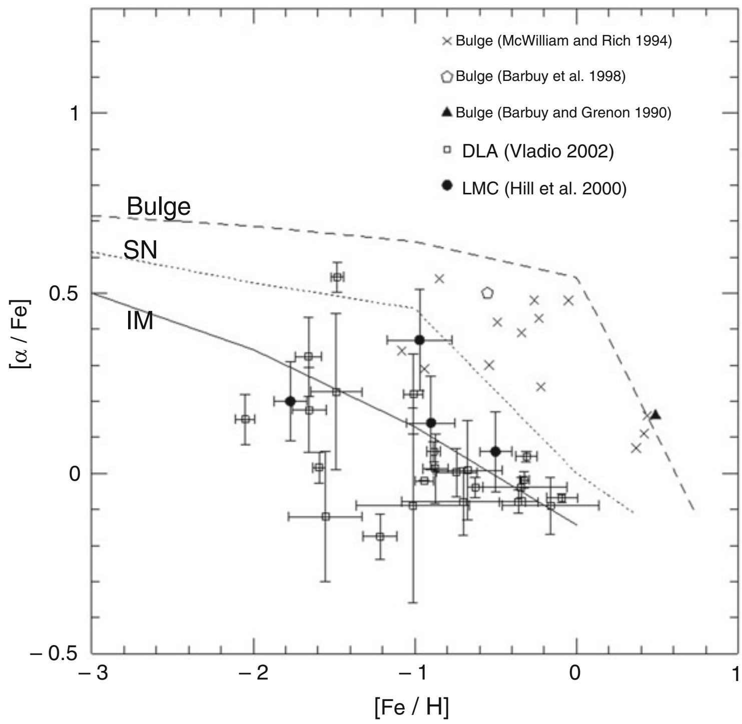

Fig. 4.20 An example of the time-delay model for explaining the abundance patterns in galaxies. We plot the [α/Fe] ratios vs. [Fe/H] expected in the gas in galaxies of different morphological type. The various curves refer to: the Galactic bulge as an example of spheroid, the solar vicinity (SN) and a Magellanic Irregular galaxy (IM). The curves are obtained just by adopting different star formation efficiencies in the various objects. Different star formation efficiencies coupled with the time-delay model for the formation of the α's and Fe determine the different shapes of the curves. Figure from Matteucci (2012)

into their ISM could have been enough to trigger galactic winds, with or without the support of the active galactic nucleus (AGN) (see Romano et al. 2002). These galaxies, in fact, do not show cold gas at the present time, and this could also be due to ram pressure stripping phenomena, at least in galaxy clusters. Either the galactic wind or the ram pressure stripping can quench the star formation since they subtract gas from the system. Last but not least, either galactic winds or ram pressure stripping distribute metals in the intracluster (ICM) and intergalactic medium (IGM), so by studying the chemical abundances outside galaxies one can constrain the mass loss from galaxies and the stellar feedback. However, we have not yet clearly understood the physical processes underlying the feedback stars-ISM, and the majority of galaxy evolution models treats the feedback by means of free parameters.

Are theoretical models able to explain the large variety of modern observations and what kind of new observations could improve in the future our theoretical knowledge?

Theoretical models of galaxy evolution are able to explain several important observations such as, for example, the abundance patterns observed in stars in the Milky Way. Our Galaxy is the best known galaxy from the point of view of chemical abundances, since single stars can be resolved and their chemical abundances measured with high precision. Many chemical abundances have been measured in Galactic stars nowadays, in particular the α-elements such as O, Mg, Si, S, Ca as well as C, N, Fe plus several Fe-peak elements and s- and r-process elements. The most common way of plotting abundances is [X/Fe] vs. [Fe/H], where X is a generic element and $[X/H] = log(X/H)_{\odot} - log(X/H)_{*}$, namely relative to the Sun. In this notation $[Fe/H]_{\odot} = 0$, and $[X/Fe]_{\odot} = 0$.

In Fig. 4.21 we show an example of predictions by a chemical evolution model for the Galaxy compared to stellar data. The model predictions refer to two different sets of stellar yields: as one can see, some of the elemental ratios are very well

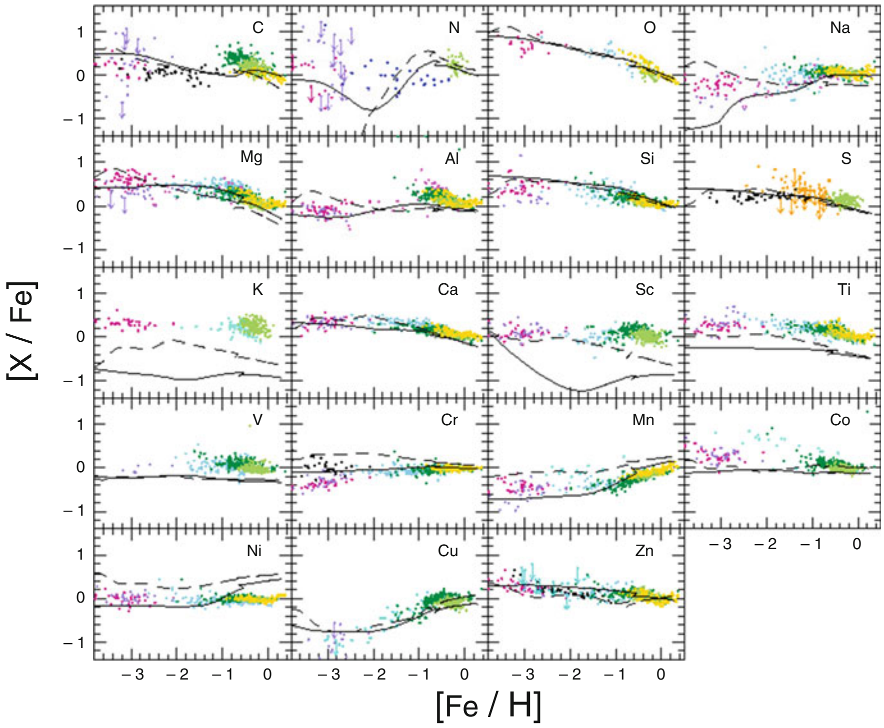

Fig. 4.21 Predicted and observed [X/Fe] vs. [Fe/H] relations for the stars in the solar vicinity. The model predictions are obtained for different sets of stellar yields (for details see Romano et al. (2010)). Figure from Romano et al. (2010)

reproduced whereas others are not. The main reason for not reproducing some ratios resides in the still existing uncertainties in the stellar yields. For α-elements, such as oxygen, the stellar yields are reasonably well known and models are able to reproduce the [α/Fe] vs. [Fe/H] relation. This relation is generally interpreted in the framework of the time-delay model, namely by assuming that α-elements are mainly produced by short living stars, i.e. core-collapse SNe, whereas Fe is produced on a large range of timescales which can be as long as a Hubble time. This is due to the fact that Fe is mainly produced by Type Ia SNe, which are originating in white dwarfs in binary systems.

One still existing problem concerns the light element Lithium, which is a key element in cosmology since is one of the few elements synthesized during the Big Bang. The problem consists in the fact that the abundance of ^7Li measured in the oldest stars in the Galaxy does not agree with the value derived from `WMAP` for the primordial Li abundance: in particular, the primordial value of `WMAP` is higher than the stellar value. If the `WMAP` value (Hinshaw et al. 2009) is correct, we therefore should revise our interpretation of the ^7Li abundance in halo stars (Population II stars) being the primordial one, and assume that some Li astration has taken place in these stars. The ^7Li is also produced by stars during galaxy evolution, in particular SNeII, novae and asymptotic giant branch (AGB) stars have been suggested as Li producers. The Galactic production of ^7Li is confirmed by the Li abundance measured in very young local stars, such as TTauri stars which exhibit a Li abundance ten times larger than that found in the old halo stars.

Present and future large surveys of the Milky Way (RAVE, OGLE, APOGEE, HERMES, GES, LAMOST, PanSTARRS, LSST, WEAVE) from present and future telescopes (`VISTA`, `VST`, `ALMA`, `JWST`, `E-ELT`) as well as space missions such as `GAIA`, will provide chemical abundances, radial velocities and distance of millions of stars in our Galaxy thus providing a new and unprecedented amount of data which will greatly help us to perform galactic astro-archaeology in order to understand galaxy evolution. Moreover, telescopes, such as `JWST` (James Webb Space Telescope) will provide new precious information on primordial galaxies. In particular, we will be able to study directly the assembly of galaxies.

4.11 The Scaling Relations

We enter here at the heart of the problem of the galaxy structure. How the different morphologies were developed? What are the properties in common to all galaxies? Why galaxies obey the so called "scaling relations"? What are the relationships among the various components? Why stars seem to know where they are?

These are only some questions related to this complex problem that is obviously linked to how galaxies formed and evolved. Now George Djorgovski attempts some first answer to clarify and define what we know and what is still not understood.

Questions for George Djorgovski:
the studies of the scaling relations between the structural parameters of galaxies had a profound impact on our understanding of their formation mechanisms. You have been one of the scientists that discovered the Fundamental Plane (FP) relation of Early-Type galaxies. Could you briefly review the major steps forward coming from the FP studies? Why the FP relation and in general the scaling relations are so important? Do we have evidence that the scaling relations vary with the cosmic epoch?

This is a huge and vibrant subject, and first of all, let me apologize for not citing many good papers in my comments below, in following your instructions that these contributions should not be standard reviews aimed at the experts, but rather an outline the key ideas and developments from our personal points of view.

My own interest in this subject was motivated by the desire to somehow fully characterize properties of galaxies in a systematic and quantitative way. I thought that we have to do that if we are to use galaxies in cosmology, or to try to understand their evolution. I was thus very intrigued by the pioneering papers by Brosche (1973) and by Brosche and Lentes (1983). They used a principal component analysis (PCA) to explore properties of early-type galaxies, and, while being limited by the quality and heterogeneity of data available to them at the time, they did find that there are two principal components among the quantities they studied. They did not pursue this any further, and their work was largely ignored by the community, and did not have much impact at the time. However, I thought that this is the right approach. What was needed was systematic surveys of sufficient numbers of early-type galaxies, and the way to obtain quantitative measurements of their morphology, we needed surface photometry. This is where the CCDs made a real difference.

In the early 1980s I embarked on a thesis project under Marc Davis, to conduct a surface photometry survey of elliptical galaxies, with a goal to improve on the Faber-Jackson (FJ) relation (a correlation between the absolute luminosity and velocity dispersion) as a distance indicator. The focus back then was on improving distance indicator relations for galaxies, mainly Tully-Fisher (TF) and FJ, as tools to be used to study the large scale structure and improve the measurements of the Hubble constant, which was then known to a factor of two, and accompanied by much controversy. The discovery of the Fundamental Plane (FP) came from a search for the "second parameter" that would improve the scatter in the FJ relation, which it ultimately replaced—not by the desire to improve our understanding of the early type galaxies per se.

While starting our own survey, we did a pilot project using the surface photometry of a modest number of ellipticals, obtained by Steve Kent (Djorgovski et al. 1985). The sample was too small to really do much, but I also made a methodological blunder: in addition to the parameters such as various forms of radii, enclosed luminosities, surface brightness, and the spectroscopic ones such as the velocity dispersion, velocity anisotropy, or metallicity, we also evaluated a number of "shape" parameters: mean ellipticities, ellipticity gradients, isophotal twists, slopes of surface brightness gradients, etc. The result was that there were too many significant eigenvectors, so that the PCA approach did not seem to help much. The crucial insight, that one should exclude the shape parameters and focus only on those that reflect quantities that describe sizes, luminosities, densities, and kinetic temperatures of early-type galaxies, had to wait until I completed my own survey and started its analysis. The dimensionality reduction that produces the FP and makes it the optimal distance indicator for elliptical galaxies (among other things) applies only in this select subset of measurable parameters. This removes a number of other statistically significant, but otherwise unimportant (in the context of this problem) eigenvectors that reflect the uncorrelated mess of shape parameters.

I did have that insight while analyzing the data from my thesis, in the early 1986 (Djorgovski and Davis 1986), with the journal paper (where we also named this new bivariate correlation the Fundamental Plane) that followed (Djorgovski and Davis 1987). Based on our surface photometry, the optimal correlation expressed a distance-dependent quantity, a consistently defined metric radius (actually, a semi-major axis, but the common usage is the word radius) of the galaxy, as a bivariate power law fit to two other quantities, a mean surface brightness within the isophote of that radius, and the projected central surface brightness. This metric radius could be, e.g., the effective radius derived from the surface brightness profile, but there are other possible operational choices, e.g., those based on Petrosian's eta function. Alternatively, a measure of luminosity (e.g., as enclosed within that radius) can be used as a distance-dependent quantity instead of the radius. The fact that the residual scatter around this best-fit power-law surface was entirely consistent with the measurement errors, i.e., that the intrinsic scatter was undetectable, implied something fundamental about the way elliptical galaxies are constructed, and thus the name of the FP.

Independently and at the same time, the FP was discovered in a somewhat different packaging, as the $D_n - \sigma$ relation, by a group of astronomers calling themselves the "Seven Samurai" (7S) (Dressler et al. 1987). It is not hard to show that this relation is a slightly oblique projection of the FP. In keeping with the original intent, they used it to measure relative distances to early-type galaxies in clusters, and therefrom derived the peculiar velocities of these clusters, and concluded that there is a coherent infall over the scales of $\sim$ 100 Mpc into the Hydra-Centaurus supercluster, which they renamed the "Great Attractor" (Lynden-Bell et al. 1988).

I was skeptical about this claim, since it was based on the assumption that the zero-points of these correlations—whose physical origin we still do not fully understand—are constant to better than a few percent in different environments, something we simply could not measure back then. This did not endear me to the 7S, resulting in some matters that are best left undescribed here. There were early hints that there is some environmental dependence of the FP coefficients (de Carvalho and Djorgovski 1992), but it took much larger, homogeneous samples to answer this question: there is some environmental dependence, but it is very modest, and it does not dominate the peculiar velocities (La Barbera et al. 2010).

An important fact is that the properties of ellipticals that reflect the history of their star formation history and chemical enrichment, namely various measures of metallicity, and metallicity (and mean age) sensitive colors, also participate in the FP (de Carvalho and Djorgovski 1989, 1990). Thus the evolution of their stellar populations is closely coupled with their dynamical structure.

A common misconception is that the FP is only a particular bivariate scaling relation in the 3D space of radius, velocity dispersion, and surface brightness. This is incorrect. It is a bivariate relation embedded in a much higher dimensionality space of observed and derived quantities, that include consistently defined radius, luminosity, luminous mass, dynamical mass, velocity dispersion, mean surface brightness, mean density, phase space density, metallicity, various colors, and masses of their central supermassive black holes. Any one of these parameters can be expressed as a combination of any two others. At some level, the shapes of the radial surface brightness profiles, e.g., as quantified by the exponent in the Sérsic formula for the surface brightness, also participates in the FP.

My focus was always on the understanding of the physical origins and implications of the FP, and its disk galaxy cousin, the TF relation (Djorgovski 1987). We have quickly shown (Djorgovski et al. 1988) that both FP and TF can be derived from the Virial Theorem, provided that galaxies obey some highly non-trivial conditions. For elliptical galaxies, the requirement is that they are a (nearly) homologous family of objects, i.e., that their dynamical structures can be scaled along the axes corresponding to the FP parameters. For example, we know that the more luminous ellipticals tend to have shallower surface brightness profiles (which changes the mapping of an observationally defined radius, such as the effective radius, to the mean mass-weighted radius that can be entered in the Virial Theorem) and that their velocity distributions tend to be more anisotropic (which changes the mapping of the observed, projected velocity dispersion to the mean kinetic energy per unit mass). It is also required that their mass-to-light ratios scale weakly with the luminosity or mass, which could be due to a change in the mean metallicity, stellar mass function, or the relative amounts of dark matter and luminous baryons. These gradual trends along the FP account for its tilt relative to the pure Virial Theorem, and to this day various research groups argue about the relative importance of all of these factors, and all of them seem to be relevant at some level.

This explains the tilt of the FP, but not its small scatter: somehow all of these intrinsically noisy trends combine into a (nearly) scatterless bivariate scaling relation. That is the real puzzle of the FP, which remains unsolved until the present day. It is especially puzzling, given the stochastic nature of the elliptical galaxy assembly, through various numbers of mergers of various mass ratios and geometries, accompanied with various amounts of dissipation and star formation. Regardless of their individual, diverse formative and evolutionary histories, elliptical galaxies assume certain well defined dynamical and structural forms, and we do not yet know why only those, and not something else. The equivalent puzzle applies to the origin of the TF relation, where a dark halo driven property (maximum circular rotation speed of the disk) determines the luminosity, a quantity that is a product of the integrated star formation history of the disk. Likewise, dwarf galaxies and globular clusters also follow their own analogs of these scaling relations, which are different from those of the normal ellipticals.

I proposed that the parameter space of galaxian fundamental properties in which these scaling relations are embedded is effectively a galaxy equivalent of the H-R diagram for stars, itself a 2D parameter space in which stars form 1D sequences. It is a framework in which we can study formative and evolutionary processes for the various galaxy families, just as we use the H-R diagram to probe stellar evolution and physics. Different evolutionary processes move galaxies or their progenitors in different ways within this parameter space. I call this parameter space the G-space (Djorgovski 1992a,b); its minimum representation is in 3D, with the axes representing measures of galaxy "size" (e.g., mass, luminosity, radius), "density" (e.g., surface brightness), and "temperature" (e.g., velocity dispersion, or the maximum rotation speed for disks). I discussed these ideas at the time openly and extensively at conferences, seminars, and individual conversations, considering them more as a framework for a new research program than a research result. I was then surprised when another group of astronomers, who were well aware of these ideas and where they came from, published them without any reference as to their origin, picking a particular choice of coordinate axes and calling it a κ space.

To encapsulate the significance of the FP and its analogs for other types of galaxies: First, their differences represent an objective, quantitative way of distinguishing between galaxies of different families (e.g., ellipticals, disks, various types of dwarfs), as opposed to a traditional and somewhat superficial classification based on the visual appearance of galaxies along the Hubble sequence. Second, they are telling us something about the physics of galaxy formation, that we still do not understand, namely, why is their scatter so small. Third, they are by construction the optimal distance indicator relations for galaxies. And finally, they are a potentially powerful probe of galaxy evolution, due to their sharpness.

Several groups pursued the evolution of the FP in ever more distant clusters through the 1990's. There are several effects seen. First, there is a gradual brightening of the FP intercept along the surface brightness axis at larger redshifts, due to the evolution of their stellar populations. The best fitting models imply a formation of the stellar components of elliptical galaxies at large redshifts, with a relatively passive evolution since then, in an agreement with our overall understanding of galaxy evolution. Second, at intermediate redshifts where the evolutionary effects are not string and can be reliably modeled, the intercept of the FP along the surface brightness axis can be used in the Tolman test for the expansion of the universe: a standard surface brightness (by analogy with a standard candle in a Hubble diagram) is expected to get dimmer with redshift as $(1+z)^4$. This was indeed observed (Pahre et al. 1996), and it was the first successful application of the Tolman test. Third, the evolution appears very similar in clusters and in the general field, although with a larger scatter for the field ellipticals sample, which would be expected if they had a broader range of ages. And finally, the FP rotates (its power law exponents change in time), in a way that is indicative of a mass-depended evolution, with the more massive galaxies being older than the lower mass ones, an effect that has been seen in other galaxy evolution studies, and called "downsizing".

Thus, studies of the FP and its evolution continue to provide us with new insights into their structure and evolution.

There are also alternative interpretations of the correlations observed among galaxy parameters. These are mainly connected to the statistical nature of these relationships. Now Didier Fraix-Burnet will disclose his main concern about the nature of the Fundamental Plane relationship.

Questions for Didier Fraix-Burnet:
you suggested an alternative interpretation of the Fundamental Plane, one of the most famous scaling relations of elliptical galaxies. May you explain your point of view?

Globally, considering galaxies statistically as an ensemble, the mass of galaxies increases with time, with the evolution of our Universe. This is because gravity is attractive, mass attracts mass. Luminosity, radius and surface brightness also increase with more stars being formed and accreted. Velocity dispersion globally should increase as well due to the increasing occurrence of interactions and internal orbital perturbations. One can discuss the details of these evolutions, but I don't think this raw image is wrong.

If all these quantities vary with a same parameter according to some monotonic functions, then correlations appear. If the functions are linear, then the correlation is linear. In three dimensions, this makes a plane. No need for physics here. For instance, the distance of the Voyager probes to the Earth and the average temperature on Earth since their launch both increase with time. A nice correlation thus exists, but would you conclude that the launch is responsible for the global warming? Certainly not. Time is here the confounding factor. Correlation is not causality, this is a principle to keep in mind.

The fundamental plane is known for a long time, and still resists a clear understanding. My point of view is that we should enlarge the way we consider this scaling relation to solve this mystery. I am saying that the statistical evolution of all the parameters creates a non-causal correlation. This is hard to avoid. We have thus to take it into account before detecting any causal correlation. Let me explain the consequences.

Usually, the fundamental plane is compared to the virial plane which is associated with two important assumptions. First galaxies are virialised. Second, since we do not have access to the mass (involved in the virial relation) but only to the luminosity, an hypothesis must be made on the M/L ratio. The so-called virial plane corresponds to M/L being constant. Unfortunately, the observed fundamental plane is tilted with respect to the virial plane. The most convincing "explanation" is that M/L is not constant. Empirically, it is found that M/L depends on a power of M. Why? To my knowledge, nobody knows. At least there is no emerging consensus from the physics.

In my interpretation (Fraix-Burnet 2011), M, L, surface brightness, velocity dispersion and radius depend on a hidden factor. Observations suggest that this dependence most probably is a power law but this is not so important. Consequently, M/L has no reason to be constant and can be expressed as a function of the hidden factor, or equivalently as a function of M or L. Exactly as observed. But there is more than that: by constraining the functions with the observations, I can *derive* whether the galaxies are virialised or not.

By simply assuming that mass, luminosity, velocity dispersion, radius and surface brightness are monotonic functions of a same hidden factor, I can *deduce* from the observations: (i) its nature, (ii) the expressions of the dependence functions, and (iii) whether and which galaxies are virialised. There is no other assumption in this interpretation of the fundamental plane.

Now, the dependence functions must be explained. As we have seen, it is hard to avoid evolution as a confounding factor. Why the functions seem to be linear? This should be interpreted in the statistical sense, and I have not yet the precise answer. Somehow, these functions can be seen as statistical laws induced by the physical processes of galaxy diversification. This is similar to the statistical physics which derives macroscopic laws from the statistics at the microscopic level. My suggestion is that we should develop a kind of statistical extragalactic astrophysics, this would be invaluable to better represent and understand the galaxy diversification process, and to fully explain the so-called fundamental plane as well as many other correlations.

Finally we must keep in mind that the fundamental plane is not planar everywhere. This is true only for galaxies that are the most diversified (i.e. that have gone through many transformation events) as we have shown Fraix-Burnet et al. (2010). Again, the correlations are different depending on the class/population of galaxies.

The accurate determination of fundamental galaxy scaling relations as a function of redshift and environment is the target of most important future surveys like those involving LSST. What is your suggestion?

I like to look at the historical evolution of ideas in science. I find quite stimulating to see that the biologists were first confronted to the complexity and diversity of the living organisms. They thus devised classification techniques to deal with that, and then more and more sophisticated statistical tools. But thanks to the progress in technology they came to the heart of the cells so that now they explore fundamental and detailed physical and chemical processes.

Astronomy has made the reverse path. In some sense, we are living within a cell—our Galaxy—and have logically first developed a detailed understanding of the chemical and physical processes within galaxies. We can touch the complexity of galaxies when we try to simulate them. But Hubble discovered many other similar cells, and the progress of technology now provides us with a huge diversity of objects, so that we have in our turn to deal with problems like populations and classification. Statistics in other words.

This is to say that we should probably have to renounce to master both the details and the complexity of galaxies in the same envelope. I understand that the proponents of a physical classification would like to establish the physics before doing some classification, in other words physics before statistics, but this is unrealistic. Physics and statistics are complementary.

I personally do not put too much attention to scaling relations in the sense that they are convenient because we think we can understand them. My strong recommendation is that we should *now* work hard through astrostatistics and astroinformatics to analyse the various and large data sets already available. I think in particular to the SDSS data base, but there are many others even if smaller. Surely enough, the future instruments and surveys are a significant leap toward a data and statistically driven astrophysics. But we can and must learn now to adapt our ways of analysing data, interpreting them and building models to compare with. Future surveys are designed with our present practice, but obviously they will require something different. The LSST has triggered astroinformatics to deal with the incredible data flow. But the astronomers around the world should invest a lot of efforts for astrostatistics. How could you still imagine to classify millions of galaxies from the LSST or equivalent projects with the Hubble morphological classification? How can you envisage to analyse millions of galaxies described by tens or hundreds of parameters with scatter plots between some a priori selected variables?

We need now to learn the data mining tools and the statistics approach will tell us, among many other diagnostics, what are the correlations, that you can call scaling relations, and whether they are causal correlations or spurious ones created by some confounding factor that we have to determine. My astrocladistics studies have revealed many new correlations with two or three parameters because they are projections of relationships found in a higher dimension parameter space. Hence focusing observations on a particular scaling relation might not be the most informative approach since we severely limit the quantity of information that we get with a strong a priori choice. As I have shown, these correlations depend strongly on the population of galaxies. And we have not yet a good multivariate picture of these populations.

I am totally convinced that we have to consider the galaxies as an ensemble of populations, in evolution of course, with interactions between each other and with their environment. This obviously defines a society, and astronomers should not be reluctant to use the adequate tools similar to the ones used in Human and Biological Sciences. In particular, in any scaling relation, there are very probably several hidden factors creating a confounding correlation. We must learn how to deal with that.

Many galaxy parameters used in the scaling relations are derived from the observed luminosity distribution of galaxies. Which is our current knowledge of the observed light profiles? What is the physics behind the distribution of light? With the next interview Alister W. McK. Graham will provide a very impressive picture of the current understanding of galaxy profiles.

Questions for Alister W. McK. Graham:
the determination of simple empirical laws fitting the light profiles of galaxies have characterized the first years of research on galaxies. The light profiles of early-type galaxies are today generally fit by the Sérsic law. Could you review how this empirical fitting function has gained this widespread use?

Over the years there has been quite an array of empirical functions used to quantify the radial distribution of star light in galaxies. This endeavour started a little over a century ago, with the introduction of Plummer's (Plummer 1911) internal density model[3] and Reynolds (Reynolds 1913, 1920) projected surface-density model for Andromeda (M31). This latter model was developed by Reynolds under the belief that the "Andromeda nebula" was not actually a distant galaxy but rather the glowing dust and haze of nebulous matter surrounding a hidden central star. The intensity distribution of the image was modelled as roughly falling off with the inverse square of the projected distance, i.e. radius r, such that $I = I_0/(1+r)^2$. Reynolds' model is often referred to as the Reynolds-Hubble model or somewhat unfairly as just the Hubble model after Hubble (Hubble 1930) introduced a scale radius. Of historical note, it is interesting that Hubble used the isothermal sphere model introduced for objects not thought to be distant galaxies, and that Hubble (Hubble 1934, 1937) did not accept that the redshifts of galaxies actually reflected their recessional velocities and thus distances from us in an expanding Universe.

Shortly after the two World Wars had finished, de Vaucouleurs (de Vaucouleurs 1948a,b) introduced, in French, his "luminosity law", a new fitting function for early-type galaxies which came to be known as the $R^{1/4}$ law because of the way the surface brightness declined linearly with the 1/4-power of the radius (de Vaucouleurs 1953a). de Vaucouleurs found this provided a better description of the distribution of light in elliptical galaxies than Reynolds' model. Given the perception that the bulges of disc galaxies are akin to small elliptical galaxies, the $R^{1/4}$ model was also used for performing bulge/disc decompositions, with the exponential model (e.g., Patterson 1940) used to describe the disc component of the galaxies (de Vaucouleurs 1957, 1958). de Vaucouleurs (1953b) felt that the area within which 50 % of the total galaxy light resides was of particular interest because that was where the photometric measurements were most reliable. He wrote that the "axes of this particular area constitute a reliable and physically significant measure of the apparent dimensions of the nebula [galaxy], practically independent of instrumental and observational circumstances",[4] thereby circumventing the issue as to the outer boundary of elliptical galaxies. Ellipticity aside, the two scale parameters in the $R^{1/4}$ model are thus the radius containing 50 % of the galaxy light, which de Vaucouleurs referred to as the "effective dimension", and the associated "effective surface brightness" at this radius.

Working at the Observatorio Astronómico in Córdoba, Argentina, Sérsic (Sérsic 1963; Sérsic 1968) introduced and then applied his $R^{1/n}$ generalisation of de Vaucouleurs' $R^{1/4}$ model to many galaxies in his now famous Atlas de Galaxias Australes (written in Spanish). Sérsic's generalised model was introduced because Sérsic felt that the combination of an $R^{1/4}$-bulge plus an exponential-disc, for galaxies along the Hubble-Jeans sequence (Hubble 1936, 1926; Jeans 1919, 1928), could be approximated by this $R^{1/n}$ function. The model has a third parameter, n, which controls the curvature of the profile and thus how centrally concentrated it is.

[3]Although Plummer's model found popularity for describing globular clusters, due to its simple form many theorists used it to approximate elliptical galaxies and the bulges of disc galaxies.

[4]Nearly 70 years on, the misunderstanding that this has led to is epic. There is nothing physical about this arbitrary 50 % area.

Rather than regarding this model as a threat, de Vaucouleurs embraced this idea and regularly cited Sérsic (1968) atlas and model.

Much credit goes to Capaccioli (1985, 1987, 1989) who pushed the need for Sérsic's model amid a growing awareness of the inability of the $R^{1/4}$ model to describe the light profiles of early-type galaxies (e.g., Capaccioli et al. 1988; Michard 1985; Oemler 1976; Schombert 1986). Although de Vaucouleurs and Capaccioli (1979) had shown that NGC 3379 is remarkably well fit by the $R^{1/4}$ model over an impressive 10 mag arcsec^{-2} (but see Capaccioli et al. 1991), this was not the case for fainter and brighter early-type galaxies. Indeed, with similarly deep, radially extended, light profiles for an additional 32 ordinary early-type galaxies in the Virgo cluster, Caon et al. (1990; see also Bertin et al. (2002)) revealed that they do not all have $R^{1/4}$ light profiles.

It was however the paper by Caon et al. (1993) which revealed that the $R^{1/n}$ model provides a good description to the extended light profiles of the early-type galaxies in the Virgo cluster, down to a typical limiting surface brightness of $\sim$28 B-mag arcsec^{-2}, which sparked global recognition for the Sérsic model. This may have been because Caon et al. (1993) showed that the range of Sérsic indices n correlates with the half light radii of galaxies (derived independently of the fitted $R^{1/n}$ model), and they noted that there is also a strong (absolute magnitude, M)–(Sérsic index, n) relation. Immediately following this, D'Onofrio et al. (1994) showed that the same behavior was present among the early-type galaxies in the Fornax cluster.

In something of a pioneering effort, Davies et al. (1988) had actually already revealed the suitability of the $R^{1/n}$ model for describing the distribution of star light in dwarf early-type galaxies, and Cellone et al. (1994) and Young and Currie (1994, 1995) further showed the applicability of this model for dwarf galaxies. Davies et al. (1988) was not the only paper that appeared before its time. For example, Sparks (1988) had provided equations for the 'seeing' correction, and Ciotti (1991) had derived expressions for the associated internal density and dynamical profiles of Sérsic's model.

Helping to seal the versatility of the Sérsic model, Andredakis et al. (1995) revealed that it can be used to quantify the distribution of light in the bulges of disc galaxies, and Graham et al. (1996) showed its suitability for brightest cluster galaxies, and revealed a continuous M–$R_{\rm e}$ relation from dwarf to giant early-type galaxies. An often overlooked importance of the paper by Andredakis et al. (1995) is that they took Sérsic's model in a new direction. Because it was not yet recognised just how many early-types galaxies consist of a bulge and a disc, and thus many were thought to be single component systems by Caon et al. (1993), their light was effectively modelled as a single component system, which was admittedly the intention of Sérsic. However, Andredakis et al. (1995) taught us that we can, and should, model the bulge component with a Sérsic function while simultaneously modelling the disc with an exponential function.

Additional studies in the 1990s showed the benefit of replacing the $R^{1/4}$ bulge model with the $R^{1/n}$ bulge model (e.g., Heraudeau and Simien 1997; Iodice et al. 1997, 1999; Schwarzkopf and Dettmar 1997; Seigar and James 1998; Wadadekar et al. 1999). This eventually led to the realisation that most bulges in early-type disc galaxies have $n < 4$, and that the luminosity of the nuclear star clusters which they house correlates with the luminosity of the bulge (Balcells et al. (2003), see also Graham and Guzmán (2003) for the elliptical galaxies). The notably lower bulge luminosities, no longer obtained with $R^{1/4}$ models (e.g., Graham and Worley 2008; Laurikainen et al. 2005), also correlates well with the mass of the central supermassive black holes that they harbour, and the various bulge-(black hole) scaling relations have recently been reviewed in Graham (2015).

It should perhaps be noted that acceptance of the $R^{1/n}$ model (for which readers can find a review in Graham & Driver 2005) was not as smooth as described above. After all, the $R^{1/4}$ model had been so ingrained that it was referred to as the $R^{1/4}$ "law", and observers would actually adjust the local sky brightness of their image so that it resulted in the best possible $R^{1/4}$ profile for their early-type galaxies (e.g., Tonry et al. 1997; see also the "7 Samurai" team data from Burstein et al. (1987) as presented in D'Onofrio et al. (1994), their Fig.4). Healthy challenges to the $R^{1/n}$ model persisted, until about the middle of the first decade of this century. Not surprisingly, some argued that proponents of the $R^{1/n}$ model had got the sky-background wrong and that everything was $R^{1/4}$ after-all, or that if they did have the sky-background correct then it was the combination of an $R^{1/4}$-bulge plus an exponential-disc that was producing the $R^{1/n}$ profile, or that multiple $R^{1/4}$ profiles superimposed on each other were effectively responsible for producing the observed $R^{1/n}$ profiles. Indeed, and to add a small anecdote, just a little over a decade ago, in 2003 when the author applied for research funding in the USA, both Caon et al. (1993) and the author's own work with the Sérsic model were collectively dismissed as a "small cottage industry". The anonymous referee went on to write that from the author's papers which had used the Sérsic model "it is apparent that he is going down a rather slippery slope where science is ignored, and personal choices dominate", before rejecting the application to advance Sérsic's model.

For those who may be interested in reading further about the development of Reynolds' model (e.g., Oemler 1976; Rood et al. 1972, and the rise of de Vaucouleurs (1948a,b)) $R^{1/4}$ model, its generalisation by Sérsic (Sérsic 1963) half a century ago to give us the $R^{1/n}$ model, and the introduction of a partially-depleted core[5] a decade ago to give the core-Sérsic model (Graham et al. 2003) these topics are detailed in the review of galaxy structure by Graham (2013). In careful studies today, a range of stellar components (e.g., bulge, inner bars, outer bars, nuclear star clusters, large scale discs, rings, etc.) are routinely fit with their own separate model, which makes sense given the different formation paths that built each of these components.

Theorists have also developed a large array of internal density profiles since Plummer (1911), including popular models by King (1962, 1966); Jaffe (1983);

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[5]The centres of massive spheroids have long been known to be depleted of stars (e.g., King and Minkowski 1966, 1972; Young et al. 1978), which is likely due to the scouring action of super-massive black holes after a galaxy collision and merger with another galaxy also containing a super-massive black hole (Begelman et al. 1980).

Hernquist (1990); Dehnen (1993); Navarro, Frenk & White (NFW, Navarro et al. (1996)); Prugniel and Simien (1997) and the somewhat resurrected[6] model of Einasto (Einasto (1965), written in Russian). As described in Graham et al. (2006), Einasto's 3-parameter model has exactly the same functional form as Sérsic's model, but it was independently developed to describe internal density profiles rather than projected, surface-density profiles.

Is it possible to give a physical meaning to the empirical models used to fit the light profiles?

In regard to the $R^{1/4}$ model, de Vaucouleurs (1953b) wrote that "for all their diversity, they [elliptical galaxies] are but nature's variation of a single theme—the expression of a universal law governing some types of large aggregations of matter". It may not be important how the matter in elliptical galaxies is assembled, because some over-arching law of physics ultimately shapes and stabilises their density profile. In the early 1990s Gerald de Vaucouleurs wrote to the author that the dissipationless N-body simulations of a cold collapse, as expressed through the work of van Albada (van Albada (1982), and references therein), seems to offer clues to this.

Although almost all of the models mentioned above were developed without a valid physical framework,[7] there have been a couple of papers which offer a potential explanation for the Sérsic model. Hjorth and Madsen (1995) have shown how galaxy mergers without star-formation, coupled with the physics of violent relaxation (Hénon 1964; King 1966; Lynden-Bell 1967), will generate galaxies with a range of light profile shapes (see also Farouki et al. 1983 which generated a greater range in profile shape than (van Albada 1982)). In a series of papers (Gerbal et al. 1997; Lima Neto et al. 1999; Márquez et al. 2001) it has been suggested that the maintenance of the quasi-constant specific entropy during the post violent-relaxation stage of galaxy mergers will naturally produce a range of light-profiles whose shape/curvature depends on the mass of the system.

Cen (2014) has also speculated that, for isolated galaxies which have not experienced merging events, their range in bulge/disc structures may be connected with the random Gaussian fluctuations in the early cosmological density field that gave rise to the individual galaxies. However the changes in galaxy concentration (or global Sérsic index)[8] associated with this varying bulge-to-disc flux ratio are more connected with the concentration class of the simplified Yerkes classification system (e.g., Morgan 1962), which has no relation to the varying Sérsic index within spheroids of differing masses. As such it is not discussed further here.

[6]Navarro et al. (2004) and Merritt et al. (2005, 2006) showed that the 3-parameter Einasto model describes simulated dark matter halos better than the 3-parameter, generalised NFW model.

[7]The one exception is King (1962, 1966) model for globular clusters, although it does not provide an optimal description to the observed luminosity distributions in galaxies.

[8]The Sérsic index varies monotonically with the central concentration of light (Trujillo et al. 2001).

Can we distinguish between families of galaxies on the basis of their light profiles?

No. Further information is required. Although it has been common practice over the past decade for *Sloan Digital Sky Survey* (SDSS: York et al. 2000a) papers to bin galaxies into late-type or early-type based on their Sérsic index (e.g., Shen et al. 2003; Shimasaku et al. 2001), the SDSS galaxy samples are dominated by bright galaxies. However, *both* disc-dominated galaxies and low-luminosity early-type galaxies can have exponential light profiles (Binggeli et al. 1984; Faber and Lin 1983). That is, a spiral galaxy and a dwarf elliptical galaxy can both have light profiles that are well described by a Sérsic index of 1. In fact, most spiral galaxies (bulge plus disc) and dwarf early-type galaxies ($M_B < -18$ mag) have Sérsic indices $n < 2$. Therefore, the separation of galaxies into the late-type bin if they have $n < 2 - 2.5$, and into the early-type bin if they have $n > 2 - 2.5$ can be problematic, depending on how far down the luminosity function the galaxy resides.

The analysis of light profiles, while definitely a worthy endeavour, can be a tricky business. Indeed, much of the community were fooled for decades into believing that pure, pressure supported elliptical galaxies are far more common than they really are. While large scale stellar discs can be seen in lenticular galaxies when the orientation of the disc is close to edge on to our line-of-sight, they cannot be seen in images when the disc is somewhat face-on. While the literature is sprinkled with careful imaging studies that managed to identify the two component bulge+disc nature of some light profiles belonging to lenticular galaxies that were previously thought to be elliptical galaxies (e.g., Capaccioli 1987, 1990; Capaccioli et al. 1990; Carter 1987, and references therein), it was really the advance of kinematical information which uncovered the widespread extent of large scale stellar discs. For example, while D'Onofrio et al. (1995) discovered rotating discs in 6 of the 9 galaxies in their Fornax cluster sample that were previously classified as elliptical galaxies, Graham et al. (1998) extended this by reporting that only 3 of the brightest dozen galaxies in the Fornax cluster that had previously been classified as elliptical galaxies were actually true pressure supported systems with the other galaxies containing discs and bars. They wrote that "the true number of 'dynamically hot' stellar systems is much lower than previously thought", supporting the early conclusion by Nieto et al. (1988) that at least 30 to 50 % of 'elliptical' galaxies must have a disk based on the kinematical information they had compiled. Surveying a much larger number of galaxies, the ATLAS^{3D} survey (Cappellari et al. 2011) used the SAURON two-dimensional spectrograph on the William Herschel Telescope in the Canary Islands to learn that most early-type galaxies contain large scale rotating discs (Emsellem et al. 2011). It is basically just the giant elliptical galaxies with depleted cores that do not contain large scale, rotating stellar discs. Therefore, binning galaxies into the elliptical class or the disc galaxy class can require a certain level of finesse when analysing light profiles alone, as the discs can be missed.

Finally, simply plotting some galaxy parameter X versus galaxy parameter Y, extracted from a model fit to the light profiles from a sample of galaxies, can be highly misleading if one does not properly understand what X and Y actually represent. Through our knowledge of how the radial concentration of stellar light—

as quantified by the Sérsic index—changes systematically with total luminosity and mass, we have gained great insight. Many relations are linear or log-linear when including bulges or galaxies spanning from $n < 1$ to $n > 4$, such as the mass-metallicity relation or the related colour-magnitude relation (e.g., Terlevich et al. 2001), the magnitude-(velocity dispersion) relation (e.g., Kourkchi et al. 2012a; Matković and Guzmán 2005), or the magnitude-Sérsic index relation (e.g., Caon et al. 1993; Graham and Guzmán 2003, and references therein). On the other hand, the distribution of galaxies in diagrams involving the "effective" parameters are curved. While elliptical galaxies or bulges with a Sérsic index $n < 2$ follow one branch of the curve, those with $n > 2$ follow a different branch. However this does not mean that the concentration of the light profile, i.e. the Sérsic index, can be used to identify distinct families of galaxy, such as dwarf elliptical versus ordinary elliptical galaxies, or pseudo-bulges versus classical bulges. All it tells us is that the 50 % radius R_e, and its associated surface brightness μ_e, do not scale linearly with absolute magnitude. Different radii scale linearly with absolute magnitude (e.g., Forbes et al. 2008 their Fig.3), and for over a decade I have thought that it might be helpful if we consider additionally using these to avoid creating false dichotomies between galaxies.

Would you discuss what have been in your opinion the main advantages and drawbacks of these studies?

As with Hubble's modification of Reynolds' model, de Vaucouleurs' $R^{1/4}$ model similarly contains two scale parameters. As noted before, there is a scale radius known as the "effective half light" radius R_e which contains half of the model's light, and the "effective surface brightness" μ_e at this radius provides a calibration to the light profile's flux. One of the primary advantages that these simple 2-parameter models provide is just that, they enable astronomers to quantify how big and bright galaxies are. This in turn allows astronomers to perform objective comparisons between galaxies and thereby explore possible connections, and to develop evolutionary theories which quantitatively match real galaxies. It should however be noted that we were recently reminded by Harris et al. (2014) that care is needed when measuring the effective radius: individual galaxies have been reported to have a remarkably large range of values by different authors. Obviously this also results in a large range of effective surface brightnesses reported for the same individual galaxies.[9] However, of greater concern is that the use of these two simple scale parameters has contributed to a widespread, fundamental, misunderstanding of galaxy structure, which is undoubtedly a major drawback of these models.

Although most researchers have now adopted the $R^{1/n}$ model, which removes the systematic biases introduced from force-fitting a profile that does not follow the

[9]As an aside that may be of interest to some readers, the error made in measuring R_e is fortuitously counter-balanced by the associated error in μ_e in such a way that the Fundamental Plane (Djorgovski and Davis 1987) remains thin for bright early-type galaxies (Capaccioli et al. 1992b), their Fig.6́6; Trujillo et al. (2001), their section 4). The Fundamental Plane is the tangent sheet to a curved manifold on which dwarf and ordinary early-type galaxies reside, as noted in Graham (2005).

$R^{1/4}$ form (e.g., Brown et al. 2003; Trujillo et al. 2001, many researchers overlook (the significance of) the third parameter n. A key benefit / advantage of the $R^{1/n}$ model is that this third parameter reveals a continuity from dwarf to giant early-type galaxies. A major drawback is that without a proper appreciation of what this means for galaxy structure, the use of R_e and μ_e continues to contribute to the disunity of both bulges and early-type galaxies across their mass spectrum due to apparent bimodal distributions in diagrams involving these parameters (a topic reviewed in Graham (2013, 2014)).

The last years have seen a large debate on the bimodal distribution of early-type galaxies in several observational diagrams involving the photometric parameters of galaxies. Many researchers believe that this behavior is due to a different formation mechanism active in the various galaxy families. You do not believe in this interpretation. Could you explain why? Which is your alternative idea?

There are two main parameter diagrams which led to the belief that different formation mechanisms must operate for early-type galaxies brighter and fainter than $M_B = -18$ mag; giving rise to the alleged dichotomy between dwarf and ordinary early-type galaxies. I will start with the (absolute magnitude, M)–(central surface brightness, μ_0) diagram, then I shall progress to the (effective half light radius)–(effective surface brightness) diagram, showing that neither of them are evidence for the claimed dichotomy or different formation mechanisms.

Perhaps the most cited article advocating this dichotomy between dwarf and ordinary early-type galaxies is Kormendy (1985). Graham and Guzmán (2003) challenged this claim and the story, involving the M–μ_0 diagram, is as follows.

At absolute magnitudes fainter than $M_B \approx -20.5$ mag, the M–μ_0 relation was previously considered linear (e.g., Caldwell 1983; his Fig.6). Furthermore, Binggeli et al. (1984; their Fig.11) had revealed that there was a linear M–μ_0 from $-12 > M_B > -23$ mag, when using the inward extrapolation of King models fit outside of the core region of early-type galaxies. Kormendy (1985; his Fig.3) subsequently produced an M–μ_0 diagram which displayed two disconnected distributions nearly orthogonal to each other (see Fig. 4.22 for a representation). In one distribution he had the 'spheroidal' galaxies ($-13 > M_B > -17$ mag) which he felt connected to the dwarf spheroidal galaxies ($M_B > -13$ mag), and in the other distribution he had the elliptical galaxies ($M_B < -19$ mag). He advocated that very different formation processes must be responsible for these two very different distributions, and that $M_B = -18$ mag denoted the demarcation point between dwarf early-type galaxies (which he calls dwarf spheroidal galaxies) and ordinary early-type galaxies. It should be noted that Kormendy (1985) had constructed an M–μ_0 diagram with a sample that was missing galaxies with absolute magnitudes $M_B = -18 \pm 1$ mag. A dichotomy had been heralded, in an era when it was thought that dwarf early-type galaxies had exponential light profiles while ordinary early-type galaxies had $R^{1/4}$ light profiles.

A decade later, the self-named *Nuker team* (Faber et al. 1997; Kormendy et al. 1994; Lauer et al. 1995) were exploring the nuclear properties of a sample of predominantly ordinary early-type galaxies (i.e. $M_B < -18$ mag) with $R^{1/4}$ model

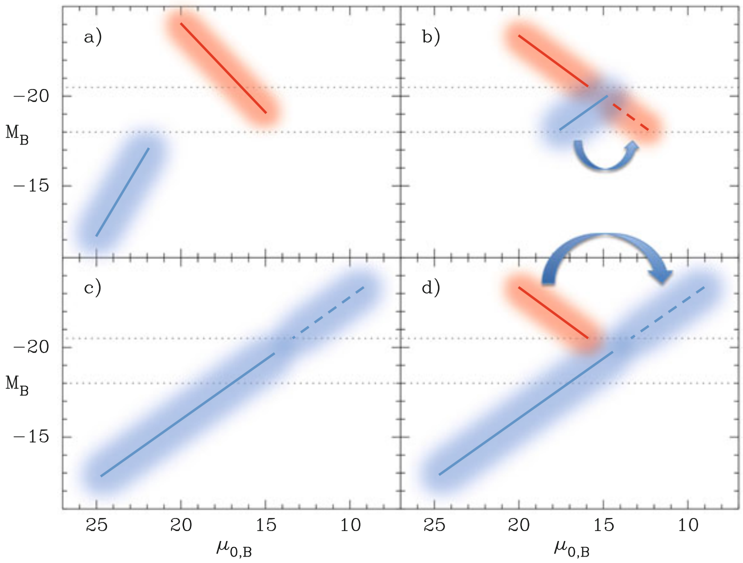

Fig. 4.22 *B*-band absolute magnitude versus central surface brightness. Panel (**a**) (Kormendy 1985) claims a dichotomy. Panel (**b**) (Faber et al. 1997) suggest that their 'power-law' galaxies should have brighter μ_0 than observed (to give the *dashed line*). Panel (**c**) (Jerjen and Binggeli 1997) note a continuous linear relation exists (see *dashed extension*) if the Sérsic model μ_0 is used (see also Binggeli et al. (1984)). Panel (**d**) (Graham and Guzmán 2003) note that the galaxies with depleted cores would have brighter μ_0 (see *dashed line*) prior to the depletion of their cores

parameters for the outer profile and their team's double power-law model used to describe the inner profile. Faber et al. (1997) showed and discussed how bright galaxies with shallow inner profile slopes have been depleted of stars in their inner region due to core scouring from the coalescence of supermassive black holes (Begelman et al. 1980). Their results are illustrated here in Fig. 4.22 panel b, where the central surface brightness (at $0''.1$) is seen to decrease as one moves to brighter magnitudes among the brightest galaxies. Adding to Kormendy's suspected division between galaxies with $M_B < -18$ mag and those fainter than this, Faber et al. (1997) wrote that they suspected that at absolute magnitudes fainter than $M_B \approx -20.5$ mag, the true central stellar density continues to *increase* as the absolute magnitudes get fainter, thereby preserving the linear relation which Kormendy (1985) had found for galaxies brighter than $M_B = -18$ mag (Faber et al. 1997; their Fig.4c). They used the nucleated, compact elliptical galaxy M32 to support this. They suggested that the observed systematic dimming of central surface brightness, as they inspected galaxies with absolute magnitudes fainter than $M_B \approx -20.5$ mag, was mainly an artifact of spatial resolution, and if we were closer to the galaxies then we would measure brighter and brighter central surface brightnesses in fainter and fainter (ordinary) early-type galaxies (Fig. 4.22 panel b, at least until $M_B = -18$ mag). However, excluding additional nuclear components such as the one in M32 (a practice advocated and largely followed by the Nuker team, e.g., Byun et al. (1996), fainter than $M_B \approx -20.5$ mag, the central surface brightness of early-type galaxies decreases as the absolute magnitude decreases (e.g., Drinkwater et al. 2001; Hilker et al. 2003; Karick et al. 2003). The data in Faber et al. (1997) did however no longer have a sample selection gap such that there was 2 mag of disconnect between the dwarf and ordinary early-type galaxies (as in Kormendy (1985)). The second improvement was that the connection between their galaxies with and without partially depleted cores now occurred at the bright end of the distribution (cf. Fig. 4.22 panel b with panel a).

In the same year, Jerjen and Binggeli (1997) pointed out that if one inwardly extrapolates the outer Sérsic profile of elliptical galaxies, over the partially depleted cores observed in the massive galaxies, and under the additional nuclear star clusters seen in the less massive galaxies, then there is a linear relation between the absolute magnitude of the galaxy and the central surface brightness[10] (see also Jerjen et al. (2000)). This unbroken, linear relation (see Fig. 4.22 panel c), which had effectively been seen in Binggeli et al. (1984), unifies the dwarf and giant elliptical galaxies and reveals a commonality behind the physics of their formation, as does the linear M–n relation (Caon et al. 1993). It is galaxies with depleted cores that follow a distribution in the M–μ_0 diagram which departs from the distribution followed by the fainter galaxies that do not have depleted cores, Kormendy (1985) had concluded that there are two distinct species of galaxy. However, as shown and discussed in Graham and Guzmán (2003), see also Côté et al. (2007) and Dullo and Graham (2014), there is no transition at $M_B = -18$ mag in this diagram. Rather, the departure which occurs at $M_B \approx -20.5$ mag is due to the early-type galaxies with partially depleted cores (Fig. 4.22 panel d). That is to say, there is a continuous, unifying relation for the so-called dwarf elliptical galaxies ($-13 > M_B > -18$ mag) and ordinary elliptical galaxies ($-18 > M_B > -20.5$ mag), as was shown by Caldwell (1983); Binggeli et al. (1984); Bothun et al. (1986), and others. They are not distinct species of galaxy.

This brings us to the second diagram which has been used to claim a dichotomy between dwarf and ordinary galaxies: the μ_e–R_e diagram. While in the past, the central surface brightness of the spheroid was not usually measured due to complications with seeing, image saturation, or additional nuclear components, the Sérsic index was even less likely to be reported as it was felt by many that early-type galaxies followed the $R^{1/4}$ law. Compounding the misconception about a divide between dwarf and giant early-type galaxies was a lack of appreciation for how systematic changes in the Sérsic index, with absolute magnitude, affect the half light radii and associated surface brightnesses.

In passing from the M–μ_0 diagram to the μ_e–R_e diagram, it is helpful to review the (absolute magnitude, M)-size (M–R) diagram. The M–R relation was originally linear (e.g., Oemler 1976; Strom and Strom 1978), and it still is when a faint

[10]Using the Sérsic model, rather than the inner power-law of the Nuker model, gives finite central surface brightnesses at $R = 0$.

isophotal radius is used (likely related with the virial radius or the radius enclosing a fixed over-density relative to the background universe). This linear relation can be seen in Forbes et al. (2008) (their Fig. 3), van den Bergh (2008), and Nair et al. (2011). However, things were to change with the wide-spread up-take of the $R^{1/4}$ model's 50 % parameter R_e which started in ernest during the late 70s. The issue is not that R_e was derived from a model that was fit to the light profile, the same issue exists with model-independent derivations of the half-light radius. The problem is that there is simply nothing physical about R_e other than it contains half of a galaxy's light. Now *if* the $R^{1/4}$ model was universal and there was thus structural homology, then the ratio of R_e to some actually physically meaningful radius, such as the virial radius, would be equal the same constant factor for all galaxies. If that was the case, then it would not really matter that R_e itself is not physically meaningful, because there would just be a constant factor involved. However, galaxies do not all follow the $R^{1/4}$ profile, and as such R_e remains a physically unimportant, and (crucially) highly misleading, quantity. Although a thorough discussion of this point is beyond the scope of this interview, the impact of using R_e, and the surface brightness associated with this radius, can be presented. What follows is not meant to be an argument to abandon the use of R_e and μ_e, but rather an attempt to foster a greater understanding of these two terms and why they result in curved scaling relations that do not imply different formation processes must be at play.

Although Caon et al. (1993) and D'Onofrio et al. (1994) stimulated a breakthrough in how we study galaxies, Caon et al. (1993) looked for, but did not find, convincing evidence for a divide at $n = 4$ in the $n-R_e$ diagram. They did so because they wanted to see if it could be associated with an apparent divide at $R_e = 3$ kpc which had previously been advocated by Capaccioli et al. (1992a, 1993)[11] to separate the faint from the ordinary early-type galaxies which follow different arms of the curved μ_e–R_e distribution.

Plotting $\log R_e$ versus μ_e, Kormendy (1977) had shown that a sample of ordinary early-type galaxies roughly follow a linear relation which now bears his name. Including many more early-type galaxies, in particular fainter ones, Capaccioli et al. (1992a) (their Fig.4) had shown that the full distribution is remarkably bent or curved, so much so that there appears to be two relations which meet at $R_e = 3$ kpc (or $M_B = -19.3$ mag). In a sense, it appeared that Capaccioli et al. had discovered a second relation in the μ_e–R_e diagram. Now, why do I claim that this diagram does not reveal a division in terms of distinctly different formation processes between bright and faint early-type galaxies? The reason is that the impact of a varying Sérsic index on the half light radii and associated surface brightness needs to be realised, which is the issue I raised before and will address here.

[11] It should be noted that some of the evidence collated by Capaccioli et al. (1993), their Fig.3 does support a division, although not at $R_e = 3$ kpc and $M_B = -19.3$ mag, but rather a division at larger $R_e = 6$–8 kpc and brighter $M_B \approx -20.5$ mag, between galaxies with and without partially depleted cores.

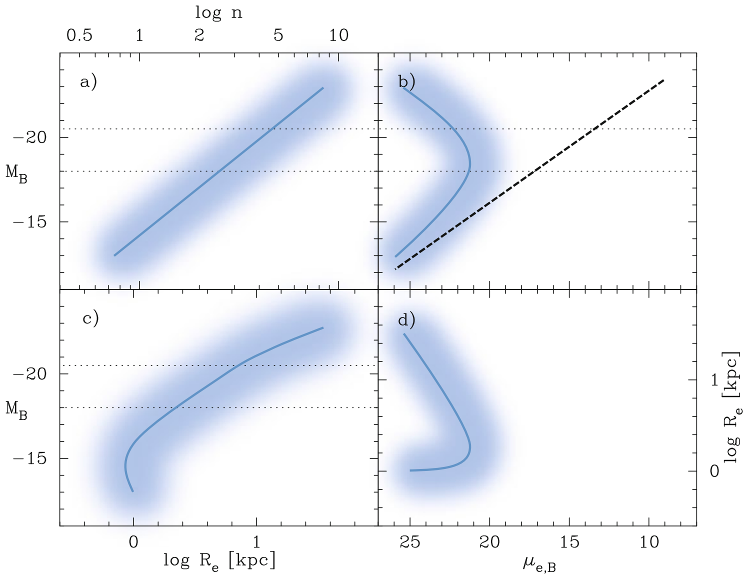

Fig. 4.23 The linear relations in panel (**a**) and Fig. 4.22 panel c (shown here by the *dashed line* in panel (**b**) map into the curved relations shown in panels (**b**), (**c**) and (**d**). The maximum curvature appears near $M_B = -18$ mag and $R_e = 2$ kpc, creating the false impression of a dichotomy. See text for details

What Sérsic's model eventually revealed is that elliptical galaxies, and the bulges of disc galaxies, do not all have the same stellar distribution after normalisation by the 50 % scale parameter for the radius R_e and the associated surface brightness μ_e. Instead, a range of light profile shapes exist. The *curvature* of these light profiles is quantified by the Sérsic index n, which is known to vary systematically with the absolute magnitude M (see Fig. 4.23 panel a). As such, due to these variations in the radial concentration of light, the difference between the central surface brightness, $\mu_0 \equiv \mu(R = 0)$, and the effective surface brightness, $\mu_e \equiv \mu(R = R_e)$ varies smoothly and systematically with the galaxy luminosity (because the luminosity varies with n). The difference is given by the expression $\mu_0 = \mu_e - 2.5b/\ln(10)$, where $b \approx 1.9992n - 0.3271$ for Sérsic indices $0.5 < n < 10$ (Capaccioli 1989), giving $\mu_0 \approx \mu_e - 2.171n + 0.356$. Now because the M–μ_0 relation is linear (when extrapolating under additional small nuclear components and over partially-depleted cores; Fig. 4.23 panel d), while M varies linearly with the *logarithm* of the Sérsic index,[12] the M–μ_e relation is curved (Fig. 4.23 panel b; see Graham and Guzmán 2003 for more details). This curvature in the M–μ_e diagram does not imply different formation processes at the bright and faint ends. Remember, the M-log n and M–μ_0

[12]Recall that $1/n$ is the exponent in the Sérsic model.

relations are linear, requiring the same physics to operate at the bright and faint ends.

It is worth repeating this key point. While there is a linear relationship between the absolute magnitude of early-type galaxies and the *logarithm* of their Sérsic index (e.g., Caon et al. 1993; Graham and Colless 1997; Jerjen and Binggeli 1997; Young and Currie 1994), and between their absolute magnitude and their (non-depleted) central surface brightness (e.g., Jerjen and Binggeli 1997), the varying Sérsic index results in a highly non-linear relation between the absolute magnitude and the effective surface brightness ((Capaccioli et al. 1993; their Fig.2b; Fig. 4.23 panel b)). Had the $R^{1/4}$ and $R^{1/n}$ models been expressed in such a way that R_e corresponded to the radius enclosing say 90 %, rather than 50 %, of the total light, the curvature in the M–μ_e diagram would look very different. The point is, this curvature is artificial; it has no relevance to the formation physics. This is what I was getting at before when I noted that simply plotting X versus Y can be highly misleading if one does not properly understand galaxy structure and what X and Y are. For the same reason, i.e. due to what is referred to as structural non-homology, the relation between the absolute magnitude and the logarithm of the effective radius is also non-linear (see Graham and Worley 2008, their section 5.3.1 for a derivation of this; shown here in Fig. 4.23 panel c). In fact, every relation involving half light radii and the associated surface brightnesses are non-linear, including the μ_e–R_e relation (Capaccioli et al. 1992a; Graham 2013; his Fig.10; Fig. 4.23 panel d).

The location of greatest curvature in diagrams using the 'effective' 50 % parameters occurs at a Sérsic index of around 2 to 2.5 and an absolute magnitude $M_B \approx -18$ to -19 mag. Not surprisingly, this is, in part, responsible for the alleged dichotomy between dwarf and ordinary elliptical galaxies and also the alleged dichotomy between pseudo-bulges and classical bulges (see Graham 2013, 2014 and references therein for a discussion). While massive early-type galaxies have larger sizes than dwarf early-type galaxies, there is a continuity which is tracked by the Sérsic index. Just as human beings come in a continuous range of heights and masses, one can introduce an artificial divide between children and adults at say 18 years of age, but children and adults are not distinct species. Similarly, the alleged divide at $M_B = -18$ mag ($n \approx 2$–2.5) is artificial. There is (i) a linear M–$\log n$ and (ii) a linear M–μ_0 relation which both span the alleged divide at $M_B = -18$ mag. Further independent evidence of a continuity rather than a dichotomy at $M_B = -18$ includes (iii) the linear colour-magnitude relation and (iv) the linear magnitude-(velocity dispersion) relation stretching across the claimed demarcation magnitude. Furthermore, (v) the presence of large scale stellar discs in early-type galaxies on either side of the alleged divide, and (vi) the similar occurrence of kinematical substructure (e.g., Caon et al. 1990; Emsellem et al. 2011; McDermid et al. 2006; Toloba et al. 2015, 2014) reveals that these galaxies have experienced the same formation/growth processes. One thus has four linear relations uniting galaxies across the alleged divide at $M_B = -18$ mag, and curved relations whenever half-light parameters—which have no physical significance—are used. Three of these linear relations show a break at $M_B \approx -20.5$ mag such that in brighter galaxies the central surface brightness is depleted (e.g., Faber et al. 1997; Graham and

Guzmán 2003), the colour remains constant (Tremonti et al. 2004), and the velocity dispersion no longer rises as steadily with luminosity (e.g., Matković and Guzmán 2005). All of these three patterns are consistent with dry galaxy merging involving supermassive black holes, rather than a dwarf/ordinary early-type galaxy dichotomy. Furthermore, the actual curved relations involving μ_e and R_e would look different if the radius enclosing say 10 % or 90 % of the galaxies' light was used.

Kormendy et al. (2009) has taken to colour coding the data in diagrams involving the half light parameters to highlight his ongoing view that early-type dwarf galaxies are distinct from, and experienced a dramatically different formation process than, ordinary early-type galaxies. He additionally includes the rare compact elliptical galaxies, which were previously thought to have $R^{1/4}$ light profiles but are now considered to be stripped disc galaxies (e.g., Bekki et al. 2001; Graham 2002; Nieto 1990), and which overlap with the location of bulges in these parameter diagrams (Graham 2013; his Fig.1). Together, this creates the impression that the compact elliptical galaxies are the faint end to the distribution of ordinary elliptical galaxies brighter than $M_B = -18$ mag, and that the elliptical galaxies fainter than $M_B = -18$ mag are a separate and distinct population because they follow a different arm of the curved relations involving μ_e and R_e. The apparent deficit of early-type galaxies in his Virgo cluster data at around $M_B = -18$ mag does not help the situation; this dip in the early-type galaxy luminosity function is not seen in other clusters (e.g., Capaccioli et al. 1992a; their Fig.2) and it may not exist in the more complete Virgo cluster data set (Graham 2005; his Fig.4).

Looking to the future, much of the action and money has left the local universe, with many astronomers now funded to quantify the distribution of star light in intermediate- and high-redshift galaxies. Doing so correctly will enable astronomers to explore the evolution of galaxies across a significant fraction of cosmic time. However, we need to be careful not to repeat the same mistakes made when studying the local universe. Early-type galaxies do not all have $R^{1/4}$ profiles, and the use of $R^{1/4}$-bulge plus exponential-disc fits is similarly inappropriate. Such fits result in systematic biases in the effective radii, surface brightness and magnitude. More importantly though, even when using the $R^{1/n}$ model (or model independent estimates of the half light parameters) there needs to be an understanding of what these parameters are. Given the recognition that galaxies typically consist of a range of components, we will also need to be careful to track the evolution of components, rather than galaxies as single entities, or potentially risk another decade or two of misunderstanding.

Up to now we have mainly addressed the problem of the scaling relations observed in early-type galaxies. The next interview to Brent Tully will concern one of the most famous scaling relations to which spiral galaxies seem to obey.

Questions for Brent R. Tully:
the Tully-Fisher (TF) relation was one of the first scaling relation demonstrating that the galaxy luminosity is correlated to the rotation velocity. Could you review the impact of this discovery and the development of these kind of studies? What is the physical meaning of the TF relation and which was

its origin? How the TF relation could be connected to the other scaling relationships?

To a first approximation, it is clear that there should be a correlation between the luminosity and rotation rate of a galaxy. More massive galaxies should have more stars and the motions within those systems should be greater. The tightness of the correlation was a surprise. My personal interest has been to measure distances to galaxies and the correlation gives us a powerful tool for this use. My concerns have been practical, related to divining how much scatter is intrinsic, as opposed to observational, and if intrinsic then for what reasons. Are there environmental or type variations and are they manifested in, say, colors or surface brightness?

These same issues interest other researchers for the more fundamental reason of trying to understand how galaxies form and evolve. It has been a challenge for modelers to get their simulations to resemble the real world, though by steps the situation is improving. Impressive spectroscopic observations with the largest telescopes are demonstrating that the luminosity-linewidth correlation sets in at high redshift. There are a variety of points of view on the matter. Other reviewers in this project might care to comment.

There is an aspect that particularly intrigues me. Two galaxies can be considered that have the same intrinsic luminosities and the same rotation rates. Yet one might be compact and high surface brightness while the other is extended and low surface brightness. To a remarkable degree, galaxies with these diverse properties cohabit the same space in a luminosity-linewidth plot. What is this telling us about galaxy formation?

4.12 To Summarize

In this Section we try to briefly summarize the main points addressed in the above interviews about the anatomy of galaxies, in particular after the WWII. Clearly. As the length of the Chapter suggests, the last seventy years have seen an explosion of data and theoretical efforts that have greatly impacted our knowledge of galaxies in all areas of Astrophysics. It follows that the list presented here is partial and should be considered a sort of vademecum *of the Editors of the most important progresses obtained in this field. In parallel, we provide a series of questions that in our opinion are still open today.*

According to the structure of the Chapter we believe that the following things, remarked in the interviews, need to be emphasized:

- *The nature of the central power source seen in many galaxies has been now robustly associated to the presence of a massive central object confined in a small region, probably a super-massive BH. The standard model of AGN has passed several tests and it is now widely accepted, although there are still many basic questions that have not found yet a definitive answer. Are all quasars similar?*

Are all sources of emitted radiation clearly understood? In which way quasars evolve? Are we sure of the existence of the event horizon?

- *The growth and evolution of the central black holes cannot be dissociated from the evolution of the galaxy as a whole. The discovery of the* $M_{SBH} - M_{bulge}$ *and* $M_{SBH} - \sigma$ *relations have opened this very important aspect of galaxy formation and evolution. However, whether the co-evolution of SBH and galaxies occurred at the same rate or not is still far from clear. Tracing the cosmic evolution of SBH is quite difficult, mostly for the different methods used to measure SBH masses and for the presence of selection effects and systematic biases.*
- *Large mass accretion are required to sustain the big luminosity of the AGN and dissipational processes are involved in the fueling of the central power source of galaxies. How this process occur is still not clear. Is the material feeding the SBH of internal origin, i.e. gas present in the ISM, or is it acquired from outside, e.g. from galaxy interactions? How the duty-cicle of AGN across the cosmic time can be reconciled with their feeding activity?*
- *Gravitational interaction produces a significant enhancement of the star formation rate in the disk and in the nuclei of galaxies. Interactions induces star formation and accumulation of a gas reservoir in the central region of a galaxy. This fact open some questions: to what extent galaxy evolution is influenced by gravitational interactions? Why bright nearby active quasars rejuvenated by recent mergers and strong tidal interactions are not seen?*
- *Nuclear activity is inhibited in the high density regions of the Universe. Here galaxies segregate according to the morphology-density relation. What are the mechanisms behind this behavior is not completely clear yet. A significant role is played by the sweeping of the gas away from the galaxies, either by the presence of an hot IGM and by gravitational interactions. However, the way in which galaxies transform their morphology is not fully understood yet.*
- *The origin of the bulge is still a matter of debate. After a first period in which the monolithic collapse model and the concept of stellar populations seemed to explain the origin of the spheroid and disk components, the situation is now more complex. The monolithic framework has been substituted by the hierarchical or semi/hierarchical scenario in which galaxies originate in a bottom up flow of merging events, and the concept of two main stellar populations replaced by the idea of multiple generations of star formation, even in the oldest stellar systems, like the GCs, where two or more main sequences have been detected. Bulges could originate not only from the collapse of the primordial galaxy, but also from instabilities of the disk component or from merging events.*
- *The disk component presents a number of unresolved issues. While it seems well established that disks are marginally stable at all radii and that there is a sort of balance between the star formation activity and the gravitational stability, it is not clear yet the way in which the whole disk was assembled. The inside-out scenario is not widely accepted. Gradients are explained by a combination of age and metallicity effects, but the presence of dust and the inclination to the line of sight complicate the picture and the entanglement among these actors, so that the properties of disks are always inferred from statistical studies. It is also poorly*

known what fraction of DM is contained in them and what originate the various luminosity profiles observed in disk objects.

- *Numerical models have clearly demonstrated that bars are the main instabilities in cold disks and that there are clear relationships between bars, rings and lenses, the typical substructures observed in disk galaxies. There are however a number of problems still unanswered connected to the length and speed of the bars, to the influence of the DM matter component, as well as of the bulge and halo components. It is also poorly known how much these structures depend on the environment and on the morphology of the host galaxy. In which way these structures contributed to the evolution of the galaxies? Why their presence in high redshift galaxies is low?*
- *The spiral pattern in galaxies occurs on different scales. On small scales the typical morphology is flocculent, while on large scale the pattern is more regular and often a grand design structure dominate it. The origin of this behavior has been a puzzle for several years, but today the density wave theory with self-excited modes is able to explain many properties of the spiral structure. Of course new theoretical and observational efforts are required to better understand the frequency of the observed patterns, the response of the cold gas interstellar component with respect to the stellar one, the role of tidal interactions and the influence of triaxial halos as well as of massive bulges and bars. A further problem comes from the numerical simulations in a cosmological context, which seems to favorite the flocculent morphology and the idea of spiral arms as transient phenomena.*
- *The last 20 years have seen the enormous development of the studies of the gravitational lensing phenomenon, either strong and weak. The applications of this Einstein' prediction have mainly concerned the measurement of the masses of the halos of the galaxies and that of the cluster of galaxies. Several cosmologically relevant data have also been obtained, last but not least that of the Hubble constant with a very small uncertainty. For what concern galaxy halos the strong gravitational lensing is very promising for studying the inner mass distribution of this component.*
- *A revival of interest is actually seen for the GC systems as tracers of the merging history of galaxies and for the recent discovery of multiple stellar populations inside them. This is only an example of the number of studies that will be dedicated to understand the galaxy halos in the near future.*
- *The HI and molecular gas provide precious information on the star formation activity of galaxies. This is particularly important for high redshift galaxies because these studies can reconstruct the history of star formation. While the HI content is regularly decreasing from late to early-type objects, this is not the case for the CO content. The cold gas is subject to dissipational processes and is extremely sensible to dynamical interactions. The empirical relation between gas density and star formation rate is tighter for the molecular gas than for the HI. The physics behind this relation is not yet understood. The depletion time, i.e. the time necessary to end the star formation, is connected with mass of the galaxies*

and their environment. This is the very popular problem of the "quenching" of the star formation that we will better analyze in Chap. 7.

- *The role of dust is fundamental to understand many properties of galaxies, such as their energetics, their structure and their physics. Historically the recognition of the role of this galaxy component was very slow and difficult. The presence of dust affect the spectral energy distribution of stars and could be at the origin of several biases in galaxy measurements. The origin of dust is still not completely understood. New high redshift observations have indicated their presence even at early epochs.*
- *Several X-ray satellite missions have greatly impacted our knowledge of the X-ray emission coming from galaxies. The main star contributors to the X-ray flux have been identified in the HMXB and LMXB in different proportion according to the galaxy types. They partially contribute to the hot and diffuse X-ray emission which surrounds many galaxies. The nature of this emission is still largely debated, as well as the related mechanisms of gas inflow and outflow that characterize many galaxies. The metallicity content of the hot gas is still a matter of controversy, as well as the way in which galaxies was enriched of metals in their halos. Last but not least the X-ray luminosity function appears connected with the star formation rate. This research area is very active also for the connection of the X-ray emission with the inner regions around the BHs, for the cosmological implications of the baryonic mass measurements and for the characterization of the ISM and IGM.*
- *Since the early eighty magnetic field are considered important galaxy components. They can be revealed from the linearly polarized radio emission. They exist on different scales. The large scale is often dominant in terms of emission and generally trace the trailing spiral patter between the arms. In E galaxies, where the rotation is small they cannot be observed. On smaller scale they can be found inside the spiral arms, but sometimes also in the spheroidal component and in the halo. The characterization of the magnetic field is highly demanding in terms of observation time since multi-wavelength data at different frequencies are required. Notably the strength of the field is connected with the star formation rate. Magnetic field affect dynamically the turbulent ISM and gas flows, e.g. in spiral arms, and they can transport the angular momentum. On the theoretical side the gross features of the large scale magnetic field are well understood by the dynamo theory, but on small scale there are still several problems.*
- *The astro-archeological approach in the study of the stellar populations has currently superseded the old idea of Baade of two main stellar populations. The way to address these studies, when the telescope resolution is sufficient, is now that of tracing the star formation history of galaxies, i.e. the convolution of the star formation rate and the initial mass function. Some problems however still exist in accurately reproducing single elements, such as e.g. Oxigen or Lithium. This is because the stellar yields are still poorly known. In general the time-delay model, which assumes that α-elements are mainly produced by short living stars, i.e. by core-collapse SNe, whereas Fe is produced on large range timescales as*

long as a Hubble time by Type Ia SNe in white dwarfs in binary systems, provides a good framework of reference for the interpretation of the data.

- *The origin of the scaling-relations of galaxies is only partially understood. In particular the small scatter observed in many some of them, e.g. the Fundamental Plane and the TF relations, is quite difficult to understand in a framework where galaxy merging is active since recent epochs. There is still an ample debate whether the Kormendy relation and the relationships connecting the absolute magnitude with R_e and $< \mu >_e$ do reflect the existence of different populations of early-type galaxies or not. At the same time it is not clear why two galaxies with the same luminosity and rotation rate cohabit the same region of the TF relation but could have completely different compactness. There is clearly some unknown physics behind these observed behaviors. Observers speak sometime of fine-tuning, because the dynamical and morphological structure of the galaxies seems linked to the stellar populations and star formation.*

The new era signed by the explosions of extra-galactic surveys will hopefully provides many answers to the open problems in this research area.

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Chapter 5
The Impact of Surveys

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Who Giants know, with lesser Men
Are incomplete, and shy
For Greatness, that is ill at ease
In minor Company

A Smaller, could not be perturbed
The Summer Gnat displays
Unconscious that his single Fleet
Do not comprise the skies
E. Dickinson Poems [796]

...nothing is great or little otherwise than by comparison...
J. Swift *The Gulliver's Travels*

5.1 Chapter Overview

Since the most ancient times astronomers felt the need to collect and list in atlases and catalogs all the visible objects in the sky. The first stellar catalog known in the western world being the one of Hipparchus (second century BC). We have to wait until Charles Messier at the end of the eighteenth century to have the first incidental *catalog of nebulae, i.e. including a mixture of fuzzy objects, nebulæ, that telescopes of the epoch could detect. In Chap. 1 we have already discussed the atlases and catalogs that soon after the discovery of galaxies appeared in the literature describing the properties of the nearby galaxies, in particular their morphologies in Chap. 3. The subject of extragalactic papers, during the photographic plate era, was one or few galaxies, whose properties were carefully scrutinized looking at all*

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the details resolved by telescopes in the optical waveband. This happens also today, of course, basically at all wavelengths. However, the impact of new technologies permits in the last two decades to tackle survey programs addressed to the study of specific extragalactic problems considering millions of galaxies.

These systematic investigations of enormous galaxy samples require dedicated observing, reduction and storing/retrieval facilities provided, in the Big Science era, *by international consortia. Data are treated in a statistically way, combining the multi-wavelength information coming from several instruments, scanning galaxy properties as a function of the redshift and of the environment. The big teams of scientists and engineers that has planned and built the instrumental facilities, including sometimes the telescopes themselves, are also charged of providing a nearly immediate access to the data, as well as their maintenance and calibration. The data are easy available through simple queries on the web. Usually one of the main step of these large teams is to build a catalog of the detected sources, providing the first measures typically obtained from automatic softwares of analysis. These data are then cross-correlated with other data available for the same sources in the web databases, possibly refined with better calibration. Relations between entries are evaluated and discussed at the light of theoretical models and simulations by members of the same team. Observations have the strong tendency to produce facts so models are refined and data-set revisited and/or integrated with new observations.*

This chapter is dedicated to galaxy surveys. It is even difficult to offer a complete overview of the enormous number of galaxy surveys today available and/or on-going. We interviewed scientists asking them to present the most significant surveys, in their view, in their area of scientific interest and to emphasize the main results obtained by the surveys that have seen their active collaboration.

Before entering the core of such discussion George Paturel will provide us in Sect. 5.2 a much clear idea of the efforts that are necessary to build a good galaxy catalogue and to homogenize the entries in a database. The information about the single galaxies are indeed so wide that a new concept of data managing has been developed: the Virtual Observatory (see Sect. 9.9). Since the beginning of the astronomical use of photographic techniques, big plates archives are preserved basically in all observatories. Thanks to their large field of view and easy storability, astronomers often re-used this patrimony over the time, e.g. to follow time variable phenomena or to inspect several different objects in the field of view of the plates. Along this line Virtual Observatories have been conceived for providing an easy retrieval of the multiple types of data available for individual objects.

In Sect. 5.3 Alessandro Boselli and Laura Ferrarese will characterize the galaxy environments that are coming out from the various sky surveys, dealing in particular with the Virgo and Fornax clusters, our closer biggest associations of galaxies. Then, in Sect. 5.3.1 Bianca Poggianti will draw the picture emerging from WINGS, the WIde field Galaxy cluster Survey, dedicated to the study of the nearby ($z < 0.07$) *galaxy clusters. Nils Bergvall (Sect. 5.3.2) and Valentina Karachentseva (Sect. 5.3.2) will present the properties of galaxies inhabiting the low density environments up to isolation. Martha Haynes and Riccardo Giovanelli will discuss the HI surveys in Sect. 5.4 and related subsections. Luciana Bianchi will introduce the UV surveys,* *with a particular emphasis for the results obtained by* `GALEX` *in Sect. 5.5.1. The most important IR and X ray surveys will be discussed by Alessandro Boselli and Ginevra Trinchieri respectively in Sects. 5.5.2 and 5.5.3. Finally, in Sect. 5.6 Jonathan Bland-Hawthorn and Bianca Poggianti will give a panoramic sketch of the main spectroscopic surveys.*

5.2 From the Sky to Databases

Questions for George Paturel:
You have contributed to the transition between the preparation of classical catalogs (RC3) and the implementation of first large digital catalogues and galaxy databases, e.g. `HYPERCAT`. May you trace the history of such transition? What is/will be the impact of surveys in the building of the next generation of galaxy catalogues (`LSST` will produce parameters for $\approx 10^9$ galaxies at different z)? May you discuss the homogenization strategies of galaxy parameters behind the preparation of large catalogues?

The evolution, from classical catalogues to modern databases can be seen as a series of steps. I'll describe some of them using my personal experience. I would like to comment on the technique of homogenization within this historical part. In this way, it will be easier to explain how very large catalogues have changed the homogenization step.

In the introduction of his famous Uppsala General Catalogue (UGC), the Swedish astronomer Peter Nilson recalls that Knut Lundmark dreamed, in 1930, of collecting and updating all known data on galaxies. Of course some catalogues existed, such as the Messier catalogue of nebulous objects or the not less famous New General Catalogue (NGC) by Dreyer (actually a compilation of observations by many astronomers, including Herschel's General Catalogue). Unfortunately these catalogues not only contained galaxies but all kinds of nebulous objects, such as star clusters or gaseous nebulae.

It is regrettable that Lundmark's dream didn't come true, because the scientific world was just entering an incredible new era with the discovery of the real nature of our Universe: a Universe of galaxies. How many hours of tedious research of data would have been saved if the project had started that early. How many duplication of efforts would have been avoided. Nevertheless, some catalogues of galaxies were published here and there. They were the seed of our present image databases. The databases themselves will probably be the seed of the future Virtual Observatory.

Let me reproduce part of one of the pioneer works: the first catalogue made by hand by Gérard de Vaucouleurs in 1952 (see Fig. 5.1). In his office, not only did Gérard de Vaucouleurs his handmade catalogue but he also had a long wooden box in which he gathered cards with a detailed description of bright galaxies. Sometimes the description was illustrated by a drawing. This box is the poor ancestor of our present image databases.

NGC	Type	m_H	β	$a \times b$	m'_H	Δm_1	Δm_β	m	m'	W	m_B	W_B	Remark
178		12.9	−77				0.01						= IC 39
185	Ep	11.8	−14	3.5′2.8	14.27	0.98	1.09	9.73	12.20	.07	10.1:	2.0	•
205	E5p	10.8	−20	8.0′3.0	14.25	0.98	0.67	9.15	12.60	.10	8.85	3.75	•
-				10.7′5.2	15.17	0.83		9.30	13.67	.16			
210	Sc	12.5	−76	4.5′2.5	15.12	1.01	0.01	11.48	14.10	.35			
214	S:	12.8	−37	1.1′0.7	12.52	0.05	0.23	12.52	12.25	.50			
221	E2	9.5	−22	2.6′2.1	11.35	0.11	0.58	8.81	10.66	.10	9.05	5.25	= M32 •
-				3.8′3.0	12.15	0.23		8.69	11.34	.20			
224	Sb	5±	−21	160′40	14.5:	0.78	0.62	3.6:	13.1:	.07	4.00	3.5	= M31 •

Fig. 5.1 The first catalogue by Gérard de Vaucouleurs: A revision and homogenization of the Harvard catalogue. New series of magnitudes from Hubble, Whitford, Stebbins, Redman and Bigay are included after reduction to a homogeneous system m. The standard magnitudes m_B are given (if any) with their weight W_B. The dimensions of each galaxy are noted $a \times b$. The mean surface brightnesses are noted m'. The galactic latitude is β

Images are essential for the identification of galaxies using simultaneously, coordinates and a few geometrical parameters (e.g., if the studied galaxy is seen edge-on, it will not be misidentified with a face-on galaxy, even if their coordinates are not discriminating). The first step that lead us to the modern time came from the photographic survey covering the whole northern sky and a large part of the southern one, down to −40° of declination. This survey was conducted around the years 1950–1960, with the Palomar Schmidt telescope. Each plate covered a large field of six by six degrees. About 2000 plates were necessary. Later, the European Southern Observatory (ESO) covered the southern hemisphere. Photographic copies on paper/film were sold all around the world. This further helped to draw up larger catalogues of galaxies, at the expense of great efforts.

In the Soviet Union, Vorontsov-Vel'yaminov and co-workers produced the *Morphological Catalogue of Galaxies* (MCG). 36,000 galaxies were measured: coordinates, internal and external major and minor axis diameters, estimate of magnitudes, morphological description with specific codes, and many notes describing the environment, such as small companion galaxies. What a tremendous work. How many students spent hours at this task? We must admit that the coordinates were not accurate (an error of many arc-minutes was common). Nevertheless, I remember to have used this catalogue many many times. A clear improvement started with the Swedish group: P. Nilson and A. Lauberts, when they published their catalogues for galaxies larger than 1 arc-min, with relatively precise coordinates. This is the result of a long Swedish tradition of research in extragalactic astronomy, after Knut Lundmark and Erik Holmberg.

As a young astronomer my first extragalactic study was the comparison of diameters of galaxies taken from different catalogues: UGC, MCG, the Bright galaxy catalogue (BGC) by de Vaucouleurs and the photometric catalogue by Holmberg. The definition of a galaxy diameter was somewhat unclear. To make a trivial comparison, it is like the diameter of a town. There is no clear limit except the legal one. This means that we must adopt a definition. De Vaucouleurs proposed to measure the external diameters of a galaxy at the brightness level of 25 magnitude flux per arc-sec square. In this way I learned how to reduce diameters from different catalogues to a same definition. This is what we shall call "homogenization". To perform it, we must simply have a sample obeying a clear definition (for diameters it was the catalogue by Holmberg). I discovered something else: *simple is efficient*. Indeed, I embarked on a program of isophotal measure of galaxy diameter that turned into a nightmare: 2 h of exposure for each galaxy with photographic plates on a 1.2 m telescope which meant many hours of calibration and reduction. After 1 year of such a tedious task, I had only a few good measurements. Comparing them with UGC measurements made directly on the photographic plates with a ruler, they were not much more accurate. Meanwhile, I learned from Gérard de Vaucouleurs that by inter-comparing three samples (i.e., computing the 2×2 dispersions σ_{ij}), one can retrieve the individual dispersion (σ_i) of each sample. This has been generalized to larger number of samples (Paturel and Petit 1999). This shows that the more data you have, the better the judgment on each source. This makes possible the calculation of weighted means with their individual mean errors. Another interest of such analysis comes from the fact that you can easily detect bad measurements (bad outliers). Let me give an example. If you have four radial velocities for a given galaxy (e.g., in km s^{-1}: 3100, 3080, 7200, 3110). It is obvious that $V = 7200$ km s^{-1} is wrong. Either the measurement is erroneous, or it does not belong to the considered galaxy. In both cases, this must be corrected. The mean is probably $V = 3097 \pm 9$ km s^{-1} (not 4123 ± 1026).

A new impulsion for us came from the discovery by Tully and Fisher (1977), that the HI[1] rotation velocity of a galaxy is directly correlated with its absolute magnitude (a logarithmic expression of intrinsic luminosity). This was suspected by some astronomers (Bottinelli et al. 1971; Gouguenheim 1969; Roberts 1962), but it was thought to be more complex. The clever idea by Brent Tully was to make a direct plot, without additional parameters, but with good data. I must say, that I admire Brent Tully very much for his efficiency. While I was spending time improving insignificant corrections, he made this major discovery, that definitively changed the calculation of extragalactic distances. It is important to open new fields of research. The detailed improvements should come afterwards.

After this astonishing discovery, we started to collect all HI data measurements. Indeed HI data provided us with both a measurement of the maximum rotation velocity W and the cosmological velocity V. From W one obtains the absolute magnitude of the galaxy through the Tully-Fisher relation, and then its distance d by comparing it with the apparent magnitude. Finally, one gets directly the Hubble

[1]Emission line of the neutral Hydrogen, on the rest wavelength $\lambda_o = 21$ cm

constant ($H = V/d$). This was our scientific target. The detail calculation is a little more sophisticated, but the principles are the same.

In January 1982, we sent a letter to all radio-astronomers in the world. We collected 121 papers and extracted the relevant data. I remember having measured the HI line width W directly on the publication, using an ordinary ruler (see Fig. 5.2). The scale was determined by measuring the tick marks on the same figure. My pocket calculator converted millimeters into the proper unit of width (km s^{-1}). Each line was measured at four levels, 0, 20, 40, 50 % of the maximum. I tried to measure with the best precision, nearly 0.3 mm. Imagine this: about 1800 HI lines to be measured at four levels: 7200 measurements! When the authors gave their own measurements a comparison was made. In one case the original widths significantly exceeded our measurements. It was traced by M.S. Roberts to a systematic error in a reduction program used at NRAO. I was proud of my ruler! To this day I keep it on my desk, to remember this hard work (see Fig. 5.2). Our catalogue of HI data was published in 1982.

Our catalogue was simply a big file (not so big when one considers the size of present hard disks). In the first three columns appeared the galaxy name (typically NGC number) and its two coordinates. When, we started to update it with new publications, we quickly encountered difficulties. Some authors used different names and sometimes poor coordinates. So we created more columns for alternative names from different catalogues: NGC, IC, MCG, UGC, ESO, etc. We discovered that a same galaxy may have several NGC numbers, or worse that a same NGC number may designate two different galaxies because of misidentification. For each

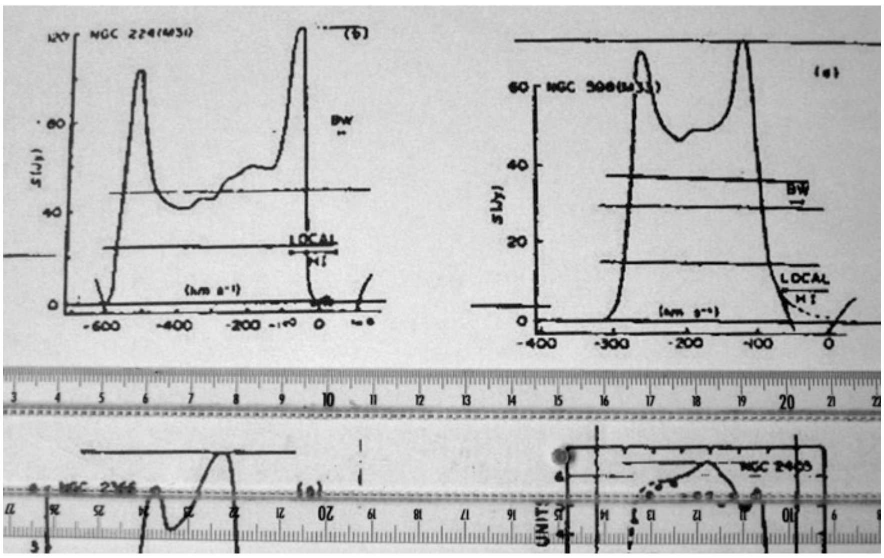

Fig. 5.2 The widths of HI lines were measured with a simple ruler. These line profiles are taken from the original paper by Tully and Fisher (1977)

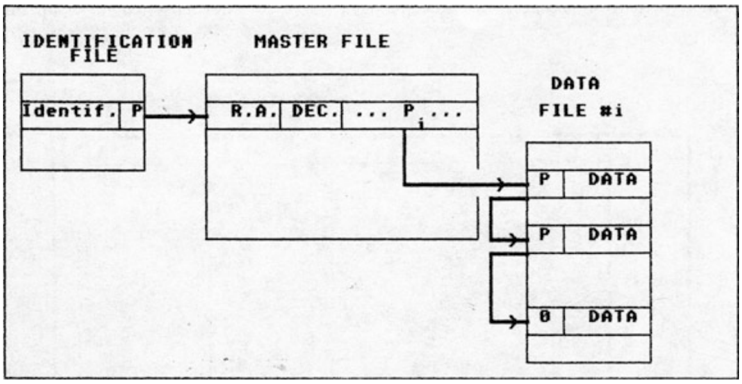

Fig. 5.3 Simple structure of our first database program

new galaxy added to the file we had to search into our compilation of galaxy names. Furthermore, some galaxies had many measurements of a given parameter. For instance, 31 radial velocities were given for NGC 224 and only 3 for NGC 15. It is not possible to create 31 blank columns for each galaxy just because NGC 224 has 31 radial velocity measurements. I first created a special structure of the file in order to optimize the disk-space but the management was very difficult. So, I started to dream of using a database.

I briefly explain what is a database. Instead of collecting measurements in a sequential file, one records them in an arbitrary order but each measurement receives a pointer telling where it is attached to (see Fig. 5.3). So, retrieving all measurements attached to a given galaxy is very fast and adding a new one is quite easy. Some memory space is dedicated to the pointers, but it is quite negligible (there is a pointer only for existing measurement). It would have been possible to work with the Centre de Données Stellaires (CDS, today Centre de Données de Strasbourg). Clearly, the CDS software was not made for managing galaxies because of some specific parameters. Furthermore, it would have been difficult for us to develop the homogenization step, which was essential for our research work. At that time (end of 1982), we used a computer with a hard disk of 10 Mbytes (to be shared with my colleagues). I searched for a database software compatible with our computer and able to manage 40,000 galaxies (or more). The program I found allowed us to manage 32,768 objects. Even if I had had funds to buy it, it would have been useless. Thus, I decided to write my own database program, in 1983.

The strategy for the homogenization of the parameters is the following (see Fig. 5.4): we store only raw data, as they are published, each kind of parameter being expressed in a common unit. When the data differ by their definitions or by their experimental condition the relevant codes are recorded together with the raw data, in order to describe how the measurement was made. For instance, for apparent diameters we recorded the major and minor axis measurements in a standardized unit, a code for diameter type, a code for the photometric band, and a code for

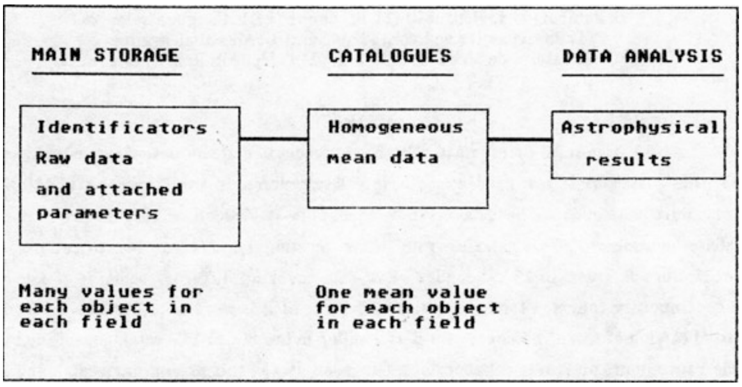

Fig. 5.4 The strategy of our data management inherited from Gérard de Vaucouleurs

the bibliographic reference. From time to time, a statistical study produces an inter-comparison of each homogeneous class of galaxy. It gives us relationships to convert each raw parameter to a homogenized catalogue in which each galaxy appears with a clear identification and a set of mean astrophysical parameters. This catalogue is not stored in the database itself, because it is subject to future improvement, after a new statistical analysis. It is simply used to produce a temporary catalogue giving the best weighted mean parameters, constructed on all available material. Further, each parameter is given with a realistic uncertainty based on the comparison of individual measurements. This is the heritage of Gérard de Vaucouleurs's strategy used in his series of Reference Catalogues (RC1, RC2, RC3). The Third Reference Catalogue was produced in this way with many contributors.[2] Probably the last catalogue on paper (see Fig. 5.5).

In the field of extragalactic databases, the most important event has been the creation of the Nasa Extragalactic Database (NED[3]) created by G. Helou and B. Madore. In 1988, I had some financial difficulties to manage our database. We had the opportunity to solve our problems by selling the preliminary version of our Principal Galaxy Catalogue to NED, on May 9th, 1988. We are happy to have slightly contributed to this remarkable database.

We maintained our specificity by producing mean parameters as inherited from G. de Vaucouleurs. This allows the selection of large, homogeneous samples through the standardized query language (SQL). The users can select their own sample simply by choosing which data they want and what accuracy they accept for each parameter.

[2]A. de Vaucouleurs, H. Corwin, R. Buta, S. Odewhan, P. Fouqué and many others (see the printed version of RC3).

[3]NED is a wonderful name. You probably know that in "*20,000 lieues sous les mers*", the famous novel by Jules Verne, Ned is the name of the assistant of an outstanding scientist, exactly what a database should be.

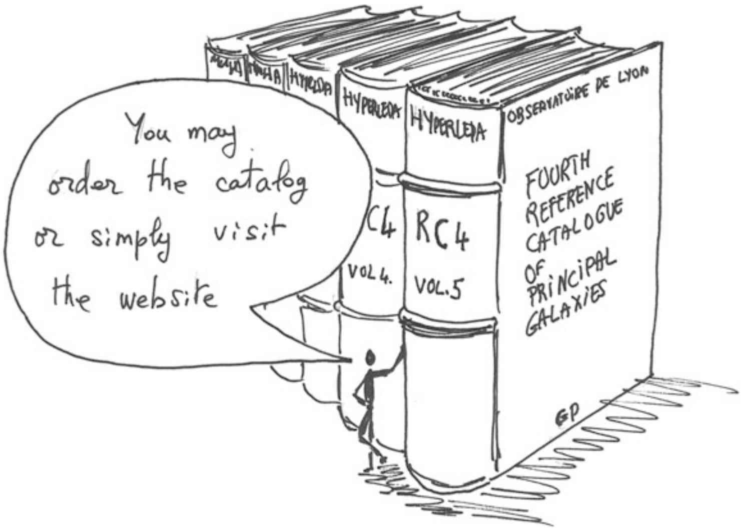

Fig. 5.5 The future catalogue

The evolution of our database has continued. We soon understood the necessity of storing images. At first, a rich technocrat refused our project saying: "It is not necessary to do that, because American guys will do it!". A colleague told me that I should have answered: "American guys have kids; no need to have our own". Nevertheless, we started to digitize thousands of galaxies from the Palomar sky survey, using a poor equipment. In fact this experience of managing images became useful, when the digitized sky survey had been available, and later when our database had been chosen for extragalactic sources of the infrared DENIS survey (the name LEDA had been chosen at that time). Our database jumped from a few hundred thousands of galaxies to some millions of them. The next evolution came from the merging activities of LEDA and HYPERCAT, a multimedia database made by my young colleague Philippe Prugniel. Thanks to him the HYPERLEDA[4] became a nice tool, well documented and richer than before. Several mirror databases are installed in different countries. A young Russian astronomer, Dmitry Makarov, is updating the database, as we did ourselves in the past, with my colleagues Chantal Petit, Robert Garnier and some students.

The publication of large samples has already changed the homogenization method. During the past 30 years, we saw an obvious evolution of the amount of galaxies per paper. For instance, at the beginning of radio astronomy, each paper was dedicated to one or two galaxies. Progressively this number increased up to several hundreds. In classical photometry we even entered the domain of large survey. A practical consequence is that now we can get the large sample directly from

[4]HYPERLEDA: http://atlas.obs-hp.fr/hyperleda/.

the Web. At the beginning we had to collect papers one by one to keypunch data into the database. In an intermediate phase, scans associated with optical character recognition (OCR program) were used.

For the homogenization of many small samples we used an iterative statistical method [we called it INTERCOMP (Bottinelli et al. 1982)]. For larger samples, the inter-comparison can easily be replaced by linear regressions to reduce each sample to a reference one. Hence, we invented a new method [the EPIDEMIC method (Paturel et al. 2003)] (see Fig. 5.6). This is quite simple too: through a preliminary analysis we sort the samples according to a criterion mixing size and quality. Then, the first sample in the list is defined as the reference sample. We then reduce the second sample in the list to the reference sample and merge them both as a new reference sample. After, we continue to propagate the reduction to the third in the list, then to fourth, and so on. The homogenization propagates like a (good) epidemic wave. Each statistical analysis made for homogenization of different catalogues must be conducted by specialists of the concerned parameter because the choice of the method must be guided from scientific considerations.

The publication of very large or extremely large samples will change drastically the scientific approach. Three preeminent surveys of the last decade were 2MASS, DENIS and SDSS. They produced an impressive amount of data (typically a detailed surface photometry leading to many parameters: magnitudes and diameters at different brightness levels and more).

- 2MASS was an infrared all-sky survey of about 1.7 million extended sources in three infrared photometric bands J(1.25 μm), H(1.65 μm) and K_s(2.17 μm). An important follow-up, the 2MASS redshift survey, produced 0.2 million redshifts that allowed the clear extragalactic identification of sources.

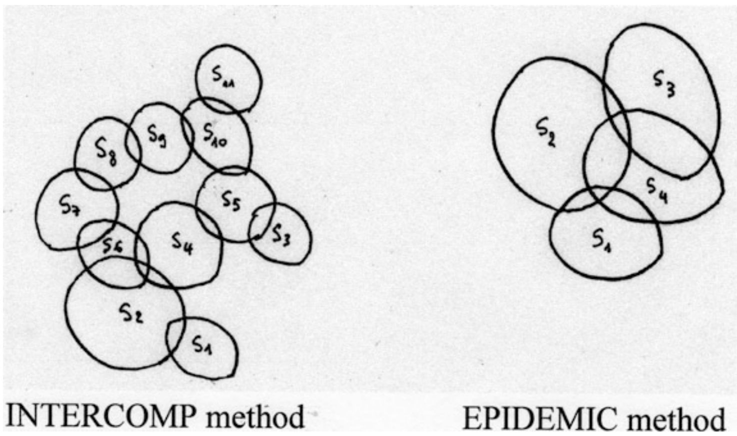

Fig. 5.6 Domain of use of INTERCOMP and EPIDEMIC methods, with many small samples or a few large samples, respectively

- DENIS was an infrared survey limited to the southern sky, performed in three infrared photometric bands I(0.80 μm), J(1.25 μm) and K(2.12 μm). Extragalactic sources were incorporated in LEDA leading to a sample of 0.8 million galaxies. Except for the I-band, this survey is a duplication of a part of 2MASS. I would have preferred an all-sky survey in I-band only.
- SDSS Legacy Survey is the extragalactic part the SDSS. It covers a fraction of the sky (35 %) distributed in three stripes and a wide region of the North Galactic Cap. It is deeper than the two others ($z \leq 0.7$ for galaxies, and $z \leq 6$ for quasars). It gives photometry in five photometric bands covering all the spectrum from UV to near IR: u(0.35 μm), g(0.49 μm) r(0.63 μm), i(0.78 μm) and z(0.93 μm). There are almost a million spectra of galaxies and 120,000 spectra of quasars.

Each of these large surveys is a database by itself, but none of them cover all needed parameters, such as dynamical ones used for distance determinations (e.g., HI-widths, internal velocity dispersion) or far infrared data for exploration of the zone hidden by our Milky Way. This explains that we must prepare interoperability between all kinds of databases. This is the target of Virtual Observatory.

For the future the Large Synoptic Survey Telescope (`LSST`) is a very impressive project. It is a wide field 8.4 m ground based telescope. The site would be in Chile, one of the best astronomical site. This project will scan rapidly the sky in six photometric bands. It will detect billions of galaxies and measure their redshifts. This is a dream for an astronomer. This project should produce 30 terabytes of data each night, equivalent to half the production of books since the invention of printing. I am scared by such a project. Do we need more data to solve the pending questions of astrophysics? If I want to study the daisy flowers on the Earth, should I pick them all before to start? Isn't important to measure dynamical parameters to get better distances better masses?

I am not sure that `LSST` it is the most urgent priority, I explain why. First of all, a ground based telescope will not produce an all-sky survey. I would prefer an international space mission that covers all the sky with exactly the same equipment. Of course, space missions are very expensive today, but I am confident that the price will diminish in the future. Today, all projects promised to solve the problem of dark energy and dark matter. I am convinced that these missing forms of energy will be understood by a deep analysis of fundamental physics (e.g. definition of time). This is not a problem of lack of data. Dark matter and dark energy are the epicycles of modern time. This is my personal point of view. I may be wrong.

What do we really need? What can be done with a database? An extragalactic database can be used for instance to determine some general properties of galaxies at different epochs (i.e. distances) or to determine the large scale distribution and motion of galaxies (see Fig. 5.7). For the first subject we need a very deep survey with galaxies at different stages of their evolution. In this case, it is not necessary to have a complete coverage of the sky. On the contrary, for the second subject we need a complete sample with a large coverage over the sky (an all-sky survey). Further, we need tools for reducing the amount of data to the most significant parameters (this is the step after homogenization). We also need a large distribution of source

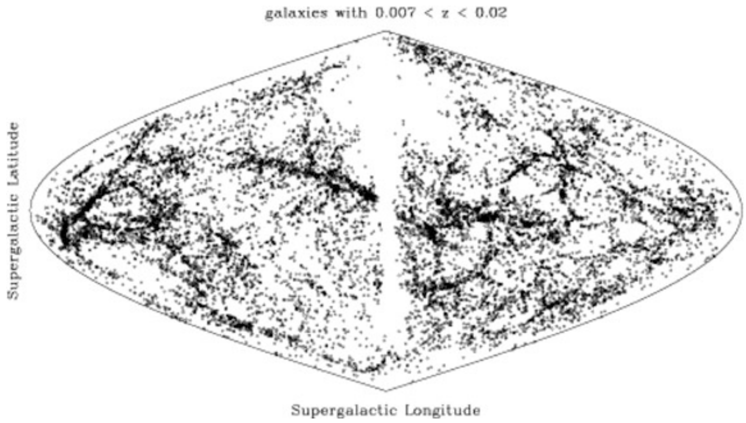

Fig. 5.7 Galaxies with a cosmological velocity over the range $2100 < V < 21{,}000\,\mathrm{km\,s^{-1}}$ ($z = V/c$) are extracted with the standard query language and presented in a Flamsteed equal area projection in Super-galactic coordinates. The structures surrounding our local region are visible. The blank belt reveals our Milky Way hiding extragalactic galaxies. One can suspect a link between the two regions from each side of the Milky Way, near the center of the plot

codes for allowing people to play easily with data (this is a way to allow an external control of very complex codes).

Let us give two examples illustrating: (1) the reduction of data to the most significant parameters (2) a free access to code (a tiny example in SQL) to play with data.

- In 1973, Peter Brosche (1973) made a pioneering study on galaxy properties using the Principal Component Analysis method. Indeed, the observed parameters are not completely independent from each other. It is important to know how many independent parameters describe completely the intrinsic properties of a galaxy. This is a way to reduce the amount of data without loosing any information. For instance it would be interesting to apply an analysis on multi-wavelength magnitudes. I made a test (see Fig. 5.8) with data from the three above surveys (2MASS, DENIS and SDSS-LS) and LEDA: 13 photometric domains (from $\lambda = 0.3\,\mu\mathrm{m}$ to $\lambda = 2.2\,\mu\mathrm{m}$) and more than 4 millions entries (by comparison, Brosche used a sample of 30 galaxies with seven parameters!). After correction for non intrinsic effects (inclination, galactic extinction K-effect), all photometric bands can be replaced by a single magnitude (J) and a parameter describing how it changes with the wavelength (i.e., with the shape of the spectrum). In this kind of study describing the mean properties of galaxies, outliers may carry important clues for the discovery of new objects or new properties, providing that they do not result from a misidentification.
- The second example is the use of a very simple code as presented in HYPERLEDA (http://atlas.obs-hp.fr/hyperleda/) to illustrate the capabilities of the SQL language (see examples in the SQL option in HYPERLEDA). It is the calculation of the Hubble constant from a simple method (method of Sosies, lookalike, galaxies). The principle is easy to understand. If one selects in the database all

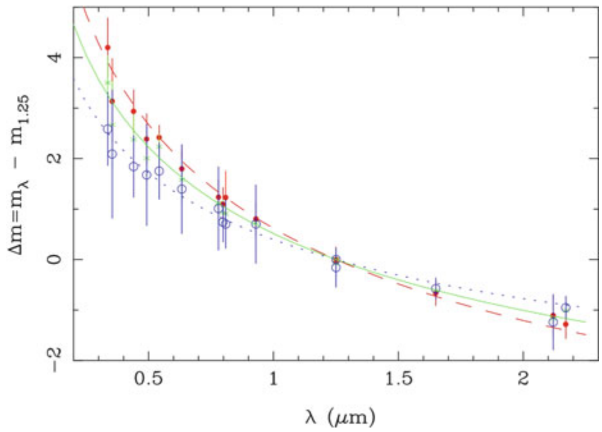

Fig. 5.8 The spectral distribution for three classes of morphological types: Elliptical galaxies (*red dashed line*), Sa galaxies (*green full line*) and Sc galaxies (*blue doted line*). All magnitudes are reduced to a J-band magnitude ($\lambda = 1.25\,\mu$m) and a spectral type index, well correlated with the morphological type

galaxies that have the same maximum rotation velocity as a calibrating galaxy (NGC 224), they all should have the same absolute magnitude in virtue of the Tully-Fisher relation. Using the SQL language one obtains directly the mean value of the Hubble constant (detailed explanation are given on the website). In this example, one needs an all-sky coverage to obtain a representative mean value of the Hubble constant without influence of local peculiar motions. Further, the sample must be complete down to a certain limiting magnitude in order to avoid statistical biases (for Sosie galaxies the limiting apparent magnitude is equivalent to a limit in distance, thus in radial velocity). One can play with this calculation. If one changes the limiting radial velocity for a deeper value, the Hubble constant will increase. Similarly, if one repeats the calculation with a fainter calibrator (e.g., NGC 598[5]), the Hubble constant will increase again. This is a clear illustration of the effect of the Malmquist bias (see Teerikorpi 1997). This bias was responsible for the historical controversy about the value of the Hubble constant.

To conclude, I would like to mention that HYPERLEDA uses a resource of some external image databases, that prefigures the future Virtual Observatory.

The doubt of Georges Paturel about the need to collect all-sky `LSST` *observations every 3 days: "If I want to study the daisy flowers on the Earth, should I pick them all before to start?" is of general value. We may notice that papers on few selected objects studied in detail, producing general insights on galaxy evolution are*

[5]In this case the distance modulus is 24.77, the apparent corrected magnitude is $btc = 5.77$ and the $log(vrot) = log(100.3)$.

flourishing, even in the Big Science era. Astronomers are not prisoniers condemned to the hard labour of collecting more and more data. Certainly the above question emphasized the terrific investigation power that current technology put in the hands of astronomers and as a consequence the growing complexity in planning useful/reliable observing strategies.

In the next sections we interview several astronomers about the most significant results obtained using the survey approach exploring galaxies and their environments in several wavelengths.

5.3 Characterizing the Galaxy Populations in Dense and Poor Environments with Surveys

5.3.1 Virgo and Fornax

Questions for Alessandro Boselli:
You are involved in the large effort for the definition of the Virgo cluster members. What is the structure and the size of this cluster? What are the properties of its galaxy population (luminosity function, morphological class, etc.)? What are the results of the multi-wavelength surveys, from far UV to Far Infrared? Did you identified new classes of galaxies in Virgo?

The Virgo cluster is the richest cluster of galaxies closest to the Milky Way. It was first identified as an overdensity region of nebulae in a note relative to the galaxy M91 (NGC 4548) in the famous "Catalogue des Nébuleuses et des amas d'Étoiles" by Messier in the updated version published in the "Connoissance des Temps" of 1784 (Messier 1781). Here Messier wrote: "The constellation of Virgo, and especially the northern Wing is one of the constellations which encloses the most Nebulae: this Catalog contains thirteen which have been determined: N. 49, 58, 59, 60, 61, 84, 85, 86, 87, 88, 89, 90, and 91. All these nebulae appear to be without stars: one can see them only in a very good sky, and near their meridian passage. Most of these nebulae have been pointed to me by P. Méchain." It was only at the beginning of last century, however, that it was recognized as a cluster of galaxies (Ames 1950; Shapley and Ames 1926, 1929). Since its discovery, it has been a milestone in the calibration of different distance indicators and in the definition of the distance scale (Hubble 1936; Hubble and Humason 1931; Humason et al. 1956; Sandage 1958). It was, indeed, one of the main targets of the HST Extragalactic Distance Scale Key Project (Freedman et al. 2001). Smith (1936) used the distribution of the velocity dispersion measured with 32 galaxies to estimate the total dynamical mass of the cluster and, indirectly, the total mass of galaxies. The Virgo cluster was also studied to identify and quantify the effects of the environment on the evolution of galaxies. The first evidence of the morphology segregation effect (early-type galaxies are dominant in clusters while late-types in the field; Dressler 1980) comes from the study of the Virgo cluster of Hubble and Humason (1931). It is also in the Virgo cluster that Davies and Lewis (1973) and Kennicutt (1983) first noticed the low atomic gas content and star formation activity of spiral galaxies in high-density regions.

The complex structure of the cluster, formed by different subgroups, was already noticed by Shapley and Ames (1929). de Vaucouleurs (1961) made the first dedicated study of the structure of the Virgo cluster. By analysing the distribution of 212 bright galaxies on the plane of the sky and in the velocity space, de Vaucouleurs (1961) pointed out the presence of several groups and clouds located at different distances and populated by different objects. The most recent works on the structure of the Virgo cluster are mainly based on the beautiful Virgo cluster survey done by A. Sandage, G. Tammann, and B. Binggeli in the 80s. This photographic survey was possible only after the construction of the 2.5 m (100-in.) Irénée du Pont telescope at Las Campanas (Chile) occurred in 1977. The telescope was designed to have an exceptionally wide field for direct photography ($1°.5\times 1°.5$) and was thus perfectly tuned to cover the Virgo cluster region. The survey of the Virgo cluster (140 sq. deg.) started in 1979 and was completed in 1983 (67 photographic plates of format 50×50 cm) and a complete catalogue including 2096 galaxies was published in 1985 (VCC; Binggeli et al. 1985).

The analysis of the VCC has confirmed the presence of several substructures in the cluster. The most prominent one is that associated to the giant elliptical galaxy M87. This substructure is generally called Virgo cluster A (Binggeli et al. 1987, 1993). A second peak in galaxy density, called Virgo cluster B, is centered on the other giant elliptical galaxy M49. Other peaks in galaxy density are observed around the elliptical galaxies M60 (Virgo cluster C), NGC 4261 (W cloud), NGC 4365 (W' cloud), and NGC 4168 (M cloud). *ROSAT* observations allowed to trace the distribution of the hot and dense intergalactic medium emitting in X-rays in the Virgo cluster region (Böhringer et al. 1994). These observations revealed that most of these galaxy overdensity regions are associated to peaks in the X-ray emission, thus proving the non-virialized nature of the cluster (Schindler et al. 1999). Its complex structure is also evident in the velocity distribution of galaxies along the line of sight. The different substructures are generally well separated in the velocity space since located at different distances. Using different distance indicators, several authors have shown how the different subgroups are infalling onto cluster A (Gavazzi et al. 1999; Tully and Shaya 1984). For these reasons the Virgo cluster is generally considered as a cluster in formation analogue to high-redshift systems.

Ironically, the study of the structure of the Virgo cluster did not make significant progresses since the VCC. This was mainly due to the extension of the cluster on the plane of the sky, which exceeds 100 sq. degrees. It was indeed impossible to cover this wide region until recently, when new generation large panoramic detectors were made available to the community. At the same time, the determination of spectroscopic redshift, necessary for an accurate membership assignation to the different cluster subgroups, is particularly difficult in Virgo where most of the galaxies without a velocity measurement are dwarf ellipticals. Here, the lack of emission lines and the low surface brightness make the determination of a redshift using absorption lines particularly hard. A crude selection of galaxies belonging to the cluster has been made possible using surface brightness criteria (Binggeli et al. 1985), but the accuracy of this technique is not sufficient to assign galaxies to the different cluster subgroups.

The most recent study of the 3D-structure of the cluster has been presented in Boselli et al. (2014a). This has been made possible thanks to the advent of the SDSS survey, which covered the entire Virgo cluster region at a uniform depth in different photometric bands. Using spectroscopic redshift for more than 850 galaxies over ∼300 sq. deg. and the Voronoi tessellation method to identify the different substructures, Boselli et al. (2014a) determined the 3D-distribution of galaxies in different ranges of velocity up to the outskirts of the cluster, as depicted in Fig. 5.9. The figure shows the different peaks in the galaxy distribution associated to cluster A, B, C, and to the W, W' and M clouds. It also shows the Low Velocity Clouds (LVC) almost matching the M cloud on the plane of the sky, but clearly separated in the velocity space, the first composed of galaxies with a recessional velocity $vel < 400\,\mathrm{km\,s^{-1}}$, the second including objects with $1500 < vel < 3500\,\mathrm{km\,s^{-1}}$. The diffuse overdense region to the south east of the cluster is generally called the Southern Extension. Cluster A, B, and C, as well as the W' cloud, have all a recessional velocity close to $1000\,\mathrm{km\,s^{-1}}$. The W and M clouds have $vel \sim 2100\,\mathrm{km\,s^{-1}}$, while the LVC $vel \sim 85\,\mathrm{km\,s^{-1}}$ (Boselli et al. 2014a). The most recent estimate of the distance of Virgo cluster A is 16.5 Mpc and it has been determined using the surface brightness fluctuation method applied to ∼100 galaxies from the ACS Virgo cluster survey (Mei et al. 2007). Using the Tully-Fisher relation to measure distances for late-type galaxies and the fundamental plane relation for early-types, Gavazzi et al. (1999) have shown that, despite a similar recessional velocity, Virgo cluster B is located at ∼23 Mpc, thus behind cluster A. The M and W clouds are even further, at ∼32 Mpc. While the M and W clouds seem in Hubble flow, Virgo cluster B is infalling from behind on cluster A at $\sim 760\,\mathrm{km\,s^{-1}}$ (Gavazzi et al. 1999).

It is clear that, given its complex structure, it is very difficult to measure a typical size of the cluster. This, indeed, is generally done using the virial theorem, and thus requires that the cluster is in equilibrium. It is generally assumed that the main body of the cluster, Virgo cluster A, satisfies this condition. This assumption is quite reasonable because this is the dominant structure of the cluster, associated with the diffuse X-ray emission tracing the distribution of the gravitational potential. By studying the galaxy and gas distribution within the cluster and applying the virial theorem, McLaughlin (1999) determined that the virial radius is $R_{vir} = 1.55 \pm 0.06\,\mathrm{Mpc}$ (5°.383 at a distance of 16.5 Mpc) and the dynamical mass $M_{dyn} = (4.2 \pm 0.5) \times 10^{14}\,\mathrm{M_\odot}$. Using similar criteria, Ferrarese et al. (2012) deduced that the mass of Virgo cluster B associated with M49 is $M_{dyn} = 1.0 \times 10^{14}\,\mathrm{M_\odot}$ and the virial radius $R_{vir} = 0.96\,\mathrm{Mpc}$. Using more recent `XMM-Newton` data gathered on a radial strip northward from M87 to trace the radial distribution of the gas in cluster A, combined with `ASCA` observations, Urban et al. (2011) obtained slightly smaller values for the virial radius ($R_{vir} = 1.08\,\mathrm{Mpc}$) and the total dynamical mass ($M_{dyn} \sim 1.4 \times 10^{14}\,\mathrm{M_\odot}$). Considering the infall of the different subgroups on the

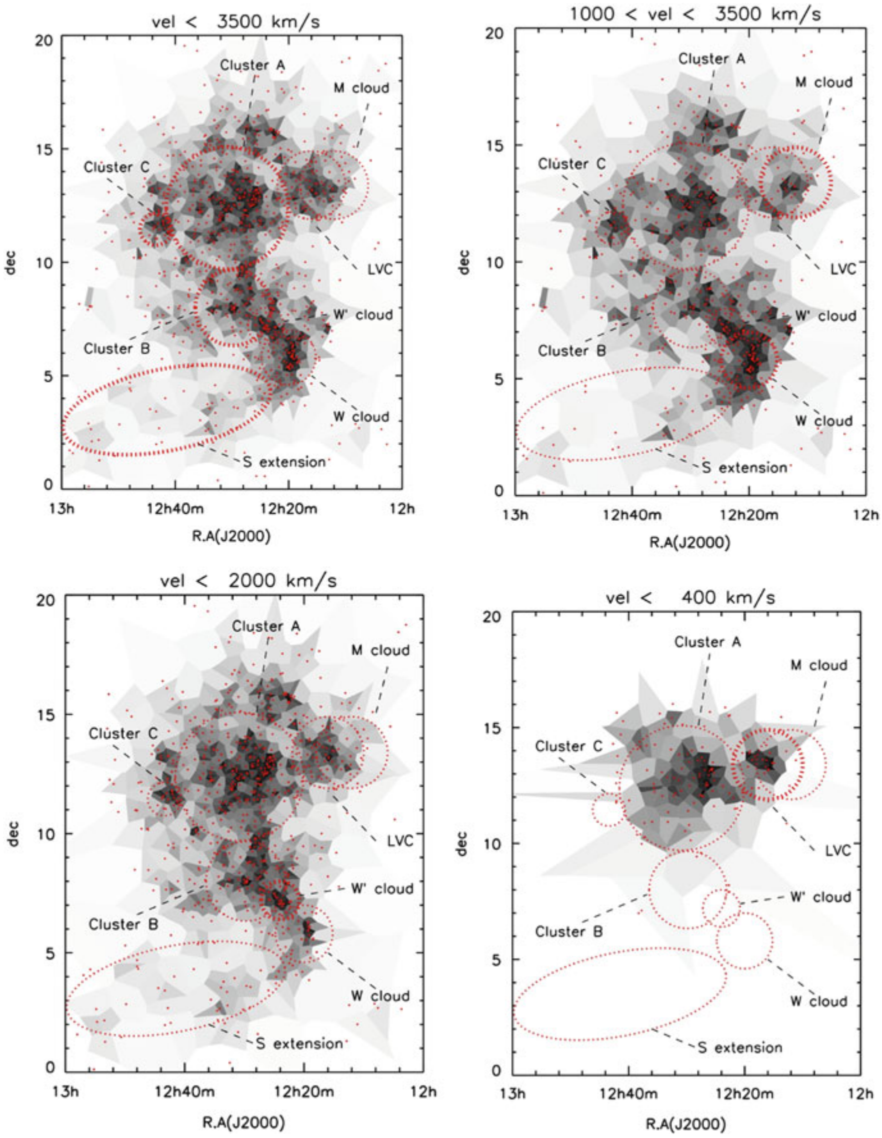

Fig. 5.9 The Voronoi tessellation of the Virgo cluster region with darkness increasing according to the local density. The four plots show the Voronoi tessellation done by using the whole sample of galaxies with recessional velocity $< 3500\,\mathrm{km\,s^{-1}}$ (*upper left*), and in three subsamples in the velocity space: $1000 < vel < 3500\,\mathrm{km\ s^{-1}}$ (*upper right*), $vel < 2000\,\mathrm{km\,s^{-1}}$ (*lower left*) and $vel < 400\,\mathrm{km\,s^{-1}}$ (*lower right*). *Red dots* indicate the galaxies. The different cluster substructures are identified with *red-dotted circles*. Thicker contours are used whenever the structure has been identified within that velocity range with the only exception of the M cloud. Adapted from Boselli et al. (2014a)

main body of the cluster, Gavazzi et al. (1999) and Tully and Shaya (1984) obtained total masses for the whole Virgo cluster of the order of $\sim 1-3 \times 10^{15}$ $M_{\odot}$. These values are obviously larger than those determined when limited to cluster A, since a large fraction of the mass lies outside the main body of the cluster, as indicated by its complex dynamical structure.

Different groups have tried to determine the luminosity function of the cluster at different wavelengths, from the UV (Boselli et al. 2011) to the radio continuum (Gavazzi and Boselli 1999). Still today, the reference luminosity function in the optical bands is the one determined using the photographic magnitudes by Sandage and collaborators (Sandage et al. 1985). In this work, that I still consider as one of the best works ever published in extragalactic astronomy, they fitted the luminosity function down to $M_B \sim -13$ with a Schechter function of slope of $\alpha \sim -1.4$. Thanks to the high quality of their plates, they where able to quantify the contribution of the different morphological classes, and clearly state that the observed increase of galaxies at the faint end is due to dwarf ellipticals, a population of galaxies typical of rich clusters. Similar values have been obtained few years ago using SDSS data by Rines and Geller (2008) ($\alpha = -1.25$ in the r-band). A significant improvement in the study of the optical luminosity function will soon be provided by the Next Generation Virgo Cluster Survey (NGVS, Ferrarese et al. 2012), a 104 sq. deg. optical survey done in the u, g, i, and z photometric bands using `MEGACAM` at the `CFHT`. The impressive sensitivity of the instrument is allowing the detection of dwarf low surface brightness galaxies ($\mu_g \sim 29\,\mathrm{mag\,arcsec}^{-2}$) down to absolute magnitudes of $M \simeq -6$. Using complex criteria based on the typical scaling relations of galaxies to identify Virgo members, the number of objects that can be used to sample the luminosity function is now close to 5000. The first attempts seem to indicate that the analytic form of the luminosity function determined by Sandage and collaborators 30 years ago is still valid and extends to much lower magnitudes. What is striking is that the shape of the optical luminosity function of Virgo is very similar to that of the field as determined from the SDSS (Blanton et al. 2005), provided that low surface brightness galaxies are properly considered (Boselli et al. 2008a). What drastically changes is the contribution of the different galaxy populations at faint luminosity. Star forming systems are dominant in the field, where dwarf ellipticals are virtually lacking, while quiescent objects are the most numerous in the cluster. This is a further evidence of the morphology-segregation effect , in the Virgo cluster first noticed by Hubble and Humason (1931) using the set of data of Shapley and Ames, and its extension to low luminosities (Sandage et al. 1985). We should remember, however, that despite this evident morphology-segregation, the Virgo cluster is considered as a spiral-rich cluster if compared to massive and relaxed clusters such as Coma.

The Virgo cluster region has been fully covered at different wavelengths. Besides the aforementioned NGVS survey, we can recall the `GALEX` Ultraviolet Virgo Cluster Survey (GUViCS, Boselli et al. 2011), the `Herschel` Virgo Cluster Survey (HeViCS, Davies et al. 2010) in the 70–500 μm spectral domain, and the ALFALFA (Giovanelli et al. 2005) HI survey. Combined with the photometric and spectroscopic data from the SDSS, WISE data in the mid infrared, plus several targeted high resolution spectroscopic observations, the dataset now available for Virgo galaxies is the best suited for the study of the effects of the environment on galaxy evolution. The statistical properties of the cluster galaxies have been recently revisited using, for the first time in the literature, a complete and statistically significant sample with multifrequency data spanning a wide range in stellar mass and morphological type (Boselli et al. 2014a; Gavazzi et al. 2013). It is now clear that early-type galaxies are the dominant population of cluster A, while star forming systems are still frequent in the other subgroups. There is also growing evidence that cluster spirals have, on average, a lower atomic (Gavazzi et al. 2005; Solanes et al. 2001; Vollmer et al. 2001) and molecular (Boselli et al. 2014b; Fumagalli et al. 2009) gas content than similar objects in the field. The recent Herschel observations have revealed that, as the other constituents of the interstellar medium, also the dust component is less abundant than in cluster spirals (Cortese et al. 2010b, 2012). Thanks to the angular size of the observed targets and the high angular resolution of the instruments, it has been shown that the different gaseous components and the cold dust are removed mainly in the outer disc of late-type galaxies. The stripping process, thus, is working outside-in. The lack of gas quenches the activity of star formation in the outer parts, lowering the total activity of cluster galaxies, and producing discs with color gradients opposite to those generally observed in normal spirals, blue in the inner regions where star formation is still ongoing, and red in the outer disc (Boselli and Gavazzi 2006; Boselli et al. 2006). There are also evidences of an enhanced radio continuum activity of cluster spirals with respect to the field (Gavazzi and Boselli 1999). The complete multifrequency surveys of the cluster have also shown that the lack of gas and the quenching of the star formation activity is more pronounced in spirals located within cluster A than in those belonging to the other groups or clouds. The same multifrequency data have also shown the presence of several dwarf galaxies with physical, structural, and kinematic properties intermediate between those of low-luminosity star forming and quiescent systems. Indeed, there are several morphologically classified dwarf ellipticals with weak spiral arms, discs or bars (Lisker et al. 2006), characterized by a relatively young stellar population (spectra typical of post-starbursts; Boselli et al. 2008a), and rotationally supported (Toloba et al. 2009, 2011). Some of them have also gas and dust in their inner regions (De Looze et al. 2010, 2013) able to sustain a nuclear star formation activity (Boselli et al. 2008a, 2014a). This intermediate class of objects, as the massive gas deficient spirals, populates the green valley located in between the blue cloud, formed by typical unperturbed field late-type galaxies, and the red sequence composed of evolved early-type systems. Among early-type systems of different stellar mass, those pressure-supported are located in the highest density regions (Cappellari et al. 2011) and virialized within the potential of the cluster (Boselli et al. 2014a), thus they are member of Virgo since its formation. Those rotationally-supported, on the contrary, are preferentially located in the outer parts of the cluster and have deviant velocities with respect to the mean velocity distribution within the cluster indicating that they have been accreted only recently.

It is worth mentioning that the simple picture of the Virgo cluster that we have today and that I tried to describe above is the results of more than 30 years of investigations. In 2014, when multicolour images and spectra of ~2000 galaxies can be obtained just by a few clicks on the web, and observations through standard proposals are generally done in service mode, we easily forget the huge effort that we all had to make since the 80s to gather the unique set of data that allowed us to reach this understanding of the Virgo cluster. Indeed, 20 years ago obtaining a single monochromatic image or a long slit spectrum of a 15 mag galaxy at a 2 m class telescope required ~30 min, thus a complete survey of the Virgo cluster was a real challenge. Late in the 80s, when I was still an undergraduate student, we started with my friend Peppo Gavazzi several multifrequency surveys of galaxies in nearby clusters. Using photon-counters in the first years, than 2D detectors, we carried out complete broad band optical, near infrared and narrow band Hα imaging surveys of galaxies in the Virgo cluster and in the Coma/A1367 supercluster. We also observed the same galaxies in spectroscopic mode using the drift scan technique. To complete this ambitious project we spent more than five hundreds nights at the telescope in the last 20 years and a few thousands hours at millimeter and centimeter radiotelescopes to gather CO and HI data. After having combined our multifrequency dataset with others available in the literature, we have constructed a dedicated database, GOLDMine (Gavazzi et al. 2003), to make the data available to the community. I must admit that this huge observational effort has been motivated not only by the striking results that we were obtaining analyzing the data, but also by the pleasure of being in fantastic places where the telescopes were located. Among them I would like to remember the TIRGO telescope on the top of the Gornergrat in the Swiss Alps, or San Pedro Martir in Baja California, Mexico.

Which is the range of galaxy masses of the different morphological types inhabiting the Virgo cluster? Is the wide spectrum of galaxy masses the same for clusters at much higher redshift?

The Virgo cluster, located at 16.5 Mpc from the Milky Way (Mei et al. 2007), is the richest concentration of galaxies in the nearby universe. Just for comparison, we can remind that it has a distance modulus 3.74 mag smaller than the other well known nearby rich cluster of galaxies, the Coma cluster. Thanks to its proximity, the Virgo cluster is thus a unique laboratory to study the dwarf galaxy population in high-density environments. Because of its closeness, however, the cluster is extremely extended in the sky (~100 sq. deg.), requiring a huge amount of observing time to fully cover it at different wavelengths. This has been recently done in the optical bands by the Next Generation Virgo Cluster Survey (NGVS, Ferrarese et al. 2012), a survey conducted at the CFHT telescope using the MEGACAM camera. This survey, which took more than 500 h of observing time at the telescope, mapped the cluster out to the virial radius in four photometric bands (u, g, i, and z) down to a magnitude limit for point sources of 25.9 mag in the g band and to surface brightnesses of $\mu_g = 29\,\mathrm{mag\,arcsec^{-2}}$. With these excellent performances, NGVS allowed the detection of low surface brightness dwarf galaxies down to $M \sim -6$, thus to absolute magnitudes typical of the dwarf spheroidal systems of the Local Group.

The detection of these objects is obviously unthinkable at higher redshift. Just for comparison, the HST Frontier Field survey of clusters of galaxies in the 0.3–0.5 redshift range, which will provide the deepest observations of clusters with HST, will detect galaxies down to mag ~29 in the optical and near infrared bands.

At this depth, however, most of the detected objects are background sources. Out of the ~30 millions of detections over 104 sq. deg., only ~5000 are galaxies in the Virgo cluster. The distribution of the different morphological types as a function of their total magnitude for galaxies brighter than $M_B < -13$ as determined from the VCC survey has been beautifully described by Sandage et al. (1985) 30 years ago. Among the newly detected objects of the NGVS survey there are extended, very low surface brightness sources hardly visible on the reduced images and detectable only applying ad-hoc procedures during both the observations and the data reduction. There are, however, thousands of globular clusters associated to the Virgo galaxies, and an important number of Ultra Compact Dwarf (UCD) galaxies. These are compact sources barely resolved at the distance of Virgo with properties in between those of compact dwarf galaxies and globular clusters. First discovered in the proximity of the elliptical galaxy NGC 1399 in the Fornax cluster (Hilker et al. 1999), they have been later found in the vicinity of bright galaxies in several nearby clusters, groups and even in the field. Their origin is still far to be understood. Different scenarios have been proposed: they can be the bright end of the luminosity function of globular clusters (Mieske et al. 2012), they can be the products of the aggregation of massive star clusters occurred after the gravitational interaction of gas-rich galaxies (Fellhauer and Kroupa 2005), or they can be the remnants of nucleated dwarf ellipticals tidally stripped during their interactions with nearby companions (Bekki et al. 2001; Drinkwater et al. 2003). The complete census of these objects within the Virgo cluster is under way, it is thus still impossible to give their exact number within the surveyed region. The first analysis of the data, however, clearly indicates that they are frequent: more than one hundred have been already discovered over 1 sq. deg. centered on M87, and slightly smaller numbers have been found associated to the other massive ellipticals M49 and M60.

Virgo galaxies have been scrutinized by HST. Although HST is not a telescope studied for surveys it contributed enormously in mapping the galaxies properties in the nearby dense environments, allowing to map galaxies at all levels in the luminosity function, from the brightest systems to the faintest dwarfs.

Questions for Laura Ferrarese:
You are involved in the HST-ACS study of Virgo and Fornax clusters. When galaxies are investigated at the HST resolution, in a multi-wavelength approach, what has emerged with respect to past studies in term of galaxy morphology?

If I were to summarize it in one sentence, I would say that the most important legacy of our HST work on Virgo and Fornax galaxies has been the clear demonstration that the structure of early-type galaxies—both on nuclear and global scales—changes in a continuous and regular fashion as one moves down the luminosity function, from the brightest systems (such as Virgo's cD M87) to galaxies almost a factor 1000 less luminous (or massive). This was quite a drastic departure from the view that was prevalent (although not unchallenged) in the mid 2000s, when we published our first results. That view compartmentalized early-type galaxies in disjoint populations, each claimed to be characterized by distinct structural properties. For instance, a change in the global and nuclear structure of galaxies at $M_B \sim -17.5$ mag (or, in terms of mass, $M_* \sim 6 \times 10^9\,M_\odot$) had been claimed to separated bright "normal" ellipticals from fainter "dwarf" spheroidal galaxies [Kormendy (1985), but see e.g. Graham and Guzmán (2003); Jerjen and Binggeli (1997); Caldwell (1983); Caldwell and Bothun (1987), and Gavazzi et al. (2005) for a different view]. At brighter magnitudes, $M_B \sim -20.5$ mag ($M_* \sim 2 \times 10^{11}\,M_\odot$), an equally abrupt change in the logarithmic slope of the central surface brightness profiles led to the separation of galaxies into "core" and "power-laws" [e.g., Ferrarese et al. (1994); Lauer et al. (1995), but see also Rest et al. (2001); Ravindranath et al. (2002)]. It is not simply a question of nomenclature: if two populations show distinct morphologies, they are likely to have followed independent evolutionary paths. On the contrary, a continuity in structural properties also implies a continuity in the processes that have, through cosmic time, affected and shaped the galaxies we observed today.

As a short introduction, the ACS Virgo and Fornax Cluster Surveys (ACSVCS/FCS, Côté et al. 2004; Jordán et al. 2007) were two large imaging programs carried out with the Advanced Camera for Surveys on HST and motivated by the desire to understand the family of early-type galaxies through the study of their structural properties as well as the properties of their globular cluster systems. Needless to say, these were not the first studies addressing such questions. What differentiated the ACSVCS/FCS from previous studies was, first and foremost, the sample selection. Most previous studies selected galaxies based on morphology (i.e. choosing "pure" samples of regular ellipticals, lenticulars, dwarfs, etc.) under the belief that each "class" can be understood in and by itself. However, morphological classifications can be subjective (someone's dwarf can be someone else's elliptical!). Furthermore, if samples are limited to a particular class, any possible connection with the population as a whole would be obviously missed.

For this reason, the ACSVCS/FCS targeted a sample of early-type galaxies, irrespective of any existing morphological classification. By doing so the ACSVCS/FCS effectively targeted passively evolving galaxies belonging to the "red sequence", a criterium widely adopted in selecting early-type galaxies in high redshift clusters. I will note that the ATLAS^{3D} project, which focused mostly on the dynamical and stellar population structure of early-type galaxies, also used a similar selection and also unveiled a continuity of properties (Cappellari et al. 2011). In the end, the ACSVCS/FCS sample comprised 100 early-type galaxies in Virgo (while not complete, the same was unbiased down to $M_B \sim -15$ mag) and 43 galaxies in Fornax, complete to $M_B \sim -16.1$ mag, each observed with two filters, equivalent to the SDSS g- and z-bands.

This choice paid off: the ACSVCS/FCS showed that while the structure of early-type galaxies does change along the luminosity function (i.e. fainter galaxies are not simply "scaled-down" versions of more luminous ones, namely early-type galaxies do not form a homologous family), such changes are continuous and well behaved. In particular, at no point there is any evidence of a discontinuity that would indicate

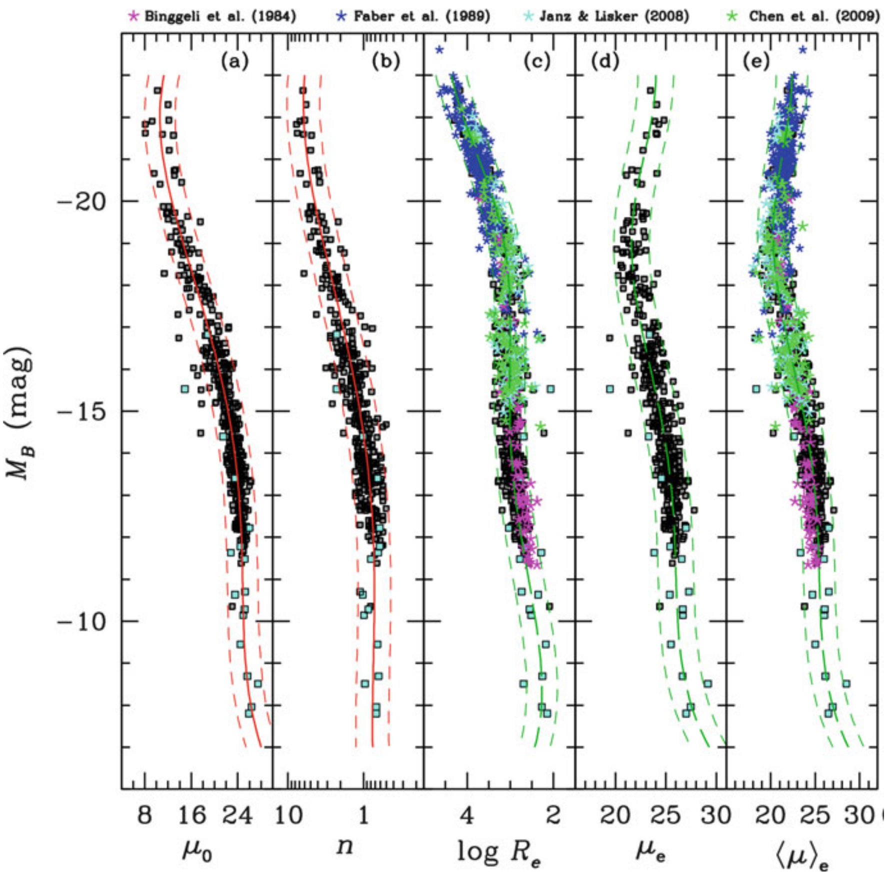

Fig. 5.10 Scaling relations for early-type galaxies, showing a continuum in their structural properties over a factor 500,000 in luminosity

the existence of disjoint populations. This can be seen in Fig. 5.10 [adapted from Côté et al. (2007)], which uses data from the ACSVCS/ FCS combined with a sample of Virgo dwarf galaxies from Gavazzi et al. (2005) and Stiavelli et al. (2001) (and, in the case of the third and last panel, additional sources as indicated in the legend). The faintest cyan points are Local Group galaxies, i.e. the dwarf companions of the Milky Way and M31. The figure shows the relation between absolute B-band magnitude and various structural parameters, specifically (from left to right) central surface brightness, Sérsic index, effective radius, surface brightness at the effective radius and surface brightness averaged within the effective radius. In all panels, a continuous sequence can be seen extending from $M_B \sim -22$ down to $M_B \sim -8$: a factor of 500,000 in luminosity (or, roughly, mass), from the Virgo cD M87 down to faint dwarf spheroidal galaxies in the Local Group. Although not shown, for the ACSVCS/FCS galaxies, other properties, such as isophotal shapes, colours, as well as the properties of globular cluster systems are also continuous. In particular, there is no indication from the data of a separation between "regular" and "dwarf" ellipticals. Our conclusion is that the processes that help shape early-type galaxies (merging, harassment, ram-pressure stripping, etc.) act *continuously*, although with *different weights*, across the luminosity sequence, from dwarfs to giant ellipticals.

Continuity is key also when looking at the *nuclear* properties of galaxies. Thanks to HST 's superb spatial resolution, the ACSVCS/FCS revealed that the frequency of nucleation in early-type galaxies brighter than $M_B \sim -15.0$ mag falls in the range 66–82 % (Côté et al. 2006), roughly three times higher than previous estimates (Binggeli et al. 1985) and similar to the nucleation fraction observed in late type galaxies (e.g. Böker et al. 2002, 2004; Carollo et al. 1998) The properties (sizes, luminosities, masses, and, to a lesser extent, colours) of stellar nuclei correlate with those of the host galaxies: brighter galaxies host more luminous, more massive, and larger nuclei. These nuclei are not only extremely interesting in their own right, but also because of a possible connection to central supermassive black holes, as I have already mentioned in Chap. 4. But to come back to the issue of continuities: I mentioned earlier the "core/power - law dichotomy": galaxies brighter than $M_B \sim -20.5$ mag have shallow density cores, generally interpreted as the result of the evolution of supermassive black hole binaries (e.g. Milosavljevic and Merritt 2003), while fainter systems have sharp density cusps, likely resulting from gas dissipation. The ACSVCS/FCS data showed that far from being a dichotomy, the transition between these two classes is continuous (Côté et al. 2006; Glass et al. 2011; Turner et al. 2012). When measured relative to the inner extrapolation of the Sérsic models that best fits the main body of the galaxy, bright galaxies display a luminosity "deficit", i.e. their cores are under-luminous compared to the expectations. As one moves down the luminosity function, the deficit decreases, and become negligible for galaxies in the range $-20 < M_B < -19.5$ mag, which are well fitted by a Sérsic function all the way to the centre. At fainter magnitudes still, $M_B > -19.5$ ($M_* < 10^{10.6}\,M_\odot$) the "deficit" transitions to an "excess": these galaxies harbor stellar nuclei (Côté et al. 2006; Ferrarese et al. 2006). The transition from "deficit" to "excess" is shown using three representative galaxies in the left panel of Fig. 5.11 (from Côté et al. 2006, 2007). The panel to the right shows the "magnitude" of such deviations, quantified as the ratio of the light enclosed by the best fit Sérsic model to the light enclosed by the observed profiles, both measured within 2 % of the effective radius (the region within which deviations are generally seen), and showing a clear progression from deficit (to the left) to excess (to the right). Although these deviations typically amount to less than 1 % of the total galaxy luminosity and are confined to within less than 1 % of the radial range over which Sérsic models fit with high accuracy, understanding this continuity and, in general, the structure of galactic nuclei, is important to understand the evolution of galaxies as a whole.

While the results listed above are the most relevant to the topic of this book, there were many more results from the ACSVCS/FCS, particularly concerning the study of "Ultra Compact Dwarf Galaxies" (Haşegan et al. 2005) and globular cluster systems (Jordán et al. 2005, 2006, 2007; Peng 2007; Peng et al. 2006). I will

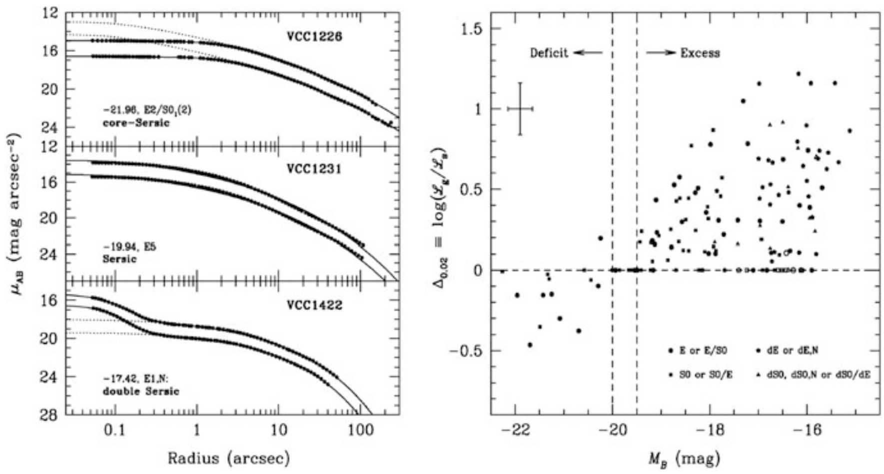

Fig. 5.11 Nuclear properties for the ACSVCS/FCS sample, showing the continuous progression from luminosity deficits to excess as one moves from brighter to fainter galaxies

conclude by mentioning the obvious, namely that there is still much to be learned. The ACSVCS covered less than 0.2 % of the Virgo cluster, and targeted only 5 % of known Virgo members. For this reason, in 2009 we embarked in a large imaging survey of the Virgo cluster using the 1 square degree imager MEGAPRIME on the CFHT. This Next Generation Virgo Cluster Survey (NGVS; Ferrarese et al. 2012) has produced deep (reaching, in the *g*-band, a surface brightness limit of 29 mag arcsec^{-2} and a point source limit of 25.7 mag), high resolution (0.6 arcsec FWHM in the *i*-band), panchromatic (u, g, r, i, z) images of the entire cluster, from its core to virial radius, for a total areal coverage of 104 sq. deg. While the ACSVCS/FCS reached galaxies as faint as $M_B \sim -15$, the NGVS has allowed us to detect galaxies as faint as $M_B \sim -6$ examples of which, to date, were known and studied only in the immediate vicinity of the Milky Way and of the Andromeda galaxy. The NGVS gives us a unique and unparalleled opportunity to study the structure of galaxies—both early and late type—their number density, luminosity function, nuclear properties as a function of environment in this benchmark cluster.

What are the main difference and/or similarities between the two clusters in term of galaxy populations and properties? Could Virgo and Fornax be considered good prototypes of the population of nearby clusters?

We found no differences in the structural parameters of Virgo and Fornax galaxies: a bit of a surprising result in view of the fact that the two clusters show some obvious differences, with Fornax being more representative of groups and poor clusters in which most galaxies reside. In particular, Fornax is more regular and probably more relaxed than Virgo, it is also considerably less massive (by an order of magnitude), more compact (its virial radius is about 40 % smaller) and denser (by a factor ~ 2 in the central regions). Another peculiarity is that Fornax's brightest galaxy, the well known merger remnant NGC 1316 (=Fornax A) is not at the dynamical centre of the cluster (marked by NGC 1399), but rather is located at the outskirts, almost 3° to the southwest. In contrast, the centers of Virgo's two main sub-clusters, Virgo A to the North and Virgo B to the South, are marked by the cluster's two brightest galaxies, M87 and M49. In spite of all this, the scaling relations of Virgo galaxies are indistinguishable from those of Fornax, as is the fraction of nucleation, as well as the nuclear properties in general.

From the ACSVCS/FCS, the only significant difference between the two clusters affects globular clusters (GCs), which are appreciably brighter, by about 0.2 mag on average, in Fornax than in Virgo (Villegas et al. 2010). This difference can be explained if Fornax GCs are younger than Virgo GCs by about 3 Gyr. This in turn is broadly in agreement with cosmological models that indicate that the epoch at which star formation peaks is a function of halo mass: early-type galaxies hosted in more massive haloes have stellar populations that are on average older than those hosted in less massive halos (De Lucia et al. 2006; Springel et al. 2005).

The environment has certainly played a role in shaping the morphological appearance of galaxies. But how important is this role? Bianca Poggianti will now attempts to clarify this sometimes misleading concept.

Questions for Bianca M. Poggianti:
You have worked with the data of several surveys. The WIde field Galaxy cluster Survey (WINGS) is one of these explicitly dedicated to understand the properties of nearby clusters. Could you please tell us which is the role of the environment in the galaxy evolution across the Hubble time? Do you observe significant differences in the influence of the cluster environment for the different morphological types? Which is your feeling about the role of environment in galaxy evolution?

After working on galaxy evolution and environment for the past 25 years, I believe that asking what is the role of environment on galaxy evolution can be a very misleading question, for two main reasons.

The distribution of galaxy properties (stellar history, morphological type, gas content etc.) strongly depend on *where* a galaxy is located. Observationally this is evident, and it is also natural in hierarchical simulations. However:

Reason (1) A galaxy "environment" is an elusive concept, because environment can be defined in many different ways: being part of a cluster, a group, a filament, or a void; being part of a dark matter halo of a given mass; being located in a denser or less dense region of the Universe, with density possibly being defined in many different ways and on different scales. The large scale structure can matter too, and being the central galaxy or a satellite in a halo should make a big difference according to current modeling.

The dependence of galaxy properties on environment can vary significantly depending on the definition of environment adopted. Not knowing "which environment" matters the most (or, more precisely, matters the most for the galaxy property you are studying) is in fact one of the main questions we are after.

Therefore, general statements affirming that a given galaxy property "depends, or does not depend, on environment" should always be avoided. I hear many colleagues making this mistake, and I am sure I still make it too, at times.

Moreover, it is often erroneously assumed that, since all the definitions of environment correlate *at some level*, finding a dependence on "environment" defined in one way should imply a dependence on environment defined in any way. This can be far from the truth. The most common mistake is to believe that a "more massive halo" means a "denser environment", for example that clusters of galaxies are on average denser environments than groups. This is not the case, as we realized when we looked at the distribution of local galaxy densities in simulations (Poggianti et al. 2009): clusters and groups, at least with masses above $10^{13}\,M_{\odot}$, have very similar local density distributions. Thus, it is important to be extremely precise and not use general statements.

Reason (2) By "environmental effects" astronomers usually mean one of the physical processes that can affect a galaxy when it enters a bigger halo, such as ram pressure stripping, strangulation, harassment, mergers and so on [see De Lucia (2011) for a review of such processes]. However, not all the differences of galaxy properties with environment must be due to one or more of these "environmental effects". The mere effect of being in one particular place in the Universe can shape a galaxy history, without any of these processes taking place.

Hopefully an example will better clarify what I mean: massive galaxies with old stellar populations not only formed their stars very early on, but also assembled most of their mass very early on. That is because, from the beginning, they were located in the densest regions of the Universe, with the largest masses available for gas cooling and the right conditions for this to happen, and therefore they were "destined" from the beginning to evolve at an accelerated pace compared to other regions of the Universe. In a hierarchical model of the Universe this is natural, because a galaxy environment today is linked with the galaxy environment and environmental history at all previous times.

Coming now to answering your question: I think "environment" (= the environmental effects listed above) can determine whether a galaxy is red or blue (i.e. it is passive or it is forming stars) at the time we observe it, and can influence a galaxy "morphological appearance" (how prominent is the disk at the time we observe it). But both of these properties are transient and, although they are the most easily observable quantities, they are not the most fundamentally defining characteristics of a galaxy. The most fundamental galaxy property is when and in what shape (disk or spheroid) it formed most of its mass, and this is most likely decided by its primordial environment.

In my current view, the primordial environmental conditions (a "galaxy destiny") are responsible for the epoch and mode of formation of most of the galaxy stars, while the subsequent environmental history (being accreted into a bigger structure) and the consequent environmental effects can modify the galaxy "look". These statements above are applicable to massive (giant) galaxies. As we consider lower mass galaxies, and dwarfs, environmental effects may well be the most dominant ones driving the whole history.

Talking only about galaxy clusters is easier. Clusters are in some sense the “best” defined of all environments. The membership of a galaxy to a cluster and the cluster dynamical (=dark matter halo) mass are more easily defined than in all other cases. Clusters have the strongest environmental influence on galaxies, both in terms of galaxy destiny and in terms of environmental effects.

Some environmental effects are directly observable in clusters. There are several observations showing the effects of the hot intracluster gas on the galaxy interstellar medium (ram pressure stripping) in nearby galaxy clusters [Fig. 5.12, see Fumagalli et al. (2014) for a recent MUSE spectacular example].

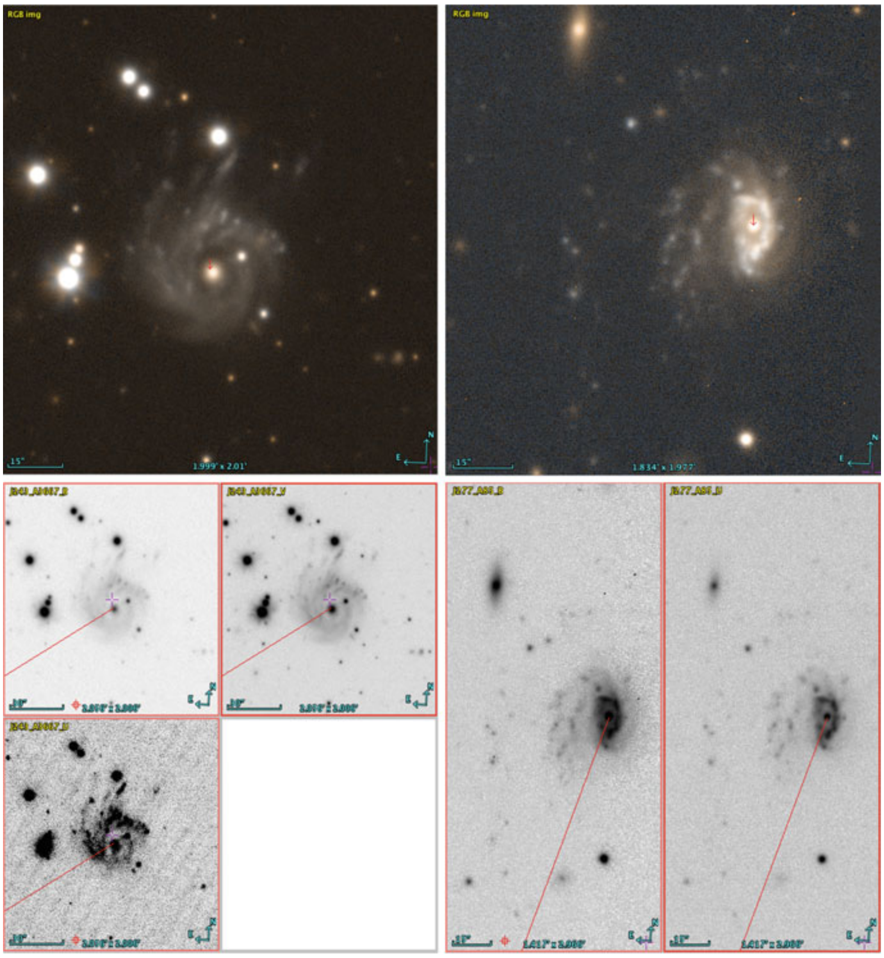

Fig. 5.12 Environment at work: two examples of so-called “jellyfish galaxies” that are suffering from stripping while moving in the hot intracluster gas. The *top images* are colour-composites of OMEGACAM/VST images of WINGS galaxy clusters at low redshift, while the *bottom images* show the same galaxy in different filters, with the *red line* pointing in the direction of the cluster center (Poggianti et al. in prep.)

From the theoretical point of view, galaxy models expect clusters to be the site where most of the "oldest" galaxies (those that formed their stars and their mass at early epoch) will reside today.

Therefore, clusters are favorable environments both for the formation of ellipticals and for the trans-formation of spirals into lenticulars due to environmental effects occurring at $z < 1$. This has been spectacularly shown by the Hubble Space Telescope images, beginning with Dressler et al. (1997). However, the evolution from spirals to S0s is not only confined to clusters, it probably happens in groups as well (Just et al. 2010; Poggianti et al. 2010; Wilman et al. 2009). As it is often the case, evolution is "amplified" in clusters, as they are the extreme tail of the distribution of halo masses, but we are coming to realize that clusters are probably "less special" places than it was thought several years ago. Even mechanisms that until recently were considered cluster-specific, such as ram pressure stripping, may play a role also in lower mass haloes, due to dishomogeneities in the intragalaxy medium, such as shocks and strong temperature gradients resulting from the merging of structures.

One thing we have learned, I think: studying galaxy evolution in different environments requires a global view, from clusters to groups to filaments and voids. The two communities of "cluster people" and "field people" should work much more closely together (read each other papers, essentially), if we want to make good and fast progress, without re-discovering what we already know over and over again.

Galaxies are therefore more evolved in dense galactic environments. These are not only found in large galaxy clusters, but quite often in compact and binary groups. Here galaxy interactions play a key role. Now Nils Bergvall will discuss the early attempts to produce dynamical models of such interactions on the shape and morphology of galaxies.

5.3.2 Galaxy Groups, Pairs and Low Density Environments

Questions for Nils A.S. Bergvall:
A large effort has been dedicated to the identification and study of poor galaxy associations since the beginning of extragalactic astronomy. Catalogues of physical pairs, of poor, loose as well as of compact groups have been prepared with different recipes. Can you give a short history and motivations of this huge effort? What have we learned about galaxies from these studies and what remains to do?

Soon after the cosmic distance scale was established, astronomers began to investigate the clustering tendencies among galaxies. The cosmological principle was based on the notion of a homogeneous universe and it was important to find out if this was a valid approximation. Charlier (1922) argued for the possibility that the universe was hierarchically clustered. In such a Universe the Friedmann equations would not be applicable. Hubble was one of the first to comment on the clustering tendencies (Hubble 1936). He was worried about the problems with dust obscuration but concluded that *"It is only when these various effects of galactic obscuration are evaluated and removed, that the nebular distribution i.e. the distribution of galaxies over the sky is revealed as uniform, or isotropic (the same in all directions)"*. Furthermore he claimed that *"Thus, the observable region is not only isotropic but homogeneous as well it is much the same everywhere and in all directions"*. Harlow Shapley (1932) had a different opinion and noted a remarkable irregularity in the apparent distribution of galaxies even if dust obscuration roughly was taken into account. But it was not until Bart Bok (1934) investigated the astrometric data of the galaxy population from a statistical point of view that it became evident that the clustering of galaxies was deviating from a random distribution.

Extragalactic research in the early twentieth century was electrified by the discovery of galaxies remote from the Milky Way. Many galaxies were found in pairs. Were they formed by captures or by splitting of a galaxy into smaller parts? Could a close encounter lead to a capture? One of the pioneers in this research field was Erik Holmberg. His curiosity led to the famous analogue simulation of a close encounter between two galaxies (Holmberg 1941). In this experiment he placed light bulbs in a pattern analogous to two disk galaxies and used photocells to measure the "gravitational force" of the companion galaxy, the candle power being proportional to mass. The result was that part of the orbital energy could be transferred to the internal kinetic energy of the stars in the galaxies, resulting in a capture. It would take more than 30 years before we could use computers to carry out similar simulations (Toomre and Toomre 1972) and confirm this result (Fig. 5.13).

Holmberg, inspired by Knut Lundmark's ideas (Lundmark 1927), calculated (Holmberg 1940) how long it would take to attain the clumpiness we observe today if we started from a random distribution. His calculations showed that it would take about 40 Hubble times to obtain the fraction of binary galaxies we observe today. So (without knowledge about the existence of dark matter) maybe the galaxies were formed side by side? Holmberg found that the color and surface brightness of one component correlated with those of the other—the so called "Holmberg effect" (not to be confused with Holmberg finding that disk galaxy satellites tend to crowd in the polar directions). From this, and the timescale argument, he concluded that the pairs and multiplets in the majority of cases are formed by disintegration of a larger system. Several other investigations based on larger samples have confirmed the Holmberg effect. In 1972 Karachentsev published "The Northern Catalog of Isolated Pairs of Galaxies" and in 1995 we obtained a similar catalogue, "Southern Catalogue of Isolated Pairs" (Reduzzi and Rampazzo 1995), based on data from the ESO-LV (Lauberts and Valentijn 1989) catalogue and using the same selection criteria as was used by Karachentsev. Both confirmed the Holmberg effect (Karachentsev and Karachentseva 1975; Reduzzi and Rampazzo 1996) and also found an excess of pairs of early type galaxies. How could this be understood? Karachentsev and Karachentseva (1975) also found a higher proportion of AGNs in pairs. These findings indicated that galaxy interactions could induce activities in the form of increased star formation and gas inflows that might trigger AGN activity. In this way gas was consumed faster in pairs than in isolated galaxies. But

Fig. 5.13 Here is shown the results of two of Holmberg's experiments where he let the gravitational force from two encountering galaxies be represented by the flux from light bulbs placed in positions corresponding to the stars in the galaxies. To the *left* we see the result of an encounter corresponding to two positions along an orbit of parabolic motion with clockwise rotations. To the *right* the galaxies have counterclockwise rotations. The development of a bridge and tidal tails are clearly seen in the *rightmost image*

the interpretation at that time was that the systems were in a state of formation and it would take another few years before the young galaxy hypothesis was abandoned.

An important goal in the studies of double galaxies was to determine dynamical masses [for an excellent review of these projects see Faber and Gallagher (1979)]. These studies demanded rigorous selection criteria to find dynamically isolated binaries and to avoid optical pairs. Holmberg (1937, 1954, 1958) developed the tools for deriving statistical masses based on fairly large samples of pairs where it could be assumed that the orbits were circular and randomly oriented. He also dealt with the problem of optical pairs and derived the distribution of the separations between the components, a necessary information for the statistical mass determination. This work was carried further by Thornton Page (1952, 1962). From a larger sample of galaxy pairs, he concluded that the masses of the components of pairs were very similar to those of field galaxies if those masses were derived from M/L values based on photometry. A few years later this result would come into conflict with other mass determinations.

The '60–'70s were turbulent times (Burbidge 1975; Burbidge and Burbidge 1959; Einasto et al. 1974). Clusters and groups of galaxies seemed to be expanding. Still, massive clusters like Coma appeared to have a relaxed core. Big Bang cosmologists had a problem explaining why stars were older than the universe. The Steady State theory proposed a way around these problems but caused new problems. The newly discovered Quasi-stellar objects opened the door for speculations. Vorontsov-Velyaminov (1962) seemed to leave traditional physics and had an idea of self-organization on a high level: *"Certain pairs of living organisms are capable of self-reproduction.[…]. Something similar may occur in the universe of galaxies"*. But also new deep and detailed images of pairs and multiple galaxies made the excitement grow. First it was the catalogue of Vorontsov-Velyaminov (1959) and then Halton Arp's magnificent Atlas of Peculiar Galaxies (Arp 1966). The world "peculiar" echoed a state of confusion. But two important discoveries made during this epoch would soon change our concept about the universe. One was the detection of the Cosmic Microwave Background Radiation (CMBR) in 1965. The second major breakthrough was the acceptance of the presence of dark matter in the universe.

While the Big Bang model quickly was accepted, the physics of Arp's peculiar galaxies needed a longer time to mature. The amazing details at low surface brightness of the galaxies were breathtaking. How could long thin, straight filaments be formed between two galaxies? Were we ignorant about the magnetic fields? To interpret the often remarkable structures was a challenge for astronomers. But one paper would change the scene. A few years after the Arp atlas was published, Alar and Juri Toomre and independently Alan Wright presented their computer simulations of interacting and merging galaxies (Toomre and Toomre 1972; Wright 1972). They demonstrated clearly that the thin bridges between interacting galaxies could be explained by tidal effects on cold stellar disks. The Toomres successfully explained the morphologies of famous systems as M51, the "Antennae" and the "Mice" galaxies. These studies, along with a growing awareness of the importance of interactions and mergers on star formation and starbursts, boosted the interest in the evolution of pairs and poor groups as a tool for understanding the morphological diversity among galaxies. The dominating subject in the field of interacting and merging galaxies was the starburst phenomenon. Since the seminal paper by Larson and Tinsley (1978), whose results we refuted in our paper on isolated pairs of interacting galaxies (Bergvall et al. 2003), the number of papers with "starburst" in the abstract increased rapidly and peaked at 1000 papers per year in 2005. Numerous investigations have confirmed an increased star formation activity in gas rich binary systems and mergers. Inflow of gas and an increase of molecular content has been confirmed both by observations and modelling (Barnes and Hernquist 1992; Combes et al. 1994). But, as we and others have shown, true starbursts are rare. Most of them occur in mergers but many gas rich mergers do not result in starbursts. We still do not fully understand the mechanism behind this dramatic phenomenon. For a general discussion of the starburst concept, see Knapen and James (2009).

Now was the time for a critical revision of the previous mass determinations of binary galaxies. As more and more data were collected it became evident that the previous mass estimates of the binary galaxies were in clear contradiction to mass estimates based on rotation curves and dynamical masses of groups and clusters (Ostriker et al. 1974). In 1976 Edwin Turner (Turner 1976; Turner and Gott 1976) presented a well-defined statistical sample of binary galaxies. He improved the statistical and dynamical analyses and concluded that previous mass determinations were hampered by selection biases that led to an underestimate of the masses with a factor of at least 10. Three years later Peterson (1979) presented a study based on both optical and HI observations. The sample was selected from the Uppsala General Catalogue of Galaxies (Nilson 1973) and contained wider pairs than Turner's, had more reliable radial velocities but was more likely to be contaminated by optical pairs. Peterson also arrived at high M/L ratios, supporting the existence of massive, dark halos. However, this is not the end of the game. Both Turner's and Peterson's work received criticism. One problem was optical pairs and another was that the errors in the velocities were underestimated. Applying corrections to the samples by Turner and Peterson, Rood (1982) found significantly lower M/L values but still larger than for individual spiral galaxies.

The results of the analyses of the dynamics of small systems now started to converge and astronomers gradually learned to accept the existence of dark matter. It was realized that it would be possible to do N-body simulations of the evolution of systems of galaxies in a realistic way. Two important questions emerged what is the lifetime of a compact group of galaxies and what would be the outcome of a multi-merger of the components?

As more and more redshift data became accessible and the computers became smarter, studies of the dynamical properties of groups and associations were intensified. An important problem was to find out how much dark matter there was on spatial scales of the size of a group. Was it sufficient to close the universe (dark energy was unknown at the time)? One difficult problem was how to define a group. Turner and Gott (1976) provided the first objective group defining algorithm and they presented a catalogue of more than 100 groups. They could carry out a dynamical analysis of 39 of these and concluded that they were dynamical entities, detached from the Hubble flow. The mean density within a typical group was however only 12 % of the critical density. Brent Tully (1987) studied the clustering properties of the galaxies in his Nearby Galaxies Catalogue (Tully and Fisher 1988). He used a rigorous algorithm developed by Materne (1978) to assign memberships to what he called clouds, associations and groups. He found the 69 % of the galaxies belongs to groups, 20 % were in associations and 10 % in clouds.

During these years there was also an increasing interest in the fate of small compact groups. But a significant problem was that a large fraction of the compact groups have interlopers. Two iconic compact groups were Stephan's quintet (Fig. 5.14) (Limber and Mathews 1960) and Seyfert's sextet (see image Fig. 1.20 in Chap. 1). Both have interlopers and although the groups are compact one has to be aware of this problem. The enhanced interest in compact groups resulted in several catalogues. The most well-known are the Shakhbazyan (1973) and the Hickson catalogues (Hickson 1982). It surprised astronomers that there were so many compact groups around as the lifetimes should be just a fraction of a Hubble time. Computer simulations showed that if the galaxies were embedded in a common dark matter halo, this would increase the lifetimes with a factor o a few. But was this enough? Hickson et al. (1992) studied the dynamics of the Hickson groups and found that in general the systems were bound and that the galaxies had short crossing times. Also it was found that early type galaxies were overrepresented and that the relative number of early type galaxies increased with degree of compactness.

Fig. 5.14 Stephan's quintet. *Credits*: X-ray (*blue*): NASA/CXC/CfA/E. O'Sullivan Optical (*brown*): Canada-France-Hawaii-Telescope/Coelum

Apparently a morphological evolution took place such that gas rich galaxies merged to form more gas poor and more massive components. In numerical simulations Barnes (1989) finds that compact groups typically merge into a remnants that have properties of ellipticals. These are later fed by infall of smaller companions.

Zabludoff and Mulchaey (1998) studied 12 poor groups of galaxies. They presented a scenario in which some of the galaxies in compact groups merge in the centre and then the group falls into larger clusters. They were also worried about the persisting problem of the short lifetimes of the compact groups. One proposed mechanism that might explain why the number of compact groups is larger than the expected is the so-called secondary infall scenario. Here it is assumed that the groups are being continuously rejuvenated by infall of new galaxies from the environment (Barnes 1989; Gunn and Gott 1972; Mamon 2007 and references therein). This idea is supported by both numerical simulations (Governato et al. 1996; McConnachie et al. 2008) and observations of the galaxies in the field (Ribeiro et al. 1998; Vennik et al. 1993). These studies demonstrate that one cannot isolate the studies of compact groups but have to take the surrounding galaxy population into consideration when deriving masses and group lifetimes.

Today we are aware that probably all fairly massive galaxies harbor a supermassive massive black hole. In connection to the presumed mergers between galaxies in poor groups it is therefore interesting to ask what happens to the black holes. In a pioneering work by Saslaw et al. (1974) it was proposed that, if e.g. three galaxies merge, the slingshot effect would eject one of the black holes, sometimes with a velocity exceeding the escape velocity. We would thus expect to find a population of free-floating black holes around. Even mergers between two galaxies can lead to a recoil of one of the black holes but is not likely to leave the system (Blecha and Loeb 2008; Blecha et al. 2011). Some observational support for this has been presented in the sense that in some mergers there is an offset between the position of the optical core and the radio peak. Free-floating black holes would be very difficult to observe and a confirmation of their presence is as yet lacking.

Another important consequence of a gas rich merger, presuming that the black holes form a tight binary, is that a massive gaseous disk forms in the nuclear region and activates an AGN. In dry mergers (gas-poor) the binary black hole may heat the stellar population in the centre, forming a stellar core profile, as in M 87 (Hoffman and Loeb 2007).

What is the importance of studies of binary galaxies and groups today? First of all, some of the old questions still linger on. As an example, we can have a look at the investigation by Patton et al. (2011). They used the Sloan Digital Sky Survey to select 21347 galaxy pairs for a study. As in previous studies, they find a higher fraction of red galaxies in pairs, probably as a consequence of these pairs residing in higher density regions than non-paired galaxies or that the most compact groups have experienced mergers that have led to consumption or heating of the gas, driving the evolution towards earlier types. Patton et al. also find an increasing circum-nuclear activity with decreasing separation and they also confirm the Holmberg effect. The same group, also based on SDSS data, also found support for gas inflow leading to AGN triggering (Ellison et al. 2011). But we need to know more in detail about the gas flows and the different feedback processes.

A more unconventional way of utilizing galaxy pairs was presented by Tempel and Tamm (2015). They find a significant alignment of galaxy pairs with the large scale filaments, thereby confirming the anisotropic flows predicted by ΛCDM. Hopefully, numerical modeling of large scale structure in the future will make it possible to more in detail compare model predictions with structure on small scales (Reddick et al. 2013). However, it will not any longer be a topic of binary galaxies or groups, we have to take into account how they connect gravitationally to the cosmic web and the flows over larger volumes (Moreno et al. 2013). And at high redshifts the world will look very different.

In a highly structured Universe in which galaxies tend to clusterize in groups, clusters and filaments, isolated galaxies were always believed to be a puzzling by-product of galaxy formation. Valentina Karachentseva was among the first to look for isolated galaxies producing a catalogue that is still used by novel investigations like those proposed by the AMIGA team (Verdes-Montenegro et al. 2005).

Questions for Valentina Karachentseva:
You have cataloged isolated galaxies. Galaxies have been found also in the so called voids. After decades of studies, do there really exist isolated galaxies?

According to contemporary view, a galaxy is considered to be isolated when it has not experienced any gravitational influence from its neighbors over the past few billion years. Therefore, the processes taking place in it should reflect the features of their origin and internal evolution. Identifying these galaxies against their near and far background is the main task while compiling the catalogs and lists of isolated galaxies.

Why do we need such catalogs? Compiling the first "two-dimensional" Catalog of Isolated Galaxies (CIG) (Karachentseva 1973) two main goals were set: to determine the fraction of isolated galaxies among the CGCG galaxies and get a "reference sample" to compare its properties with those of galaxies in associations.

As a result, the isolation criterion used in the CIG compilation has revealed 1050 (around 4 %) of the CGCG galaxies with apparent magnitudes $m_{pg} \leq 15.7$. Statistical considerations given in the CIG show that $\sim 1/4$ of the CIG galaxies can not be completely isolated because of the presence of small dwarf neighbors as well as large foreground galaxies.

A detailed study of the properties of CIG galaxies is performed since 2005 by the AMIGA[6] team. New observational data allowed the team (Argudo-Fernández et al. 2014; Verley et al. 2007) to conduct a quantitative test of isolation of the CIG galaxies. They have classified as non-isolated and excluded approximately 15–20 % of the CIG objects, due to the fact that dwarf galaxies with similar radial velocities were in their neighborhood. Hence, the relative number of isolated galaxies has decreased to ~3 %.

I took the liberty of dwelling on the most studied catalog to show the difficulties in solving the question of the share of isolated galaxies. It is accepted now that the isolated galaxies exist, but they are very few. The results of various studies of isolated galaxies are published in the ASP Conference Series *Galaxies in isolation: exploring nature versus nurture* held in Granada in 2009.

Let us now speak about the voids. The voids are an important constituent of the large-scale structure of the Universe. They are delineated by the galaxy "walls" and filaments and, according to the current data, have a characteristic number density of galaxies at least an order of magnitude lower than the global mean density. The population of voids are predominantly dwarf irregular, blue compact and disrupted spiral galaxies with absolute B-magnitudes in the range of $[-13.0, -16.7]$. They are characterized by active star formation. Gas reserves per luminosity unit in them are two to three times higher than those of dwarf galaxies in the normal environment (Elyiv et al. 2013 and references therein; also see the reports presented in Granada). Note that the observed number of dwarfs in voids is by an order of magnitude smaller than these expected number at a uniform distribution.

What is the astrophysical importance of galaxies that may have evolved in isolation?

As noted above, the galaxies, whose evolution goes on without the influence of the environment, make it possible to compare the observed characteristics of isolated galaxies with the properties of galaxies in pairs (including interacting), in groups and clusters, i.e. to reveal the role of "nature vs. nurture". In this case, the comparison should take into account the sampling conditions. Hence, in the CIG, 2MIG catalogs with a limiting stellar magnitude the proportion between the elliptical and normal spiral galaxies is ~(1:4), while the share of irregular galaxies does not exceed 5 %. However, in the LOG catalog (Karachentsev et al. 2011) not limited by the galaxy fluxes, but their distances $D < 50$ Mpc, the fraction of dwarf irregulars and disrupted spirals is already ~50 %.

[6]http://iaa.es/AMIGA.html.

Are episodes of interaction also foreseen in extremely poor environments?

Signs of interaction, such as distortion, the presence of "bridges", "tails", as well as the presence of a young stellar population are expected and are well known in tight pairs of galaxies. In galaxies located in a poor environment, in particular isolated, such signs were difficult to imagine in advance.

However, the features of the morphology (evidence of plumes, shells, dust lanes) and the presence of emission lines in the spectra were found even among the very isolated E, S0 galaxies (details can be found, for example, in Reda et al. 2004; Stocke et al. 2004 and other authors). The presence of isolated early-type galaxies is unexpected based on the Dressler "morphology-density" global relation. Different authors searched for the explanation for this in that the isolated E, S0 galaxies formed as the final product of a merger of members of close groups, or as a result of capture of faint companions by the dominant galaxy. To check for these assumptions additional observations and numerical modeling are required.

What are the properties of galaxies in such poor environments?

Here I would like to draw attention to some of the features of the nearby isolated galaxies.

1. Among 510 galaxies of the LOG catalog we have only discovered 17 early-type objects with $T < 1$. They have low luminosities (median absolute value $M_B = -17.7$). More than a half of them are the IRAS-sources (having a significant amount of dust). Three galaxies are detected in HI, with fluxes corresponding to masses of of about 10^8–$10^9 M_\odot$. It can be assumed that the evolution of isolated E and S0 galaxies occurs through a significant influence (accretion) of the intergalactic medium.
2. Among the LOG galaxies we noted 21 galaxies with peculiar morphology. The presence in them of a distorted spiral structure or a perturbed disk with loops or a wide tidal tail is quite difficult to explain without invoking the idea of interaction with an invisible massive body. The existence of such dark sub-halo objects without stars is quite acceptable in the standard cosmological model (Klypin et al. 1999).
3. The LOG catalog contains an excessive number of ultra-thin spiral galaxies as compared to their expected number at a random orientation of the axes. This means that the low density of the medium favors formation and continued existence of galaxies with thin "cold" disks without bulges.

The type as well as the role of the galaxy evolving mechanisms are difficult to figure out if looked through a limited wavelength domain. Their understanding received an acceleration once a multi-frequency approach for nearby galaxies have became possible. Alessandro Boselli will discuss below how the combination of observations and simulations have changed our vision about galaxy evolutionary mechanisms.

5.3.3 What Are the Evolving Mechanisms in the Different Environments?

Questions for Alessandro Boselli:
You have been active in defining the properties of galaxy associations. What are the dominant mechanisms affecting the galaxy evolution in groups, in clusters and in very low density environments? What is missing from our understanding of the role of the environment in galaxy evolution?

Answer to this question is very difficult since it would require a full understanding of the role played by the environment on galaxy evolution. Although we made huge progresses in this field, I am not sure that the community has a unique clear and coherent view of galaxy evolution since the formation of the first structures to the local universe. I can thus give you my personal view and describe the ideas that I put together in more than 20 years of work on this topic. It is now clear that two main parameters have modulated galaxy evolution since their formation: the mass of the galaxy itself and its surrounding environment (Boselli and Gavazzi 2006; Boselli et al. 2001; Cowie et al. 1996; Gavazzi et al. 1996). These two parameters, which span a wide range of values, have significantly changed during the evolution of the universe itself, it is thus very difficult to quantify their role and importance at different epochs and under different conditions.

Galaxies are distributed within the universe in a non uniform way, spanning a wide range of densities from the core of rich clusters, to compact and loose groups, filaments and voids. Since the seminal work of Dressler (1980), which indicated a clear morphological segregation in the distribution of galaxies as a function of density, it became evident that the environment plays a major role in shaping galaxy evolution. Cluster of galaxies are mainly composed of quiescent objects (ellipticals and lenticulars), while star forming late-type systems are dominant in the field and in less dense environments. Furthermore, the few spiral galaxies inhabiting high density regions have, on average, a lower gas content and star formation activity than their field counterparts (Boselli and Gavazzi 2006).

Although containing only $\sim$5 % of the local galaxies, clusters are ideal laboratories to study the various processes at play. We can thus use these systems to study the undergoing processes and later see whether the results obtained in these particular regions can be extended, and under which conditions, to less extreme environments. Several physical processes have been proposed to explain the observed differences between cluster and field galaxies, as reviewed in Boselli and Gavazzi (2006). These processes can be divided in two main families, those related to the perturbations induced on the galaxy by the gravitational interaction with other cluster members or with the potential of the cluster (tidal stripping, harassment), and those related to the interaction with the hot and dense intergalactic medium trapped within the potential of the cluster and emitting in X-ray (thermal evaporation, ram pressure stripping, starvation). The role and the importance of each of these processes in shaping the evolution of galaxies in different environments and at different epochs is still under debate. Many variables are indeed at play, including the mass of the perturbed galaxy, the density of the perturbing region, and the epoch of the interaction.

Hydrodynamic cosmological simulations suggest that the quenching of the activity of star formation in high-density regions results from a passive consumption of the cold gas via star formation (starvation). This scenario, however, is not fully supported by the observations since it over-predicts the fraction of red dwarf galaxies compared to what observed in nearby clusters (Weinmann et al. 2011). These simulations also fail to reproduce the observed radial profiles of gas stripped, star forming galaxies in nearby clusters (Boselli and Gavazzi 2006). Galaxy harassment (the combined gravitational interaction with the cluster potential and with other members after multiple fly-by encounters) is capable of reproducing several of the observed properties of cluster early-types (Mastropietro et al. 2005): however, it requires relatively long timescales to become efficient, which might be incompatible with the observational evidence of a recent formation of the red sequence at faint luminosities (De Lucia et al. 2007; Stott et al. 2007) and of a large infall rate of galaxies measured in nearby clusters (Boselli et al. 2008a; Gavazzi et al. 2013). It is, however, plausible that gravitational interactions, including major merging events, are responsible for the formation of the most massive early-type galaxies in clusters during the accretion of small groups at early epochs (pre-processing; Boselli et al. 2014a).

Ram pressure stripping (Gunn and Gott 1972), the dynamical pressure exerted by the hot and dense intracluster medium on galaxies moving at high velocity ($\sim$1000 km s^{-1}) within the cluster, has been often proposed to explain the typical atomic gas deficiency of late-type cluster galaxies (e.g. Vollmer et al. 2001). This process is expected to be efficient mainly in the core of massive clusters, where both the velocity dispersion of galaxies and the density of the X-ray emitting gas are at their maximum. For this reason, ram pressure is often criticized for not being able to explain the observed quenching of the star formation activity already present at $\sim$1 virial radius (e.g. Boselli and Gavazzi 2006). Two recent observations, however, seem to indicate that ram pressure stripping is more efficient than previously expected, and that it can act also at the periphery of rich clusters. These are the striking observation of a few intermediate-mass galaxies with long ($\sim$100–200 kpc) HI (Scott et al. 2012) and Hα (Gavazzi et al. 2001; Yagi et al. 2010) tails of neutral and ionized gas generally pointing in the opposite direction than the cluster core, in the periphery of Coma and A1367. The lack of any associated old stellar component, expected whenever the tails are produced by gravitational interactions, is a clear sign of an ongoing ram pressure stripping event. Preliminary results of the current imaging surveys seem to indicate that the presence of tails of ionized gas is a quite common phenomenon ($\sim$50 % of the observed objects in Coma and A1367). This observational evidence, supported by recent hydrodynamic simulations (Tonnesen and Bryan 2009), makes ram pressure a compelling alternative process that affects the evolution of late-type galaxies in nearby, rich clusters.

How do these considerations compare with the most recent results obtained thanks to the multifrequency analysis of nearby clusters, and in particular to those obtained for the Virgo cluster mentioned above? The most important result of these works is that the Virgo cluster environment has deeply modified the evolution of its members. The dominant elliptical galaxies of each single cluster substructure have been formed during a major merging event occurred late in the past, when the cluster was assembling through the accretion of small groups. The most massive galaxies ($M_{star} > 10^{9.5}\,\mathrm{M}_{\odot}$) were also affected by strong gravitational interactions active within the groups infalling into the cluster (pre-processing). At lower luminosities, however, the dynamical interaction with the hot and dense intergalactic medium emitting in X-rays has played a more and more important role. In dwarf systems, the shallow potential well is not sufficient to retain the gaseous component anchored on the disc in galaxies moving at high velocity ($\sim$1000 km s^{-1}) within the cluster. The dynamical pressure exerted by the IGM (ram pressure) is sufficient to rapidly remove their interstellar medium quenching, on short timescales, their star formation activity, thus transforming gas-rich star-forming systems into quiescent dwarf ellipticals (Boselli et al. 2008a,b). The different components of the ISM (atomic and molecular gas, dust) are removed outside-in, producing truncated discs in the young population tracers in massive objects, while retaining gas only in the nucleus in the brightest dwarfs. Indeed, late-type galaxies in Virgo are generally devoid of their atomic and molecular gas (Boselli et al. 2014b; Solanes et al. 2001), and the most recent `Herschel` observations have also indicated a stripping in the dust component in the outer discs (Cortese et al. 2010b, 2012). This picture is fully consistent with the formation of the faint end of the red sequence at recent epochs, as well as with the large infall rate of dwarf galaxies observed in Virgo (Boselli et al. 2008a; Gavazzi et al. 2013). It also explains the kinematic properties of dwarf elliptical galaxies, often supported by rotation when located at the periphery of the cluster (Toloba et al. 2009, 2011), as well as the structural properties of a large fraction of the dwarf Ellipticals of the cluster (presence of discs, spiral arms, bars, etc.; Boselli et al. 2008b; Lisker et al. 2006). This evolutionary picture explains the origin of a typical category of cluster members, those generally called "transitional objects". These are low-luminosity galaxies with spectrophotometric, morphological, and structural properties intermediate between those of Im-BCD and dE-dS0 (Boselli et al. 2008a), whose existence was first noticed by Binggeli et al. (1985). As their name clearly indicates, these are galaxies now undergoing the transformation.

How can these results be extended to less extreme environments such as groups and filaments? Clearly, here both the density of galaxies and that of the intergalactic medium decrease significantly. It is also the case for the velocity dispersion which significantly drops given the lower mass of the system. Since ram pressure stripping is proportional to $\rho_{IGM} V_{gal}^2$ (where ρ_{IGM} is the density of the intergalactic medium and V_{gal} is the velocity of the galaxy moving within the cluster), its role becomes less and less important with the decreasing mass of the cluster system. It might be, however, still important in dwarfs, where the gravitational potential well is very shallow and can thus hardly retain the gaseous component anchored to the stellar disc. The physical conditions encountered in groups can be comparable to those observed at the periphery of rich clusters, where the first effects of the environment on galaxy properties are visible (at $\sim$1 virial radius) (Boselli and Gavazzi 2014).

Because of the decrease of the velocity dispersion of the group, the gravitational interactions between its members last longer than in rich clusters and become thus more and more important. It is thus conceivable that in low density regions galaxy harassment becomes more important than the dynamical interactions with the hot intergalactic medium. The observations in the local universe clearly show that the red sequence of galaxies is already formed in relatively low density regions such as those encountered in relatively small groups in the Great Wall structure within the Coma/A1367 supercluster (Gavazzi et al. 2010). We can also remember that these structures are very similar to those present at early epochs during the first formation of massive clusters, that cosmological simulations suggest occurred via the aggregation of small groups of galaxies (Gnedin 2003; McGee et al. 2009). We can thus imagine that the evolutionary picture that we have described here is valid through cosmic time: the relative importance of gravitational interactions with respect to that of dynamical interactions with the intergalactic medium decreased with the age of the universe since the mass of the dynamical systems grew with time (local clusters are obviously more massive than those present in the past). At the same time, gravitational interactions become more and more important in galaxies of increasing stellar mass, where the dynamical interaction with the intergalactic medium becomes important only in the highest density regions and after long timescales.

When I present the most recent results on the study of the effects of the environment on galaxy evolution in conferences or seminars, I am often asked how i can explain the presence of galaxies in Virgo with clear signs of tidal interactions (NGC 4438 is the clear case) if I consider that the dominant perturbing process is ram pressure. I am fully convinced that, although ram pressure stripping is dominant in local rich clusters, this does not mean that the other processes are not acting as well. The effects of the different processes are additive, and make the perturbations on galaxies more and more efficient. The typical example is a fast ($>1000\,\mathrm{km\,s^{-1}}$), fly-by encounter of two gas rich galaxies in a cluster. The gravitational perturbation on the physical properties of the two galaxies can be minor given that the interaction does not last enough. It can, however, modify the gravitational potential of both systems, making it shallower, and thus favoring a ram pressure stripping event. We have also to remember that the considerations given above are generally based on statistical results and take into account the mean timescales necessary for a process to be efficient. The timescale for ram pressure stripping in a dwarf galaxies in Virgo, for instance, is very short (100–200 Myr; Boselli et al. 2008a), significantly shorter than that for a merging event, for a major gravitational interaction, or for multiple fly-by encounters (Boselli and Gavazzi 2006). Given that most of the dwarf galaxies, only recently entered in the cluster, have been perturbed (they are mainly quiescent dwarf ellipticals), it is thus plausible that ram pressure is the dominant process. This, however, does not rule out that in a fraction of galaxies gravitational interactions have been also important.

My personal view is that we all, observers and simulators, should still make a considerable effort in communication to try to make our works directly comparable. Simulators should try to predict the evolution of variables that can be easily and directly determined from the observations. They should study the evolution of those quantities that observers indicated as mostly affected with respect to isolated objects. At the same time, observers should try to define new observing strategies to obtain those physical quantities that the simulations identify as the most adapted to constrain the different perturbing processes. In the few cases where this effort has been done, the results have been really spectacular. One major difficulty is that simulations should consider at the same time large scales, such as those defined by clusters and their surrounding regions, where the perturbing processes start to become efficient, and small scales, required for instance to resolve the different gas phases down to the size of giant molecular clouds and HII regions.

On a more general context, my feeling is that, despite the observational evidence collected so far is quite clear an coherent, we still need several years to convince the community that the role played by the environment on galaxy evolution is not far from the one I have tried to describe above. These relatively long timescales necessary to convince astronomers on the validity of new ideas are quite common. I remember that when late in the 90s Peppo Gavazzi and myself were proposing the idea that most of the normal field galaxies have been formed through a secular evolution process mainly governed by their total mass, we were defending an evolutionary picture in total contrast with the commonly accepted hierarchical formation scenario. Our results were based on a multifrequency analysis of large samples of nearby galaxies, at that time only possible in the local universe. The multifrequency data allowed us to study at the same time the different galaxy components (stars, dust, atomic and molecular gas etc.) and thus have a coherent and complete view on galaxy evolution, fundamental for this kind of work. Now that multifrequency data are available also at higher redshift, it is striking how the evolutionary picture that we proposed $\sim$15 years ago and often criticized at that time is close to the one now mostly accepted by the community. The role of mass in shaping galaxy evolution, generally called downsizing-effect, is no more questioned, while it is widely recognized that major merging events are important only in the formation of the most massive elliptical galaxies. I am thus confident that we will have a consistent view of the role played by the environment on galaxy evolution once multifrequency data for objects at different redshift, in different bins of stellar mass, and belonging to regions of different density will be homogeneously analyzed and compared to the predictions of tuned models and simulations, exactly as we are only recently doing in the local universe.

Other signals of environmental effects come from HI observations. Spiral galaxies are often observed to be deficient in their HI content in the cluster environment with respect to their field counterparts. Martha Haynes reviews for us this subject.

5.4 HI Surveys

Questions for Martha P. Haynes:
You touched different aspects of galaxy clustering, identifying large-scale galaxy associations and exploring key environmental effects in rich environments. In the 80s you proposed evidence that cluster spirals are gas deficient, "anemic", with respect to spirals in the field and that other important effects, together with the overabundance of early-type galaxies in the center of clusters by Alan Dressler (1980), do operate in this environment. May you sketch an history of the researches on galaxy associations and address the problem of the environmental influence on galaxy properties? What progress has been achieved with new HI surveys in terms of the properties of galaxy classes?

The fact that most elliptical galaxies are found in overdense regions like the Virgo cluster was known long before a real understanding of galaxy morphology developed. My own initial work coincided with many other studies of how morphology and environment were related. It's significant to note that I began my PhD thesis working with Mort Roberts at NRAO at about the same time that Alan Dressler (1980) was undertaking his classic work to quantify the variation in the morphological population fraction as a function of local density. It is also noteworthy that, during the same time frame, Christine Jones, Bill Forman and their colleagues were moving from their early `Uhuru` cluster studies to ones making use of the new capabilities of the `Einstein` Observatory to explore how the structure of the extended X-ray emission varied with cluster properties (Jones et al. 1979). And, down the hall from them, John Huchra, Marc Davis, David Latham and John Tonry were undertaking the first CfA Redshift Survey (Huchra et al. 1983). It seems that during the 1980s extragalactic astronomy was undergoing a period of accelerating expansion.

Working with Mort Roberts, I was of course interested in the HI content of galaxies and in particular, how we could use the HI 21 cm line to learn something about the intergalactic medium (Haynes 1978) and how environment might play a role. A few years before I started my thesis research, Rod Davies and Murray Lewis (Davies and Lewis 1973) compared the HI content of 25 galaxies in the Virgo cluster with that of similar galaxies in the field. They concluded that the Virgo spirals had a decreased HI content compared to field counterparts of comparable morphology or color. While they examined the likelihood that such gas deficiency could result from collisions between galaxies in the cluster environment, they also noted the possibility that hot gas could be responsible. As of that time however, the extended X-ray emission had not been detected in Virgo so that they proposed ram-pressure stripping only as a possibility.

Soon after Davies and Lewis (1973) published their results on gas deficiency in Virgo, Bottinelli and Gouguenheim (1974) pointed out that the Virgo spirals in the earlier study were characteristically more luminous that the field spirals with which they were being compared. This residual dependence of M_{HI}/L raised the question of how to establish a fair comparison sample and how to incorporate further possible dependencies, for example on morphological type, into the analysis. My introduction to multiwavelength astronomy and the need to cross-correlate datasets was just beginning.

Fortunately for me, the library at the NRAO in Charlottesville had an amazing collection of international astronomical literature under the watchful eye of amazing librarians. Somehow, I stumbled across the original publication, in Russian, of Karachentseva's "Catalog of Isolated Galaxies" (Karachentseva 1973). And while I could not read Russian, the numbers are obvious, so I could figure out coordinates, and with a little help from various friends, was able to read enough to understand the criteria that Karachentseva used to compile her catalog. At the same time, I began my first foray into cross-catalog matching, using digital versions (on very large reel magnetic tapes rather than punch cards—truly "modern" technology) of the magnitude-limited Zwicky catalog (Zwicky et al. 1961) with the diameter-limited catalog by Nilson (1973), the latter including morphological types for entries. Only those of us old enough to remember the days of punch cards and *before* the days of computer screens will appreciate what a job this was. Within a few months, I had for myself a list of spiral galaxies that might be members of nearby clusters (their redshifts were largely unknown at this point) and a suitable sample of isolated spirals for comparison.

Being a graduate student in residence at NRAO gave me a great opportunity to learn from its staff about radio astronomy techniques and instrumentation and to be on the front line as new improvements were made to the receivers, spectrometers and software and new ways of using them to make observations. In fact, my thesis had several components, because we were trying to push the technology to explore several intriguing lines of research without really understanding what was likely to pay off, because it was all too new. One of my dissertation studies consisted of an attempt to detect HI in emission in galaxies in a set of nearby Abell clusters using the former 300-ft telescope in Green Bank. It was hard work, often frustratingly of only marginal success, and very much, only a first step. The HI in clusters project was never published beyond my thesis because its statistics and data characteristics were too poor. I needed more collecting area, a smaller beam and a better spectrometer. Fortunately for me, the reflecting surface of the huge Arecibo dish had just been replaced with a finer mesh making it a real 21 cm telescope, and I was ready to use it.

In 1978, Riccardo Giovanelli and I took up positions on the staff at the Arecibo Observatory with the explicit duty to build up the capability for 21 cm HI line science. There was almost no software, the computational resources for data reduction were minimal, and it was very hands-on. We were often called out from home to help visiting observers and for numerous other reasons, especially because we lived very close to the observatory (many of the other scientists lived more than an hour away). And, many times, we had the satisfaction of being able to troubleshoot successfully or to be useful in other ways (I once ran the telescope while Riccardo drove a sick telescope operator to the hospital).

During the first 6 months we were there, a lot of the problems could have easily been avoided had observatory staff paid a bit more attention (making changes in the software just before leaving for home; leaving a switch on a synthesizer up on the suspended structure in the wrong position). When we were called back from home five out of six nights in a row, including our first wedding anniversary, we went to the Observatory director and *strongly* suggested that the last 30 min of each daytime maintenance period be reserved for system checks. We set up a protocol for these tests and trained the telescope operators to run through the checklist. A technician who left a switch in the wrong position, requiring a 30 min round-trip trek to the platform to adjust it correctly just at quitting time, made this mistake only once. This change of routine led to a much lower rate of avoidable system problems, and we had a lot more peaceful evenings.

Because Riccardo and I made up a large fraction of a very small on-site staff in the days before remote or service observing, we helped a lot of visitors. Most of them were great and we enjoyed meeting them and were happy to help. But there were a few "others". Like the famous astronomer who called me one day because of an "emergency". It seems that he had gone running in the rain the day before and then had left his "favorite" well-worn running shoes to dry on *top of the waste basket*. He was ready to go running again, but had just discovered that they were gone, along with the trash. What was I going to do about this "emergency"? Indeed some visiting scientists seemed to assume that we were responsible for all observatory functions: "I can't find a book that I need in the library" or "The dryer in the laundry doesn't work". Was it an accident that some visiting scientists always got assigned to Room 6 (closest to the noisy cafeteria)?

But being on the Arecibo staff wasn't really about the duty; it was always exciting, scientifically promising, intellectually stimulating, and ... very tropical! And, we often had the opportunity to fill in holes in the observing schedule or be the back-up program in case other experiments could not be run. In fact, nearly 85 % of the observations for our HI line survey of the Karachentseva isolated galaxies were conducted in "back-up program" mode. Somewhat ironically, the astronomers (us) would take over the telescope when the astronomers could not use the time because it was cloudy (for airglow and meteor studies). The radar transmitters often broke, with the resultant calls on the short wave radio (there were no telephones in rural Puerto Rico on those days) calling us in the middle of the night (or the middle of a social event). At least one of us would be on our way to the Observatory within minutes of the call and ready to start observing quickly after that. It was rumored that we were the "telescope vultures" circling around hoping the klystron would fail, but that is not really true.

Undertaking surveys of large numbers of galaxies also raised interesting issues having to do with bookkeeping. The concept of "metadata" did not exist; very little information was recorded in data files. We collected boxes and boxes of index cards with hand-written notes containing information on each target galaxy and the details (observing setup, scan numbers, zenith angles, etc.) of individual observations, each of which was overseen by one of us or our students (no remote or service observing in those days). The isolated galaxies were on green cards; galaxies in Pisces-Perseus, on white ones. Many of those card boxes can still be found on the fifth floor of the Space Sciences Building at Cornell if anyone needs them.

Another chore that we faced had to do with obtained accurate coordinates for each galaxy in our target list. The recorded positions of galaxies in the Zwicky and Nilson catalogs were not good enough for the small Arecibo beam, so we got to measure a lot of positions the "old fashioned way". That process involved printing out a star field and the catalogued position of the target galaxy on a piece of transparent plastic and then overlaying that plastic onto a reproduction of the first Palomar Observatory Sky Survey (POSS) print containing the target of interesting with the star field aligned. Then, using a handheld magnifying eyepiece with a built-in reticle, we would measure the offset of the apparent position of the galaxy from its catalogued position. We thought we could record positions to within about 5–10″; that was certainly better than the original positions themselves and quite adequate for Arecibo's 3.5 arcmin beam and 30″ pointing (in those days). Over the years we measured the positions of a lot of galaxies using this method, without the benefits of the on-line digital imaging tools that exist today.

Since HI is a property of disks, it wasn't entirely surprising that the hydrogen mass to luminosity ratio might show a residual dependence on luminosity as noted by Bottinelli and Gouguenheim (1974) since the total optical light includes a contribution from the bulge and earlier spirals are typically brighter than later ones. The completion of the Karachentseva isolated galaxies survey in the early 1980s led us to a definition of HI deficiency in terms of linear diameter rather than luminosity with a further dependence of morphological type. The HI deficiency parameter <DEF> was defined as the difference, on a logarithmic scale, between the observed HI mass M_H and that expected for a galaxy of "normal" HI content, as defined by the isolated galaxies, of similar linear diameter, D_l, and morphology, T:

$$< DEF >=< logM_H(D_l, T) > -logM_H(D_l, T)_{obs} \tag{5.1}$$

The scaling relationships between the HI mass and the linear diameter for galaxies of different morphologies were presented in Haynes and Giovanelli (1984); (we didn't call them "scaling relations" in those days). The total sample size was only 324, the early types are strongly underrepresented, and our sample was based on the isolated galaxies from Karachentseva's list that were also in the Uppsala General Catalog (and also visible from Arecibo) so that the sample was diameter limited. Somewhat to our surprise (and embarrassment, given the dataset), that standard of normal HI content has been used in the literature until only recently, despite its relative crudeness.

The uncertainty in extending the relation to smaller angular diameters was obvious (measuring diameters is not as easy as it might sound), and so an improved analysis was undertaken with us by José-M. Solanes et al. (1996). Most recently, José's student Carmen Toribio used the much hugely statistics and uniform datasets provided by `ALFALFA`, the SDSS and the Galaxy Zoo to redo the analysis, looking also for additional terms to define the scaling relations for isolated galaxies (Toribio et al. 2011a,b). As before but with much more confidence, the best predictor of the expected value of M_H remains the diameter of the stellar disk, here D_{25}. The increase in sample size, and thus the robustness of the results, since the earlier work has been dramatic!

At the same time that we were undertaking the isolated galaxy survey and starting to explore clusters, others were also exploiting Arecibo's new HI line capabilities. Among them in those early days were Ed Salpeter, Lyle Hoffman, George Helou and Carlo Giovanardi. They produced lots of excellent early results on the HI content of nearby galaxies, focused largely on the Virgo cluster. In fact, because of their strong interest in the Virgo region (and thus the over-demand for telescope time at those sidereal times), Giovanelli and I turned our attention to the opposite part of the sky and thus began our exploration of the Pisces-Perseus Supercluster (an endeavor which proved quite fruitful to us).

While much of the work on Virgo was undertaken by others, the cluster did not completely escape our attention. Virgo is close enough that even its HI deficient galaxies can actually be detected, and, for the larger galaxies, HI distributions could be mapped. While detailed studies of the HI distribution require the resolution of HI synthesis telescopes, we were able to make crude measurements of the sizes of the HI disks in Virgo using the Arecibo "flat" feed system, a special line feed tapered to reduce the pickup of emission in the side-lobes. While its beam response was more manageable in terms of side-lobe contamination, the flat feed had its own set of challenges. In particularly, the feed suffered from an impedance mismatch when water droplets stuck to its slots, a circumstance of some frequency in tropical Puerto Rico. We had to hope either that the weather was dry or that the rain poured down (so that water flowed rather than sticking around the edges of the slots). In the end, a solution was suggested by the engineers, and we helped in the job to cover over the slots on the whole feed with mylar tape. Thereafter, the water would flow down the feed much better, without sticking. This simple fix improved the baseline stability of the HI line spectra considerably, even on the foggiest of nights. Over the next years, we mapped the HI distribution in both a set of isolated galaxies and Virgo spirals with Jackie Hewitt, then a post-baccalaureate research assistant working with us for 7 months. The analysis involved modeling the fluxes measured with the flat feed along the major axis of each disk to make a uniform measurement of HI size (Giovanelli and Haynes 1983; Hewitt et al. 1983), not rocket science today, but challenging the computers we had available to us then.

In 1986, we were able to put together all the measurements of HI in Virgo, including the flat feed mapping results, to investigate where within the cluster the HI deficient galaxies reside; perhaps unsurprisingly (in retrospect at least), the most HI deficient galaxies are found in the regions where the galaxy density is highest, in particular in the region around M87. And, although the maps of the HI distribution obtained with the flat feed were crude (not just in retrospect), we found clear evidence that the most HI deficient galaxies have shrunken HI disks, as would be expected from ram pressure stripping. Looking at our results now, the dataset looks pretty marginal, even if it required a lot of observing, processing and analysis time and what was then, very hard work.

Over the next 15 years, lots of measurements of Virgo were done, and by 2002, José Solanes was able to re-do the analysis much more carefully, using both old and new data, to trace the HI deficiency in Virgo in comparison with the X-ray emission (Solanes et al. 2002). Of course, many other 21 cm line detection and mapping programs focused on Virgo have been undertaken at Arecibo, Nançay, Westerbork and, most notably the Very Large Array, of the HI distribution of Virgo galaxies. All of these point to the conclusion that the HI disks of the HI-deficient galaxies in Virgo were truncated, as would be expected by ram pressure stripping, e.g. Cayatte et al. (1990); Chung et al. (2009).

With the standard of HI normalcy defined by the isolated galaxies, we embarked on the quantitative assessment of HI deficiency in other nearby rich clusters. A lot of our early work was undertaken with our good friend Guido Chincarini (Haynes et al. 1984). About every decade, improvements in system sensitivity and spectroscopic capability enabled new advances as we, and many others, attempted to expand the statistical studies of the relationship of HI content to local environment. Again with us, José Solanes et al. (1996, 2001) analyzed thousands of HI line flux measurements for isolated and cluster galaxies to explore the more subtle effects of orbits within clusters (HI deficient galaxies tend to be on more radial orbits) and timescales for depletion (gas removal is very efficient once a galaxy enters the cluster core).

The early works laid the foundations for the current day multiwavelength studies of Virgo, especially those associated with the VLA Imaging of Virgo in Atomic Gas (VIVA; e.g. Vollmer et al. 2012) and the GALEX Ultraviolet Virgo Cluster Survey (GUViCS; Boselli et al. 2014a) which confirm many of the earlier conclusions but with a tremendous increase in the richness of detail. Of particular note are the numerous recent works by Peppo Gavazzi and Ale Boselli (2006) presenting multiwavelength statistical studies and detailed observations of individual objects (Fossati et al. 2012; Fumagalli et al. 2014). Their wonderful GOLDMine database (Gavazzi et al. 2003) makes their treasure trove of multiwavelength data available for the rest of us to use.

Questions for Riccardo Giovanelli:
Radio galaxy surveys are complementary to optical surveys and have now a great development (e.g HIPASS, ALFALFA). Could you provide an historical perspective of radio surveys and in particular of HI surveys highlighting what have been their major scientific achievements for our understanding of galaxies? What is the future of radio surveys?

There are two main categories of extragalactic HI surveys: (1) the observed sample consists of targets selected from a catalog obtained at another spectral band, e.g. an optical catalog; and (2) there is no a priori catalog of sources, but every line of sight contained within a given solid angle of sky is fully sampled up to some parametric limit. The second category is usually referred to as a *blind survey*; I shall refer to the first category as a *pointed survey*. Because most lines of sight of a blind survey will contain no sources, such a survey conducted with a single beam telescope will be observationally expensive, i.e. the return in terms of detections per unit of observing time will be quite low. Blind HI surveys have then been made practically possible only after receiver arrays which sampled simultaneously many independent lines of sight came on line. The two most notable blind surveys are named HIPASS and

ALFALFA. They will be discussed in Sect. 5.4.3. Before that, however, I will focus on a couple of pointed surveys that kept me and my colleague and spouse Martha Haynes busy for a couple of decades.

5.4.1 The Perseus-Pisces Supercluster Survey

I first arrived at the Arecibo Observatory (AO) in 1976, as a visiting observer. The observatory was still in the process of digesting its first major upgrade, which replaced the wire mesh of the original primary reflector with a set of solid panels that gave the telescope excellent response at 21 cm wavelengths. Having been born in the style of a university observatory most AO users were insiders and detailed documentation was a scarce commodity. Upon arrival for my run I was given an "observer's book", one of four copies of a sort of survival manual, about 20–30 pages long, half typed and half handwritten. It contained instructions on telescope characteristics, how to cable up for your experiment, calibrate and process your data, deal with the logistics, do's and dont's of the site, including the (sometimes useful) additions and corrections by previous users. Among my memories of that visit are that of reading the contents of the book by the 40 ft long swimming pool[7] and, most vividly, that of riding the tiny cable car to the focal platform, which hangs from a set of cables tied to three towers, 500 ft above the primary. That 5-min ride to the top of the extraordinary, daring feat of engineering that is the AO telescope ranks as one of the most exhilarating experiences of my professional life. That first observing run was a bust, for I discovered that the observing configuration I was using was vulnerable to random calibration errors due to an (undocumented) engineering test switch. It did however educate me to the power of the telescope and its potential for extragalactic work. On the following year I applied for a staff position at AO. The application was successful and in late January of 1978 I moved to Arecibo. Martha defended her thesis and joined AO as a postdoc in late summer of that year.[8]

In the late 1970s, the mainstream view on the clustering properties of galaxies was quite simple: there were field galaxies, distributed randomly in space, and there were groups and clusters on scales of up to a few Mpc. The latter are gravitationally bound structures and it was thought that there was not enough time since the Big

[7]The pool had been built by (wise) decision of a former AO site director, John Findlay, the designer of the 300 ft telescope at Green Bank. That pool and the 1 km long track around the edge of the primary reflector of the telescope were—and remain—the two sporting facilities on the site. My proudest sport achievement, ever, remains that of running the 1 km track in 3 min plus 1 s, with one important regret: that of never being able of breaking the 3 min wall.

[8]I spent 13 professionally glorious years working at AO, living in a wooden house Martha and I had built in 1979, atop a hill overlooking the telescope, barely a mile away from the AO site. We designed and built the house by ourselves, working at it evenings and weekends, with occasional, honorary participation by a number of colleagues as inept, but just as optimistic as we were. Not a nail was hammered by a professional. The house still stands, still in use, after 35 hurricane seasons.

Bang for larger structures to coalesce. However, this was not the view of some independently minded folks, like Gérard de Vaucouleurs (1958), who believed that larger, coherent structures were observed, most notably what was to be known as the Local Supercluster. The sparse redshift data base available at the time gave sufficient wiggle room for both sets of views. In the late 1970s, a number of papers appeared, calling attention to streams of galaxies whose redshifts suggested the interpretation that bridges connected the widely separated clusters A1367, Coma and Hercules (Chincarini and Rood 1975; Tifft and Gregory 1976). Others pointed to entirely empty, huge volumes of space, the opening salvos of the new discipline referred to as "Voidology" by Igor Karachentsev (Gregory and Thompson 1978; Kirshner et al. 1981) [see also Thompson and Gregory (2011) for a historical review].

At the time, Martha and I were collaborating with Guido Chincarini on a project regarding the evolution of galaxies in clusters, discussed by Martha in this book. Conversations with Guido, one of the founding players of the supercluster game, were thus important in stimulating our attention to the developing debate on large-scale structure of the galaxy population. AO was then running a summer student research program, which included the invitation of a prominent figure to have an extended visit to AO and give a series of lectures for students and staff. Martha and I urged the AO administration to invite Jim Peebles, a leading figure in Cosmology. Jim accepted the invitation and visited for a week or so, during the Summer of I think 1981. His view of the supercluster and giant void claims was negative. He believed they were the results of the human brain's tendency to connect and associate, seeing structure where there was none being a life preserving evolutionary trait of early humans. In his lectures he showed several slides illustrating redshift distributions of real data vis-a-vis random or signal containing distributions of comparable sample size, and challenged the audience to tell which one was which. To Jim's annoyance, the audience tended to pick the correct answer. I think it was that week with Jim that finally challenged Martha and me to get into the redshift survey game.

The main source of uncertainty at issue was the small size of the redshift data samples. The purported bridge between A1367 and Coma had fewer than 50 galaxies. We knew that AO could detect the HI emission—and thus the redshift—of a spiral galaxy at the Coma cluster distance, in about 15 min of observing time. In 10 h we could then, for example, double the sample size which had been used to claim the Coma bridge. Using a variety of optical catalogs, we explored the positional distribution of galaxies accessible, given the restricted zenith angle coverage of the AO telescope. The same restriction imposed that a source could be tracked at most for some 2 h per day, so proposal pressure at AO was and remains a strong function of the right ascension of observational targets. The northern galactic hemisphere, with Virgo, Coma, Hercules and the innermost part of the Milky Way, was—and remains—in high demand by extragalactic HI and pulsar projects. The section of the southern galactic hemisphere accessible by the AO telescope (roughly 22^h to 04^h in RA) was in much lower demand. We also noticed that the sky distribution of the galaxy population in that region, when projected on the plane of the sky appeared not to be random [something Bernheimer (1932) had noticed in

1932, we later learned]: the "field" galaxies showed a strong preference for being located along a linear structure , a roughly 90° long filament of sorts, along which several rich clusters and groups were seen, like beads on a string.

At the distance of the clusters apparently embedded in it, the length of the filament translated to approximately 100 Mpc, many times bigger than any cluster of galaxies. We estimated that a survey of pointed observations of about 1500 galaxies would nicely do, in order to verify or negate the 3D coherence of the structure beyond any doubt. We were advised to not request telescope time all at once, but rather to present annual requests based on evidence of success from previous runs. We then did the survey in piecemeal fashion, as we saw the filament slowly showing its true nature.[9] The filament turned out to be real. Martha and I were awarded the Draper Medal by the National Academy of Sciences in 1989 for our contribution to "Cosmological Physics", which was nice.

5.4.2 The Peculiar Velocity Field

The 1990s were the decade of another major pointed survey for us. By measuring the peculiar velocities of a large sample of galaxies we would reconstruct a 3D map of the mass distribution in the local Universe and measure its "convergence depth". This would also allow the determination of the peculiar velocity of the MW, providing a corroboration of the Doppler nature of the dipole component of the CMBR field. The basic assumption of this program was that the cosmic expansion is locally affected by the gravitational perturbations arising from density inhomogeneities, so the observed recession velocity of a galaxy is the vector sum of two components: the Hubble expansion and the peculiar velocity induced by the cumulative perturbation due to all density inhomogeneities. The measure of a galaxy's peculiar velocity requires an accurate redshift and a redshift-independent estimate of the galaxy distance. The HI observation of a galaxy would deliver the first and part of the second.

Spiral galaxies have been endowed by Nature with a very tight scaling relation, first noted by Mort Roberts. It relates the optical flux of a galaxy to its rotational velocity. Since the measurement of the optical flux is dependent on the distance of the galaxy and the rotational velocity of the disk is not, in 1977 Brent Tully and

[9] Much progress with observations tended to be made during each year's end holiday period, taking advantage of the fact that most astronomers preferred to spend time with their families than with the telescope, on that period. Moreover, on some days like Christmas and New Year all telescope operators were given the day off, and only a few staff members were allowed to run the telescope in "solo" mode. It then became a tradition for us to request that time each year, and spend it with the galaxies. Actually, there was another form of sharing. For several years, at midnight on December 31st I would connect the output of the music player in the telescope control room to the PA system up on the telescope platform, at full volume: for a few minutes, Pavarotti would be broadcast up to many miles away from AO, welcoming the new year with Puccini's *Nessun Dorma* from Turandot.

Rick Fisher published an influential paper proposing that the relation could be used to estimate the distances of galaxies, independently on the value of their redshifts.

Rotational velocities can be obtained from the line-width of a galaxy's integrated profile. Having collected a large sample of HI detections for the PPS survey and other projects, part of the data base for the peculiar velocity survey, named SFI (for Spirals Field I-band), was already in hand. However, much work was needed to extend the sky coverage of that sample and to obtain near infrared photometry for all the targets. A broad alliance was necessary, providing access to telescopes, specific technical know-how and manpower for what was to become a severe challenge in more than one way. At the same time, a competing team was pursuing similar science goals. They called themselves the "Seven Samurai" and their paramount discovery was called "The Great Attractor". We referred to our group as "Snow White and the Seven Dwarfs". Our Great Attractor was not as great as that of the Seven Samurai.

The need for whole sky coverage led us to join forces with Don Mathewson, long time director at Mt. Stromlo. He arranged for Martha and I to be invited to Australia as Visiting Fellows of the Australian National University in 1988 and was a wonderful host. We spent several weeks at Stromlo and carried out two intense observing runs: one at the Parkes radiotelescope, where we had been allocated HI time for a long series of 24 h observing days and a second at the Anglo-Australian Observatory at Siding Spring Mountain, where we enjoyed the longest stretch I have ever had of photometrically perfect I-band imaging nights.

It took us several years to complete the peculiar velocity project. We realized that the most important part of the project was the full understanding of error propagation and thus the quality of the template luminosity–linewidth relation, which we would use as a kinematical reference frame. Other experiments had adopted as reference that defined by galaxies in a single cluster, such us Coma. We thought we could do better (and more correctly) by using as reference the combination of a basket of clusters, *after* the peculiar velocity of each had been corrected for. As a result, our template luminosity–linewidth relation was based on 782 galaxies in 24 clusters, which yielded a "zero point" accuracy of 0.02 mag. That figure, and the absolute calibration of the template using 15 Cepheid distances yielded a value for the Hubble constant at $z \simeq 0$ of $H_0 = 69 \pm 5\,\mathrm{km\,s^{-1}}$ (Giovanelli et al. 1997). We also recovered the peculiar velocity of the Local Group with respect to the CMB reference frame of $611\,\mathrm{km\,s^{-1}}$ toward $l = 273^{\mathrm{deg}}$, $b = +27^{\mathrm{deg}}$ (Giovanelli et al. 1998) (Fig. 5.15).

5.4.3 ALFALFA

The second Arecibo Upgrade matured through the 1990s. Until then, correction for the spherical aberration of the primary reflector was done by "line feeds", tapered waveguides with very narrow bandwidths. The ones operating at 21 cm were about 40 ft long with bandwidths of 45 MHz, a severe constraint. The first phase of the upgrade consisted in building a 50 ft wide, reflecting ground screen

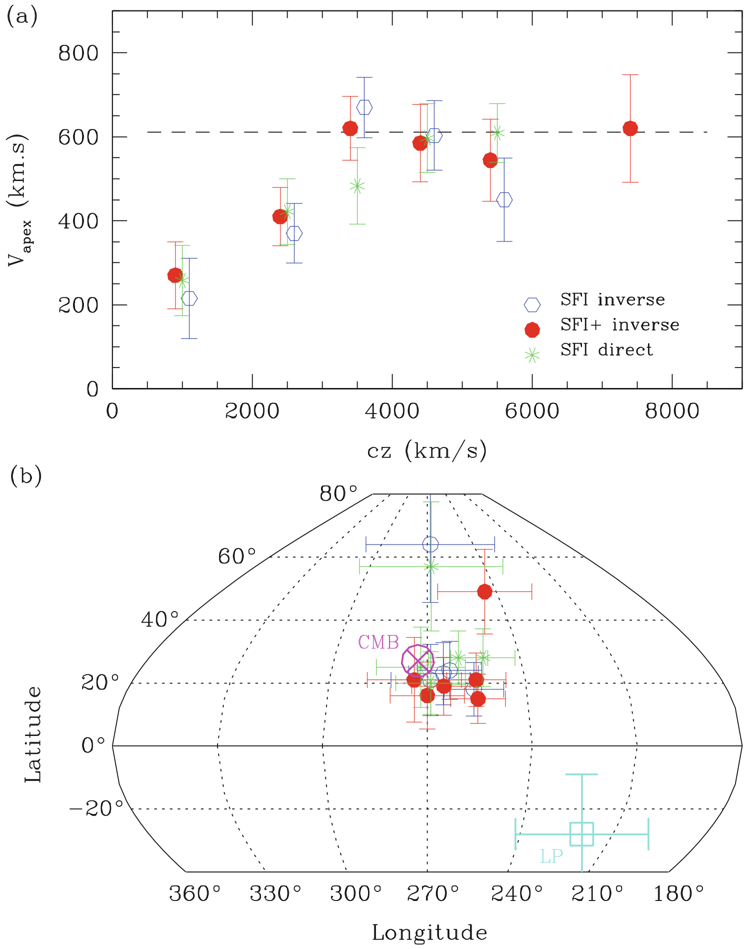

Fig. 5.15 The *upper panel* shows the convergence of the reflex motion of the LG with respect to galaxies within spherical shells of mean radii of 1000, 2500, 4500, 5500 and 7500 $km\,s^{-1}$. *Different symbols* refer to different treatments of the error propagation. The *horizontal dashed line* corresponds to the peculiar velocity of the Local Group as measured in the CMB reference frame. The *lower panel* shows the apex of the LG motion with respect to each of the concentric shells, asymptotically tending toward the CMB dipole, both in amplitude and direction

around the 1 km long perimeter of the primary, the purpose of which was reducing the impact of vignetting for observations at high zenith angles. With the second, more important phase line feeds were replaced with an optical system consisting of a secondary and tertiary Gregorian subreflectors, which dramatically increased the instantaneous bandwidth, frequency coverage and sensitivity of the telescope. One of the rejuvenating effects of the Gregorian system was that of delivering a new field of view several beamwidths wide. This made possible the implementation of multiple feed arrays. In other words, with such a device, named ALFA, AO could turn into a 7-pixel camera. It became then possible to carry out ambitious blind surveys in times which would not exceed the duration of an average astronomer's lifetime.

Although I had left Arecibo and moved to Cornell in 1991, I had remained actively involved with the Upgrade, particularly in planning discussions for the feed array. My one and only paper in the engineering IEEE publications was as a co-author in the design of the array. I was eager to see the array built and to start using it. Unfortunately there were delays in the completion of the Gregorian upgrade and the production of the array. In the meantime, the HIPASS survey was carried out, with a 13 feed array mounted on the 64 m Parkes antenna. HIPASS covered a large fraction of the sky and had an important scientific impact. ALFA started operating at AO in 2004. There were several survey proposals submitted; ALFALFA was, in terms of its technical readiness, the most mature of the lot. Observations started in February of 2005. The data processing pipeline, a major software design and production effort, was entirely designed and developed by our group at Cornell, mainly by then graduate students Brian Kent and Amelie Saintonge and myself. We had decided that in order to guarantee high data quality, each observing run would be monitored by a member of the survey team, either remotely or in person at the site. Martha's organizational talents were dedicated to the training of observers, mastering and documenting protocols for data flow and for the creation of a highly successful enterprise named the Undergraduate Alfalfa team (UAT). UAT is a consortium of faculty and students at 19 undergraduate college institutions. It monitored a large fraction of the ALFALFA observing runs and processed data streams through the calibration, bandpass correction and RFI flagging. In exchange for these important commitments, research projects were reserved for members of the UAT, carefully tailored to the special circumstances of the faculty and students at their institutions. An annual workshop have been held regularly at AO, with the participation of about 40 students and faculty with core members of the ALFALFA survey each year. Martha and Rebecca Koopmann, a Physics Professor at Union College, have together been heart, brain and backbone of this program, which has been funded and enthusiastically used as an exemplary paradigm by the US National Science Foundation.

Observing time was initially allocated effectively to the survey, but when we were about past the midpoint mark, major emergencies at AO slowed the observations' flow, and instead of taking 5 years, the completion of observing took nearly 8 years. On October 26 of 2012, after 808 observing sessions and 4741 h of telescope time, we declared victory. Coming after the very successful HIPASS, the challenge to ALFALFA was tough, but the superior quality of our survey shined. While HIPASS covered 30,000 square degrees of sky, ALFALFA covered only 7000, but while the average detection rate of HIPASS was less than one source every 5 square degrees, that of ALFALFA was about 5 sources to the square degree: ALFALFA is delivering more that 30,000 detections, vs. the 5000 of HIPASS. A large fraction of HIPASS sources are confused, due to the poor angular resolution of the Parkes antenna, while fewer than 2 % are confused in ALFALFA. The median redshift of HIPASS detections is about 3000 km s^{-1}, while that of ALFALFA is about 8500 km s^{-1}, which thus provided for the first time a cosmologically fair sample of the HI Universe.

The success of ALFALFA to date has largely rested on its collaborative organization, the continued engagement of its broad and diverse team and its emphasis on the hands-on involvement of students. ALFALFA is an open collaboration, and new members continue to join the team "free of charge" to carry out studies which utilize extant data sets, provided that they do not interfere with previously approved projects, especially those involving students. Thirteen completed Ph.D. dissertations (8 at Cornell) have been based largely on ALFALFA to date and 12 current graduate students are actively engaged in ALFALFA-based thesis research. Running a successful survey must be a labor of love, as well as an endurance contest. You must be ready to give a lot and expect little in return, in terms of recognition for the thousands of hours you have spent, glued to your terminal writing or fixing code, flagging, processing, fighting poor data, unruffling feathers of oversensitive colleagues.

Thank you Riccardo for the vivid picture of the huge effort taken in performing a very demanding radio survey. Below we review results from space missions that either specifically or at least in part have been dedicated to sky surveys with a large impact on our knowledge of galaxies.

5.5 Galaxy Surveys from Space

5.5.1 UV Surveys

Questions for Luciana Bianchi:
The Galaxy Evolution Explorer (GALEX) imaged the sky in the Ultraviolet (UV) delivering the first sky surveys at these wavelengths. Could you briefly describe the survey and its most important results? What have been the progresses with respect to previous UV satellite observations?

UV observations have opened an important sky window. Which kind of studies take advantages of these data? Which progresses could be achieved in the next future?

In contrast with a steady succession of increasingly powerful sky surveys at all other wavelengths, there had been no UV survey prior to GALEX. Because of this persisting gap, by the time GALEX was built, detector technology and data transmission and storage had made huge progress. As a result, the first UV survey was not a tentative "first look", as early X-ray or IR surveys had been, but it equalled depth and photometric quality of major ongoing surveys at other wavelengths, optical-IR in particular, and even surpassed them for classes of objects whose emission peaks in UV (Bianchi et al. 2011a). It is then not surprising that GALEX opened new avenues of research, in the realm of galaxies in particular, as well as provided several comprehensive results. And I believe many more are awaiting to be extracted from the vast GALEX database.

When we put GALEX surveys in a wider perspective, you may wonder why no sky survey was performed in UV before. The *International Ultraviolet Explorer* (IUE) has provided some 10^5 high and low-resolution UV spectra from 1978 to 1996. Shortly after HST was launched, O'Connell noted "UV astronomy to date has been overwhelmingly based on spectroscopy", and advocated—as many others did—the science potential of extensive UV imaging, demonstrated by Astro-1 (O'Connell 1991) (see Sect. 1.5.1). The lack of a UV survey was even more surprising given that conventional telescopes yield good imaging in UV, while X-ray imaging required significant technology development. Each generation of instruments on HST included UV spectrographs (GHRS, FOS, then STIS and COS) as well as imaging cameras with UV capabilities, and the usage and role of UV spectrographs remained most prominent. In HST 's early years, this prominence was perhaps enhanced because the perfect mirror with imperfect curvature delivered the expected sharp FWHM, but left $>80\,\%$ of the source light outside the sharp core, affecting the expected imaging performance but not as much the spectroscopic capabilities.

Many scientists and space agencies did realize that a small investment in a UV sky map would have maximized the scientific return from the increasingly powerful UV instruments on Hubble, as well as enabled critical progress in many fields. The need for a UV survey was long recognized; the first attempt I know of was an idea to fly IUE's spare telescope, equipped with UV imagers. Many proposals for UV surveys, with varied designs tuned to specific objectives, were submitted to space agencies. Why was none funded and built until the 90s? Perhaps an underlying cause was in the technology not being ripe for a UV survey that would deliver breakthrough results (detectors in particular). Finally, in 1992 NASA-ASI JUNO (Bianchi and Martin 1998)[10] was approved, to perform the first UV sky survey. But after phase A, very positively evaluated, JUNO nonetheless did not proceed due to funding issues. It was then turned into GALEX, with a slightly modified design to address the then most compelling science questions, such as measuring the history of star formation in the universe from redshift 0 to 2. This time, it flew.

GALEX, a NASA *Small Explorer* launched in 2003, imaged the UV sky for almost a decade (Bianchi 2014; Martin et al. 2005a). A 50 cm Ritchey-Chrétientype telescope fed light to a FUV ($\lambda_{eff} \sim 1528$ Å, 1344–1786 Å) and an NUV ($\lambda_{eff} \sim 2310$ Å, 1771–2831 Å) micro-channel plate detector simultaneously, thanks to a dichroic beam splitter. With a field of view of $\approx 1.2°$ diameter and spatial resolution of $\approx 4.2/5.3$ arcsec (FUV/NUV) (Morrissey et al. 2007), GALEX conducted imaging and spectroscopic sky surveys of different depth and extent (Bianchi 2009; Bianchi et al. 2014b; Morrissey et al. 2007). The All-Sky Imaging survey (AIS)

[10] Joint Ultraviolet Nightsky Observatory, a bilateral collaboration between USA's NASA and Italy's ASI (C. Martin and L. Bianchi PIs for the two agencies), was ranked first among NASA's selected SMEX missions and by ASI, then cancelled, then turned into GALEX.

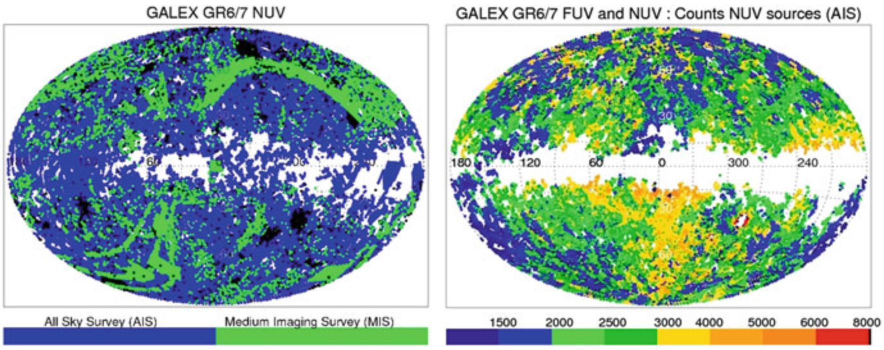

Fig. 5.16 *Left:* sky coverage of GALEX UV surveys in Galactic coordinates (AIS in *green*, MIS in *green*, all other surveys in *black*). *Right:* density of NUV sources, from AIS data with both FUV and NUV detectors exposed The source counts, even at the AIS depth, contain a considerable fraction of extragalactic objects, the number increasing at faint magnitudes and dominating the counts at $m_{NUV} \gtrsim 19$ABmag. See Bianchi et al. (2011a, 2014b) for discussion of the UV surveys

covers most of the sky to a depth of $m_{FUV} \sim 20/m_{NUV} \sim 21$ ABmag, the Medium Imaging Survey (MIS) reaches ~22.7 ABmag in both FUV and NUV (Bianchi 2014; Bianchi et al. 2014b), Fig.5.16. Deeper surveys covered limited areas (but large cosmological volumes), their very long exposures accumulated during repeated visits also allow serendipitous variability searches (Conti et al. 2014 and references therein).

The GALEX database at the end of the mission contains sky images in FUV and NUV, 214 million source measurements, and >100,000 UV grism spectra.[11] GALEX provided deep-sensitivity, panoramic UV morphology of extended nearby galaxies (Bianchi et al. 2014c; Gil de Paz et al. 2007; Thilker et al. 2005), and unbiased measurements in two UV bands of tens of millions of galaxies across the sky. The instrument sensitivity and the darkness of the UV sky allowed it to trace star formation (SF) over several orders of magnitude, and to discover it in environments where it had been elusive, or even believed to not occur. Extended UV-emitting disks were discovered in ~30 % of galaxies (Sect. 7.3. UV-emitting stellar complexes were also revealed in the Leo ring , a ~200 kpc wide gas structure seen in radio HI light, presumed to be left over from the formation of two central galaxies, where no deep imaging had previously succeeded to reveal signs of star formation. Under some assumptions, GALEX measurements translate into $\Sigma_{SFR} \sim 2 \times 10^{-4}\ M_{\odot}/yr/kpc^2$ (Thilker et al. 2009); whether the UV sources in the Leo ring are tidal dwarf galaxies with no pre-enrichment, must be assessed with abundance measurements.

[11]GALEX data and pipeline products are accessible at http://galex.stsci.edu; more science-ready catalogs and tools can be found at http://dolomiti.pha.jhu.edu/uvsky, including information on sky coverage, science products, UV source classification, coefficients for extinction correction and magnitude transformation (Bianchi 2009, 2011, 2014; Bianchi et al. 2007, 2011a).

Regarding the comparison with previous UV instruments, there has been no precursor for surveys, therefore the progress enabled by GALEX is complementary to, and different from, any other. Selection of some classes of objects, traditionally based on optical colors, X-ray properties, etc., can at last benefit from unbiased UV source catalogs, notably sample selection of star-forming galaxies, $z \sim 1.0$ QSOs (Hutchings and Bianchi 2010a,b), hot white dwarfs (Bianchi et al. 2011a). The wide field-of-view of GALEX uniquely enabled detection of extended UV low-surface brightness structures, such as tidal streams between galaxies, extended UV-emitting nebulae, low-level extended SF (Fig. 5.17). A stunning example of GALEX's sensitivity to young stellar populations is the Magellanic Bridge (Fig. 5 of Bianchi 2014). FUV easily reveals the hot stars, hence unambiguously traces recent star formation, unconfused by earlier SF history (SFH). Because hot massive stars evolve rapidly, they carry the imprint of their birth clusters, yielding a spatial and temporal tomography of SF across the galaxy, while the optical light is the combination of stars formed throughout the galaxy's history and of their dynamical mixing (Fig. 5.17).

For comparison, the UVOT telescope on SWIFT and OM in XMM have imaging capability in NUV and optical filters, with smaller field-of-view and slightly higher resolution than GALEX, but lack FUV capabilities (and are not performing wide surveys). FUV affords higher sensitivity to the hottest stars, and the dark sky in FUV facilitates detection of otherwise elusive star-forming sites. UVOT and OM filters, combined with GALEX, could however contribute to characterization of dust extinction.

The main science driver for GALEX when it was designed was to measure the history of star-formation in the red-shift range 0–2, 80 % of the life of the universe, when most stars were formed, and star-formation appeared to have undergone significant evolution. Several initial works addressed this topic, and showed the "downsizing" of SF galaxies mass (Lee et al. 2011; Martin et al. 2005b, 2007; Salim et al. 2007; Wyder et al. 2009). A significant contribution of GALEX is the color-magnitude diagram (CMD) of galaxies (Salim et al. 2007; Schiminovich et al. 2007; Wyder et al. 2007): when UV measurements are added to optical measurements, the *red sequence* of quenched, passively evolving galaxies and the *blue cloud* of star-forming galaxies clearly separate. In between, in the so-called *green valley*, transition galaxies were found in some cases to evolve in the opposite (to conventional evolution) direction, due to rejuvenation episodes (Chap. 7.3).

Finally, GALEX UV surveys uniquely enabled an unprecedented, unbiased census of Milky Way hot white dwarfs, which are elusive at all other wavelengths for their high temperatures and low optical luminosity. These samples are relevant for understanding the chemical yields from intermediate mass stars (Bianchi et al. 2011a). Too faint to be observable beyond the Milky Way, for now on Galactic results rests our knowledge of such objects.

The GALEX archive will remain a long-lasting resource for statistical studies of $z \lesssim 2$ QSOs, star-forming galaxies, hot stellar objects, nebulae and the ISM. It provides the road-map for planning future UV instrumentation and follow-up observing programs in the UV and at other wavelengths.

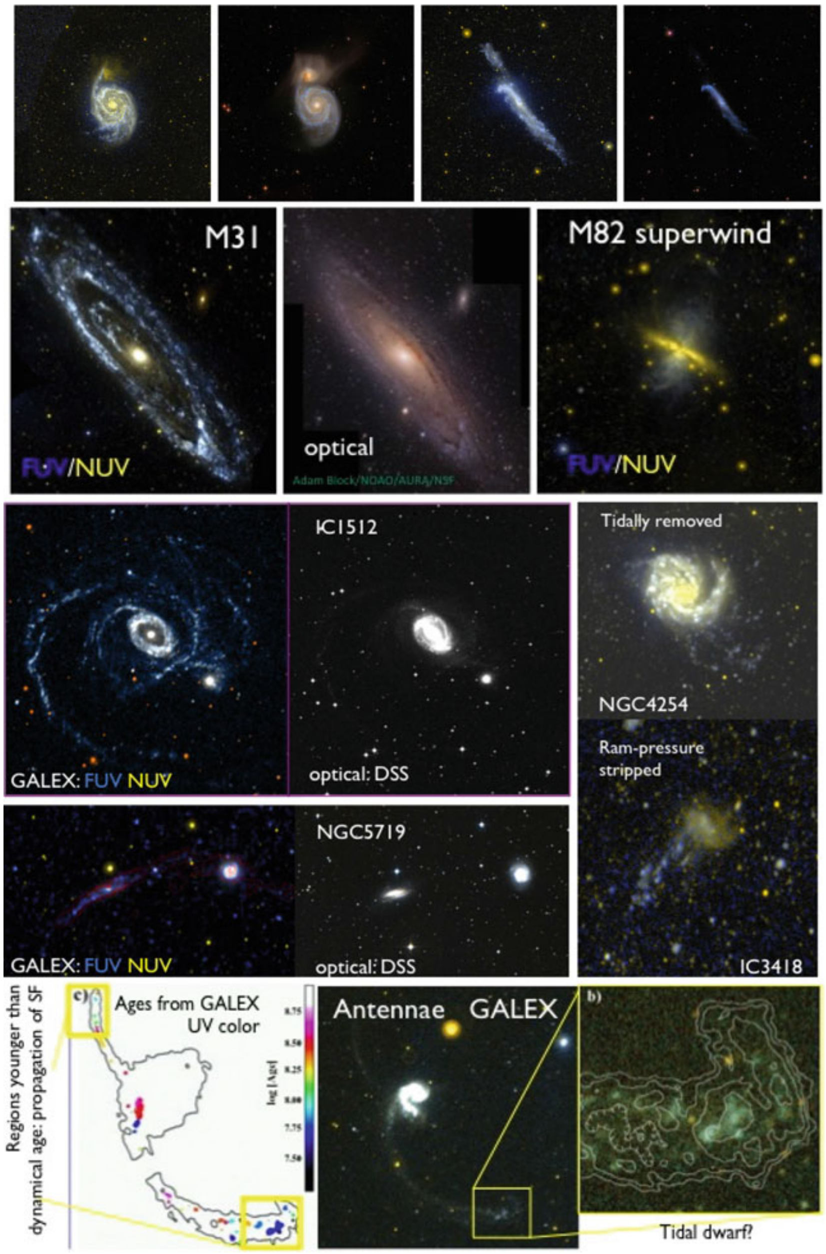

Fig. 5.17 *From top:* galaxy morphology in UV (*left*, GALEX) enhances young stellar populations and suppresses cold, longer-lived stars: companion galaxies appear or disappear [M51 (Calzetti et al. 2005), NGC 4656; *right panels*: SDSS]. Massive star forming galaxies M31 (*left*; GALEX, *right*: optical) and M82 (GALEX). Examples of SF driven by strong interactions (Neff et al. 2005). Ages of UV clumps derived from GALEX data suggest outwards propagation of SF in the Antennae (Hibbard et al. 2005)

While GALEX have only in this last decade provided a UV sky coverage, in the far IR domain we started to acquire important data since the epoch of IRAS. We ask Alessandro Boselli to provide us a short history and summary of the results obtained after the launch of ISO and Herschel.

5.5.2 Infrared Surveys

Questions for Alessandro Boselli:
Herschel is one of the most recent space telescopes devoted to big nearby galaxy surveys in the IR region of the electro-magnetic spectrum. Could you trace the history of previous IR surveys (e.g. ISO) and give us a hint of the exceptional results achieved today by Herschel in the definition of galaxy properties?

In the spectral domain 5–1000 μm the continuum emission of normal galaxies is due to the thermal emission of the dust component of the interstellar medium. During their evolution, massive stars produce and inject into the interstellar medium heavy elements (metals) that later aggregate to form dust grains of different size and composition. These dust grains efficiently absorb the bluer component of the general interstellar radiation field. This captured energy is later re-emitted in the mid and far infrared spectral domain. Dust, thus, plays a major role in the process of star formation since it participates actively to the cooling process of the interstellar medium. Furthermore, this spectral domain is also characterized by different atomic and molecular emission lines of primordial importance in the study of the process of star formation (tracers of star formation, cooling of the gas) and in the determination of the physical properties of the interstellar medium, in particular those of the different gaseous components, as summarized in Boselli (2011).

The study of the infrared emission of galaxies virtually begins with the advent of the IRAS mission (Neugebauer et al. 1984), by far one of the most fruitful space mission since ever. IRAS made an all sky survey in four photometric bands (12, 25, 60, and 100 μm) and detected hundreds of thousands of extragalactic sources (Beichman et al. 1988; Moshir et al. 1992; Sanders et al. 2003). The study of the far infrared integrated properties of galaxies was literally busted by the success of this mission. IRAS discovered, for instance, the ultra-luminous infrared galaxies, objects whose infrared luminosity exceeds $10^{12}\,L_\odot$. This high luminosity is produced by a powerful starburst probably formed during a merging event where the stellar emission is heavily attenuated by the dust component (Sanders and Mirabel 1996). IRAS was also perfectly suited for making statistical studies such as those aimed at determining the far infrared luminosity function of galaxies in the local universe (Soifer and Neugebauer 1991). Because of its limited angular resolution ($\sim$1.5 arcmin), however, the study of the infrared properties of resolved galaxies was limited to less than one hundred nearby extended objects (Rice et al. 1988). The success of the IRAS mission pushed the community to define other ambitious infrared space missions. The first of these was the *Infrared Space Observatory (ISO)* (Kessler et al. 1996), launched in 1995 by the European Space Agency. Contrary to IRAS, the ISO mission was designed to make pointed observations of selected targets. The novelty of ISO with respect to IRAS was that of harboring four different instruments: a photometer able to extend the spectral domain to ∼180 µm (ISO-PHOT, Lemke et al. 1996), a camera able to take images and low resolution spectra in the 2.5–10 µm spectral domain (ISO-CAM, Cesarsky et al. 1996), plus two spectrographs working in the 11–44 µm (ISO-SWS, De Graauw et al. 1996) and in the 43–197 µm (ISO-LWS, Clegg et al. 1996) spectral domain. Although mainly focused on the study of the high redshift universe, several works targeted nearby galaxies with the aim of characterizing their spectral energy distribution (Boselli et al. 1998, 2003; Dale and Helou 2002; Dale et al. 2001), of determining the physical conditions of the ISM (Malhotra et al. 2001), of studying ultraluminous infrared galaxies (Klaas et al. 2001; Lutz et al. 1998; Thornley et al. 2000; Tran et al. 2001) and AGNs (Tacconi et al. 2002), or of identifying new star formation tracers using the PAHs emission (Boselli et al. 2004; Roussel et al. 2001).

The advent of the Spitzer space mission (Werner et al. (2004)) significantly improved our knowledge of the far infrared properties of galaxies. Thanks to its performing imaging and spectroscopic capabilities [IRAC (Fazio et al. 2004), MIPS (Rieke et al. 2004), and IRS (Houck et al. 2004)] Spitzer provided the community with unique sets of infrared data in the spectral domain 3–160 µm for well defined samples of normal nearby galaxies. The SINGS survey (Kennicutt et al. 2003) is certainly the most representative among these. SINGS is a complete infrared imaging and spectroscopic survey of 75 local galaxies selected to cover a wide range in morphological type, luminosity, and galaxy properties. Similar set of data have been obtained for other important nearby galaxies including the Magellanic clouds (Meixner et al. 2006). These data have been of fundamental importance for characterizing the typical far infrared spectral energy distribution of local galaxies (Dale et al. 2005, 2007) and determine their typical dust mass, PAH abundance, and stellar radiation field using tuned models of dust emission (Draine et al. 2007; Mu noz-Mateos et al. 2009). They have been also of paramount importance for determining accurate dust attenuation recipes and calibrating empirical star formation tracers now widely used for quantifying the activity of star formation of galaxies at all redshift (Calzetti et al. 2007, 2010; Hao et al. 2011; Kennicutt et al. 2009), for studying the relationship between the different gas components of the ISM and the activity of star formation in resolved galaxies generally called Schmidt law (Bigiel et al. 2008; Calzetti et al. 2005; Kennicutt et al. 2007; Leroy et al. 2008), and compare the dust to gas ratio to the Galactic one (Leroy et al. 2007). The Spitzer spectroscopic data have been used to quantify the importance of metallicity in the emission of PAHs (Engelbracht et al. 2005; Smith et al. 2007). I can also mention the more recent Spitzer post-cryogenic mission S^4G survey of ∼2300 nearby galaxies in the 3.6 and 4.5 µm bands (Sheth et al. 2010).

Few years later (2006) was launched the AKARI satellite (Murakami et al. 2007) by the Japanese Aerospace Agency. This mission was designed to make an infrared all sky survey in the 9–200 μm spectral domain (Ishihara et al. 2010), thus extending IRAS in spectral range and sensitivity. A major improvement in the study of the infrared properties of nearby galaxies, however, came from the ESA Herschel space observatory (Pilbratt et al. 2010), launched in may 2009. With its 3.5 m diameter primary mirror, the largest space telescope ever in orbit, Herschel had a collecting area $\sim$ 17 times larger than that of its predecessor Spitzer. Herschel was equipped with two imaging cameras/medium resolution spectrometers, PACS (60–210 μm, Poglitsch et al. 2010) and SPIRE (194–671 μm, Griffin et al. 2010), and a high-resolution heterodyne spectrometer HIFI (De Graauw et al. 2010). Several guaranteed time or open time key projects have been devoted to the study of the infrared emission of nearby galaxies. The largest among these is certainly the KINGFISH project (Kennicutt et al. 2011), an imaging and spectroscopic survey with PACS and SPIRE of the SINGS sample. The Herschel Reference Survey (HRS, Boselli et al. 2010a) is a SPIRE and PACS imaging survey of a complete volume-limited, K-band-selected sample of 323 galaxies in the local universe. To have an idea of the time requested to define and prepare a guaranteed time key project such as the HRS, I remember that I first proposed to the extragalactic working group of the SPIRE consortium the observation of a complete sample of nearby galaxies late in 1998, thus more than 10 years before the launch of Herschel. These two projects are very complementary since the first one, taking benefit of the spectroscopic data, is perfectly defined for the study of the physical properties of the interstellar medium, while the completeness of the second one is recommended for determining the statistical properties of an unbiased sample. To these projects we should also add the Very Nearby Galaxy Survey, a detailed imaging and spectroscopic survey of 13 well known nearby representative objects (P.I. C.D. Wilson), and the Dwarf Galaxy Sample (DGS, Madden et al. 2013) a survey of 50 metal poor, star forming galaxies in spectroscopic and imaging mode. Other important projects are HELGA (Fritz et al. 2012) and HERM33ES (Kramer et al. 2010) devoted to the study of the dust properties of M31 and M33.

The exploitation of the Herschel data is still under way. The results obtained so far are very interesting and are giving us a new view of the dust properties of nearby galaxies. There is, indeed, a growing evidence that the diffuse dust of the ISM, including the cold component emitting in the sub-mm spectral domain, is heated by both the general interstellar radiation field and the ionizing radiation produced within the most active regions of star formation (Bendo et al. 2010, 2012; Boquien et al. 2011; Boselli et al. 2012). Through the study of the infrared SED, the Herschel data have been of paramount importance to show that metal-poor, star forming galaxies have an excess of emission at 500 μm whose physical origin has still not been fully identified (Boselli et al. 2010b, 2012; Ciesla et al. 2014; Dale et al. 2012; Kirkpatrick et al. 2013; Rémy-Ruyer et al. 2013). These data have been of paramount importance for determining dust masses and gas-to-dust mass ratios and to trace the typical scaling relations concerning these parameters in local galaxies spanning a wide range in morphological type, stellar mass and metallicity (Cortese et al. 2012; Galametz et al. 2012; Rémy-Ruyer et al. 2014; Smith et al. 2012). The Herschel data have been also used to study the CO-to-H_2 conversion factor within galaxies at a kilo-parsec scale (Sandstrom et al. 2013), or to study on similar scales the variation of dust attenuation over the disc of galaxies (Boquien et al. 2012, 2013; Kreckel et al. 2013). Detailed studies of the far infrared spectroscopic properties of a few nearby representative objects have been also done using Herschel data: these includes starburst galaxies such as Arp22 (Rangwala et al. 2011), Mrk 231 (Van der Werf et al. 2010), and M82 (Panuzzo et al. 2010), or dwarf galaxies (Cormier et al. 2010a), but are still under way in normal galaxies.

A complete and coherent view of the emission properties of galaxies in the spectral domain covered by Herschel is still far to be reached. This is mainly due to the complex nature of the ISM as revealed by the huge number of emission lines only recently discovered thanks to the spectacular performances of the different instruments. The various teams involved in these studies are also making a huge effort in trying to characterize and compare the properties of the different components of the ISM (dust, atomic and molecular gas, metals), and understand the role of the different heating sources (stars of different age and temperature, X-rays, cosmic rays) to the energetic balance regulating the physical properties of the ISM within galaxies.

The X-ray domain requires long exposure time per object so its is quite difficult to produce surveys. We ask Ginevra Trinchieri to provide a shapshot of the main results obtained with the X-ray satellites.

5.5.3 X-Rays Surveys

Questions for Ginevra Trinchieri:
May you provide an historical perspective of the development of X-ray galaxy surveys and of their main goals? What have been the more relevant results achieved?

The launch of the Einstein satellite, with the first images of the X-ray sky, has changed our view and our interest in galaxies, and opened a new way of studying them. The issue of the Astrophysical Journal dedicated to the first Einstein data contains the first images ever of the Virgo cluster galaxies and of M31 in the X-ray band (Forman et al. 1979; Van Speybroeck et al. 1979). It soon became evident that normal galaxies are intrinsically faint and complex systems, located in environments that are often stronger sources of X-ray emission than the galaxies themselves. Deep and high resolution X-ray images provide the most direct and powerful way to detect galaxies and to resolve them in their individual components. As we have learned from experience, the Einstein satellite had limited capabilities relative to the needs of galaxy studies, both in terms of spatial resolution and of spectral range and resolution. However, as the first mission to observe galaxies, Einstein has given an incredible contribution to the field, and has laid the foundations of many of the still unsolved questions of today. Accreting X-ray binary systems (XRB) were observed for the first time outside the Milky Way and the Magellanic clouds in spiral galaxies: this opened a new study of the stellar population at different stages of evolution, since now the evolved stages could be investigated through the high energy signatures from XRBs and Supernova Remnants; a hot interstellar medium was discovered in early-type galaxies, until then considered "gas-poor" systems, and hot halos could be searched for in spiral galaxies as well. A first comprehensive summary of the early discoveries on galaxies can be found in Fabbiano (1989).

Far from being of the quality of the Chandra images that we can obtain and use today, still the first X-ray images of local galaxies immediately revealed extended emission and a complex morphology, and laid out the foundations for new discoveries.

M31 and M33, in the local group, observed first with Einstein and then with ROSAT, showed a large number of individual bright sources scattered around the whole stellar body (Figs. 5.18 and 5.19). In the bulge of M31, sources are at higher density than in the disk, but sources could be traced out to the outer galaxy regions well covered with ROSAT. Similarly, slightly more distant spiral galaxies like M101, M83, M51 and many others gave a broadly similar view: several sources could be seen scattered over the entire stellar body, very much like what we observed in the Milky Way. Only the brightest sources could be detected individually: the limiting luminosities of the first Einstein observations were of the order of a few $\times 10^{36}$ erg s^{-1} for M31/M33. Fainter sources appeared as a more diffuse, unresolved emission in the disks. Later observations with ROSAT, which were geared to obtain images of deeper sensitivity, were able to reveal more sources, although the real breakthrough in population studies required the much higher resolution Chandra images.

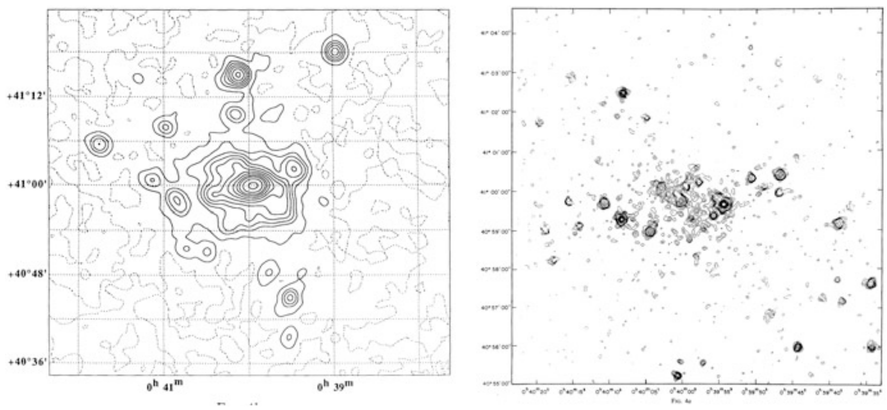

Fig. 5.18 Images of M31 obtained with the Einstein satellite: the larger view obtained with the lower resolution IPC instrument (*left*) and higher resolution central region with the HRI (*right*) [from Trinchieri and Fabbiano (1991)]

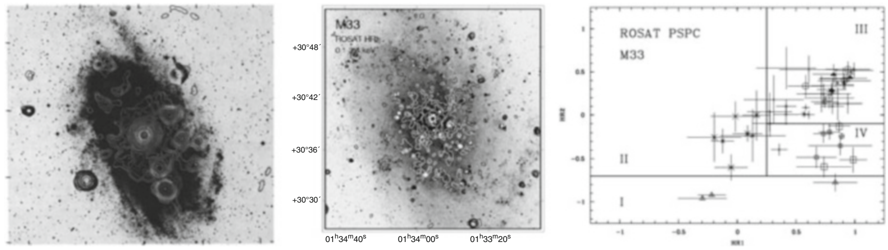

Fig. 5.19 Images of M33 obtained with the Einstein (*left*) and ROSAT (*center*) satellites. The *rightmost panel* shows "X-ray" colors" of the sources in M33, defined as source count ratios in three separate energy bands. Four regions are identified, used to separate different classes of sources: I=SSS, II=foreground stars, III=AGN and XRB, IV=SNR [from Fabbiano et al. (1992) and Haberl and Pietsch (2001)]

Spectral parameters could be obtained only for the brightest sources, and with a simple spectral model. For most sources, only colors were derived, based on the count ratios in different energy bands, typically soft/intermediate/hard, and compared to assumed models. X-ray colors have been used since, with energy bands re-defined according to the specifics of the mission/detector used, and better geared to differentiate sources into broad classes: among the first attempts, Fig. 5.19 shows the four groups chosen to classify the M33 sources studied with ROSAT, which were divided into SuperSoft Sources, SNR and XRB, belonging to M33, and Stars and AGN as interlopers in the foreground and in the background. The larger class is composed of XRB and AGN, which are grouped together since they cannot be distinguished based on their colors.

In fact, with the sole exception of the nuclear sources associated with AGNs, which could be identified and excluded from the analysis with the aid of imaging data, X-ray binaries (both Low and High mass systems) and Supernova Remnants were found to contribute most of the observed emission in normal galaxies, just as was known to be the case for the Milky Way. Coronal emission from stars, detected in the Galaxy, is too faint to provide a relevant contribution even as the integral of the whole population, and was therefore essentially neglected until the much deeper Chandra surveys, where significantly fainter individual sources could be identified and subtracted from the whole.

Two new and interesting classes of sources were found: thanks to Einstein, Ultraluminous X-ray sources were observed for the first time, compact bright sources with luminosities in excess of $L_X \sim 10^{39}\,\mathrm{erg\,s^{-1}}$ that could be interpreted as Black Hole (BH) binaries with $M_{BH} > 100$–$1000\,M_{\odot}$ (see Fabbiano 1989; Fabbiano and Trinchieri 1987; Long and van Speybroeck 1983). This mass regime proved to be of immediate interest as it could provide a convenient link between the stellar mass BH and the supermassive examples located at the center of galaxies. For this reason these sources have prompted theoretical and observational work to interpret their nature and their properties, a quest that is still on-going [see a recent review by Feng and Soria (2011) and references therein]. Observation of the Magellanic clouds with Einstein (Long et al. 1981) also revealed a class of Super Soft Sources

(SSS), characterized by an extremely soft spectrum and medium-high luminosities, which were interpreted as accreting binary sources with a massive White Dwarf (WD). With the softer spectral response of ROSAT, more were identified in the MC and discovered in M31 (see Kahabka and van den Heuvel 1997). With deeper Chandra and XMM-Newton observations, SSS were also discovered in nearby spiral and elliptical galaxies. We now know that SSS are a more heterogenous class of objects, not always associated with WDs: they have been observed in external galaxies of all kind, although they are more frequently found in later types, and they could reach very high luminosities (USS, Ultraluminous SSS class) and slightly higher energies (QSS, Quasi-soft X-ray sources). A whole new line of investigation to better define the properties of this class of sources is occupying scientists and promoting dedicated Chandra and XMM-Newton observations of nearby objects [e.g. M31, see a review by Di Stefano et al. (2010)].

It soon became evident that the galaxy morphological type was a key factor in determining the X-ray characteristics of normal galaxies: broadly speaking, spiral galaxies were typically dominated by individual sources, the brighter examples visible directly in the images, while elliptical galaxies appeared to be brighter in X-rays and more extended than spirals, with little evidence of individual sources, and with a relatively smooth and quasi-symmetric emission that could be traced well beyond the extent of the stellar population.

Prior to the first Einstein observations of galaxies, early-types were typically assumed to be "gas-poor" systems: with very few exceptions, the observations failed to detect evidence of cold gas in them, and different mechanisms were proposed to explain how the gas produced internally by stars was removed. The discovery of the extended X-ray emission in these sources, interpreted as due to massive halos of a hot interstellar medium, changed our view of these systems, making them "gas-rich" galaxies (Forman et al. 1985; Trinchieri et al. 1986).

This interpretation was supported by several observed properties of early-type galaxies. X-ray luminosities are higher than expected from the XRB, rescaled from the optical light and compared to luminosities in spiral galaxies. Spectrally, the overall emission is "softer" than in spirals (Fig. 5.20). The emission extends outside of the optical body and in some cases with tails and distortions (e.g. M86, NGC 4472 in the Virgo cluster , NGC 7619 in Pegasus I, among the first examples; Fig. 5.20). All together, these were convincing evidence for the existence of a hot gaseous halo, dynamically interacting with the hotter intracluster medium, known to exist from previous high-energy missions.

The discovery of these hot halos in early-type galaxies prompted many new inquiries. First, as tracers of the potential well of these systems, they were used to measure the total mass and hence to constrain the Dark Matter they contained: from the observed properties of the gas, such as the radial surface brightness profiles and the spectral results on the temperature and its radial distribution, and assuming gas in hydrostatic equilibrium, large total masses were then measured, with mass-to-light ratios significantly higher than expected from the stars, reaching values as high as 50 $M_\odot/L_\odot$ (see Fig. 5.21). Thus early-type galaxies acquired large amounts of dark matter together with the long-sought for interstellar medium!

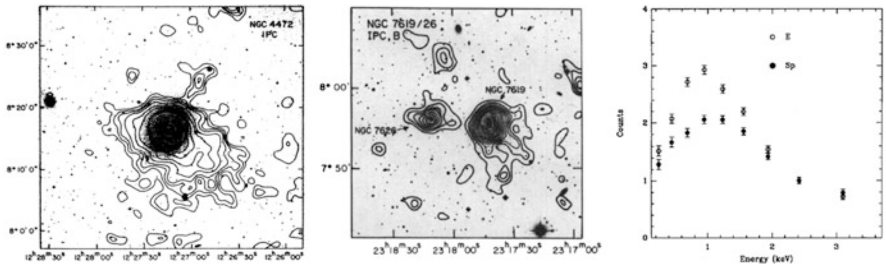

Fig. 5.20 Images of NGC 4472 in the Virgo cluster and NGC 7619 in Pegasus I group, obtained with the `Einstein` satellite. The *rightmost panel* shows the spectral distribution of the photons resulting from the average of the "spiral" and "elliptical" spectra in the `Einstein` data. The softer E spectrum is evident in the larger soft/hard photon ratio [from Fabbiano et al. (1992) and Kim et al. (1992)]

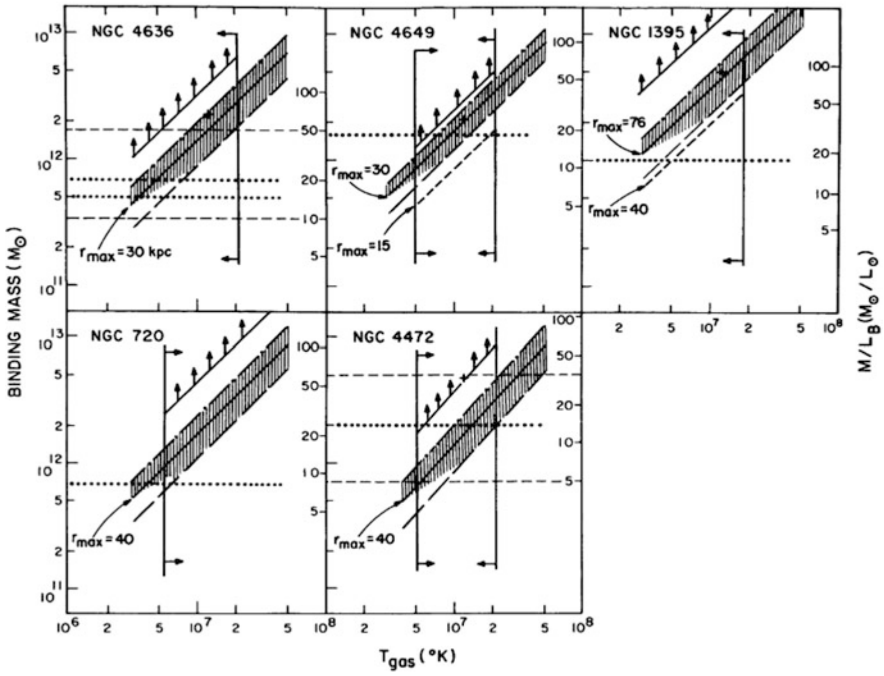

Fig. 5.21 Mass estimates with uncertainties and mass-to-light ratios (*dotted lines*) obtained from the early `Einstein` observations of elliptical galaxies, compared to the mass-to-light estimates obtained from the optical velocity dispersions (*dashed lines*). Different assumptions on the radial temperature profiles and outermost radius determine the *shaded region*. Details in Trinchieri et al. (1986)

Only with later galaxy surveys could we really understand the validity of the underlying assumptions: in many objects the assumed azimuthal gas distribution was not confirmed, and significant distortions, cavities and structures were later discovered; the average temperatures measured with the Einstein and ROSAT spectra were heavily contaminated by the presence of a population of XRB, and obey a more complex temperature distribution than assumed, that, when neglected, gave wrong results; hydrostatic equilibrium and the subsequent measures of total mass were challenged, in particular for lower luminosity objects, where the competing emission from the stellar component is not negligible; the total extent of the emission needed to be revised in light of more sensitive observations, and considering that many of the brightest examples are in general located at the center of a group, implying a strong relation with the environment, and the group's potential well, deeper than that of the galaxy alone. Nonetheless, and in particular for bright gas dominated objects, hot halos could be still used to estimate total masses, once all the uncertainties and relevant cautions have been properly applied.

While the presence of hot gas was accepted as an established property in early-type galaxies by everybody, how much gas is present is each object has been a subject of debate, and it is still difficult to predict from the other observed properties, mostly based on optical/IR data and linked to the stellar population. In particular, a key ingredient to be considered when measuring the gas properties is the LMXB population, which is always present and contributes, although in different proportions to the gas component. Failure to account for it has contributed to the general confusion in the field, in particular with the limited capabilities of the instruments prior to Chandra and XMM-Newton. A second important consideration is that assuming models that are too simple could lead to incorrect results, such as for example, the assumption of single temperature plasmas, when more complex situations could be present. A simple example of the consequences introduced by assuming the wrong spectral model was done already in Trinchieri et al. (1994), with ROSAT spectral data for NGC 4636 [Fig. 5.22, see a more comprehensive discussion in Buote and Fabian (1998)]: three different spectral models assumed (a single temperature plasma with low abundances, two and three temperature plasmas with 100 % abundances) give virtually identical results in terms of quality of the fit, but the three models indicate very different physical conditions of the gas! These considerations were refined later, and not just for the early-type galaxies [a spectacular example is given by the analysis of the Antennae galaxies (Baldi et al. 2006), see Buote (1999) for comments on early-type galaxies].

A proper measure of the chemical composition of the extended hot gaseous component is needed if we want to understand the connection between the history of star formation and the metal enrichment history. Hot halos in massive elliptical galaxies are expected to retain the metals injected by previous generations of stars, keeping track of the star formation history via the heating and enrichment by supernovae. They also are a record of any contribution from external acquisition and interaction/merging phenomena. The chemical composition and metal contents derived from the spectral data were wrongly measured in many works, as a result of poor modelling combined with the limited constraining power of the data quality

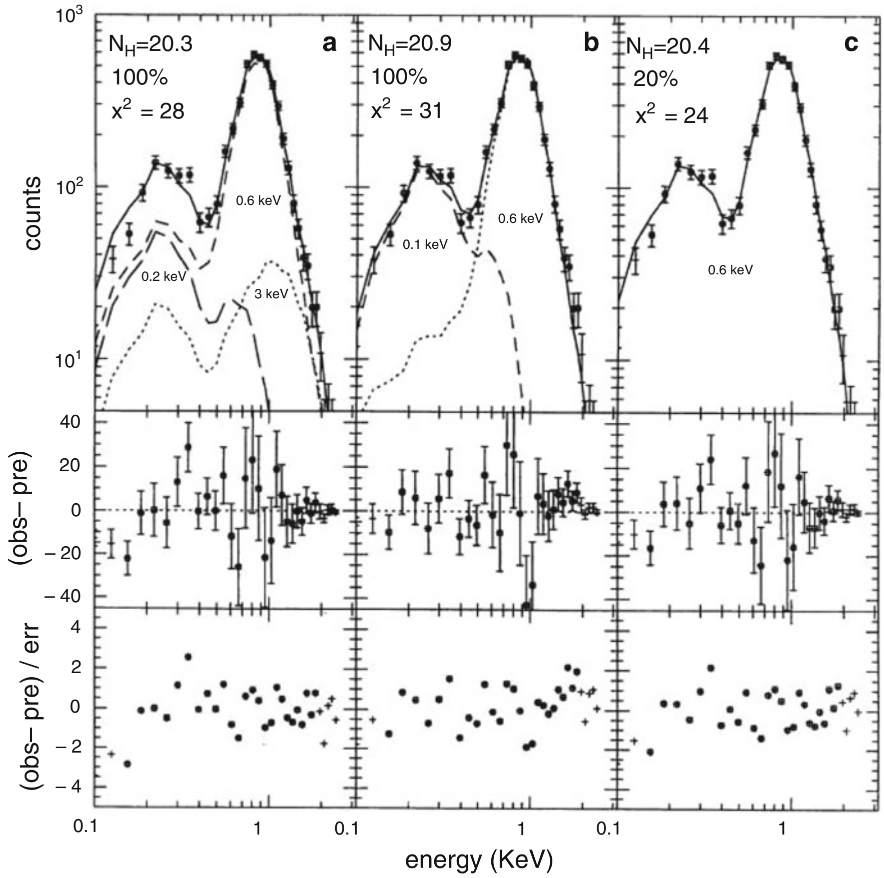

Fig. 5.22 Comparison of the different spectral models applied to the ROSAT data in the inner 1′ region of NGC 4636. Details in Trinchieri et al. (1994)

[see a summary in Sarazin (1997) and references therein]. The suggested sub-solar Fe abundances accepted were in contrast with expectations from theoretical stellar evolution models and were also different from the metallicities measured in the stellar population. To reconcile these discrepancies, both the reliability of plasma codes and of the models for mass injection rates from SN (Type I in particular) were questioned. We are now aware of the potential inhomogeneities in the gas distribution, and the importance of a multi-temperature spectral model, or, better, of spatially-resolved spectra, cleaned of the contamination from binaries, to properly measure the spectral characteristics of the gas. We are also coming to realize that the picture might be more complex still, and that the metal content may be different in galaxies with different X-ray luminosities/gas content; yet these early results, though partially incorrect, have nonetheless given rise to many debates and discussions, and have greatly helped to advance in the field.

Hot halos, and generally gas, found in early-types, prompted the next natural question early-on: is there gas in late-types? is it in a halo outside the stellar component? The short answer is: some gas was reported in disks (but it was hard to separate it from the integrated emission of unresolved sources), but not in halos, except when associated with starbursting activity. NGC 253, M82, NGC 3079, NGC 4631, all have outflows, but they are also characterized by enhanced starformation and diffuse or filamentary Hα emission associated with outflowing gas. Gas was searched for, edge-on spirals were selected and observed specifically to test model predictions, but very little evidence of hot halos was reported.

The different average characteristics of the early- vs. late-type galaxies have influenced how we have been studying them since. Statistical studies of the X-ray properties have been looked at separately and the two classes have been compared to look for similarities and/or differences (see Fabbiano and Trinchieri 1985; Trinchieri and Fabbiano 1985 and Fig. 5.23). This separation has been refined later, as we progressed in our understanding of the galaxy properties. Spiral galaxies were then separated into subclasses; starbursts were analyzed as a different class; early-type galaxies have been classified into fast/slow rotators, core vs cuspy light distribution objects, boxy vs disky in shape, young vs old in stellar population... Nonetheless the main results of those first investigations are still valid and can still be used for a rough, but still representative, description of the main average characteristics,

The first and most natural comparison between the optical and X-ray total luminosities indicated that these two quantities are correlated for both spiral and elliptical galaxies, but with significantly different slopes and scatter: in the spiral sample, the correlation is tight and L_X scales roughly with L_B, consistent with emission from binary sources, representing a nearly constant fraction of the galactic stellar population; in the early-type sample, the scatter is much larger and the correlation steeper. The interpretation of this diagram has been at the center of long debates.

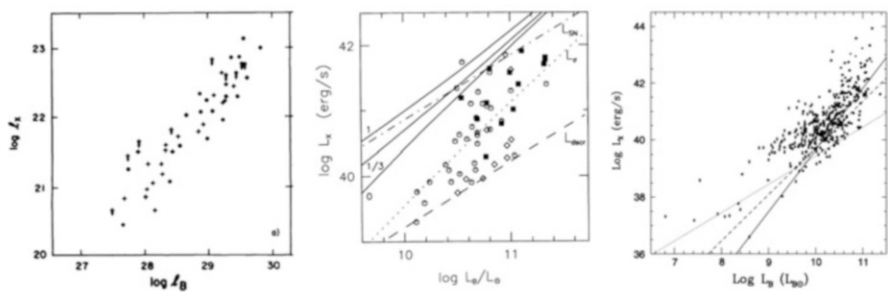

Fig. 5.23 Observed distribution of the L_X-L_B relation for late- and early-type galaxies from Einstein data (*left* and *middle panels* respectively), and from ROSAT data (*right panel*) for the early-type sample. *Lines* in the central panel indicate the different contributions to the observed emission expected: from discrete sources; gravitational input, SN heating. Details are in Fabbiano and Trinchieri (1985); Ciotti et al. (1991); O'Sullivan et al. (2001)

The scatter in this correlation, and the difficulty in relating the presence and amount of hot gas to other galaxy properties, has stimulated many works since, both theoretical and observational.

The bottom part of the diagram could be interpreted as due to emission linked to the XRB, roughly proportional to the optical luminosity or mass, as in spiral galaxies. In spite of no direct evidence of individual sources of the kind observed in spiral galaxies, nonetheless XRB must be present in all early-types as well. They are present in the bulge of M31, the relation derived from the spiral sample defines a sort of minimum emission also in the E+S0 diagram, and the theory predicts that LMXB form in globular clusters and in the general stellar population. Therefore a fraction of the emission must come from XRB in all galaxies. In addition, the spectra of lower luminosity ellipticals appeared harder than that of high luminosity objects, a signature of growing importance from LMXB. All doubts and debates on the contribution of LMXB in early-type galaxies have been cleared many years later by `Chandra`, who imaged them in all galaxies, regardless of their hot gas content, in fact also reducing considerably the importance of hot halos in low-luminosity systems. As a result, now all analysis consider multiple components for the unresolved emission, which take into account both XRBs and plasma emission.

At the high luminosity end of the distribution, emission hot gas is responsible for the "excess" emission. This component appears to be almost independent of the luminosity, or of the luminous mass. This evidence has prompted a wealth of research activities, both theoretical and observational, focused on interpreting this and on finding proxies and tracers that could allow some "predictive powers". Galaxies have been proposed to be in different stages of evolution, from inflows capable of retaining and heating the gas to the observed temperatures to outflows responsible for producing winds that would expel the interstellar medium and lower the X-ray luminosity to the values due to the stellar component alone. We now understand that hot halos result from a balance between gravitational heating, feedback from stellar evolution and/or a central AGN, and confinement/interactions with the environment. The physical properties and metal enrichment that can be measured in the hot gas can in principle be exploited to reconstruct the evolutionary history of both the interstellar matter and the host galaxy.

We have come a long way since the first `Einstein` data in our understanding of galaxies in X-rays, and the advent of the more advanced observatories has given us the opportunity of confirming original ideas that were based on much cruder observational proofs. Many issues are still unsolved, and more needs to be done to unravel the complexity of these faint and complex sources. However, though tentative, most of the relevant issues that would further our understanding of galaxies and their evolution were laid out based on the first cruder `Einstein` images.

Spectroscopic surveys are the natural follow-up of imaging surveys. Most of our knowledge on the large scale structure of the Universe comes from these observations. We ask to Jonathan Bland-Hawthorn and Bianca Poggianti to sketch the successes obtained with these surveys.

5.6 Spectroscopic Surveys

Questions for Jonathan Bland-Hawthorn:
A great observing effort has been dedicated to map the Universe through redshift surveys. Generations of instruments have been specifically projected for this purpose. May you draw a short history of the redshift surveys and of the instrumental development? What are in your view the main results, after decades of observations, and few generations of instruments, in terms of galaxy mapping in the Universe? What is the future in this area?

This is a very big question requiring a major review to cover all aspects of it. I can really only give a few off-the-cuff remarks here. Redshift surveys are mostly in optical and infrared wavelength regions although object selection can be at any other band, e.g. selection from existing radio, X-rays and UV surveys. The most massive surveys under discussion are the 'photometric redshift' surveys that use all-sky broadband imaging in order determine crude redshifts from the transformed spectrophotometric profile for each object. I am not overwhelmed by the results to date although one can see that this is likely to be a powerful technique in the `LSST` era.

For spectroscopic redshifts, large multi-object surveys of galaxies have been possible with two distinct approaches. I would make a distinction between:

1. multi-slit spectrographs doing large surveys of more distant galaxies (e.g. `Keck/LRIS`, `Magellan/GMACS`, `CFHT/MOS`, `VLT/FORS`, `Keck/DEIMOS`, `Gemini/GMOS`); and
2. multi-fibre spectrographs obtaining single spectra for large samples of galaxies (e.g. `SDSS`, `AAT/2dF`, `AAT/6dF`, `VLT/FLAMES`).

The largest and most cited of these studies are the multi-object, single-fibre surveys. Several million galaxies now have estimated redshifts. Arguably the key result from these studies was the detection of baryon acoustic oscillation (first peak) by the 2dF and SDSS teams (Cole, Peacock, Eisenstein) for which the Shaw Prize was awarded in 2014. Other results include the evolution of the galaxy and quasar luminosity function, and the build-up of clusters, groups and galaxies through mergers and accretion.

Some of the most successful surveys have focussed on following up the deepest imaging from the `HST` and the `Subaru` Deep Field. This has led to an unambiguous identification of the earliest galaxies and QSOs beyond z$\sim$ 7, and the star formation rate density and the build-up of metals with cosmic time. These surveys have made use of the superior spectroscopic performance of multi-slit spectrographs (e.g. `Keck/LRIS`, `Gemini/GMOS`), specifically, for more accurate sky subtraction.

On spatially resolved surveys, a combination of large imaging and spectroscopic surveys have led to important new insights on how galaxies evolve across the galaxy color (e.g. U-B) vs. stellar mass diagram (or luminosity), and resolve into different 'clouds.' Much like stars in the Hertzsprung-Russell diagram, we even talk about a 'main sequence' when plotting galaxy baryon mass vs. the total star formation rate.

An interesting development is the use of multi-band photometry to measure the stellar mass of a galaxy, rather than dynamical measures. Since baryons dominate the central parts of galaxies, these are thought to be equivalent to a factor of two. Galaxy properties are now understood to depend on the importance of galaxy mass and the depth of the central gravitational potential.

There are other approaches but the scientific return has been much less notable. Interestingly, even with millions of galaxy redshifts behind us, the interest in huge galaxy surveys continues. Next generation instruments for the extremely large telescopes will include multi-object capability. Presently, these are focused on the optical and infrared, although the latter suffers from strong OH emission lines that dominate the background. Instruments like `FMOS` on `Subaru` and `Mosfire` on the `Keck` are beginning to explore this region but still have to combat the bright infrared sky. In Australia, we have been exploring photonic solutions to total sky suppression with some success. But to generalize these techniques for existing instruments is challenging largely because of the difficulty of mass production. We foresee widespread use on `ELT`s fed by adaptive optics. It seems to me that we have barely begun to explore AO-assisted instrumentation.

I spend a great deal of time peering into the future. There are so many technological ideas, but one has to balance beautiful concepts with practical considerations like funding, risk and complexity, reliability and robustness. For example, 15 years ago, in order assist the high-redshift discoveries at `Subaru` Telescope through the use of Lyα detections, I developed a new instrument concept that was reviewed in detail by a `Subaru` delegation. I published the design of a tuneable filter that could operate in an f/2 beam (e.g. `Subaru Hyper SuprimeCam`) while retaining monochromaticity over the field. It uses cascading Lyot layers, half wave plates and polarisers. In order for this instrument to be realised, we will need nanoscale patterning across multilayers that are cemented together. The required technology exists but is already expensive over 20 mm surfaces, let alone the 300 mm surfaces needed at `Subaru`.

An interesting recent development has been the desire to combine the power of integral-field spectroscopy with multi-object spectroscopy. First off the blocks is the Sydney-AAO Multibundle Imaging (`SAMI`) spectrograph which will have mapped 3400 galaxies by the end of 2016. The SDSS `Manga` instrument will have mapped 9000 galaxies by the end of 2017. In Sydney, we are now building a `SAMI` successor called `Hector` that will map 100,000 galaxies by the end of the decade. In the near-infrared, ESO has recently commissioned `KMOS` which deploys 25 image slicers over a wide field. Complementary efforts are the `SKA` precursor telescopes, in particular, the `ASKAP` focal plane array that will map 600,000 galaxies in HI over the same time frame.

Questions for Bianca Poggianti:
Galaxy spectroscopy provides, even at low resolution, the first fundamental information about recession velocity, inner kinematic, chemical abundance, etc. Galaxy spectra, obtained at different wavelength ranges, have often been organized in Atlases. What have been in your view the main Spectral Atlases?

Can you, please, discuss the contribution they give in understanding the nature of galaxies?

Spectroscopic surveys (like e.g. `VIMOS`) have largely contributed, not only to define the large scale structure of the Universe, but also to characterize the galaxy properties, as stellar composition element abundance, etc. May you provide an historical perspective of the development of spectroscopic surveys and of their main goals? What have been the more relevant results achieved by spectroscopic surveys?

Integral field spectrographs are today the frontier of such research studies. Could you provide a brief panoramic view of the new 3D spectroscopic surveys? What is their advantage?

You are right that galaxy spectroscopy is a primary source of information for studies of galaxy evolution, the formation of structure in the Universe and, more in general, for almost every field of astrophysics today. Although in the last decades approximate redshifts of large samples of galaxies have been sometimes derived from photometric information alone, based on the so-called photometric redshift technique, spectroscopy is necessary to obtain precise redshift measurements, "locate" a galaxy in the Hubble flow and find its cosmological distance, as well as determine its membership to a group or cluster of galaxies and trace the cosmic web of structures.

It is useful to stress that a redshift measurement can now be converted with a relative small uncertainty to a "time" from the Big Bang, and a lookback time from today, thanks to the fact that the cosmological parameters defining the relation between redshift and time (Hubble constant, matter density parameter and vacuum or "dark" energy density parameter) are known to a good accuracy. When I started to do astronomy, "just" 25 years ago, this was not the case, and while stellar evolution was already able to age-date the stars in galaxies, the uncertainty in converting this into a corresponding redshift was very large, in some cases larger than the age-dating error. Now it is the opposite.

Spectral atlases are collections of galaxy spectra, usually for low redshift samples, chosen according to certain criteria, that are made publicly available to the whole astronomical community. A very influential atlas has been the one of Kennicutt in 1992 (Kennicutt 1992), who provided the first atlas of optical *integrated* galaxy spectra for galaxies spanning all morphological types. The availability of such atlases is very useful for systematic studies of the variation of spectral properties, for providing a local set of spectral templates and in some cases for deriving K-corrections. More recent and larger spectral atlases now exist in the optical (e.g. Jansen et al. 2001) and in the near-IR (Mannucci et al. 2001) and even at longer wavelengths (Rampazzo et al. 2013), and when combined with photometric data they allow to build spectral energy distributions over a wide range of wavelengths (Brown et al. 2014).

The notion of "spectroscopic survey" has changed a lot through the years, following of course the technological progress. For example, the first "spectroscopic surveys" of galaxies in distant clusters, obtained in the early 80s (e.g. Dressler and

Gunn 1982), consisted of less than 20 spectra, were taken with a single slit and, yet, they represented a great step forward for cluster studies. The advent of optical spectrographs with multiplex capabilities, and the improvement of such capabilities over the years, have revolutionized extragalactic astronomy, and the field of galaxy evolution in particular. Today, we are routinely taking spectra of hundreds or even more than a thousand distant galaxies at once, with either multifibre or multislit facilities such as `AAOmega` (see Fig. 5.24) on the Anglo Australian Telescope , `IMACS` on the Magellan Telescope , `VIMOS` on the Very Large Telescope , and several others in the world. Without multiplex spectrographs on big telescopes, astronomy could not have achieved even 10 % of the amazing progress of the last 20 years. It is therefore hard to overstate the importance of spectroscopic surveys.

Spectra contain much more information than just the redshift, depending on their signal-to-noise and resolution. A galaxy integrated spectrum carries information about all the galaxy components (its stars, gas, dust, even its dark matter content), and has a record of all its stellar history throughout the Hubble time. Extracting from the integrated spectrum the galaxy properties (its current rate of star formation, past stellar history, chemical composition of its stars and of its gas, stellar and dynamical mass, etc.) requires a sufficient spectral quality. The higher the signal-to-noise and the resolution, and the larger the wavelength coverage, the better.

That is why I often make a distinction between a “redshift survey” (a collection of spectra that can yield little more than the redshift information, due to the limited spectral quality), and a “spectroscopic survey”, which provides good quality spectra that can be used also to study other galaxy properties in detail.

An important landmark for redshift surveys was the 2dF Galaxy Redshift Survey (Colless et al. 2001) that provided a detailed picture of the large scale structure in the low redshift Universe, leading to a spectacular confirmation of the Cold Dark Matter paradigm for the growth of structure on our Universe.

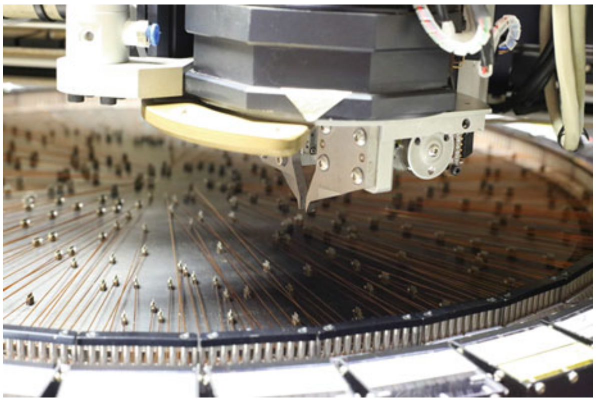

Fig. 5.24 The fiber-positioner of the `AAOMEGA` spectrograph at the Anglo-Australian Telescope operating at the Siding Spring Observatory, Australia. Each configuration can have up to 400 fibres allocated (courtesy Sarah Brough, Australian Astronomical Observatory)

As for spectroscopic surveys, there is no doubt that the Sloan Digital Sky Survey (SDSS) (York et al. 2000) has been the project with the strongest impact on galaxy studies, with a legacy value for the astronomical community that is unmatched to this date. The SDSS is an imaging and spectroscopic survey with a dedicated 2.5-m telescope at the Apache Point Observatory that covers more than a third of the sky and has obtained spectra for more than a million galaxies and quasars. In a nutshell, the SDSS has provided us a detailed view of the low redshift Universe, allowing an investigation of essentially all main galaxy properties on a statistically large sample. With the SDSS it is possible to carry out a multivariate analysis as a function of the key parameters that can play a role (galaxy mass, size, morphology, environment etc.).

Among the reasons for the great success of SDSS, besides the spectral quality and the great statistics, there is surely the strategy adopted for the project resulting in a high average spectroscopic completeness (still improvable, however) and, most important of all, the easy accessibility of the data and data products for all astronomers in the world.

Still at low redshift, the next step forward has been GAMA (Driver et al. 2011), which has pushed up to $z \sim 0.3$ the detailed analysis of the baryonic and dark matter components of the Universe, and has improved on the SDSS for completeness and depth, allowing to study the relation between matter and light over a large range of scales (kcp to Mpc and beyond).

For galaxy clusters, arguably the best dataset in the low redshift Universe is WINGS (Moretti et al. 2014) and its upgrade OMEGAWINGS, which is a wide-field photometric and spectroscopic survey of a large sample of X-ray selected clusters at z = 0.04–0.07, with a wide range of cluster properties (X-ray luminosities, velocity dispersions, dynamical status etc.).

At higher redshift, the advent of `VIMOS` on the `VLT` has opened the way for a new class of spectroscopic surveys for galaxies up to $z \sim 1$ and beyond, that require an 8 m class telescope. Surveys like VVDS (Le Fèvre et al. 2005), zCOSMOS (Lilly et al. 2007), DEEP2 (Newman et al. 2013) and others have produced a great number of results on galaxy evolution and its relation with environment over this redshift range. Among the main results, it is worth mentioning the evolution of the galaxy stellar mass and luminosity functions, of galaxy colors (and relative quenching), and of the relation between star formation and galaxy mass. Even those surveys whose main aim is not galaxy evolution but understanding cosmic acceleration, such as VIPERS (Guzzo et al. 2014), have a strong galaxy evolution component.

In parallel, spectroscopic surveys of galaxy clusters in the same redshift range have clarified the evolution of galaxies in the most massive tail of the dark matter halo distribution [MORPHS, Dressler et al. 1999; EDisCS, White et al. 2005; ORELSE, Lubin et al. 2009; GCLASS, Muzzin et al. 2012; ICBS, Oemler et al. 2013; the ongoing CLASH-VLT survey (Biviano et al. 2013) to name a few]. Cluster studies have often anticipated discoveries that several years later have been found to be universal: qualitatively, galaxy evolution proceeds in the same way regardless of environment, while the rate of such evolution changes with environment, being accelerated in clusters. This is one of the reasons why galaxy clusters are so important for galaxy evolutionary studies in general.

In the last few years, large studies of galaxies up to $z = 1$ are more often carried out as piggy-back programmes of surveys whose declared main goal is dark energy investigation. This has been the case because there is sometimes the (wrong) perception that in the regime $z = 0$–1 the past spectroscopic surveys have unveiled everything was there to discover, and that only "minor details" are left to be uncovered. I would argue this is a severe misconception, given that *none* of the main scientific answers have been answered yet: what is the reason for the declining star formation since $z = 1$–2 in currently star-forming galaxies, and for the quenching of currently passive galaxies? how did the $z = 0$ Hubble sequence get shaped, i.e. what is the origin of today's morphological types? Why did galaxies evolve the way they do between $z = 1$ and $z = 0$, over half of the age of the Universe?

For the future: we are working on spectrographs with a larger multiplex capability and a larger field of view, such as WEAVE, which will be on the William Herschel Telescope (WHT) in a few years with 1500 fibres on a 3+ degree square field, as well as better multiplex on spectroscopy-dedicated 10m telescopes such as the proposed MSE, the Mauna Kea Spectroscopic Explorer.

The future is already begun for Integral Field Spectroscopic Surveys. First with the stunning SINFONI results for high redshift galaxies (Förster Schreiber et al. 2006, 2009) that have radically changed our beliefs (expectations) regarding z=2 disk galaxies; now with the first large scale low redshift integral field surveys, such as CALIFA (Sánchez et al. 2012) and the SAMI Galaxy Survey (Allen et al. 2015), who are beginning to dissect galaxies into their components with unprecedented details; and in the near future with the upcoming surveys like MANGA (https://www.sdss3.org/future/manga.php). The great advantage of integral field surveys is the ability to study the spatially resolved properties of galaxies, following the characteristics and history of its various components (disk, bulge, nucleus etc.). This overcomes the severe limitation of treating galaxies as one global entity, and can trace the inside-out or outside-in growth, the outflow and inflow of gas and all the relevant physical processes on a galaxy scale.

Finally, I'd like to mention wide area, narrow band imaging surveys, like J-PAS, the Javalambre Physics of the Accelerated Universe Astrophysical Survey (Benítez et al. 2015), which provide essentially a "low spectral resolution", integral field mapping for very large samples of galaxies over most of the visible sky. Many interesting results can be expected from these narrow-band surveys too, also on the galaxy evolution front.

5.7 To Summarize

In the overture of the Chapter George Paturel stressed, once more, the daunting work of collecting galaxy data sets and to homogenize them in order to prepare catalogues of general use. However, there is also space for "emotions" as those well described *by Halton Arp and Barry Madore preparing their Catalogue of Southern Peculiar Galaxies and Associations we report at the beginning of the summary of Chap. 3. The time of handwritten lists, notes with sketches about galaxies peculiarities seen by George in the office of Gerard de Vaucouleurs (without mentioning the bibliographic mental notes of Antoinette, many times mentioned to me (RR) by Massimo Capaccioli) is definitely over. Hundred of thousand galaxies with multi-wavelength images and associated spectroscopy are now available via web. We remark that there are different approaches in offering data: from FITS files, e.g. SDSS , to totally digested data sets. As examples of this last way, we mention The Carnegie-Irvine Galaxy Survey (CGS).*[12] *Although limited to 605 brightest galaxies, observed at the 2.5-m Du Pont at Las Campanas (PI Luis Ho), it provides on-line B, V, R, I luminosity and color profiles, 2D image fitting, 2D residuals after* `GALFIT` *fitting, analysis of spiral arms etc. Remarkable on the Virgo cluster theme the* `GOLDMine` *database by Giuseppe Gavazzi and collaborators which allows multi-wavelength statistical studies and detailed observations of individual objects. In general catalogues are an essential byproduct of any large or mini survey: we fully agree with Martha Haynes "they makes their treasure trove of multi-wavelength data available for the rest of us to use".*

- *Multi wavelengths surveys greatly contributed to our understanding of the cluster structures, their luminosity functions and the galaxy evolution in such dense environments. The above interviews were mainly dedicated to the Virgo and Fornax clusters. The Virgo cluster has been covered by the NGVS survey, by the* `GALEX` *Ultraviolet Virgo Cluster Survey (GUViCS, Boselli et al. 2011), the* `Herschel` *Virgo Cluster Survey (HeViCS, Davies et al. 2010) in the 70–500 μm spectral domain, and the ALFALFA (Giovanelli et al. 2005) HI survey. In the 1980s there was a large effort to define the Virgo cluster members with the survey of 140 square degrees by Binggeli, Sandage and Tamman. They produced a catalogue that includes 2096 VCC members. The X-ray* `ROSAT` *surveys confirmed the results by optical analyses: Virgo is not a virialized cluster, but includes many substructures called Virgo A, Virgo B, Virgo C and the W, W' and M clouds, that are infalling towards Virgo A centred on M87. ETGs are the dominant population of cluster A, while star forming systems are still frequent in the other subgroups. The total mass of the Virgo cluster is estimated in $\sim$ 1–3 $\times 10^{15}\,M_\odot$ with a virial radius of about 1 Mpc. Today the number of galaxies used to sample the Optical Luminosity Function (OLF) is $\approx$5000 galaxies. The analytic form of the OLF is similar to that obtained by Sandage and collaborators thirty years ago and extends toward much lower magnitudes. Amazingly, the shape of the Virgo OLF is very similar to that of the field as determined from the SDSS. Surveys of the Fornax cluster made with* `HST` *find out a large numbers of UCDs around NGC 1399. This class of dwarfs (see also Chap. 3.5), of still debated origin, are found in large number also in Virgo.*

[12] http://cgs.obs.carnegiescience.edu/CGS/Home.html.

Laura Ferrarese showed us how well coordinated efforts on a global survey of the Virgo and Fornax galaxy clusters, aimed at covering all galaxies down to $M_V \simeq -6$, *revealed a continuous variation in the structural properties of early-type galaxies over a factor 500,000 in luminosity: a striking conclusion which is not only valid for the global properties of galaxies but also for their nucleus, which show similar continuous scaling laws compared to global properties. We can therefore conclude that similar processes, at all galaxy scales, affected and shaped the galaxies we observe today through the cosmic time.*

- *Poor galaxy associations like pairs, poor and compact groups have been studied for many decades starting from the pioneering studies of Erik Holmberg. There have been (and there are) serious difficulties in defining clean samples of physically associated galaxies: intruders, like optical alignments as well as "false" (compatible redshift but galaxies are not gravitationally bound) pairs and/or group members are present in the catalogues. Pairs and groups studies open window on the modification (from morphology to star formation properties) of the member galaxies due to interactions (e.g. the Holmberg effect) and to the presence of dark matter. Simulations had a fundamental role in understanding the galaxy evolution under interaction. First catalogues of pairs and groups included hundreds of objects: e.g. 603 pairs in the Igor Karachentsev's Catalogue of Isolated Pairs, 100 compact groups in the Paul Hickson's catalog. Today's binary samples selected from e.g. SDSS surveys includes several thousand of pairs. The interest for pairs is now shifted toward the mechanisms which originated them in large scale filaments, while groups are studied in their extreme cases, the so called "fossil groups" (see also Chap. 10).*

  In the 1970s, when redshifts determinations were still quite rare, the Karachenseva's CIG catalogue included galaxies which were isolated according to well defined geometrical and photometric criteria. Further studies reduced the fraction of true isolated galaxies in the nearby Universe from 4 % to 3 %. In the current interpretation these galaxies did not experience, at least in the last few Gys, interaction/accretion episodes. Late-type galaxies dominate in these very poor environments: only 1 out of 4 galaxies are early-types. In a highly structured Universe, voids are the extreme example of poor galaxy environments. Dwarf irregulars, blue compact and spiral galaxies populations are actually illuminating voids with their active star formation owing to the large reserves of "fresh" gas. Puzzling is the presence of distortions in spiral galaxies.
- *Surveys are going to provide a much clear view about the physical mechanisms behind galaxies evolution. Two parameters appear to be determinant: the halo mass and the galaxy environment. Since they both span a wide range of values, the on-going researches try to quantify their role and weight at different epochs.*

  *The morphology-density relation highlighted in the 1980s (*Dressler 1980*) keeps up the role of environment. Evolving mechanisms are thought to depend on environment. In clusters two classes of evolving mechanisms are believed to be in action: the gravitational ones that are related to the perturbations induced by other galaxies or by the cluster potential (like tidal stripping, harassment, etc.) and those related to the interactions with the intergalactic medium (like ram* *pressure stripping, evaporation, etc.). In groups, where the velocity dispersion of the member galaxies is comparable to the inner stellar velocity dispersion, the dominant evolving mechanisms are likely mergers and accretions. Anyway, the role and the importance of each of these processes in shaping the evolution of galaxies in different environments and at different epochs is still under debate.*

Concerning the role of the halo mass in galaxy evolution, important hints come from the analysis of the stellar populations of ETGs. Clemens et al. (2006, 2009) claimed for a combined mass-environment effect on ETGs. They suggested that "the timing of the process of formation of early-type galaxies is determined by the environment, while the details of the process of star formation, which has built up the stellar mass, are entirely regulated by the halo mass." Using a SDSS spectral data-set of 14,000 ETGs, Clemens and collaborators investigated the trends in the star formation history as a function of galaxy mass, parametrized by the velocity dispersion, the density of environment and the galactic radius. They found that age, metallicity and α-enhancement all increase with galaxy mass and that field ETGs are younger than their cluster counterparts by about 10 % (up to 2 Gyr). Similar results have been found, on a more limited sets of galaxies, by Thomas et al. (2005).

- *The HI 21 cm line surveys largely contributed to map the gas distributions in galaxies located in different environments. Comparing isolated galaxies, from the Karachenseva catalogues, with their doubles in the Virgo cluster environment allowed to discover the phenomenon of the HI deficiency in cluster galaxies in the 1980s. The more deficient galaxies are located in the more dense part of the cluster. Later (multi wavelength) works put into evidence that HI disks appear truncated as simulations of ram-pressure stripping predict. The more truncated galaxies tend to be in more radial orbits, and the truncation becomes more efficient when the galaxy enters the cluster core.*

  HI 21 cm surveys contributed to build our view of the 3D structure of the Universe, unveiling structures like the Perseus-Pisces Supercluster in the 1980s when the concept of superclusters itself was accepted by only a bunch of scientists. HIPASS and the ALFALFA surveys are real core sampling of HI: their median redshift is $\sim$3000 km s^{-1} and $\sim$8500 km s^{-1}, respectively.
- *An historical view of the UV satellites is given in Sect. 5.5.1. The first UV mission providing an all sky imaging survey is `GALEX`, Launched in 2003. Previous missions like `IUE` but also `HST`, privileged spectroscopy over imaging. The large field of view of `GALEX` (1.2°) and FUV filter made the contribution of this 50-cm telescope still unique. The source catalogue counts about 24×10^6 sources up to $z\sim2$. `GALEX` produced breakthroughs mapping SF over several orders of magnitudes, in galaxies located in different, sometimes unexpected, environments. The large FoV and sensitivity permitted to follow SF in extended structures such as tidal streams between galaxies and in several cases showing SF outside the galaxy optical boundaries.*
- *The first important all sky survey of the infrared sky (see also Sect. 5.5.2 for an historical view) has been produced by `IRAS`: the source catalog produced in four bands (12, 25, 60, 100 μm) counts hundred thousands extragalactic objects.*

Only `AKARI`*, launched in 2006, has been dedicated to an all sky survey in the 9–200 μm spectral domain extending the IRAS coverage. The IR space telescopes* `ISO`*,* `Spitzer`*,* `Herschel` *have been dedicated to pointed observations and were equipped with instruments providing both imaging and spectroscopy. Small surveys were dedicated to selected galaxies (few hundreds objects), while a particular attention was reserved for the study of the dust properties.*

- *An historical view of the investigation of the X-ray sky is presented in Sect. 5.5.3.* `ROSAT` *produced the first X-ray all sky survey RASS ;* `Einstein`*,* `XMM-Newton` *and* `Chandra` *provided pointed observations. However, they contributed at different levels to the characterization of early and late-type galaxies with real breakthroughs. ETGs were considered gas poor before* `Einstein` *discovered their hot X-ray emitting gas halos. At odds in late-types the X-ray emission is mostly due to discrete sources and very little comes from hot halos.* `Einstein` *observations evidenced some distorted halos;* `Chandra` *is showing details of these halos as blobs, cavities, etc. Hot halos result from a balance between gravitational heating, feedback from stellar evolution and/or a central AGN, and confinement/interactions with the environment. The halos confines the gas lost by stars during their evolution so physical properties and metal enrichment of the hot gas hide the evolutionary history of both the interstellar matter and the host galaxy.*
- *The most important spectroscopic surveys are the fruits of the* mise-au-point *of several multi-slit and multi-fiber spectrographs at the largest telescopes on both hemispheres. Several million galaxies now have estimated redshifts mapping the large scale structure of the Universe. Combined with* `HST` *deep optical imaging these spectroscopic surveys contributed to the unambiguous determination of the redshift of galaxies and QSOs up to $z \sim 7$ and beyond (see Chap. 6). Spectral information have been used by astronomers to build-up a picture of clusters, groups and galaxies evolutionary mechanisms. One of the key results obtained (from a cosmological points of view), was the detection of the first peak of baryon acoustic oscillation (BAO). Investments to built new multi-objects spectrometers with IFU characteristics, in particular in IR, are still continuing with the aim of tracing the inside-out or outside-in growth of structures, the outflow and inflow of gas, and all the relevant physical processes on a galaxy scale.*

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Chapter 6
In Pursuit of High Redshift Galaxies

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Hobbits are an unobtrusive but very ancient people,
more numerous formerly than they are today…
J.R.R. Tolkien *The Lord of the Rings, Prologue*

6.1 Chapter Overview

Some contributions in Chap. 1 have highlighted the impact of the discovery in the 1960s of a handful of radio galaxies and Quasars in the redshift range $z \sim 0.2$–0.4. About 40 years later, at the end of the twentieth Century, the systematic exploration of galaxies reached $z \sim 1$–3. The combination of HST deep imaging and the coming into operation of the 8–10 m class telescopes with their spectroscopic capabilities, move ahead the limits. At the same time, astronomers greatly improved their strategies to hunt high-redshift galaxies. Today, it is not infrequent the spectroscopic confirmation of galaxies at $z \sim 7$–8, pushing the detection limits more or less to the end of the re-ionization era. The gauntlet to observe the so called "first galaxies", i.e. those assembling during the first billion years of the cosmic time, is throw down.

The study of high-redshift galaxies directly probes the evolutionary phases that link them to their "mature" counterparts, the galaxies in the local Universe, whose variety in morphologies and structures is described in Chaps. 3 and 4. Behind the idiom "high-redshift galaxies" there is a vast class of objects, evolving at different epochs. As noticed by Pierre-Alain Duc above a redshift of 2, galaxies are still named according to the selection criteria that were used to identify them—BzKs, LBGs, EROs, LAEs, i-band dropout, etc. The exploration has started but a vast territory is still virgin.

This Chapter is focused on the high-redshift galaxies hunting and on the analysis of their structures, masses and evolution. Section 6.2 begins with an historical overview of the search for high redshift galaxies and of the methods developed for this search. Section 6.3 provides a brief insight about the structure, morphology and size of high-redshift galaxies. Their properties are compared with that of galaxies simulated by the current models of galaxy formation based on the hierarchical assembly. Galaxies change their star formation rate and their gas content across the Hubble time. This important part is addressed in Sect. 6.4. The properties expected for the first galaxies are discussed in Sect. 6.5. Finally, in Sect. 6.6 Volker Bromm *discusses the ingredients required to form the first galaxies in the cosmological framework and why we expect to detect them with the future generation of observing telescopes and instruments.*

6.2 Historical Perspective and Detection Methods

Questions for George S. Djorgovski:
At the beginning of the 1990s the spectroscopic research of high-redshift galaxies was in the pioneering phase so that, until 1995, just an handful

of galaxies with $z > 1$ were know. 1990s have also seen the development of new search methods, basically photometric, e.g the *dropout* method that demonstrated to be successful. May you trace a critical historical evolution of the search methods of high-redshift galaxies? What was the main driver at that time for the research of galaxies with $z > 2$? What are the new classes of high-redshift galaxies that have been historically identified?

Searches for galaxies at ever larger redshifts were always motivated by the desire to understand better their evolution. There are, however, obvious selection effects: at any given redshift, we will detect the most luminous objects first, and get increasingly incomplete at the intrinsically lower luminosities—the same selection effects that plagued the classical Hubble diagrams as a cosmological test.

The initial quest for normal galaxies at large redshift was through the first redshift surveys of the faintest observable galaxies at the time, e.g., by Humason et al. (1956). This was limited by the detector technology available at the time, reaching only to the redshifts of a couple of tenths.

Quasars have been observed at cosmological redshifts ever since the early 1960s, but their brightness greatly outshines that of their host galaxies. More recently they have been used as signposts to point to regions where there may be other galaxies nearby.

Radio galaxies were the probes of choice for many years, starting with Minkowski's identification in 1960s of 3C295 at $z = 0.461$ (Minkowski 1960), and continued through 1980s and 1990s by many groups, notably by Hyron Spinrad and collaborators (e.g., Spinrad and Djorgovski 1984); a good review of this is by Spinrad and Stern (1999). This quest was boosted enormously by the first CCD spectrographs, yielding the first galaxies known at $z > 1$, gradually pushing to $z \sim 2$ and beyond. The Hubble diagram for 3C radio galaxies provided the first strong evidence for galaxy evolution (Djorgovski et al. 1985a). However, objections were raised to the effect that these enormously powerful radio sources are not representative of the general population of the more "normal" galaxies, and that is certainly true. Nevertheless, radio galaxies provided us with the first glimpses of galaxy evolution at high redshifts.

The first deep redshift surveys of field galaxies with 4 m class telescopes gradually pushed out to $z \sim 1$ [see, e.g., Koo and Kron (1992) for a review]. But the field really blossomed with highly multiplexed spectrographs on 8–10 m telescopes in the late 1990s and 2000s, resulting in massive efforts such as the Keck DEEP (e.g., Davis et al. 2003) and VVDS (e.g., Le Fevre et al. 2003). These surveys established the evolution of normal, field galaxies out to $z \sim 2$.

The first successful searches for galaxies at $z > 3$ were using narrow band imaging searches for the Lyα line emission, in the fields around high redshift quasars, exploiting the fact that galaxies tend to cluster, and using quasars as markers of sites where more galaxies can be found (Djorgovski et al. 1985b). Deep searches for Lyα galaxies in the field, using 4–5 m class telescopes in the early 1990s produced some candidates, but they could not be spectroscopically confirmed at the time; it took spectroscopy with 8–10 m class telescopes to put such searches on a firm footing (Djorgovski 1992, 1996; Pritchet 1994; Thompson and Djorgovski 1995; Thompson et al. 1995). Initially, objections were raised with the claims that the Lyα line emission would be effectively quenched by the resonant scattering and/or extinction by dust. While such effects must exist, there are now abundant examples of high redshift galaxy samples selected through their Lyα line emission. Now this technique is used to find galaxies out to $z \sim 7$ (e.g., Shibuya et al. 2012).

Mid-1990s also saw the first successful applications of the Lyman break technique by Steidel and collaborators (e.g., Steidel et al. 1996). This method was already discussed by Meyer, Tinsley, and collaborators in the mid-1970s, but finally succeeded once spectroscopy with the 10 m telescopes was possible. This became the standard method to discover large samples of normal galaxies at $z > 2$ or so, and much of our current understanding of galaxy evolution at such redshifts comes from the studies of galaxies selected through the Lyman break technique. This method now dominates the searches for high redshift galaxies, and it was given an enormous boost by the various HST deep fields.

Sub-mm and space-based IR imaging has also revealed populations of highly obscured galaxies at $z \sim 3$ and beyond, thus complementing our picture of the unobscured component of the cosmic star formation history. However, there is no indication that there is something fundamentally new that is being revealed by these studies.

The search for high-redshift galaxies saw the combined effort of the largest ground based telescopes and HST. May you mention the more successful ground based high-redshift galaxy surveys? What have been, in your view, their relevant results?

The deep spectroscopic field surveys mentioned above have now established our understanding of galaxy evolution out to $z \sim 2$ for the field galaxies in general, and out to $z \sim 5$–6 for the samples selected through the Lyman break technique. Studies of their photometric evolution also go hand in hand with the studies of the evolution of clustering and bias. In addition, Lyα surveys done at the Subaru telescope have revealed samples of galaxies at $z \sim 4$–7 and probed their (biased) clustering. They complement nicely the surveys that use the Lyman break technique.

Overall, I think that we now have a fairly compelling picture of galaxy evolution since the end of the reionization era at $z \sim 6$, at least in the broad-brush strokes.

The effort done with HST has been enormous. What has been the role of HDFs and HUDF (and today XDF) in pushing forward the study of high-redshift galaxies?

The synergy of HST imaging and ground-based spectroscopy with the 8–10 m class telescopes has been spectacularly successful out to $z \sim 4$–6 or so. At higher redshifts, galaxies are too faint even for our largest current telescopes.

Obviously, by going fainter, we can see galaxies at ever higher redshifts. There is now an established industry of selecting high-redshift ($z \sim 8$–12) galaxy candidates on the basis of their colors and population synthesis models. This is done by several groups, all of them using the same data and the same models. Whereas some, but probably not all of these candidate high-redshift galaxies may be indeed correct, I would much prefer to see some spectroscopic confirmations.

What are the new veins of investigation opened by Hubble deep fields asking for the new generation of telescopes?

Clearly, we need actual spectroscopic confirmation of galaxies claimed to be at redshifts $z > 7$ on the basis of their colors, which will require the next generation of extremely large, 20–30–40 m class telescopes.

Due to the high redshifts involved, the action has clearly moved to the near IR. Deep imaging with the `JWST` may continue the HST path to study in more details the first galaxies during the reionization era.

Up to what z do we have information about the structure and kinematics of galaxies? What is the contribution to the zoo from "isolated" discoveries of very high-redshift galaxies, like those coming from GRBs?

It appears that the Hubble morphological sequence is set at about $z \sim 1$ or so. At higher redshifts, morphologies become more clumpy and compact. Some of that is probably a genuine evolution, galaxy assembly in action, but some may be simply surface brightness selection effects, that let us see only the bright, compact clumps in otherwise more extended galaxies.

Just like quasars, GRBs can point to high-redshift host galaxies that we can study briefly in absorption. Such cases are still very rare, but they are consistent with what is seen in deep imaging and redshift surveys.

Overall, I would say that we now have a fairly well established picture of galaxy evolution since the end of the reionization era around $z \sim 6$ until today. This interleaves nicely with our understanding of the galaxy-AGN co-evolution, and the evolution of the large scale structure. Whereas there is still much of the ironing out of details to be done, I would be very surprised if this picture changes fundamentally.

The new frontier is the formation of the first galaxies during the reionization era ($z \sim 6$–12?) and the end of the dark ages that preceded it.

The following interviews concentrate on the morphology, structure and mass of high redshift galaxies. Extensive observational efforts have shown the vast spectrum of galaxy morphologies and structures, as well as the variation of the galaxy properties with time since $z \sim 3$. From small, compact and peculiar systems in the distant Universe we gradually observe the formation of the Hubble sequence, dominated by spirals and ellipticals.

6.3 The Structure of High-Redshift Galaxies

Questions for Debra M. Elmegreen:
May you discuss from an observational point of view the morphological change as function of the redshift? Does the Hubble classification still apply at high redshift?

Simulations suggest a hierarchical evolution in the assembly of galaxies, across the Hubble time. Which are the main observational evidence of such hierarchical evolution at high-redshift?

The advances in technology that allowed galaxies to be resolved at increasingly higher redshifts have revolutionized our ideas about how galaxies form and evolve. Among the first breakthroughs were those stemming from observations of the Hubble Deep Fields (HDF) North (Williams et al. 1996) and South (Williams et al. 2000). While spirals and ellipticals are recognizable at redshifts $z = 0.1$ to 1, galaxies become increasingly more peculiar at higher redshifts. Cowie et al. (1995) obtained deep HST images of regions in the Hawaiian Survey Fields and discovered linear strings of star-forming clumps in galaxies, which they referred to as "chain" galaxies. van den Bergh et al. (1996) presented a detailed classification catalog of HDF galaxies according to the DDO system, following the survey of Abraham et al. (1996), but noted the wide range of morphologies at higher redshift; they found that peculiar morphologies, such as "tadpole"-shaped galaxies, amounted to at least 30 % of the sample, and that there was a paucity of barred or grand design spirals. Conselice (2004) found that the fraction of peculiar galaxies increases beyond $z = 1.4$ in the HDFs, while Lotz et al. (2006) found that bright galaxies are primarily late types and have irregular morphologies beyond $z = 0.7$. With the Advanced Camera for Surveys (ACS) on Hubble, the improved resolution allowed kiloparsec-scale star-forming clumps to be resolved in galaxies out to redshift $z = 5$. Bruce (Elmegreen) and I examined the chain galaxies in the background of the Tadpole Galaxy field, one of the first deep fields imaged with ACS (Tran et al. 2003).

The Hubble Ultra Deep Field (Beckwith et al. 2006) further advanced our knowledge of galaxy evolution by probing out to $z = 7$ or so. Bruce and I did a systematic study of the 1000 galaxies larger than 10 pixels radius out to $z = 5$, classifying them as chains, clump clusters (which have several clumps in an apparent disk), tadpoles, doubles (two main star-forming clumps), spirals, and ellipticals (Elmegreen et al. 2007), as shown in Fig. 6.1. In co-moving volumes, star-forming spirals and ellipticals fall off in number with increasing redshift, while the clumpy types increase (Elmegreen et al. 2007).

The star formation group led by director Reinhard Genzel at the Max Planck Institute has pushed the current technological limits by obtaining velocity fields in $z \sim 2$ galaxies using the VLT SINFONI spectrometer at Paranal. Their breakthrough SINS (Spectroscopic Imaging in the Near-Infrared with SINFONI) study of over 60 galaxies showed that they divided into those dominated by rotation, those dominated

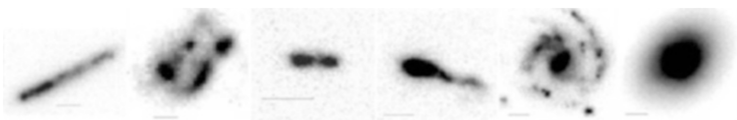

Fig. 6.1 The Hubble ultra deep field morphology zoo, with chain, clump cluster, double, tadpole, spiral, and elliptical morphologies; adapted from Elmegreen et al. (2007)

by velocity dispersion, and those with irregular fields that appeared to be mergers (Forster-Schreiber et al. 2009).

The advent of very large surveys of high redshift galaxies, such as DEEP2 (Davis 2002), COSMOS (Scoville et al. 2007), Extended Groth Strip (Noeske et al. 2007), and CANDELS (Wuyts et al. 2011), is yielding statistics that aid in understanding galaxy evolution. There is growing evidence both from observations and from numerical simulations that the predominant growth mechanism of galaxies is through cold flow accretion of gas from the cosmic web, as detailed in a recent review (Sanchez Almeida et al. 2014a). A survey of massive galaxies in GOODS observed with NICMOS provides indirect evidence for growth primarily through gas accretion (Conselice et al. 2013). A recent comprehensive review of galaxy evolution over cosmic time is presented by Conselice (2014). Galaxies are about half their current size when the Universe is about half its current age (Elmegreen et al. 2005). A study of over 21,000 galaxies (Conselice et al. 2009) indicates that merger rates increase between $z = 0.7$ and 3, and that a typical galaxy has only 1 to 2 major mergers more recently than $z = 1.2$. The observed planar arrangements of star-forming clumps indicate that they must be ab initio star formation and not accreted clumps. This idea is reinforced by simulations, which show that if more than about 10 % of stars are in the halo, then chain and clump cluster structure is eliminated (Bournaud and Elmegreen 2009). The observed anti-correlation of metallicity with the brightest star-forming regions in local tadpole galaxies is consistent with accretion of low metallicity gas that then leads to star formation (Sanchez Almeida et al. 2014b).

Well-ordered spiral structure first commonly appears by about $z = 2$ (Elmegreen and Elmegreen 2014), when disks have settled into a state dominated by rotation (Kassin et al. 2014). Large clumps interact with each other and can build up a bulge or dissipate to build the exponential disk in about a Gyr; they are present in turbulent disks (Bournaud et al. 2014). Figure 6.2 shows a numerical simulation alongside a

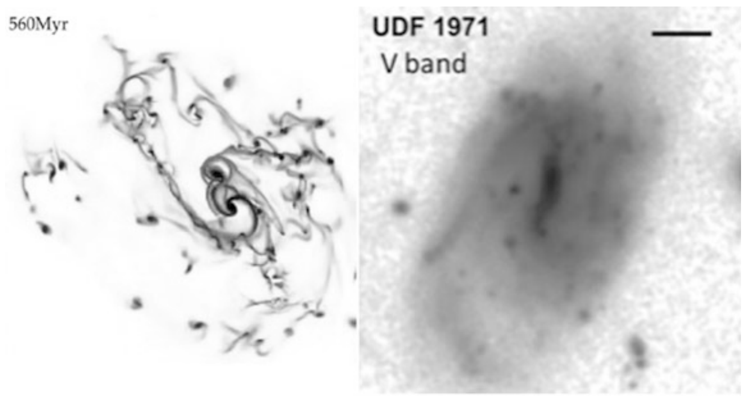

Fig. 6.2 Numerical simulation modeling the gas distribution after 560 Myr in a high redshift galaxy (*left*) compared with a high redshift galaxy in the UDF (*right*); adapted from Bournaud et al. (2014)

UDF galaxy, at a stage mid-way towards developing a spiral morphology. I look forward to the possibility that the James Webb Space Telescope may be able to image galaxies shortly after their formation.

Questions for Bianca M. Poggianti:
Several studies have recently claimed that the size of galaxies varies across time. Could you discuss which observations have permitted to establish such result? Why the questions is today amply discussed in the literature?

There are several observations which suggest the existence of super-dense galaxies only at high redshift. Could you comment this finding? Is it true that these peculiar galaxies are not present at much lower redshifts?

Obviously, the sizes of galaxies must evolve, from the time their first stars were born and while they assemble their mass, either via in situ star formation or through external accretion. No doubt about that.

One of the great debates of the last few years has been whether galaxies that *were already massive at high redshift* (hence had already assembled a large stellar mass early on) undergo a strong evolution in size between $z = 2$–3 and now. Beginning with the first works (Cimatti et al. 2008; Daddi et al. 2005; Trujillo et al. 2006; van Dokkum et al. 2008), numerous studies have found that massive galaxies at $z = 1-3$, mostly already devoid of star formation, have small radii. The radius is usually measured as the circularized or major axis radius along the single Sersic's profile best fitting the galaxy light. Such studies are based on deep Hubble Space Telescope images, and seem to be confirmed even by the best current imaging available such as CANDELS.

The sizes of these high-z galaxies are much smaller than the average size of similarly massive and passive galaxies in the low redshift Universe. This is why the evolution of the median mass-size relation of galaxies has received so much attention lately. Moreover, the first searches for compact and massive galaxies at low redshifts found very few of such galaxies in the Sloan Digital Sky Survey (Taylor et al. 2010; Trujillo et al. 2009).

These findings have suggested that the sizes of high-z massive compact galaxies evolved significantly with time, of a factor up to 6 depending on the sample examined. From the theoretical point of view, the most promising candidate physical process is minor (dry) merging, that is the accretion of many low mass galaxies. This could lead to a significant size growth without accreting too much mass, given that the descendants of high-z massive galaxies would otherwise be far too massive today compared to what is observed.

The question is amply discussed in the literature because it is related to a fundamental issue of galaxy evolution: how did galaxies acquire their stars? What fraction of their stellar mass was born "in situ", and what fraction was accreted by merging?

The standard picture depicted above has been challenged in the last few years by a number of results.

- Massive and compact galaxies have been discovered also at low redshift. The best place to find them is galaxy clusters, where our own work has found a significant fraction of galaxies with masses and sizes similar to the high-z population (Valentinuzzi et al. 2010). In clusters they are more common than in the field (Poggianti et al. 2013a), and their number density at low redshift is not too far from the number density of compact massive galaxies at high-z (Poggianti et al. 2013b; Saracco et al. 2010).

  Spectacular individual cases of compact galaxies have been discovered (or re-discovered) also close to us (Trujillo et al. 2014) and, though samples with detailed studies are still small, they suggest compact massive galaxies at low-z may contain an over-massive black hole (van den Bosch et al. 2012), opening interesting scenarios for the formation and the (lack of) evolution of these systems.
- It has been realized that the dramatic evolution in the median mass-size relation must be at least partly due to "progenitor biases". We, and many others, have found that there is a correlation between galaxy sizes and its stellar population ages: at a given mass, smaller galaxies have older stellar ages [see Poggianti et al. (2013a) and references therein]. By selecting passive galaxies at each redshift, at low-z we are including those galaxies that have stopped forming stars more recently, that are on average larger in size. This results in a strong evolution of the median mass-size relation, and mimics an evolution in individual galaxy sizes that is only apparent (Valentinuzzi et al. 2010). A number of works are starting to recognize the importance of this effect (e.g. Belli et al. 2014; Carollo et al. 2013a; Cassata et al. 2013b).
- Simulations tell us that the majority of massive and already passive galaxies at $z \sim 2$ will end up being Brightest Cluster Galaxies in massive clusters today. This agrees with the different frequency of compact massive galaxies we observe in clusters and field today. It also shows that high-z massive and passive galaxies cannot be considered as progenitors of *the whole population of massive galaxies today*, and that these two populations cannot be compared at face value as progenitors and descendants. Environmental effects play a role, as Brightest Cluster Galaxies are exceptional galaxies in exceptional places, and undergo a very strong evolution, both in mass and in size, because they sit in the bottom of a deep potential well swallowing everything that falls onto them.
- It remains true that there are no local counterparts to the most extreme cases of compact massive galaxies at high-z found e.g. by van Dokkum et al. (2008), which are also among the highest redshift ones. There have been speculations that sizes evolve very rapidly between $z \sim 2.5$ and $z = 1.5$–1. We have proposed a possible alternative explanation: if high-z galaxies are observed very soon after star formation is terminated, they will significantly evolve in mass simply due to passive evolution of the stellar populations (Poggianti et al. 2013b). This could make them move towards lower masses in the mass-size diagram, without having to invoke an exceptionally strong evolution in size.

This subject has been hotly debated in the last few years, and a general consensus has not been reached yet.

We now ask Daniela Calzetti to focus on the variation of the Star Formation Rate (SFR) across the cosmic epochs.

6.4 Star Formation Across the Hubble Time

Questions for Daniela Calzetti:

May you sketch the history of researches about the variation of the SFR with the cosmic time?

The calibration of the SF indicators is extremely important. What are the more reliable and what are the difficulties in the required measurements?

What are the hypotheses underlying our present measure of the SFR in galaxies across the Hubble time and what is the current picture ?

How much our picture of high redshift galaxies is hampered by the absorption effects due to dust?

The investigation of high redshift galaxies had its first major boost during the early-mid 1990s, when the refurbished HST started to observe deep fields and major ground-based optical facilities with 8–10-m mirrors started to come on-line. The earliest report on the evolution of the cosmic SFR (i.e., averaged over all galaxies within the volume at each redshift slice) is due to Madau et al. (1996), where the authors based their measurements on the rest frame UV light of distant galaxies observed in the Hubble Deep Field. That paper did not include any correction for the effects of dust, but it became quickly apparent that even in the high-redshift Universe dust was going to be a concern. The evidence came from two different sources: (1) the UV spectral slope of the high redshift galaxies was typically redder than what would be expected for a dust-free young stellar population, suggesting dust reddening effects similar to those observed in nearby starburst galaxies (Calzetti et al. 1994); (2) ground-based sub-mm facilities had started to detect dust emission in galaxies at high redshift (Smail et al. 1998). As early as 1998, the cosmic SFR was being corrected for the effects of dust.

When measuring SFRs, ideally one would need to capture both the dust-obscured and unobscured SFR. The former is usually obtained by measuring the IR emission, either its bolometric value or, more practically, its value at one specific wavelength. The latter requires a single monochromatic measure: at high redshift the most common wavelength range is offered by the rest frame UV, while in the intermediate and low redshift regimes both UV and Hα are used. Combinations of one UV-optical measure and one IR measure have been extensively calibrated to yield unbiased SFR indicators (reviews in Calzetti 2013; Kennicutt and Evans 2012). The best monochromatic IR indicators are those on the Wien side of the IR emission (λ <50–60 μm, Calzetti et al. 2007), although longer IR wavelengths may still yield reliable SFRs if the dust emission is dominated by heating from young stellar populations.

Recent compilations of the cosmic SFR as a function of redshift (Madau and Dickinson 2014) show that, when considering only the *observed values*, the SFR(TIR) is higher by a factor up to ∼5–6 than SFR(UV), up to redshift z∼2; the difference appears to be tapering off at higher redshifts. Thus, dust reprocessing of the star formation is a major effect in galaxies since the time the Universe was only a few Gyr old. When dust corrections are included in the SFR(UV), using similar methods to those originally derived by Calzetti et al. (1994); Meurer et al. (1999); Calzetti et al. (2000) for nearby starburst galaxies, the difference between SFR(UV) and SFR(TIR) virtually disappears. This result suggests that dust correction methods developed for nearby starburst galaxies apply to the high-redshift Universe, at least in first approximation; this conclusion had been already reached by a number of authors comparing specialized UV and IR data of high redshift galaxy samples. The most recent of such analyses is due to Reddy et al. (2015), where they suggest modest corrections to the local starburst attenuation curve in order to adapt it for redshift z∼2 galaxies.

The main challenge to the above result is brought by the uncertain knowledge of the galaxy luminosity functions in the UV and, especially, in the IR, which becomes more uncertain with increasing redshift. This implies that the description of the cosmic SFR history requires extrapolations for the unknown portion of the luminosity functions, and these extrapolations become heavier with redshift; the picture becomes highly incomplete beyond z≈4. The combination of `JWST` and `ALMA` should mitigate this problem, although they will not eliminate it, since neither is a survey facility. `JWST` will detect the UV emission from galaxies all the way to first light, and the mid-IR up to z≈2–2.5. `ALMA` will detect the long wavelength IR emission from galaxy up to z∼10, although it will also face two potential problems: (1) below z≈4, `ALMA` will not probe the peak of the dust emission, thus inheriting objective problems in constraining the SFR; (2) beyond z≈4, the decrease in the dust content of galaxies may suppress their overall IR emission and detections may trace the tail of galaxy luminosities, rather than probing their representative behavior. IR emission from cooling lines, like [CII](158 μm), could provide an alternate route to IR continuum emission for tracing obscured SFRs at high redshifts. These lines, however, also show potential problems: [CII] displays about one order of magnitude in both systematic variations and random scatter with galaxy properties (Dìaz-Santos et al. 2013). Clearly, much is unknown in this area, and only actual observations can constrain uncertainties.

If galaxies become, on average, progressively more transparent with higher redshift, as expected and, tentatively, measured (Bouwens et al. 2014), dust corrections based on the UV slope may prove more economical than detecting faint IR emission. In this respect, establishing the dependency of the current UV-slope-based dust corrections on luminosity, metallicity, and other galaxy properties will be of paramount importance for setting the stage for `JWST` science.

Questions for Françoise Combes:
High redshift galaxies are known to contain cold gas. Could you briefly trace the development of these studies up the recent `ALMA` observations? What has

been the contribution to our understanding of galaxy formation coming from these studies?

The idea that galaxies acquire and eject gas across the Hubble time is today amply debated. What are the main observational evidences of these phenomena? What is your personal feeling about the present understanding of these physical processes? Is the gas exchange more relevant for high redshift galaxies?

The first detection of CO at high redshift was performed by Bout Brown and vanden Bout (1991) towards a lensed ultra-luminous galaxy at z=2.28. Although the signal was barely detected, it was confirmed later and this stunning discovery opened up a new window on the universe. It was stunning since the redshift was more than 10 times greater than that of the most distant galaxy with detected CO at this epoch. During the following decades, many other detections were obtained at high z, up to z=7, and today about 200 galaxies have been detected at z larger than 1. The big surprise was also that molecules and dust are observed in some objects with abundances close to solar ones, for lookback times up to 95 % of the age of the universe! While it was thought that it will take billions of years to sufficiently enrich the gas in heavy elements.

At the beginning of this research domain, the detections were towards exceptionally bright objects, selected from their high dust continuum (or far infrared light in their reference frame). There were many lensed galaxies, ultra-luminous quasars and sub-millimeter galaxies. Now the observations have evolved towards massive star-forming objects, closer to the main sequence, and also resolving galaxies, with small maps and kinematics (e.g. Tacconi et al. 2013). Also many molecular lines have been detected, allowing to determine the physics of the gas, its excitation, density, temperature and metal abundance. At very high redshift, the first CO lines fall in the centimeter domain, and it is easier to detect fine structure lines, such as CII at 158 μm wavelength, redshifted in the millimeter domain. This line could be instrumental for redshift surveys in the future (Carilli and Walter 2013).

One caveat of the CO line studies is the uncertainty in the CO-to-H_2 conversion factor to obtain the molecular masses. For quiescent galaxies like the Milky Way, the factor has been well calibrated through many line studies (the CO ladder, its isotopes, dense gas tracers, dust, γ-ray and cosmic rays, etc.). Already at z=0, ultra-luminous starburst galaxies have been attributed a factor almost six times lower, since the CO gas is denser and warmer. At high redshift, galaxies are forming more stars, and the physical state of their gas, together with is metallicity, are less known. Our knowledge of this factor is however improving, and deep studies with ALMA will refine it.

It is now well established that most of the stars in the Universe have been formed in the first half of its age; the cosmic star formation density is peaking towards z$\sim$2 (Fig. 6.3), and then dropping by a factor 20 down to z=0 (e.g. Bouwens et al. 2011). What is causing such an evolution? Since the H_2 gas is the cradle of new stars, it is the key issue here. The observations until now have established that galaxies were more gas rich at high redshift, the fraction of gas reaching 50 %, and also that the

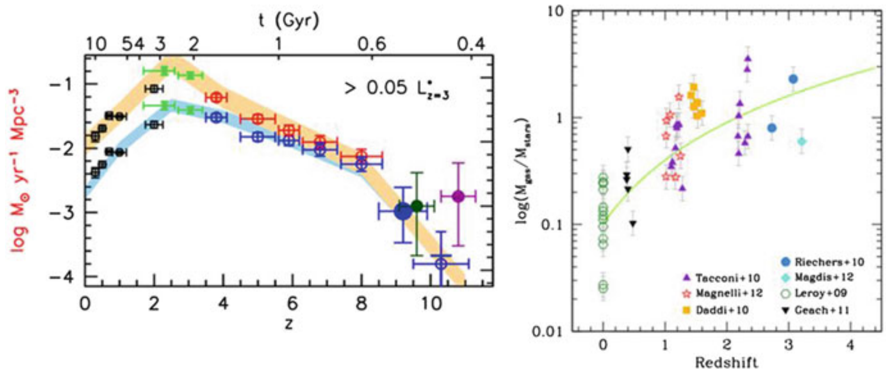

Fig. 6.3 Redshift evolution of the cosmic star formation rate density (*left*, Bouwens et al. 2011; *blue* is from optical tracers, *orange* is corrected for dust extinction), and the gas to stellar mass ratio (*right*, from Carilli and Walter 2013). The curve is the relation $M_{gas}/M_{stars} = 0.1\ (1+z)^2$

star formation efficiency was higher: the depletion time-scale is smaller at high z (Combes et al. 2013; Tacconi et al. 2010).

Since gas was denser in the past, it transformed more frequently from the atomic phase to molecular phase. It is expected that at high redshift, the H_2/HI ratio increases, may be varying as $(1+z)^{1.6}$ (Obreschkow et al. 2009). As the cosmic star formation density is well calibrated now, the goal is to establish the cosmic evolution of gas density. The present surveys are still preliminary, sources are selected from their far-infrared or optical luminosities. With ALMA, it will be possible to make directly blind surveys in the millimeter, to have the H_2 cosmic evolution without any bias. The total gas density requires knowledge of the atomic phase, and this will have to wait for SKA.

The source of the gas in these high-z galaxies, with gas fraction equal or larger than 50 % is yet to be understood. Of course it is expected that very young galaxies have not yet consumed all their gas. However, the main sequence galaxies observed at high z are very massive, and have already as many stars as the Milky Way; Also their depletion time-scale is short. Their star formation rate cannot be sustained beyond one billion years, unless they still accrete significant amounts of gas. Gas can be provided by mergers, but more frequently, it must be accreted from cosmic filaments. Cold gas accretion has been observed in cosmological simulations, and is much more abundant at high redshift. This gas accretion is difficult to observe directly, since it is very diffuse. What is observed ubiquitously now is gas outflows due to star formation of AGN feedback. These observations have bloomed in the recent years, since the molecular outflow detection in the prototypical Mrk231 galaxy (Feruglio et al. 2010). Many more will be studied with ALMA at high redshift, and will help to follow the gas history in galaxy disks.

The study of high-redshift galaxies is connected with the search for the ancestors of present day objects. We start discussing this problem with Malcolm Longair and Wolker Bromm in the next interviews.

6.5 The Ancestor Problem and the Search for First Galaxies

Questions for Malcolm S. Longair:
In your view, what should be the possible investigation strategies to make progresses in identifying the progenitors of galaxies of the nearby universe? What are the open questions which will be or are expected to be solved with the study of distant galaxies with future observations?

The first thing to say is that it is quite unambiguous that the properties of galaxies have been observed to change in many ways over the redshift range roughly ten to zero, corresponding to times when the Universe was only about a thirtieth of it present age to today. Even over the redshift range 0–1, which means only looking back to when the Universe was only about 30 % of its present age, there is consensus that the global rate of star formation was ten times greater than it is at the present day. Furthermore, it is certainly the case than there are galaxies at large redshifts which have similar properties to those nearby, but they are smaller and less luminous. Thus, major changes in the properties and populations of galaxies as a whole are facts of observational cosmology, not a conjecture.

In general terms, it has to be remembered that at redshifts 8–10, we are dealing with very different physical conditions from those in the Universe today. The mean density of the Universe was 1000 times greater than it is now, the Cosmic Microwave Background radiation was ten times hotter and its energy density 10,000 times greater than it is today and the Universe was just beginning to become transparent with the onset of the epoch of re-ionization. Clusters of galaxies could scarcely have existed since they could not have separated out from the primeval plasma. There are the great challenges facing observers and theorists in understanding the astrophysical processes before, during and after re-ionization epoch, which must have occurred about a redshift of 10.

It is not at all surprising that this is a complex story. It is revealing to contrast the problems of understanding the formation of the large-scale structure of the Universe with the problem of forming actual galaxies. The standard Λ-CDM model of the Universe can account for the observed properties of the Cosmic Microwave Background Radiation in exquisite detail and provide estimates of cosmological parameters to an accuracy of a few percent, which are in agreement with all the other cosmological test—it should be noted that the CMB estimates are far superior to those derived by the other methods. A key feature which gives us confidence in this picture is the fact that we are dealing with a *linear Universe* at a redshift of about 1000. By linear Universe, I mean that, on the last scattering surface at a redshift of 1000, the seeds from which galaxies and larger scale structures were to form, were still in the linear regime, $\delta\rho/\rho \ll 1$ and so the physics of the evolution of these structures was linear. There is not much doubt that we can carry out the physics calculations properly. I would also make the point that the observations made by the ESA Planck satellite are of such quality that all the cosmological parameters can be determined from these data alone, without reference to any of the other cosmological tests, in particular, the information from the $m-z$ relation for Type Ia supernovae is not needed. It is an added bonus that they agree so well.

As soon as objects such as galaxies start to form, however, we enter the non-linear stage of evolution of the Universe. These are the physical phenomena which give rise to the detailed complexity of the galaxies we observe today. These dissipative baryonic stages of galaxy formation are addressed in more detail in my responses to the next set of questions.

I would emphasize again the importance of using all wavebands for the study of distant galaxies. This is particularly the case for the comparison of nearby and extremely distant galaxies. Thus, for a galaxy observed at, say $\lambda_0 = 400\,\mathrm{nm}$ in the middle of the optical waveband today, we need to observe similar galaxies at a wavelength $\lambda = (1+z)\lambda_0 = 4.4\,\mu\mathrm{m}$ at a redshift of 10. This eliminates the need to worry about K-corrections, but it does mean we need to have telescopes operating in 'difficult' wavebands. This is one of the reasons why the James Webb Space Telescope is so important for the astrophysics of the formation and evolution of galaxies. It has been optimised for performance in the infrared waveband and it will enable us to make proper comparisons between galaxies in the nearby Universe and their counterparts at redshifts of 10, meaning when the Universe was only about 3 % of its present age—it is scarcely surprising that these earliest 'galaxies' may bear little resemblance to what we understand by galaxies at the present day.

I should emphasise that the studies of these galaxies carried out by the Hubble Space Telescope, the infrared Spitzer and Herschel Space Observatories have been extraordinarily successful. The proponents of these missions could not have imagined that they would be observing galaxies at redshifts of 6 and greater with these facilities.

Questions for Volker Bromm:
Could you discuss from a theoretical point of view the progress made in characterizing the properties of the ancestors of local galaxies?

Progress in this endeavor has been dramatic, since the introduction of the cold dark matter (CDM) model for cosmic structure formation in the mid 1980s (Blumenthal et al. 1984). This model allows us to connect the quantum fluctuations imprinted during the inflationary period very early in cosmic history with the observed large-scale structure, such as galaxies and galaxy clusters, at more recent times. The basic feature of the CDM model is its bottom-up, or hierarchical, nature, where small objects form first, and subsequently grow via mergers or smooth accretion. In its most modern guise, the ΛCDM model, with parameters determined to very high precision by WMAP and *Planck*, provides us with a powerful interpretative framework for galaxy formation. Specifically, we now have a convincing model for the dark-matter driven assembly history of the Milky Way and the Local Group. This understanding derives from supercomputer simulations that trace the evolution of the dark matter from the early universe to the present-day (Springel et al. 2005).

The big challenge is to understand the behavior of the baryonic component (the hydrogen, helium and heavy chemical elements of the cosmic gas). On large scales, the baryons just 'coast along' with the dominant dark matter, collapsing wherever the dark matter collapses. However, on smaller scales, where the collisional nature of the baryons fully come into play, the baryons may effectively 'decouple' from the dark matter. Indeed, on the smallest scales, the standard ΛCDM model is beset by problems, where the dark-matter predictions do not match the observations. Among the most crucial challenges are the 'missing satellite' problem, where simulations predict the existence of hundreds of small MW satellites, whereas only a few tens of low luminosity dwarf galaxies are seen, and the 'too big to fail' problem (Boylan-Kolchin et al. 2011). The latter problem, where simulations predict the existence of massive satellites, with such deep potential wells that stellar feedback should not be able to disrupt them, that are *not* observed, however, is even more puzzling. Despite these challenges, the ΛCDM model does provide a convincing theoretical framework to connect the present-day Galaxy with its ancient building blocks.

What are the earliest ancestors of the Milky Way? Within ΛCDM cosmology, we robustly predict that the first building blocks, primitive dwarf galaxies that comprised total masses of a few hundred million solar masses, formed in the redshift range $z \sim 10$–15, corresponding to an age of the universe around 300–500 million years after the Big Bang (Bromm and Yoshida 2011). I will further discuss these first galaxies in greater detail below. An important test of our theoretical understanding of the Milky Way ancestors is to look for local relics, in a pursuit that is often termed 'near-field cosmology' (Freeman and Bland-Hawthorn 2002). Specifically, the recently discovered ultra-faint dwarf (UFD) satellite galaxies are candidates for local survivors of the first galaxies (Frebel et al. 2014). These systems are ideal laboratories for the earliest stages of galaxy formation, as they only contain a few hundred stars, such that a complete census of the entire stellar system can be carried out with high-resolution spectroscopy. These detailed observations can then be contrasted with cosmological simulations that model the enrichment process in the wake of the first supernova explosions.

In summary, important challenges remain, but thanks to the confluence of supercomputing technology, enabling ever more realistic simulations, with large surveys of the stellar content of the Local Group, such as the ongoing, billion-star `Gaia` survey, we are well on track to unravel the early formation history of our Galaxy.

Cosmological models distinguish different phases in the history of the Universe. The era of galaxies marks the end of the Dark Ages characterized by no source of light. The birth of first stars, BHs, supernovae and galaxies are deeply interconnected at different z intervals.

The available generation of ground and space telescope has opened a new scientific question that will be one of the main drivers of the future planned telescopes (`JWST` + 30 m+): are the first galaxies observables? We ask Volker Bromm to introduce the passage from first stars to first galaxies.

6.6 From the Ingredients to First Galaxies

Questions for Volker Bromm:
Could you briefly trace the historical development of first galaxy studies? Which is the prevailing picture of the first galaxies properties? What information could be gained by means of simulations? How the first galaxies may have contributed to the cosmic re-ionization of the Universe? Which redshift intervals should be important to cover in order to anchor cosmological models with observations?

First galaxies also mean first stars. What is the situation of the current researches on these objects? Do we find remnants of first stars in the MW?

These are all intriguing questions, and I will try to fashion a response from my viewpoint as a theorist, but with the observable signature clearly in mind. I will address these questions in turn, but would like to begin by considering the 'Big Picture' context.

Cosmological context

These are exciting times in the exploration of the high-redshift frontier, concerning the first billion years of cosmic history. Advances in supercomputing technology have resulted in an increasingly realistic picture of how the cosmic dark ages ended (Loeb and Furlanetto 2013; Wiklind et al. 2013). At its foundation lies the prediction that the first stars, the so-called Population III (Pop III), were typically massive, with masses of $\sim$10–50 $M_{\odot}$ (Bromm 2013). As a consequence, these stars rapidly changed the state of the pristine intergalactic medium, via the input of energy and heavy chemical elements, what is often termed 'feedback'. Specifically, the first stars initiated the reionization of the universe through their efficient output of ionizing photons (Barkana and Loeb 2007; Meiksin 2009; Robertson et al. 2010), and enriched the primordial, pure hydrogen/helium, gas with the initial complement of heavy chemical elements upon their violent death (Karlsson et al. 2013). Once the first stars appeared on the scene, the universe made a rapid transition to an ever more complex state, eventually leading to the emergence of fully-developed, self-regulated galaxies, including the assembly of supermassive black holes in their centers (Bromm and Yoshida 2011).

This emerging theoretical picture will soon be tested with an upcoming array of next-generation observational facilities, such as `JWST`, scheduled for launch in $\sim$2018, and the planned giant 30–40 m telescopes on the ground. The former will provide unprecedented near-IR imaging sensitivity, ideally complemented by the adaptive optics-enabled spectroscopic capabilities of the latter. In-situ probes, aiming at detecting the signposts of the first stars and galaxies at high redshifts, stand next to the equally-promising near-field cosmological probes, often termed 'Stellar Archaeology'. In this local approach, surveys of metal-poor stars in our Galaxy, and in other members of the Local Group, yield constraints on the properties of the first stars via their unique nucleosynthetic patterns that are preserved in the atmospheres of surviving, low-mass stars. Just ahead of those next-generation telescopes and greatly enlarged stellar-archaeological surveys, there is the exciting prospect for serendipitous "pre-views" into the very high-redshift frontier. An example are gamma-ray bursts (GRBs) that already probe the early intergalactic medium out to redshifts of $z \gtrsim 9$ (see the response to the next query below).

First galaxies properties and observability

The questions above are all closely related, and I therefore attempt to address them in a coherent fashion. The properties of the first galaxies, which in turn determine whether they are directly observable, depend on their assembly history. Specifically, we need to understand what are the lowest-mass dark matter halos that are able to host bona-fide galaxies. If these host halos are small, low-mass systems, they will result in low-luminosity galaxies that might not be observable; if, on the other hand, the host halos are more massive, the corresponding galaxies would be more luminous, thus boosting the likelihood of their detection. The mass scale of the dark matter host is set by the strength of the feedback from the first, Pop III, stars. Let me explain this in somewhat greater detail.

The impact of the first stars on the assembly history of the first galaxies sensitively depends on their mass, which in turn determines the strength of the supernova feedback at the moment of their death. Basically, there are two main classes of Pop III supernovae, the hyper-energetic pair-instability supernovae (PISNe), and the less energetic, standard, core-collapse explosions. There has been a revision in the consensus view, away from an almost exclusive PISN channel to one where core-collapse supernovae dominate, as a consequence of the recent downward revision of the Pop III mass scale.

A PISN, resulting from Pop III progenitors with mass ~ 140–$260\,M_{\odot}$, is characterized by a huge yield, where almost one half of the stellar mass is transformed into metals, $y = M_Z/M_* \sim 0.5$ (Heger and Woosley 2002). This is in stark contrast with typical core-collapse yields, $y \lesssim 0.05$. It had long been argued that the observed abundance patterns in Galactic metal-poor stars do not show any signs for predominant PISN enrichment, such as a strong odd-even effect, or the absence of any neutron-capture elements (Beers and Christlieb 2005). Empirically, this seems to favor core-collapse enrichment, in agreement with the recent theoretical revision of the Pop III mass scale. However,it is important to keep an open mind. After all, the Pop III mass function is predicted to be broad, possibly extending to high masses in the PISN range as well.

Assembly of the first galaxies

The standard model of first star formation (see below) robustly predicts that the first stars formed in so-called 'minihalos', bound dark matter systems of a million solar mass or so, emerging at $z \sim 20$–30, corresponding to 200 million years after the Big Bang (Bromm 2013). The kind of explosion, PISN vs. core-collapse, encountered by the dying Pop III star governs how seriously the minihalo host is disrupted. The extreme explosion energies, $E_{\rm SN} \gtrsim 10^{52}$ erg, associated with a PISN, result in the complete disruption of the host system with its shallow gravitational potential well. It then takes of order a local Hubble time, $\sim 10^8$ yr, for the hot ejecta to cool, and to be reassembled into a more massive dark matter halo, where the first galaxies can form, resulting in long-lived stellar systems that are dominated by metal-enriched, low-mass (Population II) stars.

The 'recovery time', however, is much shorter for core-collapse explosions. Metal-enriched material then can recollapse, and provide the raw material for the next round of star formation, already after a few 10^7 yr. Thus, the nature of the first supernovae determines when and where the first *bona-fide* galaxies can form. The latter are often defined as dark matter halos that host long-lived stellar systems. PISN feedback would correspond to delayed recollapse, thus rendering the first galaxy hosts more massive, and supposedly luminous, whereas core-collapse feedback would correspond to lower-mass, fainter systems. Regardless of the nature of the Pop III enrichment channel, however, any first galaxy would already be metal-enriched, hosting Population II stellar systems. The truly metal-free, minihalo progenitors will likely remain out of reach, due to their extreme faintness. These ultimately are questions for the JWST, when the metallicity and luminosity function of the first galaxies will be measured in ultra-deep field campaigns.

Empirical probes

The most direct way to probe the signature of the first galaxies is the imaging and spectroscopy in the near-IR, possible with the upcoming frontier facilities, primarily the JWST. One prime avenue is to detect the emission lines emitted by the ionized regions around the central stars; emission line ratios can then serve as a diagnostic of the stellar population(s) involved, and as a tracer of the respective initial mass function (IMF). Specifically, a strong contribution from the He II 1640 Å line would indicate a top-heavy Pop III stellar system (Pawlik et al. 2013; Schaerer 2003). The search for high-redshift galaxies has now reached a spectroscopically confirmed redshift of $z \simeq 7.5$ (Finkelstein et al. 2013). Even higher redshifts are expected in the ongoing Hubble Frontier Fields, exploiting the magnifying power of gravitational lensing.

A powerful probe of the metal content in pre-galactic gas clouds is provided by bright background sources, with lines of sights that intersect the intervening medium. Traditionally, quasars have served as such back-lights, now extending to $z \sim 7$ (Mortlock et al. 2011). However, quasars are getting exceedingly rare at high redshifts, rendering them ineffective to probe even earlier times. Here, GRBs take over as searchlights of the early universe (see below). We are already finding clues to the enrichment state of the high-z intergalactic medium, employing the traditional quasar backlights. Two new tantalizing discoveries have been made. One is the detection of seemingly completely unenriched, truly primordial material (Fumagalli et al. 2011; Simcoe et al. 2012). The presence of such islands of pristine gas at $z \lesssim 5$ indicates that pre-galactic metal enrichment was incomplete, and probably confined to the highest-density regions. The other is the detection of carbon-enhancement in low-metallicity damped-Lyman-α (DLA) clouds (Cooke et al. 2011), possibly pointing to a Pop III origin of the heavy elements found there.

Finally, there is the hunt for PISNe, triggered by the death of very massive Pop III stars. We do not know whether Pop III ever gave rise to these extreme explosions. It is, however, important to search for them, as any positive, or negative, result would provide us with valuable constraints on the upper-mass end of the primordial IMF. Recent radiation-hydrodynamics (RHD) simulations clearly show that PISNe were sufficiently bright to be picked up by JWST with its near-IR camera. The problem, however, may be that they were so very rare. A survey strategy employing a wide-field mosaic, with individually only modestly-deep exposures, seems optimal. Undoubtedly, the potential for any such serendipitous discoveries in the high-redshift universe is considerable, and it will be fascinating to see this unfold.

The first stars and possible MW remnants

Star formation in general is a highly complex process, involving non-linear and non-equilibrium physics (McKee and Ostriker 2007). One of the appealing features of primordial, Pop III, star formation is that we have a very good understanding of the initial conditions, provided by the successful ΛCDM model of cosmological structure formation. This is in difference from the present-day case, where initial conditions are given by the non-linear density distributions and velocity fields that result from the supersonic turbulence in giant molecular clouds. The basic result is that the first stars formed in so-called 'minihalos', with total (dark matter plus gas) masses of $\sim 10^5 - 10^6 M_\odot$, at redshifts $z \simeq 20 - 30$. This result is quite robust, and rather drastic deviations from standard ΛCDM are required to modify the properties of the primordial star formation site, such as warm dark matter (WDM) scenarios.

One significant recent development, which does impact when and where the first stars formed, is the discovery of a subsonic, relative streaming velocity between the dark matter and baryonic components (Tseliakhovich and Hirata 2010). This relative motion is imprinted at the epoch of recombination, when the baryonic sound speed experiences a precipitous drop from near-relativistic to few $\mathrm{km\,s^{-1}}$ values. Furthermore, the streaming motions are coherent on cosmological scales (technically a few comoving Megaparsec). The supersonic streaming velocity acts as an additional source of effective pressure, assisting the conventional thermal pressure in preventing gravitational instability. As a consequence, collapse of primordial gas into minihalos is delayed, and on average shifted to more massive systems. However, at $z \lesssim 15$ the effect becomes increasingly negligible, as the streaming motions decay due to the Hubble flow.

The traditional paradigm of Pop III star formation, where only one massive star was thought to form per minihalo, has recently been revised in important ways (Bromm 2013). The new picture, based on very high-resolution simulations which, crucially, are able to follow the evolution for many free-fall times, posits that the first stars typically formed in small multiple groups. This ubiquity of stellar multiplicity in Pop III is akin to what is typical for the present-day case where stars typically form in a clustered mode. It derives from the gravitational instability in the accretion disk that forms around a central protostar from the delayed infall of material with increasing levels of specific angular momentum. The gravitational torques acting to transport spin out, and mass in, are unable to drive sufficiently strong mass accretion rates to process the high infall rates, onto the disk, from the surrounding, hot envelope. Consequently, the Pop III disks are inevitably driven toward instability, and fragmentation into multiple protostellar systems ensues.

Recent debate has centered on whether the Pop III accretion disks could possibly be stabilized, thus suppressing any fragmentation and effectively restoring the one star per minihalo picture of the pre-2009 era. One idea invokes unresolved turbulence as a stabilizing agent. For brief periods after the initial, central protostar has formed, such stabilization is indeed seen, either in runs with extremely high resolution, or those that employ sub-grid models for the unresolved turbulence on small scales. However, these studies suffer from 'Courant myopia', where the simulations grind to a halt when the first parcel of gas, here the central protostar, reaches high density. It remains to be seen whether the disks can retain stability over the many free-fall times required to really settle this key question.

The ultimate goal is to predict the Pop III IMF. To that extent, simulations need to be pushed into the late-stage RHD regime, where the UV radiation feedback from the growing protostar(s) will act to limit the final mass of a Pop III star. It soon became clear that this radiative feedback would primarily work by evaporating the surrounding accretion disks. Recently, two- or three-dimensional RHD simulations have converged on final Pop III masses of order a few tens of solar masses. This implies progenitor masses that would typically lead to core-collapse supernovae, instead of the more extreme PISNe that were preferred earlier on.

A powerful test of our emerging theory is the near-field cosmological search for relics from the era of the first stars. These are foremost the ancient, most metal-poor stars in our Galaxy, and its dwarf satellite systems. A number of key lessons have emerged (Beers and Christlieb 2005): chemical abundance patterns in metal-poor stars can be reconciled with standard core-collapse nucleosynthesis in the majority of cases; there is currently no evidence for any true metal-free, Pop III, surviving low-mass stars, although recent simulations at least do not categorically exclude that possibility, and there is the problem that any primordial signature might be 'masqueraded' through pollution, or accretion, from the interstellar medium of the Milky Way; there is currently no direct hint for Pop III PISNe enrichment; and there is a curious trend towards carbon-enhancement towards the lowest metallicities.

The problem of C-enhancement indeed has recently become even more intriguing. Since the discovery of the two most iron-poor stars, attempts have been made to explain their peculiar abundance pattern, i.e., low in all elements with the notable exception of the ultra-enhanced light ones (C, N, O). The most convincing one is to invoke faint supernovae, triggered by Pop III progenitors that are sufficiently massive to leave black holes (BHs) behind (Iwamoto et al. 2005). Basically, most of the heavy elements are then locked up in the central BH, and only the lightest ones (C, N, O) from the outer layers are expelled. Such C-enhancement nicely resonates with some theoretical predictions of cooling thresholds to enable the formation of low-mass stars. However, this picture has been challenged, both on theoretical and observational grounds.

Theoretically, there is the debate whether fine-structure cooling, mostly due to C II and O I, are driving the transition from top-heavy Pop III to low-mass dominated Pop II, or dust cooling. And observationally, there is the recent discovery of the most metal-poor star, in terms of the overall mass fraction locked up in metals, yet (Caffau et al. 2011). Significantly, this star is *not* C-enhanced, but instead 'C-normal'. It thus lies in what had been termed the 'forbidden zone' of the fine-structure cooling theory, thus indicating that dust cooling must have been responsible for its formation. Basically, dust operates at very high densities, thus being able to imprint sub-solar Jeans masses. The C-riddle, however, remains. There seems to be a dichotomy, 'C-enhanced' vs. 'C-normal' at very low metallicity, which has tentatively be linked to two physically distinct pathways to low-mass star formation. Basically, one pathway would be classical Jeans instability, ultimately relying on the ability of the star forming gas to cool even at high densities, since the Jeans mass scales with temperature and (number) density as $M_{\rm J} \propto T^{3/2} n^{-1/2}$. This (thermal) pathway requires cooling due to dust grains, as other coolants are ineffective at high densities. An alternative pathway to low-mass stars can operate in a clustered environment, where the complex N-body dynamics amongst multiple protostars can lead to the ejection of some fragments from their birth cloud. Those 'ejectees', therefore, never will have the chance to accrete the full complement of their Jeans mass, as determined by the temperature and density of their initial formation site. This (dynamical) pathway suggests fine-structure cooling, since the latter has been shown to determine whether star formation happens in a clustered mode or not.

Next to individual metal-poor stars in the halo of the Milky Way, increasing attention is being paid to the newly identified UFD satellites. Each of them contains only a few hundred stars, so that, in principle, a complete census is possible, a feat that is completely out of reach for the Galaxy. Because of their shallow potential well, only a small number of supernova explosions could have contributed to their enrichment. Any Pop III signature would thus be much less diluted than in systems with more complex chemical histories, such as the halo and bulge of our Galaxy. The UFDs, therefore, likely provide us with 'Rosetta Stone' systems, giving us a sporting chance to directly constrain the Pop III IMF.

6.7 To Summarize

From the 1990s several surveys have started to explore the world of high-redshift galaxies by combining spectroscopic observations from the large ground based telescopes and space facilities, in particular `HST`*, with deep field imaging (e.g. HDFs, HUDF). As a first result there has been a sensible increase in the detection of galaxies with redshift $z > 2$. Photometric sample sizes are of the order of $> 10^4$ galaxies at $z \sim 3$ and $> 10^3$ galaxies at $z > 5$, while spectroscopic samples are about an order of magnitude smaller. The HUDF deep field has imaged many galaxies with redshift $z \sim 6$–7. The spectroscopic confirmation comes from the measure of Lyman-α emission or through the spectral break associated with the absorption of the intervening hydrogen. In Fig. 6.4 is shown a recent findings by Oesch et al. (2015) for the Lyman break galaxy EGS-zs8-1 at z=7.7*

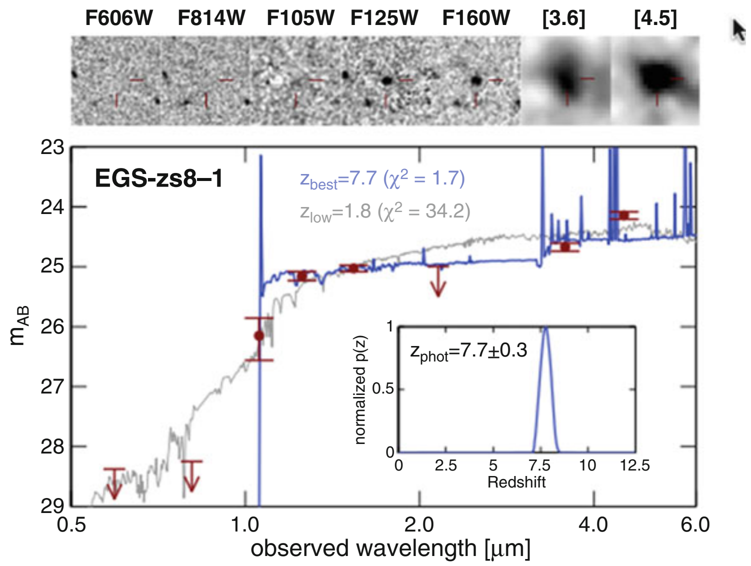

Fig. 6.4 The spectrum plus multi-band imaging (FoV=5“×5”) of the Lyman break galaxy EGS-zs8-1 at z=7.7302±0.0006. The source is perhaps the brightest and most massive z∼8 Lyman break galaxy in the full CANDELS and BoRG/HIPPIES surveys, having already assembled $10^{9.9\pm0.2}$ $M_\odot$ of stars at only 650 Myr after the Big Bang (Oesch et al. 2015) (courtesy of Pascal Oesch)

The magnifying power of gravitational lensing is a further method to find out distant galaxies. Surveys of lensed galaxies (e.g. COSMOS), are expected to find $z > 7$ galaxies. An example is shown in Fig. 6.5.

GRBs can outshine in few cases their high-redshift host galaxies. `SWIFT` *is hunting these individual explosions. A handful of GRBs are hosted by $z \sim 6$ galaxies (Tanvir 2013), but some confirmed redshift are larger than 8 (GRB 090423 and GRB 120923A at spectroscopic redshifts of 8.2 and 8.5 respectively).*

Surveys started to provide very important results about galaxy evolution. The HS is recognizable up $z \sim 1$ although, regular spiral structures appears at $z \simeq 2$: chain of clumps and irregular morphologies dominates at higher redshifts, although the elliptical morphology is present.

There is an indication that the merger rate increases between $z = 0.7 - 3$. This should have consequences on many properties of galaxies. Bianca Poggianti reviewed the possible growth in size of high-redshift ($z = 1 - 3$) massive compact galaxies. Their significant evolution in size (up to a factor of 6) is however put into question by several observations. There is not a general consensus about the evolutionary path followed by galaxies at high z and consequently about the progenitor of massive galaxies observed today.

The study of high-redshift galaxies has been used to infer the variation of the SFR with the cosmic time. First measures, which not include any correction for the

Fig. 6.5 COSMOS0211+1139 at z=$0.90^{+0.06}_{-0.04}$ is part of a survey of lensed galaxies in the COSMOS Field (Faure et al. 2008) [HST Gallery; Credit: NASA, ESA, C. Faure (Zentrum für Astronomie, University of Heidelberg) and J.-P. Kneib (Laboratoire d'Astrophysique de Marseille)]

effect of dust at high-redshift, stimulated a debate, only partially resolved at present, concerning the proper correction to the observed SFR for obtaining more reliable measures at high-redshift. This is a future `JWST+ALMA` *job. However, Fig. 6.3 (left panel) has clearly shown that the SFR density has a peak at $z \sim 2$, dropping by a factor of 20 down to $z = 0$. High-redshift galaxies are more gas rich (gas is up to 50 % of the mass) and appear more efficient in forming stars. The picture is therefore sketched.*

High-redshift galaxies need to be linked to local galaxies: this is a strong test for any galaxy formation theory. The present theoretical context is provided by the ΛCDM cosmology, a bottom-up vision. At present, this model has his own plague with the so called "missing satellite" problem. Simulations in ΛCDM cosmological context suggest that the majority of massive galaxies passively evolving at $z \sim 2$ will be transformed into local BCGs. But this is not the case for all local massive galaxies. The ancestors of the Milky-Way should be primitive dwarf galaxies with masses of few hundreds million solar masses formed between $z \sim$10–15. UFD galaxies (see the Carme Gallart contribution in Chap. 3) should be the local survivors of those primitive dwarfs (`GAIA` *will tell us). These dwarfs, containing few hundreds of stars are the best place where to test Pop III signatures.*

Will first galaxy be finally observed with `JWST+30-m`*? What is emerging from the super-computers of theorists? The observability depends on what are the lowest-mass DM halos that are able to host bona-fide galaxies, says Volker Bromm. Small* *halos will result in low-luminosity undetectable galaxies. The watershed is set by the PopIII stars mass function and the consequent type of SNæ they produce. PISNe will lead to more massive and hopefully more luminous first galaxies already enriched by metals. These, however, seems rare at odds with core-collapsed SNæ. The new observing facilities will point to probe directly first galaxies in near-IR imaging and spectroscopy. They will probe metallicity in gas clouds via bright background high-z sources of different types and finally will hunt for PSNe.*

It is worth also to mention a different approach to the problem of distant galaxies. What if high-redshift galaxies are not the ancestors of local galaxies? This question has been recently discussed by Disney and Lang (2012). They explored the possibility that high-redshift galaxies discovered by `HST` and showing Tolman dimming > 10 could be the representatives of a quite different dynasty whose descendants are no longer prominent today. They pointed out the difficulties that current stellar evolution models have in explaining such a dramatic dimming in surface brightness in $z \sim 7$ galaxies. They developed what they call the Succeeding Prominent Dynasties Hypothesis (SPDH) as opposed to the notion of Evolving Single Dynasty Hypothesis. The SPDH approach succeeded in explaining several observations like the "downsizing", a mere illusion effect within SPDH, without evolutionary effects. According to Disney and Lang "In one sense, one must hope that the SPD hypothesis is wrong, for it is right then extragalactic research is going to be so much harder. The obvious program of decoding galaxy formation and evolution simply by building larger instruments such as `JWST` or `ELT` to look at fainter, more distant objects will not work because a given dynasty of galaxies will remain visible through our visibility window for only a limited range of redshifts, that is, for only a restricted portion of its life. We might see the infant of one dynasty, the children of another, the adults of a third, and the grizzled elders of a fourth only among our neighbours."

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Chapter 7
The New Boundaries of the Galaxy Concept

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"... Bertoldo demonstrated that even when he was tearing out marble to get rid of what he did not want he must work with rhythmical strokes so that he achieved circular lines around the block. He was never to complete any part, but work on all parts, balancing relationships. Did he understand?
I will, after you turn me loose among these marbles. I learn through my hands, not my ears."
I. Stone *The Agony and the Ecstasy* Book 3: The Palace (dialog between Bertoldo and Michelangelo)

7.1 Chapter Overview

In Chap. 6 we outlined the research strategies implemented for the studies of high redshift galaxies, briefly addressed their structures, morphologies and star formation, discussed the ancestor problem and touched the theme of the origin of the first galaxies. With this chapter we certainly enter in the modern view of galaxies, as members of a big society. Up to now we have essentially described and characterized the properties of nearby isolated galaxies, that are sufficiently relaxed to show their almost unperturbed properties. However the history of this society, not differently from the man society, is full of conflicts and battles for surviving. The present knowledge of the cosmic web, of the hierarchical nature of the structures in the Universe, and of the galaxy components have clearly demonstrated that gravitational interactions, gas accretion and outflows, as well as merging events and gravitational interactions are the true past history of galaxies. Galaxies change their structure and morphology across the Hubble time and many of their observed properties today depend on their past history, as well as in many cases on the environment in which they evolved.

The title of this chapter reflects our tentative effort of looking at galaxies along this viewpoint. What are the current boundaries of the galaxy concept? In other words, to what extent the structures we see today were present in the past and what are their limits in mass, luminosity, size, stellar populations and chemical enrichment across the Hubble time? What is the role of the dark matter? In which way the energetic phenomena observed in the galaxy nuclei and in SNe have changed the properties of galaxies? The suspect is that we have built the concept

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of galaxies looking only at their mature appearance and not at their whole life. Can we speak of man describing only its adult phase and not considering his interaction with the whole society?

The following interviews will clarify several things connected to this new point of view. We start in Sect. 7.2 with a nice review of the effects of gravitational interactions and merging that will highlight the progresses done by simulations since the early Toomre' pioneering work. We then address in Sect. 7.3 the problem of the disk assembling and the remarkable extended UV disks found in many galaxies. The current limits in the mass function of galaxies, from dwarfs to giants, are discussed in Sect. 7.4. The various effects of the presence of an AGN at the center of galaxies are analyzed in Sect. 7.5, while the activity of SNe is addressed in Sect. 7.6. Finally, Sect. 7.7 provide the different point of views on the role and nature of the dark matter.

7.2 The Work of the Interactions and Mergers

Questions for Curtis Struck:
the manifold of galaxy shapes is incredible, in particular what emerge from deep images. Fritz Zwicky was among the first astronomers who understand that these shapes may be due to tidal interaction. May you sketch the history of such important scientific achievement?

This would be a fascinating topic for a study by serious historians of science. I cannot claim expertise in that area, so I'll limit myself to a few brief highlights and impressions of the early history of this field, starting with Zwicky. He was, of course, very interested in the topic of morphological analysis and classification in all areas of science. Because there is such a huge range of shapes, this is a wonderful area for such analysis. Interacting galaxy morphologies are certainly more complex than the regular galaxies classified by Hubble! Zwicky had an extensive background in fluid and turbulence (as well as condensed matter) physics, so he had a variety of physical models to bring to this problem. His intuition that these were largely the result of tidal effects was certainly correct, as was his conjecture that colliding ring galaxies like the Cartwheel galaxy (which he discovered) are the result of some type of "centrifugal effect".

Zwicky was not the first to notice some very odd objects among the binary and double galaxies. Bertil Lindblad and Erik Holmberg made extensive studies of galaxy groups in the 1920s and 1930s, as noted in my book on colliding galaxies (Struck 2011). From an early date, Holmberg also recognized that these were probably tidal structures. Harlow Shapley commented on some of the oddities as well, including some that have been extensively studied in the modern era, like the "Antennae" galaxies. Nonetheless, Zwicky's review article on "Multiple Galaxies" (Zwicky 1959) can well be taken as the birth announcement of the field of colliding galaxies. It really emphasized how the extended structure of these galaxies could be classified as a few generic tidal forms, e.g., "bridges and filaments," or as we now say, bridges and tails.

Up to Zwicky's time telescopes were not available with the light gathering power to observe most tidal features, which can be of very low surface brightness. Thus, only hints of what would be seen later were visible to early observers. The Palomar Sky Survey on the 48 inch Schmidt telescope, with follow-up imaging from the 200 inch Hale telescope, changed the game for the catalogers of odd galaxies, like Halton Arp and B.A. Vorontsov-Velyaminov. Their catalogs (e.g., Arp 1966), in turn, provided the inspiration and sample objects for hundreds of subsequent studies of interacting galaxies.

The images in these catalogs begged the questions—what are they? How do they form? What are their lifetimes, and what is their role in galaxy evolution?

The question of lifetimes is actually the easiest, at least in terms rough estimates. Once you determine typical galaxy sizes and masses, which requires knowing galaxy distances, a topic of intense study through the twentieth century, then you can estimate dynamical timescales in galaxies. That is, free-fall or orbital timescales. Roughly speaking, for a typical star in a typical (large, not dwarf) galaxy, like the Milky Way, these timescales are around a few hundred million years. They're about an order of magnitude shorter in the galaxy core and up to an order of magnitude longer well out into the galaxy halo. If the odd morphologies are the result of transient tidal disturbances, then we expect them to "relax" or smooth away after a few dynamical times. And again, in a very rough way, this is what is observed. The time it would take a perturbing galaxy to move well away from its companion victim (or to merge with it) is of the order of the halo timescale, or several halo timescales. Thus, when we see galaxies with very disturbed disks, we can usually spot a nearby companion, because with its medium dynamical timescale the disk will probably relax by the time the companion leaves the field or returns to merge. On the other hand, astronomer François Schweizer has published some beautiful studies of systems where faint tidal features can be still found in the halo, despite the fact that stellar components of the galaxy have settled to an appearance of normalcy.

The other questions posed above cannot be answered with such basic physical arguments; answers generally require detailed computer modeling. Such models began to appear in the astronomical literature in the late 1960s and early 1970s. The most comprehensive of these early studies was that of Alar Toomre and his brother Juri (Toomre and Toomre 1972). They addressed an interesting range of interactions, described the tidal actions through these encounters, and made plausible conjectures on their effects. That is, they gave what might be regarded as preliminary answers to all of the questions above, but were subsequently shown to be generally correct. By current standards these simulations were very simple. The net gravitational potential of each galaxy was represented by a simple, fixed form, which simplified the potential of a real galaxy with bulge, disk and stellar halo components. Massive dark halos were unknown, though the evidence was beginning to appear. This didn't matter too much because the Toomre's studied close, rapid encounters. The stellar disks were represented by a very modest number of massless test particles. This also didn't matter, indeed, such simple "restricted three-body" models still have important uses. The Toomre's were able to show that such encounters can produce enhanced spiral arms, disk rings, bridges between galaxies, and long tails.

The observations can only provide us with snapshots of samples of the evolutionary stages of some of the wide range of possible collisions. Given the faintness of extended tidal structures, these can only be studied in great detail in the very rare nearby interacting systems. It would be nearly impossible to understand the full dynamics of galaxy interactions without computer models. It would also have been impossible to begin this study with the computers of the 1970s unless simplifications like the restricted three-body approximation were valid. The Toomre's timing was excellent! Just as Zwicky launched the observational study of interacting galaxies, the Toomre's launched the theory.

From the mid-1970s this field grew rapidly, and many new questions and directions were explored. Toomre (1977) gave the field another big push with the suggestion that dynamical friction would greatly reduce the relative velocity in galaxy encounters, and so, most close encounters between comparably sized galaxies (now called major mergers) would result in merger rather than escape. This was a very surprising suggestion at the time, but repeatedly confirmed by ever improving computer models in the 1980s and 1990s. Toomre further proposed that, given that mergers might induce large amounts of star formation with subsequent gas dispersal, and that stellar orbits might be almost chaotically mixed, major mergers between gas-rich disk galaxies (now called wet mergers) might form elliptical galaxies. He further noted, based on a rough estimate of the merger frequency, that mergers could produce most of the ellipticals.

This was a highly controversial proposal at a time when monolithic collapse models held a nearly consensus position. However, it energized the study of elliptical formation for decades. An interesting history could be written on this topic alone. For present purposes, suffice it to say that galaxy archaeology via high redshift studies is providing enormous input into such questions, augmented by cosmological structure formation simulations. There has been a surge of publications in recent years on elliptical formation. (A search on the words "elliptical galaxy formation" or "galaxy merger" in the Bookworm:ArXiv website indicates a near doubling of articles per year since 2009.) Recent insights include the recognition that many ellipticals formed rapidly in dense environments from multiple, near simultaneous mergers of young galaxies, and unformed accreting material, falling in from surrounding cosmic filaments. This is not exactly the same as the binary, wet merger scenario, but it is very wet (gas-rich), and perhaps even more chaotic. The essential elements are similar. Beyond this the recent evidence suggests that a significant fraction of the mass in ellipticals is acquired through the remaining age of the Universe via a number of minor mergers. Pieter van Dokkum (e.g., van Dokkum et al. 2008) of Yale University and collaborators have vigorously pursued observational studies which have supported this view.

Another seminal suggestion of the Toomres' was that the interstellar gas compressions and torques in galaxy collisions and mergers would stimulate star formation, e.g., in a burst mode, and fuel nuclear activity. The predicted star formation has been confirmed from studies in several areas. One spectacular example was the discovery of ultraluminous infrared galaxies (ULIRGs) in far-infrared observations made with the IRAS satellite in the 1980s. In most cases, the huge emission luminosity of these galaxies is thought to originate in a superstarburst in a heavily dust-obscured core of the remnant of a major merger. At the opposite end of the intensity spectrum, statistical studies over the last decade (reviewed in Struck 2006), based on observations in a wide range of wavelengths, have confirmed that galaxies in on-going interactions (or at least with very near neighbors), have several times the average star formation rate of isolated comparison objects.

It is rather harder to confirm the prediction of nuclear activity, since many active nuclei also occur in dust-obscured regions with intense star formation activity. It can be difficult to separate the emissions from different sources, but a great deal of recent work seems to confirm merger-induced nuclear activity. This statement is also less firm than in the case of induced star formation because the process appears to be more complex, including for example, time delays relative to the peak of merger-induced star formation. Perhaps it would please Zwicky to see the confirmation of predictions for such phenomena, which were made on the basis of the 'morphological' evolution of simple numerical models.

At what level are simulations of galaxy-galaxy collisions of nearby galaxies providing explanations of odd shapes?

At many levels! And yet, as we seek ever more detail the dynamical complexities go up exponentially.

What the early restricted three-body models did was to show how simple impulsive tidal dynamics, and subsequent kinematic motions, could yield explanations for some of the most dramatic collision morphologies, like: rings, induced spirals, bridges and tails. In the 1980s ever improving N-body simulations supported Toomre's suggestion that major mergers could be completed relatively promptly (i.e., in a few dynamical times). In first years of this decade these models consisted of single component galaxies (e.g., ellipticals with no halos) on initially bound orbits, and represented by a very modest numbers of particles. By the end of the decade, and the beginning of the next, the models had collisionless disk/bulge/halo components, many more particles, and often a gas disk component as well. For example, the well-known Barnes & Hernquist models (e.g., Barnes and Hernquist 1991) showed offsets between the halos and the visible components during the merger process, and the dumping of large quantities of interstellar gas into the nuclei of the merger remnant. The latter result provided evidence in support of the Toomres' prediction of induced nuclear star formation and nuclear activity, and showed it was even stronger than in the early models, as observed.

Often after great advances in a given area, the science will slow for a while. With some real understanding of the major merger process, and many multi-waveband observational confirmations and constraints, this might have happened in this area. However, from the mid-1990s Hubble Space Telescope observations of increasing numbers of interacting galaxies started to become available. The sensitivity of HST gave us a better view of some extended tidal features, but the real power of HST was its increased resolution. It is not an exaggeration to say that from this time the terminology in this field changed from 'knots of star formation' in interacting galaxies, to discussions of (dozens or hundreds of) 'resolved star clusters.' The former meant bright, but unresolved regions of young star emissions. The latter obviously meant that HST could resolve scales of objects recognizable as star clusters like those in very nearby galaxies. However, some of these objects weren't like those in the Milky Way; they were much more massive and brighter than (present-day) Milky Way clusters (e.g., Whitmore and Schweizer 1995). The term 'super-star cluster' was born (or rather borrowed from studies of nearby dwarf galaxies), as was the hope that these objects might prove to be powerful clues to the origin of globular clusters. A large majority of these supers were found in interacting and merging systems. At about the same time HST studies revealed evidence for multiple populations of globulars in early-type galaxies, providing some indirect evidence for their merger origin. These studies continue to the present.

Another exciting and related discovery at that time was the class of objects called tidal dwarf galaxies (see the review article of Duc 2012). I use the word 'discovery' somewhat loosely here, since some of these objects were known many years before (e.g., in the Antennae galaxies). However, more were discovered, and could be studied in much more detail with HST observations. Most importantly, the case could be made from the observations that they are self-gravitating, and thus, likely distinct structures, not just transient regions of enhanced star formation in tidal tails. Although they are larger and more massive than globular clusters, there is little evidence or reason to think that they have dark matter halos. Thus, they are a kind of transition object between globulars and dark halo dominated dwarf galaxies. Unfortunately, they are small, and even HST resolution is not all that we might want for detailed studies of these objects. I suspect that limited observational resolution has dampened enthusiasm for studies of these objects for the time being, despite the fact that many questions remain.

My main point here is that by the mid-1990s we had largely explained much of the bulk tidal structure, but new observations, obtained with new technologies opened the curtain on a new kind of interaction-induced phenomenon. A final example, there is evidence for an anti-correlation between the presence of a tidal dwarf galaxy at the end of a tidal tail and large, young star clusters strung along a tail (Knierman et al. 2003).

The question above also has a more global side, i.e., can we expect to account for all the strange morphologies produced in galaxy collisions and mergers? Most modeling and analysis in the last couple decades has focused on either the structure of the final merger remnant, or on impulsive first close approaches which generate relatively symmetric structures like induced spirals, rings and tidal tails. Intermediate time, or early merger stages tend to very messy with a lot of detailed structure that would be very hard to model in detail, and there are few fundamental questions that might be answered by trying to reproduce such systems with models. Thus, they have been largely neglected, except for special cases like the Antennae galaxies, and a few others in Toomre's (1977) famous merger sequence. Even in those cases, often it isn't the chaotic inner structure that is modeled, but rather the tails and other 'outer' structures. Similarly, late, post-merger residual structures have primarily been studied in the specific context of the so-called shell galaxies. Recently, there has been a little more interest in the details of infall out of tidal tails, which should be quite similar to infall onto galaxies out of cosmological filaments. There has also been a good deal more interest in loops around galaxies, which likely consist of material stripped out of satellite galaxies. A primary reason for this interest is that it now appears that many of the small satellites orbiting the Milky Way and the Andromeda galaxy are part of such great loops (e.g., Ibata et al. 2013; Pawlowski et al. 2012a), which immediately raises the question of how common is this phenomenon.

Thus, we see that the most spectacular forms have been well modeled, even to the level of determining the differences in tidal tails as function of the structure of the dark halo containing them. So too have the phases that have the most to teach us about the effects of mergers and interactions on galaxy evolution, ranging from early induced star formation to the structure of major and minor merger remnants. A few areas have been neglected as so complex, that they apparently cannot teach us enough to justify the effort, or with too few observational constraints to have any hope of modeling. Such considerations are important, my collaborators and I have worked to match a couple dozen multi-waveband observational constraints in modeling the NGC 2207/IC 2163 system. This system appears to be an early stage flyby, but there is still complexity (Struck et al. 2005). And then there are a few areas that are just beginning to be studied now, like the 'micro-mergers' in which small satellites are disrupted and can form the large loops.

Different shapes and/or galaxy sizes are connected to observations in different wavelength bands. Would you discuss the results of imulations in modeling e.g the more recent observations like UV extended disks, presence of neutral gas filaments, interaction with dense environments, the presence of intra-cluster light?

The study of interacting galaxies is a small part of the extensive web of modern extragalactic astronomy, as evidenced by this book! Many other areas like the ones you mention ultimately connect to them in some way. However, the following examples provide some nice illustrations of such connections.

The so-called XUV disks were first commonly observed in the ultraviolet images from the GALEX satellite, in mostly isolated galaxies (see Sect. 7.3). HI observations have long taught us that disks extend well beyond their optically visible radii. We would have expected a few, old stars or old clusters there, but the discovery of young stars out in that tenuous gas was surprising. External triggers of star formation, like near passages or penetrations of very small dwarf companions, or empty dark halos, are quite possible. Some of the XUV disks show spiral structure, which could also be externally triggered via flybys of small or dark companions. Recent case studies include NGC 4625 (Bush et al. 2014), and NGC 404 (Thilker et al. 2010). Intriguingly, these studies show how minor interactions can at least transiently ignite the generally quiescent outer gas disks.

As to cool gas filaments, the first thing that I would point out is that it has been hard to find cases of apparent infall out of cosmological filaments in nearby systems (Heald et al. 2011). It appears that epoch is largely over, and the best hunting for such objects will be at higher redshift. The great loops noted above may be in part 'archaeological' remnants of filament infall that brought in dwarf galaxies as well as gas. Residual infall may be small and largely in the form very tenuous warm/hot gas (Joung et al. 2012).

As to environmental interactions, perhaps the most important is ram pressure stripping, which can have a number of interesting effects, including: (1) removing fuel for star formation to varying degrees, (2) compressing removed clouds and generating star formation for the intracluster medium, (3) stressing and making waves within the unstripped disk remnants. The first of these is well known, though it is my impression that there is still much to learn about stripping rates along different kinds of orbits in different environments. This is especially true in galaxy groups that develop hot halos over a long timescale, or relatively late in the history of the Universe. The second is a more recent study, especially studies of objects called 'jellyfish' galaxies. In these objects long tentacles (several galaxy diameters) of gas clouds, diffuse gas, and even stars gravitationally grasped by the clouds are pulled by ram pressure out of galaxy disks (see e.g., Yoshida et al. 2004). Star formation occurs in some of the gas clouds, probably as a result of the intracluster medium pressure. Some of this material may fall back onto the parent galaxy, but much of it may be liberated into the intracluster medium, contributing to the inter-cluster light. The third process depends on the likelihood that ram pressure doesn't completely strip the gas component out of disks in all cases, but only the less tightly bound outer disk gas. When this occurs models (Schulz and Struck 2001) have demonstrated that tidal compressions resulting from the ram pressure can induce the formation of spirals, which can trigger star formation. This is a bit counter-intuitive, since we might expect the removal of a large fraction of the gas to promptly quench star formation. However, the Virgo cluster studies of J. Kenney and collaborators (e.g., Koopmann and Kenney 2004) showed that the outer HI disks of Virgo cluster spirals were commonly removed, but not the inner molecular disks, which continue to form stars in many cases.

A nearly equally important environmental effect is that of induced interactions. Of course, most galaxy collisions are induced, either in small groups or via feeding from large-scale structures into groups. In the early twentieth century galaxies were seen as very separated 'island Universes,' and random encounters appeared extremely unlikely. This viewpoint changed with the discovery of massive dark halos, greatly increasing the size of galaxies, and of the cosmic web, with galaxies located mostly in the restricted volumes of sheets and filaments. Gravitationally bound groups orchestrate major and minor collisions between pairs of galaxies. However, there are higher levels of orchestration, including: harassment in dense clusters, group galaxy interactions induced by a cluster potential, and multiple or rapid successive interactions in compact groups like Stephan's Quintet. Incidentally, these processes do not strictly follow the hierarchical structure formation paradigm. Harassment is the result of many, long-distance disturbances of a galaxies by others in the cluster. For a galaxy it is like being jostled on a busy street in a large city. And any type of disturbance can drive evolution (personal growth?) in a galaxy disk.

Just as urban growth leads to suburbs encompassing former villages or towns, it has become very clear in the last few decades that galaxy clusters are still growing due the infall and merger of other groups and clusters. In the case where the infalling group is smaller and its constituent galaxies are less evolved than those in the target cluster, the effects on the former can be dramatic. Ram pressure will act quickly on any infalling galaxies passing near the large cluster core. At the same time that ram pressure is working to remove material from group galaxies, the group is becoming immersed in cluster dark halo material. If the group and its own dark halo were somewhere near virial equilibrium before entering the cluster, this additional dark matter will unbalance it. The group will tend to collapse, while still falling through the cluster. This will likely generate interactions between group members (Struck 2006). Some evidence for this process has been presented in recent years. Relatively isolated groups can experience similar processes, especially if they are being fed new galaxies (e.g., out of large-scale filaments). We seem to be seeing something like that in Stephan's Quintet with recent interactions involving a high velocity 'intruder' galaxy (see Hwang et al. 2012).

What do we still lack in the field of nearby galaxy simulations?

One of the primary goals of simulations of interacting galaxies has been to accurately model the induced star formation. The main obstacle to accomplishing that goal is achieving particle and spatial resolution sufficient to resolve both the overall interaction on a scale of about 100 kpc and the massive gas clouds or young clusters on scales of 10 pc. This is not as large a range of scales as treated in cosmological structure formation simulations, but still one that requires enormous computer power. For this reason, such simulations are generally carried out by groups, rather than individual investigators and at supercomputer centers. These groups must compete with others working on different problems requiring large-scale computer resources, so their share of these resources is modest. However, the results of some these high-resolution models have begun to appear in the literature, especially models of the nearby favorite, the Antennae system, and plans are afoot by several groups to win computer time and carry out more.

Another lacuna in recent modeling is the opportunity to compare detailed model kinematics to observation of nearby interacting galaxies. Excellent morphological fits have been published for a number of nearby systems (e.g., Privon et al. 2013). Good fits are also achieved relative to HI observations of the kinematics of extended tidal structures. Yet, in most cases the kinematic data have nowhere near the spatial resolution of the morphological observations. However, new integral field spectrographs are facilitating a number of new surveys of nearby galaxies of all types, normal and interacting. Currently, these survey projects include: ATLAS3D, CALIFA, SAMI, and MaNGA (e.g., Sanchez 2014). This exciting development should considerably improve the database of kinematic observations (as well as local population data derived from spectral fitting), though the resolution will still be much less than that of the best optical imagery. Nonetheless, any deviations of detailed models of individual systems from observation will lead to further improvements in the models of those systems.

There are more goals in such work than simply to make ever better dynamical models, and reconfirm fundamental tidal theory to higher degrees of accuracy for a few canonical systems. One of these is that with kinematic matching we can be more confident that the models are correctly predicting regions of gas convergence, and shock wave development, and then be better able to evaluate the effects of those processes in triggering star formation. Another is a consequence of the likelihood that this high level of model/observation comparison will require some knowledge of the pre-collision structure of the galaxies for concordance. To date, most models of interacting galaxies have assumed quite simple initial conditions, based on the reasonable assumption that the extreme dynamics of the interaction and merger will dominate until long after the merger is completed. There are exceptions to this generalization, such as studies of the effect of barred progenitors (Berentzen et al. 2004), or the assertion that the spirals in NGC 2207 could not be entirely produced in its early-stage interaction (Struck et al. 2005). Once models routinely reach a level where such questions can be addressed, we will be able to study how initial structures interact with tidal disturbances.

Another goal that is becoming achievable is to use models to learn about detailed dynamics of the turbulent interstellar medium, and specifics about the mechanisms of induced star formation. In some ways this is marvelously ironic. That's because, when first discovered, colliding galaxies were initially seen as messy and their genesis complex. But now we are beginning to understand them well enough to use them as cosmic experiments, freely provided for the data taker! For example, consider the important questions of how do large-scale density waves stir the ISM turbulence and generate gravitationally unstable clouds and star formation? We can study these processes in nearby isolated galaxies, but there remains a great deal we don't understand about spiral waves in such galaxies. Current theory suggests that they may be transients that continually dissolve and reform (Sellwood 2014). If so, their effects on the ISM are also time-dependent, which makes it difficult to decipher. Waves driven by a bar component can also be relatively complex. On the other hand, in a colliding ring galaxy or a prograde flyby, we know how the driving waves formed, and how they will evolve. If a model can match the overall large-scale morphologies (and kinematics) we can also make a good estimate of the wave strength and how it evolves. This means that we can not only study the effects of such waves in the immediate vicinity of the wave where we can measure its amplitude, but we can also look at effects in the gas downstream with some knowledge of the character of the wave when it passed over those regions. To a degree, we know what happened and we can measure its after effects.

Aside from interacting galaxies, another area where models must progress is in the study of the structure of nearby barred galaxies. Barred and oval galaxies have a wide range of structures, as can be seen in the Carnegie Atlas of Galaxies (Sandage and Bedke 1994). There has been much progress in the last couple decades in the theory of some aspects of the evolution of bars. However, my impression is that there still many open questions concerning bars, and much high resolution modeling work yet to be done.

Surveys show that galaxies may vary their structures and masses across the Hubble time and that different mechanisms are at the origin of such variations according to the galaxy environments. Which are the main physical mechanisms driving of the galaxy "mutations" in different environments? What are the time scales of such variations?

I've addressed several specific topics related to these questions already above. From a more general point of view, it might be worth adding a few words on a few great (cosmological) epochs in galaxy evolution, which are beginning to become apparent, especially as a result of high redshift studies. The first of these would be the onset of galaxy, star and active nucleus formation, and reionization by the young seeds of galaxies. Generally, these topics are beyond the scope of this interview, except to say that recent research seems to suggest that they took place surprisingly rapidly.

In a second stage, it appears that the initial buildup of the most massive galaxies, especially massive early-type galaxies, was also fairly rapid. That is, by a redshift of $z = 1 - 2$, most of these galaxies had acquired at least half their present-day mass, and a good part of their general structure (e.g., Hubble type). Both of these statements are rough and qualitative. Exceptions include the facts that at early times elliptical galaxies were much more likely to have very compact surface density profiles, while disk galaxies were much more gas rich, and commonly had a clumpy irregular, structure, rather more orderly spirals and bars. These processes were, of course, dependent on the environment. Nascent galaxy clusters and groups formed at the intersections of multiple sheets and filaments. In these structures galaxies began to form while joining accelerating flows into the cluster core. Simulations show typical young ellipticals formed in such environments via multiple mergers, or rapid successions of mergers. Spirals may have commonly formed in less dense, but nonetheless, likely still experienced high volume, filamentary accretion of small companions, and intergalactic gas. The accretion rate was probably faster than the gas consumption rate for some time, leading to gravitational instability and the observed clumping in the young disks.

The cosmic star formation rate peaked at redshifts of about 1–2, and then began to decline. No doubt this is a result of the accretion processes slowing. Material deeply bound in local gravitational wells would have been largely eaten, while the infall of more distant material would be slowed by the Hubble flow. Thus began the third, long epoch of slow evolution. In this period, accretion onto spirals must have slowed, below their star formation rates. Then they could settle into a more quiescent state, with beautiful spirals. That is, unless they fell into one of the still growing galaxy clusters, and were quenched, e.g., as a result of ram pressure stripping. Especially in late-evolving groups, some spirals might suffer a (likely final) major merger, leaving an early type remnant a la Toomre. Clearly a variety of processes still operated on the disk galaxies, but less violently, and on a longer timescale than previously. The same is true of the ellipticals. Because quite mature ellipticals are found already at moderate redshifts, and because major interactions or other large-scale disturbances involving them are rarely seen at intervening redshifts, it is currently believed that their main evolutionary driver in this period are minor mergers (van Dokkum et al. 2008). These both build them up to their present masses, and input internal energy to make them less compact.

Almost everything described above is recently discovered, still far from fully understood, and being confronted with new observations frequently. To conclude, we might consider very briefly how the current picture of galaxy evolution compares to some of the early ideas. Recall the two major ideas about how galaxies form that came out of the 1970s: monolithic collapse, and hierarchical buildup, with the latter usually visualized as a sequence of distinct major mergers between galaxies of increasing mass at each step. Monolithic collapse seems to have been demoted to a theory of how the first seeds of galaxies (and individual stars within them) began their formation. However, even in the early days of this theory there was discussion of continuing accretion after the initial collapse. What was the addendum may have become the dominant theme.

As to hierarchical buildup, we have already seen a number of important processes in galaxy evolution that either violate the simple idea of a step-by-step buildup (e.g., galaxies merging at the same time as the group containing them merges with a larger cluster), or the whole picture (e.g., ram pressure stripping in dense environments). We've also seen that 'continuing accretion' is now thought to equal or rival mergers as an important evolutionary processes. Yet mergers are still seen as a major player, and the importance of minor mergers has become recognized. Monolithic collapse of galaxy seeds is probably more a matter of cosmological genetics (or 'nature'), than environment ('nurture?'). But the society of galaxies has a major role in almost all of the other processes. While it is true that the biggest effect of the environment may be the local timescale for galaxy evolution, its role in inducing mergers and quenching galaxies is also very important.

To paraphrase Newton, it may be that galaxy evolution researchers stand in a human anti-hierarchical pyramid, with a few giants, including those discussed at the beginning of this interview, at the base, and many more somewhat smaller figures at each level up. We are no longer island Universes, we work in a complex, interrelated society, like our beloved galaxies.

The framework depicted by Curtis Struck is fascinating. Galaxies are no more island Universes and we should take this new point of view to study their properties. Along this line the next interview to Luciana Bianchi address a very important problem connected to the formation of the disk structure in galaxies: the UV disks. In which way such disks were assembled? What was the influence of gas refueling in assembling such structures? To what extent the idea of gravitational interactions and merging is compatible with the observed disk structures? What are the consequences of such discovery?

7.3 XUV Disk: Galaxy Refueling or Assembling?

Questions for Luciana Bianchi:
GALEX has shown that galaxies may have in the UV light a larger extension than at optical wavelength (XUV disks). What are these extended component? How are they correlated to the galaxy environment and to HI refueling?

One of the unexpected discoveries enabled by GALEX's wide-field UV imaging was the presence of UV emission extending up to several times the optical size of some disk galaxies (Gil de Paz et al. 2005; Thilker et al. 2005). The UV-emitting spiral-arm filaments clearly disclosed young stellar populations in outermost regions, considered stable against star formation for their low azimuthally-averaged gas density. But the relations between star-formation rate (SFR) and gas density established until then (e.g. Kennicutt-Schmidt relation) and SF threshold criteria (Toomre Q) were based on data of ordinary (bright) galaxy disks.[1] GALEX sensitive, wide-field UV imaging opened the realm of SF studies in the low-density regime, and some accepted knowledge on SF began to be revised.

In the first study of 200 disk galaxies, extended UV disks (XUVD) were found in ∼30 % of the sample, and a classification in two major types was proposed (Thilker et al. 2007). Type I (prototypes M83 and NGC 4625) are sparse, spiral-arm like structures extending up to ∼4−5 times the radius corresponding to the canonical HI density star-formation threshold; they are seen in UV without an optical match in POSS red plates or SDSS images. There is a definite spatial correlation on kpc scales between HI and the UV emission,[2] suggesting that these galaxy disks are still growing, and undergoing low-level star formation from disky gas reservoirs (new or renewed) surrounding otherwise ordinary looking spirals. Type II are a highly filled, exceptionally UV-bright, low optical surface brightness zone inside the SF threshold contour but beyond the 80 % stellar mass contour (estimated from the K_S flux). Type I are more common, ∼20 % in the Thilker et al. (2007) sample, with no marked preference for spiral subtype, while Type II were mostly found at Hubble types T∼5–8.

In defining XUVDs, the original intent was to exclude cases of extended SF structures obviously associated with strong interactions or tidal stripping, such as pairs in which the only extended UV emission is a tidal tail. In these cases star formation outside the main galaxy disk is expected rather than surprising (but again, only UV data reveal the full extent of the triggered SF out to hundreds of kpc, and enable its precise age-dating (Fig. 5.17 in Chap. 5). However, it is not always possible to identify past flyby perturbers; the XUVD samples include some

[1] In outer disks, Bigiel et al. (2010) later showed the SF efficiency to be reduced by a factor of ∼30.

[2] Instead, *global* galaxy morphology parameters, such as effective radius and concentration, in HI and UV do not necessarily correlate, and XUVD do not stand out in particular, although asymmetries in HI and UV may be used to select XUVD candidates (Holwerda et al. 2012).

interacting galaxies, and span a range of the tidal perturbation parameter (Thilker et al. 2007).

The original criteria developed for identification and classification of XUVD by Thilker et al. (2007) were expanded in subsequent studies, e.g. Lemonias et al. (2011) and Holwerda et al. (2012). The first sample already showed some outliers from the basic Type I and Type II; a comprehensive study of >6,700 galaxies with both FUV and NUV data shows growing complexity: subtypes and "contaminants" emerge and Type II classification is refined (Thilker et al. 2015).

Presence of young stellar populations, mostly in the form of FUV-bright outer rings, were also detected in early-type galaxies (e.g. NGC 404; Thilker et al. 2010), where they account in some cases for >70 % of the FUV flux, though they contain only a few percent of the galaxy mass (Donas et al. 2007; Marino et al. 2011a,b, 2014). UV colors typically indicate ages younger than 1 Gyr. The relevant implication of this discovery, again uniquely enabled by UV imaging, was that galaxies in the UV-optical CMD can cross the *green valley* in two directions: not all galaxies are evolving towards the red sequence, some rejuvenation may occur. Moffet et al. (2012) refined Type I criteria, originally developed by Thilker et al. (2007) based on a S0-Sm sample biased towards T$=2-8$ Hubble types, and applied them to 38 E/S0 galaxies. They find extended UV rings in 40 % of them, especially in the low-mass, gas-rich ones. A higher fraction was found in an HST sample by Salim and Rich (2010) (Figs. 7.1 and 7.2).

The relative fraction of XUVD incidence found by different studies depends on the depth of the UV data (e.g., GALEX's AIS (All sky Imaging Survey) data have a ∼2–3 mag brighter limit than MIS (Medium Imaging Survey), but span a much larger, varied sample), on the quantitative criteria adopted for classification, and finally on the wavelength of the images examined. The contrast of the UV emission over sky background is enhanced in FUV, the more so the younger the stellar population. But given the greater availability of data at longer wavelengths, searches for XUVD are being expanded using NUV and U-band data. Regardless of details, the fraction of at least 20–30 % suggests that outer-disk SF or "frosting" still occurs in the present Universe, and it is not a rare occurrence (given the short lifetime of the UV-emitting stars), although at low SF rates.

Galaxies with XUVD are ∼2× more gas rich than non-XUVD galaxies of similar L_K or SFR; Type II XUVD have high specific SFR, doubling the galaxy mass in less than 1 Gyr (preferentially in outer regions); Type I XUVD account for a few % of the UV luminosity, and have an azimuthally averaged Σ_{SFR} less than $\sim 3 \times 10^{-4}$ $M_\odot$ yr^{-1} kpc^{-2}, or a SFE some 30× lower than in the inner high-density disks. The XUVD morphology may relate to timing and origin of gas delivery or SF triggering. Different UV light profiles may disclose different fueling modes (∼continuous flow or discrete event, misalignment of pre-existing and incoming gas).

Counter-rotating HI disks favour a later, external gas source. Cold-mode gas accretion, interactions, and other mechanisms have been proposed. Models have succeeded to predict disk growth, but still mostly at lower levels than observed.

Sparse sources outside the canonical galaxy boundary had been detected from H_α imaging in a few galaxies (e.g. Ferguson et al. 1998), but only GALEX's sensitive

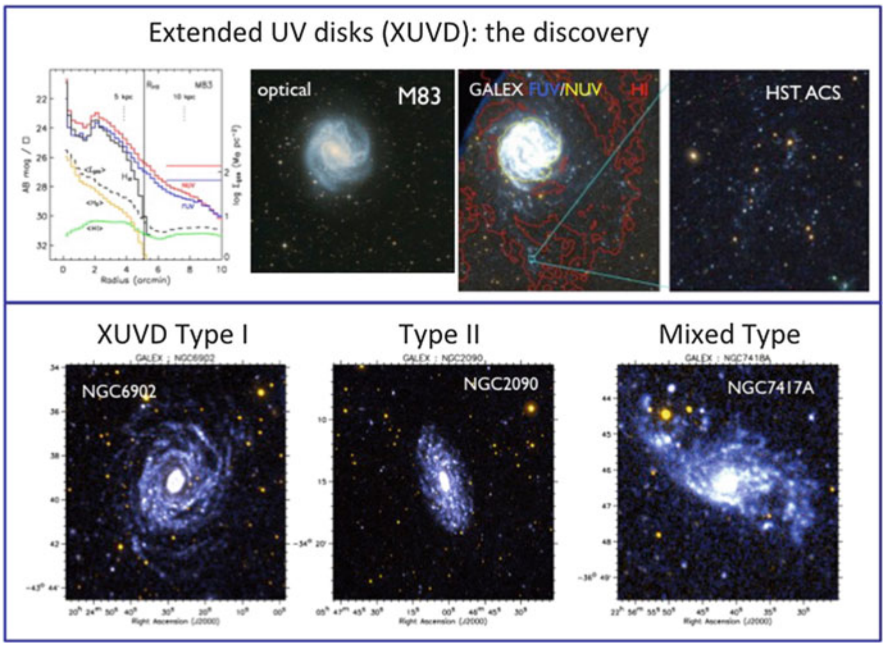

Fig. 7.1 *Top:* one of the two first XUVD discovered from GALEX early data, M83 (Thilker et al. 2005); the insert plot of flux density profiles at different wavelengths shows the smooth decline of the UV flux, unlike the sharp threshold at optical wavelengths. A GALEX UV source in M83 XUVD is resolved with HST in sparse clusters of young stars. *Bottom:* examples of XUVD classification from Thilker et al. (2007)

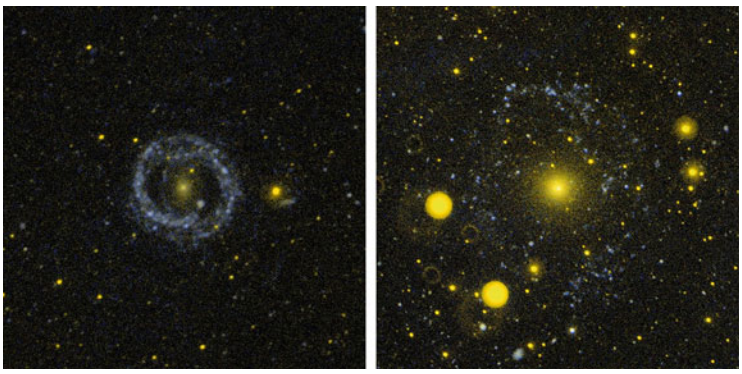

Fig. 7.2 UV-bright rings surrounding ETG: NGC 5701 (SB0/a, *left*, Bianchi 2011) and NGC 404 (*right*; SFR$\sim$2 10^{-5} $M_{\odot}$ yr^{-1} kpc^{-2} (Thilker et al. 2010): optical imaging (not shown) only matches the *yellow* (NUV) central spheroid; the FUV (*blue*) ring extends $>4\times D_{25}$)

FUV imaging revealed the whole extent of XUVDs. Even subsequent, deep H_α imaging only shows sparse dotted emission matching a subset of the UV sources. Reasons for the unique effectiveness of FUV in disclosing these structures are: (1) UV traces stars up to $\sim$100 Myrs, while H_α traces only the hottest, short-lived stars, and (2) the darker sky in FUV. In addition, (3) the very low gas density favours escape of ionizing photons, and, finally, (4) only small-mass, loose clusters are formed in these environments (masses $\approx 10^2$–10^3 $M_\odot$), therefore the top of the IMF may be truncated, and, simply, stochasticity makes the presence of very massive stars unlikely in low-mass clusters. If and how IMF may differ in such extreme environments is a question addressed by many follow-up studies, and still awaiting conclusive answers, while it is well established that stochasticity significantly affects interpretation of light from low-mass clusters.

Clearly standing out in UV images, XUVD have long remained elusive at optical wavelengths. SDSS imaging is generally too shallow to reveal measurable counterparts. Some of the UV-identified structures have a visible counterpart in SDSS *Stripe82* data, and in deeper Pan-STARRS images. Many programs have been undertaken with the largest telescopes following `GALEX`'s discovery. With `Subaru`, Koda et al. (2012) and (priv. comm.), successfully detected optical counterparts of some XUVD, at 27−29 mag arcsec^{-2}. Ultimately, the sky, much brighter in the optical than in UV, sets the limit to how faint a structure can be easily detected. In particular, it is difficult to look for evolved counterparts of XUVD; no gravitationally bound clusters seem to form in this rarefied environment, and when the UV-bright stars will die out, the low-mass sparse associations, seen in clumpy UV emission at early ages, will dissolve with the disk rotation, and the optical surface brightness will fade.[3]

Abundance measurements would be an important test to pin down the source of fuel for the growing outer disks. Metallicity gradients are observed in ordinary disks of spirals, and predicted by inside-out disk models (e.g. Chiappini et al. 2003). In the optically fainter XUVD, spectroscopy of the stellar populations is practically out of reach[4]; measurements of HII regions found metallicity to be low, though not as low as to be primordial ($Z \sim 0.1-0.2$ solar, 12+log(O/H)$\sim$8.1−8.3, Bresolin et al. 2009; Gil de Paz et al. 2007), and higher than what in situ enrichment could have been produced if the current low SFR was approximately constant in the past. No gradient is observed in the outer disks, consistent with the rather homogeneous level of SF suggested by the UV images.

In sum, XUVD are galaxy disks still growing, or undergoing renewed (low-level) star formation, in outermost disky reservoirs of gas, via disk building mechanisms which also operated at intermediate redshifts.

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[3]By accumulating many hours of exposure, new devices such as the "Dragonfly Array" (Abraham and van Dokkum 2014) can reach 30 mag/arcsec^2, but it will take some time before the sky can be surveyed at these depths, and the UV surveys remain the ideal pathfinder to identify XUVD.

[4]Kudritzki et al. (2014) analyzed low-resolution spectra of a few supergiants in NGC 3621, one of them is just outside of D_{25}, in the innermost portion of the XUVD.

Some connections have also been proposed between XUVD and massive low surface brightness galaxies (mLSB) like Malin I (Barth 2007; Thilker et al. 2007). In a two-stage formation scenario, an ordinary "host galaxy" (high-surface-brightness disk and bulge, or "dead" ETG) later acquires significant additional gas, building a mLSB or a hybrid XUVD.

Future progress in understanding SF in low-density environments and how galaxy disks grow, requires wide-field UV imaging with ad hoc filters, and interferometric HI surveys matching the sensitivity of the UV data.

In the hierarchical Universe suggested by the cosmic web and the CDM scenario, structures grow in a bottom up way. Small mass structures evolve with time in big mass structures. Is this what we observe? The next interviews to Bianca M. Poggianti, Jack W. Sulentic and Brent Tully deal with the mass limits of galaxies, the effects of the environment on the observed mass functions, and the masses of isolated galaxies that presumably have not acquired mass from recent merging events.

7.4 Amidst Dwarfs and Giants in Different Environments

Questions for Bianca M. Poggianti:
do we observe significant differences in the mass function of galaxies belonging to different environments? What are the current limits in mass of this function? What variations are observed in the mass function of different morphological types? How the mass function evolves with redshift?

Let me first remind the reader that by galaxy mass function in this context we mean the *stellar* mass function, that is the mass in stars plus stellar remnants. A determination of the distribution and evolution of galaxy *dynamical masses*, i.e. total masses = stars + interstellar medium + dark matter, is beyond reach for now, given the limited galaxy samples for which we have dynamical mass estimates.

As is often the case in astrophysics, the answer to the question depends on the exact conditions of applicability. In this case, on the mass limit and what you mean by "environment".

The GAMA (Galaxy And Mass Assembly) survey and SDSS studies of galaxy masses push the limit for low redshift field studies to below $10^7 M_\odot$, though the mass function can be considered reliable down to $10^8 M_\odot$ (Baldry et al. 2012; Li and White 2009).

Generally speaking, the stellar mass function depends on environment. This dependence is more evident as we consider lower mass limits. If we only consider massive galaxies (above $\log M_\star \sim 10 M_\odot$), the mass functions in clusters and in the general field are very similar, both at low and at intermediate redshift (Calvi et al. 2013; Vulcani et al. 2011, and Fig. 7.3). This is telling us that the striking differences in other galaxy properties (morphological distributions, star formation distributions,

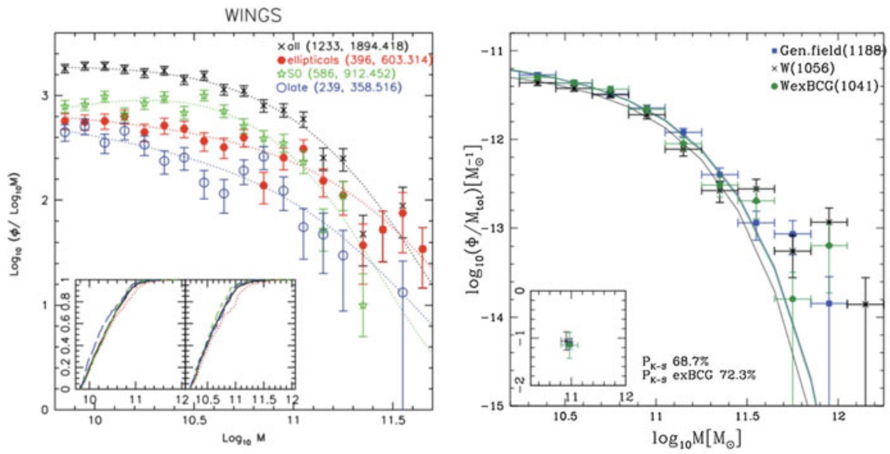

Fig. 7.3 *Left* Stellar mass functions of galaxies of different morphological types (ellipticals, S0s and later types) in low redshift clusters from the WINGS survey (Vulcani et al. 2011). The *bottom left* inset shows the cumulative distributions. *Right* Comparison of the stellar mass function of galaxies in clusters (W) and field (Gen. field) at low redshift (Calvi et al. 2013). WexBCG is the mass function having excluded the Brightest Cluster Galaxy in WINGS clusters. The *bottom left* inset shows the Schechter fit parameters $M^{\star}$ and α. P_{K-S} are Kolmogorov-Smirnov probabilities of the two distributions to be drawn from the same parent distribution

etc.) in this mass regime are *not* due to different mass distributions. Environment does play a role, at a fixed stellar mass.

A few years back, some works would claim that "galaxy mass is king", i.e. that everything that matters for defining a galaxy properties is its mass. Many studies have shown this is not the case.

The evolution of the mass function in the field is now well established up to relatively high-z (see Moustakas et al. 2013; Muzzin et al. 2013; Tomczak et al. 2014), and it is mostly anti-hierarchical: the massive end of the mass function is already in place at high z, while the population of intermediate and low mass galaxies grows with time.

It is only at very high redshift, $z > 3$–4, that we start seeing a hierarchical galaxy growth, with the high-luminosity end of the luminosity function evolving significantly suggesting a dearth of luminous galaxies compared to $z < 4$.

In clusters, there are just a few studies of the evolution of the galaxy mass function: Vulcani et al. (2013) have shown that the evolution of the mass function proceeds in a very similar fashion in clusters and field from $z = 0.8$ and $z = 0$. This is somewhat unexpected, and is remarkable if one considers how stronger is the evolution of other galaxy properties in clusters compared to the field. Again, galaxy mass is not the only ruler, environment plays a key role.

Finally, regarding morphologies, it is well established that the stellar mass function varies with galaxy types = morphology (ellipticals, lenticulars, spirals) (Calvi et al. 2013; Vulcani et al. 2011, Fig. 7.3). Still, galaxies of the same morphological type have different mass functions depending on environment.

Questions for Jack W. Sulentic:
which is the range of galaxy masses of the morphological types evolving in isolated environment? Is it different to that of galaxies in groups and other associations?

Mass ranges for the isolated AMIGA (Analysis of the interstellar Medium of Isolated GAlaxies) sample are $\log(M_*/M_\odot) = 9$–11 for late-types and 10–11 for early-types. We find no isolated (very massive) ellipticals that might be merger candidates (no early- or late-types with masses exceeding 11.2. An earlier study also using the CIG (Catalog of Isolated Galaxies) concluded that they could not be the post-cursors of isolated compact groups (Sulentic and Rabaca 1994). Perhaps the early-types are all disky systems—right now E and S0 appear to be equally represented but this issue has not been addressed in detail. The appearance of lenticulars in such an isolated sample may be the biggest surprise of all. AMIGA galaxies derive from a bright magnitude-limited sample ($B_{corr} \sim 15.5$) that spans a significant distance range $V_R = 1 - 15{,}000$ km/s. This means that low luminosity galaxies are only sampled in the nearest volume ($V_R < 1500$ km/s) within the Virgo supercluster where isolation is more difficult to define. If low luminosity/mass galaxies cluster preferentially around more massive spirals [remember Holmberg (1969)] then maybe there is no significant low-mass isolated galaxy population. SDSS allows the magnitude/redshift limits to be lowered but at the cost of less accurate determinations of morphology. The most complete AMIGA sample involves galaxies spanning only 1dex in mass ($\log(M_*/M_\odot = 10$–11). A problem with all of the AMIGA studies has involved the lack of large well matched control samples. That is a mis-statement—AMIGA is the ultimate control sample for local studies—it is the zero level. All other samples, by definition, involve galaxies in richer environments. The best comparison samples up to now have been those of Shen et al. (2003) and Nair and Abraham (2010). Of course spirals in richer environments usually include more E/S0 and early-type spirals with larger bulges (larger B/T). An unpublished comparison of spirals in (isolated) mixed pairs and spirals in CIG-AMIGA finds the former with earlier types (larger bulges) by 1 Hubble subtype. Does this imply larger masses for the galaxies in groups and clusters? Probably "yes" for early-types and "maybe not" for spirals—for comparisons with cluster members. Comparisons with group galaxies do not show a statistically significant difference. It all comes down to properly selected samples—before we had no useful isolated galaxy sample and now we lack well defined group samples. The situation can change overnight in the SDSS era.

7.4.1 Galaxies in Voids

Questions for Brent Tully:
we know that galaxies evolve in associations of different richness. Galaxies are also found to inhabit very low density regions, we call Voids. What are the extremes in the galaxy richness, from Voids to cluster/compact groups? What are the fundamental differences between galaxies inhabiting such different environments? May you sketch the implications of this variety of environments in the context of galaxy evolution?

Galaxies find themselves in diverse environments, from rich clusters to small groups, and a few hermits are in voids. Galaxies come in colors of blue, for star forming, and red, for dead. Galaxies downsize: massive galaxies form stars early and low mass galaxies extend the cycle of star-birthing over a longer time. What are the operative mechanisms that differentiate?

We can distinguish between mechanisms strictly internal to an individual galaxy and those that are environmental. Typically there is little star formation going on today in the inner parts of massive galaxies, save for situations where there has been a recent transport of cold gas toward the center. Meanwhile dwarf galaxies with gas have fractionally high rates of star formation. It is sometimes said that the giants are inefficient and the dwarfs are efficient at star formation but, of course, it is exactly the opposite. The giants are so efficient that they transformed their gas to stars long ago and immediately transform any fresh ingestion of gas into stars. The dwarfs are so poor at the job that it is an ongoing process. We can expect that most of the star formation is going on in disks, which are rotating at rates mandated by the mass. Those rates govern the properties of density waves, with higher velocity streaming and greater shocks in more massive systems. The dynamics control Toomre's "Q" factor that is a prescription for instabilities leading to star formation.

As to the environment, it is now clear that there are two regimes: clusters and the field, with respectively little and lots of star formation going on. There are many operative mechanisms affecting galaxies in clusters: merging, tidal disruption, harassment, ram pressure stripping, and my favorite, starvation. Whether any of the other mechanisms are involved in a given instance, starvation is inevitable. Isolated galaxies can draw gas from their primordial reservoir but that reservoir is lost the instant a galaxy falls into a cluster because of a Roche limit created by the cluster potential. The gas of the galaxy's reservoir contributes instead to the cluster inventory. Starvation and all of the environmental mechanisms work on all halo scales, from clusters at $10^{15} M_{\odot}$ to groups at $10^{12} M_{\odot}$. Most companions within the virial radius of a halo are gas-depleted, red and dead, while galaxies of a similar size outside a halo contain gas and are forming stars. Some companion galaxies within a halo do have gas and young stars but arguably these systems are new arrivals. It is to be clarified that the central dominant galaxy in a halo is a special case. These systems have ways to be fed fresh gas.

In this picture, it is not to be expected (nor it is seen) that galaxies in Voids are different from galaxies in filaments or sheets, except that few massive galaxies are seen in Voids. The main determinant governing a galaxy's development is whether it is central-dominant in its halo or whether it is a satellite. OK, a second important determinant governing the property of a central-dominant is how often and how recently it has experienced a major merger. There is an evident correlation between the rate of such occurrences and the mass of a halo since massive halos are usually dominated by ellipticals and the small halos of groups are usually dominated by a spiral.

We know today that almost all galaxies host an active nucleus at their center which coevolve with the galaxy itself. The next interviews will clarify to what extent the presence of this energetic components affects the entire evolution of the galaxies.

7.5 Galaxies Hosting AGN

Questions for Paola Marziani:
AGN are thought to be a phase in the evolution of a galaxy nucleus. The widely accepted paradigm is that BHs are present in all galaxy nuclei and coevolve with the galaxy spheroidal component. Do galaxies hosting an AGN share the same $M_{BH} - M_{Bulge}$ correlation of normal galaxies?

The paradigm of black hole and host bulge or spheroid coevolution is indeed widely accepted, supported by a well-known correlation between black hole mass M_{BH} and stellar velocity dispersion $\sigma_{\star}$ that leads bulge mass M_{Bulge} (Ferrarese and Merritt 2000; Gebhardt et al. 2000). The most accurate black hole mass determinations are the ones involving a study of the truly central regions of the galaxy, where the gravity of the black hole is the dominant force. This occurs within a distance from the black hole $r_{\mathrm{h}} = GM_{\mathrm{BH}}/(\sigma_{\star})^2 \approx 43 M_{\mathrm{BH},8}\sigma_{\star,100}^{-2}$ pc, where M_{BH} is units of 10^8 solar masses, and the $\sigma_{\star}$ of 100 km s^{-1}. The black hole sphere of influence has been resolved in several nearby galaxies, presumably hosting the most massive black holes that were shining bright at earlier cosmic epoch, at $z \approx 2$, where the most luminous quasars were observed (Lynden-Bell 1969).

The relation between M_{BH} and $\sigma_{\star}$ should be however taken with special care in the lower M_{BH} range. It is not obvious whether a significant $M_{\mathrm{BH}} - M_{\mathrm{Bulge}}$ correlation exists at all, or whether it results from a bias due to the difficulty of detecting a black hole whose sphere of influence is much smaller than the telescope resolution (Gultekin et al. 2011). In other words, the correlation may refer only to the maximum M_{BH} for each M_{Bulge}. In addition there are examples of galaxies whose black hole has a mass reaching even 15 % of the total galaxy mass (Reines 2014; Seth et al. 2014). These galaxies may be pathological in the sense that their outer part may have been pruned by repeated encounters with other galaxies giving at least to one of them the appearance of an ultra-compact dwarf galaxy. An even more extreme case is provided by a quasars without... a galaxy (Magain et al. 2005). I do not know whether this for-now sparse evidences of over massive black holes will eventually grow and lead to the correlation demise or at least to significantly larger dispersion.

Regardless of the correlation intrinsic strength, a constant $M_{\rm BH} - M_{\rm Bulge}$ ratio implied by the correlation has been extensively used to derive quasar $M_{\rm BH}$ from the ratio $M_{\rm BH}/M_{\rm Bulge}$ or from a proxy of the stellar velocity dispersion. The main difficulties are summarized by Marziani and Sulentic (2012). Here I would only like to voice again the concern expressed by Mathur (2011): it is risky to scale Type-1 AGN virial estimates to the observed $M_{\rm BH} - M_{\rm Bulge}$ for normal galaxies to determine a geometrical structure factor for the emitting regions of AGN. Not all Type-1 AGN are the same, and they show different structure factors associated with differences in kinematics and geometry (Collin et al. 2006).

Going back to your question, whether galaxies hosting an AGN share the same $M_{\rm BH} - M_{\rm Bulge}$ correlation of normal galaxies, I must say that an early answer was affirmative: AGN have the same BH-bulge relation as ordinary (inactive) galaxies (Wandel 2002). Recent work points toward a more complex scenario.

One has first to consider another aspect of the puzzle: the $M_{\rm BH}/M_{\rm bulge}$ ratio estimated at low z is not independent from z. Radio-quiet quasars seem to follow the established $M_{\rm BH}$-$\sigma_\star$ relation up to $z \approx 0.5$, with a modest evolution in the redshift range $0.5 \lesssim z \lesssim 1$ (Salviander et al. 2007). Between redshift 1 and 2, there is instead a significant evolution of the $M_{\rm BH}/M_{\rm Bulge}$ ratio, that is $\propto (1+z)^{0.68}$ (Merloni et al. 2010): black holes become over massive for a given bulge mass with respect to low-z. Studies at even higher redshift find again $M_{\rm BH}$ and $M_{\rm bulge}$ values that indicate over-massive black holes (Targett et al. 2011). The evolution as a function of cosmic epoch can be interpreted in several ways, the most straightforwards one being a rapid growth of supermassive black holes at high redshift, and/or a change of structural properties of AGN hosts. There are intriguing caveats with the first interpretation. Black hole masses (unlike galaxy masses!) can only increase with cosmic epoch. If a merger-driven hierarchical scenario that implies the concomitant growth of bulges and black holes is taken literally, the larger $M_{\rm BH}/M_{\rm Bulge}$ ratio at high z implies that mergings affect more bulge than black hole masses at cosmic epoch associated with $z \gtrsim 1$. Hence the suggestion of an anti-hierarchical growth or downsizing of nuclear activity at low-z (Hirschmann et al. 2012).

Another important aspect is however that narrow-line Seyfert 1s nuclei [NLSy1s, local AGN accreting at high rate, Chap. 4 in Marziani and Sulentic (2014)], often host in dwarfish, high surface brightness galaxies (Krongold et al. 2001) possess under-massive black holes (Chao et al. 2008; Mathur et al. 2001). NLSy1 nuclei reside in disk-dominated galaxies that are characterized by pseudo-bulges, not real bulges (Orban de Xivry et al. 2011). Pseudo-bulges are more closely related to the disk evolution and may be representative of systems that did not undergo yet a minor or major merger that may have led to a real bulge development. Disk-dominated galaxies deviate from the $M_{\rm BH} - M_{\rm bulge}$ correlation. However, if one considers only the bulge component, a recent work shows that quasars do follow a relation consistent with the local one (Sanghvi et al. 2014).

Summing up, AGN with elliptical/bulge-dominated host may follow a relation consistent with the one of normal galaxies (after all, we observe preferentially

AGN with large $M_{\rm BH}$!). The $M_{\rm BH} - M_{\rm bulge}$ may be holding mainly for massive, evolved systems. Significant deviations are likely associated with disk dominance. The local NLSy1s may be, in this respect the local prototype of very high z quasars, when massive bulges in a hierarchical scenario were not yet formed, as originally suggested by Mathur (2000) and Sulentic et al. (2000) on the ground of their optical, UV, and X-ray spectroscopical properties.

7.5.1 AGN Energetics

Questions for Paola Marziani:
Could you discuss AGN from the point of view of their energetics with respect to other important sources, like SNe and GRBs? How does the energetic of AGN change with the cosmic epoch? How much is important in nearby galaxies?

Quasars (high-luminosity AGN) may be righteously considered the most luminous stable sources in the Universe. Radio quiet AGN and quasars (i.e., the vast majority of AGN) do vary even on relatively short timescales, but the amplitude of their variations are usually modest, and the timescales long, if compared to the ones of supernovæ and γ-ray bursts (GRB). As a rule of thumb, supernovæ reach maximum in about 2 weeks and then decrease by 6–8 magnitudes (in B photometric band) from maximum in less than 1 year. GRB are very short duration events, from few milliseconds to 20 min (GRB lasting $\geq$ 2 s are said to be "long duration"!), when up to 10^{55} erg s^{-1} are emitted, if radiation is isotropically emitted (Gomboc 2012). The suddenness and amplitude of luminosity increases in both GRB and supernovæ suggest a strong discontinuity in physical conditions before and after a SN or GRB event i.e., an explosive nature of the processes involved. Long-duration GRB may be associated to the most extreme core collapse supernovæ (Mazzali et al. 2008), while short-duration GRB have been linked to the merging of compact stellar objects.

In the old days of quasar research—when the idea of cosmological redshift was not fully digested and the black hole idea appeared still far fetched to observational astronomers—it was thought that AGN activity could be perhaps explained by massive star formation leading to a rapid sequence of supernova explosions. There was some observational support to this idea, not last rare examples of supernovæ with the spectra typical of Type-1 quasars (Filippenko 1989). Variability on short timescales was then explained as due to uncorrelated events, and not necessarily as causally connected region of extremely small size. This idea does not appear anymore tenable due to the well-defined, tight upper boundary for the size of the quasar emitting regions. The model was not avoid of difficulties since the beginning, because a large number of supernovæ was required. Type Ia supernovæ have an absolute magnitude at maximum $M_{\rm V} \approx -19.4$. A luminous Seyfert 1 nucleus may have $M_{\rm V} \sim -22$, which means it needs 10 supernovæ shining at maximum to be accounted for.

GRBs and supernovæ are catastrophic events, but AGN are not. The accretion process that is believed to be at the origin of all AGN produces steady configurations whose exact form depends on the accretion rate (Abramowicz and Straub 2014). Accretion fuel, as reviewed earlier, may come abundant from a wet merger process, or be provided by secular mechanisms inherent to the internal dynamics of galaxies. Low-luminosity AGN may be well sustained by very modest accretion rate associated with the mass loss of an evolved stellar population. Luminous Seyfert galaxies and quasars need an ad-hoc supply. Low luminosity activity is very frequent in the local Universe, and involves the majority of early type galaxies (Ho et al. 1995). We leave at a cosmic epoch where mergers are much rarer than in the past. The powerful outflows of matter produced during the major activity phase created hollow volumes (filled with highly rarefied, high-temperature gas) surrounding the central black hole. This explain why—at an epoch where we have the most massive black holes, since black hole mass can only increase with cosmic age—we observe very few luminous quasars: nearby galaxies (especially of early morphological types) have lived their "glory days" of activity in a distant past.

We may distinguish three main regimes: low accretion rate, with $\dot{m} \lesssim 0.01$ ($\dot{m}$ is the mass accretion rate normalized by the accretion rate necessary to obtain the Eddington luminosity i.e., the maximum accretion luminosity for a given black hole mass), where viscosity is not an efficient heater of the accretion disk, and radiative efficiency is very low. This is the condition of low-ionization nuclear emitting regions (LINERs), that may show an active nucleus whole luminosity is lower than the host galaxy, with a distinguishable low-ionization spectrum, and a flat spectral energy distribution with significant hard X ray emission (Márquez et al. 2007). They can be seen as the high mass counterparts of stellar-mass black hole candidates in the low-accretion, hard state, and are very frequent in the local Universe. More luminous AGN may entail a geometrically thin, optically thick accretion disk where dissipation of gravitational energy occurs through viscosity at a relatively high efficiency $\approx$ 0.1–0.4 depending on the spin of the black hole (Wang et al. 2014). Above $\dot{m} \gtrsim$ 0.1–0.2, the accretion flow is again expected to be less radiatively efficient, with the formation of a thick structure whose luminosity tends to saturate at a given mass (i.e., whose radiative efficiency decreases to 0 with increasing $\dot{m}$). The energetics of quasars may not change intrinsically with cosmic epoch, in the sense that AGN radiating in the three accretion regimes may be present at all cosmic epochs. There is an obvious accretion rate evolution since massive black hole accreting at a high rate are, as mentioned, extremely rare in the local Universe. However, the evolution, at least up to $z \approx 2$, may affect mainly the relative frequency of AGN in the different accretion modes (Marconi et al. 2006) even if at large distances we are presently able to observe only AGN with large black hole mass accreting at a fairly high rate (Sulentic et al. 2014).

7.5.2 *Galaxies and Gamma Ray Burst*

Questions for Malcolm Longair:
galaxies are the site of the most energetic phenomena in the Universe, such as the Cosmic gamma-ray bursts (CGRBs). Their detections certainly represent a big step forward of high energy astrophysics. Could you briefly review what we know today about their origin? What have we learned about galaxies from CGRBs? What is the energetic involved in galactic GRBs ?

The simplest response is to recommend Chap. 22 of my book *High Energy Astrophysics*, which is devoted to compact sources and superluminal motions in high energy astrophysics (Longair 2011).
The γ-ray bursts are indeed among the most extreme events observed in the Universe, but I find it helpful to place them in the broader context of other extreme high energy astrophysical objects which also must involve superluminal motions. By *superluminal*, I mean sources in which the observed expansion, or bulk velocities, appear to exceed the speed of light—in fact, casuality is not being violated because the source components, or beams of particles, are moving at speeds close to the speed to light and are observed at an angle close to the direction of the ejection of the particles from the parent body.
Let us first discuss the superluminal radio sources which were discovered by the radio technique of Very Long Baseline Interferometry in the late 1970s. In most compact radio sources, the jets are observed to move at speeds exceeding the speed of light, which is not allowed according to the Special Theory of Relativity. The explanation is that the source components are moving towards the observer at a sub-luminal, but highly relativistic, speed at a small angle to the line of sight (Rees 1966). The maximum observed transverse motion is γv where v is the speed of the component and $\gamma = (1 - v^2/c^2)^{-1/2}$ is the corresponding Lorentz factor. Thus, very large superluminal velocities are possible if v is close enough to the speed of light. Thus, for example, if the velocity of the jet were $0.98c$ and the jet ejected at an angle of $11.5°$ to the line of sight, the apparent sideways velocity of the component on the sky would be five times the speed of light. One of the great achievements of the US Very Long Baseline Array (VLBA) was to demonstrate that, in a large sample of compact radio sources, speeds up to 32 times the speed of light were measured, implying that the values of the Lorentz factor γ had to be 32 or greater. Because of relativistic beaming, the luminosities of the source components would be greatly enhanced, by a factor of typically γ^n, where $n \sim 3$–5. This is a means of creating extraordinarily luminous, variable and superluminal sources.
The next class of sources which require similar motions consists of the γ-ray sources in active galactic nuclei. These were observed in considerable numbers by the Compton Gamma-ray Observatory. These are extremely luminous and variable γ-ray sources observed in some of the most extreme active galactic nuclei, many of which are also superluminal radio sources. The energy densities in the source regions are so great that relativistic beaming has to be invoked to explain the existence of the sources at all. The favoured emission mechanism for these sources

is synchro-Compton radiation, but in addition the emission regions need to be relativistically beamed towards the observer. The range of Lorentz factors is similar to that required to account for the superluminal motion of the compact radio sources discussed in the last paragraph.

At last we get to the γ-ray bursts. The above prologue was intended to show that relativistic beaming of radiation occurs in other contexts in high energy astrophysics. The conditions needed to understand the γ-ray bursts are even more extreme but now involve stellar mass objects rather than the huge black hole masses found in active galactic nuclei. The bursts' characteristic features are extreme luminosities and extremely short time-scale variability, the most extreme having durations between about 0.1 and 1 s. These sources have been observed out to the very largest redshifts at which quasars and galaxies have been detected. Because of their extreme variability, it was very challenging to identify them with known astronomical sources, until it was realised that the bursts have associated with them afterglows at X-ray and longer wavelengths (Costa et al. 1997). The locations of these afterglows enabled the parent galaxies to be identified and their redshifts measured.

Putting these pieces of evidence together, one is forced to conclude that the sources must be associated with stellar mass objects and that the emission regions are not only relativistically beamed, but also the radiation must itself be omitted within a narrow cone if the energy requirements are not to become unphysical. Even so, the Lorentz factors involved are $\gamma \sim 1000$. Thus, the γ-ray bursts are not unique in requiring relativistic beaming and highly directed emission, but they are the most extreme examples and take place on the stellar scale rather than that of an active galactic nucleus, a difference of roughly 10^6 in mass. A popular picture associates these sources with the collapse of very massive stars such as the Wolf-Rayet stars, the cores of which collapse to form Kerr black holes. Axisymmetric collapse of the outer envelope would continue onto the collapsed core. This model is often referred to as the *collapsar* model for γ-ray bursts.

The γ-ray bursts are so luminous that they can be identified in extremely distant galaxies. The gamma-ray burst GRB 090423, discovered by the SWIFT γ-ray telescope, has one of the largest redshift of any known object, $z = 8.26$. Cosmologically, these objects therefore provide probes of the reionisation era when the intergalactic gas was heated and reionised by the ultraviolet radiation of the earliest generations of stars in galaxies. As expressed by Gehrels and his colleagues in their comprehensive review, '(γ-ray bursts) are now rapidly becoming powerful tools to study the detailed properties of the galaxies in which they are embedded and of the Universe in general' (Gehrels et al. 2009).

The host galaxies are different. The long bursts are associated with star-forming galaxies, with typical luminosities $L \approx 0.1\,L^*$ and metallicities only about 10 % of the solar value—these values are significantly smaller than galaxies from the Sloan Digital Sky Survey. The association of the long bursts with core-collapse supernovae has been convincingly demonstrated in many cases. The statistics of short bursts are much smaller than those of the long bursts but there is a clear correlation with regions of low star formation, either in elliptical galaxies or in a region of low star formation rate within galaxies. The luminosities of the elliptical host galaxies correspond to $L \sim L^*$ galaxies.

What is really spectacular about the rate of discovery of large redshift γ-ray bursts is how rapidly the number of objects has increased since their discovery and the use of afterglows to measure their redshifts. As a consequence, this promises to be a very fruitful source of extremely large redshift galaxies with which to probe the epoch of reionisation.

Among the high energy sources in the Universe that might have influenced the evolution of galaxies, SNe are probably the most important ones. Now Francesca Matteucci will review for us their role.

7.6 The Job of the SNæ

Questions for Francesca Matteucci:
Supernovae are thought to provide the largest contribution in the chemical enrichment of metals in galaxies, but are also claimed to originate strong winds that could stop the star formation in galaxies. Could you explain how SNe contributed to galaxy evolution and in which way? Which galaxies could suffer the quenching of SF from the SN wind? What is the energetic connected to SNae ?

Supernovae can be of two main types: I and II. They differ mainly for the presence or absence of H in their spectra: SNe I, which do not show H are then subdivided into Ia, Ib and Ic, whereas Type II SNe show H in their spectra. Type II, Ib and Ic SNe are thought to originate from the core-collapse of massive stars and therefore they are called *core-collapse supernovae*. Supernovae Ia are believed to be the result of the thermonuclear explosion of a white dwarf in a binary system, after reaching the Chandrasekhar mass ($\sim 1.44 M_{\odot}$). Supernovae Ia and II have similar explosion energies ($\sim 10^{51}$ erg), whereas SNe Ib and Ic can be also more energetic and have energies of $\sim 10^{52}$ erg: in this case, they are called *hypernovae*. Supernovae are the main producers of metals in galaxies but they are also the most important sources of energy for the ISM. Mass loss from massive stars injects energy into the interstellar medium but this energy is negligible compared to that restored by SNe (Bradamante et al. 1998). Supernovae can trigger galactic winds in galaxies since they heat the ISM, which can acquire an expansion velocity larger than the escape velocity and leave the galaxy as a supersonic wind. These winds, when they occur, quench the process of star formation since they carry away the gas. Moreover, after a galactic wind has started, the SNe Type Ia, which continue to explode even in the absence of ongoing star formation, heat the residual gas more and more thus contributing to keeping the galaxy without star formation even in the presence of the gas restored by dying stars. A typical situation of this kind can be found in elliptical galaxies, which show no traces of recent star formation and are empty of gas. In these galaxies we observe only SNe Ia and not SNe II, Ib and Ic, which originate from short living massive stars and are present only in regions of active star formation. Supernovae II, Ib and Ic contribute to the galactic chemical enrichment in α-elements (O, Ne, Mg, Si, S, Ca) and a little fraction of Fe, while SNe Ia mainly contribute to Fe enrichment ($\sim$70 %). As we have already explained before, this implies that α-elements are produced more rapidly than Fe, thus producing a different evolution of these elements with time (time-delay model). The rate of star formation coupled with the time-delay model can explain the different abundance patterns seen in galaxies of different morphological type.

Elliptical galaxies are the most likely candidates to suffer the quenching of star formation from the galactic wind and this is due to the intense star formation that they must have suffered in their early stages of evolution. The high SN rates deriving from a high star formation rate produce high rates of energy transferred into the ISM. Both core-collapse (Type II, Ib, Ic) and Type Ia SNe contribute to the thermal energy of the ISM in ellipticals. However, while core-collapse SNe contribute only during the period of active star formation, the SNe Ia continue to explode until the present time, thus contributing to keeping the ISM warm. In fact, even if the galactic wind carries away most of the gas, the dying stars keep contributing gas into the ISM and this gas can also escape from the galactic potential well owing to the energy of Type Ia SNe. The SN winds can also quench star formation in dwarf spheroidal galaxies and in dwarf starbursting galaxies. However, in these latter the star formation can be quenched only for limited periods of time, since in these objects the wind does not carry away most of the gas, as in the ellipticals and dwarf spheroidals. This is because the star formation rate in dwarf starbursting galaxies is mild and occurs intermittently [see Matteucci (2012), for a review on the properties of these galaxies].

Each SN event generally produce $\sim 10^{51}$ erg but only a fraction of this energy heats the ISM since a large fraction is lost through cooling processes which in turn depend on the boundary conditions, as explained above. It is still largely unknown how much energy can be transferred from SNe into the ISM. This is a very important phenomenon since it influences dramatically galaxy evolution by means of galactic winds and star formation quenching: if a galaxy stops forming stars in the early stages of its evolution, most of the stars will show high [α/Fe] ratios since the SNe Ia will not have time to pollute significantly the ISM in Fe. On the other hand, a galaxy with ongoing star formation will show stars with average [α/Fe] ratios at the present time which are solar or undersolar. Therefore, the energetics connected to SNe regulates indeed the process of galaxy evolution.

7.6.1 Odd SF Histories

Questions for Francesca Matteucci:
the study of the galaxy star formation history shows that some galaxies have had very special history, which in turn, help to better define general trends

for the different morphological types. May you provide a picture of "strange galaxies" in terms of star formation history, metallicity and/or abundances?

The most "strange" galaxies in my opinion are dwarf irregular galaxies because they show a variety of different properties and a large spread when plotted on typical evolutionary diagrams. For example, a typical evolutionary diagram is metallicity (Z) vs. $log(M_{gas}/M_{tot})$ with M_{tot} being the total mass of gas plus stars in a galaxy. The so-called "Simple Model" of chemical evolution predicts a simple relation between metallicity (Z) and the fractionary mass of gas $G = M_{gas}/M_{tot}$, in particular:

$$Z = y_Z ln(G^{-1}) \tag{7.1}$$

where Z is the global metallicity and y_Z is the so-called *yield per stellar generation*, i.e. the mass restored in the form of metals by a stellar generation, relative to the mass which stays locked up in stellar remnants and never dying low mass stars (Tinsley 1980). Dwarf irregular galaxies do not follow that relation, like most of the other galaxies, since it represents the unrealistic case of a closed-box model, but they show also a large spread not observed for other galaxy types (see Matteucci and Chiosi 1983). Among the dwarf irregulars, the blue compact ones show an active star formation at the present time but large amounts of gas and low metal content. The strangeness lies is in the fact that if they had the same star formation rate we observe now for the whole galactic lifetime, then the gas must have been all consumed. A possible explanation is that star formation in these galaxies was not a continuous process but it occurred in short episodes followed by long quiescent periods (Searle and Sargent 1972). In addition, the large spread in their metallicities and amounts of gas requires that these galaxies must have suffered either galactic winds or infall of gas at different rates. Among the blue compact galaxies we recall IZw18, a small galaxy of the Virgo cluster with a metal content which is 1/50 $Z_\odot$ ($Z_\odot = 0.0134$, Asplund et al. 2009). For a long time, this galaxy was considered as a survivor primordial object which had started to form stars only now. However, deep observations with the Hubble Space Telescope have shown that also in this galaxy there are stars as old as 1 Gyr (Aloisi et al. 1999), indicating a past star formation activity besides the present one.

What is the morphology that present the largest metallicity excursion?

Elliptical galaxies show the largest excursion in metallicity and also in mass. In fact, the average metallicities of ellipticals range from $< [Fe/H] >\sim -0.8$ dex to +0.3 dex (Kobayashi and Arimoto 1999) and the stellar masses vary from $10^7 M_\odot$ and $10^{12} M_\odot$!

What is the range in metallicity shown by nearby galaxies?

The range in metallicity is quite large because it goes from $\sim 10^{-2} Z_\odot$ in the Milky Way halo stars, although (Caffau et al. 2011) claimed to have found a halo stars with $Z \sim 4 \cdot 10^{-5} Z_\odot$ (not yet confirmed), to the oversolar metallicity measured in the stars of the Milky Way bulge (up to ten times solar).

What is the expected metallicity of first galaxies?

The metallicity of the first galaxies can either be very low or high (solar and oversolar) depending on the morphological type of the primordial galaxies. A spheroid (elliptical galaxy or bulge of spiral) can attain a high metallicity in a very short time, if the star formation rate is strong enough. In fact, in such a case many SNe core-collapse producing metals can enrich the ISM in a few hundreds thousands years. This is the case of quasar (QSO) hosts, which are large ellipticals at high redshift. The metallicity inferred from the broad emission lines of QSOs indicate solar and oversolar abundances in these objects (see Maiolino et al. 2006). The QSO hosts confirm that different galaxies had very different star formation histories. On the other hand, if the star formation rate is low then the metal content can be comparable with the metallicity of the stars in the Galactic halo and be several orders of magnitude lower than the solar metallicity. However, a more important parameter than the absolute metallicity is represented by the abundance ratios, such as, for example, the already mentioned [α/Fe] ratios. These ratios, coupled with the metallicity, measured by [Fe/H], can give us an idea of the type of primordial object we are observing, since the [α/Fe] vs. [Fe/H] relations are different for different galaxies, as indicated in Fig. 4.20 of Chap. 4. On the base of the diagram of Fig. 4.20 we can therefore infer the nature of high redshift objects: in fact, in Fig. 4.20 overplotted on the theoretical curves are also data for Magellanic Irregulars and Damped Lyman-α systems (DLAs; objects observed at high redshift whose nature is unknown), and the comparison between models and data indicates that the unknown DLAs are very likely to be irregular galaxies. In particular, irregular galaxies show low [α/Fe] ratios at low [Fe/H] because of the slow star formation they suffered.

In the current standard model of cosmology baryons represent only $\sim$4 % of the energy density of the Universe, while up to $\sim$22 % is enclosed in the DM component. The dark energy seems to drive the whole energy density with up to $\sim$72 %.

Discovered during the seventy through its gravitational action, DM has up to now escaped any direct detection, posing the problem of their true existence. We enter with the following interviews in this almost unexplored territory of the modern astrophysics. DM dominated galaxies should manifest the presence of this component in their kinematics. We therefore start our approach to this subject with few questions about galaxy dynamics and kinematics.

7.7 Galaxy Dynamics: Dark Matter or MOND?

Questions for Luca Ciotti:
understanding galaxy dynamics has been one of the big efforts of the past century. What have been in your opinion the most significant progresses achieved in this research area? What are the limits of present day models and

simulations? In which way dynamical studies might provide constraints to the galaxy formation and evolution theories?

The proposed questions are very relevant in general, and even more from my particular point of view. However, I think any sufficiently simple answer is necessarily incomplete and questionable, considering the enormous range of applications of Stellar Dynamics when applied to the study of formation, evolution and structure of galaxies (the so-called Galaxy Dynamics). In any case, I will attempt to answer in a sufficiently objective and concise way.

The first point to be stressed is that the pillars upon which Stellar Dynamics is built are among the most studied branches of classical physics, i.e., Gravitation, Dynamics, Statistical Mechanics, Fluido-dynamics, with major contributions from giants like Newton, Maxwell, Boltzmann, Poincarè (just to recall some names, but the list would include almost all of the prominent physicists and mathematicians one can think of). From this point of view it is hardly believable that new relevant and original contributions can still be obtained in the field. However, this is not true, as *observations* of increasing quality and resolution provide a fresh flow of unexpected and very interesting problems, spurring whole new fields of application of the "old" theories. Before discussing some of them (not because I attribute to them any special significance, but just because it occurred to me to work on them), I would like to stress my view about two general points, that quite often arise in discussions about Galaxy Dynamics.

The first: Galaxy Dynamics as a tool. Over the years, talking to colleagues not directly involved in Galaxy Dynamics research, I found a common attitude to think about this subject as a "boring-but-sometimes-useful" collection of techniques to be used for the interpretation of the observations. I can easily accept that for someone Galaxy Dynamics is a boring discipline, but I strongly disagree with the view that it is just a "tool". Quite the opposite, the applications of Galaxy Dynamics to the interpretation of observational data are just one of the *two* relevant aspects of the discipline, the other being the *understanding* of the dynamics of astronomical systems made by a very large number of components and ruled by gravitation. From this last point of view, Galaxy Dynamics is connected with the study of non-linear and collective phenomena (like Plasma Physics), a field very far from being completely explored and understood.

The second: Galaxy Dynamics and computers. It is a quite widespread idea that "after-all-we-now-have-computers so let's use them to integrate equations, look at the results, and spare the time (and the painful work) needed for their understanding". The weakness of this position should be clear to everyone: the job of astrophysicists is to understand the physics behind the observed phenomena, not to contemplate the results of numerical simulations and be satisfied if they agree with observations. Computers and numerical simulations should be seen as *invaluable* tools for better understanding physics, not just to reproduce observations (or, even worst, to produce results that are studied instead of the physical Universe).

About the specific questions proposed. As fundamental progresses made in Galaxy Dynamics in the past century, I think a general consensus can be obtained for any list containing entries such as violent relaxation, construction of collisionless equilibria and study of their stability (with particularly important results for elliptical galaxies), integrability, relaxation times and dynamical friction, spiral density wave theory, dynamical evolution of weakly collisional systems (e.g., Globular Clusters, galactic nuclei with SMBHs). On a more observational side, I would list among the major accomplishments the discovery of the strict connection between structure and dynamics of the different galaxy morphological types, the evidences of Dark Matter on galactic scales, the existence of global Scaling Laws relating in a surprising way structural, dynamical, and stellar populations properties of ETGs, the presence of SMBHs at the centers of stellar spheroids. Among the relevant references, covering a large part of the subjects listed above, I would mention the books of Spitzer (1988); Binney and Tremaine (2008); Merritt (2013), and Bertin (2014).

On a more personal side, I will focus on some aspects of the multifaced problem posed by the existence of Scaling Laws of ETGs, their interpretation, and the consequences for theories of galaxy formation. My interest in Stellar Dynamics began during the Ph.D. thesis work, when I was involved in the study of gas flows in ETGs under the supervision of Alvio Renzini. I was assigned to work on the dynamical modelization of the galaxies used for the hydrodynamical simulations. I was very interested by the mathematical aspects of Astrophysics, and I found my problem beautiful. In particular, in parallel with the Thesis work, I wrote a short paper on the dynamics of Sérsic models for elliptical galaxies (Ciotti 1991), that I sent for comments to Giuseppe Bertin (then at Scuola Normale Superiore in Pisa). This was the starting point not only of a lifelong friendship with Giuseppe, but also of a continuous source of learning and inspiration for my studies of Galaxy Dynamics. The two other persons that were fundamental for my scientific growth in this field were Jerry Ostriker and James Binney, and more recently Renzo Sancisi, Tjieerd van Albada, and Tim de Zeeuw.

During the galaxy modelization work for the thesis, Alvio maintained close contacts with George Djorgovski (Caltech), who gave us some advice on how to place our galaxy models on the Fundamental Plane of elliptical galaxies (hereafter FP) that was recently discovered (Djorgovski and Davis 1987; Dressler et al. 1987). The new galaxy models represented a big step forward in the field of cooling flow studies. From this work Alvio started to think on the implications of the FP itself for the understanding of formation and evolution of elliptical galaxies. We wrote a paper (Renzini and Ciotti 1993), and I also started to meditate about the meaning of the FP. I tried to work out the consequences by myself, and I soon realized that—with few notable exceptions—the astronomical community was quite confused about the meaning of the FP. For example there were papers dealing with the problem of the "deviation of the FP from Virial Theorem" (the so-called FP tilt), and even attempting to "reconcile" the two relations. This was clearly a physical nonsense, as the Virial Theorem by itself does not necessarily imply *any* Scaling Law for virialized systems (what about spiral galaxies then? are not they equilibrium—i.e. virialized—systems? but spiral galaxies certainly do not obey a FP!). I like to illustrate the case stressing the conceptual analogy between the

FP and the Main Sequence in the HR diagram: pretending that the FP is nothing else than the Virial Theorem in disguise is the same logical error as to pretend that the Main Sequence is nothing else than the locus of hydrostatic equilibria of gaseous spheres. Virialized galaxies, as gaseous spheres in equilibrium, could be placed *everywhere* in their respective parameter spaces: the existence of the FP and of the Main Sequence are actually telling us something completely different (and more important!) than an equilibrium condition. In fact, as the Main Sequence reveals something fundamental about energy generation in the stellar interiors, the FP contains important information about the structure, dynamics and formation of ETGs (Nipoti et al. 2002). The FP tilt does not measure any departure of ETGs from the Virial Theorem, instead it shows that for some reason ETGs "deviate" in a well determined way from structural and dynamical *homology*, i.e., they are not exact scaled-up/down versions of the same prototypical object, but the "deviations" actually depend in a very well defined way on their total luminosity and size, with a surprisingly small scatter (see, e.g., Ciotti 2009 and references therein). This systematic deviation it is called *weak homology* (e.g., see Bertin et al. 2002). It is never stressed enough that the very existence of the FP give another important clue about ETGs: in fact, in order to have the observed weak homology, not only structure and dynamics of the stellar component must be related, but also the *stellar mass-to-light ratio* of the stellar population and the amount and distribution of dark matter must be. I consider this empirical fact as one of the most strong arguments against merging as the main channel of formation of ETGs.

The last point opens another important consideration about the risk of a partial view of the problems addressed by Galaxy Dynamics. In fact, quite often dynamicists (and even more people working on numerical simulations) tend to think to galaxies as systems made by "gray dots", just ruled by gravity. Of course, this is quite true, but not completely, as stars are not grey dots: they have ages, luminosities, metallicities, and it may well happen that purely gravitational considerations can be ruled out by considering additional, non-gravitational aspects such as chemical evolution. I consider this one of the important lessons learned working with Alvio. One of such problems is that about the importance of *dry* and *wet* merging in the formation and evolution of ETGs. In fact, from the purely morphological point of view, merging appears to be—on average—able to reproduce some gross properties of ETGs. However, it is an elementary back-to-the-envelope exercise to show that in parabolic dry (i.e., in absence of gas dissipation) mergings with no substantial mass ejection the velocity dispersion of the final product cannot be larger than the larger one among those of the progenitors. This is in contrast with the Faber-Jackson law, therefore this simplistic picture is ruled out (e.g., Ciotti and van Albada 2001). Of course, gas dissipation (wet merging) can help to increase the velocity dispersion and reduce the size of the resulting system, however the more dissipation we need, the younger will be the stellar population of the new galaxy, and this must be reconciled with the empirical fact that more massive ETGs are older and more metallic that smaller systems. These kinds of problems are tentatively addressed by scenarios like the "anti-hierarchical formation of ETGs"; personally, I think that merging (in the usual sense attributed to the word) is much less important than commonly assumed in the formation of ETGs (Ciotti et al. 2007).

In my opinion, one of the future developments of Galaxy Dynamics (in addition to the study of very basic questions related to important mathematical and physical aspects of the theory), should be sought in the field where Stellar Dynamics meets Fluido-dynamics, i.e., in the problems concerned with the coexistence of pure gravitational (e.g., N-body) phenomena with hydrodynamical phenomena, such those involving the gas component of spiral galaxies and ETGs. Examples are those of the dynamics of spiral arms and of the extraplanar gas in spiral galaxies, and of the combined use of gas stellar dynamics to measure the amount and distribution of Dark Matter in ETGs. In fact, in spite of all the work done, and the many claims, the latter problem is far from being settled. I find quite curious to have papers dealing with Dark Matter in ETGs where not only the amount of Dark Matter is measured, but even its radial profile is discussed, sometimes at the level of minor details, against the expectations of "universality" as obtained by impressive cosmological numerical simulations of increasing resolution. While it is reasonable to contrast observations with the results of simulations, I would like to stress that the problem of the determination of the Dark Matter halos density profile is not even solved for *disk galaxies* (are the best solutions maximum disk? minimum disk?), in spite of their "simple" orbital structure (in first approximation almost circular velocity for the gas and stars in the disk). Therefore, my impression is that the current claims about ETGs, with their more complicate orbital structure (e.g., mass-anisotropy degeneracies, particularly affecting modeling techniques based on the Jeans equations), and with gaseous halos whose hydrostatic equilibrium (a common assumption made in mass studies based on X-ray observations) is far from being assured (see e.g., Pellegrini and Ciotti 2006), should be considered *at best* indications of the true radial distribution of Dark Matter halos. A significant progress in this field (where also gravitational lensing gives a fundamental contribution) will be reached when our global understanding of the physics of the mutual interaction between stellar, dark matter and gaseous components (e.g., Barnabé et al. 2006) will improve beyond the level where the different components are just "added" as to produce our preferred "pet galaxy models".

With the next two interviews we enter in the still ample debate about the existence and nature of the DM component.

Questions for Jaan Einasto:
the nature of Dark Matter (DM) is still a mystery after more than 20 years. You have deeply investigated in your recent book "Dark Matter and Cosmic Web Story" the presence and the role of DM in galaxies. What are the most significant observational proofs of its existence in galaxies?

Actually there are two problems with DM—its existence and nature.

The existence of DM is a problem already for 80 years when Fritz Zwicky discovered the mass paradox in the Coma cluster of galaxies (Zwicky 1933). A similar paradox was found in galaxies—the rotation curve of galaxies remained flat at large galactocentric distances in contrast to the expected Keplerian decrease

(Oort 1940; Roberts 1966). Also a high total mass was found in our Local Group of galaxies (Kahn 1959), and in double galaxies (Page 1959).

Initially it was believed that DM is made of faint stars. But soon it was clear that this hypothesis has problems—dynamical measurements showed that all stellar populations have mass-to-light ratios (M/L) in the interval from 1 to about 7 in solar units (Einasto 1974; Faber and Gallagher 1979), but the DM population should have $M/L \geq 1000$. Thus instead of faint stars hot gas was assumed as the DM candidate (Einasto 1974; Kahn 1959). However, in mid-1970s it was clear that DM can be neither low-mass stars nor gas, thus its nature was unclear (see among others Einasto et al. 1974; Holberg et al. 1973; Silk 1974).

The strongest argument against the baryonic nature of DM comes from Cosmic Microwave Background (CMB) observations. Theoretical calculations show that at the epoch of recombination the density (and temperature) fluctuations must have an amplitude of the order of 10^{-3}, otherwise structure cannot form, since the gravitational instability that is responsible for the growth of the amplitude of fluctuations works very slowly in an expanding Universe—the amplitude of fluctuations grows linearly with the expansion factor $a = 1/(1+z)$, and the redshift of CMB radiation is $z_{CMB} \approx 1000$.

CMB fluctuations have been searched for with best equipment available, but in late 1970s only upper limits about 10^{-4} have been found. The main conclusion from these observations was that DM must be non-baryonic (Rees 1977). Density perturbations of non-baryonic DM already start growing during the radiation-dominated era, whereas the growth of baryonic matter is damped by radiation. If non-baryonic DM dominates dynamically, the total density perturbation can have an amplitude of the order 10^{-3} at the recombination epoch, which is needed for the formation of the observed structure of the Universe.

The first natural non-baryonic matter candidate was neutrino (Silk 1982). However numerical simulations of the evolution of the structure of the Universe show that neutrino-dominated DM cannot create fine structure of the cosmic web as shown by Zel'dovich et al. (1982). For this reason other non-baryonic DM candidates were suggested which allow the formation of the fine structure of the Universe. Such DM particle candidates have lower velocities and are called Cold. Numerical simulations of structure evolution based on CDM model were conducted by Melott et al. (1983). They showed that the CDM model is in good agreement with observed structure of the cosmic web. A more detailed study of the Cold Dark Matter model was performed by Blumenthal et al. (1984). However, the name CDM is only a term to designate it, the actual nature of DM is unclear still today.

Presently the existence of DM in galaxies and in Universe in general is supported by a very wide body of astronomical observations: fluctuations of CMB radiation, distribution of galaxies in the cosmic web, flat rotation curves of galaxies, velocity dispersions of galaxies in clusters and stars in dwarf galaxies, X-ray data on hot gas in clusters and massive galaxies, gravitational lensing of distant galaxies by clusters of galaxies.

The angular power spectrum of CMB temperature fluctuations has the first maximum at wavenumber $l = 200$, which suggests that the total matter/energy density of the Universe is equal to the critical density (Bennett et al. 2003). The shape of the angular power spectrum of CMB temperature fluctuations is sensitive to the whole set of cosmological parameters. Seven years data from the WMAP were analysed by Komatsu et al. (2011). The distribution of luminous red galaxies of the Sloan Digital Sky Survey (SDSS) also yield values of cosmological parameters (Reid et al. 2010; Tegmark et al. 2006). The mean values from this dataset are: Hubble constant $H_0 = 70.2 \pm 1.4$, baryonic matter density in units of the critical density $\Omega_b = 0.0458 \pm 0.0016$, DM density $\Omega_{CDM} = 0.229 \pm 0.015$, the the density of dark energy $\Omega_\Lambda = 0.725 \pm 0.016$. According to Planck Collaboration 2013 cosmological parameters have the following values: $H_0 = 67.4 \pm 1.4$, $\Omega_b = 0.0490 \pm 0.0004$, matter density (baryonic plus non-baryonic) $\Omega_m = 0.314 \pm 0.020$, $\Omega_\Lambda = 0.686 \pm 0.020$. The age of the Universe according to new Planck data is 13.813 ± 0.058 Giga-years. The reason for this small difference between Planck and other data is not yet clear.

Dark energy or the cosmological constant has the property that it causes the Universe to expand with an accelerating rate. The acceleration of the Universe was actually detected by comparison of distant and nearby supernovae by Riess et al. (1998) and Perlmutter et al. (1999).

The presence of DM in galaxies is most clearly seen in flat rotation curves of galaxies (Bosma 1978; Roberts 1966; Rubin and Ford 1970; Rubin et al. 1978). As shown by Einasto (1974) and Einasto et al. (1974) such flat rotation curves can be explained by the presence of a massive and large non-luminous population—corona. To find the mass and radius of the corona, all populations are to be modeled in a multi-component dynamical model. Here the most difficult problem is to find mass-to-light ratios of stellar populations. As shown by Einasto (1974) and Faber and Gallagher (1979), mass-to-light ratios of galactic populations are rather low, for the most massive population—the bulge—about $3 \ldots 7$ in solar units. Thus the only way to explain flat rotation curves is to assume the presence of a non-luminous DM population in galaxies.

For clusters of galaxies total masses can be found from measurements of the temperature of the hot X-ray emitting gas with ROSAT and XMM-Newton satellites. Such data show that clusters have masses up to about 2×10^{15} $M_\odot$, which yields mass-to-light ratios up to several hundreds in solar units (Arnaud et al. 2010; Reiprich and Böhringer 2002).

How the DM is distributed in the various types of galaxies?

DM is distributed unevenly in galaxies of different type. In giant galaxies ordinary matter (stars and interstellar gas) forms about 10 % of the total mass, but dwarf galaxies are almost completely DM-dominated. One of the most important developments in recent years is the detection of very faint companions of the Galaxy and our neighbour, the Andromeda galaxy M31. With giant telescopes radial velocities of individual stars in dwarf companions of the Galaxy have been measured. This allows to calculate total masses of dwarf galaxies. These observations show that dwarf galaxies have high mass-to-light ratios and are DM dominated (Kalirai et al. 2010; Wolf et al. 2010).

The DM content of galaxies and clusters of galaxies can be estimated by the half-light mass-to-light ratio as a function of the galaxy/cluster half-light mass. Recent dwarf galaxy analyses and compilations of data for giant galaxies and clusters show, that the half-light mass-to-light ratio versus the half-light mass curve has a minimum about 3 in solar units at half-light mass 10^{9-11} $M_\odot$. For faintest dwarf galaxies of half-light mass $\approx 10^6$ $M_\odot$ it has a value over 1000, and for massive clusters of half-light mass $\approx 10^{15}$ $M_\odot$ it has a value a bit less than 1000 in solar units (Wolf et al. 2010).

These measurements indicate an increase in dynamical half-light mass-to-light ratios at both smaller and larger mass and luminosity scales. This result can be interpreted as a decrease of the efficiency of galaxy formation in the smallest and the largest DM haloes. A similar trend is observed in the luminosity function of galaxies, as suggested already by White and Rees (1978).

The half-light mass does not include outer parts of galaxies. To get total masses and mass-to-light ratios full dynamical models of galaxies are needed. Results of my first attempt to calculate dynamical models of nearby galaxies with DM halos gave for M31 the mass of visible populations 1.8×10^{11} $M_\odot$, and for the DM halo the $M_{halo} \gg 1.8 \times 10^{11}$ $M_\odot$ (Einasto 1974). The most recent dynamical model of M31 yields for total mass of visible populations 1.0×10^{11} $M_\odot$ and for the DM halo 1.1×10^{12} $M_\odot$ (Tamm et al. 2012). The mass-to-light ratio of visible populations in red colour is according to this model 4.0 in solar units.

New data on the velocity dispersion of stars of faint dwarf galaxies suggest that there may exist a lower limit of total masses of galaxies, about 10^6 $M_\odot$ (Wolf et al. 2010). Among other implications the existence of a lower limit of the mass of dwarf satellites may hint to the existence of a lower limit of DM halos. If confirmed this can give a clue to the nature of DM—it can be Warm, not Cold as thought so far. In the Cold DM scenario there should be no lower limit to masses of DM halos. In the Warm DM scenario the minimal mass of halos depends on the wavelength of the cutoff of the initial power spectrum of density perturbations in the early Universe.

Do exist galaxies dominated by the DM with no or very few baryons?

Whether there exist DM halos without visible stars or not is unclear. But even if there are DM halos without stars primordial ordinary matter should exists in these halos, because there is no way to separate completely DM "gas" and ordinary baryonic gas from each other.

The baryon content of Milky Way and Andromeda dwarf satellites has been recently investigated in detail (Geha et al. 2006; Kalirai et al. 2010; Simon et al. 2011). Authors used the SDSS survey to detect faint dwarf satellites of our Galaxy and Andromeda galaxy, and the SPLASH Survey (Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo). The darkest galaxy currently known is the satellite of the Milky Way Segue I. The velocity dispersion of stars in this galaxy is only 3.7 km/s, the mass within the half-light radius is 5.8×10^5 solar masses, the total mass-to-light ratio in red light is 3400 in solar units (Simon et al. 2011). Segue I has the highest DM density of any known galaxy: 2.5 solar masses per cubic parsec (Simon et al. 2011). For comparison, the density of the Galaxy in the solar neighbourhood is only 0.1 solar masses per cubic parsec (Gilmore et al. 1989; Kuzmin 1955).

What is your favorite explanation of the DM phenomenon?

This problem was discussed in detail by Bertone et al. (2005). Authors argued that this was a problem since Newton published his classical work "Philosophiae Naturalis Principia Mathematica". Whenever anomalies were observed from the Newton's law of gravity, the question arose: should such anomalies be regarded as a deviation from the laws of gravitation or as an indication of the existence of unseen "dark" bodies. The second approach proved to be correct in the case of anomalous motion of Uranus, which led to the discovery of Neptune. The first possibility was realised when anomalies in the motion of Mercury led to the Einstein's theory of general relativity.

My favorite explanation of the DM phenomenon is some kind of particles, as suggested by most investigators, for overview see (Bertone et al. 2005). I wrote in my book (Einasto 2014): *"One has to keep in mind that despite us having a good idea of what might make up DM, the DM paradigm is remarkably simple: one just needs an additional cold collisionless component that interacts only through gravity. Once this component is accepted, a host of apparent problems, starting from galaxy and galaxy cluster scales and extending to the largest scales as probed by the large scale structure and CMB, get solved. So in that respect one might say that there is certainly some degree of elegance in the DM picture."*

But I may be in error, it is not excluded that DM is some completely new phenomenon. Whatever the explanation is, it changes our present world view in physics and cosmology.

Which further explanations cannot be accepted?

It seems to me clear, that it is not possible to explain the whole variety of phenomena related to DM by sole change of the law of gravity. Changes in the law of gravity or explaining the DM phenomenon with unseen stars or planets are in conflict with observational data discussed above: the whole set of cosmological parameters from CMB and galaxy distribution (Planck Collaboration et al. 2013; Reid et al. 2010; Tegmark et al. 2006). In other words, in my view the DM phenomenon has deep implications to physics and to our understanding of the very early Universe or even multiverse—the multitude of Universes.

Questions for Pavel Kroupa:
you clearly speak in several of your recent works of a "Dark Matter Crisis". May you summarize your point of view on this subject, with particular reference to the consequences of your ideas for the commonly accepted view of galaxies as DM dominated systems?

If, as you say, the DM paradigm is wrong, what changes are necessary to reconcile observations with theoretical models?

The recent publications meant here are Kroupa et al. (2010, 2012); Kroupa (2012), and Kroupa (2014a). The argument is straight forward: In any realistic cosmological model there are two types of dwarf galaxies (the dual dwarf galaxy theorem). In the standard model of cosmology (SMoC), the dual dwarf galaxy theorem implies a bifurcation: the one type of (primordial) dwarf galaxy (PDG) resides in and is dominated by a dark matter halo, while the other type of dwarf galaxy (tidal dwarf galaxy, TDGs) contains no significant amount of dark matter by the nature of their formation in tidal tails drawn out in galaxy–galaxy encounters. The dual dwarf galaxy theorem is falsified by the real Universe in that no evidence published to date can be found to distinguish the dark matter content of these two different types of dwarf galaxies. The explicit tests made are on the baryonic Tully-Fisher relation and the radii of pressure supported dwarf galaxies. Therewith, given the presently available data, the SMoC is ruled out as a model of the real Universe:

$$\text{SMoC} \Rightarrow \text{PDGs} \neq \text{TDGs} \quad \Longleftrightarrow \quad \text{PDGs} = \text{TDGs} \Rightarrow \cancel{\text{SMoC}}. \tag{7.2}$$

Is this deduction correct? Clearly, by deducing the SMoC to be invalid, I am arguing against the main stream scientist, where the majority of colleagues appear to be convinced that dark matter particles exist such that the SMoC is a physically relevant model of the Universe. The conviction that this is true is so powerful, that very major professorial chairs, directorships and vast amounts of money are being expended to fund a large number of research groups to work in the framework of this model and to search for the dark matter particle(s).[5] With a deduction such as the above (Eq. (7.2)) I am putting my reputation at stake, so I need to be completely convinced, without a shadow of a doubt, that my conclusion is true: *If the deduction (Eq. (7.2)) is wrong, then there should be indications in the astronomical data which would imply it to be wrong*. Is this the case? Or, do independent data rather support the deduction?

In performing the consistency checking, it is useful to first reconsider the foundations of the SMoC. The SMoC is based on assuming that Albert Einstein's Theory of General Relativity (GR) (Einstein 1916) is valid everywhere. As discussed in the above mentioned papers of mine, this assumption is found to quickly fail multiply times leading to the discovery of new physics we refer to as inflation, dark matter and dark energy (Eq. (7.3) below). But is GR really correct? I had no reason to doubt this fundamental assumption, especially given the fundamental axioms such as the equivalence principle it rests upon and the very accurate and precise tests of

[5]Cases in point are found in footnote 8 in Kroupa (2014a): Lang (2014) writes "Due to a large number of astrophysical observations ... we know today that dark matter exists" (originally: "Aufgrund einer Vielzahl von astrophysikalischen Beobachtungen ... wissen wir heute, dass Dunkle Materie existiert") and "The question is thus not: does dark matter exist? Rather, the issue is to find out: what does it consist of?" (originally: "Die Frage ist also längst nicht mehr: Existiert die Dunkle Materie? Vielmehr gilt es herauszufinden: Woraus besteht sie?"). A similar statement is found in Chap. 25 of the Review of Particle Physics (Olive 2014): "The existence of Dark (i.e., non-luminous and non-absorbing) Matter (DM) is by now well established", although the correct statement should have been something like "The existence of Dark (i.e., non-luminous and non-absorbing) Matter (DM) is at present a favored hypothesis".

it in the strong field regime (Solar System and stronger in terms of acceleration) (Byrd et al. 2014). But in 2010 I realized that Einstein had to work entirely with empirical constraints on gravitation as available within the Solar System only, and that tests performed many decades later of GR in the weak-field regime are not conclusive, because the requirement to introduce dark matter particles may merely be fixing a failure of GR. That is, Einstein had no other data at hand, apart from the precession of Mercury's orbit, than those already used in the seventieth century by Isaac Newton who discovered his law of universal gravitation from such empirical data. Galaxies had been realized as to what they are only decades after GR was published, and the motion of matter within them was mapped even later, at the end of the 1970s and early 1980s by Vera Rubin and Albert Bosma. *Thus, assuming GR to be valid everywhere constitutes an extrapolation of an empirical law by many orders of magnitude beyond the experimental data range it was originally derived from*. This realization led to a loss of confidence on my belief in the SMoC, making it all the more plausible, in my eyes, that the above deduced falsification of the SMoC is correct, and that the "new physics" mentioned above merely constitute mathematical additions to reduce the tension between an extrapolation and the data. The SMoC is discussed critically from a mathematical point of view by e.g. Krizek and Somer (2014).

The consistency of the above deduction is tested using independent data in Kroupa et al. (2010, 2012); Kroupa (2012), and Kroupa (2014a). Here a few of the arguments are listed again:

- The arrangement of dwarf satellite galaxies in a rotating disk-of-satellites (DoS) around Andromeda or in a vast-polar-structure (VPOS) in the case of the Milky Way (MW) and other host galaxies within distances of 100–250 kpc rule out their origin as dark-matter sub-structures (Ibata et al. 2014a,b,c; Pawlowski and Kroupa 2014; Pawlowski et al. 2012b, 2014). But the dwarf satellite galaxies within and outside of the DoSs have indistinguishable physical properties (Collins et al. 2015; Kroupa 2014a), such that their apparent dark matter content cannot be due to the presence of dark matter.
- The lack of solutions with *Chandrasekhar dynamical friction* for dark-matter dominated dwarf galaxies orbiting in the putative dark matter halo of the Milky Way (Angus et al. 2011).
- The lack of evidence for the merger activity (Shankar et al. 2014) in the galaxy population in that the vast number of galaxies brighter than about $10^{10}\,L_\odot$ (Delgado-Serrano et al. 2010) are thin disk galaxies with radii extending to dozens of kpc and the majority of these not even having a classical bulge (Kormendy et al. 2010).
- Related to this is the lack of variation of galaxies [they are all too similar as pointed out by Disney et al. (2008)].
- And, still concerning disk galaxies: the observed rotation curves are not matched by even the most advanced and the most recent hand-picked and fine-tuned modelling attempts within the SMoC framework (Wu and Kroupa 2015).
- The downsizing problem.

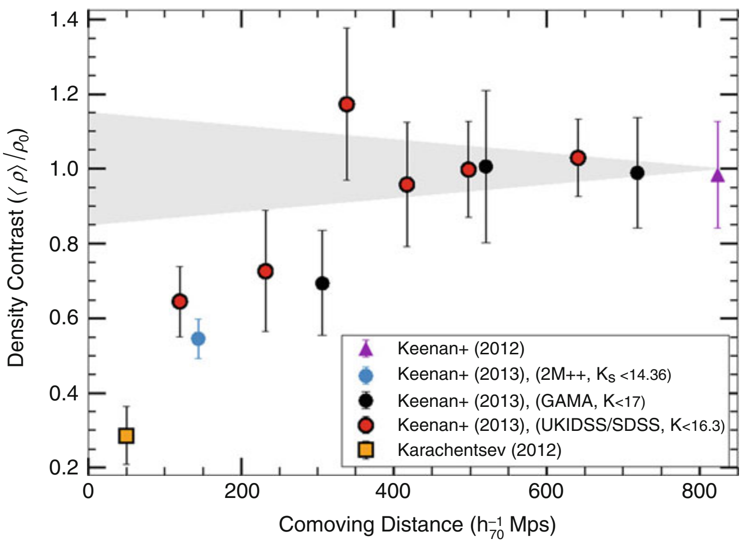

Fig. 7.4 The observed significant underdensity of matter within about 300 Mpc of the Milky Way appears to be in extreme conflict with the SMoC which requires a value of one in the density contrast with fluctuations (see Fig. 1 in Kroupa 2015)

- The Bullet cluster.
- The local highly significant matter under-density on scales of 10–300 Mpc (see Fig. 7.4 and Fig. 7 in Kroupa 2014a).
- And many more.
- Not discussed in the above papers of mine is the additional evidence against extended heavy dark matter halos by the longness of tidal tails drawn out in galaxy–galaxy encounters (Dubinski et al. 1996, 1999). This is failure 23 (see the list of 22 failures in Kroupa 2012).
- A particularly interesting and directly relevant very recent observational result, not mentioned in the above papers of mine, is that Lena et al. (2014) have found that super-massive black holes (SMBHs) do not show the displacements they ought to show if merging were as common as is expected in the SMoC. Remember, in the absence of dark matter galaxies would not merge when they interact unless they have small, penetrating impact parameters (Toomre 1977). This is failure 24.
- An additional new failure of the SMoC is the finding that within the local 10 Mpc volume there is a highly significant deficit of massive dwarf galaxies (Klypin et al. 2014). This is failure 25.
- A further additional new failure of the SMoC is the too-massive-to-fail problem for dwarf galaxies in voids (Papastergis et al. 2015). This is failure 26.
- The highly symmetrical structure of the Local Group of galaxies (Fig. 9 in Pawlowski et al. 2013) was also not known until 2013 and is well beyond being understood in any current theoretical framework, and is certainly entirely

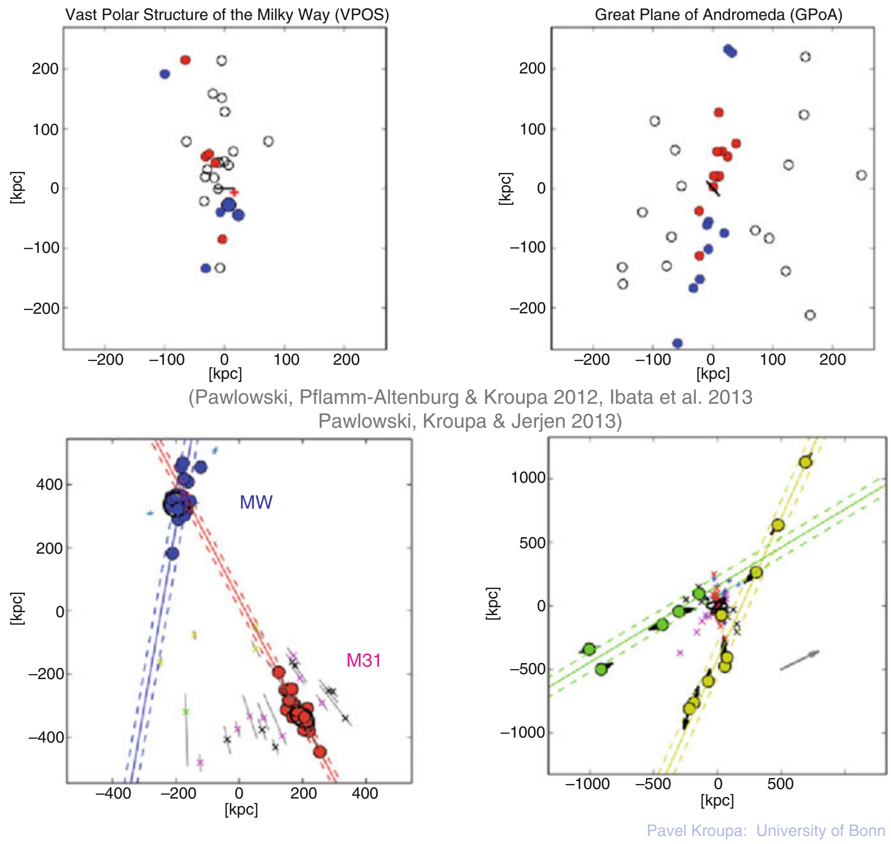

Fig. 7.5 The Local group is highly organised: the satellite galaxies of the Milky Way are in a vast polar disk-like structure (*blue ones* are moving one way, *red ones* the other). Andromeda also has a great plane of satellites (*blue satellites* are moving in the same direction as the *blue ones* in the case of the Milky Way). The two satellite systems of the Milky Way and of Andromeda are aligned (*lower left panel*). All non-satellite galaxies in the Local Group are in two symmetric planes with near-equal properties (*extension, thickness*). For details see Fig. 2 in Kroupa (2014b)

inconsistent with the Local Group being the result of a long history of mergers of dark matter halos. This is failure 27. The related extraordinarily symmetrical structure of the Local Group is shown in Fig. 7.5.

None of these problems have ever been solved convincingly. All tests performed are well consistent with the above conclusion (Eq. (7.2)), such that dynamically relevant particle dark matter on galaxy scales cannot be present. That evidence for dynamical friction on the dark matter halos is absent nearly entirely in the data solidifies this conclusion, which is also consistent with the problem of observed tidal tails in interacting galaxies being much longer than what they ought to be if the extensive and massive dark mater halos were present. To my astonishment, virtually every *prediction* made within the framework of the SMoC seems to have been falsified by observation. This is visualized using the *Theory Confidence Graph* of Kroupa (2012) (which does not include a number of failures, such as the length-of-the tidal tails, the absence of evidence for dynamical friction, the lack of recoiling black holes). While I am fully aware of many of my colleagues portraying the converse of this, also in lectures to undergraduates, the blatantly obvious disagreement, time and again, between the SMoC results and predictions and the observational data I am finding stunning.

If each "problem" (more correctly: failed prediction) is associated with a loss of confidence of 50 (or 30) % that the SMoC is valid, then the overall remaining confidence becomes $0.5^{22+5} = 1/10^{8.13}$ (or $0.7^{27} = 10^{-4.18}$), i.e. 7.5×10^{-7} (or 6.6×10^{-3}) %.

It follows that independently of the falsification of the SMoC through the dual dwarf galaxy theorem, all the 27 tests above lead to the SMoC being ruled out with at least 4 sigma, taking a conservative loss of confidence per failed prediction of only 30 %.

What were the reactions to your ideas?

Historically, an interesting sociological process began acting in *two phases* in repressing the notion that the SMoC may not be a valid model.

The *primary phase* is understandable conceptually because GR has been found to be an excellent description of gravitational phenomena where precise tests have been possible in the strong-field regime. Big Bang cosmology based on GR is a convincing theory, and alternatives, such as the steady-state model of the Universe, have been ruled out by observation.

The *primary phase* involves the additions of major new physics notions: the first failures emerged quickly but were considered to be evidence for new physics, which is a relevant scientific procedure. Thus, in 1980 and 1998, respectively, inflation and dark energy (DE) were introduced as similar mathematical extensions of GR. They are well motivated and solve a number of otherwise not understood observational problems. In 1981 the non- or at most weakly-interacting non-relativistic dark matter particles (DMPs) were introduced into the model in order to allow structures to grow in the diluted inflated model and to account for the observationally discovered mismatch between data and Newtonian gravitation on scales of galaxies and larger. Thus the current mathematical formulation of the SMoC can be summarized as

$$\text{SMoC} = \text{GR} + \text{inflation} + \text{DE} + \text{DMPs}. \tag{7.3}$$

The philosophically unattractive aspects of these three major extensions of the original model based on GR is that neither inflation nor dark energy are understood theoretically thereby also displaying important conceptual problems (Baryshev 2006; Brandenberger 2008; Steinhardt and Wesley 2009). And, although the standard model of particle physics (SMoPP) has been found to be an excellent description of nature apart from gravity, dark matter particles are neither covered by it nor is there direct experimental evidence for these particles despite a few decade long and financially rather impressive effort.

The *secondary phase* began as further failures were becoming evident after the late 1980s, in that the observed galaxy population was not emerging in the SMoC. Astronomers began to argue that the physics of the known baryonic matter is so uncertain such that the structures driven by the supposedly well known and dominant but undetected dark matter cannot be quantified properly. Thus, for example, that the computed galaxy population consisted of largely barely rotating spheroidal or compact rotational systems in disagreement with the more than 90 % of all galaxies brighter than about $L > 10^{10} L_{\odot}$ being large thin disk galaxies (Delgado-Serrano et al. 2010) is being argued away by the baryons exerting an essentially unknown effect onto the dark matter particles such that they readjust in order to allow thin extended disk galaxies to grow. In truth it has only been possible to obtain models which roughly resemble real disk galaxies by hand-selecting individual dark matter halos without significant recent mergers (Wu and Kroupa 2015). That the galaxy population calculated in the SMoC has severe problems in representing the real galaxy population is evident in the most recent very major and also celebrated computational Illustris Project,[6] in which the feedback physics is modelled with the stellar wind speed being a few times the one-dimensional velocity dispersion of the dark matter halo within which they occur. This is unphysical [see also Schaye et al. (2015), who apply a physically much more convincing feedback model], and such models are ruled out by the observation that TDGs do form and survive for Gyr (Duc et al. 2014) despite them not having dark matter halos (Barnes and Hernquist 1992; Bournaud 2010). In the end, which physical principle that may be derivable from the SMoPP or from dark matter physics can arrange such a coupling between baryons and dark matter which do not couple apart through gravitation and perhaps weakly? And, this would imply that present work on stellar winds and supernova explosions would be wrong since their hosting dark matter halos are not included in stellar astrophysical modelling.

As another example, the *satellite galaxy over-prediction failure* became the *missing satellite problem* which is now deemed to be solved with such a wide range of post-dictions that any observation would be consistent with the model. According to the models by Hargis et al. (2014), essentially any number of satellite galaxies will be consistent with the observed numbers, whatever they turn out to be. Any baryonic-physics processes introduced and fine-tuned to solve some particular problem is thereby typically not checked for its affect on other issues. For example, "solving" the satellite over-prediction problem may lead to incompatibilities with the properties of disk galaxies.

Related to this last issue and to how dark-matter computational astrophysics is applied to satellite galaxies and as an example of state-of-the art research, Bahl and Baumgardt (2014) address the problem of whether ultra-compact dwarf galaxies (UCDs, i.e. essentially extremely massive globular clusters) may be the stripped

[6] http://www.illustris-project.org/.

nuclei of PDGs falling towards the centre of a galaxy cluster. They model the dark matter halo of the host, but neglect the dark matter halos of the PDGs, finding that they can be destroyed leaving their nuclei as possible UCD satellites. This work is now being cited as evidence that UCDs may be stripped nuclei in the framework of the SMoC. But this is wrong because the result is obtained using a highly inconsistent method: (1) if the SMoC is assumed to be valid (this is perfectly in order as an assumption, although being unrealistic) then the dwarfs would have large and massive dark matter halos (Kroupa 2014a) such that dynamical friction would have them merge with the host within a few orbital times and stripping of the nuclei would become unlikely because first the dwarf galaxy halo needs to be removed before it's stellar body is stripped. The authors have not shown this to be the case. (2) If, on the other hand, the dark matter halo is neglected as the authors do (this is also an assumption which is admissible but with constraints) then the only physically relevant option the authors have is to switch to effectively non-Newtonian dynamics, because the rotation curves of galaxies need to be accounted for but without dark matter. But their integrations of the equations of motion are Newtonian. Thus, here too the authors have not shown that stripping works, since they computed the wrong problem. (3) The computation the authors made and their assumption of neglecting the satellite galaxy dark matter halo might be argued to be correct within the SMoC if the satellite galaxy with its nucleus is a TDG, since TDGs do not have dark matter halos in the SMoC. However, this is a superficial view because this approach would also be fundamentally flawed by the dual dwarf galaxy theorem: if there are TDGs that play the role assumed in this problem, then their numbers would be so large (they'd be dE galaxies) that no room remains for the expected large numbers of PDGs. The points (1)–(3) exemplify the type of internally inconsistent (but technically correct) research passing the peer-review process in this field of study. It is not the only case, and a reader might ask the question: *What has actually been shown by this type of work such that it can be applied to understanding the observations?*

Individual members of the community develop amusing reactions to the failures of the SMoC. A prominent Cambridge member of the observational community searching for new satellite galaxies around the MW at the IoA simply said, after my colloquium in June 2013, that the VPOS [described in much detail by Metz et al. (2007, 2008); Pawlowski et al. (2012a), and Pawlowski and Kroupa (2013)] simply does not exist. Here it is to be noted that the new discoveries (since 2012) of satellites beyond about 10 kpc distance achieved by non-Cambridge teams showed that each and every newly discovered system lies *in the VPOS* (Kim and Jerjen 2015; Pawlowski and Kroupa 2014). Until now there is no evidence for any object beyond about 10 kpc from the centre of the MW which does not seem to be linked to the VPOS. Despite the research papers by Metz et al. and Pawlowski et al. being the foundational research papers on the properties of the VPOS and the amazingly organized and symmetrical structure of the Local Group (in contrast to the chaotic but spheroidal structure expected from the SMoC merger tree, see Fig. 7.5 above) (Pawlowski et al. 2013), their papers are systematically not being cited by some of the prominent teams who explicitly work and publish on the Local Group, its structure and properties and on the spatial distribution of the satellite galaxies of the MW and of Andromeda (e.g. Bowden et al. 2013, 2014; Diaz et al. 2014; Hargis et al. 2014).[7] The point here is not that individual papers are not cited, but that there appears to be a systematic attempt by researchers at some prestigious institutions at possibly suppressing or ignoring some rather important research results.[8] Obviously this unscholarly behaviour may have an effect on young researchers which may be susceptible to non-scientific influence.

The way in which it is being argued, perhaps too often, on the scientific platform may seem, at least to some, problematical: The VPOS can neither have been formed from the accretion of a group of dwarf galaxies (Metz et al. 2009) nor from the accretion of satellite galaxies onto the MW, which is a 10–11 Gyr old disk galaxy, along a cosmological filament (Pawlowski et al. 2012b). There is therefore no solution for the DoS/VPOS in terms of dark-matter satellite galaxies, such that (Libeskind et al. 2011) suggest, "While the planarity of MW satellites is no longer deemed a threat to the standard model, its origin has eroded a definitive understanding." At a topical meeting of the American Astronomical Society in 2013 a prominent astronomer declared that the Local Group cannot be used to test the SMoC. In the end, perhaps the MW and even the Local Group may just be extreme outliers, exceptions as it were.[9]

But, meanwhile more trouble for the SMoC emerged: Andromeda also has an extreme version of a rotational DoS! This shocking result has been established by the seminal work of Ibata et al. (2013, 2014a). A brilliant idea of testing how often phase-space correlated satellite systems occur was conceived and applied by the same remarkable team (Ibata et al. 2014b). They showed with very high statistical significance that satellites on opposite sides of their host galaxies and within projected distances of about 100–150 kpc, have anti-correlated line-of-sight velocities in contrast to no correlation expected if the satellites are dark-matter dominated PDGs, as explicitly tested using SMoC simulations and intuitively expected because PDGs merge with host dark mater halos more or less isotropically and stochastically, and most importantly, independently of each other. This is independently supported

[7]The titles of the research papers in question are (Hargis et al. 2014): "Too Many, Too Few, or Just Right? The Predicted Number and Distribution of Milky Way Dwarf Galaxies"; (Bowden et al. 2013): "Triaxial cosmological haloes and the disc of satellites"; (Bowden et al. 2014): "On Asymmetric Distributions of Satellite Galaxies"; (Diaz et al. 2014): "Balancing mass and momentum in the Local Group".

[8]Citing from the A&A author's guide—July 2013: "Papers published in A&A should cite previously published papers that are directly relevant to the results being presented. Improper attribution—i.e., the deliberate refusal to cite prior, corroborating, or contradicting results—represents an ethical breach comparable to plagiarism."

[9]This argument is invalid as long as properties are studied which are generic such as the wide (on scales of >100 s of kpc) distribution of matter and its correlation in phase-space, which is not sensitive to the details of sub-grid baryonic physical processes. Testing the SMoC against observational data becomes inconclusive if specific questions are raised such as where a particular satellite galaxy is, what the number of satellites is and which star formation history a particular galaxy may have had.

by the known satellite systems around a number of well observed host galaxies also having phase-space correlated satellite systems (Pawlowski and Kroupa 2014).

A major host galaxy thus appears to typically have its faint satellite galaxies arranged in disk-like rotating structures within distances of 100–150 kpc, at odds with the expectations from SMoC models. The conclusion by Chiboucas et al. (2013) "In review, in the few instances around nearby major galaxies where we have information, in every case there is evidence that gas poor companions lie in flattened distributions." is noteworthy here.

Despite the observational evidence for rotational DoSs being so strong and the robustly obtained result using various statistical tests that such highly phase-space correlated satellite galaxy populations do not occur in the SMoC if these are composed of dark matter dominated PDGs (many research papers by Metz et al., Pawlowski et al., Ibata et al.), various teams nevertheless attempt at demonstrating that this is not so. Thus Goerdt and Burkert (2013) (until now not published by a journal, but also not withdrawn) argue that such phase-space correlated structures arise naturally in the SMoC if satellite galaxies are accreted along thin baryonic streams. This argument has never been shown to actually work in any simulation, and is ruled out since dark matter satellites will not line-up like beads on a string as they fall into the major host halo (Kroupa 2014a). Pawlowski et al. (2014) have ruled out this beads-on-the-string scenario. In another attempt, Bahl and Baumgardt (2014) retest the claims by Ibata et al. (2013) apparently discovering that, contrary to the deduction by Ibata et al. (2013), SMoC models do naturally yield DoSs as found around Andromeda. Ibata et al. (2014a) and Pawlowski et al. (2014) showed that their conclusions to be flawed because they did not apply the appropriate criteria (e.g., searching for disks using criteria that also allow spheres will yield the wrong conclusion on the frequency of occurrence of disks). *Nevertheless, various teams cite these flawed papers (e.g. Bowden et al. 2014) without citing the rebuttals nor the phase-space correlated DoSs.*

The most recent and amusing development in this arena is the rebuttal by Cautun et al. (2015) of the Ibata et al. (2014b) result concerning the overabundance of anti-correlated satellite pairs when the real galaxies are compared to SMoC galaxies. Cautun et al. (2015) neither show that Ibata et al. (2014b) have made an error nor do they demonstrate that the analysis of Ibata et al. (2014b) is flawed, they merely argue that the significance of the result obtained by Ibata et al. (2014b) weakens significantly when the selection criteria are changed, e.g. by using a larger search radius around the host galaxies. Ibata et al. (2014c) have already countered this. Essentially, phase-space correlated satellite galaxy systems, such as the DoSs of the MW and of Andromeda, do have physically relevant scales and these are similar for major host galaxies (100–200 kpc).

Thus, none of the attempts (Bahl and Baumgardt 2014; Cautun et al. 2015; Goerdt and Burkert 2013) to argue away that the DoSs are in highly significant disagreement with the expectations form the SMoC models, have added much to progress, but these attempts are cite-able research papers which make-believe that the original, rigorous discovery papers may not be as solid. The contents of the introductions to, e.g. Bowden et al. (2014) and Cautun et al. (2015), are cases in point. Speaking to individual researchers, the sense seems to have arisen that *opinion* is what counts, rather than hard evidence: "Yes, but they are voicing a different opinion, so the situation is not clear." Perhaps this is why such weak counter arguments, which are even partially flawed, get published at all; the authors are allowed to voice their opinion more than actually showing that another analysis is faulty. Thus, Cautun et al. (2015) might have rather written that their analysis agrees and supports the original paper by Ibata et al. (2014b) on the anti-correlated satellites, which it does. They may then have shown with their analysis that the signal disappears beyond a certain radius scale, which would have been an interesting new result. Therewith they could have constructively pointed out the new valuable scientific result that phase-space-correlated satellite systems occur only within a limited radial scale about their host galaxies. Instead, the stance is taken to try to weaken the seminal results by Ibata et al. (2014b). Finally I would like to point out why I have the impression that the scientific method may indeed be already compromised: in Libeskind et al. (2009) and in Deason (2011) make very specific, explicit and valuable statements on how likely DoSs are around MW like galaxies if the SMoC is assumed to be valid, given that N satellites have measured proper motions that make them co-orbit. From Pawlowski and Kroupa (2013 and as re-explained in the Introduction of Pawlowski et al. (2014), the current data robustly rule out the SMoC models, given the results of the SMoC teams (Deason 2011; Libeskind et al. 2009):

At least 6 (and up to 8 within current uncertainties) out of the brightest 11 of the real satellites have orbital angular momenta aligned within 22° of their average angular momentum direction which has a probability of 0 % according to Fig. 9 of Libeskind et al. (2009). With this test alone the SMoC is ruled out, given the data. *The perplexing issue however is that the community opinion appears to be that this is not the case*, without having ever shown that the work of Libeskind et al. (2009), Deason (2011), and Pawlowski et al. (2014) may be wrong.

The community appears to have developed an unhealthy sense of simply ignoring or burying previously obtained results if these are highly inconsistent with the SMoC. The above failure is terminal, that is, no baryonic physics or other effects can change the results. Herewith the SMoC is ruled out as a viable theory of the Universe. A particularly troubling case in point is the manuscript published on the archive by Sawala et al. (2014) in which they claim that by adding baryons to the structure formation simulations the "missing satellite" problem, the "too big to fail" problem and the "planes of satellites" problem are solved. I have been receiving e-mails from members of the community pointing this out. A detailed analysis of this manuscript reveals that their Fig. 1 is made with a radiative transfer code which gets processed significantly before being made into the figure such that the faintest features in the figure are unknown. The manuscript thus contains material which cannot be quantified. Furthermore, the authors did not test the planarity of the 3D distribution, but use only two dimensions. They do not test for the clustering of orbital angular momentum poles of their model satellites and their data are in fact perfectly consistent with a purely random spheroidal dark-matter-only simulation. There are other flaws, e.g. concerning their test of the Andromeda system, and generally it can be stated that they re-phrase the known problems in a way such that they can pretend to have solved them using not very robust tests or no real tests.

In addition to a certain degree of perhaps dis-honestness of parts of the cosmological community alluded to above, the unhealthiness of the cosmology-relevant research environment is suggested with the following few instances: a close collaborator of mine, with whom I began the project which ultimately resulted in the publication (Kroupa et al. 2010), dropped authorship of this paper because of the fear that having his or her name on this paper would compromise his or her chances of obtaining a job in astrophysics. Two other very close collaborators of mine refuse to cite Kroupa (2012, 2014a), despite being relevant for the arguments in their own papers, again, because citations to these two publications of mine may mire their own papers in the eyes of the community. I know of some authors being told by referees that citations to these two papers of mine should be dropped. I have spoken to fairly senior scientists who refuse to openly criticize the SMoC for fear of having their chances reduced for obtaining research grants. Especially in the USA this is problematical because the summer salary depends on obtaining grants in a highly competitive environment. A brave Ph.D. student, on giving a presentation on MOND in Cambridge, was asked publicly by a highly senior astronomer how many angels are on a pin head. A Ph.D. student of mine was told, again by someone from Cambridge, that he or she ought to stop following me, and I have also been told by a very senior astronomer that I should stop arguing that there can be no dark matter, and a German die-hard SMoC director walked out of one of my colloquia at his institution in northern Germany. Instances are documented where attempts are made in removing the research budget and secretarial support from "dissidents", whereby other reasons than scientific ones need to be applied. Clearly, if legal action were to be taken on such instances, a scandal may ensue. Apart from hindering an advancement in understanding of data (such as the above mentioned notion that the Local Group data cannot be used to test the SMoC), such incidences contribute to a general atmosphere of fear of criticizing the SMoC.

The above examples are uncomfortable but reveal that the research environment concerning cosmology has become unhealthy. Too many researchers are willing to write flawed manuscripts but are not willing to make significant conclusions when their results contradict or exclude the SMoC. This is fully consistent with the adverse behavior noted in other scientific disciplines (Fanelli 2010; López-Corredoira 2009; The Economist 2013a,b) and may be due to the "perish or publish" doctrine married to a strong bias towards seeing the SMoC as the only valid model which was established by the now highly influential senior scientists.

Which implications have these alternative ideas?

If dark matter particles do not exist then there are a number of implications. Some are listed here.

- The direct implication for the galaxy population is that *mergers between galaxies are very rare in reality*, because the dynamical friction on the expansive and massive dark matter halos does not occur, as already realized by Toomre (1977).

This is further evident in the ratio of the number of star forming galaxies to elliptical galaxies (about a few percent) not changing within the uncertainties since redshift of about 6 (Fig. 7 in Conselice 2012).

- The large observed uniformity of the galaxy population with more than 90 % of all galaxies with luminosity $L > 1.5 \times 10^{10} L_{\odot}$ (Delgado-Serrano et al. 2010) being disk galaxies which are on the main sequence (Speagle et al. 2014) then becomes readily understandable. This is because the haphazard, stochastic and different merger histories which would lead to a large variation of galaxy properties (Disney et al. 2008), does not occur. Instead, galaxies are self-regulated (Koeppen et al. 1995) slowly growing, largely isolated structures which sometimes interact, such as the MW and Andromeda (Zhao et al. 2013). During encounters dwarf galaxies are formed as TDGs in DoSs.
- Understanding galaxies purely as baryonic, self-gravitating systems becomes simple and predictive with remarkable success: that one disk galaxy resembles another follows from self-regulation, as just noted above. Taking a dark-matter-free TDG, placing it on an orbit within the potential of a host galaxy, leads to surprising agreement with the observed satellite galaxies of the MW and of Andromeda. Before delving into this, I'd like to explain how I managed to stumble onto the result that the SMoC is not valid (Eq. (7.2)):

I have had no reason to be against dark matter, and indeed in the history of physics there were incidences when hitherto unknown particles or bodies were postulated to be present which were also found. Famous examples are the neutrino and the planet Neptune. The brilliant work of Einstein and the discovery of redshifted galaxies were beautifully consistent, as was the discovery of the cosmic microwave background radiation flux with its remarkable properties which support the notion of a hot Big Bang. And so, in order to make structure formation work in an inflated and thus diluted early Universe and to account for the high dynamical mass-to-light (M/L) ratios of some galaxies, the postulate that there must be cold or warm particle dark matter which is dynamically and gravitationally dominant on the scales of galaxies was to be taken very seriously indeed (Eq. (7.3)). Because the equations of motion in the appropriate limits remained linear and Newtonian, it was easy to develop computer programs to calculate the emergence and the formation of structure in the SMoC Universe. With increasing computer power the calculations became relevant for studying the properties of the computer galaxies, and I remember how convincing the movies of disk galaxies with their satellite galaxies looked like in the mid-1990s, as shown for example in a brilliant colloquium held in Heidelberg by Simon White. I remember this very vividly indeed. A very strong, extremely well funded international community developed in many countries performing such computations. With the realisation that the computations did not yield the observed galaxies, the many world-wide active groups became entrenched in ever more conflicts concerning fine tuned and detailed considerations of sub-grid baryonic physics processes.

During the early 1990s I have been witnessing these developments as a spectator, as at that time I was much more concerned in understanding how populations of binary stars in star forming regions, which had been observed for the first time with the new infrared observing platforms, could be made consistent with the significantly lower binary fraction in the Milky Way field population. This is where I learned stellar dynamics, essentially by reading and from Sverre Aarseth in Cambridge. Sverre is perhaps the most remarkable and stimulating scientist I have come to know, and he influenced me tremendously, probably more than any other person. Only decades later in 2011 did I learn that Sverre had actually done, in 1979, the very first and pioneering cosmological structure formation simulation (Aarseth et al. 1979), but he had left this too-speculative field (Kroupa 2012). In the early 1990s I lived in Heidelberg but, still being a Rouse Ball Scholar, visited him often, bringing with me a good supply of German white wine, in expectation of receiving driving lessons with his N-body codes. At that time he refused to do sacrilegious experiments with young star clusters containing 100 % binaries, since at that time it was thought that only a few percent of binaries are in clusters. I had to do these computations myself, and for that the array structures in his codes had to be updated. In any case, then the binary-star problem was a hobby, as at that time I was employed in Heidelberg by Roland Wielen to work on satellite galaxies and their dynamical and possibly disruptive influence on the thin disks of major spiral galaxies. I had no reason to consider that dark matter did not exist, and I began this work by first learning to set up spherical satellite galaxies and computing their evolution in the dark matter halo of the Milky Way. I used the programme SUPERBOX developed by Bien et al. (1991); Madejsky and Bien (1993) and Fellhauer et al. (2000) in Heidelberg, a particle-mesh code with nested sub grids. After some adjustments and modernisations of this code I obtained my first solutions which had me raise my eyebrows.

What I found did not fit into the general picture as portrayed by the community that the properties of the satellite galaxies of the Milky Way can only be understood if they had their own substantial dark matter halos. They were observed to have very large dynamical mass to light ratios, larger than ten, and in some cases a few hundred. My own computations yielded hitherto unknown solutions to this finding (Kroupa 1997).

My satellite models assumed that mass-follows-light, they were set-up as TDGs, and I calculated their evolution in very high resolution for that time for a Hubble time and on eccentric orbits within the massive and extended dark matter halo of the Milky Way. I found the satellites to loose particles at every periastron, until, after only about 10–1 % particles remained in them, a sudden change in their properties occurred. They catastrophically lost even more particles, but a remnant always remained for many more orbits. These remnants, containing about 1 % of their original particles, were quasi stable and clearly identifiable condensations of particles in phase space and in orbit about the Milky Way model. Observing them in the computer as a real observer does real satellites, by removing velocity outliers, I found these remnants to have tremendously high dynamical (apparent, i.e. not true) M/L ratios and velocity dispersion and spatial extensions comparable to the real satellite galaxies. I published these results in a paper with the title *Dwarf spheroidal*

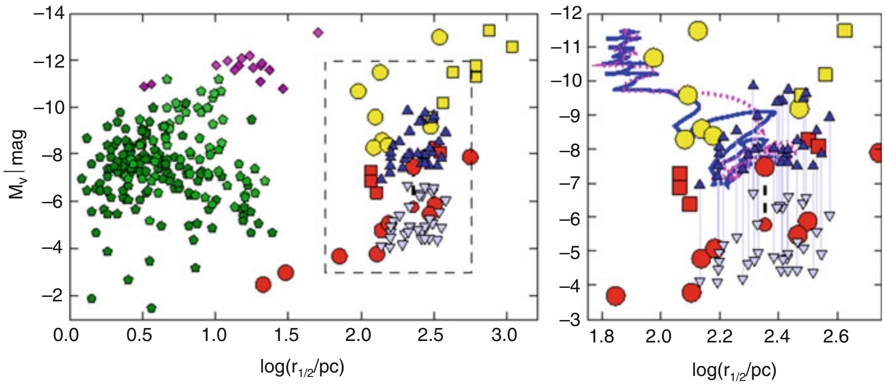

Fig. 7.6 Absolute magnitude versus half-light radius for Globular Clusters (pentagrams), ultra compact dwarf galaxies (*diamonds*), Milky Way (*circles*) and Andromeda (*squares*) dSph satellite galaxies, and simulated ancient satellite TDGs (*triangles*). For the observational data of the MW and Andromeda, the *dark green symbols* mark the ultra-faint dwarf (UFD) additions until 2007 to the known list of companions from the SDSS, while *light yellow symbols mark* the longer-known ("classical") dSph's. For the MW dSph galaxy in Boötes two values for the absolute magnitude are given (see Metz and Kroupa 2007), the values are connected by a *thick, dashed line*. For the simulated data by Metz and Kroupa (2007) absolute magnitudes derived within a fixed projected distance $r_{\mathrm{bin}} = 1.5\,\mathrm{kpc}$ (*dark triangles*) and within the variable half-mass radius $r_{1/2}$ (*light triangles*) are shown. No parameter adjustments are applied; mass-follows light and the adopted V-band mass-to-light ratio of each particle is $(M/L)_{\mathrm{true}} = 3$. In the *right panel*, the region in the *left panel* marked by the *dashed rectangle* is enlarged. Corresponding absolute magnitude values for the simulated satellites are connected by *light solid lines*. The evolutionary tracks of the models RS1–5 (*solid curve*) and RS1–113 (*dotted curve*) are shown. Adapted from Metz and Kroupa (2007), their Fig. 2. The models have observed, dynamical $M/L > 100$ for most cases (Fig. 3 in Metz and Kroupa 2007)

satellite galaxies without dark matter (Kroupa 1997).[10] This work demonstrated to me that what we are observing as real satellite galaxies may not be dark-matter dominated objects after all. Further work confirmed these results using an entirely different computer code (Klessen and Kroupa 1998) (see also Casas et al. 2012 for a parameter survey). With Ph.D. student Manuel Metz we reconsidered the observational properties of these systems, finding them to be surprisingly similar to the real satellite galaxies (Fig. 7.6).

Particularly stunning, in retrospective, was the accidental prediction of a Hercules-type satellite galaxy I made in the 1997 paper: model RS1–5 of Kroupa (1997), shown in that paper as a snapshot (and here in Fig. 7.7), is an essentially perfect match to the dSph satellite Hercules (see Fig. 2 in Coleman et al. 2007)

[10]This paper, by the way, drew interesting comments by a few well-established senior scientists. Once, in a train going back from Switzerland from a conference, I was told that writing a paper with such a title is suicidal. At a dinner in 2003 a very senior professor told me in Bonn that I am un-hirable by having written such a paper.

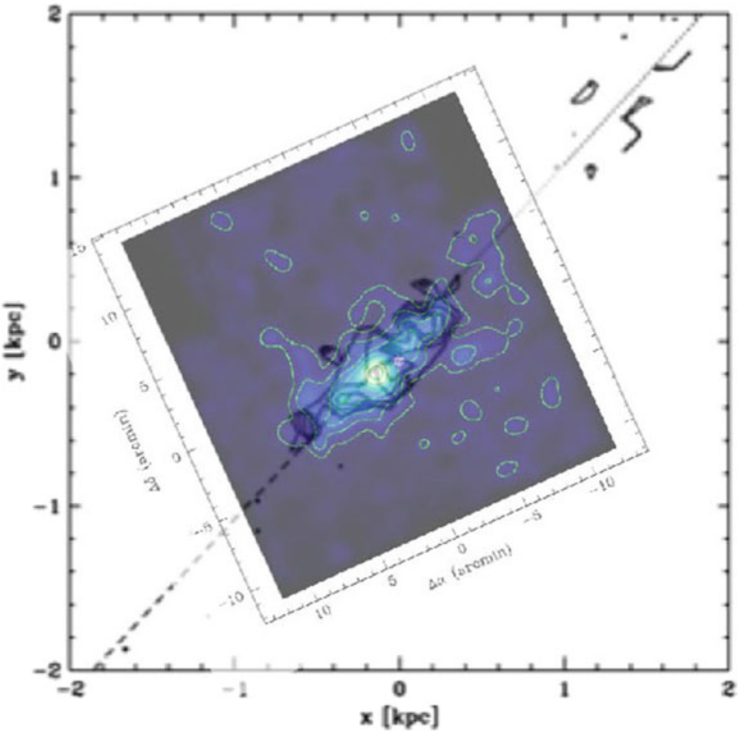

Fig. 7.7 Model RS1–5 from Kroupa (1997) (on the kpc grid) is plotted over the surface brightness contours of Hercules by Coleman et al. (2007) (celestial coordinate grid). The *dashed and dotted curve* are, respectively, the past and future orbit of RS1–5

discovered 10 years later by Belokurov et al. (2007). The half-light radius is 180 pc in the model and 168 pc for Hercules, RS1–5 has a velocity dispersion of about $2.8\,\mathrm{km\,s^{-1}}$ (Table 2 in Kroupa 1997), while Hercules has a measured velocity dispersion of $3.72 \pm 0.91\,\mathrm{km\,s^{-1}}$ (Adén et al. 2009), and the inferred mass-to-light ratio that one would deduce from velocity dispersion measurements based on the assumption of equilibrium is about 200 in both cases. Both RS1–5 and Hercules have luminosities agreeing within one order of magnitude (the model being the brighter one), yet RS1–5 has no DM.

I am not aware of any other (dark matter based) models having been able to *predict* with such accuracy a really found satellite galaxy (Fig. 7.7). I am also not aware of any other models which, without fine-tuning of parameters, so naturally account for the observed properties of the MW and Andromeda satellites (Fig. 7.6).[11]

[11] I should emphasize that today I do not consider these solutions to be valid in their entirety: if there is no dark matter in galaxies, then the flat rotation curves of disk galaxies force us to use

At this time (late 90s) I could have left this field, but I sensed that this issue of the satellites may well be central to uncovering a fundamental property of the Milky Way, and more importantly, may impinge on the issue of the existence of dark matter. Thus I began to seek other clues, and the spatial distribution of satellite galaxies around the Milky Way was such a clue. It was well known from the much earlier work in the 1970s by Lynden-Bell (1976, 1982) and Kunkel and Demers (1976) that the satellite galaxies and the distant globular clusters were in streams. But their work was either ignored or forgotten by the cosmological community which needed the satellite galaxies to be part of the dark-matter dominated sub-halo population. Indeed, the satellite galaxies do have very large dynamical M/L ratios (if the analysis is done assuming Newtonian dynamics), so this was a logically correct association. However, my solutions published in (Kroupa 1997) suggested that this interpretation with dark matter may not be needed. So the highly anisotropic distribution of the then known satellite galaxies became interesting and telling. My own tests in 2005 with Christian Boily and Christian Theis of the real distribution against that expected from the haphazard merging of sub-halos due to the cosmological merger tree showed that the latter was inconsistent with the real spatial distribution with a high significance (Kroupa 2005). With my Ph.D. students Manuel Metz and Marcel Pawlowski we continued this work using actual SMoC simulation data as the null hypothesis and more sophisticated statistical tests, some of which were ported from the mathematical literature, and we followed the new discoveries: initially we were excited with each new satellite galaxy, and even more thrilled when it turned out that every new discovery up until now strengthened the DoS (more generally the vast polar structure, VPOS) (Kim and Jerjen 2015; Metz et al. 2007; Pawlowski and Kroupa 2014; Pawlowski et al. 2012a), that it is rotational (Metz et al. 2008; Pawlowski and Kroupa 2013) and that it is an extremely robust structure defying an explanation within the SMoC (Ibata et al. 2014a,c; Metz et al. 2009; Pawlowski et al. 2012b, 2014), that its explanation as mapping out fossil tidal arms is consistent with them being TDGs (Metz and Kroupa 2007; Pawlowski et al. 2011), and that the entire Local Group appears to be highly structured and symmetric (Pawlowski et al. 2013). Other such systems have begun appearing too (Chiboucas et al. 2013; Ibata et al. 2014b; Pawlowski and Kroupa 2014).

In this context, since 2007 the work of Gerhard Hensler and his group in Vienna on theoretically understanding the formation and evolution of dark-matter free TDGs is impressive and ground-breaking: Recchi et al. (2007) and Ploeckinger et al. (2014, 2015) are significantly contributing to our understanding of self-regulated star-forming TDGs showing them to follow a mass–metallicity relation and to survive for many Gyr despite star-formation and baryonic feedback processes. That TDGs emerge very naturally in gas-rich galaxy–galaxy encounters has already been demonstrated by the pioneering work (Fouquet et al. 2012; Hammer et al. 2010; Wetzstein et al. 2007; Yang et al. 2014). This enhances the missing satellites prob-

effective scale-invariant dynamics (SID, or Milgromian dynamics). The computations I published in 1997 (Kroupa 1997) thus need to be redone in this gravitational framework.

lem of the SMoC because TDGs without dark matter ought to be abundant according to these simulations, all of which were made within the SMoC framework. That the number of TDGs produced within the SMoC is as large as the observed number of dE and other satellite galaxies has been pointed out by Okazaki and Taniguchi (2000).

- The existence of the main sequence of galaxies at various redshifts (Speagle et al. 2014; Tasca et al. 2014) is remarkable and has not been predicted within the SMoC. Indeed, the apparently highly self-similar behavior of galaxies of different masses in terms of their star formation rates being simple functions of their stellar masses remains unexplained, and intuitively unexplainable by any stochastic haphazard merger-driven galaxy evolution theory (Disney et al. 2008). The notion that the main sequence is a consequence of smooth accretion onto the galaxies may be correct, but how is it to be arranged given the cosmological merger tree? Instead, the main sequence of galaxies appears to be more consistent with galaxies which are largely isolated and self-regulated objects such that the mergers driven by dynamical friction on the expansive and massive dark matter halos do not play a role.
- Another, more fundamentally important implication is that the standard model of particle physics (SMoPP) therewith remains valid for all matter in the Universe; an extension of it to accommodate additional (exotic) dark matter particles is unnecessary and in fact there is no room for such particles given the astronomical evidence.

In summary: without particle dark matter theoretical galactic astrophysics becomes simple and predictive with remarkable success. Galaxies merge rarely and typically evolve as self-regulated systems and most satellite galaxies are TDGs.

If, as you say, the DM paradigm is wrong, what changes are necessary to reconcile observations with theoretical models?

The implications of Eq. (7.2) are manifold, and some of the more obvious astrophysical ones are discussed before.

If there is no cold or warm dark matter particle, then particle physics is in a very good shape. But then, effective gravitation needs to be non-Newtonian. "Effective" gravity means that either Einstein's field equation needs to be extended (e.g. Bekenstein 2004, see also Moffat 2006), or it remains valid but processes in the vacuum may change the equations of motion (Milgrom 1999).

A promising avenue for further research is, to my mind, the implications of the following scaling of Minkowski space-time: $(\mathbf{r}, t) \longrightarrow \lambda(\mathbf{r}, t)$, where $\mathbf{r}$ is a Cartesian vector and t the time and λ a number. Demanding that the gravitational acceleration scales as $a_g \longrightarrow \lambda^{-1} a_g$, just as the kinematical acceleration does, immediately leads to basically all observed laws of galactic dynamics in the weak gravitational regime. The essence here is that this last requirement yields (for spherical systems) $a_g = (a_0\, a_N)^{1/2}$, where a_N is the Newtonian gravitational acceleration and a_0 is Milgrom's constant which needs to be introduced simply on dimensionality grounds. A single galaxy rotation curve yields $a_0 \approx 3.8\,\mathrm{pc/Myr}^2$, and realms within which the acceleration $a < a_0$ are the weak-field regime. This was pointed out by (Milgrom 2009) and discussed didactically by Kroupa (2014a) and Wu and Kroupa (2015).

These latter discussions clarify how a Newtonian observer will misinterpret the motions of satellite galaxies or of matter in disk galaxies as being due to an isothermal dark matter halo. This halo is not real, it is merely a mathematical formulation when the gravitation being used is Newtonian. In Milgromian, or scale-invariant dynamics (SID), there is no particle dark matter halo. Galaxies effectively exert a stronger gravitational force on their neighbours, because $(a_0\, a_N)^{1/2} > a_N$ for $a_N < a_0$, such that the equivalence principle is broken. That is, a galaxy subject to an external force will accelerate according to its baryonic mass only, but it will pull at other galaxies with an effective larger force, as if it were heavier through a phantom dark matter halo.

The phantom halos are effectively truncated through external fields, and this leads to a new gravitational phenomenon unknown to Newtonian dynamics. The *external field effect* (EFE) makes Milgromian gravitation richer and may well explain a few hitherto unaccounted for observations (Kroupa 2014a; Wu and Kroupa 2015). A transition into the Newtonian regime when the acceleration is larger than Milgrom's constant, $a_N > a_0$, can be deduced from processes in the vacuum, as suggested by Milgrom (1999), or simply by designing a transition function μ. This is an equivalent process to how Max Planck originally introduce Planck's constant prior to understanding its role in quantum mechanics. The whole mathematical description incorporating the Newtonian regime and the SID regime, is known as Modified Newtonian Dynamics, or MOND, and has been extensively discussed and originally introduced by Milgrom (1983).

MOND is a classical effective but non-linear theory of gravitation with a generalized Poisson equation (Eq. (3) in Bekenstein and Milgrom 1984). Attempts have been made in developing general relativistic formulations [for the break-through paper see Bekenstein's (2004), see also Bekenstein (2011)]. Reviews of this entire subject are available in Famaey and McGaugh (2012) and Trippe (2014), see also the references provided in Kroupa (2014a).

Without dark matter the SMoC is ruled out as a relevant model for the Universe. This means that the redshift-distance, redshift-age relations are likely to be different, thus much of what we know about the Universe from observations may need perhaps major revision. First steps towards developing cosmological models which are consistent with SID have been undertaken by the seminal work of Llinares et al. (2008) and (e.g. Angus et al. 2013). But such simulations still need to rely on an assumed Einsteinian expansion history of the Universe which is the same as that of the SMoC, the simulations treat the baryons as non-dissipative non-star-forming particles which thus essentially behave just like the dark matter particles of the SMoC, and a hot dark matter component in the form of, for example, 11 eV sterile neutrinos, needs to be postulated (e.g. Angus 2009). This hot dark matter component may be less of a problem than the exotic cold or warm dark matter particles required in the SMoC, because it may be added to the SMoPP naturally in accounting for the masses of the active neutrinos.[12]

Thus, a very conservative cosmological model appears to be emerging (Kroupa 2014a): it is based on GR, has inflation and dark energy, and the exotic cold or warm dark matter particles of the SMoC are naturally avoided by vacuum effects yielding SID with sterile neutrinos entering as a hot dark matter component. This model has been introduced by Garry Angus, who constraints the mass of the sterile neutrino to be about 11 eV (Angus 2009; Angus and Diaferio 2011; Angus et al. 2010, 2013). As of a few months ago full-scale purely hydrodynamic simulations of structure formation in MOND have become possible with the code *Phantom of Ramses* (PoR) developed by Fabian Lüghausen in collaboration with Benoit Famaey and myself as a patch to Romain Teyssier's RAMSES (Lüghausen et al. 2015).

Given that the SMoC is ruled out, new models are being studied which naturally account for the observed gravitational and dynamical properties of galaxies without dark matter. However, given the pressure in the community against non-SMoC research, progress is very slow and even haltering. The widely-held interpretation that the population of galaxies we observed today is a result of mergers is certainly wrong; mergers play a minor role only (Sect. 7.7). *Galaxies, as they are observed, cannot be reproduced in the SMoC.* Observational cosmology is providing important new constraints, but applications of the redshift—distance and redshift—age relations from the SMoC to interpret these data is almost certainly wrong in that *the true nature of the physical systems at high redshift is likely to be distorted when interpreted within the framework of the SMoC.*

Among the alternative ideas on the DM problem, the Modified Newtonian Dynamics (MOND) has reached a considerable number of supporters. The next interview to Luca Ciotti will present his point of view on this theory.

Questions for Luca Ciotti:
up to now, several alternative theoretical explanation to the DM have been attempted. MOND is a theory that does not require exotic particles but a modification of the Newtonian law at specific conditions. Could you briefly explain MOND and address the question of the advantages and disadvantages of this approach? Are you aware of other theoretical approach to the DM problem that could be promising?

As universally known, Modified Newtonian Dynamics (nowadays there are several variants, but here I will generically refer to all of them as MOND) is a theory developed to avoid the introduction of Dark Matter in Astronomy, obtained by suitably modifying the gravity law (e.g. Bekenstein and Milgrom 1984; Milgrom 1983). In practice, in the most known formulation, the Poisson equation $\nabla^2\phi = 4\pi G\rho$ relating the gravitational potential ϕ to the given mass distribution ρ, is

[12]Note that the often invoked limits on neutrino masses using standard-cosmological arguments become invalid by discarding the SMoC.

replaced by the field equation

$$\nabla \cdot [\mu(||\nabla\phi||/a_0)\, \nabla\phi] = 4\pi G\rho, \tag{7.4}$$

where $\mu \sim 1$ for $||\nabla\phi|| >> a_0$ (the Newtonian limit) and $\mu \sim ||\nabla\phi||/a_0$ for $||\nabla\phi|| << a_0$ (the so-called "deep-MOND" regime). The characteristic acceleration scale—empirically determined—is $a_0 \simeq 1.2\, 10^{-8}$ cm s^{-2}.

My interest in MOND started when Bob Sanders (Groningen University) visited Bologna for a few days following an invitation of Renzo Sancisi. He gave a talk on the general principles behind MOND, and I recall well the first impression I get. I was struck by the fact that MOND was clearly based on a quite beautiful and deep mathematical structure, and had the enormous merit (admittedly, a rarer and rarer property in the steadily increasing number of astrophysical papers!) to be right or wrong. During the talk, I realized that the two-body relaxation time in MOND (and dynamical friction as well) should be very different than in Newtonian gravity (with or without dark matter), essentially because the field strength in the weak regime goes like r^{-1} instead of r^{-2}, so that we do not have the Coulomb logarithm and the MOND effects should be much stronger than in classical gravitation. In turns, this should imply that stellar systems in MOND should be much more collisional than in Newtonian gravity, with all the internal dynamical evolution much faster than routinely assumed, with important observational consequences. But I also soon realized that the standard approach to the computation of relaxation times could not be applied to MOND, as the theory is intrinsecally non-linear, and you cannot just "sum" the effects of gravitational interactions as in the classical Chandrasekhar approach. I studied the problem in detail, and finally—after a visit to James Binney in Oxford where we solved some non-trivial issue due to non-linearity, we wrote a paper (Ciotti and Binney 2004), showing that indeed MOND is more collisional than Newtonian gravity, with interesting (but not so dramatic as I initially expected) consequences.

After this work, I concluded that in order to have a better understanding of MOND in realistic cases, one should move away from the study of spherically symmetric systems where—for technical reasons that I cannot touch here—the computations are quite simple, but also quite special. By extending a technique developed with Bertin to produce non-spherical exact density-potential pairs in Newtonian gravity, it was possible to introduce a mapping method that allows the construction of ellipsoidal-like, analytical density-potential pairs in MOND, so that their orbital properties can be studied with standard numerical codes. In fact, one of the main aspects of MOND, its non-linearity, is reflected by the fact that the associated field equation in the deep-MOND regime reduces to the so-called "p-laplacian", a non linear partial differential operator. After this analytical work it was clear that the next step would be the development of a numerical MOND solver, and with the fundamental contribution of dr. Pasquale Londrillo (INAF—OABo), in a joint work with dr. Carlo Nipoti (Bologna University) we finally wrote NMODY, a numerical code able to run N-body simulations in MOND. This was the first MOND code extensively used in literature, and we made a free distribution of it.

With this code we studied for the first time several interesting problems in MOND, such as violent relaxation radial orbit instability, dynamical friction, with the hope to find some important discrepancy with respect to the corresponding "Equivalent Newtonian Systems".[13] Remarkably, we found instead that the differences were not so big, even though well detectable and going in the sense indicated by theoretical arguments (such as the rigorous time-independence of the virial function W in time-dependent, deep-MOND systems, and the long-lasting virial oscillations of MOND systems approaching equilibrium, e.g., see Nipoti et al. 2008). On a more theoretical side, in collaboration with Tim de Zeeuw (Leiden University) and H.S. Zhao I also studied the properties of Stäckel systems in MOND. Also in this case we find, quite surprisingly, that the so-called "Kuzmin theorem" (i.e., the fact that for a Stäckel potential the assignment of density along the short axis fixes the density everywhere) is not a peculiar property of Newtonian gravity but also holds for MOND or, more technically, also of the *p-laplacian* applied to potentials separable in ellipsoidal confocal coordinates (Ciotti et al. 2012).

The general lesson I learned from the studies mentioned above (and others on disk galaxies not discussed here) is that MOND is on one side conceptually very different from Newtonian gravity plus dark matter, *however*, when applied to systems similar to the observed ones, the MOND predictions are in general surprisingly similar (see, e.g., Sanders and McGaugh 2002). Of course, there are differences in the predictions of the two theories, but none of them appears fully inconsistent with observations or, in any case, the discrepancies can be debated (even in the most problematic cases for MOND, such as the "Bullett Cluster"). This is a most remarkable because MOND was initially introduced just to explain the flat rotation curves of spiral galaxies, so that all other predictions for different systems (ETGs, cluster of galaxies, etc.) can be considered impressive accomplishments (see Sanders book). The successes are even more surprising considering that in MOND you just have a *single* free parameter (the acceleration scale a_0), and everything is determined by the baryonic distributions.

So, what is my view of MOND? I think that MOND is mathematically deep and elegant, and it has some interesting aspect worth to be discussed against Classical Gravitation and General Relativity (plus dark matter, plus the even more mysterious "Dark Energy"), especially because it is falsifiable. On the physical side, I'm personally very conservative, and I believe that MOND is *not* the correct description of gravity on large scale objects such galaxies, which I believe is strictly Newtonian and obeys the *superposition principle*, with all the related consequences (for example, the fact that the internal dynamics of a system is independent of the acceleration in case of free fall). May be MOND is just telling us that Dark matter and baryons in real systems "talked" each other at the epoch of the formation

[13]Obviously, proper comparison of MOND with standard gravity must be done with Newtonian systems plus an amount of DM as would be predicted by the application of MOND to the purely baryonic component. These systems are what we called "Equivalent Newtonian Systems".

of cosmic structures much more than what we usually think, and this mutual relationship is qualitatively captured by the existence of a“universal” constant, a_0.

I think the most interesting future development of MOND on the theory side will be the possibility to run simulations of structure formation in the cosmological setting. Of course, this will depend on the numerical ability to treat baryonic physics, as in MOND we do not have (in principle) Dark Matter!

7.8 To Summarize

The aim of this chapter was that of showing that our idea of galaxies is still changing today, after one century since their discovery. The first beautiful image of galaxies as unperturbed Island Universes floating in a uniformly expanding space is already behind our shoulders. The time of the primitive scenario provided by the monolithic collapse of a protogalaxy regulated by relative simple physical mechanisms that originated the main galaxy components is definitively over. It is necessary to accept the idea that galaxies are the results of a complex evolution and that we have only a partial knowledge of the mechanisms that operated the transformation of galaxies across the Hubble time. Galaxies, like men, live in a complex and evolving society that sometime change forever their properties.

Galaxies are also the site of the most energetic phenomena observed in the Universe. We have discussed some of them in this chapter trying to understand their relation with the host galaxy. How much these phenomena influence the whole galaxy evolution? What are the consequences of these tremendous energy deliver for the galaxy itself and for its environment?

Like for the other chapters we try here to summarize the most important facts emerged in our interviews.

- *After the pioneering observations of Zwicky, Holmberg, Arp, Vorontsov-Velyaminov and many others, astronomers began conscious that gravitational interactions might change the morphology of galaxies and produce a number of new structures that sometimes are stable on medium-large dynamical timescale. The Toomre' simulations opened the way towards the modern large N-body simulations that are now able to explain several of the observed morphologies of interacting systems: rings, induced spirals, bridges, tails, shells, loops, etc.*
- *Tidal dwarf galaxies are an example of objects created by gravitational interactions. These galaxies might reach stable configurations and are likely not embedded in a dark halo.*
- *Environmental interactions can be as important as close encounters in affecting the evolution of galaxies. The gas stripping and the consequent starvation are only one of the mechanisms with which the environment can operate. Other effects connected to the environment are the compression of removed gas clouds igniting a star formation in the ISM, or the stressing and wave generation in the gas not removed from the disks. Galaxy harassment is also very important. It is the result*

of a series of large distant disturbances operated by other galaxies in the cluster environment. Through this mechanism galaxies could loose their outer regions and change their surface brightness profiles.

- *Simulations are still facing the problem of reproducing the induced star formation produced by gravitational interactions. This is a serious obstacle because it does not depend only on the lack of resolution of simulations on various scales, but also on the lack of knowledge of the detailed physics of the star formation process.*
- *Wide-field UV imaging revealed the existence of disks, extended up to several time the optical radius, characterized by a young stellar population and a SF efficiency $\sim$30 % lower than in normal spirals. UV rings were also discovered around some early-type galaxy. The existence of young stars in these structures indicate that recent star formation events took place, rejuvenating the galaxy so that they cross the green valley of the color-magnitude diagram in the opposite way, i.e. from the dead and red region to the blue region. The analysis of the surface brightness profiles points toward different mechanisms of cold gas fueling these structures: accretion, interactions and wet merging are again the candidate explanation of this phenomenon.*
- *The stellar galaxy mass function, i.e. the distribution of galaxy masses in a given volume, has been largely debated in these years with often controversial results. The controversy mainly concerns the dependence of this function on the environment. Many studies claim that this function depends and evolves with the environment. The striking feature is that its behavior appears anti-hierarchical, with the high-mass end already in place at high redshift and the low-mass end still growing today. Even taking into account the different star formation efficiency in high and low galaxy masses, the problem remains that the large galaxy halos hosting the high mass ellipticals were already formed at high redshift.*
- *The analysis of isolated galaxy samples revealed that no massive ellipticals reside in these regions. This is a strong indication that these galaxies could form only by successive merging events. Quite surprising it is to find S0 galaxies in these samples. Many believe that these galaxies could only originate after an event of gas stripping which stopped the star formation process. However, recent works have shown that S0 galaxies could also originate from merging events, so it is possible that the detected objects were in the past part of a small group or a binary system (see also Chap. 3).*
- *The galaxies hosting an active nucleus seem to follow the same correlation between the BH mass and the bulge mass or the central velocity dispersion. However, the correlation is far from robust particularly in the low mass regime, where BH masses are difficult to measure. So, the linear co-evolution of BH and galaxies is not established yet. We already commented this in Chap. 4. Examples exist of galaxies in which the BH mass reach only $\sim$15 % of the galaxy mass and of quasars without a galaxy. Whether these are only extreme cases or are the rule is too early to say. It is also difficult to reconcile the observed relation with the idea of multiple merging events affecting both the galaxies and the BHs.*

- *Quasars are the most luminous stable radiating sources in the Universe. Comparable luminosities can be found only in transient sources, such as SNe and GRBs. Luminous quasars are almost absent in the local Universe, their glorious days were at redshift $z \sim 2$–3, but they have been observed up to $z \sim 7$–8. This rise the question of their possible contribution to the re-ionization of the Universe. Their effects were also relevant for galaxy evolution through their feedback. We will examine this problem in Chap. 8.*
- *It is believed that most of the observed GRBs are associated with the collapse of the nucleus of a SN to form a rapidly rotating BH. The energy involved in this process is enormous and it is probably beamed in a way similar to that of superluminal sources. These objects can be seen up to the epoch of the Universe re-ionization. The progresses in this area are mainly due to the detection of the X-ray afterglow that follow the γ-ray emission. The short duration events have been also associated to the coalescence of a binary BH.*
- *Supernovae are another transient phenomenon involving an enormous energy. Their importance for galaxy evolution resides in the fact that these objects are the main producers of metals and are also the most important sources of energy for the ISM. The mass loss from massive stars also injects energy into the interstellar medium, but it is negligible compared to that of SNe. At present it is not completely clear how much energy is transferred from SN to the ISM. The heating of the ISM can create winds that can sweep the gas away from the galaxies quenching the star formation. The Type-Ia SNe have contributed to the actual picture of an accelerating Universe. They are only found in elliptical galaxies, while Type II, Ib and Ic are found only in galaxies which manifest an ongoing star formation. These are thought to originate from the core collapse of a SN, while Type Ia come from the thermonuclear explosion of a white dwarf after reaching the Chandrasekhar limit.*
- *Galaxies have not produced stars in the same way and with the same rate. Among the oddest SF histories, those of dwarf irregular galaxies are really peculiar. In these galaxies the SF events have been sporadic, irregular and of short duration, so that these objects show a large range of metallicities. Many of them might have experienced either the infall of new gas from cosmic web filaments that the ISM winds which deprived them of their gas content. Metallicity is not the only parameter which describe the SF history. Abundance ratios are also very important. When these are available we can reconstruct the complex processes that lead galaxies to the actual stellar content.*
- *The study of the galaxy dynamics has greatly contributed to the present view of stellar systems. The interpretation of phenomena like violent relaxation, the equilibrium and stability of collisionless systems, the dynamical friction, the spiral density wave theory, the dynamical evolution of weakly collisional systems, etc. are only a short list of the successes of this discipline. Last but not least galaxy dynamics has envisioned the idea of dark matter and that of a strong coupling between the stellar content of galaxies and their dynamics.*
- *The strongest argument against the baryonic nature of DM comes from Cosmic Microwave Background (CMB) observations. These measurements have set the*

amplitude of the density perturbation at the epoch of recombination at a level of 10^{-4}*. Only non-baryonic DM seems capable of producing such perturbations at the required redshift, since they started to grow during the radiation dominated era, when baryonic perturbations were damped. Neutrinos were discarded since the hot DM simulations did not produce the fine structures observed in the cosmic web, so up to now the nature of DM, although unknown, is linked to cold-warm non-baryonic candidates, such as e.g. the Weakly Interacting Massive Particles (WIMPS). Up to now however no direct detections of these particles have been obtained either from the LHC. Apart from the fluctuation in the CMB, the existence of DM is supported by the distribution of galaxies in the cosmic web, the flat rotation curves of galaxies, the velocity dispersions of galaxies in clusters and stars in dwarf galaxies, the X-ray data on hot gas in clusters and massive galaxies, the gravitational lensing of distant galaxies by clusters of galaxies. The DM appears to be distributed unevenly in galaxies of different type. In giant galaxies ordinary matter (stars and interstellar gas) forms about 10 % of the total mass, but dwarf galaxies are almost completely DM-dominated. The content of DM in galaxies and clusters of galaxies can be estimated by the half-light mass-to-light ratio as a function of the galaxy/cluster half-light mass.*

- *The DM paradigm has been challenged up to now by several observations and new theories. Among the observations that have greatly impacted the* Λ*CDM standard cosmological framework, that is still widely accepted, are those concerning the DM content of dwarf galaxies that are particularly relevant. As mentioned before, tidal dwarf galaxies are known to form as a consequence of strong gravitational interactions. These objects are expected to be not surrounded by a DM halo, whereas the "pure" dwarf galaxies, naturally born in the cosmic web, are DM dominated. At present observations seem not to find any significant difference in the dynamics of these two categories of dwarf galaxies. In support to the failure of the standard model come many other tests that are actually largely debated. One of these is the observed disk-like and polar arrangement of dwarf satellites around the MW and M31, which can be difficulty considered a product of DM substructures in the cosmic web. Yet, the dwarf satellites within and outside these structures have indistinguishable physical properties. In conclusion we should remark that there are many possible failures of the standard model, but up to now none of these tests seem to have seriously affected the validity of the current framework. The only thing we want to add as Editors about this problem is that the scientific method should always be respected, avoiding stiff and schematics ideas preclusive or any other point of view.*
- *From the theoretical side MOND is the alternative to the DM paradigm that has gained more supporters. In the MOND framework stellar systems are more collisional. This is attributed to a failure of the Newtonian gravity in weak field regimes. The theory has a beautiful mathematical formulation and makes several predictions that up to now have been confirmed by observations. It will be interested to see the application of MOND to numerical simulations. Anyway even on the theoretical side nothing has really damaged the standard model of cosmology up to now.*

The next chapter will face more directly the problems connected to the physics of galaxy formation and evolution.

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Chapter 8
The Physics of Galaxy Formation and Evolution

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Until recently the great majority of naturalists believed that species were immutable productions, and had been separately created. This view has been ably maintained by many authors. Some few naturalists, on the other hand, have believed that species undergo modification, and that the existing forms of life are the descendants by true generation of preexisting forms.
C. Darwin *On the origin of species.* Preface (1859)

8.1 Chapter Overview

The theoretical studies about galaxy formation and evolution are the subject of this Chapter. They started with the recognition that the Hubble sequence is not a simple morphological description of galaxies, but a possible scheme separating and characterizing the physical processes that bring galaxies to their present form. When the Hubble tuning fork reached its actual shape—around 1936 with the discovery of the S0 galaxies—, the Hertzsprung-Russell diagram that revealed the existence of the main sequence of stellar structures was already in place, but its explanation in terms of nuclear reactions was still to come (the p-p chain of Bethe appeared in 1939). Just before the end of the WWII the time was mature for the concept of stellar populations formulated by Baade, but only $\sim$ 20 years later appeared the first monolithic collapse model of galaxies formation by Eggen et al. (1962). In 1964 Arno Penzias and Robert Woodrow Wilson measured the CMB radiation opening the way toward the current cosmological model. With the 1970s the idea that merging events have produced many of the actual galaxy structures appeared in the literature with the Toomre' works. Leonard Searle and Robert Zinn proposed that galaxies form by the coalescence of smaller progenitors. At the same time the discovery of the existence of dark matter (DM) rapidly changed our idea of galaxies and how structures form in the Universe. White & Rees and Fall & Efstathiou developed the actual view of galaxy formation, in which baryons fall into the potential wells of hierarchically growing dark matter structures. The two decades 1980s–1990s have seen the development of Semi-Analytic Models (SAM) of galaxy

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formation and evolution and of numerical hydrodynamical simulations of increasing resolution and complexity. With the new century, the Universe was discovered to accelerate its expansion and thanks to the big redshift galaxy surveys the idea of the cosmic web started to be accepted. Today the dominating paradigm is that provided by the ΛCDM cosmology, a framework in which the Universe is believed to be composed of $\sim 70\,\%$ of dark energy (DE), $\sim 26\,\%$ of cold and hot DM, and $\sim 4\,\%$ of baryons. Within this model the values of the cosmological parameters, such as the Hubble expansion rate H_0, are known with great accuracy. This is the precision cosmology era*, a very awkward situation in which the cosmological parameters are known very well, but we do not know what the Universe is composed of.*

The following interviews go over some theoretical investigations that, along this century of extra-galactic research, tried to shed some light on the galaxy formation and evolution. Section 8.2 deals with the first attempts to simulate the Hubble tuning fork from basic physical principles. Then, in Sect. 8.3 we better define the differences between the monolithic scenario of galaxy formation and the hierarchical scheme, introducing some hybrid versions of the two frameworks. In Sects. 8.4 and 8.5 we provide a much clear view of the star formation history, i.e. of the convolution of the Initial Mass Function (IMF) and the Star Formation Rate (SFR). The role of feedback is analyzed in Sect. 8.6, that of chemical enrichment in Sect. 8.7, and that of Magnetic Fields in Sect. 8.8. We finally propose a panoramic view of the comparisons between observations and models in Sect. 8.9.

8.2 The Theoretical Foundation of the Hubble Diagram

Questions for George Lake:
you have examined several times the theoretical foundation of the Hubble diagram for the morphological classification of galaxies. Would you be so kind to summarize here for us the main conclusions coming from these studies?

The origin of the Hubble sequence has been a favorite problem of mine!

The broad brush is that galaxies come in two basic flavors, ellipticals and spirals. The elliptical galaxies are dense and slowly rotating while the spiral galaxies are more diffuse and rapidly rotating. There are numerous schemes for classifying galaxies with well-justified additional complexities. However, this simple "theorist's cartoon" already highlights the big problem: Why do the compact ones rotate slowly while the bigger ones rotate rapidly. It takes just a few minutes of playing on a piano stool to see why this is a problem. Start rotating with your arms out. When you pull them in, you spin fast. How did elliptical galaxies become so compact without spinning rapidly?

Edwin P. Hubble's tuning-fork classification of galaxies was brilliant and insightful. He saw that there were relatively featureless galaxies that always had the same radial brightness profiles and elliptical isophotes (contours of constant surface brightness). They were distinguished only by the eccentricity of their isophotes which never got flatter than about 2:1. Spirals, with their disks and arms, show more diversity. The arms could be tightly wound or relatively open. They often had central bulges of varying prominence. The prominence of the bulge and the winding of the spirals tends to go hand in hand. The larger the bulge-to disk ratio (B/D), the more tightly wrapped are the spiral arms There is a parallel sequence of barred spiral galaxies, ones where the spiral arms seem to connect to a strong linear feature, the bar, in the center of the disk.

I would like to point out an interesting bit of history regarding the Hubble sequence. In his Annual Review article, Sandage (2005) tells us that 'the classification be made on the basis of morphology alone, not on the basis of supposed physics that some wish to be introduced to "explain" the classification' (see also discussions in Chap. 3). The Hubble sequence is definitely a place where that has not been true! Galaxies that didn't have disks were classified as E0 through E7 by Jeans (1919). The number is $10 * (1 - b/a)$ where b/a is the ratio of the minor to major axis, so an E0 is round and E5 is flattened 2-to-1, an E7 is flattened roughly 3-to-1. Jeans was the first to propose a scheme that is close to that associated with Hubble (1926, 1936). For decades, morphologists found galaxies to classify as E7. None of them really fit the part, clearly showing disks (NGC 3115 was the prototype) and modern morphologists now find ellipticals only as flat as E5.5. So, why E7? Jeans explain the transition for E7 to Spiral by noting that if you spin fluid objects, they undergo bifurcation when spun fast enough to be as flat as E7. At that point, they create bars and evolve in other ways. So, the galaxies found between E5.5 and E7 for decades owe their classification to a theoretical argument by Jeans. Just looking has lead to something different.

Around 1970, there were some first stabs at simulating galaxies. Ostriker and Peebles (1973) had their famous 300 particle simulations that argued disks would be unstable if there weren't some mass than was flattened. It was another paper with Yahil that made the clearer argument that this mass should be an extended very massive 'dark halo'. Richard Larson (1969, 1974) also did some simulations of galaxy formation. But, the sense was that the problem was both ill determined and ill conditioned. So, these were groundbreaking, but not compelling in their conclusions.

Back in 1984, I was at AT&T Bell Labs. Industry is very different than a University. At that time, researchers at American Universities had extremely limited access to supercomputers. The less powerful University mainframes weren't justified unless they were saturated with jobs. It was a terrible time to do large scale computing at Universities.

At Bell Labs, there was a big shiny Cray that was justified by being nearly empty. That way, when someone wanted to design a new communications processor, there were sufficient resources to get the job done in a short time. They would load the machine up for a job that took days—and they didn't have to wait a month for it to finish. The AT&T device designers were doing the job in a fraction of the time of their competitors. [The chips for the work horse switches that would take care of hundreds of homes were designed and fabricated in less than a year. Management claimed that without the ever-at-the-ready Cray it would have taken 5 years.] It made good business sense to keep a nearly empty Cray around. Basic researchers at the lab could buy “stand-by” time for just 100/h when the going market rate for an hour was 6,000! With the Cray being 200–600 times faster than the University VAXes, it was a great opportunity. That factor of 200–600 was the difference between walking and taking the Concorde. In absolute terms, those Crays were 35 Megaflops. Today, I use the Swiss National Supercomputer Center. Their fastest computers is 200 Million times faster. It computes in a second what the Cray took 10 years to do and the VAXes of that era needed several millennia. That Swiss computer is only the 6th fastest in the world, there are others nearly 10× faster.

For astrophysicists, the Cray was hot stuff. But, even 100/h busted the basic science computing budget quickly. I burned up the Physical Science Research Lab allocation in a couple of weeks. A friendship with a numerical analyst (Wes Petersen, we still work together today’ now on archeological problems!) led to the cutting a deal with Nils-Peter Nelson who ran the Cray. If I stayed out of everyone’s way, I could have all the time I could eat. He called it his NSF grant-Nelson Slush Fund.

The lab got a new Cray, this one has TWO fast processors (modern supercomputers have $>$ 3 million). Ray Carlberg and I jumped in and set a record for Cray time use outside of national defense. We also made some key discoveries of how to make spirals versus ellipticals.

Before our simulations, every one did galaxy formation by ‘dropping’ particles from rest. We touted our ‘cosmological conditions’ where we let the particles expand by a factor of 2 before collapsing. But, that little change had a real impact.

We ran a lot of simulations and found an odd thing. The main control parameter was how ‘hot’ our initial conditions were. If they were cold, lumps would grow during expansion and the collapses were lumpy and chaotic. That made things that looked like ellipticals. If they were hot and small scale fluctuations didn’t grow, the smooth collapses made disks. The fit to some of the gross phenomenology was amazing. We started with the same amount of specific angular momentum in both cases, but if we looked at the product of the half light radius times rotation velocity, it was 8× different in the final states of the gas that turned into stars. We found there were 3 factors of two that multiplied to make that factor of 8. The first was trivial, the different states need pre-factors that are 2× different to turn these simple numbers into specific angular momentum (while the stellar distribution of ellipticals is more compact that spirals, they also have more matter at several times their half-light radii). The next factor of 2 was that in the lumpy collapses, angular momentum was transferred from the inner parts to the outer parts. This transferred angular momentum from luminous material to the more extended dark matter. Finally, star formation was less efficient in the ellipticals and only the inner gas formed stars while the outer gas was a more effective reservoir for angular momentum. This outer reservoir of gas also fit the gross phenomenology. Ellipticals were known to have extended distributions of hot gas that didn’t form stars. Although, at the time, the community was not aware that star formation was so much less efficient in ellipticals.

We finally had a physical control parameter for the Hubble sequence: the presence or absence of substructure during collapse. We executed this mechanism by changing the random motions of particles. The substructure could grow when the initial conditions were "cold". It was suppressed by the random motions when the protogalaxies were "warm". This result was published in two papers in the October 1988 issue of The Astronomical Journal (Lake and Carlberg 1988a,b).

We still needed a cosmological context for what we thought of as 'hot' vs. 'cold' or 'quiet' vs. lumpy. Back in the 1980s, it also became clear that while spirals and ellipticals overlap in luminosity, ellipticals are generally more massive then spirals and they appear preferentially in clusters.

There is the problem of 'missing satellites'. This problem wasn't presented in a sharp way until the 1990s (Klypin et al. 1999; Moore et al. 1998), but it was clear much earlier that a scale-free power spectrum predicted a mass spectrum such that at low mass there should be roughly 10× more galaxies every time you looked at 1/10 of the mass. But, we knew that there weren't nearly that many dwarf galaxies. This is the mass function that emerges form the theory of Press-Schechter (Press and Schechter 1974). Something clearly suppressed dwarf galaxies that were less massive than the Magellanic Clouds. If you suppress fluctuations below a given mass scale, then things that are 10× that mass will collapse in a smooth way and things 100× that mass will be very lumpy and chaotic. Since the dwarfs were missing, suppressing lumps of a given scale seemed like the way to go.

That's not a popular idea now. The typical phrases one here describing galaxy formation are downsizing which describes the tendency for massive galaxies to be older than less massive ones, as well as seeing massive galaxies form at modest redshifts at an accelerated rate compared to less massive galaxies.

We imagined that happening because the dark matter (DM) was still, now the dominant notion is that the baryonic component is showing a stiffness owing to energy input from supernovae and active galaxies. I'm a bit contrarian in stressing "stiffness" rather than "feedback". I think the earliest objects preheat large volumes to create stiffness rather than feedback being a local process that can eject gas from galaxies after they've collapsed. I argue that preheating takes 30× less energy and you just don't have the energy budget to eject things (I have colleagues who think that gas goes into galaxies and is ejected multiple times; you just don't have the energy to do that).

So, the shift has been away from my early ideas that focused on the ability to make lumps in dark matter and instead quiet the formation of small things using the stiffness of energy generation.

There's one comic aspect to our simulations. They were redone multiple times because people thought they were so poor. It was a terrible presentation on my part. When we did our simulations, we saw things that were clearly disks and even had nice spiral arms and we had dense slowly rotation things. We also had some that were hard to call. Instead of putting pictures of nice spirals into the 1988 papers, I instead put in the ones that were hard to call and was clear about how we called them. Since nobody reads papers but only figure captions, it was assumed those were the best disks we'd made. Incredibly stupid on my part and grossly lowered the impact of those papers.

The basic features of the Hubble sequence, i.e. the decreasing contribution of the bulge component with respect to the disk going from early-type to late-type galaxies, and the evidence that the bulge contains old and metal poor stars while the disk younger and metal rich stars were modeled by Eggen, Lynden-Bell & Sandage (1962) at the beginning of the sixty. Their model represents the first idea of the monolithic collapse of a galaxy. They noted that the eccentricity of the orbits of dwarf stars is correlated with the UV excess; the stars with the largest excess (i.e. the lower metal content) move in highly elliptical orbits, while those with almost no excess have generally round orbits. This result was discussed in terms of the dynamics of the collapsing proto-galaxy. The oldest stars were formed in from gas falling toward the center of the galaxy and the collapse was very rapid ($\sim 10^8$ *yrs). The disk stars formed later when the gas was already settled in a disk structure. This model was the first picture of the galaxy formation process that interpreted coherently the various properties observed in nearby galaxies. Since then, more detailed observations of galaxy stellar populations and dynamics, the discovery of DM, and the evidence of the cosmic web structure, progressively bring researchers to prefer the hierarchical model. The next interview try to summarize the advantages and disadvantages of both ideas.*

8.3 From Monolithic to Hierarchical Models and Beyond

Questions for Cesare Chiosi:
the modern prevailing picture of galaxy formation was formulated almost 30 years ago by White and Rees (1978) and Fall and Efstathiou (1980). Gas falls into the potential wells of hierarchically growing dark matter structures and is additionally governed by dissipational processes. Could you discuss the pro and cons of this theoretical picture? Which observations are in contrast with the dominating paradigm of the hierarchical merging scenario? Why has the monolithic collapse scenario been abandoned for this new paradigm? If galaxies formed by successive merging events is it possible to reproduce theoretically their stellar population content?

In a Universe containing three main components in cosmic proportions: Dark Energy (DE, 70 %), Dark Matter (DM, 25 %), and Baryonic Matter + Neutrinos (BM, 5 %), the formation and evolution of galaxies are among the hottest topics of modern astrophysics. Current understanding of the nature of DM indicates the weak interacting massive particles (shortly named WIMPs) as the best candidates. They should have come into existence in the early Universe with a mass in the energy range GeV-TeV. The Universe is thus pervaded by slowly moving, non relativistic WIMPs, which manifest themselves only via gravitational interaction. The ratio of the total DM mass to that of BM is expected to be about 6:1 according to the present-day cosmological paradigm of the Universe. Based on this view, simulations of the cosmological growing of primordial perturbations into bigger and bigger objects under the action of gravitational interaction became the classical scenario in which the formation of galaxies was framed (White 1978). This view culminated in the recent spectacular Millennium Simulation (Springel 2005; Springel et al. 2005). Very soon White, Rees, Fall and Efstathiou (Fall and Efstathiou 1980; White and Rees 1978) called attention on the role of BM: gas falls into the potential wells of hierarchically growing DM structures and is additionally governed by dissipational processes. The formation of true galaxies made of BM and DM is started. This view was shortly termed the ***Hierarchical Scenario*** of large scale structures and galaxies in turn. Initially, DE was not taken into consideration (Standard CDM), whereas nowadays DE and associated cosmological constant (Λ) are the leading terms of the mass-energy pattern (the so-called ΛCDM Universe). Reducing the complexity of the hierarchical scenario to a sentence: small and low mass objects come first, whereas large and massive objects come later in a hierarchy of structures of increasing size, mass and complexity as time goes by. Owing to the large DM to BM mass ratio, DM was considered to lead the game. Therefore, cosmological simulations of large scale (typically 500 Mpc on a side) have been calculated in which, owing to the huge number of DM haloes (proto-galaxies candidates) coming into existence, there was no room to include also BM and to follow the formation of real galaxies with the desired accuracy. Therefore, the large scale cosmological simulations usually left BM aside. However, since they provided the mass assembly history (MAH) of haloes (see e.g. the large scale Millennium Simulations by Springel (2005); Springel et al. (2005) in the ΛCDM cosmology), they have been largely used as the back bone of all scenarios of galaxy formation. Given the MAH of haloes, either retrieved from cosmological simulations or built up with Monte-Carlo probabilistic techniques (Lacey and Cole 1993), the BM is added to haloes. Suitable prescriptions are then assumed for gas cooling and heating, star formation (often with chemical enrichment), energy feedback by SNa explosions and AGN (the central black hole), morphological transformation of disks into elliptical structures as a consequence of mergers, and population synthesis techniques to simulate luminosities, magnitudes and colors of the stellar content, *etc.* In other words, the structure and history of a galaxy are determined.

Current models of galaxy formation and evolution can be grouped in semi-analytical (SAMs) and hydrodynamical (HDMs). The latter in turn split in two categories according to the numerical technique in use: the cell-based in the modern version with adaptive meshes to follow a large range of scales (see Springel 2010a, and references therein) and the particle-based in the modern version of smoothed particle hydrodynamics (see Springel 2010a,b, 2014, and references therein). Over the past two decades, SAMs have been world widely adopted. Modern SAMs are very sophisticated codes (e.g., Benson 2012), relatively easy to use, and often publicly-available together with their outputs. Using the SAMs, the importance of various physical processes can be easily tested and gauged. The weakness of SAMs is that the physics is somewhat controlled by hand and largely parameterized. The success of SAMs and the hierarchical scenario in turn generated an impressive number of studies that dominated the scene for about three decades. To mention a few we recall here (Almeida et al. 2007; De Lucia et al. 2006; De Lucia and Blaizot 2007; De Lucia et al. 2011; González et al. 2009; Parry et al. 2009).

However, in recent times, thanks to the wealthy of data at higher and higher redshift some failures of the hierarchical scheme became evident. A recent, critical review of the observational data and the success and drawbacks of the SAM modeling is by Silk and Mamon (2012) to whom the reader should refer. The problem is further exacerbated by the nature of DM and the partial failure of the cold DM scenario itself, see Domcke and Urbano (2015). In brief, the cold DM scenario agrees with the observations only on cosmological scales (Ade et al. 2014), e.g. individual haloes, groups and clusters of DM haloes, filamentary structures, whereas surprisingly fail to match the observations at small scales ($\sim$ Kpc, the scale of galaxies). According to Romano-Díaz et al. (2009) part of the problems with pure DM simulations could be solved by introducing BM. Of the body of observational data that could not be easily explained by the standard hierarchical view of galaxy formation (in the simple SAM context) we recall the rapid decrease in the cosmic start formation rate (SFR), the number of dwarf galaxies, the observed downsizing that simply opposes to the hierarchical view (Bundy et al. 2005, 2006, 2007), the issue of gas accretion *versus* mergers in driving star formation, and the recent evidence of a systematic steepening of the initial mass function in massive early type galaxies (see Bundy et al. 2006; Silk and Mamon 2012). The frontier for high redshift objects has been continuously and quickly extended from $z \sim$4–5 (Madau et al. 1996; Steidel et al. 1999), and $z \sim 6$ (Dickinson et al. 2004; Stanway et al. 2003) to $z \sim 10$ (Bouwens et al. 2014; Oesch et al. 2012; Zheng et al. 2012). According to the current view, first galaxies formed at $z \sim$ 10–20 (Rowan-Robinson 2012) or even $z \sim$ 20–50 when DM haloes containing BM in cosmological proportions gave origin to the first sufficiently deep gravitational potential wells (Gao et al. 2007a,b; Tegmark et al. 1997). In addition to this, there is observational evidence for large and red galaxies already in place at very high redshift (see Marchesini et al. 2010; Mortlock et al. 2011). Finally, the high redshift Universe is obscured by copious amounts of dust (see Carilli et al. 2001; Michałowski et al. 2008, 2010a,b; Robson et al. 2004; Shapley et al. 2001; Wang et al. 2008a,b), whose origin and composition are a matter of debate (Draine 2009; Dwek et al. 2009; Dwek and Cherchneff 2011; Gall et al. 2011a,b,c) but surely are of stellar origin thus implying star formation activity at very early (high redshift) epochs. Recent reviews of all these issues are by Renzini (2006); Bromm and Yoshida (2011); Silk and Mamon (2012); Courteau et al. (2014); Graham (2013); Graham (2014); Chiosi et al. (2014). Over the years, the hierarchical scheme has been amended giving rise to two complementary alternatives known as *Dry Mergers* (fusion of gas-free galaxies to avoid star formation) and the *Wet Mergers* (the same but with some stellar activity).

In parallel, another scenario for galaxy formation and evolution has been developed. It stems from the properties of stellar populations in real galaxies, the early type ones in particular, and the pioneering studies by Eggen et al. (1962); Tinsley (1975); Audouze and Tinsley (1976). Exhaustive reviews of the many observational hints for an alternative to the hierarchical scheme are by Chiosi et al. (2014);

Matteucci (2014). It is named ***Monolithic Scenario***: massive early type galaxies (ETGs) form at high redshift by rapid collapse and undergo a single, prominent star formation episode, ever since followed by quiescence. Over the years this view has been changed to the ***Revised Monolithic*** scheme: a great deal of the stars in massive ETGs are formed very early-on at high red-shifts and the remaining ones at lower red-shifts, and finally it incorporated the hierarchical scheme itself, generating an hybrid mode of galaxy formation and evolution named ***Early Hierarchical, Quasi Monolithic*** (Merlin et al. 2012).

Combining the N-Body Tree formalism used to treat the gravitational interaction (Barnes and Hut 1986) with the Smooth Hydrodynamics technique to simulate a real fluid by a discrete number of particles (Springel 2010b), model galaxies in the early hierarchical, quasi monolithic scenario have been presented by several authors, see (Chiosi and Carraro 2002; Kawata 1999, 2001a,b; Kawata and Gibson 2003; Merlin and Chiosi 2006, 2007; Merlin 2009; Merlin et al. 2010, 2012), and references therein). The merit of these models is the effort to describe the formation and evolution of individual galaxies made of DM and BM according to a given cosmological view of the Universe (e.g., S-CDM or ΛCDM) from the time of their appearance as perturbation seeds at a certain red-shift to the present. The models follow (i) the growth of the initial seed by early aggregation of other seeds toward more and more distinct structures (maybe via the aggregation of many sub-lumps of matter); (ii) the cooling and collapse of baryons, and the conversion of gas into stars at a certain rate and specific efficiency; (iii) the chemical enrichment of the gas by self pollution via mass loss by stellar winds and SNa explosions; (iv) the decline of star formation both by gas heating due to energy feedback and gas consumption; (v) the interplay between gas cooling and heating and the establishment of a duty cycle among the various competing physical agents; (v) the presence of AGN phenomena (not always included because of the uncertainties and difficulties of this issue); and finally (vi) the gas ejections in form of galactic winds. The goals of all those studies are the evolutionary history of a galaxy from its initial conditions to the present situation and the comparison of the structural and physical properties of the model galaxies with their observational counterparts. To better illustrate the above issues, let us summarize the results recently achieved by Merlin and collaborators on the formation and evolution of ETGs in ΛCDM cosmology:

(1) In brief, Merlin et al. (2012) adopt the ΛCDM concordance cosmology, with values inferred from the WMAP-5 data (Hinshaw et al. 2009): flat geometry, $H_0 = 70.1$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.721$, $\Omega_b = 0.046$ (giving a baryon ratio of $\simeq 0.1656$), $\sigma_8 = 0.817$, and $n = 0.96$. The growth of primordial perturbations is followed by means of COSMICS (Bertschinger 1995) but limited to a suitably chosen portion of a standard cosmological grid ($\simeq 500$ Mpc on a side). The sub-portion is supposed to contain perturbations with assigned over-density, mass, and dimensions chosen a priori. This means that the size of the sub-portion is fixed in such a way that the wavelength of the perturbation corresponding to the chosen over-density and mass is similar to (but suitably smaller than) the size of the sub-portion itself (about 10 Mpc on a side). Casting the problem

in a different way, instead of searching the perturbation most suited to our purposes within a large scale realistic cosmological box, we suppose that a perturbation with the desired properties is already there, and derive the positions and velocities of all its DM and BM particles from a self-consistent, small-size cosmological box tailored to the perturbation we have chosen. It is known from long time that the simulation size determines the maximum perturbation wavelength. If the long wavelengths are dropped out, the strength of subsequent clustering is reduced, but at the same time the number density of intermediate mass haloes (with total mass of the order of $10^{12}-10^{13}\,M_{\odot}$) is enhanced (Power and Knebe 2006). Since we are interested in objects with the size of galaxies and not of galaxy clusters, this is less of a problem. Furthermore, according to (Power and Knebe 2006) the truncation of the initial power spectrum (*i.e.*, the small size) of the simulation has little impact on the internal properties of the haloes. Late refuelling of gas (and stars and DM) or equivalently late mergers are inhibited. This is less of a problem because (Merlin et al. 2012) intended to explore the modalities of galaxy formation and evolution in alternative to the hierarchical scheme. To conclude, the above initial conditions are not in conflict with the cosmological paradigm and the halo masses that are adopted as a function of the redshift are compatible with the creation and growth of cosmological DM perturbations (Lukić et al. 2007). For all other details see Merlin et al. (2012).

(2) *Histories of Star Formation*. Using simple initial conditions, Chiosi and Carraro (2002) demonstrated that at given initial over-density the SFH changes from a single dominant initial monolithic episode to a bursting-like series of events at decreasing total mass, whereas at given total mass the SFH changes from a dominant initial episode to bursting mode at decreasing initial over-density. This basic dependence of the SFH on the total galaxy mass and initial over-density (environment) has been amply confirmed over the years by many observational and theoretical studies and it is also recovered by the (Merlin et al. 2012) models with cosmological initial conditions. *Downsizing and delayed star formation are naturally reproduced*. Furthermore, since the star formation rate is taken proportional to the ratio gas mass to the free-fall time scale t_{ff}, the specific star formation rate is simply the inverse of t_{ff}. All this strongly suggests that the gravitational potential well of BM + DM drives the whole process and dictates the efficiency and duration of the star formation process. A galaxy, thanks to its gravitational potential, knows in advance the kind of stellar populations (very old or spanning a large age range) it is going to build up.

(3) *Assembling the Stellar Mass*. The building up of the stellar mass of a massive galaxy as a function of the redshift is nearly completed much earlier than in the low mass ones and in any case earlier than redshift $z = 2$. Furthermore, the net efficiency of the star forming process and the duty-cycle given by gas cooling-star formation—gas enrichment—gas heating—gas cooling is such that on the average 20 % of the initial BM is converted into stars, the rest is either expelled in form of galactic winds or heated up and parked away for future use.

(4) *Stellar Ages and Metallicities*. In early epochs, the stars are preferentially created in the central regions, then the star forming activity expands to larger radii (inside-out mechanism), and moving towards the present time, the stellar activity tends to shrink again towards the center. This simply mirrors the SFH and the mechanism of mass assembly above. There is a satisfactory agreement between theory and observational data concerning the mean metallicity and the metallicity gradient. Finally, the mean metallicity increases with the stellar mass of a galaxy and beyond some value tends to flattens out (Tremonti et al. 2004).

(5) *Mass Density Profiles*. The geometrical structure of the model galaxies is best traced by the surface mass density profiles and comparison of these with the (Sersic 1968) profile,

$$\sigma_S(r) = \sigma_0 \times e^{(0.324-2m)\left[\left(\frac{r}{R_e}\right)^{1/m}-1\right]}$$

where R_e is the effective radius of the galaxy (as defined by Hernquist 1990), σ_0 the surface density at R_e, and m the *Sersic index* ($m = 4$ corresponds to the de Vaucouleurs profile). All profiles are computed starting at 0.2 % of the virial radius of the galaxies to avoid the very central regions where softening may introduce spurious numerical effects. The best-fitting Sersic index is $m \sim 4$, $m \sim 1.5$, and $m \sim 2.5$, for high-, intermediate-, and low-mass models, respectively. In other words, high-mass models tend to have higher m, in qualitative agreement with the existence of a luminosity-Sersic index relation for ETGs (Caon et al. 1993). However, one should notice that the most massive ellipticals in the local Universe tend to have $m \sim 8$ (e.g., Ferrarese et al. 2006), while Merlin et al. (2012) find $m \sim 4$. Moreover, the intermediate-mass models have somewhat lower m than the low-mass ones. Even considering the large scatter, this is not fully consistent with the luminosity-m relation.

(6) *Core or Cuspy Luminosity (Mass) Profiles?* The overall agreement between the models and the Sersic curves is good in the external regions. However, a clear departure from the expected fits is evident in all models at small radii (some fraction of R_e). In the central regions, the model galaxies tend to *flatten out* their mass density profile. Given the adaptiveness of the force softening, this feature can hardly be ascribed to numerical artifacts. Most likely, the high value of the efficiency of star formation adopted by Merlin et al. (2012) is the cause of it. Amazingly enough, similar galaxy models by Chiosi and Carraro (2002) with the same assumptions for the star formation rate but different initial conditions (much simpler than the present ones) yielded the opposite, *i.e.*, star dominated DM in the most central regions of the model galaxies. To single out the cause of disagreement is a cumbersome affair that cannot be discussed here (see Chiosi et al. (2014) for more details on the issue).

(7) *Surface photometry and Kormendy's scale relationship*. Finally, the early hierarchical quasi monolithic scenario folded with the classical spectro-photometric synthesis technique predicts SEDs, magnitudes and colors in many photometric systems both in the rest-frame and as a function of the redshift. In particular, one

may derive the structural parameters of galaxies, such as the effective radius R_e, the luminosity within R_e, the shape indices through Fourier and Sérsic analysis, the color profiles, and the radial profiles of most of the parameters that define the structure of galaxies. The luminosity profiles of the model galaxies at $z = 0$ can be reasonably fitted with a Sérsic $R^{1/n}$ law. They can be compared with the photometric data for large samples of galaxies together with the fundamental scale relations such as the Kormendy relations and the Fundamental Plane. Theory and data are in remarkable agreement (see Tantalo et al. 2010).

(8) *Mass-Radius Relationship (MRR)*. The MRR of ETGs (Chiosi et al. 2012) stems from the action of several concurring factors: (a) the Cosmic Galaxy Shepherd (CGS) visualizing the cut-off mass of the halo mass distribution at each redshift (Lukić et al. 2007). It is set by the cosmic growing of gravitationally bounded density perturbations and associated $N(M_{DM}, z)$. The slope of the CGS goes from 0.5 to 1 as the mass increases. It is reminiscent of the slope of the MRR for dissipation-less collapse; (b) The manifold of lines of equal initial density but different redshift along which pro-haloes of any mass crowd (slope of this mass-radius relation is 1/3 by construction); (c) given the initial density, collapse redshift, and star formation efficiency, the proto-haloes of different mass filiate baryonic galaxies with certain values of M_s and $R_{1/2}$ at the present time. The baryonic components of galaxies crowd along mass-radius relations whose slope changes from 0.3 to 0.2 or less as the galaxy mass (either total or stellar) decreases. The MRR of ETGs is the locus on which the manifold of MRRs of individual BM galaxies of any mass would intersect the CGS. The galaxies at the intersection are close to the cut-mass and evolve in condition closely following the dissipation-less collapse. They trace the MRR of ETGs we observe today.

The main lesson we learn from these models of formation and evolution of galaxies is that starting from cosmological initial conditions for the perturbations one sees the aggregation of lumps of DM and BM in the common potential well and the growth of all this to the size of a real galaxy on a short time scale while star formation occurs and the stellar content of a galaxy is built up. By redshift $z = 2$ a great deal of the action is completed, even massive objects can be in place. Hierarchical aggregation has taken place within a rather short time scale, about 1–2 tenths of the Hubble time. If let evolve on its own, the resulting object will show at the present time a pattern of properties very similar to those of real galaxies. This is the main reason for naming the whole process "*early hierarchical, quasi monolithic galaxy formation*". What happens to this object if in the course of its life it undergoes later mergers with similar objects? "*The outcome depends on the relative mass of the merging galaxies and the mode of star formation*". Major mergers will greatly affect the dynamics, morphology, stellar content, and the integral SED of the resulting galaxy. Minor mergers scarcely affect the properties of receiving galaxy. The details on the outcome are not of interest here, however the signatures of the merger can be traced back in the stellar content and cannot be easily wiped out, see the discussion by Chiosi and Carraro (2002), Tantalo and Chiosi (2004) on the age and size of mergers that are compatible with the maximum dispersion of broad band colors of ETGs. Since there is observational evidence of major and minor mergers , their occurrence cannot be excluded. What we may say is that mergers are not the only way to assembly massive galaxies, ETGs in particular. Most likely, both concur to the overall formation and evolution process of galaxies.

There is another important consideration to make, *i.e.*, the difference between the above approach and what is commonly made in classical SAMs. Quoting (Silk and Mamon 2012) "in SAMs, galaxies are painted on haloes built from halo merger trees or detected in cosmological dissipation-less (DM only) simulations". In other words, BM is added later to haloes, the mass assembly of which has been derived without BM. "Painting BM" is not the same as taking both DM and BM together from the very beginning. Indeed the dissipative collapse of BM and occurrence of star formation in the potential well of DM will certainly affect the dynamical behavior and hence mass assembly history of the latter. Maybe this is the simple explanation for the occurrence in Nature of early hierarchical quasi monolithic galaxy formation.

Given the achievements of the new scenario for galaxy formation, it is no longer necessary to consider mergers between proto-galaxies (or disks) as the main way in which massive ETGs are formed. Likely, Nature follows the hierarchical mode when aggregating matter on the scale of groups and clusters, and the early hierarchical quasi monolithic mode when aggregating matter on the scale of individual galaxies. On the other hand galaxy mergers cannot be completely ruled out, simply because we have direct observational evidence of their occurrence. They are beautiful, spectacular events, but not the dominant mechanism by which galaxies (the ETGs, in particular) are assembled and their main features imprinted.

The picture emerging from this analysis is that *nature* seems to play the dominant role in building up the ETGs we see today, whereas *nurture* by recurrent captures of small objects is a secondary actor of the fascinating and intriguing story of galaxy formation and evolution. In the forest of the galaxy formation theories, *ex pluribus unum.*

In this context it is important to better understand the role of SAMs and their actual limits. The next interview will clarify this aspect more precisely.

Questions for Gabriella De Lucia:
Semi-analytic models have been largely used to understand the mechanisms of galaxy formation and evolution. What is their potential and what are their limits?

The hierarchical clustering is the current paradigm of the ΛCDM cosmology. Could you discuss and explain this idea and its history? Which observational evidence support this scenario? Which are the models and simulations that have better implemented this idea? What these models and simulations are not able to explain yet?

In the last decades, a number of different observational experiments have converged to establish the ΛCDM cosmology as the *de facto* standard cosmological paradigm for structure formation. In this scenario, the mass-energy budget of the Universe is dominated by two unknown forms of matter (the ‘dark matter’) and energy (the ‘dark energy’), while only a few per cent is composed of the (baryonic) visible matter we know.

The first observational evidence of a *missing mass* problem (that is what we now call dark matter) dates back to the 1930s, when Zwicky (1937) estimated that the speeds of galaxies in the Coma cluster are too large to keep the system gravitationally bound, unless the dynamical mass is at least 100 times larger than the mass contained in galaxies. The reality of the problem, however, gained a hold upon the astronomical community only in the mid-1970s, when different studies showed that the rotation curves of spiral galaxies are either flat or rising at the optical edge of the galaxies (Rubin and Ford 1970), contrary to the Keplerian fall off that is expected if the visible stars and gas were the only mass in the system. In the 1980s, much work focused on the nature of the unseen dark matter component. Initially, many studies focused on neutrinos as the most likely candidates for the dark matter. It was soon realized, however, that in a neutrino-dominated Universe, structure would form by fragmentation (top-down), with the largest super-clusters forming first in a sort of flat ‘pancake’-like sheets (Zel’dovich et al. 1982). These must then fragment to form smaller structures like galaxy groups and galaxies—a picture that conflicts with observation, as shown by detailed simulations of structure formation (White and Frenk 1983). During the same years, a number of different dark matter candidates were provided by particle physics models based on super-symmetry. These weakly interacting massive particles (WIMPs) are today considered the most likely candidates for dark matter. Because their masses are much larger (and therefore their velocities are much smaller) than those of neutrinos, these particles are said to be ‘cold’. Cold dark matter (CDM) decouples from the radiation field long before recombination so that its density fluctuations can grow significantly before the baryons decouple from the radiation. When this happens, baryons are free to fall in the dark matter potential wells (the halos) that have formed. This allows structure formation to occur at a rate sufficient to be consistent with the large-scale structure observed at present (Davis et al. 1985). In the early 1990s, measurements of galaxy clustering showed that the then ‘standard CDM’ model (in which the Universe was composed only of CDM and baryons) predicted less clustering on large scales than observed (Maddox et al. 1990). Several alternatives were proposed, with the ΛCDM model becoming the new concordance model after the discovery of the current acceleration of the cosmic expansion through supernovae observations (Perlmutter et al. 1999). In recent years, it has been shown that this model is able to match simultaneously a number of other important constraints, including the large-scale clustering of galaxies in the local Universe (Percival et al. 2010), the structure seen in the Lymanα forest at $z = 3$ (Viel et al. 2009), and the cosmic microwave background fluctuations at $z \sim 1000$ (Bennett et al. 2013).

Semi-analytic models are one of the available methods to study galaxy formation and evolution in a cosmological contest. These techniques find their seeds in the ‘two-stage theory’ of galaxy formation proposed by White and Rees (1978): dark matter halos form first, and the physical properties of galaxies are then determined by cooling and condensation of gas within the potential well of the halos. The evolution of the baryonic components is modeled using simple, yet observationally and/or theoretically motivated prescriptions. Adopting this formalism, it is possible to express the full process of galaxy formation and evolution using a set of (coupled) differential equations that describe the variation in mass as a function of time of different galactic components (e.g. stars, gas, metals). Given our limited understanding of the physical processes at play, these equations contain 'free parameters', whose values are typically chosen in order to provide a reasonably good agreement with observational data in the local Universe.

In their first renditions, semi-analytic models relied on Monte Carlo realizations of merging histories of individual halos, generated using the extended Press-Schechter theory (e.g. Cole et al. 1994; Kauffmann et al. 1993). An important advance of later years came from the coupling of semi-analytic techniques with large-resolution N-body simulations that are used to specify the location and evolution of dark matter halos—the birthplaces of luminous galaxies (Benson et al. 2000; Kauffmann et al. 1999). On a next level of complexity, some more recent implementations of these techniques have explicitly taken into account dark matter substructures, i.e., the halos within which galaxies form are still followed when they are accreted onto a more massive system (De Lucia et al. 2004; Springel et al. 2001). There is one important caveat to bear in mind regarding these methods: dark matter substructures are fragile systems that are rapidly and efficiently destroyed below the resolution limit of the simulation. Depending on the resolution of the simulations used, this can happen well before the actual merger can take place. Therefore, this treatment introduces a complication due to the presence of 'orphan galaxies,' i.e., galaxies whose parent substructure mass has been reduced below the resolution limit of the simulation.

One great advantage of these hybrid methods, with respect to classical techniques based on the extended Press-Schechter formalism, is that they provide full dynamical information about model galaxies. Using realistic mock catalogues generated with these methods, accurate and straightforward comparisons with observational data can be carried out. Since N-body simulations can handle large numbers of particles, the hybrid approach can access a very large dynamic range of mass and spatial resolution, at small computational costs. In addition, since the computational times are limited, these methods also allow a fast exploration of the parameter space and an efficient investigation of the influence of specific physical assumptions. This comes at the expenses, however, of loosing an explicit description of the gas dynamics.

One common criticism to semi-analytic models is that there are 'too many' free parameters. It should be noted, however, that the number of these parameters is not larger than the number of published comparisons with different and independent sets of observational data, for any of the semi-analytic models discussed in the recent literature. In addition, these are not 'statistical' parameters but simply due to our lack of understanding of the physical processes considered. Therefore, a change in any of these parameters has consequences on a number of different predictable properties, so that often there is little parameter degeneracy for a given set of prescriptions. Finally, observations and theoretical arguments often provide important constraints on the range of values that different parameters can assume. More important than the actual value of the parameters are, in my opinion, the 'parametrizations' assumed for the physical processes at play. Also in this case, theory and observations provide important inputs. Given we lack a complete 'ab initio' theory for most (all?) of these processes, however, different parametrizations remain equally plausible.

Given the complexity of the galaxy formation process, it is not surprising that none of the methods that we use to model the formation of galaxies is able to fully and satisfactorily explain the variety of observed galaxy properties. There are, in particular, a number of 'problems' that are shared by all semi-analytic (as well as by hydrodynamical simulations) that have been recently published: (i) the number densities of low-to-intermediate mass galaxies are systematically larger than observational estimates. Efficient stellar feedback is able to bring the low mass end of the galaxy mass function in agreement with observational results in the local Universe, but does not appear to be able to solve satisfactorily the problem at higher redshift. (ii) Low-to-intermediate mass galaxies tend to be too passive with respect to observational measurements. (iii) Massive galaxies have predicted metallicities that are too low with respect to observational measurements. A detailed illustration of these problems, and more references can be found in De Lucia et al. (2014b). The current wisdom is that the solution of the problem lies in a physical process that is able to break the parallelism between mass growth and halo growth, particularly for galaxies of low-to-intermediate mass. It remains to be seen if this can be achieved by simple modifications of the stellar feedback and gas recycling scheme.

The Toomre brothers were among the first to recognize that mergers can drive the evolution of galaxy types by transforming disks into objects that resemble elliptical galaxies. What are the limits of this idea? Is merging the correct solution for understanding the evolution of all galaxies? Theoreticians distinguish major and minor merging events. Would you explain why? Which observations suggest the two phenomena? How many major merging events may occur on average to a galaxy?

In the hierarchical scenario, dark matter haloes (and therefore the galaxies that reside in them) undergo frequent interactions with each other. These interactions have dramatic influence on the morphologies and star formation histories of the galaxies involved. Numerical simulations have shown that close interactions can lead to a strong internal dynamical response driving the formation of spiral arms and, depending on the structural properties of the disks, of strong bar modes. The developing non-axisymmetric structures (spiral arms and/or central bars) lead to a compression of the gas that can fuel starburst/AGN activity (see Mihos 2004, and references therein). Simulations have also shown that in sufficiently close encounters between galaxies of similar mass, violent relaxation completely destroys the disk and leaves a kinematically hot remnant with photometric and structural properties that resemble those of elliptical galaxies.

The merger hypothesis for the formation of elliptical galaxies was suggested early on by Toomre and Toomre (1972) and later confirmed by many numerical simulations (Cox et al. 2008; Mihos 2004; and references therein). In recent years, a large body of observational evidence has been collected that demonstrates that a relatively large fraction of early-type systems show clear evidence of interactions, mergers, and recent star formation, in particular at high redshift. However, the data also seem to indicate that only a small fraction of the final mass is involved in these episodes. This observational result has often been interpreted as strong evidence against the somewhat extended star formation history naively predicted from hierarchical models. A related issue concerns the α-element enhancements observed in elliptical galaxies. The [α/Fe] ratio is believed to encode important information on the time scale of star formation, and it is a well-established result that massive ellipticals have supersolar [α/Fe] ratios, suggesting that they formed on relatively short time scales and/or have an initial mass function that is skewed toward massive stars. The inability of early renditions of the hierarchical merger paradigm to reproduce this observed trend has been pointed out as a serious problem for these models (Thomas 1999). More recent work has pointed out that there is an important difference between 'formation' time of the stars in the galaxy and its 'assembly' time, which makes the observed trend of shorter star formation histories for more massive galaxies *not anti-hierarchical*. I will come back to this point below.

In order to model galaxy interactions and mergers, one needs to know what determines the structural and physical properties of a merger remnant. Numerical simulations have shown that these depend mainly on the following two factors: (1) The progenitor mass ratio. During 'major' mergers, violent relaxation plays an important role, and as a consequence, the merger remnant has little resemblance to its progenitors. On the other hand, during minor mergers, the interaction is less destructive so that the merger remnant often resembles its most massive progenitor. The exact value at which one distinguishes between minor and major mergers is somewhat arbitrary but is usually chosen to be of the order of $M_2/M_1 \sim 0.3$. (2) The physical properties of the progenitors.The structure of the galaxies involved in a merger plays an important role in determining the response to interactions: disks that are stable against the growth of instabilities (e.g., because of a central bulge or a lowered disk surface density) will be less 'damaged' than disk-dominated systems that are prone to strong instabilities. In addition, in a merger between two gas-rich progenitors, a significant fraction of the gas content can be fuelled toward the centre, triggering a starburst and/or accretion of gas onto the central black hole. Merger-driven starbursts are instead suppressed if the two merging systems are gas poor. These purely stellar mergers are often referred to as a 'dry' or 'red' and are believed to contribute significantly to the recent assembly of elliptical galaxies (De Lucia et al. 2006).

Naively, one expects very large number of mergers in the hierarchical scenario, where more massive systems form through the mergers of smaller units, and larger systems are expected to be made up by a larger number of progenitors. The right panel of Fig. 8.1 shows the 'effective number of stellar progenitors' of elliptical galaxies of different mass. This quantity represents a mass-weighted counting of the stellar systems that make up the final galaxy, and therefore provides a good proxy for the number of significant mergers required to assemble a galaxy of given mass. The figure shows results from a model where only mergers contribute to the

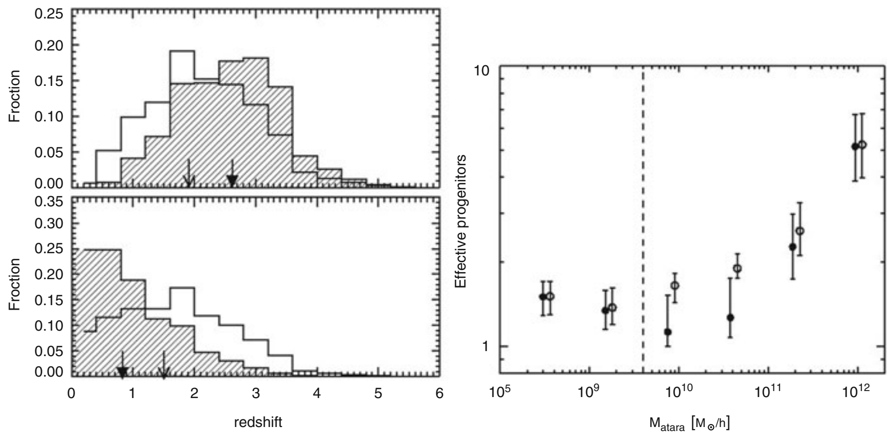

Fig. 8.1 From De Lucia et al. (2006). *Left panel*: Distribution of formation (*top panel*) and assembly redshifts (*bottom panel*). The shaded histogram is for elliptical galaxies with stellar mass larger than $10^{11}\,M_{\odot}$, while the open histogram is for all the galaxies with mass larger than $4 \times 10^{9}\,M_{\odot}$. *Arrows* indicate the medians of the distributions, with the *thick arrows* referring to the shaded histograms. *Right panel*: Effective number of progenitors as a function of galaxy stellar mass for model elliptical galaxies. *Symbols* show the median of the distribution, while error bars indicate the upper and lower quartiles. *Filled and empty symbols* refer to a model with and without a disc instability channel for the formation of the bulge

formation of bulges (empty circles) and those from a model where bulges can also form through disk instability (filled symbols). The vertical dashed line indicates the threshold above which the morphology classification can be considered robust (this is set by the resolution of the parent simulation). As expected, more massive galaxies are made up of more pieces. The number of effective progenitors is, however, less than two up to stellar masses of $\sim 10^{11}\,M_{\odot}$, indicating that the formation of these systems typically involves only a small number of major mergers. Only more massive galaxies are built thought a larger number of mergers, reaching up to ~ 5 for the most massive systems. The right panel of Fig. 8.1 shows the distribution of 'formation' (top panel) and 'assembly' (bottom panel) redshifts of model ellipticals. The former is defined as the redshift when 50 % of the stars that end up in ellipticals today were already formed, while the latter is defined as the redshift when 50 % of the stars that end up in ellipticals today are already assembled in a single objects. More massive galaxies are 'older', albeit with a large scatter, but assemble 'later' than their lower mass counterparts. Hence, the assembly history of elliptical galaxies parallels the hierarchical growth of dark matter haloes, in contrast to the formation history of the stars.

Let me finally stress that, in recent years, a large body of observational evidence has been collected that demonstrates that interactions and mergers indeed represent a common phenomenon at high redshifts, and that these processes certainly affect the population of elliptical galaxies in the local Universe. Schweizer and Seitzer (1992) found evidence for bluer colours of elliptical galaxies with an increasing amount of morphological disturbance in a study based on a small sample, with a strong bias towards isolated systems. Later studies using absorption-line indices have demonstrated that a significant fraction of cluster early-type galaxies has undergone recent episodes of star formation (Barger et al. 1996). Signs of recent star formation activity have also been detected in a number of high redshift early-type galaxies using both colours and absorption and emission line diagnostics (e.g. Menanteau et al. 2001; Treu et al. 2002). When using deep images, a large fraction (about 70 %) of local early-type galaxies show morphological signatures of tidal interactions consisting of broad fans of stars, tails, and other asymmetries at very faint surface brightness levels (van Dokkum 2005). These results favour, at least for a part of the elliptical galaxy population, a hierarchical formation scenario.

The discovery of DM and of the Large Scale Structure of the Universe, coupled with the measurements of the CMB, progressively led astronomers toward the new paradigm of the hierarchical structure of the Universe. The next interview explains why and what is the role assigned to baryons in this game.

Questions for Jaan Einasto:
the Large Scale Structure (LSS) of the Universe contain the imprint of the physical conditions at the epoch of galaxy formation. Could you discuss what have we learned from these studies?

Let me discuss our experience step-by-step.

In early 1970s very little was knows about the large-scale distribution of galaxies and galaxy systems. The commonly accepted picture at that time was that galaxies form a "field" in which galaxies and clusters are distributed almost randomly.

Our team started to study the distribution of galaxies in mid-1970s when Yakov Zeldovich asked me to find an answer to the question: Can we find some observational evidence which can be used to discriminate between various structure formation scenarios? At this time there were two main scenarios of structure formation, the Peebles hierarchical clustering scenario (Peebles and Yu 1970), and the Zeldovich pancaking scenario (Zel'dovich 1970).

When Zeldovich asked the question I had initially no idea how we could find an answer. But quite soon we understood that systems of galaxies evolve rather slowly. If there exist large-scale structures in the nearby Universe, these structures must be similar to structures during the formation of galaxies. We collected redshift data for galaxies, clusters and active galaxies and found that there exists a continuous network of galaxies and clusters we called "cell structure of the Universe" (Jõeveer et al. 1977, 1978) or the supercluster-void network (Einasto et al. 1980); presently it is called the cosmic web (Bond et al. 1996). Dominant elements of the web are chains/filaments of galaxies and clusters. The space between filaments is almost devoid of galaxies—these regions are called cosmic voids. Superclusters are high-density regions in this network. The linear shape of filaments can be explained only in case when galaxies and clusters already form inside filaments (Jõeveer et al. 1977). Otherwise it is impossible to cancel galaxy velocities perpendicular to the axis of the filament, if they form randomly in space. Some filaments are rich and consists of clusters and groups of galaxies, as the main ridge of the Perseus-Pisces supercluster. Filaments of galaxies inside large voids are poor and consist only of galaxies and poor Zwicky clusters.

In summary, studies of the large-scale distribution of galaxies in late 1970s showed the presence of the cosmic web—a hierarchical network of filaments of galaxies, clusters of galaxies, superclusters and voids between them.

The connection between the structure of the cosmic web and the nature of DM particles was discussed in 1981 at two conferences, in April in Tallinn, and in September in Vatican. At the Vatican conference Joe Silk analyzed the concept of non-baryonic DM. In addition to neutrinos he considered photinos as one of the possible candidate for the DM. He concludes his analysis as follows: “It seems that the large-scale structure of the Universe is intimately related to its microscopic structure on elementary particle scales. This is perhaps not surprising if one recalls that it is the initial seed of fluctuations at the Planck epoch that are likely to determine the asymptotic growth of irregularities in the expanding Universe” (Silk 1982). These two conferences mark probably the birth of astro-particle physics. Cosmologists and particle physicists understood that properties of the micro-world and macro-world are related.

To compare the model and observed distributions of particles/galaxies we performed together with Zeldovich and his collaborators several quantitative tests (Zel’dovich et al. 1982). We found that in most tests the pancake model is in good agreement with observations, and the hierarchical clustering model is in conflict with all tests. However, the pancake model applied by Zeldovich had one problem: it did not contain weak filaments in contrast to observations. Soon we realized that this defect is due to the fact that the model used neutrinos as DM particles.

Numerical simulations using photinos (or other Cold DM particles) were performed by Adrian Melott. In summer 1983 he visited Moscow and Tallinn to discuss his recent results. Together we performed the same quantitative tests as earlier (Zel’dovich et al. 1982). Our conclusion was that the new CDM model is in good agreement with observations (Melott et al. 1983). A still better agreement has the CDM model with cosmological constant (or Dark Energy) (Einasto et al. 1986).

The main lesson from these studies of the cosmic web was the understanding of the presence of a close connection between the two topics—the nature of DM and the structure of the web. Secondly, we understood that both physical processes, the pancaking and the hierarchical clustering, work in nature. First DM and ordinary matter flow to form high-density regions (pancakes/filaments), thereafter in these regions the hierarchical clustering (and the merging of galaxies) starts. Thus both Zeldovich and Peebles are right.

What about the density profile of DM?

Modern simulations of the web have a very high resolution, thus it is possible to study the density profile of DM halos. These studies show that DM halos of very different mass and radius have rather similar density profiles, the NFW-profile (Navarro et al. 1997). An even better profile is given by the generalized exponential model: $\varrho(a) = \varrho_0 \exp\left(-(a/a_c)^{1/N}\right)$, where ϱ_0 is the central density, a is the semi-major axis of the equidensity ellipsoid, a_c is the core radius, and N is the structural parameter, which allows one to vary the shape of the density profile. I introduced this profile to present the density distribution of galactic populations (Einasto 1965). Presently it is called the "Einasto"-profile (Navarro et al. 2010).

Why the density distributions of stellar populations and DM halos is so similar is not understood yet.

Which is the meaning of the cell structure?

Miguel Aragon-Calvo used high-resolution simulations to investigate the internal structure of voids (Aragon-Calvo and Szalay 2013). His simulations confirmed that the cosmic web has properties of a cellular distribution. He found that all cellular systems in Nature have similar properties, depending on the number of neighbouring cells. If the number of neighbouring cells is small, then during the evolution the cell shrinks and disappears (Sheth and van de Weygaert 2004). If the number of neighbours is large, then the cell expands. The most stable configuration is a cell with 8 neighbouring cells; such cells have the structure of a honeycomb. These high-resolution simulations also showed the hierarchical nature of the cellular and void structure. Within a large cell (void) there are sub-cells (sub-voids), within sub-cells there are sub-sub-cells (sub-sub-voids) etc.

When we introduced the term "cellular structure of the Universe" (Jõeveer et al. 1977, 1978), we did not guess that this term could have such a deep physical meaning. However, this hierarchical cellular structure is seen only in the distribution of DM particles. Galaxies form in high-density regions of the cellular network—filaments and knots at filament crossings. For this reason the distribution of galaxies is filamentary, and there are no continuous surfaces of cell walls, which could isolate neighbouring cells from each other (Einasto et al. 1986).

Already early studies of the web showed that cosmic cells, i.e. low-density regions surrounded by superclusters, have a certain mean diameter of the order of $100\ h^{-1}$ Mpc, where h is the Hubble constant in units of 100 km/s per Mpc (Jõeveer et al. 1977, 1978). The dominant scale of the supercluster-void network $120\ h^{-1}$ Mpc is very well seen in the distribution of rich Abell clusters (Einasto et al. 1997).

A smaller scale has been found in the distribution of groups and clusters along filaments of galaxies. In the main filament of the Perseus-Pisces Supercluster, clusters and groups of galaxies are located at regular mutual distances from each other (Jõeveer et al. 1977, 1978). Elmo Tempel developed a method how to identify galaxy filaments in the SDSS survey. He found that galaxy filaments look like pearl necklaces (Tempel et al. 2014). The characteristic length of the pattern is around $7\ h^{-1}$ Mpc.

The reason of the existence of both these regularities is not known.

The largest non-percolating systems of galaxies are superclusters. First supercluster catalogues were prepared using Abell clusters of galaxies (Einasto et al. 1994, 2001). In the last decade large redshift surveys of galaxies have been performed. These surveys have been used to calculate the luminosity density fields of galaxies, corrected to take into account galaxies fainter than the magnitude limit used in redshift surveys. Supercluster catalogues have been prepared using the two-degree-Field (2dF) survey (Einasto et al. 2007), and the SDSS survey by Liivamägi and collaborators (Liivamägi et al. 2012).

The SDSS based supercluster catalogue has been used to investigate the morphology of superclusters using Minkowski functionals (Einasto et al. 2011b, 2012b, 2014). The superclusters can be divided into two main morphological types, spiders and filaments. Clusters in superclusters of spider morphology have higher probabilities to have substructure and larger peculiar velocities of their main galaxies than clusters in superclusters of filament morphology. Clusters in superclusters with spider morphology also contain a larger fraction of star-forming galaxies than clusters in superclusters of filament morphology. The most luminous clusters are located in the high-density cores of rich superclusters (Einasto et al. 2012a).

These studies show that not only the nearby environment (clusters vs. field galaxies), but also large-scale supercluster environment determines the morphological type of galaxies.

Direct observations of very distant galaxies show that first forming galaxies are irregular dwarfs. Numerical simulations suggest that galaxy formation starts in regions where the density of the pre-galactic matter is the highest—in centres of future superclusters. During the subsequent evolution pre-galactic gas (DM and baryonic) flows from low-density regions towards filaments, in such way galaxies grow steadily. Inside filaments dwarf galaxies cluster hierarchically and merge to form more massive galaxies. Along filaments galaxies and clusters move towards supercluster centres, which become great attractors. These processes—the steady inflow of matter towards galaxies, the merging of galaxies and the flow of galaxies to supercluster centres—can be followed in the nearby Universe where the velocity flows can be calculated using direct distance indicators and galaxy redshifts, combined with constrained numerical simulations of the evolution. This combined approach allowed to define the extent of our home supercluster, called Laniakea (Tully et al. 2014). The Virgo supercluster is only a weak outlying part of the Laniakea supercluster.

The use of the velocity flows allows a physically more accurate definition of superclusters. According to Tully et al. (2014), a supercluster is a 'basin of attraction' in the velocity flow field. In other words, the boundaries of a supercluster are defined by the places at which the velocity flow field points in different directions on either side of the boundary. In this way the whole space is divided between superclusters. This definition can be applied, however, only in the nearby Universe. In more distant regions the use of the luminosity density field is the best available method to define superclusters. Liivamägi and collaborators found (Liivamägi et al. 2012), that using an adaptive threshold density limit superclusters contain 27 % of all galaxies and 3.7 % of the whole volume, and using a constant density threshold 5 in units of the mean luminosity density superclusters contain only 14 % of galaxies, and occupy 1.3 % of the whole volume. The rest is located in filaments and voids, as shown already by Jõeveer et al. (1977, 1978).

In this way the near-field cosmology and the study of very distant objects complement each other.

What are the Baryonic Acoustic Oscillations (BAO)?

The early Universe consisted of a hot plasma of baryons, photons, and dark matter. Competing forces of gravity and pressure create oscillations: the pressure forms a spherical sound wave of baryons and photons around each over-dense region. After the decoupling (recombination) the photons no longer interact with the baryonic matter and diffuse away. The pressure vanishes and the shell of baryonic matter is left at a fixed radius, called the sound horizon. This leads to the formation of peaks in the CMB angular power spectrum, discovered by the WMAP satellite. Similar features have been found in the distribution of galaxies of the SDSS Luminous Red Giant (LRG) sample by Eisenstein et al. (2005) and Hütsi (2006), using the correlation function and the power spectrum of LRG galaxies.

Baryon acoustic structures are spherical shells of relatively small density contrast, surrounding high density central regions. Recently a new method to detect the real-space structures associated with BAO was presented (Arnalte-Mur et al. 2012). The authors designed a specific wavelet adapted to search for shells, and applied this method to detect shells surrounding high-density peaks of the SDSS density field. Peaks were found using the LRG sample of galaxies; to find shells around peaks the main galaxy sample of SDSS was used. To enhance shells they were stacked around high-density peaks.

The physics of the formation of BAO cells is well understood. Presently there are numerous projects to determine redshifts of millions of galaxies in large contiguous regions of sky up to faint magnitudes. These projects have the primary goal to determine BAO cells at various redshifts, and in this way to investigate properties of the dark energy which causes the acceleration of the present-day Universe. As a by-product these projects allow to investigate the general structure of the cosmic web on largest possible scales.

Theoretical considerations suggest that all objects more distant than about 140 Mpc (as seen from a certain position) were outside the horizon after the inflation until recombination, and thus had no physical contact to each other. For this reason the skeleton of the presently visible cosmic web should be formed already during the inflation. This conclusion was confirmed by analytical calculations (Kofman and Shandarin 1988) and numerical simulations of the evolution of the cosmic web (Einasto et al. 2011a).

Thus the present structure of the web gives us information on physical conditions during the inflation.

Most of the present knowledge of the past history of galaxies comes from the good theoretical foundation of stellar evolution. When the concept of stellar populations developed, was immediately followed by the ideas of star formation. Now we start to define the basic concepts associated to the star formation history of galaxies and what are the consequences of these studies for the paradigm of a hierarchical Universe.

8.4 The Initial Mass Function

Questions for Pavel Kroupa:
the Initial Mass Function (IMF) is one of the most important theoretical ingredients of any theory of galaxy formation and evolution. The concept of IMF was first introduced by Salpeter (1955). It provides a convenient way of parametrization of the relative number of stars as a function of their mass. The IMF has been one of the most debated issues in galaxy studies.

Measurements obtained from young clusters and associations, and old globular clusters suggested that the vast majority of their stars were drawn from a universal system IMF: a power law of Salpeter index ($\Gamma = 1.35$) above a few solar masses, and a log normal or shallower power law ($\Gamma \sim 0.25$) for lower mass stars.

The shape and the universality of the IMF is still under investigation. Could you explain us why?

The Initial Mass Function (IMF, $\xi(m)$) is one of the most important theoretical ingredients of any theory of galaxy formation and evolution. The concept of the IMF was first introduced by Salpeter (1955). The IMF is defined to be the differential number of stars, dN, in the stellar mass interval m to $m + dm$, $dN = \xi(m)\, dm$. It is the distribution function of all stars formed together in one "event", and the Salpeter IMF (Salpeter 1955) is $\xi(m) \propto m^{-\alpha}, \alpha \approx 2.3, 0.4 < m/M_\odot < 10$. It provides a convenient way of parametrization of the relative number of stars as a function of their mass. The IMF has been one of the most debated issues in galaxy studies.

Modern measurements obtained from young clusters and associations, and old globular clusters suggested that the vast majority of their stars were drawn from a universal or canonical IMF: a power law of Salpeter index ($\Gamma_2 = 1.3, \alpha_2 = 2.3$) above halve a solar mass, and a log normal or a shallower power law ($\Gamma_1 \approx 0.3, \alpha_1 \approx 1.3$) for lower mass stars (fig. 4-24 in the recent review (Kroupa et al. 2013) which covers much of this material).

Before continuing one needs to establish some precise vocabulary: The stellar IMF is the distribution of stellar masses formed together in one star-formation event. It is constrained by star counts in a given star-formation event. Such a population of stars is *simple* (one age, one metallicity). The IMF of a whole galaxy is a different issue, as it is deduced from the field population of stars in a galaxy, and this field population has many different ages and metallicities, it is *complex*.

Rigorous work on the IMF needs to differentiate between the true IMF of a simple population and the IMF of a complex population. Are the two the same?

The reason why the question of whether the IMF is universal or not is still being studied and debated is that the IMF is indeed such a fundamentally important distribution function, and because constraining the IMF observationally is very hard indeed and mistakes in the analysis can easily occur if the work is not highly rigorous in every respect. Any scientist attempting this task requires intimate knowledge of all aspects of astrophysics, such as pre-main sequence and post-main sequence stellar evolution, stellar birth-rate functions, the structures in which stars typically form and their dynamical evolution including gas expulsion processes, the properties and evolution of binary systems and the corrections of star counts for various biases and uncertainties. One bias, for example, often not appreciated in dealing with Galactic-field star counts, is that by the nature of the systematically changing mass-ratio of binary stars with primary mass, the photometric distance estimates suffer a systematic bias in dependence of the primary star mass (Kroupa et al. 1993). It is comparatively easy to make a survey, count the "stars", and to construct a "mass" distribution. Following such a straight forward procedure, typically one obtains different mass functions for different populations (e.g. the Orion Nebula Cluster versus the Taurus-Auriga populations vs the Galactic field "IMF"). But the difficult and salient aspect of deriving the IMF is to correct the star counts for all biases and extracting the physically relevant information. And this is where some teams have progressed far, while others have not, and therefore significant discussion continues.

Essentially, the problem is so hard, but appears so easy, that mistakes are made readily leading to debates and argumentations which might not be necessary.

Any young researcher without very detailed knowledge of all the previous results and analyses, is likely to do avoidable and out-of-date errors therewith setting back progress unnecessarily.

Two cases in point exemplify this: some researchers keep insisting up until today that the IMF obtained from the Taurus-Auriga groups of very young stars is substantially different from the normal or canonical IMF or the IMF constrained for the Orion Nebula Cluster. But, taking into account the very major uncertainty in estimating stellar masses for $<$few Myr old stars and the known fact that most stars in Taurus are in binary systems while only about 50 % of systems in the Orion Nebula Cluster are binaries, leads to the underlying parent distribution function of individual stellar masses being consistent with the same function within the uncertainties. This has been shown a long time ago (see the review Kroupa et al. (2013)), but, for some unclear reason, this is being ignored by others. Another example is the recent claim by Reggiani and Meyer (2013) that brown dwarfs constitute a continuous extension of the stellar IMF based on the recently constrained field-star IMF by Bochanski et al. (2010). But the authors of the field-star IMF explicitly warn, in their abstract, that the functional form of the IMF they derive is only valid for a restricted mass range which excludes brown dwarfs. Ignoring this and using the functional form as a model including brown dwarfs yields wrong results. The observationally established existence of the brown dwarf desert according to which stars rarely have brown dwarfs as companions (Dieterich et al. 2012) is a primary issue where Reggiani and Meyer (2013) err. All of this discussion has been occurring in the past years, although models addressing all of these issues carefully had been published many years ago (see the review Kroupa et al. (2013)). It has already been shown in 2003 (Kroupa et al. 2003) that, treating brown dwarfs as stars in constructing binaries, leads to far too many star—brown and far too few star—star binaries, in comparison to all known populations. Brown dwarfs therefore absolutely must be treated with their own, separate, IMF, as also planets have their own IMF which is not a continuous extension of the stellar IMF.

Thus, a discussion is kept going which may not be entirely useful, rather than building upon the robust observational findings, such as the verification of the brown dwarf desert by the excellent work of Dieterich et al. (2012) in combination with the known stellar and brown dwarf binary properties.

The holy grail of IMF research is extracting the expected systematic variation of the IMF with physical conditions of star formation.

A star-formation event yields a stellar population whose mass distribution is describable by the stellar IMF of a simple population (see p. 609). Such a star-formation event occurs in a molecular cloud core typically on a sub-pc-scale and on a Myr time-scale and can be referred to as an embedded cluster. The stars belonging to such an "event" can neither be counted accurately nor precisely, but such a population is mono-metallic and coeval to within a few to ten times 10^5 yr, which is the time-scale over which an embedded cluster forms. This time scale is typically a few to ten times longer than the time ($\approx 10^5$ yr) it takes for an individual star to assemble about 90 % of its final mass (Wuchterl and Tscharnuter 2003). This is seen nicely even in supposedly "distributed" or "isolated" star formation in the Taurus-Auriga clouds (Brice no et al. 1998; Gomez et al. 1993; Kroupa and Bouvier 2003) and in the southern part of the L1641 Orion cloud (Hsu et al. 2012, 2013; Megeath et al. 2012). In these clouds the stars and proto-stars with ages younger than about 1 Myr are distributed non-uniformly in many groups of stars clustered on $\lesssim 1$ pc scales.

Thus, the direct imaging of all very young stellar and sub-stellar objects disprove the concept that there is a distributed mode of star formation below some threshold. Star formation is organized into sub-pc-scale events, which for all practical purposes can be described as embedded clusters. Direct observations suggest that the least massive embedded cluster consists of about a dozen binaries (Kroupa and Bouvier 2003).

Denser, richer embedded clusters are dynamically active and expel stars from their cores as soon as these form Oh et al. (2015). Extremely massive star clusters with stellar masses $\lesssim 10^6 M_\odot$ may retain gas for long such that their stellar populations may be complex (Wünsch et al. 2011). Even modest clusters may re-accrete gas well after their formation (Pflamm-Altenburg and Kroupa 2009a) also leading to non-simple population mixtures.

According to the IMF un-measurability theorem (Kroupa et al. 2013) *the IMF can never be measured*. It can be stated that the IMF does not have physical reality: there is never any instant in time where $\xi(m)$ is fully assembled. $\xi(m)$ is therefore a theoretical and mathematical concept or entity.

As new binary stars form, others are ejected or broken up into their binary companions, at any instant low-mass stars have not yet reached the main sequence while massive ones have already left it and/or have been ejected from their rich embedded clusters. Thus, what an observer deduces, given an available particular survey data set, is merely a part of $\xi(m)$.

The art in the game of deducing a complete mathematical form of $\xi(m)$ and the mass range over which it is valid (assuming such a form exists as a theoretical construction) is putting together the observational clues and pieces to one functional form which can be used in theoretical work on stellar populations. Indeed, a particular stellar population constitutes merely a snapshot which is but fleeting, and the same population may appear to be described by a different mass function (MF) when viewed with a different survey at a different (astrophysical) time. Apart from the highly significant uncertainties (factors of two) in mass and age determinations of individual rapidly evolving very young stars given their photometric properties when they are younger than a few Myr, as demonstrated by the seminal work of Wuchterl and Tscharnuter (2003), there is patchy obscuration by dust and, very fundamentally, a time-varying population of unresolved binary stars.

Star formation typically yields binary stars, because the contracting pre-stellar molecular cloud core needs to shed and deposit its angular momentum while the formation of three- or higher-order multiple systems can only be a rare outcome (Goodwin and Kroupa 2005).

Rich clusters, which partially survive the violent birth involving expulsion of their residual gas with the associated violent revirialisation (e.g. Banerjee and Kroupa 2013; Banerjee 2014), will, after these events, contain a stellar mass function which has been damaged by loss of stars and this may be stellar-mass dependent if the clusters were mass segregated (Marks et al. 2008). Star clusters evolve by evaporation preferentially of their least-massive stars and dissolve in about 20 present-day two-body relaxation times. While the initial or primordial binary population is broken up early (Marks et al. 2011), the binary fraction may increase with time as hard binaries[1] remain preferentially in a cluster because they have, on average, higher system masses than single stars.[2] Binary systems are typically unresolvable with observations. *At any time, a cluster thus has an observable stellar (system) mass function which deviates substantially from the original IMF of all its stars it was born with.* Direct star-formation simulations which are already approaching sufficient realism to reflect the real population can be used to study the time-variation of the observable MF of stars and binary systems such as demonstrated by the seminal work of Matthew Bate (Bate 2014).

Therefore, the proper procedure for constraining $\xi(m)$ is to pose the hypothesis that there is a parent $\xi(m)$ from which the various observed snapshots (e.g. the individual groups in Taurus-Auriga, or a particular young or old star cluster) are drawn, thereby it being essential to take into account in the analysis *all* biases and evolution effects (Kroupa et al. 2013). The mere counting-up of observed "stars" (many of which are typically unresolved binary systems) to create a histogram of masses, i.e. to obtain an estimate of the stellar mass function, suggests such mass functions to have different shapes.

[1]Hard binaries have an absolute binding energy, $E_{\mathrm{bin}} > 0$, which is significantly larger than the mean kinetic energy of the cluster stars, E_{kin}. Soft binaries have $E_{\mathrm{bin}} \ll E_{\mathrm{kin}}$.

[2]The issue of IMF invariance is related to the important issue of whether the initial binary-star distribution functions are invariant as well. Observational evidence, analyzed carefully and taking into account the dynamical evolution properly, suggests this to be the case in present-day star-forming regions (Marks et al. 2011; Marks and Kroupa 2012) and in major star burst clusters a Hubble time ago (Leigh et al. 2015).

But careful analysis has always yielded the result that the hypothesis that there is one invariant parent distribution cannot, in most cases, be rejected, given all the uncertainties and biases.

This statement is true for star-formation that is and has been occurring in the MW disk, including the Taurus-Auriga clouds and most globular clusters, the Galactic field and bulge and dwarf spheroidal satellite galaxies (Kroupa et al. 2013).

Unless the job is done extremely carefully and thoughtfully, the various outcomes of the star formation process will appear like a mess, such that somewhat careless work may imply the result "what you see is what you get", an *opinion* subscribed to by some workers. But in this light the seminal 2007 paper by De Marchi et al. (2007) reporting that low-concentration globular clusters have present-day stellar mass functions which are depleted in low-mass stars (i.e. they have bottom-light mass functions) came as a shock. The dynamical clock ticks slower in low-concentration clusters, such that the expectation was that these ought to, if anything, retain the IMF at the low stellar-mass end. This is nicely shown by the international collaboration led by Nathan Leigh (2013; their fig. 4). This surprising observational result can be explained if globular clusters were formed highly compact with radii smaller than about 1 pc, more massive than today and with an IMF which systematically becomes top-heavy with increasing birth density and decreasing metallicity of the cluster with significant expansion through the expulsion of residual gas (Marks et al. 2012). The remarkable finding by this study, led by Michael Marks, is that it is consistent with the results obtained entirely independently from two studies led by Jörg Dabringhausen concerning the dynamical M/L ratios of and the X-ray sources in ultra-compact dwarf galaxies (UCDs) (Dabringhausen et al. 2009, 2010, 2012). The dependency of the IMF on star-forming cloud density and metallicity is shown in fig. 3 and 4 in Marks et al. (2012). Furthermore, the first-ever integration of globular clusters on a star-by-star basis over a Hubble time by Akram Zonoozi et al. furthermore significantly supports these results by uncovering the initial conditions for the two clusters Pal 4 and Pal 14 after violent revirialisation through gas expulsion (Zonoozi et al. 2011, 2014). The remaining challenge will be to see if the phase prior to violent revirialisation is consistent with the above statements. The recent constraints on the canonical shape of the low-mass stellar IMF in the Arches star-burst cluster by Shin and Kim (2015) again supports these results nicely. Further independent evidence for top-heavy IMFs in extreme star-burst environments on scales of less than 100 pc is seen in the high rate of type II supernovae in e.g. Abell 220 and 299 (Dabringhausen et al. 2012; Kroupa et al. 2013; Pérez-Torres et al. 2009).

Indeed, the concept of an invariant, universally valid parent IMF stands in contradiction to all predictions star-formation theory has been making over the past decades. According to even robust and fundamental arguments in star formation theory, the IMF ought to become top-heavy with decreasing metallicity and increasing gas density and temperature.[3] Cases in point of theoretical IMF work investigating possible variations with physical conditions are (Adams and Fatuzzo 1996; Bate 2005, 2014; Bonnell et al. 2007; Elmegreen 1999, 2000; Hennebelle and Chabrier 2013; Klessen et al. 2007; Larson 1998; Padoan and Nordlund 2002).

According to the above results gleaned largely from resolved stellar populations, the following may be stated on the IMF:

The stellar IMF can be described as an invariant canonical distribution function when the star-formation rate density (SFRD) in an embedded cluster is $\lesssim 0.1$ $M_{\odot}/(pc^3 yr)$, while it becomes progressively top-heavy with increasing SFRD (Marks et al. 2012).

Why it is so difficult to get the IMF of a galaxy?

Measuring the IMF of a simple resolved population is very challenging, but deducing the IMF of a whole star-forming galaxy is a very different problem. In a star cluster the IMF can be constrained from the count of individual stellar systems (single stars and unresolved binaries). For a galaxy this is not possible, last not least because thee are far too many stars to count, if stars can be resolved at all. Estimating the IMF of a whole galaxy, the galaxy-wide IMF (GWIMF) or the IMF of a complex population, must therefore rely on the integrated light properties of the galaxy, or on spectroscopic analysis. *The former* can yield constraints on the relative number of massive and less massive stars, since a population with a top-heavy GWIMF will be blue, while a galaxy with a top-light GWIMF will be redder. But there are degeneracies, such as younger more-metal-rich populations being as red as old metal-poor populations or populations with more bottom-heavy IMFs. *The latter* constrains the stellar population mixture more precisely from its spectral energy distribution but relies on a template library of stellar spectra which need to be combined in the correct proportions to fit the observed SED. Ideally, all different methods would be used in unison to enhance the constraints, but the workload is formidable and subject to problems such as the spectral library not being complete (if a type of star is not part of the library, other stars in the library need to compensate its contribution which can bias the result—see footnote 3 on p. 614 for a possible

[3]The recent much noted and important suggestion that the IMF becomes very bottom heavy with increasing mass of elliptical galaxies has been shown to be untenable (see Peacock et al. (2014); Smith and Lucey (2013); Smith (2014), with a possible solution to the spectroscopic evidence being proposed by Maccarone (2014)). Also, no theory of the IMF has ever *predicted* such a bottom-heavy IMF, while *predictions* were always such that the IMF becomes top-heavy under extreme conditions (e.g. Larson (1998) on the basis of a Jeans-mass argument and Adams and Fatuzzo (1996) on the basis of a self-regulated star formation theory). No physical conditions are known which can generate such a bottom-heavy distribution of stellar masses (although Chabrier et al. (2014) now suggest this may be possible, at least partially in highly turbulent high-Mach-number gas). Weidner et al. (2013b) point out the problems associated with such an IMF for the metal enrichment required to account for the observed abundances. Also, the relics of the most intense pc-scale star-burst systems known in the Local Group, the globular clusters, show bottom-light MFs (De Marchi et al. 2007; Leigh et al. 2013) which can be accounted for only with significant dynamical evolution as noted above. The bottom-heavy IMF case will therefore not be discussed further here.

example of this). Also, in deriving the GWIMF it needs to be taken into account that low-mass stars have been adding up over the star formation history of a galaxy, while the massive star content is only visible as established during a time corresponding to the life time of the massive star being considered (Kroupa et al. 2013; Miller and Scalo 1979; Scalo 1986). Normalisation issues between the low-mass end and the high-mass end thus arise, as well as systematically different spatial distributions between low-mass and massive stars. Low mass stars come in ages extending to the birth of the galaxy and have thus had many Gyr to diffuse in phase space away from their original location (e.g. the ancient thick disk), while those massive stars that were not dynamically ejected from their birth clusters occupy the phase-space region they were born in (e.g. the young thin disk). Similar issues are dealt with in extreme detail by the seminal work on the IMF by John Scalo (1986) and Elmegreen and Scalo (2006).

How can the IMF of the MW be constrained?

The IMF of the MW disk can be constrained by carefully analyzing direct star-counts. This is a difficult endeavor prone to biases which, if not recognized, may affect the result to disadvantage. The conversion of the stellar luminosity function to the stellar mass function is proportional to the derivative of the stellar mass–luminosity relation which has substantial uncertainties (Kroupa et al. 1990). One can count the stars in dependence of their absolute luminosity to construct the stellar luminosity function within a small region around the Sun for which trigonometric parallax is available. This ensemble of stars is so close by, within 5 to 20 pc depending on the brightness of the star, that all multiple systems are resolved such that an estimate of the individual stellar luminosity function becomes possible. An alternative, in order to increase the number of stars and thus the statistical significance of the stellar count per luminosity bin, is to perform thin pencil beam surveys to reach the stellar population along the line of sight out to 100 or more pc. Many such pencil beam surveys can be done, and distance measurements rely on the photometric parallax method. Multiple systems remain unresolved. The biases associated with the two methods need to be understood very well, and the structure of the Galactic disk needs to be modelled, as well as the age and metallicity distribution of the stars of different masses. Thus the Lutz-Kelker bias needs to be accounted for through measurements errors in trigonometric parallax, cosmic scatter needs to be modelled to account for Malmquist bias. The break-through seminal paper on this problem has been contributed by Stobie, Ishida & Peacock in 1989 (Stobie et al. 1989). A multi-dimensional minimisation procedure, solving simultaneously for both types of star counts, has been performed only once so far, in 1993 (Kroupa et al. 1993). The resulting estimate of the IMF for main sequence stars with masses below about 1 $M_{\odot}$ for the Galactic field population turned out to be nicely consistent with Salpeter's work (Salpeter 1955),[4] and to be remarkably robust over time and to be a good model for the parent IMF which is consistent with the resolved stellar populations seen in current star forming regions and in star

[4]Salpeter constrained the IMF for stellar masses in the range 0.4 to 10 $M_{\odot}$.

clusters (see p. 609). This result by Kroupa et al. (1993) deviates from the previous seminal work of Miller & Scalo in 1979 (Miller and Scalo 1979) and Scalo in 1986 (Scalo 1986) in that the mass–luminosity relation of low mass stars was modelled physically properly for the first time (Kroupa et al. 1990), multiple systems were taken into account for the first time (Kroupa et al. 1991), and both, the nearby and the pencil-beam surveys were combined consistently for the first and until now for the last time (Kroupa 1995). The constraints of the field-star IMF by Scalo (1986) remained valid for stars more massive than $1\,M_{\odot}$, but this regime is very hard to treat because a time-evolving star-formation history introduces structure into the observationally derived IMF, as shown for the first time by Elmegreen & Scalo in 2006 (Elmegreen and Scalo 2006).

Nevertheless, the overall slope of the field-star IMF above about $1\,M_{\odot}$, derived by Scalo's analysis (Scalo 1986), turned out to be steeper with $\alpha \approx 2.7$ (Kroupa et al. 1993) than the massive-star IMF deduced in individual very young populations, notably by the ground-breaking work of Phil Massey (see his review (Massey 2003) and fig. 2 therein), $\alpha \approx 2.3$, independently of metallicity and density for current star-forming regions (Kroupa et al. 2013).

This difference between the field-star IMF and the IMF deduced in star-forming regions remained unexplained for decades, and I simply thought that the Scalo index may not be correct.

What about the other galaxies?

Deducing constraints on the GWIMF in external galaxies is hard because one deals with integrated flux in various spectral pass bands, and non-uniform extinction by dust, loss of photons, scattering of photons, all play a role. Reducing the observations to a usable result is a nightmare. But a few teams in the USA and in Australia have managed break-throughs on this problem with rather dramatic results, as will be touched upon further below in this section.

Observational evidence for a systematically top-heavy IMF in star-bursting galaxies and regions therein and at larger redshift has been suggested since decades (notably by Francesca Matteucci (1994), see also Kroupa et al. (2013) and references therein). *But an underlying systematically varying and computable IMF model, which accounts for this observational evidence and at the same time also for the universality of the IMF in local star formation, was not available*. And, the observational evidence was based on indirect arguments, such as the dynamical M/L ratios of a region, the available gas mass and its luminosity and the metallicity distribution. A computational approach did not exist at all, except to make somewhat ad-hoc assumptions as to how the IMF may change with redshift, for example, based on a Jeans-mass argument and ambient temperature. The shape of the IMF remained unpredicted.

In any case, why should the IMF of a whole galaxy or of a large region within it differ from the IMF in actual star-forming places which are observed, wherever resolution is sufficient, to occur in pc-sized cloud cores which may not know in which type of galaxy they condense in out of a molecular cloud through self gravity?

One possible argument for a similarity between the IMF and the GWIMF would be if one assumes the IMF is a probability density distribution function. That is, in small pc-sized star-forming pockets N_p stars are drawn randomly from the same IMF as also describes the random drawing process to form $N_\mathrm{g} \gg N_\mathrm{p}$ stars in a whole galaxy. Then, statistically, IMF=GWIMF.

This (naive) ansatz was favored by most researchers, including me (e.g. Elmegreen (1999, 2000); Kroupa (2001, 2002), see also the discussion in Kroupa et al. (2013)). But the computational approach has changed dramatically through the discovery of the IGIMF Theory in 2003 (Kroupa and Weidner 2003). The generic prediction of the IGIMF theory that the GWIMF steepens at high stellar masses with decreasing galaxy-wide SFR, has been confirmed by observations of thousands of star forming galaxies (Gunawardhana et al. 2011; Hoversten and Glazebrook 2008; Lee et al. 2009; Meurer et al. 2009).

As a result, neither the IMF nor the GWIMF are scale-invariant probability density distribution functions.

Before briefly explaining this computational approach it is useful to address the perhaps most important observational evidence which unambiguously indicates a systematic change of the GWIMF from top-light at very low star formation rates (SFRs) to top-heavy at high SFRs. Surveys of hundreds and thousands of star-forming galaxies have used various photometric tracers such as Hα flux to test for the high-mass end of the GWIMF, UV flux to test for the intermediate mass stellar population and red broadband colors to test for the intermediate and lower-mass end of the GWIMF (Gunawardhana et al. 2011; Hoversten and Glazebrook 2008; Lee et al. 2009; Meurer et al. 2009). The data analysis and the investigations of various biases such as from dust attenuation, loss of photons and others, is highly involved and reported in these works in much detail.

The result in all of these surveys has been consistent in that the GWIMF flattens progressively with increasing SFR. Modelling the GWIMF as a canonical IMF which has $\alpha_1 = 1.3$ for stellar masses $m < 0.5, M_\odot$ and $\alpha_2 = 2.3$ for $0.5 < m/M_\odot \lesssim 1$ with α_3 being the index above $\approx 1\,M_\odot$, the dependency of α_3 on the SFR as deduced from the data is shown in Fig. 8.2.

How can this result of a systematically varying GWIMF with SFR be understood in terms of the largely invariant stellar IMF deduced from individual simple stellar populations (p. 611)?

The clue comes from realizing that the GWIMF is but the result of the addition of all simple populations in a galaxy to build-up the complex population of the galaxy. Thus, in simplified notation (SP=simple population = embedded cluster = star-formation event),

$$\mathrm{GWIMF}(m) = \Sigma_{\mathrm{SP}}\xi_i(m), \tag{8.1}$$

where $\xi_i(m)$ is the stellar IMF contributed by the ith star-formation event.

How was this ansatz discovered? In 2002 I was reconsidering my old problem (p. 560 above) of how thin galactic disks might thicken with time, and since I was working as a hobby on N-body models of embedded star clusters which expel their

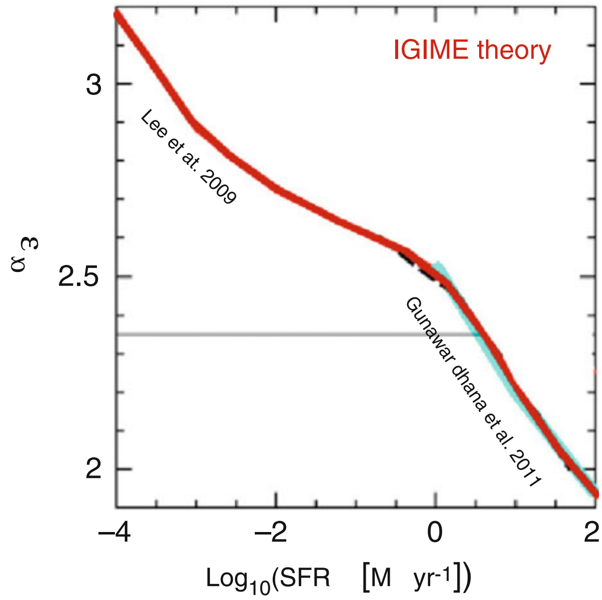

Fig. 8.2 The power-law index α_3 of the galaxy-wide IMF (GWIMF) for stars more massive than $\approx 1\,M_\odot$ as a function of the galaxy-wide SFR is shown as the *thick (red) solid line*, as constrained by Lee et al. (2009) for dwarf galaxies and by Gunawardhana et al. (2011) for more massive galaxies, comparable and more massive than the MW. The *solid curve* coincides with the systematic variation of the IGIMF with SFR, as computed with the IGIMF Theory (adapted from fig. 1 in Weidner et al. (2013c). See also fig. 1 in Gargiulo et al. (2015). The *horizontal line* marks the canonical Salpeter/Massey index $\alpha = 2.35$

unused gas through the action of their massive stellar content, I realized that such "popping" clusters may lead to hot kinematical components in the disk of a galaxy. Assuming all stars form in a distribution of embedded clusters, i.e. *that embedded clusters are the fundamental building blocks of galaxies* (Kroupa 2005), I calculated the integrals and found that it was readily possible to account for the thick disk and the subsequent thinning of the MW disk as time progressed if the SFR of the MW decreased with time until the present value of a few $M_\odot/\mathrm{yr}$ (Kroupa 2002). This work done in 2002 constituted, without me knowing, the prediction that the MW would have been resembling a chain galaxy discovered in 2004 by Bruce Elmegreen et al. (2004).

With this ansatz, a similar integral over all star formation events or all embedded clusters yielded the integrated galactic IMF (IGIMF). Together with my then PhD student Carsten Weidner we did this in 2003, finding that the Galactic-field IMF had to be steeper than the IMF (Kroupa and Weidner 2003). This, of course, explained the result which Scalo (1986) had already obtained (see Sect. 8.4). A generalization of this result to other galaxies became possible by realizing that the most-massive cluster which is forming in a galaxy depends on the SFR of the galaxy

(Weidner et al. (2004), note the extension to high SFRs by Randriamanakoto et al. (2013)). This allowed us to make the fundamental prediction that the IGIMF will flatten with increasing SFR (Weidner and Kroupa 2005). This *predicted* behavior was confirmed *later* by the observational teams mentioned above. A particular success was the prediction of the Hα flux deficit over what is expected for an invariant IMF for dwarf galaxies (Pflamm-Altenburg et al. 2009b), as confirmed by Lee et al. (2009).

One shortcoming of the IGIMF Theory as known then was that it could not predict a top-heavy GWIMF, because the IGIMF could at most only become as flat as the canonical stellar IMF (i.e. Salpeter index) above $\approx 1\,M_\odot$ in the "minimal scenario" of Weidner and Kroupa (2005). The knowledge of the top-heavy IMF in extreme star-burst clusters discussed below was not known then. However, including that knowledge, which was obtained entirely independently of the IGIMF Theory, into the right hand side of Eq. 8.1, yielded agreement with the observed GWIMF as a function of SFR as shown in Fig. 8.2. This was published by Weidner et al. in 2013 (Weidner et al. 2013c). The implication of this work is that the mass function of embedded clusters (ECMF), i.e. of star formation events, needs to also become somewhat top-heavy with an increasing galaxy-wide SFR. Galaxies with high SFRs$>10\,M_\odot$ thus also have slightly top-heavy ECMFs.

Is the IMF really a universal function?

This question can be answered readily today: *yes and no*:

The IMF within a star formation event (i.e. embedded cluster) can be taken to be a mathematically defined parent distribution function, $\xi(m)$, which follows universal rules that make it dependent on the physical boundary conditions which determine the distribution function of star formation events that are physically accessible for a galaxy.

The parent distribution function of stellar masses formed in one event (i.e. in an embedded cluster) is subject to conditions which are axioms derived empirically (for a full list see Weidner et al. (2013c)):

- For a star-formation rate density on a pc-scale SFRD$\lesssim 0.1\,M_\odot/(\mathrm{pc}^3\,\mathrm{yr})$ the IMF is just the canonical form which can, for mathematical convenience, be written as a two-part power law form, or less conveniently as a log-normal part in the approximate range $0.08-1\,M_\odot$ (see p. 609).
- Based on independently obtained evidence from globular clusters and UCDs, the IMF becomes top-heavy when SFRD$\lesssim 0.1\,M_\odot/(\mathrm{yr\,pc}^3)$ (p. 611).
- The IMF is truncated at the canonical maximal stellar mass $M_{\mathrm{max}*}\approx 150\,M_\odot$, as deduced by different independently working groups (for the occurrence of *super-canonical stars* see Banerjee et al. (2012)).
- The IMF, interpreted as an optimally sampled density distribution function (Kroupa et al. 2013), has a most massive star which depends on the stellar mass of the star-formation event or embedded cluster, $m_{\mathrm{max}}=\mathscr{K}_1(M_{\mathrm{ecl}})\leq M_{\mathrm{max}*}$ (the $m_{\mathrm{max}}-M_{\mathrm{ecl}}$ relation). The function $\mathscr{K}_1(M_{\mathrm{ecl}})$ can be either fitted to the data or it may be derived independently from solving an integral equation (e.g. eq. 4-66 in Kroupa et al. (2013)) and therefore directly follows from the shape of the IMF.

- The most massive embedded star cluster forming in a galaxy depends on the SFR of the galaxy, $M_{\rm ecl,max} = \mathscr{K}_2(SFR)$. Similarly to the function $\mathscr{K}_1$ above, this function $\mathscr{K}_2(SFR)$ can be fitted to data (Randriamanakoto et al. 2013; Weidner et al. 2004) or it may be derived independently from solving an integral equation which expresses the stellar mass forming in embedded clusters on the time-scale, $\delta t \approx 10\,$Myr, within which the inter stellar medium collapses to molecular clouds which then spawn the new population of stars (eq. 4.69 and 4.70 in Kroupa et al. (2013)).
- The mass function of star formation events or embedded clusters (the ECMF) becomes slightly top heavy when the galaxy-wide SFR$>\ 1\,M_\odot$/yr (eq. 3 in Weidner et al. (2013c)).

The *galaxy-wide IMF then follows from the above axioms* by summing together all the IMFs contributed by each star formation event over all star-formation events in a galaxy up to the most massive such event which is sustained in the galaxy, given its SFR (Eq. 8.1). This is the *IGIMF Theory*. It is a theory because it is based on one principle, namely that star formation always occurs in phase-space correlated star formation events[5] and a small set of axioms derived from independent observations, and because it is predictive. That is, with the IGIMF Theory it is possible to calculate, from a few first principles deduced from observation, how galaxies evolve, enrich with metals and buildup their stellar masses (e.g. Gargiulo et al. (2015); Ploeckinger et al. (2014); Pflamm-Altenburg and Kroupa (2008); Pflamm-Altenburg et al. (2009b); Recchi and Kroupa (2015)).

Self-similar (Disney et al. 2008; Speagle et al. 2014; Tasca et al. 2015) star-forming disk galaxies are the by far dominant galaxy type (Delgado-Serrano et al. 2010) above a luminosity of $L \approx 10^{10}\,L_\odot$. The pronounced similarity of galaxies is not expected in the Standard Model of Cosmology (Disney et al. 2008) but is a manifestation of star formation being largely self-regulated (Koeppen et al. 1995), and this fundamental aspect of galactic astrophysics is captured by the IGIMF Theory. The top-heaviness of the IGIMF at very high SFRs (fig. 3 in Weidner et al. (2013c)) immediately implies that elliptical galaxies formed with top-heavy IMFs, in nice agreement with the constraints on the IMF from the metal abundances brilliantly deduced by Francesca Matteucci already in 1994 (Gibson and Matteucci 1997; Matteucci 1994)).

Why the IMF could not be a probability distribution function?

Purely randomly sampling from a canonical IMF violates the too small spread in the IMF power-law indices deduced from many different simple populations by direct star counts (fig. 4-27 in Kroupa et al. (2013)) and also the too small spread in the $m_{\rm max} - M_{\rm ecl}$ data, the spread in these data being consistent with measurement uncertainties (Weidner et al. 2013a). The physical spread thus seems to be small,

[5]These are the maxima in the density fluctuations in a turbulent molecular cloud, also called embedded clusters. The least-massive examples of "embedded clusters" with a mass of about $5\,M_\odot$ are what some refer to as "distributed star formation", see the individual groups or clusters in Taurus-Auriga or in the southern part of the Orion L1641 cloud discussed above.

such that the physical constraints required to ensure the small spread implies that even a probabilistically sampled IMF becomes indistinguishable from an optimally sampled IMF. The physical interpretation of this result is that star-formation appears to be highly self-regulated, in agreement with an attractive model of star formation by Adams and Fatuzzo (1996). *Interpreting the IMF as an optimally sampled distribution function makes it mathematically convenient with the physical content of perfect self-regulation.*

Concerning the philosophical basis of the IGIMF Theory, there is a nice little episode that occurred recently involving one of the greatest minds in computational dynamics: in September 2014 I was attending the workshop held in honor of Sverre Aarseth's 80th birthday at an exclusive place in Sexten in the Dolomites. One day I was walking with Seppo Mikkola and I mentioned to him "*Nature must be surprisingly self-regulated*". He replied unhesitatingly, "*Yes, otherwise there would be complete chaos.*" Indeed a direct falsification of stochastic star formation has been achieved by an investigation of the very young cluster distribution in the galaxy M33 by Pflamm-Altenburg et al. (2013).

Despite the rather impressive quality of the IGIMF Theory, it seems to have implications which are unpalatable to parts of the community. One is that the seminal Kennicutt relation (Kennicutt et al. 1994; Kennicutt 1998a) for calculating the SFR of a galaxy given its Hα flux needs to be corrected (Pflamm-Altenburg et al. 2007). This centrally important relation for extragalactic studies assumed the IMF to be invariant amongst galaxies. But according to the IGIMF Theory, galaxies with a lower SFR have a comparative deficit in their massive star content while the Kennicutt relation was derived assuming an invariant ratio of massive stars to low mass stars. This has deep implications for the gas-depletion time scales and the stellar-mass buildup times of dwarf galaxies (Pflamm-Altenburg and Kroupa 2009), which consequently do not fit the present-day models tailored within the SMoC framework. With the IGIMF Theory, a most remarkable prediction became possible, namely that dwarf galaxies must have a smaller Hα/UV flux ratio than more massive galaxies (Pflamm-Altenburg et al. 2009b). The IGIMF Theory also predicts a short radial cutoff of galactic disks in the Hα flux, the disks being much more extended in the UV (Pflamm-Altenburg and Kroupa 2008). Both *predictions* are confirmed by observations (Boissier et al. 2007; Lee et al. 2009).

While we now have, for the first time, a computable IMF model which encompasses universal star formation within the local smallest-groups or "distributed mode" reaching up to major starbursts, it is amusing but also frustrating to observe how parts of the community appear to invest a very major effort to show that the IGIMF Theory is not applicable. There is nothing to be written against critical tests. But too many, and it seems all published work which claims to rule out the IGIMF Theory I am aware of, has been shown to be flawed, either because newer data made the original counter argument redundant, or because the calculations are wrong. It is worth considering these reactions, since they imply that the community is now essentially largely ignoring the IGIMF Theory for interpreting extragalactic observations, rather than using the IGIMF Theory *as one possibility* to interpret the observations. For example, although (Bruzzese et al. 2015) essentially find evidence for the IGIMF Theory by studying the stellar population in the outer region of a dwarf galaxy, the IGIMF Theory is not even mentioned, and instead stochastic star formation is used as the favored model. This is done despite the evidence that stochastic and unclustered star formation is not the appropriate description of star formation in low-density regions (see Hartmann et al. (2001); Kirk and Myers (2011); Kroupa and Bouvier (2003); Palla and Stahler (2002), fig. 1 in Hsu et al. (2012)), and the explicit result that stochastic star formation is ruled out given data (Kroupa et al. 2013; Pflamm-Altenburg et al. 2013).

A few cases in point which are fielded as arguments against the IGIMF Theory:

- In studying if a physical most-massive-star–star-cluster-mass ($m_{\rm max} - M_{\rm ecl}$) relation exists, Maschberger and Clarke (2008) write in their abstract "Although we do not consider our compilation to be either complete or unbiased, we discuss the method by which such data should be statistically analyzed. Our very provisional conclusion is that the data are not indicating any striking deviation from the expectations of random drawing." This one last sentence, *which only expresses an opinion*, does all the damage, as this paper is being cited as evidence against the existence of a physical $m_{\rm max} - M_{\rm ecl}$ relation. But Maschberger and Clarke (2008) culled their original data multiply times until they obtained a remnant distribution consistent with random selection of the most massive star from a model IMF, given N stars in a model. That is, their modelling did not demonstrate that stochastic sampling from the IMF is a preferred model. Further, they did not test the hypothesis whether the $m_{\rm max} - M_{\rm ecl}$ relation is ruled out by their data, and their analysis is made redundant in any case by the new data obtained by Kirk and Myers (2011) which show a very small spread at the low-mass end ruling out stochastic sampling (Weidner et al. 2013a).
- Analyzing the spatial distribution of massive stars, Parker and Goodwin (2007) argue that 4 % of O stars which have been interpreted to have formed in isolation are consistent with stochastic/random sampling from the stellar IMF and therewith they argue against the existence of a physical $m_{\rm max} - M_{\rm ecl}$ relation. However, this exercise has become redundant because Gvaramadze et al. (2012) have gathered data which show that virtually all of the previously thought 4 % "isolated" O stars are most likely runaways. The remaining fraction of O stars that cannot be identified as such is so small that it is not significant, but Gvaramadze et al. (2012) demonstrate that it is consistent with the expected fraction of O stars which cannot be traced back to their birth cluster due to the *two-step ejection mechanism* (Pflamm-Altenburg and Kroupa 2010). This mechanism operates by a massive binary being dynamically ejected from its birth cluster, and when the primary explodes as a supernova, the secondary is launched on a random trajectory depending on the phase of its orbit. Thus again, this "evidence against a physical $m_{\rm max} - M_{\rm ecl}$ relation" does not stand up to scrutiny.
- Notwithstanding the above rebuttals of the claims based on resolved populations fielded against the existence of a physical $m_{\rm max} - M_{\rm ecl}$ relation, Andrews et al. (2013) deduce, from their observations of unresolved very young clusters in a distant dwarf galaxy, that the relation is not evident and that the IMF is randomly

sampled. The problems their analysis suffers from are pointed out by Weidner et al. (2014), who show that once the analysis is done correctly, the same data in actuality are consistent with the physical $m_{max} - M_{ecl}$ relation. Not wavering in their quest to argue that the relation does not exist, they repeat their analysis in Andrews et al. (2014) for another galaxy publishing a paper with significant text overlap with the previous one.

- There are other claims, none of which stand up to closer scrutiny, such as sometimes unwarranted criticism of the selection by Weidner et al. of the $m_{max} - M_{ecl}$ data: the selection is based on two criteria only, namely the very young cluster has to be of age smaller than 4 Myr and must not have evidence for a supernova explosion, and the partially very large uncertainties are carried through properly into the analysis (Weidner et al. 2013a). Or, claims are put forward for cases of isolated massive star formation in nearby galaxies (such as in 2012, Bressert et al. (2012)) as an argument for stochastic star formation based on oversimplified O-star propagation times, ignoring, for the sake of the argument it seems, that a major star-forming region contains many compact embedded clusters and that the two-step ejection mechanism pointed out in 2010 (Pflamm-Altenburg and Kroupa 2010) leads to O stars that cannot be traced back to their birth cluster. One of the authors of that study just said "Who cares?" when I pointed out that this mechanism most probably explains all their "isolated" O stars.

It is true that mistakes may happen, but these cases are mentioned here as a documentation of possible evidence as to how the scientific publications are sometimes designed in order to portray an opinion rather than from evidence. Indeed, that the natural sciences have a crisis is well known (see p. 558), and the above suggests that astronomy is not an exception.

Isolated massive star formation and the $m_{max} - M_{ecl}$ relation are central issues in the IGIMF Theory, because massive stars can, according to this theory, only form in embedded clusters. It is this relation which leads to galaxies with a low SFR, and which therefore form low-mass embedded clusters only, to have a deficit of massive stars compared to a statistically under-sampled IMF. Thus, if it could have been shown that the $m_{max} - M_{ecl}$ relation does not exist, then the IGIMF Theory with all its implications for galactic astrophysics and cosmological star formation would not be valid in the way it has been applied.[6] It is amusing to see how, as the evidence mounts which demonstrates that the relation is physical, a few teams are attempting to move their criticisms to ever more distant galaxies. For example the attempts to prove that isolated massive star formation does occur (which would violate the

[6] A weaker form of the IGIMF Theory persists nevertheless if it is assumed that all stars are formed in clusters which follow a cluster mass function. Only in the trivial and unphysical case that star formation is modelled as purely stochastic drawing of stars from an invariant IMF throughout a galaxy without further constraints would the IGIMF Theory imply IMF=IGIMF (Weidner and Kroupa 2006) therewith violating the observational evidence that galaxies with a higher SFR have a systematically top-heavy IMF.

$m_{\rm max} - M_{\rm ecl}$ relation here) in external galaxies where such opinions (rather than robust calculations) can be barely disproven, given the extreme distances involved, are heraldic. Or, publishing opinions in the abstracts of peer-reviewed journal papers that unresolved very young (but partially shrouded) clusters in distant galaxies disprove the existence of the $m_{\rm max} - M_{\rm ecl}$ relation are comic at best. Most researchers do not have the time to analyze research papers in much detail, and all too often the contents of an abstract are adopted without careful perusal of the solidity of the contents. Thus opinions may be propagated which lack a firm scientific foundation to, with time, solidify a wrong but majority view.

At the end of the day, this situation is becoming as unsolvable as someone claiming that Newton's law of universal gravitation is falsified because in some distant apple trees there is evidence that some apples did not actually drop down, thereby ignoring that unseen animals devour the vanished apples. In this case the claim may not be falsifiable if the animals are unobservable (too small, too quick).

Does the IMF get heavier with M^*, σ and Z?

Yes, it does. There is strong evidence suggesting that the IMF in individual star formation events, i.e. in embedded clusters, becomes top-heavy with increasing density and decreasing metallicity (p. 611; see footnote 3 concerning the bottom-heavy IMF). The mathematical dependency on density is stronger though, such that in extreme galaxy-wide star bursts in which self-enrichment with metals from type II supernovae proceeds rapidly, the galaxy-wide IMF (GWIMF, Eq. 8.1) becomes top-heavy in galaxies with $SFR > 1\,M_\odot/yr$. Massive elliptical (E) galaxies are understood to have formed with very high SFRs ($> 10^3\,M_\odot$/yr) on a short (< 1 Gyr) time scale, while lower-mass E galaxies took longer to form (Gargiulo et al. 2015; Recchi et al. 2009).

Thus, based on the IGIMF Theory it is expected that very massive galaxies have a particularly heavy stellar population per unit light, which consists of a substantial fraction of white dwarfs, neutron stars and stellar mass black holes (Gargiulo et al. 2015; Weidner et al. 2013c). Figure 8.3 shows the results of an IGIMF model in which the metallicity is assumed to be solar.

Thus, a 10^{11} yr old massive E galaxy weighing $10^{12}\,M_\odot$ in stellar mass which formed within 0.5 Gyr (Gargiulo et al. 2015; Recchi et al. 2009) would contain about as much mass in dark stellar remnants as in shining stars, while a low-mass E galaxy ($10^8\,M_\odot$) which formed with a SFR of $< 1\,M_\odot$/yr would only have 35 % mass in dark remnants in addition to its stellar mass. Detailed IGIMF results on the dynamical M/L ratios of E galaxies in comparison to observational constraints are available in Gargiulo et al. (2015). Because the mass, M, metallicity, Z and velocity dispersion, σ of E galaxies are correlated positively (Cappellari et al. 2012, 2013), a heavier IMF per unit light correlates with larger M, Z, σ. Note that the previous result reported by Cappellari et al. (2013) that more massive E galaxies need a Salpeter IMF which has more faint (essentially dark) M dwarfs rather than a canonical IMF which has fewer M dwarf stars is degenerate with the alternative IGIMF Theory, namely a top-heavy GWIMF with more dark remnants in more

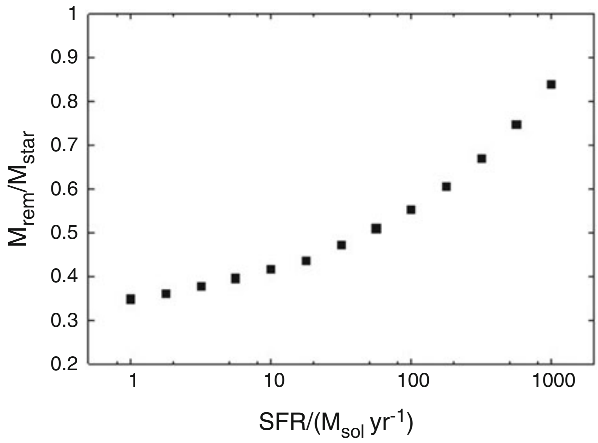

Fig. 8.3 The fraction of mass in stellar remnants (white dwarfs, neutron stars, stellar black holes), $M_{\rm rem}$ divided by the total mass in shining stars with masses smaller than $0.8\,M_{\odot}$, as a function of the SFR of a galaxy. The IGIMF is calculated according to Weidner et al. (2013c) assuming the mildly variable mass function of star formation events (i.e. of embedded clusters) and solar metallicity (see Fig. 8.2). The production of stellar remnants is treated as in Dabringhausen et al. (2009). Kindly provided by Jan Pflamm-Altenburg

massive E galaxies and a GWIMF which is closer to the canonical IMF for low-mass E galaxies.

A pioneering study in which the formation and evolution of E galaxies in a SMoC Universe is studied self-consistently by employing the IGIMF Theory has been made by Gargiulo et al. (2015). Their conclusions are rather remarkable, namely that E galaxies appear to be better described by the IGIMF theory rather than the customary invariant Salpeter IMF. They emphasize in their discussion "In general, when the argument of a variable IMF is considered to explain the [α/Fe]-stellar mass relation, the proposed IMF is treated as a free parameter..., or is varied with exploratory aims..., following no particular theory and leaving unexplored a vast region of the corresponding parameter space. In this work, we test the well defined theory regarding the integrated initial mass function of stars in galaxies with top heavy IMFs in star clusters during starbursts".

Concerning disk galaxies, the IGIMF Theory has been shown to reproduce the observational constraints on how the GWIMF varies with SFR, as discussed at p. 616.

Why is the problem of the IMF related to the DM problem?

The IMF is related to the dark matter problem because a top-heavy IMF yields dark stellar remnants which behave dynamically like cold dark matter. Thus, as Fig. 8.3 demonstrates, a massive E galaxy which formed with a high SFR$>$ $1000\,M_{\odot}/\mathrm{yr}$ would contain as much mass in dark stellar remnants as in shining stars. An astronomer analyzing the dynamical M/L ratio assuming a universal invariant IMF would wrongly conclude that the massive galaxy contains dark matter. Further, the same hypothetical astronomer may also make wrong deductions on the validity of Milgromian dynamics (Sect. 7.7).

How the galaxy-wide IMF affects fundamental physics is influenced subtly in star-forming dwarf disk galaxies (i.e. dIrrs). These are supposed to be dark matter dominated within their inner region. The large cores of their putative dark matter halos are, however, naturally and self-consistently explained in Milgromian dynamics without dark matter (Famaey and McGaugh 2012). Now, in order to calculate the contribution by stars to the potential, a galaxy-wide IMF is required. If an invariant IMF is used for an ensemble of dIrr galaxies which have different SFRs, the contribution by dark stellar remnants would be calculated to be wrong, if instead the IGIMF Theory were the correct description. Thus, a dIrr galaxy with an extremely low SFR (say SFR$= 10^{-4} M_{\odot}/\mathrm{yr}$) would appear to have a redder stellar population compared to a model with a canonical IMF, because the IGIMF contains fewer massive stars at this SFR (Sect. 8.4, Fig. 8.2). This may lead to errors in the age and/or metallicity deduction, but will also affect the calculation of the potential. If this is not taken into account, it may be concluded that Milgromian dynamics does not work well in dIrr galaxies unless Milgrom's constant a_0 is adjusted systematically with the mass of dIrrs. This has indeed been found to be the case (Randriamampandry and Carignan 2014), but it is unclear at this stage whether using the IGIMF Theory would alleviate this possible tension of Milgromian dynamics with the data. Detailed modelling will be required to study this issue thoroughly.

This highlights how the stellar IMF in galaxies affects our ability of constraining fundamental physics.

Questions for Reinaldo de Carvalho:
you have worked a lot on the problem of the IMF. Would you present us briefly the main scientific results of your investigation on this item? What kind of observations could help to clarify the alleged universality of the IMF?

How does a galaxy form its stars? What determines the total stellar content of a galaxy? The answers to these seemingly simple questions have eluded astronomers for over half a century. Star formation starting from a cold gas cloud is an extraordinarily complex problem and probably one of the most difficult in modern astrophysics. This challenging "closed-box" scenario is further complicated by the fact that most galaxies reside in larger structures, where they interact with both their neighbors and the diffuse material present in groups and clusters. What can we do to make progress on disentangling the many processes that affect the stellar mass buildup of galaxies, and understanding which ones are dominant ?

The study of the formation and evolution of galaxies in general requires their systematic observations over a large redshift range in order to pinpoint the mechanisms responsible for the properties of galaxies as they are observed today ($z = 0$). Ensuring that the datasets for local and distant galaxies contain the same objects—or more correctly, today's galaxies and their actual progenitors—itself requires knowledge of the very evolution we are seeking to understand. Early-type galaxies (ETGs), with their predominantly old stellar populations, provide the simplest systems with which to address these questions. It is simpler to observe galaxies in the nearby Universe compared to their counterparts at high redshift. This simple fact can introduce serious biases in our interpretations when comparing different samples of galaxies from different cosmic epochs. For nearby samples, once homogeneous and high-quality data became available, the study of ETGs progressed very rapidly. Now, we can investigate in detail how these systems formed, how their stellar populations evolved, and how their structural properties are modified by the environments in which they reside (Kormendy and Bender 2012; La Barbera et al. 2014).

We embarked on a longterm project back in 2008 (myself, Dr. Francesco La Barbera, and later Dr. Ignacio Ferreras) starting with the development of a package called 2DPHOT, a multi-purpose environment for the two-dimensional analysis of wide field images (La Barbera et al. 2008). This was part of a more ambitious Virtual Observatory (VO) project that is still ongoing (De Carvalho et al. 2009). The main goal of this project (SPIDER—Spheroids Panchromatic Investigation in Different Environmental Regions) was to coherently investigate the general properties of ETGs, like the fundamental plane and its environmental dependence, colors and color gradients, and the star formation history (La Barbera et al. 2010a,b,c; Trevisan et al. 2012). We studied a sample of ∼40,000 ETGs selected from SDSS-DR6, which, when matched against near infrared data from UKIRT Infrared Deep Sky Survey-Large Area Survey (UKIDSS-LAS) (DR4) comprises 5080 bright ($M_r <$ 20) ETGs, in the redshift range of 0.05 to 0.095 with *grizYJHK* photometry and spectroscopy. By conducting a systematic study of ETGs, we ended up focusing on the fundamental question of the universality of the initial mass function (IMF)—an essential component to the theory of galaxy formation.

Detailed examination of the IMF—the distribution of stellar masses in a single population at the time of birth—is a fundamental tool for understanding star formation in galaxies. In mathematical terms, the IMF expresses the distribution in mass of a newly formed stellar population as $\mathrm{d}N/\mathrm{d}M \propto \mathrm{m}^{-x}$, with masses in ($M$, $M + dM$). Some authors adopt the logarithmic slope (as we do) $\Gamma = x - 1$. It has been usually considered a universal function, partly because of the complexities in obtaining proper observational constraints. The single power law approximation proposed by Salpeter (1955) has undergone numerous updates, with more complex functions that include a significant flattening of the slope for low-mass stars (Chabrier 2003; Kroupa 2001; Scalo 1986). For a recent review on the IMF and its possible variations, see Bastian et al. (2010).

Studying a sample of ∼40,000 ETGS from our SPIDER project, Ferreras et al. (2013) found a strong correlation between a galaxy's central velocity dispersion and the slope of the IMF, indicating an excess of low mass stars in massive ETGs. This means that low mass ETGs are well described by a Kroupa IMF, while massive ETGs require a bottom-heavier IMF. La Barbera et al. (2013) analyze several spectral indices, combining gravity-sensitive features with age- and metallicity-sensitive indices, while also considering the effects of non-solar abundance variations. They conclude that central velocity dispersion, rather than alpha-enhancement, [α/Fe], drives the variation of the IMF. Although the analysis cannot discriminate between a single power-law (unimodal) IMF and a low-mass ($\leq 0.5 M_{\odot}$) tapered (bimodal)

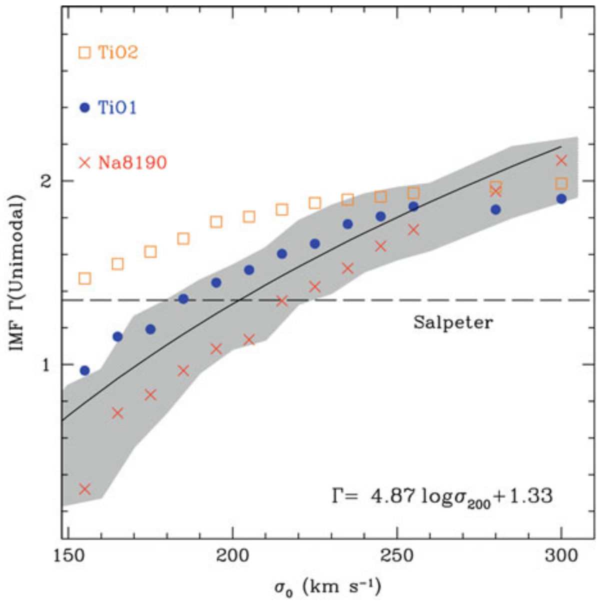

Fig. 8.4 The variation of the IMF slope vs. the central velocity dispersion, σ_0 (see text)

IMF, robust constraints can be inferred for the fraction of low-mass stars at birth. Figure 8.4 shows the variation of the IMF slope—unimodal distribution—against central velocity dispersion, which corroborates other findings based on dynamical (e.g. Cappellari et al. (2006)), stellar population analyses (Conroy and van Dokkum 2012a,b), and strong gravitational lensing analysis (e.g. Treu et al. (2010)). The shaded region corresponds to the 68 % confidence level of the joint Probability Distribution Function (PDF) including spectral fitting and all three line strengths (TiO1, TiO2 and Na8190). The horizontal dashed line indicates the Salpeter case. These results expressing the non-universality of the IMF have strong implications for theories of galaxy formation and star formation.

The IMF is one of the key unknowns in modern astrophysics and there is still great debate on its universality. It is still unclear whether it varies from place to place within a galaxy and from galaxy to galaxy. In order to clarify these issues four main paths should be taken (at least):

1. The approach of investigating the IMF through the stellar population properties of ETGS is a promising one, especially if we extend the wavelength range over which we probe the stellar content. Infrared spectroscopy out to K-band should allow us to minimize the degeneracy between true IMF variations and element abundance ratios. Along these lines, the ingredients of a Single Stellar Population (SSP) are still uncertain, deserving further detailed study (e.g. stellar evolution, stellar atmospheres, high quality stellar cluster data). In particular, theoretical and empirical work on the stellar atmospheres of cool stars is essential.

2. Originally the IMF was determined using the luminosity function of stars in the solar neighborhood plus the luminosity-mass relation and stellar lifetimes. With expanding high quality data for stars covering a much larger volume in our galaxy, we may be able to understand better the shape and variability of the IMF from place to place. Using `GAIA`'s astrometric and spectrophotometric data in our galaxy and the resolved stellar populations of nearby galaxies, we will be able to tackle the star formation history of such objects, as well as to reliably estimate their initial mass functions.
3. Observations of the cold gas in nearby galaxies reveal a more or less correlated core mass function (CMF), i.e. the masses of pre-stellar cores, and the IMF. Recent studies have investigated the relation between the CMF and the stellar IMF through numerical simulations and that is a crucial topic for the years to come—to understand what is the role of internal turbulence and external sources on the CMF by means of direct numerical simulations in grid and SPH numerical schemes.
4. The observed variations of the IMF in massive ETGs correspond to a different ISM (Inter Stellar Medium): the physical conditions of the gas in these systems (pressure, turbulence, etc.) is expected to lead to a drastically different fragmentation process. Theoretical work on this topic is of paramount importance.

The IMF is only one side of the problem of reconstructing the star formation history of a galaxy. With the next interviews we open the discussion on the physical conditions of the star formation process and on the rate with which galaxies form stars across the Hubble time.

8.5 The Star Formation and the Rate of Star Formation

Questions for Cesare Chiosi:
the Schmidt-Kennicutt law, linking the star formation to the amount of gas available in a galaxy, was established on the basis of observations. Could you remind us which observations have prompted this law? Is this law valid everywhere, and if not why? Could you briefly review for us how this law has been used to understand the process of star formation in galaxies?

Let me shortly recall the main steps on the observational evidence for the dependence of the star formation rate on the gas content: long ago Maarten Schmidt (1959), examining the stellar content of the solar vicinity, assumed that the rate of star formation for population I stars varies with a power n of the gas density, $d\rho_g/dt = -k\rho_g^n$, where k and n are constants to be fixed by observational data. The exponent n was derived from the relative distribution of young stars and gas perpendicular to the galactic plane. The value of n turned out to be about 2. Subsequently, Talbot et al. (1975) set the ground for the chemical evolution of disc galaxies (like the Milky Way), presenting a model including the radial distribution of the surface mass density of gas and stars (Σ_g and Σ_s) with radial profile of the total mass Σ in agreement with the rotation curve of the disc, the Schmidt law of star formation, and the multi-zone description of chemical enrichment (in cylindrical symmetry). More relevant to our question, the (Schmidt 1959) rate of star formation expressed by the gas volume density was translated into a new law in terms of Σ_g regulated by the balance between the gravitational settling of gas onto the equatorial plane and heating of this by the energy injection from SNa explosions. The new star formation rate is

$$\frac{1}{\Sigma(r)}\frac{d\Sigma_g(r)}{dt} = -\nu_\odot \left[\frac{\Sigma(r)}{\Sigma(r)_\odot}\right]^{2(n-1)} \left[\frac{\Sigma_g(r)}{\Sigma(r)}\right]^n$$

where the parameter k is now replaced by $\nu_\odot$.

The Talbot et al. (1975) model was extended by Chiosi (1980) to the case with infall of gas (either primordial or already metal enriched). Assuming cylindrical symmetry, the mass in each cylindrical shell was supposed to increase by infall of gas from outside (whereas radial motions of gas were neglected). The rate of gas accretion included two sources. The first one with rather short time scale (say from 1 to about 3 Gyr) was meant to simulate the fast initial accumulation of gas by dynamical collapse, the second one with much longer time scale (say from 5 to 10 Gyr) was supposed to simulate the slow accretion onto the galactic disc of gas from the surrounding halo. Owing to very short time scale of energy input from short-lived stars, it was conceivable to suppose that at any time disc did not depart significantly from an equilibrium configuration and hence from the (Talbot et al. 1975) scheme, the only major difference being that the surface mass density of gas is let increase with time. Under these assumptions the rate of star formation in the (Chiosi 1980) view became

$$\frac{d\Sigma_g(r,t)}{dt} = -\tilde{\nu}\left[\frac{\Sigma(r,t)\Sigma_g(r,t)}{\Sigma(\tilde{r},t)^2}\right]^{n-1} \Sigma_g(r,t).$$

The quantities $\tilde{\nu}$ and $\Sigma(\tilde{r},t)$ are the specific star formation efficiency and the total surface mass density at some critical radial distance from the galactic centre. They are introduced for the purposes of normalization and dimensionality, however they can also assume the meaning of some physical process controlling the radial dependence of star formation, e.g. tidal interaction between the remaining gas at the distance r and the total amount of mass in stars already accumulated in the internal regions. The spatial and temporal behaviour of the above star formation rate is such that at any given time the rate is strongly inhibited at distances $r > \tilde{r}$, whereas at any distance r the star formation rate starts small, increases to a peak value and then declines, a trend that has been confirmed by the observational data not only in disc galaxies but also in spheroidal systems, e.g. (Chiosi et al. 2014; Renzini 2006) for recent reviews of the subject.

The Chiosi (1980) model has been widely used for more than three decades with various degrees of complexity, it was extended to galaxies of different morphological type from irregulars to discs and spheroidals even in presence of DM (see Matteucci (1996, 2001, 2014); Tantalo et al. (1996, 1998) for recent reviews and referencing). It was used to study the mass to light ratios of disc galaxies (Portinari et al. 2003, 2004) and constrain the IMF (Portinari and Chiosi 1999). It was taken as the backbone of many studies of population synthesis (Bressan and Chiosi 1994; Bressan et al. 1996; Cassarà et al. 2014; Piovan et al. 2006b, 2011a,a; Tantalo et al. 1996, 1998). It was extended to include the radial motions of gas (Portinari and Chiosi 2000). Finally, it was even used to simulate the chemical evolution of the intra-cluster medium as a result of inflow of primordial gas into the gravitational well of a cluster and ejection of nuclearly processed material by galactic winds (Moretti et al. 2003).

In a long series of observational studies, Robert Kennicutt (and collaborators) systematically investigated the efficiency of the star formation rate along the Hubble sequence with particular attention to the late type galaxies and the dependence of the rate on large scale quantities. To mention a few we recall here the studies (Kennicutt 1983, 1989; Kennicutt et al. 1994; Kennicutt 1998a,b). Many observational indicators of stellar activity in different galaxies are considered, e.g. (i) Integral colors and spectra, and synthesis modeling; (ii) Ultraviolet continuum; (iii) Recombination lines; (iv) Forbidden lines; and (v) Far-infrared continuum. For all details see Kennicutt (1998b). It is worth calling attention here on the fact that large-scale star formation in galaxies customarily takes place in two very distinct physical environments: one in the extended discs of spiral and irregular galaxies; the other in compact, dense gas discs in the centers of galaxies. Each of these provides an estimate of the SFR as a function of some measurable parameter for a large number of nearby galaxies, thus delineating the main trends in SFRs and star formation histories along the Hubble sequence. Comprehensive analyses of the global SFRs of galaxies have been carried out over the years (see Kennicutt (1998b) for exhaustive referencing).

The absolute SFRs in galaxies, expressed in terms of the total mass of stars formed per year, show an enormous range, from virtually zero in present-day gas-poor elliptical, S0, and dwarf galaxies to 20 $M_\odot\, yr^{-1}$ in gas-rich spirals. Much larger values up to 100 $M_\odot\, yr^{-1}$ are measured in star-burst galaxies, and SFRs as high as 1000 $M_\odot\, yr^{-1}$ may be reached in the most luminous IR star-burst galaxies. Since the large range in the SFRs simply reflects the range of masses of the underlying galaxies, it is worth normalizing the SFR to the galaxy mass. Although there is a strong trend in the average SFRs with Hubble type, a dispersion of a factor of 10 is present in SFRs among galaxies of the same type. Several factors contribute to the SFR variations, including variations in gas content, nuclear emission, interactions, and possibly short-term variations in the SFR within individual objects. In any case, a robust correlation between the SFR and the galaxy type is indicated by the observational data. In the case of disc galaxies the SFR correlates with the surface mass density of gas. The dependence is $\Sigma_{SFR} = A\Sigma_g^n$, where Σ_{SFR} is the surface mass density of star formation in $M_\odot\, yr^{-1}\, kpc^{-2}$, A is a proportionality constant, and n falls in the range 1.5 to 2. Examining the typical global efficiencies of star formation and gas consumption time scales, it turns out that a average disk converts about $\sim$ 5% of its gas every 10^8 years. Since the typical gas mass fraction in these disks is about 20 %, this implies that the stellar mass of a disk grows by about 1 % per 10^8 years, i.e. the time scale for building the disc (at the present rate) is comparable to the Hubble time. The efficiencies can also be expressed in terms of the average gas depletion time scale, which is about 2 Gyr. Which other global properties of a galaxy influence its SFR? It is plausible to expect the mass, bar structure, spiral arm structure, or environment to be important, and empirical information on all of these are available so that their effects can be taken into account. Following the same line of reasoning, Kennicutt (1998b) focuses on the range of star formation properties of the nuclear regions and the patterns in these properties along the Hubble sequence, highlighting the effects of the environment and of galaxy-galaxy interactions. Finally, all the observations described above can be fitted together into a coherent evolutionary picture of disk galaxies and the Hubble sequence. He summarizes the evolutionary implications of these data, taking into account the distinct patterns seen in the disks and galactic nuclei and concludes with a discussion of the critical role of the interstellar gas supply in regulating the SFR, across the entire range of galaxy types and environments, Finally the following expression for the SFR is given

$$\frac{d\Sigma_g}{dt} = -(2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_g}{1\, M_\odot\, pc^{-2}} \right) \;\; M_\odot/yr/kpc^2$$

which closely resembles the SFR proposed long ago by Talbot et al. (1975). Amazingly enough, the Schmidt-Kennicutt law of star formation was largely adopted in chemical models of galaxy evolution even before its observational discovery or confirmation.

The stellar mass of a galaxy is a key astrophysical parameter to know. There are however significant differences in the mass value coming from the different theoretical approaches. Could you tell us why? What produces such differences? Are we able to derive the mass of every kind of galaxies independently on their morphology and redshift?

Galaxy masses play a fundamental role in our understanding of structure formation models. A recent review of the subject is by Courteau et al. (2014) to whom I will refer. The review addresses the variety and reliability of mass estimators that pertain to stars, gas, and dark matter. In what follows I will focus on masses derived from stellar populations, leaving dynamical masses of gas-rich and gas-poor galaxies and masses from weak and strong lensing methods aside. The estimate of a galaxy's stellar mass heavily rests on the theory of population synthesis. In brief, the stellar content of a galaxy of age T is conceived as a manifold of stellar populations with different age [τ], chemical composition [X,Y,Z], degree of enhancement in α-elements with respect to the solar partition, initial mass function [$\phi(m)$, slope(s) x and the lower ant upper mass boundaries, m_l and m_u, respectively], this in turn determines the mass of SSP, and finally the spatial distribution of the stellar generations. Each of these SSPs is weighed on the star formation rate [$\Psi(t)$], where

τ is the age of formation ($\tau = T - t$). By construction, the total mass of the stellar content of a galaxy is

$$M^*(t) = \int_0^T \Psi(t) \times M_{SSP}(\tau) dt,$$

where $M_{SSP}(\tau)$ is the current total mass of a SSP of age τ.

$$M_{SSP}(\tau) = \int_{m_l}^{m_{ev}(\tau)} m\phi(m)dm + \int_{m_{ev}(\tau)}^{m_u} m_R(m)\phi(m)dm,$$

where m_R is the remnant mass of a star of initial mass m, m_{ev} is the most evolved mass and $m_{ev} \rightarrow m_u$ for $\tau \rightarrow 0$. M_{SSP} is not constant with time because part of the initial mass in stars is lost by stellar winds and supernova explosions. Each star contributes with the mass $\Delta m = m - m_R(m)$. Only stars with lifetime shorter than the age of the Universe can contribute to ΔM, i.e. $m \simeq 0.8\, M_{\odot}$. The evolution of stars of different mass is sufficiently well known so that the current mass of SSPs in living stars and remnants (White Dwarfs, Neutron Stars, and Black Holes) can be easily evaluated. Stars in the mass interval $0.8 \leq m \leq 6\, M_{\odot}$ end up as WDs with mass $m_{WD} \propto m$ in the range 0.5 to 1.2 $M_{\odot}$. Stars in the mass interval $6 < m < 30\, M_{\odot}$ end up as neutron stars of about $1.4\, M_{\odot}$. Finally, stars more massive than about $30\, M_{\odot}$ end up as Black Holes with mass greater than $1.4\, M_{\odot}$. Stellar winds and SNa remnants refuel the interstellar medium and part of this gas may be lost by a galaxy. It is worth recalling that the mass in ejecta can be a significant fraction of the total initial SSP mass depending on the IMF.

In a similar way, with the aid of the population synthesis technique we may calculate the total SED as a function of time and hence the total luminosity (both bolometric and in any pass-band $\Delta\lambda$ according to the photometric system in use). The integrated monochromatic flux generated by the stellar content of a galaxy is defined as

$$F_{\lambda}(T) = \int_0^T \Psi(t, Z)\; sp_{\lambda}(\tau', Z) dt$$

where

$$sp_{\lambda}(\tau', Z) = \int_{m_l}^{m_u} \phi(m)\, f_{\lambda}(m, \tau', Z) dm$$

is the integrated monochromatic flux of a SSP.

In order to calculate the flux $sp_{\lambda}(\tau', Z)$ emitted by an SSP, we must construct isochrones in the CMD. The more accurate this calculation, the more precise are the fluxes for the whole galaxy. It is worth recalling that the precise shape of an isochrone depends on the properties of the underlying evolutionary tracks, while the relative number of stars in different portions of the isochrone is governed by the assumed $\phi(M)$ and the lifetimes of the stars present in the isochrone in different evolutionary stages.

The total luminosity of an SSP is obtained by integrating $sp_\lambda(\tau', Z)$ over the whole range of wavelengths

$$L_{SSP}(\tau', Z) = \int_0^\infty sp_\lambda(\tau', Z) d\lambda$$

from which the integrated absolute bolometric magnitude immediately follows

$$M_{bol} = -2.5 \times Log(L_{SSP}/L_\odot) + 4.72$$

Adopted a given photometric system, the integrated magnitudes $M_{\Delta\lambda}$ of SSP and of a galaxy as a whole are obtained by convolving the SED with the response functions of the pass-bands, see for instance (Girardi et al. 2002, 2003, 2004).

Finally, we derive the mass to luminosity ratios M_*/L and $M_*/L_{\Delta\lambda}$ for SSPs and whole galaxies. It goes without saying that the galaxy mass to light ratios are in one to one correspondence with those of SSPs. Throughout the whole procedure to calculate the mass and the luminosities (both bolometric and in pass-bands) of SSPs and whole galaxies there are several points of great uncertainty, chief among which are: the isochrones, the monochromatic fluxes over the whole spectrum which requires large and complete libraries of stellar spectra at varying gravity, effective temperatures, and chemical parameters, the use of a system of pass-bands to define broad-band magnitudes and colors, the IMF, and, in the case of galaxies, the histories of star formation and chemical enrichment, i.e. $\Psi(t, Z)$ and $Z(t)$.

Since the classical IMF by Salpeter (1955), $dN/d\log m \propto m^{-1.35}$, many alternatives have been suggested, e.g. the multi-slopes IMFs by Kroupa (2001); Scalo (1986); Chabrier (2003). Indeed, much of the attention is paid to the slope of the IMF in the mass interval relative to stars most contributing to chemical enrichment of the ISM during the Hubble time (13.7 Gyr), e.g. $m \geq 0.8 M_\odot$, whereas the real issue with the mass determination is the portion of the IMF storing stars that live for ever (or whose lifetime is much longer than the age of the Universe. The lower mass limit m_l and slope of the IMF for $m_\leq 0.8 M_\odot$ drive the whole problem. The slope can be negative (as for the high mass end), zero or even positive. Therefore the mass in stars contained in this mass interval can be high, constant or small depending on the slope. Larson (1998) suggests the following simple analytic form: $dN/d\log m \propto m^{-1.35} exp(-m_1/m)$ (case a). This function has a logarithmic slope $x = 1.35 - m_1/m$, so it approaches a power law with the Salpeter slope $x = 1.35$ at large masses, peaks at a mass $m_p = m_1/1.35$, and falls off exponentially with increasingly negative x at lower masses. Since this function has a steeper fall-off at the low end than is suggested by most of the evidence mentioned above, Larson (1998) considers also the possibility that the IMF does not decline at all at the low end. If brown dwarfs are as common as is suggested by the most optimistic recent estimates, and if the IMF accordingly is approximately flat at the low end, it may be represented approximately by the following simple alternative form: $dN/d \log m \propto (1 + m/m_1)^{-1.35}$. This function is very similar to case (a) at masses above m_1 and has a logarithmic slope $x + 1.35(1 + m_1/m)^{-1}$, so that it again approaches the Salpeter form at large masses but becomes asymptotically flat with $x \simeq 0$ at the low end (case b).

Approximations (a) and (b) are thus consistent with the evidence that the IMF typically has a Salpeter form for large masses, while there is a large range of uncertainty or variability for the lower masses, and also the possibility that the mass-scale m_1 may be variable. The mass-scale m_1 might be expected to be related to a fundamental scale in the star formation process such as the Jeans mass, and evidence supporting this possibility has been discussed by Larson (1998) and references.

Along the same line of thought, using numerical simulations of star formation in the ISM, Padoan et al. (1997) suggested a universal law for the IMF whose slope and peak value (in that similar to the Larson (1998) case a) change with the physical properties of the ISM, i.e. temperature, density and velocity dispersion. Chiosi et al. (1998) applied it to study a number of properties of galaxies (ellipticals in particular) that could find a coherent explanation in terms of systematic changes of the IMF from massive to low mass galaxies. In particular a top heavy IMF for stars above $1\,M_{\odot}$ was predicted for young massive ellipticals. Indeed a top heavy IMF is suggested by Baugh et al. (2007) for high redshift massive dusty and bursty distant galaxies. All this, to remind the reader that the shape of the IMF over the mass interval in which stars are formed bears very much on the total mass of each SSP and hence the total stellar mass of a galaxy.

The second great unknown is $\Psi(t)$, for which there are ample possibilities and uncertainties. Roughly speaking, from the observational point of view $\Psi(t)$ is discontinuous, bursty and irregular in low mass galaxies (e.g. the small irregulars, the dwarf galaxies), nearly constant with mild variations in spiral galaxies, and bell-shaped, namely it start small in past grows to a peak value with a certain time scale (about a few hundred thousand years) and then it declines with a time scale from one to a few Gyr in large mass objects (e.g. ellipticals). This is possible for galaxies of the local Universe, in which the bright component of the stellar populations can be resolved into stars thus providing CMDs and LFs. In most cases $\Psi(t)$ is simply assumed to have an analytical dependence on time according to one of the three schemes above depending on the type of galaxy one tries to simulate. Alternatively, it is supposed to depend on the volume gas density to a certain power, typically $\Psi(t) = c * d\rho_g^n/dt$, where c^* is the specific efficiency that varies in range from 0.01 to 0.1, and n falls in the range 1 to 2. In the case of spiral galaxies the volume density of gas is replaced by the surface mass density of gas $\sigma_g(t)$. Via the time dependence of the gas content, the type of star formation and the temporal behaviour of $\Psi(t)$ in turn may fall in one of the above categories depending on the physical phenomena governing the formation of a galaxy out of the cosmological tissue. Good examples of it are the NB-TSPH simulations of elliptical-like galaxies of different total mass (dark and baryonic material) and different initial over-density with respect to cosmological background, in which under the same rate of star formation $d\rho_g/dt$ we end up with different $\Psi(t)$ according to the value taken by the two parameters: bell-shaped in massive and/or high over-density systems and bursty and irregular in low-mass, low over-density systems (see Chiosi and Carraro (2002); Chiosi et al. (2014); Merlin and Chiosi (2006, 2007); Merlin et al. (2012) for more details). The case of spiral and irregular galaxies can be reproduced adding some angular momentum.

The third point of great uncertainty is the theoretical SED of a galaxy, which is needed to derive the magnitudes, colors, mass to light ratios, and line absorption indices. The SED entirely rests on our ability in modelling the elemental SEDs of SSPs at varying age, metallicity and IMF. This requires accurate and complete stellar models for ample grids of initial masses and chemical abundance parameters; accurate grids of isochrones in different CMDs; and a good coverage of the stellar atmosphere parameters (effective temperature, gravity, chemical abundances). Despite the great progress made over the past two decades (Bertelli et al. 1994, 2008, 2009; Girardi et al. 2000), the present-day situation is not fully satisfactory: spectral libraries are not complete (in particular at high and low effective temperatures), the resolution of the template stellar spectra is often insufficient, and the population synthesis technique is not fully assessed. Finally, there is the long lasting question about the computational procedure that is followed to calculate the SED, i.e. the straight integration of the contribution star by star to the integral SED versus the so-called Fuel Consumption Theorem (Audouze and Tinsley 1976; Renzini and Buzzoni 1986; Tinsley 1972). For recent discussions of all these issues see Conroy et al. (2009); Maraston (2005); Chiosi et al. (2014). The uncertainty on the elemental SEDs of SSP immediately affects the SED of the composite stellar populations.

What is the role played by dust in this context?

The advent of modern infrared astronomy has brought into evidence the role played by the interstellar dust in galaxy formation and evolution: dust not only selectively absorbs radiation (mainly from the UV) but also re-emits it in the near (NIR) and far infrared (FIR). The detailed chemical composition of the dust and spatial distribution of this in a galaxy is of paramount importance. Therefore, to fully exploit modern data, realistic spectrophotometric models of SSPs and galaxies must include this important component of the interstellar medium (ISM). In a series of papers over the past ten years Piovan et al. (Piovan et al. 2006a,b, 2011a,b,c) have addressed this issue. First they modelled the dust in the diffuse ISM and in molecular clouds (MCs), taking into account (i) three components of the dust, i.e. graphite, silicates and polycyclic aromatic hydrocarbons (PAHs); (ii) the size distribution of the dust grains; (iii) two models for the emission of the dusty ISM; (iv) reproducing the extinction curves and the emission for the Milky Way (MW) and the Large and Small Magellanic Clouds (LMC and SMC). The results are used to model the SEDs of SSPs that may be severely affected by dust at least in two types of stars: the young, massive stars while they are still embedded in their parental MCs and the intermediate- and low-mass asymptotic giant branch (AGB) stars when they form their own dust shell around. The radiative transfer problem is solved with the "ray-tracing" method, extended libraries of SSP SEDs are calculated. The theoretical SEDs successfully match the observational ones from UV to MIR and

FIR (Piovan et al. 2006a). Using these (Piovan et al. 2006b) derived the SEDs of galaxies of different morphological type and compared them with the observational data for template galaxies in the local Universe. Subsequently, Piovan et al. (2011a) derived a data base of condensation efficiencies for the refractory elements C, O, Mg, Si, S, Ca and Fe in AGB stars and SNe that can be easily applied to the traditional gaseous ejecta, in order to determine the amount and kind of refractory elements locally embedded into dust and injected into the ISM. With the aid of this, Piovan et al. (2011b) revised the properties and current chemical models of the solar neighborhood of the MW Disk (with infall and radial flows). Finally, Piovan et al. (2011c) extended the same model to the whole galactic disk. All this provided the work bench for a detailed and sophisticated chemical, spectro-photometric models for galaxies of different morphological type. Cassarà et al. (2013) using state-of-the-art models of AGB stars of low and intermediate-mass reconsidered the effect of shells of dust surrounding the AGB stars on the SED emitted by the central objects, and generated new libraries of dusty SSPs for different metallicities, ages and IMFs. The new isochrones and SSPs, have been compared with the CMDs of the field stellar populations in the LMC and SMC with particular emphasis on AGB stars, and the integrated colors of some star clusters in the same galaxies and M31. Finally, Cassarà et al. (2014) generated a new library of template models of galaxies with different morphological type from spherical structures to discs with different bulge to disc ratios and provided the magnitude and color evolution in the rest-frame and as a function of the redshift for cosmological studies. Thanks to all this, *dust has become an ordinary ingredient of population synthesis*.

Given the above premises, one may eventually get the mass to light ratios of stellar populations of different complexity and with the aid of these estimate the total mass of the stellar content emitting the light. On the theoretical side the mass to light ratios as function of the isochrones, IMF, SSPs, SEDs, and chemical parameters are highly uncertain and even worst change a lot from author to author. This is perhaps the major uncertainty for which there is no physical explanation. It is indeed entirely due to unacceptable inaccuracies in the particular algorithm of population synthesis at work. On the observational side, there are several methods to derive the M_*/L ratios by fitting spectra. Both issues have thoroughly discussed by Courteau et al. (2014) and references therein. They will not be repeated here. In the case of galaxies the great villain of the whole story seems to be the rate of star formation. The only firm conclusion is that mass to light ratios from blue pass-bands seem to scatter less than the red ones, for instance M_*/L_B vs (B-R) as compared to M_*/L_B vs (I-K) and/or M_*/L_K vs (B-R) and (I-K) see (Fig. 9 in Courteau et al. (2014)). Of course the uncertainty and scatter increase when the effect of dust is included. However, contrary to what claimed by Maraston et al. (2013) neglecting dust is not a good strategy. To conclude, the mass to light ratios are not the best way of determining the mass of the stellar content in a galaxy, unless the above points of uncertainty are systematically removed, so that *concordance* mass to light ratios for SSPs are reached (I personally recommend that (i) the task is taken by people very familiar with the subtleties of stellar evolution and (ii) the direct integration of the light and spectra emitted by the stars along the isochrones is performed), and finally the star formation and chemical histories of a galaxy are estimated from independent methods.

Questions for Alvio Renzini:
the Star Formation Rate (SFR) is the key parameter for all the studies connected with stellar population analysis. Would you explain its meaning and review how the global SFRs in galaxies are measured?

Well, the meaning is simple, the SFR is the mass of gas turned into stars per unit time, and is measured in $M_{\odot}$/yr. A whole variety of SFR indicators are currently used. Young, just formed massive stars are powerful UV emitters, part of this light is absorbed by dust and re-emitted in the Mid- and Far-IR, ionizing photons strip electrons from hydrogen atoms, which emit Balmer lines as they recombine, relativistic electrons are generated by supernovae and upon circling magnetic fields emit synchrotron radiation, and finally young, high-mass binaries with accreting neutron stars or black holes are powerful X-ray sources. So, the UV, Hα, Mid-IR, Far-IR, radio and X-ray luminosities are all used to infer the SFR, once properly calibrated.

Which techniques are generally adopted to derive it?

They are all used, though depending on redshifts some are more practical and effective than others. In the local Universe, the Hα luminosity, corrected for extinction from the measured Balmer decrement (the Hβ/Hα ratio), is perhaps the most effective way. At higher redshifts, the most reliable measurements come from combining the UV and mid/far-IR luminosities, without correcting the UV luminosity for extinction. The problem is that quite often the infrared data are not deep enough, hence for many galaxies the SFR cannot be measured in this way. In such cases one has to rely on the UV luminosity, though the extinction correction can be quite uncertain, of one can stack the IR data in several bins of stellar mass, and construct the average main sequence in this way (Rodighiero et al. 2014).

What are the limits of this concept and how good are the current measurements of the SFRs in galaxies?

As I said, the concept is simple and I don't see a *limit* to it. Actually, thanks to adaptive optics we are now capable of mapping the SFR surface density even in galaxies at $z \sim 2$, which is measured in $M_{\odot}$ yr^{-1} kpc^{-2}. Concerning the accuracy of SFR measurements, I would say that on average they are fairly good, probably within a factor of ~ 2. But occasionally, for a small number of objects, errors may be huge, with estimated SFRs orders of magnitude off the real ones. For example, dust extinction can be so high that most of the SFR is completely hidden at UV wavelengths, so SFR from UV, even corrected for reddening, can be off by large factors. In such cases, the far-IR, if available, gives the right answer. It can also happen that we make the opposite mistake: if the very red colors of an high$-z$ galaxy are interpreted as due to reddening then the extinction-corrected UV luminosity indicates a very high SFR, whereas the galaxy may have been red because there was no star formation at all and the galaxy was actually quenched (Rodighiero et al. 2014).

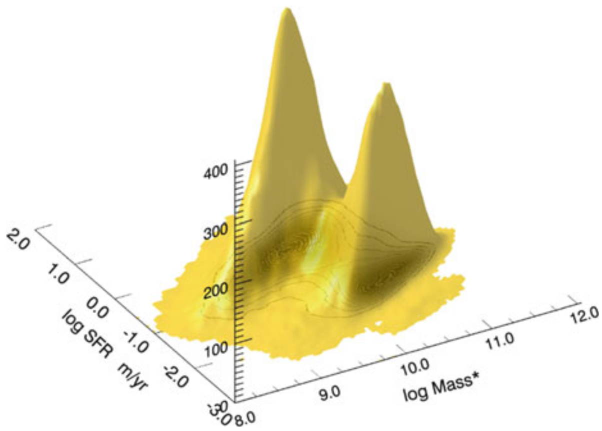

Fig. 8.5 The 3D SFR-M relation for local galaxies (Renzini and Peng 2015) in the SDSS database and redshift between 0.02 and 0.085. The third dimension is the number of galaxies in SFR-M bins. The drop towards lower masses is partly artificial, as no $V/V_{\rm max}$ correction has been applied. This offers a clearer vision of the 3D structure, with the two prominent peaks, one for star-forming galaxies and one for the quenched ones. Notice the sharp ridge line of the SF peak, the extremely steep fall off in the number of galaxies, either way of the ridge line, the divide, which is then been taken as the definition of the Main Sequence of star-forming galaxies. On the North-West side of the divide one also encounter the starburst outliers, whereas on the SE side of the divide is populated by a mixture of galaxies with lower SFR, with some being just in a temporary excursion below the MS band, while others are definitely on their way across the saddle, towards the peak of quenched galaxies. No $V/V_{\rm max}$ correction was applied in order to have a better visibility of the two peaks. Data are from the SDSS database

Why do galaxies exhibit a so large dynamic range of SFRs?

At given stellar mass, most galaxies are either on/near the MS as star-forming galaxies, or are red and dead, quenched galaxies. Few galaxies lie in between, in the so-called green valley. This is illustrated by the 3D plot of Fig. 8.5, for galaxies in the local Universe. The bimodality in the SFR distribution is very evident. Besides it, the dispersion of SFRs around the main sequence central relation is about a factor of ~ 2, probably reflecting temporary up and down fluctuations in SFR due to the stochastic nature of the star formation process. Then, *starburst outliers* from the main sequence also exist, with SFRs up to 10 times higher than the mains sequence value, or even more. At redshifts ~ 2 they account for $\sim 2\,\%$ of all star-forming galaxies, and for $\sim 10\,\%$ of the global star formation density (Rodighiero et al. 2011). So, they play a lesser role in star formation, compared to main sequence galaxies, but certainly not a negligible one.

Is it possible to apply the locally calibrated SFRs to high-redshift galaxies or in other words could we trace the evolution of the SFR?

Oh yes! This is now common practice. So, it has been shown that the main sequence itself evolves dramatically with redshift, in such a way that for fixed stellar mass (i.e., not fixed galaxy!) the SFR increases by a factor of ~ 20 between redshift zero and ~ 2 (Daddi et al. 2007). Then measurements become a bit more uncertain, but this increase appears to continue towards higher redshifts, though with a somewhat reduced pace.

The quenching of SF is today the most popular explanation of the distribution of galaxies in the color-magnitude diagram. The analysis of the SDSS data, particularly those involving the broad-band color $g - r$, shows a bimodal distribution of galaxies. A blue and a red peaks are separated by a green valley.

In a sense, the modern interpretation of the color-magnitude diagram of galaxies, is represented by Fig. 8.5, were luminosity has been replaced by stellar mass and color by the SFR (Renzini and Peng 2015). So, the blue galaxies are the star-forming ones, with most of them on the MS, and most of the red galaxies have barely detectable SFRs, i.e., they are quenched. I would say that this is the universally accepted interpretation of the color-magnitude diagram. So, I think we have a reasonable understanding of the two peaks we see in Fig. 8.5. Perhaps more intriguing is the *green valley*. It must be populated by galaxies on their way to be quenched, and therefore their number should give us insight on the quenching mechanisms. However, this green valley may also include galaxies in a temporary minimum of their SFR and will return to the main sequence in the future. Or quenched galaxies may experience a minor episode of star formation, visiting the valley for a short time. And we should not forget that a few percent of our photometric redshifts can be grossly wrong, misplacing a galaxy in the valley. So, a great deal of work may have to be done to distinguish between crossing, visiting and intruding galaxies in the green valley.

Could you summarize the problem and discuss the physical mechanisms of mass quenching and environment quenching? Can we distinguish these mechanisms observationally?

Observationally, one finds that the fraction of quenched galaxies is an increasing function of stellar mass (independently of environment) and of the local overdensity (independently of stellar mass) (Peng et al. 2010), as illustrated in Fig. 8.6. So, one speaks of mass quenching and environment quenching as two distinct and separable processes. But we are still struggling trying to understand what are the physical processes causing mass quenching and environment quenching. Many think environment quenching is ram-pressure stripping of gas from galaxies in groups and clusters, but the situation is far more uncertain for mass quenching and there are many candidates. A variety of radically different options are currently entertained for the mass quenching process, whereby quenching is either an *internal* or an *external* process. In one option for the former case sudden energy/momentum release from star formation and/or AGN (feedback) results in the ejection of all gas from galaxies that then turn passive, the 'quasar mode' quenching in current jargon (Granato et al. 2004). Powerful AGN jets may also heat the circumgalactic medium to high temperature thus preventing further accretion of cold gas, the so-called 'radio mode' AGN feedback (Croton et al. 2006). In another option for an external process, the circumgalactic gas is shock-heated to high temperatures as the mass of the host dark matter halo exceeds a critical threshold (of order of $\sim 10^{12}\,M_{\odot}$) , and therefore

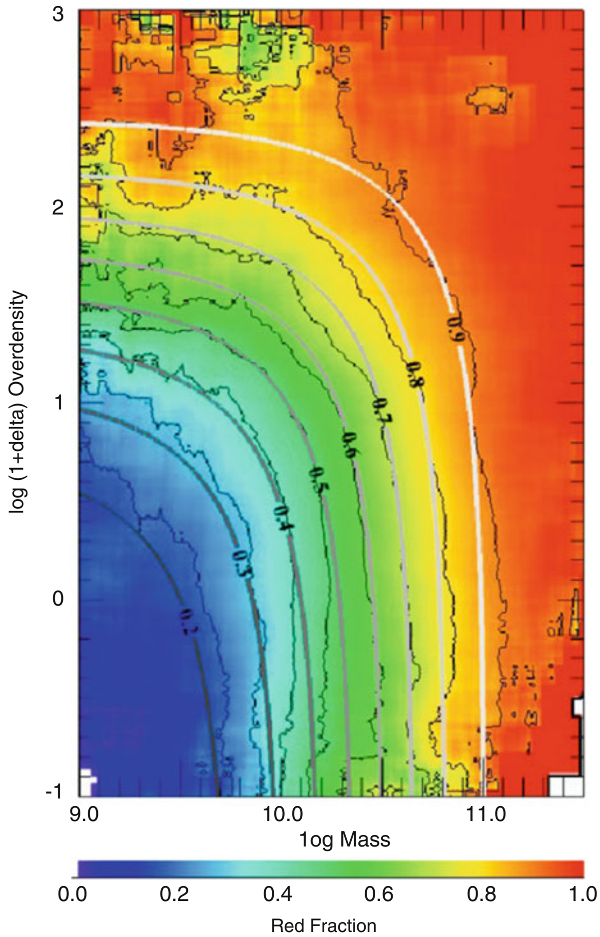

Fig. 8.6 Color-coded is the fraction of red galaxies as a function of stellar mass and local overdensity (Peng et al. 2010). In the vast majority of such galaxies star formation is actually quenched or reduced to barely detectable levels, hence the red fraction is a fair proxy for the fraction of quenched galaxies, but a marginal number of highly dust reddened, actively star-forming galaxies may be included. Data are from the SDSS database and include galaxies in the redshift range $0.02 < z < 0.085$

it stops to cool and flow into the galaxy, thus discontinuing to feed star formation (Dekel and Birnboim 2006). Finally, the growth of a central mass concentration (bulge) may *quench itself*, with increasing shear (differential rotation) suppressing the disk instability to form actively star-forming clumps, the so-called gravitational (or morphological) quenching (Martig et al. 2009). So, we have at least four options for the physical nature of mass quenching. Actually, we don't quite know what is the mass that matters in mass quenching: is it the stellar mass? Or the mass of the host dark matter halo? Or the mass of the galactic bulge? Or that of the central supermassive black hole? Each of them suggests a totally different physical mechanism for quenching, and yet they are all tightly correlated with each other, so it gets very hard to observationally identify the culprit! Yet, it is even possible that mass and environment quenching may be two different manifestation of a same, underlying physical process (Knobel et al. 2015). I hope we can solve this problem within a few years.

What is the quenching time scale? Is it the same for all galaxies?

Many groups are trying to measure the quenching timescale, which may be different for mass and environment quenching, but there is no answer yet to this question. If quenching is due to gas ejection from the galaxy, e.g., as resulting from some sort of AGN feedback, then the quenching timescale may be quite short, of the order of the dynamical time, or $\sim 10^8$ years. If instead quenching results from cutting off gas supply from the environment, then the quenching timescale could be quite long, of the order of the gas depletion timescale, i.e., $M_{\rm gas}$/SFR, or some $\sim 10^9$ years, with $M_{\rm gas}$ being the mass of gas inside the galaxy at the beginning of the quenching process. We can gather an estimate of the quenching timescale from the number of galaxies caught in such transition, but, as I mentioned earlier, the green valley can be also populated, at all redshifts, by occasional visitors and intruders.

Which is the relation between the quenching of SF and the morphological transformation?

Empirically, we see that most quenched galaxies show an early-type morphology (i.e., they are elliptical or S0 galaxies) and most early-type galaxies are quenched. But why quenching is accompanied by morphological transformation we don't not know for sure, yet. This is indeed another open question. Integral field spectroscopy of local early-type galaxies has demonstrated that the vast majority of them ($\sim 86\,\%$) are fast rotators, whereas only the residual minority are slow rotators (Emsellem et al. 2011). There is general consensus that the slow rotators are the result of merging, which then can be considered responsible for the morphological transformation for only a minority of galaxies. The fast rotators instead are likely to be the result of the evolution of the disk, via some kind of disk instability (Dekel and Burkert 2014).

We examine now another aspect of galaxy evolution, that related to the so-called feedback. With this term astronomers summarize all the processes occurring in galaxies that are energetic enough to significantly affect their evolution.

8.6 The Role of Feedback

Questions for Luca Ciotti:
the AGN feedback is claimed to be an important physical mechanism in galaxy evolution. Could you explain why and trace a short history of this idea ? Which observations prove that such feedback indeed occurred? How is galaxy

evolution affected by the feedback? Is this mechanism active in all galaxies or only in some morphological types?

The topic of AGN feedback in galaxies (in particular, in early-type galaxies, hereafter ETGs) has been, and it is right now, a relevant aspect of my research activity. As a consequence, in the following the presentation may reflect quite a personal point of view, which is not necessarily shared by all other researchers in the field. Overall, looking back over the past 25 years, since when I started to work on the subject (together with J.P. Ostriker during the sojourn at Princeton University as a PhD student), I can say that the attitude of a large part of the scientific community has been quite peculiar, ranging from initial positions like "there is no AGN feedback in ETGs", to the present "AGN feedback is the main actor in shaping the formation and evolution of ETGs, and to produce their properties as we observe them today". Well, I quite disagree with both views. I will present some arguments supporting the claim that AGN feedback *was* known to be important even 25 years ago, a necessary conclusion of elementary empirical arguments. At the same time, I claim that the main effects of AGN feedback are *not on* the galaxies, hosting at their centers the Supermassive Black Holes (hereafter SMBHs), but are essentially of more local nature, mainly affecting the growth of the SMBHs and extending at most to the galactic centers, in a $\simeq$ kpc-size region around the SMBH, and of course regulating star formation in the centers of ETGs.

In 1989–1992 I was working on my PhD thesis in an excellent research group, lead by Alvio Renzini. Annibale D'Ercole (then Astronomer at the Bologna Astronomical Observatory) and Silvia Pellegrini (also PhD student) were also in the group. Alvio was very enthusiastic about a new idea he had for the explanation of some puzzling observational property of the X-ray emission of the hot atmospheres surrounding ETGs. In particular, it was clear that, in absence of some form of heating, the gaseous halos of ellipticals, *produced by the mass ejected by the stellar mass losses of the aging stellar population* at the rate $\dot{M}_*$, i.e. the "secular evolution" of these systems, would necessarily lead to massive *cooling flows* in all elliptical galaxies, with the consequent prediction of systematically high and *unobserved* X-ray luminosities ($L_{\rm X}$). In fact, from the well established and tested theory of stellar evolution, it is known that the mass losses of an old, passively evolving stellar population of present-day total luminosity $L_{\rm B}$ (in blue solar units) can be well approximated as

$$\dot{M}_* \simeq 1.5\, 10^{-11} L_{\rm B} t_{15}^{-1.35} \quad M_\odot {\rm yr}^{-1}, \tag{8.2}$$

where t_{15} is time in 15 Gyr units.

The cooling flow model (Cowie and Binney 1977; Fabian and Nulsen 1977), with the prediction of high values of $L_{\rm X}$, was the paradigm at the epoch, but it is important to recall some important facts. That the stellar evolution would inject over cosmological times an *enormous* amount of mass in the host galaxies (summing up to 20 to 30 % of the initial stellar mass M_* of the galaxy) was so obvious that in the '70s the very important model of Supernova driven galactic wind (Mathews and

Baker 1971) was proposed as the natural solution to the conundrum posed on one hand by the unquestioned prediction of stellar evolution about mass losses, and the apparent lack of detection of gas in ETGs on the other. The whole astronomical community was well aware that ETGs, at least from the point of view of the mass budget, are certainly not *dead and red* objects. In the '80s, the detection of X-ray emission around ETGs by *Einstein* (see, e.g., Fabbiano (2012); Mathews and Brighenti (2003)) finally showed that the mass *was* there, and the *cooling flow model* became the paradigm to study this kind of problems. However, it was soon realized that if the mass injected was cooling, the final state of such cooling gas should be found somewhere in the galaxy, in form of new stars, or dark objects, or free floating baryon condensations. In addition, it became also clear that the X-ray emission L_X of medium-to-low mass ellipticals was systematically *lower* than what expected by the *standard* cooling flow model, that instead worked better (although with significant dispersion—almost two dex—in the predicted values of L_X) for massive ellipticals. Remarkably, *all* the proposed solutions attempting to reconcile the pure cooling flow scenario with observations failed, for a combination of theoretical and empirical arguments. Renzini coagulated a research group, with complementary competences, to work on the problem. In particular, by building realistic galaxy models that at the epoch were state-of-the-art (e.g., laying on the Fundamental Plane), and using the most robust prescriptions of stellar evolution, we concluded that elliptical galaxies are—from the energetic point of view—very peculiar systems, i.e., the energy needed to steadily extract the injected gas from the galaxy gravitational potential, and the energy injected per unit time in the hot ISM by SNIa explosions and thermalization of stellar motions, are *almost the same*, so that the X-ray halos are in a metastable energetic configuration. Moreover, we also found that, due to the Faber-Jackson relation, the binding energy per unit mass of the ISM (roughly proportional to the stellar velocity dispersion of the host galaxy) in large ETGs is higher than in low mass systems, so that while the latter systems should be in a global galactic wind state (in practice, mass losses from the evolving stars are ejected from the galaxy being heated to a super-virial temperatures), massive ETGs should be in the cooling flow state, with the consequent high L_X. These energy-based estimates were nicely confirmed by our hydrodynamical simulations (Ciotti 1991) that however revealed a scenario more complicated than that depicted above (for example, the remarkable fact that the time evolution of the SNIa explosion rate is very similar to the time evolution of $\dot{M}_*$, a fact without obvious physical explanation). In summary, at that time, in addition to have learnt a lot of physics from Alvio and numerics from Annibale, I had clear in mind that (1) even in isolated ETGs (i.e., in absence of major/minor merging, cold flows, etc., objects that today would be called "red and dead"), there are internal, time-decreasing, significant sources of mass just provided by stellar evolution, and (2) while the cooling flow was not the state of the atmospheres of ETGs of low/medium mass, a large fraction of the massive ellipticals (say objects with a central velocity dispersion of the order of 250 km/s or more), should be in a cooling-flow like state (for a full account of the situation see, e.g., Pellegrini (2012), and references therein).

In particular, while the work in our group in Bologna was clearly a significant step forward in understanding the evolution of the gaseous component of "red and dead" galaxies, yet the fate of the $\simeq 1M_{\odot}/yr$ produced internally and flowing towards the center in *massive* ETGs remained unsolved. It was exactly at this time that I started my sojourn in Princeton. After my arrival at the beginning of 1992 and a few weeks of "testing", Jerry decided that I would be assigned to study the problem of the fate of the cooling flows in big ellipticals. This was particularly timely, considering the important discovery that at the center of ETGs there are SMBHs with a mass of the order of $M_{\rm BH} \simeq 10^{-3}M_{*}$ (Magorrian et al. 1998), successively confirmed and reinforced by the discovery of the $M_{\rm BH}-\sigma$ relation (see, e.g., Ferrarese and Merritt (2000); Gebhardt et al. (2000); Yu and Tremaine (2002)). It is clear that in these systems AGN feedback is necessary, not as a consequence of complicated arguments, but just because of the extreme *smallness* of the mass of the central SMBHs. In fact, a rough calculation easily shows that the SMBH masses are approximately *two orders of magnitude* smaller than the gas made available by stellar evolution in isolated ETGs (and the argument is only reinforced in case of external accretion/merging). In practice, *AGN feedback is required by mass arguments, not by energetic arguments*. We started to work on the theory of AGN feedback, supported by numerical simulations of increasing quality (with improvements in the input physics still ongoing, thanks to the involvement over the years of several other researchers) to test observational predictions. In fact, for a mass accretion rate of $\dot{M}_{\rm BH}$, the emitted luminosity—for a given electromagnetic efficiency ϵ—is

$$L_{\rm BH} = \epsilon \dot{M}_{\rm BH} c^2 \simeq \epsilon (\dot{M}_{\rm BH}/M_{\odot} yr)\, 5.7\, 10^{46} \quad \text{erg/s}, \tag{8.3}$$

high enough to suppress the potential cooling flow and interrupt accretion (see also Binney and Tabor (1995)). The question we addressed in this first exploration of AGN feedback was why we do not observe quasars at the center of all massive ETGs as a consequence of the expected accretion. The answer was obtained and refined in a series of papers, based on numerical hydrodynamical simulations of gas flows in ETGs including radiative transport, with the spatial and temporal resolution needed to probe the resulting flows on cosmological times and on spatial scales ranging from galactic sizes down to the parsec scale near the central SMBH (well inside the Bondi radius, so that no "ad hoc" treatment for accretion, common in similar studies, was required). We showed that gas accretion on the central SMBH, due to the onset of a "cooling flow" phase, releases and transfers to the ISM enough energy to stop the cooling flow itself, and to evacuate the inner kpc-scale region around the SMBH. After a characteristic time, needed to replenish the central zone of the galaxy, and to increase the ISM to values large enough to start another "cooling catastrophe", the cycle repeats (for a full description of the simulations and the results, see (Ciotti 2009a,b; Ciotti and Ostriker 2012; Ostriker and Ciotti 2005)).

Quite surprisingly (for the current view), we found a strong and negative reaction to our proposal (with the exception of a few notable cases, such as Alvio Renzini and James Binney, one of the fathers of the cooling flow model then visiting

Princeton, where I met him for the first time) as in general the community was fiercely defending the cooling flow paradigm (already in crisis due to SNIa heating for low/medium mass galaxies, and now also questioned for the remaining galaxies). The reactions went so far as to claim that "ETGs were lacking signs of feedback", or proposing that the SMBHs were actually steady accreting in the "obscured modality" (i.e., without emission of significant radiation, with no feedback, and so in a sense still consistent with the cooling flow paradigm). But all these criticisms missed the point, i.e., that the low mass of central SMBHs *is* a clear observational signature of feedback, and that obscured accretion *cannot* be the solution, because the SMBH mass would grow to unobserved values (in fact, that obscured accretion cannot be used to reconcile the cooling flow model with the physics of SMBH accretion is also proved beyond discussion by the Soltan argument, coupled with the well known theoretical upper bounds on accretion efficiency of compact objects, see e.g., see e.g. Yu and Tremaine (2002)).

A few important aspects of AGN feedback should be considered. First, the time interval from the beginning of central accretion, to its shutdown due to AGN feedback, is found to be of the order of 10^7 yrs, in nice accordance with observational estimates of the "on" phase of quasars. Second, in the simulations these feedback events becomes more and more rare as the galaxy age increases (see Fig. 8.7), because the stellar mass losses need longer and longer time to produce the critical density required for a global ISM cooling event (see Eq. 8.2). Third, as the major feedback events in the life of a galaxy are just a few, it results that the *duty-cycle* of AGN activity (i.e., the time fraction so that the AGN luminosity is above some fraction of the Eddington luminosity) is much less than unity ($\simeq 10^{-2}$ or even less), thus explaining why we do not see quasars in galaxies in the local Universe, i.e., because the probability to catch a SMBH in the "on" phase is very small, and it decreases with increasing cosmic time.

As already stressed, an important aspect of the AGN feedback physics - not always appreciated—is that the main issue of the problem is not whether there is enough energy to stop a cooling flow (see Eq. 8.3), but *how much* of the energy emitted in a given accretion event can be transmitted to the ISM in the host galaxy. Theoretical estimates and physically based numerical simulations of AGN feedback show that in fact the fraction of energy transferred to the ISM (and so able to stop gas cooling) is *very small*. In other words, the energy emitted by the AGN in a given accretion event is very large (much bigger than the energy required to eject all the ISM from the galaxy in the intergalactic space), but the captured fraction (both as radiation and kinetic coupling with the conical nuclear wind launched by the AGN) is only able to momentarily stop the gas cooling.

This is a very interesting fact, as nowadays AGN feedback, after having been initially ignored or even discarded as an important aspect of the evolution of ETGs, is invoked as the final explanation of why ETGs are the systems with the characteristics we observe. For example, AGN feedback is considered the main actor in quenching star formation at the epoch of galaxy formation. My impression is that this is more an expectation than a proved statement. In fact, numerical simulations in spherical symmetry (when feedback effects are maximum for geometric reasons),

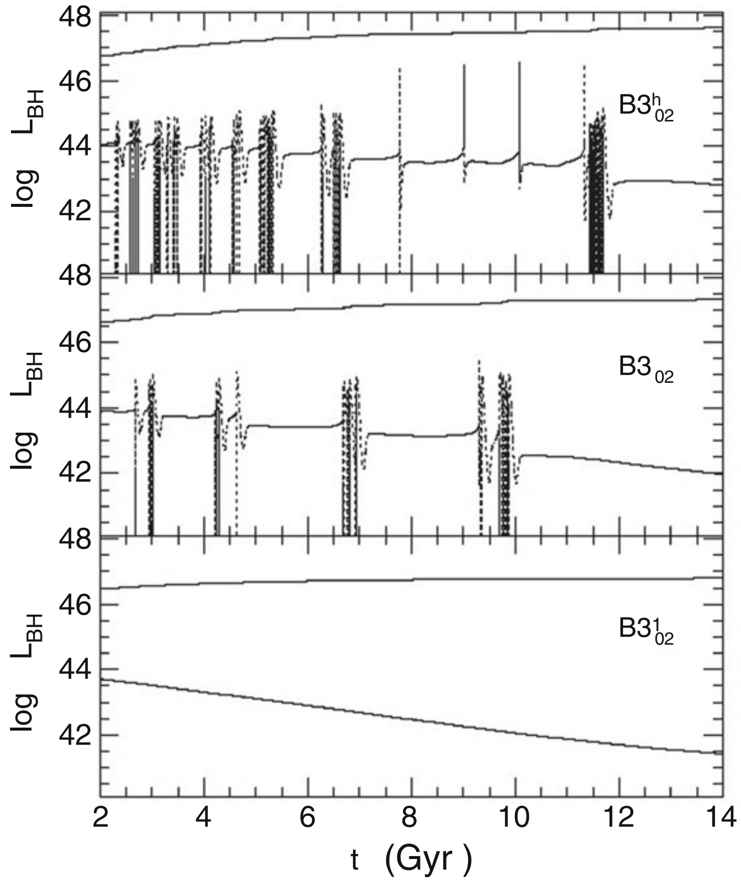

Fig. 8.7 *Dotted lines* are the optical SMBH luminosity corrected for absorption (i.e, as would be observed from infinity) for three galaxy models with central velocity dispersion of 280 km/s ($B3^{h}_{02}$), 260 km/s ($B3_{02}$), and 240 km/s ($B3^{l}_{02}$). The almost *horizontal solid line* represents the Eddington luminosity. Note how the less massive galaxy is in a state of SNIa driven permanent galactic wind, and the AGN accretion luminosity remains low (Adapted by permission of the AAS from Ciotti et al. 2010)

and with realistic coupling between radiation and matter (obtained by solving radiative transport equations) are systematically found unable to eject from massive galaxies the ISM produced by stellar evolution, even worse if we imagine the galaxy filled with all the gas needed for star formation, and a more realistic (and less efficient) non-spherical feedback geometry.

Another related interesting result that emerged from our work (Ciotti and Ostriker 2007), was the fact that actually AGN feedback can *induce* star formation, at the beginning of each major feedback event. In fact, each event (of a total duration of $\approx 10^7$ yrs), when observed at sufficiently high time resolution, is made of a series of sub-burst of increasing intensity (e.g., see the last burst in the top panel of Fig. 8.7), due to a complex hydrodynamical structure of the ISM in the $\simeq 300 - 500$ pc around the SMBH. In this region, the sequence of shock waves (direct and reflected) leads to the formation of a gaseous cold shell, with a few hundred parsecs radius, that in turns form stars at peak rates of $10^2 M_{\odot}/yr$ or more. The final sub burst in the series finally ends the sequence, and stops star formation: therefore, we found that AGN feedback is—at the same time—able to *induce* and *suppress* star formation. We also found that the new stars produced by the periodic central starbursts are distributed in the central regions of the models with a profile remarkably similar in shape and values to the observed stellar cusps in the central regions of ETGs (Graham et al. (2003), see also Ciotti (2009a,b), and references therein). It is interesting to speculate that the so-called "E+A galaxies" may be somewhat related to this recurrent activity.

In the spirit of this book, I conclude presenting a list of major results about AGN feedback that I think are quite robust, followed by a list of points that I feel should be the focus of future investigations, theoretical and observational.

(R1) AGN feedback in galaxies is required by simple mass arguments, not by energy arguments: the mass of SMBHs at the center of big ETGs is approximately two orders of magnitude smaller than the gas that would be accreted by a non-impeded cooling flow. Therefore, obscured /or radiatively inefficient accretion is not a solution to the problem of missing quasars in massive ETGs.

(R2) Sporadic quasar activity *is* present in ETGs, even in perfect isolation, due to the immense amount of material secularly injected in the galaxy by stellar evolution. Therefore, quasar statistics cannot be straightforwardly used as a measure of frequence of gas-rich ("wet") merging events, as it can be produced purely by secular internal evolution of "red and dead" galaxies.

(R3) AGN feedback is, *empirically*, fundamental to maintain the mass of SMBHs "small", however it is unable to fully evacuate the host galaxy by the mass injected by the aging stars. SNIa heating, being distributed over the galaxy body, and released at a continuous rate, is much more important. All the available indications from numerical simulations where the feedback is calculated from first principles seem to suggest that the effects at early times can be similarly small, in absence of some additional physical effects. Possibly, SNII are more important in terminating star formation at early times.

(R4) Stellar evolution has the nice property that the amount of material injected *scales linearly* with the stellar mass of the galaxy, so that the accretion of some fraction of this material on the central SMBH does not destroy (or even improves) a proportionality possibly established at the end of the period of galaxy formation.

(R5) The efficiency of AGN feedback and the rates of gas injection and cooling are essentially *unrelated* phenomena: a long-time balance between the two is impossible, so that steady-state configurations are practically impossible in massive ETGs. A possible exception is represented by low mass ellipticals, where SMBHs accretion proceeds at very low $L_{\rm BH}$, with Bondi-like accretion from hot and low-density atmosphere, as the galaxies are in SNIa assisted global winds.

Among the questions that I would like to see addressed (and solved!) in a near future:

(Q1) What is the role of angular momentum in the structure and evolution of gas flows in galaxies with some rotation? It is known that in these systems, in absence of additional heating phenomena, gas cooling would lead to the formation of massive, centrifugally-supported, kpc-size disks of cold gas, unable to reach the center. What happens of these disks? Are they consumed by star formation? Are they massive enough to become self-gravitating and unstable? If yes, will they develop non axisymmetric features, break angular momentum conservation and collapse toward the center fueling the SMBH? What kind of feedback the AGN will produce when fed by such disks?

(Q2) How can we describe in acceptable physical terms the "granularity" of the galaxy stellar distribution within the inner tens of parsec around the SMBH? Of course, a spatial and temporal smooth description of the stellar distribution and of the mass and energy injection becomes more and more unrealistic as the number of stars involved decreases.

(Q3) What is the relative role of radiative and kinetic energy in AGN feedback? What are the observational signatures of AGN induced and suppressed star formation (the so-called positive and negative feedback)? What is the relative importance for feedback of the starburst energy compared to the AGN energy?

(Q4) The contribution of AGN feedback to quench star formation at the epoch of galaxy assembly was really fundamental? Or it was just an additional contribution to SNII and SNIa activity?

Questions for Francesca Matteucci:
SNe have been indicated as possible sources of feedback mechanisms. Could you explain why? Which is the role of SNe in galaxy evolution? Which observations confirm these ideas?

As already mentioned, supernovae influence galaxy evolution through chemical enrichment and energy feedback, namely the energy that they can transfer into the ISM. The explosion energy of SNe is large, although in some cases most of it can be lost via cooling, and clearly contributes to increase the thermal energy of the ISM. Because of this, the interstellar gas can reach the escape velocity and escape from the potential well of the galaxy and in this case we speak of galactic wind, but the gas can also be temporarily removed and fall back again, in such a case we speak of galactic fountains (Bregman 1980; Spitoni et al. 2008). These fountains are likely to occur in spiral disks and are triggered by multiple explosions of massive stars. The evidence of galactic winds is given by the metals found in the ICM and IGM and they have also been observed in dwarf irregular galaxies. In particular, the observations of dwarf starburst galaxies indicate that these winds are linked to SN explosions. Martin (2002) reported `Chandra` observations of the dwarf starburst galaxy NGC 1569 in the Local Group showing the gas which is escaping from the galaxy at a rate which is a factor of a few of the star formation rate. The same author reported observations made with FUSE of other dwarf galaxies such as NGC 4214, NGC 5253 and NGC 1705 also showing that they are suffering galactic winds outflowing at a rate which varies from 1 to 5 times the star formation rate.

Stars have progressively enriched the interstellar medium of metals. In the next interviews we examine with more detail this process and its consequences, as well as how this idea has been encoded in modern numerical simulations.

8.7 The Chemical Enrichment

Questions for Francesca Matteucci:
how has the idea of the chemical enrichment of galaxies developed? What have been the main theoretical progresses in this field? Which physical mechanisms govern the chemical evolution of galaxies? Are observations in agreement with the theoretical models?

The idea of the chemical enrichment of galaxies developed in the 1970s and it was led by researchers such as W.D. Arnett, J.W. Truran, J. Audouze, B.E.J. Pagel and, in particular, B.M. Tinsley. The basic idea is simple: stars transform light elements into heavier ones in their interiors and when they die the new elements are restored into the ISM. The following stellar generation will then form out of enriched gas and the process will go on until all the gas is consumed or lost via winds. Beatrice Tinsley developed most of the analytical formulas for computing chemical evolution of galaxies. These formulas are very important and useful but their limit is related to the hypothesis of instantaneous recycling approximation (IRA), necessary to obtain analytical solutions to the equations of chemical enrichment. The IRA approximation states that *all stars with* $M < 1M_{\odot}$ *live forever and that stars with* $M \geq 1M_{\odot}$ *die instantaneously*; while the first sentence is correct, the second is incorrect and does not allow one to compute in detail the evolution of those chemical elements that are produced on the timescales of billion years, such as, for example, iron and nitrogen. One of first interesting topics dealing with galactic chemical evolution was the so-called *G-dwarf problem*: it consists in the fact that the Simple Model of chemical evolution could not reproduce the distribution of the G-dwarfs as a function of metallicity in the solar vicinity, as first discovered by van den Bergh (1962) and Schmidt (1963). In particular, the Simple Model predicts too many low metallicity stars relative to what is observed. The main assumptions of the Simple Model are: (a) the system evolves as a closed box, with no infall nor outflow, (b) the IMF is constant in time, (c) there is instantaneous mixing at any time, (d) the chemical composition of the gas out of which the system forms stars is primordial. The G-dwarf problem can be solved in several ways: (i) by assuming that the gas which formed the Galactic disk was pre-enriched, (ii) by assuming an IMF variable in time and favoring high mass stars at early times, (iii) by assuming that the Galactic disk formed by infall of gas. These solutions were discussed in important papers such as Tinsley (1974), Talbot et al. (1975) and Pagel and Patchett (1975). It has been since long concluded that infall of primordial gas (hypothesis iii) seems the most promising solution and it has been assumed in the majority of chemical evolution models. After these pioneering papers, several numerical models of galactic chemical evolution relaxing IRA were developed (Boissier and Prantzos 1999; Chiappini et al. 1997; Chiosi 1980; Matteucci and Greggio 1986; plus many others), thus starting new developments. Matteucci and Greggio (1986) in particular, were the first introducing a detailed calculation of the rate of SNe Ia originating in white dwarfs in binary systems[7]: this is fundamental in order to correctly follow the evolution of Fe and to correctly interpret the [X/Fe] vs. [Fe/H] observed relations. Later on, D'Antona and Matteucci (1991) introduced in a chemical evolution model also the chemical enrichment from nova systems, which can be important for computing the evolution of elements such as Li and some C,N,O isotopes. Argast et al. (2004) and, more recently, Matteucci et al. (2014) included in the chemical evolution of the Milky Way also the chemical enrichment from merging neutron stars, which seem to be very promising producers of r-process elements, such as Eu.

Other interesting developments in galactic chemical evolution arose from the hypotheses about the formation of the various Galactic components: halo, thick-, thin-disk and bulge. The two-infall model for the Milky Way (Chiappini et al. 1997) tried to explain the different evolution of the halo and disk by separating their formation and assuming that two main infall episodes gave rise to the two components, respectively. Several other authors assumed the two-infall concept for treating the evolution of the Milky Way (Alibés et al. 2001; Chang et al. 1999).

The main physical mechanisms governing chemical evolution of galaxies are: the process of star formation which means either the rate at which the gas is transformed into stars or the distribution of the stellar masses at birth. Then the stellar nucleosynthesis, which determines the amounts of newly created elements in stars of different mass. Then gas flows, which can be entering or leaving the galaxy, as well as radial gas flows. Finally, also stellar migration can influence the chemical evolution since stars born at a given Galactocentric distance can move, during their lives, and land at a different distance.

However, taking into account gas and star flows would require a dynamical approach besides a chemical one. Chemical evolution models can take into account these phenomena only in a parametric way. Chemo-dynamical models, where chemical enrichment and gas and stellar dynamics are present should represent one of the main future goals in studying galaxy evolution. Recently, an example of such chemo-dynamical models was presented by Minchev et al. (2013), who included stellar dynamics in a detailed chemical evolution model.

However, the already existing detailed chemical models can reproduce many chemical patterns observed in galaxies and they have allowed us to even predict what

[7]Tinsley (1980) had already suggested the Type Ia SNe as possible Fe producers on long timescales but before the (Matteucci and Greggio 1986) paper, no precise calculation had been performed.

should have been observed ahead of time. As an example, Matteucci and Brocato (1990) predicted, since no observations existed yet, that the stars in the Milky Way bulge should show high [α/Fe] ratios for a large range of metallicities and this was indeed observed by McWilliam and Rich (1994) and by many subsequent authors. The Matteucci and Brocato (1990) prediction is shown in Fig. 4.20 in Chap. 4 (curve labelled Bulge). However, we are still far from having understood the mechanisms of formation of the various Galactic components: the chemical abundances can only suggest the timescales on which the various Galactic components have formed, but they cannot tell us the details of how they formed. A lot of work is still necessary to answer to the still many open questions concerning the Milky Way and external galaxies. For example: is the IMF universal or it does it vary from galaxy to galaxy? Did the spiral disks form by accretion of cold gas occurring inside-out, as suggested by chemical models? How did the thick-disk stars form, in situ or they were accreted from the dwarf satellites? How did the bulge of the Milky Way form? Are the more massive galaxies older than the smaller ones, as chemical models suggest for ellipticals and spirals? Is the efficiency of star formation a function of the galactic mass (stars plus gas), as suggested by several chemical constraints? As a final example of observations in good agreement with chemical models, we show in Fig. 8.8 the measured abundance gradient of oxygen along the Galactic thin-disk, compared to the predictions of a chemical evolution model including radial gas flows and assuming an inside-out formation of the disk as a result of accretion of cold gas (Mott et al. 2013b).

More recently, there has been an attempt at computing Galactic chemical evolution in the framework of cosmology. In particular, models following the hierarchical galaxy formation paradigm, where massive objects should have formed by merging of smaller units. Among those we recall the work of Kobayashi and Nakasato (2011) who included detailed nucleosynthesis prescriptions in cosmological simulations of galaxy formation. At the preset time there are still two different approaches to galaxy formation and galactic chemical evolution: (a) the astro-archaeological approach and (b) the cosmological approach. In the former, which is expressed by the chemical evolution models described before, one starts from the observed chemical abundances and tries to reconstruct, by means of a chemical model, the history of star formation, gas accretion and/or gas outflow that has created the observed abundance pattern. In the cosmological approach instead, the history of galaxy formation is given by the hierarchical paradigm which descents from the ΛCDM cosmological scenario. However, this last approach, although continuously improving, has not yet allowed one to reproduce very realistic galaxies. One argument of debate among the two approaches is, for example, the formation and evolution of elliptical galaxies. In fact, observational data for these galaxies suggest that the average $< [\alpha/Fe] >$ ratio in their dominant stellar population increases with the stellar mass. This can be nicely explained if we assume that the most massive ellipticals formed their stars first and on a shorter timescale than less massive ones. This is called *down-sizing in star formation* and it predicts the contrary of what is expected in the hierarchical scenario for galaxy formation, where the most massive objects should assemble on a longer timescale than the less massive ones and should

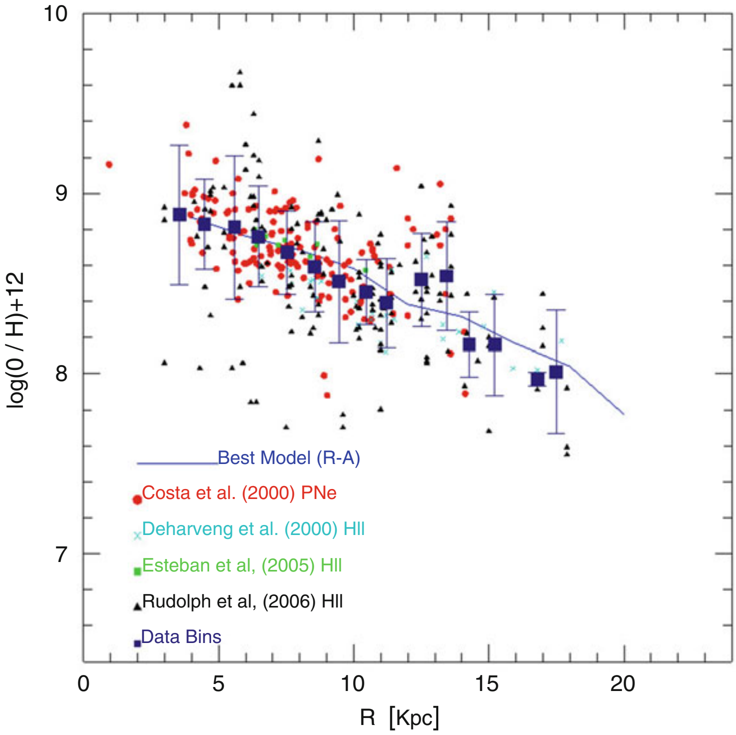

Fig. 8.8 The abundance gradient of oxygen along the Galactic thin disk. The data are HII regions and planetary nebulae. For references see Mott et al. (2013b). The model assumes inside-out formation of the Galactic thin disk, a threshold in the gas density for star formation, and radial inflow of gas with the velocity pattern suggested by Spitoni and Matteucci (2011). Figure from Mott et al. (2013b), where the references to the data can be found

have formed stars for a longer period. In order to have a high $< [\alpha/Fe] >$ ratio in massive ellipticals instead, their star formation should have been intense and short to avoid that too many Type Ia SNe exploded and polluted the ISM with Fe.

Questions for Gabriella De Lucia:
the Milky Way and the Local Group galaxies are today the only objects of the Universe for which we are able to determine the ages and the chemical composition of their individual stars. May you summarize how these data have been used in the framework of the hybrid models of galaxy formation? Could you compare these results with those based on hydrodynamical simulations?

Our own galaxy—the Milky Way—is a fairly large spiral galaxy consisting of four main stellar components: a *thin disk* that contains most of its stars, a *thick disk*, a *bulge*, and a *stellar halo* that contains only a tiny fraction of the total stellar mass. The stars in the thick disk are old, have on average lower metallicity than those of similar age in the thin disk, and are on orbits of lower angular momentum. The bulge is dominated by old and metal-rich stars, with a tail with lower abundances. Finally, the stellar halo is dominated by old and metal poor stars with low angular momentum orbits (Freeman and Bland-Hawthorn 2002).

Historically, chemical and kinematic information provided the basis for the first galaxy formation models. Eggen et al. (1962) studied a sample of local dwarf stars and found that those with lowest metal abundance were moving on highly elliptical orbits and had small angular momenta. The data were interpreted as evidence that the oldest stars in the galaxy were formed out of gas collapsing from the halo onto the plane of the galaxy, on a relatively short time-scales. About one decade later, Searle and Zinn (1978) found no radial abundance gradient in a sample of red giants and globular clusters. These observations led them to formulate the hypothesis that the stellar halo (particularly its outer region) formed through the agglomeration of subgalactic fragments, that may be similar to the surviving dwarf spheroidal satellites (dSphs) of the Milky Way.

The Searle and Zinn scenario appears to be in qualitative agreement with expectations from the hierarchical CDM scenario. Evidence in support of this picture includes the detection of significant clumpiness in the phase space distribution of halo and disk stars (e.g. Bell et al. (2008); Chiba and Beers (2000); Majewski et al. (1996)), and the detection of satellite galaxies caught in the act of tidal disruption (e.g. Ibata et al. (1994); Zucker et al. (2006)). The debate between a rapid collapse and a sequence of accretion events is, however, not settled. One difficulty was pointed out by Shetrone et al. (2001) who obtained high resolution spectra for stars in three dSph galaxies and noted that these tend to have lower alpha abundances than stars in the stellar halo. These results, later confirmed with larger samples, suggest that the Galactic stellar halo cannot result from the disruption of satellite galaxies similar to those observed in the Local Group. The counter-argument is that the *surviving* satellites might be intrinsically different from those that contributed stars to the stellar halo. Another problem with the Searle & Zinn scenario was pointed out by Helmi et al. (2006) who found a significant difference between the metal-poor tail of the dSph metallicity distribution and that of the Galactic halo, suggesting that the progenitors of present day dSphs are fundamentally different from the building blocks of our Galaxy, even at earliest epochs. Recently, however, different groups have detected very metal-poor stars both in classical and in ultra-faint dwarf satellites (Frebel et al. 2010; Kirby et al. 2008). Finally, a classical element of crisis with respect to the current cosmological paradigm is the so called *missing satellite problem*, i.e. the finding that substructures resolved in galaxy-size DM haloes significantly outnumber the satellites observed around the Milky Way (Klypin et al. 1999; Moore et al. 1999). Early studies based on semi-analytic models of galaxy formation focused on this particular aspect, and showed that the presence of a strong photoionizing background, possibly associated with the reionization of the Universe, can suppress accretion and cooling in low-mass haloes thereby suppressing the formation of small galaxies (Benson et al. 2002; Efstathiou 1992; Kauffmann et al. 1993). The discovery of a new population of ultra-faint satellites in recent years has led to a renewed interest in the physics of dwarf galaxy formation.[8] New impetus to the field has also been given by the completion of extremely high resolution N-body simulations of galaxy size haloes (Diemand et al. 2008; Springel et al. 2008).

In the last decade, different groups have taken advantage of these simulations to study the formation of the Milky Way and its satellites in a cosmological context. Bullock and Johnston (2005) combined mass accretion histories of galaxy-size haloes constructed using an analytic (the extended Press-Schechter) formalism with a detailed chemical evolution model that considers both Type II and Type Ia supernovae. For each accretion event, they run N-body simulations following the dynamical evolution of the accreted satellites, placed on orbits consistent with those found in cosmological simulations. Font et al. (2006) analysed the build up and chemical properties of the stellar halo in these models. The simulations reproduce the systematic differences between the chemical abundances of stars in satellite galaxies and those in the Milky Way. This results from the fact that the stellar halo originates from a few relatively massive satellites, accreted early on, and enriched in α elements by Type II supernovae. The model surviving satellites are accreted later, have more extended star formation histories and stellar population enriched to solar level by both Type II and Type Ia supernovae. While the approach provides a high numerical resolution for each accreted galaxy, the stellar distribution of the galaxies is not modelled self-consistently during the N-body simulation.

In a recent study (De Lucia and Helmi 2008), I applied a hybrid model of galaxy formation to a series of N-body simulations with increasing numerical resolution. We showed that our model was able to reproduce reasonably well both the estimated physical properties of our own Galaxy (its stellar mass, gas content, present star formation rate) and the metallicity distribution of its different stellar component (although the modelled bulge is more metal poor than the Galactic bulge). In this study, we also analysed the formation and structure of the stellar halo, under the working hypothesis that it is built from the cores of the satellite galaxies that merged with the Milky Way over its lifetime. In order to identify the stars that end up in the stellar halo, the full merger tree of the model Milky Way galaxy was constructed, and the galaxies that merge onto the main branch of the galaxy identified. These galaxies were then traced back to the time they were about to become satellite, and a fixed fraction (10 % in our fiducial model) of the most bound particles of their parent haloes were *tagged* with the stellar metallicity of the galaxies residing at their centre. Our results were in qualitative agreement with those by Font et al. (2006): only a few satellites make most of the stellar mass in the halo, and most of them are accreted early on. The halo has a steeper profile and is more centrally concentrated than the dark matter profile. In addition, we found that high-metallicity star particles are more centrally concentrated than star particles of lower abundances, in qualitative agreement with observational measurements (Carollo et al. 2007).

[8] It should be noted that this discovery did not alleviate the original missing satellite problem, as all the newly discovered satellites are fainter than the classical ones.

A more sophisticated tagging scheme has been recently used by Cooper et al. (2010) who take advantage of the higher resolution simulations from the Aquarius project (Springel et al. 2008). In their study, Cooper et al. assume that the energy distribution of newly formed stars traces that of the dark matter. They then order the particles by binding energy and select some fraction ($f_{\rm MB}$) of these most bound particles to be tagged. $f_{\rm MB}$ is treated as a free parameter, and is fixed by comparing model predictions with observational measurements of the structure and kinematics of the Milky Way satellites. Figure 8.9 shows a projected surface brightness map of the stellar halo, for the six Aquarius dark matter haloes. Substantial diversity among the haloes is apparent. A few haloes (e.g. Aq-B and Aq-E) are characterized by strong central concentrations, while others show extended envelopes out to $75 - 100$ kpc. Each envelope is the superposition of streams and shells that are phase-mixed to varying degrees. Most haloes exhibit a strongly prolate distribution of stellar mass, particularly in the inner regions. The brightest and most coherent structures visible can be associated with the most recent accretion events. The model stellar haloes span a wide range of accretion histories, ranging from a gradual accretion of many progenitors to one or two significant accretions.

The latest incarnations of semi-analytic models have been applied to high-resolution simulations also to study the number density and physical properties of satellite galaxies of the Local Group. These studies have confirmed that, combining a sufficiently high redshift reionization with a relatively strong feedback from supernovae, it is possible to bring the predicted number of luminous satellites in agreement with the most recent observational results (Font et al. 2011; Li et al. 2010; Macciò et al. 2010; Starkenburg et al. 2013). The same models provide a relatively good agreement with some basic physical properties measured for the Milky Way satellites, as well as an explanation for the weak dependence of M_{300} on the virial mass of the substructures hosting luminous galaxies (Strigari et al. 2008). In fact, models predict a weak increase of M_{300} for increasing luminosity which will be testable once more accurate measurements are available.

One strong limitation of all models mentioned above is that they are all based on an instantaneous recycling approximation (i.e. the models do not account for the finite lifetime of stars and its dependence on stellar mass). This is clearly inappropriate for iron-peak elements, mainly produced by supernovae Type Ia. In a recent study, we have developed a new method to trace individual abundances within a semi-analytic model (De Lucia et al. 2014a), and applied it to the Aquarius simulations. The model reproduces the [Fe/H] distributions of the stars in the disc component, as well as the global physical properties of the Milky Way. For the spheroid component (whose formation we model only through mergers), the metallicity distributions are offset low with respect to observational measurements for the Milky Way bulge. This is a consequence of narrow star formation histories, with relatively low rates of star formation. It remains to be seen if the same model is able to reproduce also the vast amount of chemical data available for the more general galaxy population, both in the local Universe and at higher redshift.

As discussed above, hydrodynamical simulations have generally had problems reproducing disk-dominated galaxies in typical dark matter haloes, when taking into

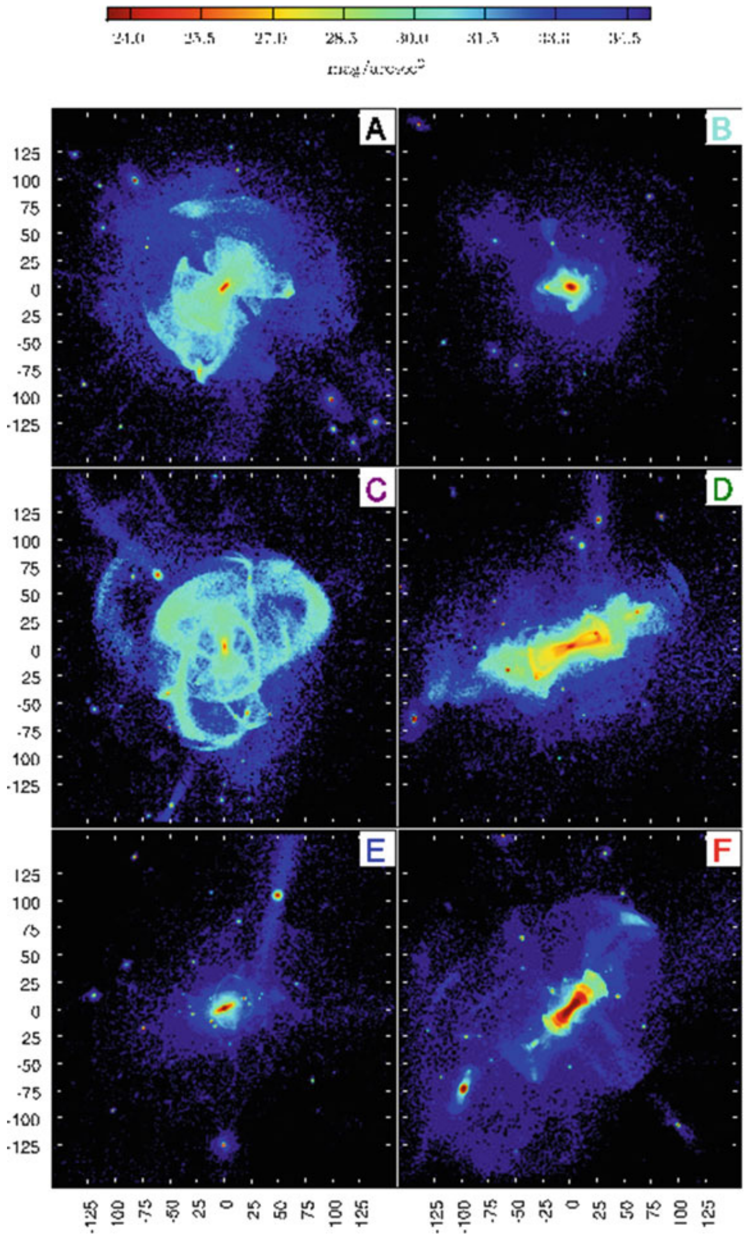

Fig. 8.9 From Cooper et al. (2010): *V*-band surface brightness of model stellar haloes (and surviving satellites), to a limiting depth of 35 mag/arcsec^2. The axis scales are in kiloparsec

account the cosmological setting. Because of these difficulties, most of the focus so far has been on reproducing thin disks similar to that of the Milky Way, rather than reproducing its detailed chemical properties. Very recent studies have started using also the detailed information available on the age and chemical properties of the Milky Way and its satellites.

Sawala et al. (2010) studied the formation and evolution of dwarf galaxies with halo masses in the range of $\sim 2 \times 10^8$ to $10^9\,M_\odot$ in cosmological simulations including cooling, SN feedback and UV radiation. Their simulated galaxies span a range of luminosity and metallicity in good agreement with Local Group dSphs. However, the observed dwarf sample is more diverse (in terms of star formation histories) than the simulated sample. For example, simulations do not include a system as luminous and extended, or with such a large age spread as Fornax. The same code and feedback scheme employed in this study had been used in Scannapieco et al. (2008) and, more recently, in Scannapieco et al. (2012) to study the formation of Milky-Way like galaxies. As mentioned above, the latter study compared results of 13 cosmological gas-dynamical codes run on the same initial conditions. The different implementations of star formation and feedback led to a large variations in the predicted stellar mass, size, morphology, and gas content. No code resulted in a simulated galaxy that resembles our own Milky Way. In particular, most codes tend to produce galaxies more massive, smaller and less rich than typical spirals, with a relatively massive bulge. The chemical properties of simulated Milky Way galaxies, based on the same code, were analysed in Tissera et al. (2012). Simulated disks are found to be more chemically enriched than the stellar halo but slightly less enriched than the central spheroids. Central spheroids are formed mainly by old stars most of which have been formed *in situ* with contributions of less than $\sim 20\,\%$ of stars formed in satellites. The stars in the outer halo are mostly accreted by satellites and are less enriched than those in the inner halo, in qualitative agreement with observational measurements.

Aumer et al. (2013) presented an update to the numerical scheme adopted in the studies mentioned above that include a more elaborate treatment of the production of metals, cooling, and a scheme for turbulent diffusion of metals. Their simulated galaxies show realistic morphologies, circular velocity curves and stellar metallicities, but overly flat metallicity gradients. Contrasting results were presented in Stinson et al. (2013) that is based on a different numerical code. In their simulations, the old stars lie in a thickened distribution with a short scalelength, while the young stars form a thinner disc, with scalelengths decreasing, as [Fe/H] increases. This translates into a metallicity gradient that is in quite good agreement with that observed for the Milky Way. Also in this case, the simulated galaxy has a prominent thick disc that is not seen in the Milky Way.

A solid theory of galaxy formation should reproduce the fundamental scaling relations of galaxies and their scatter as a function of redshift and environment, in the high dimensional space of observed galaxy properties. Unexplained scatter, or discrepancies in the scaling relations, indicates missing physics and or flows in the model. Do we have a theoretical explanation of the most important scaling relations?

Future surveys, e.g. from LSST, will produce much better defined relations and consequently outliers. Will current models survive?

Galaxies span a wide range in physical properties (masses, morphologies, sizes). However, their structural parameters obey a number of scaling relations, some of which, as you say, are remarkably tight. These relations likely hold important information on the physical processes that drive them. Therefore, a successful theory of galaxy formation needs to explain their origin.

Elliptical galaxies are concentrated on a plane in the three-dimensional space spanned by surface brightness, size, and velocity dispersion (Djorgovski and Davis 1987; Dressler et al. 1987), termed the 'Fundamental Plane'. Projections of this relationship form the Faber-Jackson relation (Faber and Jackson 1976) between luminosity and velocity dispersion, and the Kormendy relation between luminosity and radius (Kormendy 1977). Spiral galaxies also obey a well-defined scaling relation between the luminosity L and their rotation velocity (usually taken as the maximum of the rotation curve well away from the centre, V_{max}). This is known as the Tully–Fisher relation (Tully and Fisher 1977).

The origin of the Fundamental Plane is usually interpreted in terms of the virial theorem ($GM/ < R >=< v^2 >$), but the plane observed is 'tilted' with respect to that expected on the basis of the virial theorem, suggesting a variation of the mass-to-light ratio or non-homology in the class of the elliptical galaxies. There is still no consensus on what is setting the tilt of the Fundamental Plane, with some studies arguing that non-homology is responsible for large part of the observed tilt (Graham and Colless 1997), and other studies claiming that influence of non-homology is not significant (Cappellari et al. 2006). Another challenge is that of understanding why the scatter in this relation is so small. At face value, this seems difficult to explain in the framework of the current standard cosmological paradigm (the *Cold Dark Matter*—CDM—scenario) where larger systems form from mergers and accretion of smaller ones. Detailed controlled merger simulations have demonstrated that gas dissipation is a crucial ingredient in order to reproduce the observed Fundamental Plane in the framework of the hierarchical merging scenario (Robertson et al. 2006). In these simulations, the tilt of the Fundamental Plane arises primarily by variations in the M/L ratio. Simulations have also shown that mergers between gas-poor galaxies (sometimes referred to as *dry mergers*) maintain the tilt. It should be noted that these simulations are not embedded in a cosmological context, and that initial conditions are often idealized and likely not representative of the range of orbital distributions and physical parameters of the merging systems occurring in the real Universe.

Various attempts have been made to include detailed prescriptions for modelling galaxy sizes in theoretical models of galaxy formation of the kind I describe below. These are coupled to cosmological simulations but rely on prescriptions based on the simulations mentioned above (therefore often extrapolated to higher redshift and/or outside the range of parameters directly probed) to model galaxy sizes. Early models used simple formulae based on the virial theorem and conservation of energy, that are appropriate for dissipationless gas-poor mergers. More recent implementations have taken advantage of results of hydro-simulations to include the energy dissipated in gas-rich major mergers in the energy budget. This modification reduces the sizes of less massive ellipticals, bringing the predicted mass-size relation in quite good agreement with observational data (see e.g. Porter et al. (2014); Shankar et al. (2013)). Predictions from different models, however, differ in the detail (unsurprisingly) so that, in a few cases, contradicting conclusions are drawn. For example, Shankar et al. (2013) find that the scatter in sizes of elliptical galaxies at fixed stellar mass is larger than the observed one, while Porter et al. (2014) claim that their model correctly predicts the normalization, slope *and scatter* of the low redshift size-mass relation for elliptical galaxies. The latter study finds a curvature in the Faber-Jackson relation that is not observed locally and that they claim could be alleviated if more massive ellipticals have more bottom heavy initial mass functions. The observed tilt of the Fundamental Plane is also reproduced in these models, and it results from the decrease of gas fraction with increasing progenitor mass that leads to a varying central dark matter fraction (Covington et al. 2011). It will be interesting to see how model predictions compare to better defined local relations, and to more detailed observations at higher redshift. When comparing data with models, however, one should keep in mind that these models do not resolve the internal structure of galaxies: they only provide a 'bulge-to-total' parameter, that is used to assign model galaxies to different morphological classes. 'Standard' mass/light distributions are also assumed in order to estimate galaxy sizes.

Let's now turn to disk dominated galaxies. The observed Tully-Fisher relation implies a close relation between the total gravitational mass and the total amount of stars. The relation is surprisingly tight, particularly at long wavelengths (Willick et al. 1997), and has long provided a major challenge for modern theories of galaxy formation. From the theoretical point of view, such a relation can arise as a natural consequence of the correspondence between mass and circular velocity (Mo et al. 1998). A scaling similar to that observed can be obtained if the disk rotation speeds and the luminosities (that are the observables entering the Tully-Fisher relation) are proportional to the circular velocity of the halo and to the mass of the halo, respectively. In practice, these assumptions are not valid: disk rotation speeds depend in a non trivial fashion on the contribution of gas, stars, and dark matter within the optical radius of the galaxy, and the luminosity results from the entire star formation history of the galaxy, that is not uniquely determined by the mass of the parent halo.

Early N-body simulations reproduced the slope of the relation, but had difficulties in matching its zero-point (Steinmetz and Navarro 1999). These were just a manifestation of the so-called 'angular momentum catastrophe': baryons condense early in clumps that then fall into larger haloes and merge via dynamical friction. This produces a net and significant transfer of angular momentum from the baryons to the dark matter, with the result that simulated disks are generally too compact and with up to ten times less angular momentum than real disk galaxies. The formation of a realistic rotationally supported disk galaxy in a cosmological context is still an open problem. Numerical work has shown that this is in part due to limited resolution and related numerical effects that cause artificial angular momentum loss and spurious

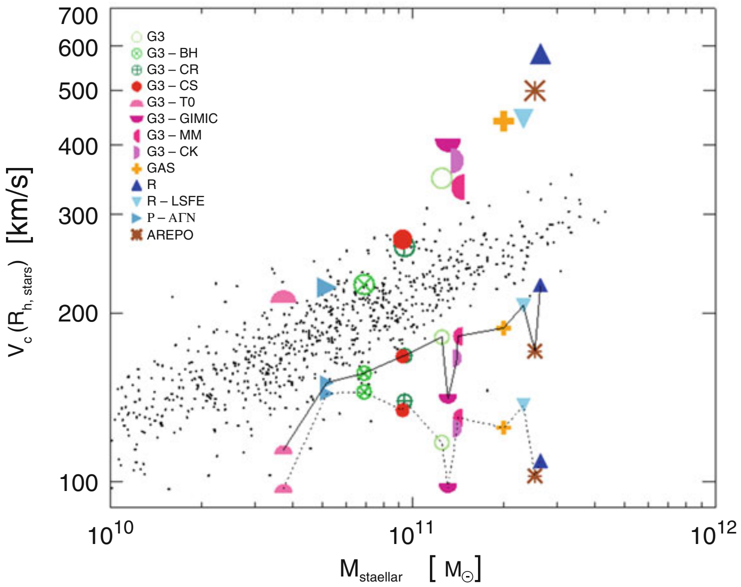

Fig. 8.10 From Scannapieco et al. (2012): The circular velocity at the stellar half-mass radius of simulated galaxies plotted as a function of stellar mass. *Small black dots* correspond to data for nearby spiral galaxies. Symbols connected by a *solid line* show the contribution of dark matter to the circular velocity at the same radius. A *dotted line* shows the same but for a dark matter only simulation. The difference between *solid and dotted curves* indicates the degree of 'contraction' of the halo

bulge formation (for a detailed discussion, see e.g. Mayer et al. (2008)). The physics of galaxy formation during the merger of the most massive protogalactic lumps at high redshift and, in particular, the feedback due to supernovae are, however, also playing a very important role (Scannapieco et al. 2012; and references therein).

Figure 8.10 shows the results from a recent work by Scannapieco et al. (2012) that has compared various cosmological gas-dynamical codes used to simulate the formation of a disk-like galaxy. The runs differ in their numerical treatment but use the same initial conditions. The figure shows that there is a clear discrepancy between the observed Tully-Fisher relation and simulated galaxies, that tend to have significantly larger velocities at fixed stellar mass. Models with more efficient stellar feedback come closer to match the observed scaling laws, but the same models often have a significant central component (i.e. the efficient feedback damages the disk).

In the framework of semi-analytic models of galaxy formation, matching the zero-point and slope of the Tully-Fisher relation is 'easier'. It remains, however, a long standing problem that of matching the zero-point of this relation and reproducing at the same time the observed galaxy luminosity function. It remains unclear if this difficulty is related to some approximation in the size calculation, or to more fundamental shortcomings of the CDM model (Baugh 2006).

Of course the fact that models are not in perfect agreement with the data does not mean that the models have to be killed. It is actually from these disagreements that we learn more about the physics that is at play!

The last aspect to examine in the problem of galaxy formation is that related to the role of magnetic fields.

8.8 The Role of Magnetic Fields

Questions for David Moss:
could contemporary galactic fields trace their origin back to the era before galaxy formation?

Perhaps the conceptually simplest explanation of the fields we see today is that fields with spatial scales greater than that of protogalaxies are created in the early stages of the Universe, and then evolve to become the fields seen today. The physics of the origin of any such field is still unclear, and presents a possibly important gap in our understanding. A number of possibilities have been proposed, including phase transitions in the very early Universe (see, e.g. Widrow (2002)), and instabilities and fluctuations after reionization (Lazar et al. 2009). Any such primordial fields would be compressed during galaxy formation and subsequently stretched and distorted by differential rotation, large-scale non-circular motions, interstellar turbulence and other flows, once galaxies have formed.

There are several basic difficulties with this scenario. Perhaps the most fundamental is the "winding problem". A generous upper limit for the strength of the primordial field is $O(10^{-12})$G—some estimates are much smaller. If this field is to be amplified to the observed microgauss strengths, even after allowing for compression during the collapse of the protogalaxy, this would require so much winding by the differential rotation that the resulting pitch angles p ($\tan p = B_r/B_\phi$), would have $p \lesssim 1°$. In contrast, typical observed values are around 20°. Additionally, such a field is rapidly expelled to near the perimeter of the galaxy (the "MHD flux expulsion effect"), and would then be inconsistent with observed RM measures.

Conversely, if there is sufficient field dissipation (reconnection) to restrict the field winding sufficiently to yield the desired pitch angles, the fields will be much too weak.

There is also a "parity problem". The parity of a magnetic field is a measure of its symmetry with respect to a plane, often the rotational equator. In galactic terms, axisymmetric fields with both azimuthal component and poloidal component (lying in meridian planes) having even symmetry with respect to the plane, are described as being of even parity, $P = +1$. Fields with the opposite symmetry properties have odd parity, $P = -1$. Of course, intermediate ("mixed") parities are possible. A component of a primordial field that is parallel to the disc plane will have even parity with respect to the plane, but we have just seen that this component cannot be expected to survive the winding process. A component parallel to the rotation axis will have odd parity, which will be subsequently preserved. In contrast, galaxy fields appear to have even symmetry with respect to the plane—see Sokoloff and Moss (2013).

This all suggests that large-scale field of observed strengths cannot be directly inherited from pre-galactic fields, and that detailed consideration of *in situ* generation mechanisms is required.

So if the contemporarily observed fields are not the direct descendants of pre-galactic fields, how can they be explained?

It is now widely accepted that galactic discs are suitable sites for large-scale dynamos to operate. In particular, galactic dynamo theory generally predicts fields of even parity with respect to the disc plane, and that field vectors near the disc are offset from the gas flow vectors—both features are in agreement with observations. In its simplest form, a dynamo is a mechanism by which an infinitesimally small "seed" magnetic field can be amplified to finite magnitude, and maintained indefinitely against decay. The possible origins of such seed fields merit some attention, but let us assume that they can be found. The most readily accessible formulation of dynamo theory is MFD theory, but note that less restrictive approaches are also being developed.

The gas in a galactic disc is turbulent. The turbulence is driven by injection of energy from supernovae (SN) explosions, winds from hot stars and dynamical instabilities. Whilst the turbulence (on scales typically of 100 pc) causes modelling problems, it is a key ingredient of the dynamo action that is believed to create and maintain the large-scale field.

In its modern form, astrophysical dynamo theory began with the seminal paper of Parker (1955). He showed that mirror antisymmetric cyclonic turbulence together with differential rotation can drive dynamo action. This paper was addressed to explaining the magnetic field in the solar convective envelope. It was soon recognized that the mechanism could also operate in galactic discs (Parker 1969). In order to tackle the dynamo problem in full it would be necessary to solve not only the basic MHD equation

$$\frac{\partial \mathbf{B}^*}{\partial t} = \nabla \times \left(\mathbf{u}^* \times \mathbf{B}^* - \eta_{\mathrm{m}} \nabla \times \mathbf{B}^*\right), \tag{8.4}$$

but also the hydrodynamic equations, and possibly the thermodynamic equations. A wide range of spatial and temporal scales, spanning many orders of magnitude are involved, and there is no prospect of solution of this "full" problem without substantial approximation and simplification. In Eq. 8.4, $\mathbf{u}^*$ is the total fluid velocity (rotation, large-scale streaming and small-scale turbulence), $\mathbf{B}^*$ is the total magnetic field and η_{m} is the microscopic diffusivity. The most dramatic, and most accessible and fruitful, simplification is the MFD theory, in which Eq. (8.4) becomes

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\alpha \mathbf{B} + \mathbf{u} \times \mathbf{B} - \eta \nabla \times \mathbf{B}). \tag{8.5}$$

In deriving Eq. 8.5, Eq. (8.4) has been averaged over some scale, and **B**, **u** are now the resulting *mean fields*, representing averages over these scales. α, which parameterizes the generative effects of cyclonic turbulence, is the key quantity in MFD theory; η is the turbulent resistivity. η and α thus represent sub-grid modelling; both may be tensor quantities. In galactic MFDs, differential rotation plays a key role in generating large-scale magnetic field by twisting and stretching poloidal field. In order to close the cycle, and maintain the overall field against decay, the alpha-effect (or something analogous) is required to create poloidal field from toroidal. In the MFD equation, in axisymmetric models toroidal (azimuthal) field is predominantly created from poloidal field (in meridian planes) by the differential rotation, whereas the converse step, poloidal to toroidal field, is achieved via the α-effect. Without such a loop, dissipation processes would dominate and the field would eventually disappear. The solution $\mathbf{B}(\mathbf{r}, t)$ of Eq. (8.5) is usually interpreted as corresponding to the observed *regular* fields, and the small scales are subsumed into the coefficient α.

Differential rotation is one of the two essential ingredients of the operation of large-scale galactic dynamos. Its absence in elliptical, dwarf and irregular galaxies provides a natural explanation for the absence of large-scale magnetic fields in these objects.

This approach was pioneered in Jena and Potsdam in the 1960s and 1970s; a comprehensive treatment is given in Krause and Rädler (1980). Early investigations were followed by an interval during which the basic concept of a significant α-effect was rigorously challenged (e.g. Cattaneo and Vainshtein (1991) and many subsequent papers). Now both theoretical studies and the results of detailed modelling of small "boxes" of gas lend support to the basic validity of the MFD approach and this "catastrophic quenching" does not occur. The basic concern was that an accumulation of small-scale field could "strangle" dynamo action, limiting large-scale fields to irrelevantly small amplitudes. Now it is generally agreed that various transport mechanisms exist that can alleviate this problem (for example, Brandenburg (2006); Chamandy et al. (2014); Kleeorin et al. (2000); Moss and Sokoloff (2012); Vishniac and Cho (2001) and many others). The simplest forms of galactic dynamos are driven by the joint effects of cyclonic turbulence (in this approximation, the alpha-effect) and differential rotation. These are conveniently summarized by dynamo numbers $R_\alpha = \alpha_0 L/\eta_0$ and $R_\omega = (r d\Omega/dr)_0 L^2/\eta_0$, where r is cylindrical radius, L is a suitable length scale and subscript zero denotes a representative value. In many cases these can be combined into a single dynamo number $D = R_\alpha R_\omega$. In most physically relevant examples dynamo action occurs when $|D|$ exceeds some threshold value. When applied to galactic discs, even simple models give results that are broadly consistent with observations—see e.g. Beck et al. (1996); Ruzmaikin et al. (1988). Some form of nonlinear back reaction of the magnetic fields onto the gas motions is necessary to limit fields at finite magnitude. Other gas motions, such as large-scale non-circular streaming, outflows from the disc—galactic winds and fountains—probably play an important role in some galaxies. Refinements can be added to models, including several explicit formulations of nonlinear dynamical feedback, such as buoyancy, cosmic rays and galactic winds. The latter, besides taking part in the basic dynamo action, may influence field structure in the halo regions above and below the galactic disc.

The MFD model is quite robust, in the sense that truncation to two or even one spatial dimension can yield useful results.

It has also become apparent that a full understanding of dynamo action cannot be attained without consideration of the properties of *magnetic helicity*, a property of the small-scale fields, that controls the α-effect. Crudely speaking, magnetic helicity is a measure of the degree of linkage of magnetic field lines. It is defined as the volume integral $\int \mathbf{B} \cdot \mathbf{A} dV = \int \nabla \times \boldsymbol{A} \cdot \boldsymbol{A} dV$, where $\mathbf{A}$ is the magnetic vector potential. (There is a clear analogy with the kinematic helicity, $\int \mathbf{v} \cdot \nabla \times \mathbf{v} dV$.) Magnetic helicity is a conserved quantity, so increase in large-scale field (e.g. by dynamo action) increases large-scale helicity, and thus small-scale helicity of the opposite sign. Dynamical feedback from the latter can strangle the dynamo action – the catastrophic quenching referred to above—unless a mechanism exists to remove the small-scale helicity.

Plausible and useful results in modelling spiral galaxies can be obtained by taking the simplest form of MFD theory, whilst bearing in mind that additional effects may need to be included, for example the effects of buoyant motions in the disc driven for example by "bubbles" from sites of multiple supernovae explosions (e.g. Ferrière (1998)), or by inflation of bubbles by cosmic rays. In a first approximation, these models can also be studied by a quantity analogous to the alpha effect (see, e.g., Moss et al. (1999)). MFD modelling has the advantage that substantial exploration of parameter space can be made with limited computational resources. Of course, this efficiency and convenience is paid for by accepting the uncertainties of parametrization of small-scale processes.

An alternative approach is known as Direct Numerical Simulation (DNS), which attempts to model more-or-less explicitly some smaller-scale dynamical and thermodynamical processes. Very substantial computing resources are required. Even so, parametrization of transport processes at small scales is still needed. DNS in relatively small "boxes" has been used to provide direct estimates of the turbulent transport coefficients α and η, and to study the evolution of statistical properties of the small-scale fields and how nonlinear feedback on the α-effect evolves. Gent (2012) gives a comprehensive review. DNS in a box has also been coupled to studies parametrizing the effects of cosmic ray heating from SN in driving the rise of bubbles from the galactic disc; this can be an effective contribution to the α-effect. At the moment, even accepting sub-grid parametrizations, adequate DNS of an entire galaxy presents very substantial computational problems. For the foreseeable future the most promising approach may be to use computationally intensive DNS in local boxes to estimate transport coefficients, and to use these estimates in global mean field models.

When discussing both observations and dynamo theory you mentioned small-scale fields. How do these arise? Also seed fields are clearly important to initiate large-scale dynamo action. What can you say about them?

Small-scale fields are known to be ubiquitous (e.g. from the observed depolarization of synchrotron radiation) and to be at least as strong as the large-scale fields. Typical length scales are of order 100 pc, compared with the several kpc scales of large-scale fields, and O(10) kpc for galactic radii. There are two potential sources of these fields. They arise naturally from the tangling of large-scale fields by the disc turbulence. There is also the possibility of *small-scale dynamo action*, in which small-scale turbulent motions can maintain small-scale fields, in approximate energy equipartition with the gas motions. The highly turbulent vicinities of groups of supernovae may be particularly favourable for this mechanism to operate.

For a dynamo to operate, a "seed field" must be initially present; dynamos do not create magnetic field *ab initio*. Large-scale dynamos amplify a seed field, organize it and maintain it against decay. It follows that discussion of the origin of galactic fields is incomplete without consideration of possible seed fields. Galactic MFDs have typical growth times (e-folding times) of about $5 \times 10^8 - 10^9$ yr, so a primordial field can only be amplified to contemporary strengths in the available time if it is near its rather optimistic upper limit of $O(10^{-12})$G. The detection of strong organized fields out to redshifts in excess of unity provides an even stronger constraint on the necessary strength of primordial seed fields. On the other hand, turbulence will rapidly (timescale $O(10^6)$ yr in a galactic disc) drive small-scale dynamo action. This generates disordered fields at the scale of the turbulence and in approximate equipartition with the kinetic energy of the turbulent motions—i.e. at least $O(10^{-6})$G. Large-scale dynamo action (as described e.g. by a MFD) can then organize such a small-scale field into contemporary structures. In models, signs of such organization typically appear after a few galactic rotations—$1 \sim 2$ Gyr say (Beck et al. 1994; Moss et al. 2013a), when this field is already of microgauss strength. Additionally turbulence, perhaps augmented by the magnetorotational instability (MRI), may tangle and amplify a weak relic field, in this way also providing a strong small-scale seed field. Another possibility is that weak fields could be generated by the Biermann "battery" mechanism, or even by a dynamo, in the first generation of stars and subsequently ejected into the ISM where small-scale and then large-scale dynamo action can operate, as outlined above; a more detailed discussion is given in Sokoloff and Moss (2013). Thus there may not be such a fundamental distinction between these various scenarios, and finding a suitable source of seed fields may not be a problem.

To what extent our ability in modeling the various processes occurred during galaxy formation and subsequent evolution is in agreement with the observational data? We explore now this aspect of the problem.

8.9 Comparing Model Predictions with Observations

Questions for Malcolm Longair:
the physics of baryons is certainly the most difficult part of galaxy formation models. Could you sketch the main processes that see baryons are the most visible ingredients of galaxies? Why is it so difficult to model these phenomena? Which processes dominate during this epoch?

The reason that the behavior of the baryons is so difficult is because baryonic matter is dissipative. This means that it can lose energy by radiation, unlike, say, the dark matter. The good news is that, because baryonic matter can lose energy by radiation, stars can condense from regions of high interstellar gas density leading to high temperatures in their cores which enable the nuclear processing of material to take place. In turn, this leads to the synthesis of the heavy elements which are necessary for organic and inorganic chemistry and so ultimately to human life. From the point of view of understanding the astrophysics of galaxies, these processes lead to the huge variety of astrophysical phenomena which all need to built into a self-consistent picture of galaxy evolution, taking into account with the vast amount of information now available on galaxy populations. We know that there must be feedback mechanisms between star formation, supernova explosions, the enrichment of the interstellar medium with heavy elements, and so on, each of which is a complex discipline in its own right.

The most ambitious supercomputer simulations nowadays aim to build realistic astrophysics into the models of galaxy formation and evolution, but there remain considerable uncertainties in key aspects of the simulations. For example, the star formation history of galaxies is an essential part of the story and yet we do not have a mature enough theory of the star formation process and its dependence upon local physical conditions to include this process in a purely physical manner – some reasonable empirical approximations have to be made. To circumvent these difficulties, semi-empirical models of galaxy formation and evolution have been constructed, in the hope that these will provide guidance about how secure the various empirical assumptions of the models really are. But this is very different from predictive astrophysics. So, galaxy formation and evolution are hard.

Notice that this necessarily complex problem contrasts strongly with the evolution of the dark matter in galaxies. Assuming the dark matter is some sort of ultra-weakly interacting particle, the evolution of the dominant dark matter in galaxies can be simulated in considerable detail and with a good deal of confidence. The structures which form under gravitational collapse and the subsequent evolution of the dark matter under two-body processes and dynamical phenomena such as violent relaxation result in structures which can account for the observed statistical properties of the Universe of galaxies in a general way. These dark matter structures provide the framework within which baryonic processes lead to the optical appearance of galaxies. To put it crudely, the baryonic matter falls into the pre-existing gravitational potential wells created by the dark matter. Then, the full panoply of dissipative phenomena come into play—star formation, stellar evolution, the deaths of stars, supernova explosions, the formation of neutron stars and black holes, stimulated star formation and many more astrophysical phenomena. Not surprisingly, the results are sensitive to the input assumptions.

But there is also a lot of good news as well, much of it coming from the availability of new data from the very large galaxy surveys and from new and future instruments for large telescopes. My own view is that one of the most important developments of the last decade has been the quantification of the properties of vast numbers of galaxies in terms of simply quantifiable physical quantities. The various correlation diagrams which have been derived from the SLOAN surveys of galaxies put the whole question of the physical and chemical evolution of galaxies on a new quantitative footing.[9] These diagrams represent global average properties of galaxies and so cannot be expected to account for the myriad of detailed features which real galaxies exhibit—but this is real progress. What I like about these studies is that, although classification decisions still have to be made, they involve objective criteria and can therefore be compared quantitatively with theory. So, despite the intrinsic complexity of the baryonic Universe, I am optimistic that much deeper insights will be forthcoming. But it will require a very major effort to get to the next step of understanding these aspects of the physics of galaxies.

Questions for Alvio Renzini:
Would you discuss the main difficulties encountered in modeling the stellar population of galaxies and their evolution?

Well, in principle there are no great difficulties. We have the ingredients from stellar evolution and from libraries of stellar spectra, so putting them together is not such a great effort after all. The question is, in case, the reliability of the results. In practice, the synthetic stellar population models cannot be perfect, hence when used to derive galaxy properties, they will imprint in the results their mismatch with reality. This clearly leads to systematic errors, which in some instances may be more important than observational errors and much more difficult to control. Derived trends of one observable versus another, such as age vs. mass, of IMF vs. velocity dispersion and the like, may be real, may be not real. They result from models giving us a somewhat distorted image of reality and therefore we should resist the temptation to soon build physical interpretations of trends that may just be an artifact of some subtle mismatch between our model stellar populations and those in the sky. I am especially concerned for models for super-solar metallicities, as we lack adequate calibrators in this regime. A long standing debate concerns the contribution of asymptotic giant branch (AGB) stars to the near-IR luminosity of stellar populations, especially relevant when measuring mass and ages of quenched galaxies at high redshifts (Cimatti et al. 2008; Conroy and Gunn 2010; Kriek et al. 2010; Maraston et al. 2006; Pforr et al. 2012).

[9]For many examples of the remarkable results of these surveys, see the relevant chapters of my books *Galaxy Formation* (Longair 2008) and *High Energy Astrophyscs* (Longair 2011).

What is in your opinion the most productive approach to gain significant theoretical improvements in this field?

I don't expect 'theoretical improvements'. In case, observational ones. New insight may be gathered by comparing synthetic stellar population models with the integrated spectra of stellar systems for which age and metallicity distributions and the stellar mass function are known independently. Globular clusters and the Galactic bulge offer the best available *calibrators* for this purpose. Unfortunately, they do not cover the full parameter space occupied by the stellar populations of galaxies at large. So, in several instances we have to work in a risky, extrapolating regime.

You have mentioned the IMF, do you think it is universal or does it depend on "space and time"?

A variable IMF is often invoked as an *had hoc* fix to specific discrepancies that may emerge here or there, which however may have other origins. For example, an evolving IMF with redshift has been sometimes invoked to ease a perceived discrepancy between the cosmic evolution of the stellar mass density and the integral over the cosmic time of the star formation rate. In other contexts it has been proposed that the IMF may be different in starbursts as opposed to a more steady star formation regime, or in disks vs. spheroids. Sometimes one appeals to a top-heavy IMF in one context, and then to a bottom-heavy one in another, as if it was possible to have as many IMFs as problems to solve. Honestly, we don't know whether there is one and only one IMF, but if appealing to a different IMF to solve one problem, at the same time one should check whether the new IMF does not destroy agreements elsewhere, or if it is not conflicting with other astrophysical constraints. I think it is perfectly legitimate to contemplate IMF variations from one situation to another, but should be mandatory to explore all consequences of postulated variations, well besides the specific case one is attempting to fix. This kind of sanitary check is most frequently neglected in the literature appealing to IMF variations.

What will be the contribution in this scientific area expected from large 30m+ ground based telescopes?

Wow, I don't know! My dream is to see galaxies at high redshifts with so much detail as we used to have, in the era of photographic plates, for local galaxies (such as Andromeda, M33, etc.). And make posters with them. I wish we could see forming/young globular clusters around galaxies beyond redshift ~ 3. I would love to see stellar color-magnitude diagrams within the effective radius of giant ellipticals such as M87, and measure their metallicity distribution function. What else? See the very first, Population III stars, or at least the first mini-galaxies at redshift beyond ~ 10, perhaps in sufficient number to make sure they are re-ionizing the Universe. But, who knows? I just wish I will still be around to enjoy the spectacle.

What do you think of our ability to model galaxy evolution from first physical principles, i.e., either constructing semi analytic models or hydrodynamical simulations?

We all believe that galaxies form within dark matter halos that grow from initial cosmological fluctuations as mapped by the cosmic microwave background. Over the past three decades this paradigm has informed virtually all our attempts at understanding how galaxies form and evolve, a paradigm which has scored great success in accounting for the growth of large scale structures (LSS) as we see them in our Local Universe. This was indeed achieved with a remarkable economy of means, as dark matter particles interact only gravitationally and N-body simulations have been able to deal with millions of such particles. This success is a result of the simplicity of the physics involved: the mere two-body gravitational interaction, over and over again, millions of times.

But galaxies as we see them are also made of baryons, and baryons give rise to a frightening variety of physical processes and phenomena. On the scale of galaxies, such phenomena include star formation, galactic winds launch and fallback, formation of supermassive black holes and active galactic nuclei (AGN), supernova explosions and their feedback, dust formation, AGN feedback, gas accretion from the circumgalactic and intergalactic media via cooling inflows and/or cold streams, ram pressure, heating and cooling of a multiphase ISM, disk instabilities and clump formation, merging and starbursts, tidal interactions, etc. We know that all such processes must be at work inside and/or around galaxies and must play a role in shaping them and in driving their evolution. Baryon physics comes indeed with a great deal of *complexity*.

Attempts at modeling all this from first principles has come in two flavors, semi-analytic models (SAM) and hydrodynamical simulations. In SAM the hierarchical growth of dark matter halos within very large cosmological volumes is taken from state-of-the-art N-body calculations, and the behavior of baryons within them is conveniently parametrized, rendering in some plausible way the physical processes mentioned above. This approach has the advantage that whole populations of galaxies can be modeled as they form and evolve from the early Universe to the present. But each galaxy is represented by a small number of quantities, such as mass, star formation rate (SFR), stellar ages and a few others. In hydrodynamical simulations the computational effort is intensive rather than extensive. Only few individual galaxies can be modeled, but this is done in great detail producing model galaxies that once conveniently visualized may appear indistinguishable from real ones. Yet, the current spatial resolution of the simulations is far from covering the huge dynamical range, from sub-parsec to megaparsec scales, at which physical processes operate. Once more, *sub-grid physics* needs to be parametrized, not unlike in the case of the SAM approach.

In the early years of the SAM practice (the 1980s and 1990s) relatively few free parameters were sufficient to construct mock galaxy populations meeting several properties of galaxies in the local Universe. A fully theoretical creation of the realm of galaxies started to be produced, predicting in great detail how galaxies would have evolved through cosmic times. Theory was enjoying an enormous success, a cultural dominance at a time when data were still scanty and we all got mesmerized, as we saw movies showing to us plausible lives of galaxies, from their first seeds to full grow. Then a flood of data started to arrive, invalidating earlier predictions, as new large facilities came on line, ensuring a continuous multiwavelength coverage from X-rays to radio and probing ever further in the distant Universe.

This has forced models to incorporate new processes, thus inflating the number of free parameters. For example, the authors of a recent set of SAMs carefully list 29 adjustable parameters of their models, with five of them fixing the cosmological model according to the current concordance cosmology, and the other 24 being needed to describe baryon physics (Benson and Bower 2010), or gastrophysics as it is called sometimes. These sheer numbers give a vivid impression of the inherent complexity of galaxies as evolving physical systems and of the quandaries one may encounter in navigating a 29-dimensional parameter space. Yet, in spite of these complexities, three remarkable *simplicities* have emerged directly from the observations. I have already mentioned two of them, the existence of the main sequence of star-forming galaxies and mass and environment quenching as two *separable* processes. The third is the evolution of the mass function of star forming galaxies, which is well reproduced by a Schechter function with constant faint-end slope α and characteristic mass M_* (Peng et al. 2010).

Thus, a sort of phase transition has taken place, and this is where we stand today: theoretical modeling of galaxy evolution has lost its early predictive power and now struggles to adjust to the data. For this reason I think that, at least in the short term, a fully phenomenological approach is more rewarding.

Based on these three simplicities a fully phenomenological model has been developed that provides a comprehensive *description* of the evolution of galaxies from high redshift to the present (Peng et al. 2010). This includes the mass growth of galaxies and the quenching of their star formation, as a function of time, stellar mass and environment. By applying simple growth and quenching rules the result is a perfect match with the mass functions of the star-forming and quenched galaxies in the local Universe. This phenomenological models has provided to me, and I hope to many others, my currently *best understanding* of galaxy evolution, though it is still a very incomplete one.

So, what do you believe are the next most pressing questions? and how much it may take before we get the answers?

The phenomenological model does not contain much physics at all. But certainly we will not be satisfied until we understand the physics. So, to me these are the most pressing questions: what are the physical mechanisms responsible for mass and environment quenching? Can they be *unified* into a single underlying mechanism? What fraction of the stellar mass of local, massive galaxies formed *in situ* and how much was accreted? How did galactic bulges form? Was the growth of bulges synchronous with the growth of their central black holes, or did they preced/follow the others? How did the metal production in galaxies proceed and how metals have circulated out of them into the intergalactic space? But I should stop here, as the list may easily diverge. For the rest, I'm optimistic. If we look back we can appreciate the enormous progress that has been made in this field in the last ten years . So, I am confident that at least the questions above will be answered within the next decade, if not before.

8.10 To Summarize

The spectrum of theoretical efforts realized up to now to explain the complex nature of galaxies is so wide that in this Chapter we have only rapidly discussed the most accredited ideas about galaxy formation and evolution, together with the main concepts that have been developed to model such evolution. Our interviews were designed to point out the qualities and failures of each model as well as the comparison with the observational data. The key point behind the whole discussion is the gradual passage from the idea of galaxies as Island Universes to that of cells of the cosmic web. Today it is no more possible to simulate the formation and evolution of galaxies without setting the right cosmological context, the right environment, and the correct energy feedback. The consequence of this increased complexity is that we cannot follow the entire process without posing a number of constraints in terms of fixed parameters and adopted scaling laws. The most important difficulties are to follow the dissipative behavior of baryons inside the DM halos, the details of the star formation process, the coupling between dark and baryonic matter in terms of angular momentum, the feedback of stars and nuclei, the yields from stars ejected in the ISM, and the frequency of merging and gravitational interactions.

The modeling of galaxies now starts with the development of the dark matter halos and proceed through the dark and subsequent re-ionization era of the Universe and the collapse of the baryons in the DM halos. In this context looking at the high redshift galaxies has certainly improved our knowledge of several phenomena, but at the same time has provided new inputs in terms of complexity. We realized that the physical processes at work in shaping the actual form of galaxies are so many that is almost impossible to identify the early progenitors of today objects.

Galaxies live in a complex and evolving society within which they form and evolve. We have only started to understand the large messy of phenomena involved in this process.

As for the other Chapters, the following items are intended to summarize the key points of each interview.

- *Numerical simulations are now able to reproduce the main features of the Hubble sequence. The key parameters are set by the initial conditions of the proto-galaxy in terms of angular momentum and random motions. Another important thing is the presence or absence of substructures during the collapse: these grow when the initial conditions are "cold" and are suppressed when the proto-galaxies are "warm". The cosmological context is still one of the problems of such simulations for what concern the power spectrum of the various galaxies, but it* *is also not yet clear the effective role of DM, in particular in exchanging angular momentum with the baryonic component.*

- *In the hierarchical scheme of galaxy formation today largely accepted, small and low mass objects come first, whereas large and massive objects come later in a hierarchy of structures of increasing size, mass and complexity as time goes by. The most used technique in numerical simulations is to reconstruct the mass assembly history of the DM component and later on add the dissipative BM that collapse into each halo with suitable prescriptions for gas cooling and heating, star formation and chemical enrichment, as well as energy feedback by SNe and AGN. The first failures of this scheme came when it was recognized that the CDM does not reproduce correctly the structures observed on small scales. Further problems are the interpretation of the rapid decrease of the cosmic start formation rate (SFR), the number of dwarf galaxies, and the observed downsizing that is anti-hierarchical. Alternative approaches to the pure hierarchical framework have been developed, such as the Revised Monolithic and the Early Hierarchical-Quasi Monolithic scenarios. In these model the keyword is to follow the evolution of the BM within each halo provided by a given cosmological context, adding all the recipes for the gas cooling, feedback, and so on. In this framework the action of merging is less important, at least for the more massive ellipticals that are formed very early in single collapse events.*
- *Semi-analytic models of galaxy formation are able to follow the variation in mass as a function of time of the various galaxies components (stars, gas, metals) with few equations and some free parameters. Today semi-analytic techniques are coupled with large-resolution N-body simulations that are used to specify the location and evolution of dark matter halos. Using mock catalogs generated by these models straightforward comparisons with observational data can be obtained. The method suffers the big number of free parameters used and the parametrization of the physical processes. The encountered difficulties are: (1) the number densities of low-to-intermediate mass galaxies that are systematically larger than observational estimates; (2) low-to-intermediate mass galaxies tend to be too passive with respect to observational measurements; (3) massive galaxies have predicted metallicities that are too low with respect to observational measurements. The solution of these problems probably lies in a physical process that is able to break the parallelism between mass growth and halo growth, particularly for galaxies of low-to-intermediate mass. An important thing to keep in mind in this context is that there is an important difference between 'formation' time of the stars in the galaxy and its 'assembly' time.*
- *The big redshift campaigns have today definitively established the cosmic web nature of the Universe. Dominant elements of the web are chains/filaments of galaxies and clusters. The space between filaments is almost devoid of galaxies – the cosmic voids, while super-clusters are high-density regions of this network. The nature of the connection between the cosmic web and the DM is still highly debated, and can be considered as the nucleus of the problem of astro-particle physicists. There is clearly a link between the large scale of the Universe we see today and the small scale phenomena that originated the density perturbations at*

the beginning of the Universe. The lack of detections of the WIMPs particles up to now poses several questions on this side. There are several arguments which lead to think that the skeleton of the present structure of the Universe should be connected with the epoch of inflation.

- *The Initial Mass Function (IMF) is one of the most important ingredients of any theory of galaxy formation and evolution. Conceptually the IMF is the distribution of stellar masses formed together in one star-formation event, while the IMF of a whole galaxy is a different issue, as it is deduced from a field population that can have many different ages and metallicities. The study of the IMF is biased by several difficulties: it requires an intimate knowledge of the pre and post main sequence stellar evolution, of the stellar birth-rate function, of the structures in which stars typically form and their dynamical evolution including gas expulsion processes, of the properties and evolution of binary systems, etc. Furthermore, corrections for various biases and uncertainties must be taken correctly into account. The single star-formation event described by the IMF occurs in a molecular cloud core typically on a sub-pc-scale and on a Myr time-scale. The IMF is a theoretical concept, there isn't an instant of time in which the full IMF can be determined: as new binary stars form, others are ejected or broken up into their binary companions, and at any instant of time low-mass stars have not yet reached the main sequence while massive ones have already left it and/or have been ejected from their rich embedded clusters. Direct star-formation simulations are now used to approach the time-variation of the observable IMF of stars and binary systems. Despite these difficulties up to now the hypothesis that in the MW there is one invariant IMF cannot be rejected, given all the uncertainties and biases. The concept of an invariant, universally valid parent IMF stands however in contradiction to all predictions star-formation theories, according to which the IMF ought to become top-heavy with decreasing metallicity and increasing gas density and temperature. For galaxies the determination of the IMF is much more complex since only the integrated properties of the stellar population are available. In general, a galaxy with a top-heavy IMF will appear blue, while a galaxy with a top-light IMF will appear red, but degeneracies can occur. The IMF of galaxies should be normalized because the low-mass and the high-mass stars have systematically different time evolution and spatial distribution. The determination of the IMF for galaxies is hampered by many sources of errors and we do not have yet a theoretical approach for this difficult problem. In this context the assumption that the IMF measured for the resolved stellar population in the MW and that of external galaxies are equal is based on statistical arguments. Recent theoretical works seem to indicate that neither the IMF of the MW that those of galaxies are scale-invariant probability density distribution functions. There are also observational evidence which indicates a systematic change of the IMF of galaxies from top-light at very low star formation rates (SFRs) to top-heavy at high SFRs. The current idea is that the IMF of a galaxy can be obtained by summing together all the IMFs contributed by each star formation event over all star-formation events up to the most massive one sustained in the galaxy,* *given its SFR. There are also now strong evidence suggesting that the IMF in individual star formation events, i.e. in embedded clusters, becomes top-heavy with increasing density and decreasing metallicity. The IMF is related to the dark matter problem because a top-heavy IMF yields dark stellar remnants which behave dynamically like cold dark matter. Therefore by analyzing the dynamical M/L ratio assuming a universal invariant IMF one would wrongly conclude that massive galaxy contains dark matter.*

- *The SFR of galaxies is the mass of gas turned into stars per unit time. The absolute SFR spans a wide range of values, from virtually zero in present-day gas-poor elliptical, S0, and dwarf galaxies up to $1000\,M_\odot\,yr^{-1}$ in the most luminous IR star-burst galaxies. For this reason it is often normalized to the galaxy mass and we speak of specif SFR. In any case the spread at each galaxy mass is quite large (nearly a factor of 10). A robust correlation is observed between the SFR and the galaxy type. The galaxy emissions in the UV, Hα, Mid-IR, Far-IR, radio and X-ray are often used to infer the SFR. Each method needs a proper calibration and has its own advantages and disadvantages. In the modern interpretation of the color-magnitude diagram the blue galaxies are the star-forming ones, while the red galaxies have barely detectable SFRs, i.e. are quenched objects. Galaxies can also populate the green valley, the region between red and dead objects and those still star forming. Several phenomena might produce a crossing of the green valley in both directions. Observations suggest that the fraction of quenched galaxies is an increasing function of stellar mass (independently of environment) and of the local overdensity (independently of stellar mass). There is not however a clear theoretical understand of the physical processes causing the mass quenching and the environment quenching. The same happens for the quenching time scale since we dot know yet whether the end of star formation is caused by a feedback mechanisms or by a stop in the gas fueling from the cosmic filaments.*
- *The AGN feedback problem has seen in these years a true revolution. Antithetic positions have been expressed on this question, ranging from the null effect of the feedback to a very significant role for galaxy evolution. In between the main effects of AGN feedback are believed to be relevant not for the whole galaxy, hosting at their centers the Supermassive Black Holes, but for the local environment surrounding the galactic centers, a $\simeq$ kpc-size region around the SMBH. The AGN feedback is connected with the so-called cooling flow problem in massive E galaxies. The feedback appears necessary not for an energetic balance but for the simple reason that SMBH masses are approximately two orders of magnitude smaller than the gas made available by stellar evolution in isolated ETGs. For a typical mass accretion rate the emitted AGN luminosity is sufficiently high to account for the stop of the cooling flow. The time interval from the beginning of central accretion, to its shutdown due to AGN feedback, is found to be of the order of 10^7 yrs, in nice accordance with observational estimates of the "on" phase of quasars. This problem is currently highly debated because many questions are still open.*

- *Supernovae influence galaxy evolution through chemical enrichment and energy feedback, namely the energy that they can transfer into the ISM. Unfortunately the exact amount of energy transferred to the ISM is still poorly known. The interstellar gas can then reach the escape velocity and escape from the potential well of the galaxy (in particular in dwarf objects) and in this case we have a galactic wind. The evidence of this is given by the metals found in the ICM and IGM. These metals have also been observed in dwarf irregular galaxies.*
- *Stars transform light elements into heavier ones in their interiors and when they die the new elements are restored into the ISM. The following stellar generation will then form out of enriched gas and the process will go on until all the gas is consumed or lost via winds. The detailed balance of the various elements produced is still not well known, in particular because we have a limited knowledge of the stellar ejecta. Chemo-dynamical models are now used to reconstruct the whole history of star formation and chemical enrichment. These take into account the rate of stellar ejecta coming from SN explosion and mass loss, but also the stellar migration. The chemical abundances can only suggest the timescales on which the various Galactic components have formed, but they cannot tell us the details of how they formed. A lot of work is still necessary to answer many open questions.*
- *The debate between the monolithic scenario of galaxy formation and the idea that galaxies form by the progressive accretion of small clumps has been very large up to now. Contrasting positions have been expressed in particular on the metallicity content of the halo stars. These data suggest that the Galactic stellar halo cannot result from the disruption of satellite galaxies similar to those observed in the Local Group. However, the surviving satellites might be intrinsically different from those that contributed stars to the stellar halo.*
- The "missing satellite problem", i.e. the finding that substructures resolved in galaxy-size DM halos significantly outnumber the satellites observed around the Milky Way, is another element of crisis for the current cosmological model. However, semi-analytic models have shown that the presence of a strong photoionizing background, possibly associated with the reionization of the Universe, can suppress accretion and cooling in low-mass halos thereby suppressing the formation of small galaxies.
- *N-body simulations have reproduced the slope of the TF relation, but had difficulties in matching its zero-point. This failure is attributed to a net and significant transfer of angular momentum from the baryons to the dark matter, with the result that simulated disks are generally too compact and with up to ten times less angular momentum than real disk galaxies. In a similar way difficulties are encountered in modeling other scaling relations, such as the FP, that will be the results of the dissipative processes occurred in the gas during the galaxy formation.*
- *Magnetic field were certainly present since the first epochs of galaxy formation, but several arguments lead to say that the large-scale field observed today in galaxies cannot be directly inherited from pre-galactic fields. The most diffuse opinion is that a dynamo action produce the fields we see in galaxies. A dynamo*

is a mechanism by which an infinitesimally small "seed" magnetic field can be amplified to finite magnitude, and maintained indefinitely against decay. The turbolent status of the gas in the ISM of a galaxy disk, due to the SN explosions, is the key ingredient of the dynamo theory. The differential rotation of the disk contribute to the formation of the large scale fields. The magnetic field modeling has reached a good level, but several problems are still open, in particular for explaining the fields on small scales.

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Chapter 9
New Eyes for Galaxies Investigation

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Within me latitude widens, longitude lengthens ...
W.Whitman *Leaves of Grass* Calamus. Salut au Monde! II part (1855)

9.1 Chapter Overview

The observational data for the extragalactic research are evolved across this century. While the first studies on galaxies were essentially based on images and spectra taken in the optical waveband and registered after hours of work at the telescope on glass photographic plates, today we receive pre-reduced multiwavelength images and spectra directly on our computers. The work of astronomers is changed completely with the technological progress. Only 30 years ago, 4–5 photographic images of galaxies, or a few spectra, were the best one can hope to get after a night of hard work at the telescope. Today, space and ground-based telescopes with big diameters and field of view are pointed toward the sky every night, collecting gigabytes of data for thousand of galaxies, that we bring with us in our laptop computers.

In the previous chapters the aim of our interviews was to clarify whether this exponential increase of observational data available for the extragalactic research has been accompanied by a parallel significant growth in our understanding of galaxies. In this chapter on the other hand, we try to offer an overview of the future scheduled or planned projects for the extragalactic research. The discussion will therefore address the most important space and ground based telescopes that have been imaged for the next future. The aim is that of clarify what are the main open questions in extragalactic astronomy and what efforts will be put forward to find their solutions.

The Chapter starts with the `Gaia` *mission that is currently mapping the stellar component of the Milky Way (MW) with unprecedented accuracy in the astrometric positions, but it is also expected to provide an incredibly large database for galaxies*

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and quasars positions. From these interviews we will gain a useful insight about the enormous range of byproducts of the MW studies for the extragalactic research.

We then address our discussion toward the most attractive telescope projects from space and from the ground. In turn, we will focus our interviews on the James Webb Space Telescope (JWST), the post-Hubble largest NASA project, and the next IR, UV, X-ray and Gamma-ray space missions of the west countries for the years to come. We will later explore the future view of galaxies coming from the ground based telescopes, like the Extremely Large Telescope (ELT) and the Large Synoptic Survey Telescope (LSST). The chapter will then offers a panoramic sketch of the extragalactic projects engaged in the east countries. Finally, we discuss the contribution of radio astronomy to the new galaxy view, examining the contribution of the Atacama Large Millimeter Array (ALMA) and the results expected from the Square Kilometer Array (SKA).

9.2 Gaia: Towards a Mapping of the MW and Its Companions

Questions for Antonella Vallenari:
Gaia, launched December 19th 2013, is opening a new era for the study of the Galaxy and their nearby companions, generating a three-dimensional map of more than a thousand million stars, mapping their motions, luminosity, temperature and chemical composition. Gaia is a special telescope which will not produce images but high precision catalogs. What aspects we expect to clarify about the evolutionary history of the Galaxy and its companions?

The ideal survey would produce a catalog of stars throughout the whole galaxy, including kinematical parameters, such as 3-D positions and 3-D velocities, chemical abundances, but also fundamental parameters such as temperature, gravity, line of sight extinction, binarity, variability, masses, and ages, with the goal to eventually reconstruction the properties not only of a single population, but of the Galaxy as a whole. Indeed such a survey is not achievable in the near future. However, this was the main principle driving the project of the Gaia mission, after the success of the Hipparcos satellite. The Hipparcos Catalog Second Release (Van Leeuwen 2007) includes 100,000 stars with a mean accuracy on the parallaxes of 700 μ arcsec and on proper motions of 1000 μ arcsec/year. This Catalog has been the basis for thoughtful studies of the Galactic structure in the solar vicinity, greatly improving our knowledge. However, only about 30,000 stars were observed with a relative accuracy better than 10 %, all in the solar neighborhood. The sample of stars having accuracy better than 10 % is complete down to $M_V = 4.5$, i.e., to non-evolved main sequence stars, only up to a distance of 50 pc (Bertelli and Nasi 2001; Bertelli et al. 1999; Binney et al. 2000).

In 1995, Lindegreen and Perryman and the group of scientists involved in the Hipparcos mission, submitted to ESA a proposal for the Gaia mission, aimed to reach a precision of about 10–20 μ arcsec down to $V = 16$ using two small (baseline APEQ 3 m) optical interferometers of the Fizeau type (Lindegren et al. 1994). It was immediately clear that the third component of the space motion, the radial velocity was necessary to properly place the stars in the 3D space. Indeed a radial velocity spectrograph was included in the design of `Gaia` (Favata and Perryman 1995). `Gaia` was declared ESA Cornerstone Mission in 2000. In 2006 the optical design of `Gaia` telescope changed. The current design is quite similar to the `Hipparcos` telescope, with two telescopes, each of 1.45 m × 0.5 m. The viewing directions are separated by a basic angle. As in `Hipparcos`, the telescopes share a common focal plane, with separate regions dedicated to astrometry, photometry and radial velocity measurements. The ESA `Gaia` mission will have a huge impact across many fields, including stellar astrophysics, exoplanets, solar system objects, the cosmic distance ladder and fundamental physics. It is impossible here to quote the (almost) thousand of papers describing the impact of `Gaia` in the various domains. Recent information can be found in Prusti (2012); Walton et al. (2012); Anguiano et al. (2014) and references therein. `Gaia` will revolutionize our knowledge of the structure, formation and evolution of the Galaxy. It will provide distances (parallaxes), space motions (proper motions and radial velocities) and astrophysical characterization through time resolved multi-wavelength photometry and spectroscopy (Bailer-Jones et al. 2013; Jordi et al. 2010) for more than one billion stars throughout most of the Galaxy. The survey will have a magnitude limit to at least $G = 20$ mag, with end-of-mission astrometric accuracies better than 5–10 μ arcsec for the brighter stars and 130–600 μ arcsec for faint targets. The solar vicinity, defined as the distance where a complete sample down to Mv=4.5 or spectral type G0V with 10 % accuracy is available, will extend from the 50 pc of `Hipparcos` to 1.5 kpc with `Gaia`. For bright halo stars (giants), `Gaia` will give a complete sample at 20 % accuracy within 10 kpc. Radial velocities will be known with an accuracy better than 5 km s^{-1} for G0V stars brighter than $G = 15.5$ (13 km s^{-1} at $G = 16.3$).

Figure 9.1 presents the expected 3D distribution of the contents of the `Gaia` catalogue in the Milky Way.

In addition to single stars, clusters improved knowledge can be used to trace the Galactic structure. In open clusters (OC), `Gaia` will measure distances for individual stars with a precision better than 1 % for objects closer than about 1 kpc and better than 10 % for the entire OC family. Higher accuracies are expected for proper motions at end of mission, reaching individual tangential velocity accuracy of the order of 0.2–0.3 km s^{-1} for low mass stars up to 1.5 kpc, and up to larger distances for bright O/B stars (Wilkinson et al. 2005). This would allow resolving both peculiar velocities and internal dispersions, which are typically of the order of 0.8–3 km s^{-1} (Fürész et al. 2008), tracing stars lost from the clusters. Kinematics and orbit reconstruction will be possible. Globular clusters can be observed outside the half mass radius where crowding is not severe. 80 out of 150 clusters are at distances smaller than 10 kpc (Bica et al. 2006). The magnitudes of the horizontal branch will range from $V = 12.5$ for the closest to $V = 19$ for clusters in the Large Magellanic Cloud. All the known globulars in the Galaxy and in the Magellanic

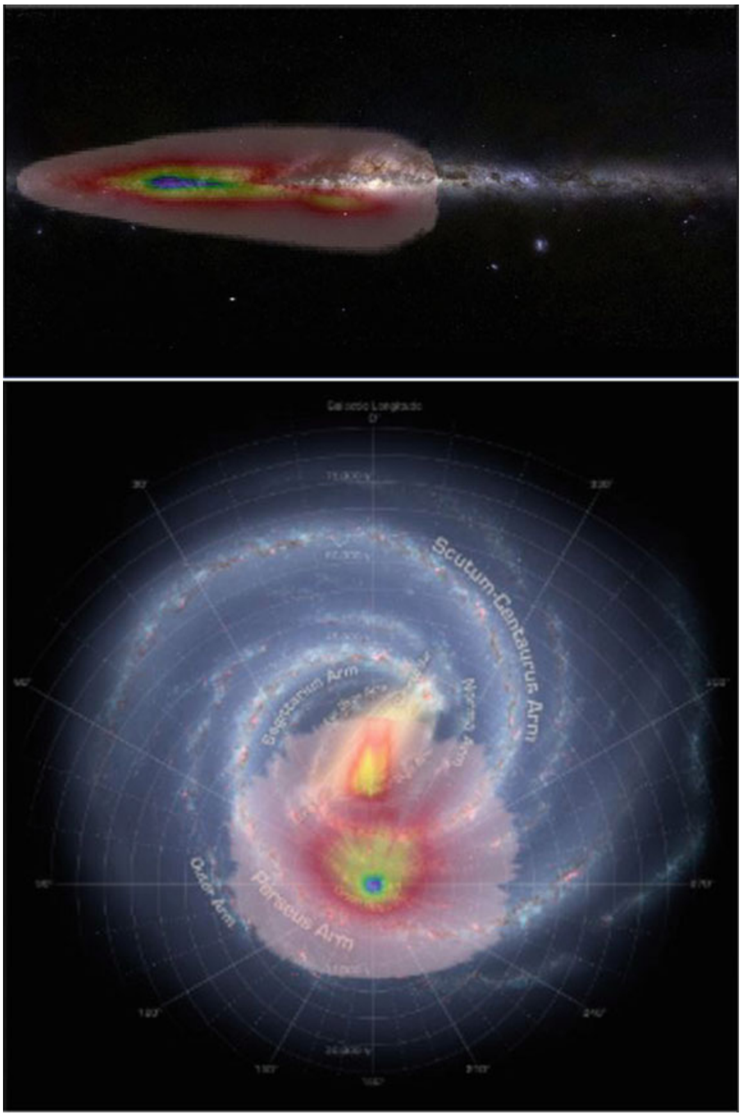

Fig. 9.1 Expected 3D distribution of `Gaia` stars in the Milky Way. Overlay of an artistic *top view* of our galaxy (NASA/JPL-Caltech/R. Hurt) and an actual picture of the Milky Way on the sky (Gigagalaxy zoom) with the results of a simulation of the contents of the `Gaia` catalogue (GUMS v8) produced by the DPAC-CU2 at the MareNostrum supercomputer. The *colours* indicates the expected density of stars detected by `Gaia` (*purple-blue* very high densities to *pink* low densities). The "spikes" pointing away from the Sun are due to windows in the interstellar extinction. The region in *yellow and red*, just below the galactic center corresponds to the high-density bulge visible through an extinction window around the galactic central region (credit X. Luri and CU2 DPAC team)

Clouds will be observed down to the horizontal branch, and clusters located closer than 15 kpc can be sampled down to the turnoff in the less crowded regions (Pancino et al. 2013).

However, Gaia will not be sufficient to define the properties of the Galactic stellar populations, and will require additional ground-based spectroscopic information (Turon et al. 2008). Firstly, the on-board low-resolution spectrograph (RVS) will not reach the same limiting magnitude as the rest of the Gaia instruments, and the majority of the surveyed stars will not have the radial velocity dimension. In addition, the limited spectral resolution and spectral coverage of RVS will only allow the determination of the abundances of a few elements. In addition Gaia will work in the visible domain, and will be hampered by high extinction. Highly crowded regions, such as the inner disk and bulge cannot be efficiently surveyed. Gaia will be complemented by on-going or proposed large-scale photometric and spectroscopic surveys, both in the visible and in the infrared: examples are RAVE (the Radial Velocity Experiment) targeting bright stars (Saito et al. 2011), the Galactic structure survey of the Sloan Digital Sky Survey Extension, the SDSS SEGUE (Yanny et al. 2009), APOGEE (Prieto et al. 2008), the Gaia-ESO Survey (Gilmore et al. 2012), VPHAS+ (Howes et al. 2014), GALAH (Vallenari 2014). A significant progress is expected in the future, combining these data with the astrometric measurements from the upcoming Gaia satellite, we should get a much clearer picture of the structure, formation, and evolution of the Milky Way and its stellar populations.

For the first time, radial velocities, proper motions and distances from Gaia, metallicity and ages from ground-based surveys will be homogeneously derived for a huge number of stars of all populations in the Galaxy. This huge and formidable database will allow us to address many key issues of Galactic astronomy, astrophysics and fundamental physics. It is clear that nowadays cosmological models are sufficiently well advanced to provide previsions we can directly tested with observations. However, we cannot say that we can simulate reality: understanding how a galaxy forms and evolves in details is still a challenge. Galaxy formation modeling is more phenomenological than based on physical theory. For instance the star formation process involves turbulence, magnetic fields, shocks, radiative transfer, stellar feedback. We are far from having completely understood these processes and having included them in our simulations. The coupled evolution of the dark matter and of the baryons is far from being an ingredient of our models. This means that our models are just simplified views to be verified, or better calibrated on the best test case we have, our Milky Way by observing the profiles of density, age, and metallicity of the structures and substructures identified in the local Universe. Indeed it is quite puzzling that the inner halo $[\alpha/Fe]$ abundances are rather constant over the whole metallicity range, broadly consistent with a rapid formation of the inner halo. This is in contrast with the observations of the Magellanic Clouds and the Sagittarius dwarf, where large variations of elemental abundances and $[\alpha/Fe]$ are detected. All this suggest that mergers might have had marginal influence on the (inner) halo formation. However, how solid is this result, and how much is it based on the small samples we have studied?

Concerning the disks, recent results based on recent data shows that the thin disk metallicity distribution was substantially unchanged over the past 8–10 Gys, with a very small scatter in elemental abundances with age. This would be consistent with a steady star formation rate with inflow of material at the consumption rate. The Local Group dwarf and Irregular galaxies present a completely different behavior, with varying star formation and large scatter of elements. Many open questions remain: was the merging history of the disk and inner halo quite marginal? Are the thin and thick disk really two different populations or is it more appropriate to assume an inner and outer disk? Where are the debris, if any, of the major merging event that has heated the early galactic disk? Is there a connection between the thick disk and the barred galactic bulge? What is the effect of non-axisymmetric perturbations due to the bar and spiral arms? What is the effect of migration on the stellar populations? If migration is such an important phenomenon in the life of the Galaxy, can we still use the properties of its stars to reconstruct the formation process, i.e. are the principle of Galactic Archaeology still valid? And finally, if the migration has not a marginal effect on the Galaxy evolution, how can we properly define and characterize a stellar population?

Questions for Gerry Gilmore:
from the `Gaia` extraordinary step forward in the definition of the stellar content what problems do we expect to solve in term of a better definition of the Galaxy structure and kinematics? What improvement about the definition and understanding of the "streams"?

`Gaia` will of course be a revolution. In fact it is already, with transient science alerts being discovered and published daily. You can see and contribute to this science at http://gaia.ac.uk. The primary role of `Gaia` is to deliver an exceptionally high-precision photometric, a spectrophotometric and an astrometric survey of the brightest one billion objects on the sky. Currently we know that type and quality of information for a few hundred sources. The transition from a few hundred to hundreds of millions will be revolutionary! Specifically for streams, we will be able to see the dynamic signatures in our part of the Galaxy which retain memory of the accretion events, evaporations, and whatever else, make up our history. It will be a time machine for galaxy evolution.

`Gaia` is expected to discover hundreds of thousands of new celestial objects, including faint and/or distant galaxies. What we may expect to learn from this new galactic data set? What follow-up are foreseen?

`Gaia` delivers both an all-sky astrometric survey, and precision high spatial resolution photometry and spectrophotometry. This will, to list just a few of many examples, provide the best available tests of General Relativity; a complete sample of distant QSOs, ideal as probes of strong gravitational lensing and cosmological mass distributions; determinations of the distribution of Dark Matter on small scales; the inner morphological structure of millions of nearby galaxies; tens of thousands of nearby supernovae, for calibration of the cosmological distance scale; precise calibration of the Cepheid star distance scale, and comparison across all distance calibrators; 6-dimensional maps of the structure of nearby star forming regions with parsec-resolution; discovery and orbit determination of inner-solar system earth-crossing asteroids. And very, very much more. About the only simple prediction I can make of the forthcoming `Gaia` era of precision astrophysics is that all our textbooks will need to be rewritten!

Questions for Paola Marziani:
`Gaia` is expected to discover about 5×10^5 new distant quasars. What we may expect to learn from this kind of survey and their follow-up?

The eyes of `Gaia` will go far beyond the edge of the Galaxy, and are expected to provide a significant improvement to our knowledge identifying 400,000 quasars, the majority of them previously undiscovered. This feat will almost triple the number of quasars known at the time of writing.

`Gaia` will have also the considerable advantage of providing observations uniformly distributed over the celestial sphere, including low galactic latitude areas that have not been considered in ground-based surveys (of course the interstellar extinction will hamper the study of extragalactic source close to the Galactic plane). The uniform coverage will be a key improvement for the definition of an inertial cosmic reference frame (ICRF) with an unprecedented astrometric accuracy, but will also be an advantage in the use of quasar spatial distribution for mapping baryonic and dark matter.

`Gaia` is not the deepest instrument for surveys aimed at quasar discovery, nor is `Gaia` well-suited for discovery of high redshift quasars, for which infrared observations are needed. The main advantages of `Gaia` are the astrometric accuracy and the ability to carry out repeated photometric observations. This will make possible the application of a selection criterion that is unprecedented for quasars. Photometric criteria are only moderately successful in finding quasars (for example the SDSS color selection criteria are 66 % efficient): a spectroscopic follow-up is needed to confirm that a candidate selected on the basis of colors is a real quasars. `Gaia` completeness in classifying quasar will be around 80–90 % at $g = 18$ but will decrease to less than 50 % at $g = 20$ following (Claeskens et al. 2005), but always with negligible contamination from other sources. As the mission progresses, `Gaia` can exploit the absence of proper motions for quasar identification: galactic stars that follow the galactic rotation, unlike quasars, will have a detectable proper motion.

Earth's motions with respect to the cosmic microwave background (CMB) provide a baseline that over a 10 years period will be ≈ 800 AU. This means that it will be possible to measure at least a tentative parallax for the nearest quasars (Ding and Croft 2009). In addition to the parallax, the quasar intrinsic variability may pose a problem at the high precision intended for the ICRF but at the same time provide a fully new view on several AGN phenomena. For example, asymmetric changes in the accretion disk emissivity (as in the case of a flare or of a rotating hot spot) as well as changes in the illumination of the molecular torus supposed to surround the active nucleus may induce a variation of the quasar photocenter. An even larger variation could be induced by a binary black hole system with parsec scale separation (Popović et al. 2012). Finally, it has been estimated that `Gaia` will provide imaging for $\sim 10^3$ strongly lenses quasars i.e., quasars whose images are doubled or even quadrupled by the gravitational lensing of matter between the quasar and the observer. Those systems are rare and the identification and eventual study of a large sample may tell a wealth of information not only on the distribution of the intervening matter and on cosmological parameters, but also on the structure of the quasar itself (Sluse et al. 2012).

`Gaia`, other survey missions, and ground-based instruments will lead to the discovery of quasars in the numbers of millions within the next decade [there are already $\sim 10^6$ quasar candidates, Flesch (2013)], as described in Chap. 8 (D'Onofrio et al. 2012a) of D'Onofrio et al. (2012b). It is my genuine hope that some unforeseen phenomena will also be discovered. However, it seems important at the moment that a better sense is made out of such a large sample of quasars. Quasars are not all the same object. Eigenvector 1-based approaches help organize quasar on the basis of physical parameters like Eddington ratio [their luminosity-to-black hole mass ratio, Sulentic et al. (2000); Marziani and Sulentic (2014); Shen and Ho (2014)]: even if AGN show some self-similarity associated with the accretion process, there are notable differences due to Eddington ratio, orientation, black hole mass, metallicity even if we restrict the attention to unobscured Type 1 AGN. This seems a necessary step for a better understanding of quasar evolution in terms of luminosity, Eddington ratio and black hole mass.

The future years of the extragalactic research will be very exciting. The first big telescope ($D > 5$ m) will be launched soon in space, and a new class of ground based telescopes with diameters larger than 30m assisted by adaptive optics will appear in the next 15–20 years. New radio interferometers with earth-size or larger baselines will map with unprecedented resolution and power the entire Universe. A lot of new surveys have been planned in all wavebands. In few words we can say that the "Golden Age" of extragalactic astronomy is coming. Why so many efforts in this scientific area? The next interviews will try to explain what will be the scientific return of such big investment.

9.3 JWST, 30m+, ALMA: First Galaxies, AGN, BH Growth and the Re-ionization Era

Questions for Massimo Stiavelli:
during the last decades astronomers have used the combination of ground based and space telescopes to tackle the testing of the standard cosmological framework, the formation of the first galaxies and galaxy-BH co-evolution. What will be the questions that `JWST` is called to solve? How the dialog between `JWST` and 30m+ ground based + `ALMA` telescopes will improve our understanding of galaxies?

Over the last decade, studies from space and from the ground have pushed the boundary of our knowledge to the end of the re-ionization era. We see significant evolution in the properties of galaxies, accompanied by a significant decrease, with increasing redshift, in the number density of bright galaxies, and a steepening of the galaxy luminosity function. Measurement of the optical depth from `WMAP` (Komatsu et al. 2011; Planck Collaboration 2014) and `Planck` provides an integral constrain to re-ionization showing that the process of re-ionization started earlier than redshift 10. Moreover, we have not seen so far indications of having detected a population of primordial, first-generation galaxies although admittedly it is not clear what our capabilities to detect and recognize a first-generation galaxy would really be at this time. This state of affairs allow us to conveniently characterize our future steps in understanding the origin of galaxies as two high level questions:

- what where the processes that set the initial conditions of galaxy formation?
- how did galaxies evolve over time from the early era to the present?

The first question encompasses the so-called Cosmic Dark Ages, namely all processes occurring from recombination to re-ionization (see Stiavelli (2009) for a review). These include: (1) the gravity driven assembly of the first cold dark matter structures and their accompanying baryons, (2) the formation of the first generation of Population III stars and, with them, of the first metals that will allow following generations of stars to form through more efficient metal line cooling, (3) the establishment of an ultraviolet background including both a Lyman-Werner background affecting the formation of Population III stars and an ionizing component, (4) the formation of the first black hole seeds which will grow to form mini-active galactic nuclei and, finally, (5) the formation of a first generation of galaxies which will likely kick start the re-ionization of Hydrogen above the small fractions realistically possible for Population III stars.

Observational constraints for this era are rare and far between. In fact, beyond the constraints from Cosmic Microwave Background experiments, we know very little and most of our understanding is driven by theory. In the following, we will see how the `JWST` will provide us with a first in depth glimpse of this era.

The second question broadly spans the processes occurring between re-ionization and redshift $z \sim 1$ when we see that galaxies are essentially in place with similar properties as observed in the present. During this time, galaxies position themselves on distinct sequences of star forming objects and of quiescent ones and differentiate into the morphological types we see today. As this is happening, super-massive black holes grow in their center and give rise to active galactic nuclei and quasars. We know a lot about these processes but we don't understand them completely and we want to know more. By enabling the use of familiar optical rest frames diagnostics throughout this redshift range, `JWST` will enable a systematic study of galaxy properties and hopefully enable us to largely complete the puzzle of galaxy evolution.

Let's look in more detail to these questions and their related sub-questions.

A number of separate physical processes set the stage for the emergence of galaxies and I will discuss them below. Given our sketchy knowledge of the Dark Ages, we will divide the problem in many sub-problems for ease of discussion.

The first stars, also known as Population III, are those responsible from raising the metallicity above the value arising from primordial nucleosynthesis. If Dark Matter is well described by the Cold Dark Matter spectrum this population begins forming very early on ($z \geq 30$) as mini-halos of about a million solar masses virialize and cool by molecular Hydrogen. On the other hand, if Dark Matter is Warm and, e.g., made of massive Majorana neutrinos (a few keV in mass) then the mini-halos could be significantly suppressed and we would be witnessing a very different scenario for the first stars (Maio and Viel 2015; O'Shea and Norman 2006). It is possible that the James Webb Space Telescope will be able to differentiate between these two scenarios by, e.g., studying Pair-Instability supernovae and, probably through lensing magnification, the first galaxies. In the Cold Dark Matter case the highest redshift galaxies that we will detect will have already been chemically polluted by the Population III stars formed in their progenitor mini-halos (Stiavelli and Trenti 2010). This is not going to be the case for the Warm Dark Matter scenario.

Unless otherwise stated, in the following I will be assuming that Dark Matter is Cold as this is the prevailing view at this time.

The early formation stages after the onset of cooling by molecular hydrogen are relatively well understood but the later stages of the stellar collapse defining the initial mass function are not theoretically as robust. The star formation history of Population III depends on how effective the Lyman-Werner (LW) radiative feedback really is (e.g. Machacek et al. 2001; O'Shea and Norman 2006; Stiavelli 2009 and references therein). Moreover, most theoretical results on Population III formation assume a standard CDM. As mentioned previously, results would be radically different if dark matter had a different power spectrum. Observational results on these objects would therefore place constraints on the dark matter power spectrum at scales not otherwise easily testable.

Assuming our present theoretical understanding of Population III formation is correct and that dark matter is in the form of CDM with the standard power spectrum, the density of Population III stars will depend primarily on the effectiveness of the Lyman-Werner feedback. If this feedback is as effective as it appears from present investigations, the formation rate of Population III stars will be around 10^{-6} stars Mpc^{-3} year^{-1}. Isolated Population III stars will also be relatively faint in the non-ionizing continuum (AB$\sim$38.5–40 at $z = 10$–25, compared to AB$\sim$31 achievable in a 10^5 s exposures by `JWST`), because most of their energy output is in the ionizing continuum (Bromm et al. 2001a; Tumlinson et al. 2003) which is efficiently absorbed by the IGM. Thus, single Population III stars will be impossible to detect directly with `JWST` (Rydberg et al. 2013). Their HII regions might be more easily detected (few 10^{-21} erg s^{-1} cm^{-2}), especially if magnified by gravitational lensing, but the detection remains challenging (NIRSpec can reach 3×10^{-19} erg s^{-1} cm^{-2} in 10^5 s) especially when coupled to the low density on the sky.

The best bet to identify single Population III stars is to search for the Pair Instability Supernovae (PISNe) that they are supposed to produce depending on their mass (Heger and Woosley 2002). These objects are bright (AB$\sim$25–27) and may or may not be searchable by `JWST` depending on model details still not well determined. In a recent study the range of expected surface densities ranges from below 1–70 SN year^{-1} deg^{-2} (Trenti and Stiavelli 2009; Weinmann and Lilly 2005). At the high end of this range they could be searched effectively with a wide shallow `JWST` survey. However, at the low end they would need to be detected by some other means, e.g., wide field near-IR imaging with a WFIRST-AFTA-style mission or perhaps, at the low redshift end, from the ground. Alternatively they could perhaps be found with a γ-ray burst mission if PISNe are visible as GRBs (which we presently don't know).

Another difficulty of searching for PISNe with `JWST` is their expected slowly varying light curve (Whalen et al. 2013). If the light curve resembles that of SN 2006 gy [which may or may not be a PISN at low-z, Smith et al. (2008)] variations of a magnitude or two would occur at high redshift on timescales comparable to the lifetime of `JWST`. Thus, finding these objects by other techniques and studying them spectroscopically with `JWST` may be the best solution.

An indirect method to study Population III stars is looking for the abundance anomalies predicted by PISNe models. This could be done from the ground or by `JWST` for high redshift objects. The first galaxies in particular might show abundance anomalies if they have been enriched by Population III stars.

It is worth noting that the models still need improvements to capture the later stages of Population III formation and predict an initial mass function more reliably than we can do now (see, e.g., Abel et al. 2000; O'Shea et al. 2005; Stacy and Bromm 2014; Tumlinson et al. 2004). Complete simulations from "first principles" models are limited to relatively late forming objects, partly because of the small volume that can be simulated to the desired resolution (Yoshida et al. 2008). It is possible that objects like this will be actually prevented from forming because of the LW and chemical feedback (e.g. Trenti and Stiavelli 2009). In any case clearly more effort needs to be spent on high dynamic range simulations and this will require more powerful computing resources which should become available in the future.

Population III stars may leave black hole remnants with mass around 100 $M_{\odot}$ (Heger and Woosley 2002) and these black holes may seed the formation of the first AGNs (Madau and Rees 2001).

Ionizing radiation from a Population III star is sufficient to expel all gas from the host mini-halo even without a supernova explosion so we should expect a delay after the end of life of the star before the black hole can begin accreting. The luminosity of the accreting black hole will remain comparable to that of the progenitor star, because both essentially radiate at the Eddington luminosity.

These black holes would become detectable with `JWST` (or perhaps with future X-ray missions) only after significant mass growth. However, whether or not these black holes can grow sufficiently is being debated because of gravitational recoil following the merger of two halos leading to possible expulsion of the black holes from their host halo [Volonteri (2007) but see also Tanaka and Haiman

(2009)]. Alternatively, black holes might form directly from the direct collapse of a primordial gas cloud (Begelman et al. 2006) and they are likely not detectable directly with JWST (AB= 33.5–35) until they have grown a factor 10 or so. Clearly, if Dark Matter is Warm only this second scenario remains viable.

Further progress in this area will require improved theoretical understanding and observation of the luminosity function of mini-AGNs and its variation with redshift. Unfortunately, the fact that in either scenario the mini-AGN is detectable by JWST only after some growth makes discrimination between models harder.

Following the formation of the first stars, the first star clusters and the first galaxies will form. It is likely that these objects will not be made of Population III stars but of more evolved metal-enriched stars. Various lines of argument based on numerical simulation (e.g. Greif et al. 2008; Wise and Abel 2008) or on the metallicity where cooling by metals becomes important (e.g. Bromm et al. 2001b) suggest a metallicity around 10^{-3}–10^{-4} solar for these objects.

The definition of "first galaxies" is ambiguous but claims of detection of these objects will be broadly speaking based on the evolution of the luminosity function, on observing very low metallicities and on the absence of pre-existing (older) stellar populations.

To carry out this type of investigation, JWST has been designed to study the luminosity function to the same relative depth as that measured in the UDF (Ultra Deep Field) at $z = 6$ (i.e. 3 magnitudes below $M^{\star}$) up to $z = 20$. With this sensitivity JWST will be able to distinguish between luminosity and number evolution and enable a detailed comparison of observations and models. As an example, based on dark halo statistics, a JWST deep field reaching down to AB$\sim$31 would identify several tens of galaxies at z>10 (Trenti and Stiavelli 2008).

The sensitivity of NIRSpec (3×10^{-19} erg s^{-1} cm^{-2} in 10^5 s) is such that JWST will be able to measure metallicity of galaxies, using the OIII] 1665 line down to 10^{-3} solar for galaxies 1.5 magnitudes below $M_{\odot}$. This metallicity appears to be close to the metallicity of gas in first generation galaxies and would enable us to establish whether the galaxies we observe are evolved systems. Finally MIRI could be used to identify older stellar population on the basis of the SED of the objects.

It is very likely that JWST will be able to push the study of galaxies to much higher redshift than presently possible and that it will effectively explore the nature of the first galaxies and their contribution to the reionization of Hydrogen.

We now understand that galaxies are complex evolving multi-component systems whose appearance is dominated by baryonic physics processes happening on the framework laid out by their—also evolving—dark matter halos. An interesting analogy to the problems we are facing is provided by the atmosphere of our own planet where we also see complex baryonic physics in action. To understand atmospheric phenomena, we differentiate between climate and weather. Climate is the study of prevailing weather conditions and patterns while weather is local both in terms of space and time. We understand climate but we don't yet have a similarly detailed understanding of weather. The physical processes occurring in galaxies are much more rich and complex than those happening in the Earth's atmosphere and I believe we need to be conscious about the difference between climate and weather and strive to understand the former first. Atmospheric weather also clearly needs to be understood in terms of its variability as we experience daily its changes. The much longer timescales of galaxies make it hard for us to see immediately what is transient and what is permanent. This is perhaps the reason why a lot of progress in our understanding of galaxies has been made possible by the study of large well defined samples of galaxies. Studies of individual galaxies can be very detailed but are affected by the equivalent of local weather, i.e. by a miriad of local factors that make it very hard to understand what is typical and general and what is specific.

The understanding derived from large, multi-facility, surveys such as COSMOS, GOODS, CLASH and others is rapidly changing our view about the detail of galaxy evolution and it is hard to formulate questions that will still be valid five years from now. For this reason I will be mostly highlighting themes rather than specific questions.

Metals produced by Population III stars and the first generation of (metal-poor) galaxies pollute the ISM of following generations of objects enough to enable metal-line cooling to be the dominant form of cooling in star formation. With metals comes also dust, in itself a problem and an opportunity as it can enable additional diagnostics related to dust thermal emission or specific spectral features such as PAHs. Metals also enable the formation of molecules which can be detected by ALMA and used as physical diagnostics or even as redshift indicators (Inoue et al. 2014).

This arsenal of tools will become increasingly important to address the transition from the early galaxies to objects with Population I and II stars as the galaxies we see around us today.

It is clear that star formation and mass assembly of galaxies do not necessarily occur hand in hand as mergers can span the whole range from "wet" leading to significant starburst activity to "dry" where star formed previously are mixed up to make a new galaxy. We do not yet know what is the right balance between burst and steady star formation and how this balance affects the properties of galaxies but this is an area that will increasingly move from being theory dominated to being observation driven as ALMA, JWST and other facilities begin to provide us with more and more data.

Spiral galaxies never stop forming stars but giant ellipticals and lenticulars do. The transition from the blue to the red sequence of galaxies and the related issue of quenching has received a lot of attention in the last few years (e.g. Carollo et al. 2013; Lang et al. 2014) and we may be on the verge of understanding this process. Among the common causes for quenching that are being assessed AGN-driven outbursts and morphological quenching are likely to play a role even though not necessarily at all masses.

Most galaxies harbor supermassive black holes in their centers and the mass of these black holes is related to the mass—or the velocity dispersion—of the host spheroid (Ferrarese and Merritt 2000; Gebhardt et al. 2000; Magorrian et al. 1998 but see also Seth et al. 2014). One possibility is that the black holes might be driving the evolution of the spheroid through the ability of quenching star formation due to their AGN activity. On the other hand it is possible that both black hole growth and galaxy star formation proceed relatively independently by being driven by an external factor such as gas supply (e.g. Gilli et al. 2014). Thus, we still do not have a complete picture of whether we are mostly seeing coexistence or coevolution.

Galaxy formation and evolution is largely a stochastic process driven by mergers and, possibly, bursts of star formation. Still, after all these random events galaxies emerge with well defined global scaling laws: the Tully-Fisher relation for spiral galaxies and the Fundamental Plane and mass-metallicity relations for elliptical galaxies and spheroids. Finally, the mass of central black holes seems to be generally well correlated with the mass (or velocity dispersion) of the host spheroid. It is likely that in the next few years with JWST and 30m+ class ground based telescope we will see major developments in our understanding of these relations.

Achieving a complete understanding of the physical processes responsible for galaxy formation and evolution is beyond the capabilities of a single facility. The James Webb Space Telescope will achieve unprecedented sensitivity in broad band imaging for galaxies thanks to its low background which is key to observing faint but spatially resolved objects like galaxies. However, the background advantage is lost at sufficiently high spectroscopic resolving power and for studies of internal kinematics of galaxies 30m ground based telescopes will be dominant. ALMA will provide complementary information on molecular gas, essential to understand in detail the conversion of gas into stars. Understanding the role played by AGNs will require deep X-ray imaging data. Ideally one would require a wide field high sensitivity, high-angular resolution X-ray telescope but no such facility is currently being planned. Thus, our best bet is to hope in the continuing operation of Chandra and later on the availability of Athena. Finally, we will need large surveys to acquire good statistical information on typical objects as well as to identify rare but potentially significant objects. These will be provided by the LSST on the ground and on orbit by Euclid in the visible and WFIRST-AFTA in the infrared. It is likely that the wealth of data from these facilities will enables us to answer all open questions on galaxy evolution and, perhaps, to ask new ones currently completely unexpected.

The new view of galaxies is multi-wavelength. With the next interviews we will bring the discussion on the future achievements of space missions in different ranges of the electromagnetic spectrum.

9.4 Infrared Missions

Questions for Daniela Calzetti:
after Spitzer and Herschel what have we learned about the dust composition and distribution in galaxies? What will be the contribution of JWST in the mid-infrared domain concerning nearby galaxies? Are there foreseen new IR space missions? What will be the key questions about galaxy evolution they will be called to solve?

Both Spitzer and Herschel have constrained models of the dust composition and its optical properties, at least for what concerns the dust in the Milky Way, and its 'sister' galaxy Andromeda (Draine et al. 2007, 2014). Most local galaxies, especially spirals, display IR emission characteristics that can be explained with the same type of dust that is found in our own Galaxy (Aniano et al. 2012; Hunt et al. 2015). However, both space facilities have also discovered characteristics of the dust emission that are still unexplained.

The sensitivity of Spitzer to the mid-IR emission has enabled a number of investigators to study the broad emission features attributed to PAHs, and their dependency on galactic environment in nearby galaxies. Variations are well documented: the features decrease in intensity relative to the TIR (Total IR) luminosity with decreasing galaxy metallicity. This decrease appears more like a 'cut-off' or 'jump' in the L(8)/L(TIR) ratio around an oxygen abundance value of 8.0–8.1 (Draine et al. 2007). A detailed study of the SMC indicates that the PAHs in this galaxy are smaller and less ionized than those in the Milky Way (Sandstrom et al. 2012). The nature of the variations, however, has not been firmly established; they could be due to either decreased production or increased processing of PAHs in low metallicity (or high energy density) environments, or a combination of the two (Gordon et al. 2008; Hunt et al. 2010). The PAH strength also decreases as the fraction of AGN in a galaxy increases, as established by ISO (Genzel and Cesarsky 2000); in this case, the 'processing' scenario for PAHs clearly applies. Unveiling the nature of the PAHs variations with galactic environment is clearly a field in which JWST will excel. This is a case in which using the spectacular angular resolution and sensitivity of JWST on nearby galaxies will secure a major step forward in understanding this important dust component. This is all the more crucial when we recall that the mid-IR emission is often used as a SFR indicator in distant galaxies.

The Herschel Space Telescope has unveiled two previously unknown characteristics of the dust emission in galaxies: (1) many galaxies show a sub-mm (500 μm and longer wavelengths) excess over the extrapolation of the best-fit SED at shorter wavelengths (Galametz et al. 2014); and (2) galaxies of decreasing metallicity display a lower dust-to-gas ratio, by up to an order of magnitude, relative to a linear extrapolation of the metallicity (Rémy-Ruyer et al. 2014). The latter could have serious implications for the detectability with ALMA and/or interpretation of the high redshift galaxies that are below the high-luminosity (high or potentially high metallicity) tail. Thus this is an area that current sub-mm facilities, including ALMA, first need to follow up on nearby galaxies.

At redshift up to 2–2.5, the combination of Spitzer and Herschel has enabled the classification of the IR SEDs of galaxies into two categories: Main Sequence, with a L(TIR)/L(8)$\sim$4 and comprising about 80 % of galaxies, and Starbursts, with a L(TIR)/L(8)>8 and comprising the remaining 20 % of galaxies (Elbaz et al. 2011). The nature of these two classes, how they arise, and whether the fraction of galaxies belonging to each changes as s function of luminosity and redshift are open questions. Unfortunately, JWST and ALMA have non-overlapping redshift ranges in this case: the range over which JWST can detect the major PAH feature (z$\leq$2.5) does not coincide with the redshift range over which ALMA can detect the bulk of the FIR emission from a galaxy (z>3–4). This poses a major problem for. e.g., developing effective recipes for deriving SFRs from the mid-IR emission of distant galaxies, since other properties (e.g., the total far-IR emission) will remain unknown.

In fact, there are no planned far-IR facilities for the foreseeable future. Because of the opacity of the atmosphere to mid/far-IR emission, these would need to be space missions. At present, the only large space telescope in advance state of completion and with a mid-IR capability up to 28 μm is `JWST`. The atmosphere becomes significantly transparent only in the sub-mm, and no ground-based facility, including `ALMA`, can operate much below $\sim$350 μm. The SPICA (Space Infrared Telescope for Cosmology and Astrophysics) mission, which was formerly led by the JAXA (the Japanese Aerospace Exploration Agency), is now being re-proposed as a joint JAXA-ESA mission. Unless SPICA or a similar facility is brought to space, astronomy will end up with a major gap in wavelength coverage, between 28 and $\sim$350 μm, thus missing the peak of the IR emission from galaxies in the redshift range $\sim$0–3, i.e. missing the peak of star formation in the Universe. While the bright galaxies in this redshift range have been probed by `ISO`, `Spitzer`, and `Herschel`, we have still profound gaps in our knowledge of the IR luminosity function as a function of redshift, in particular its faint-end behavior. This regime determines the amount of star formation present as a function of time and, ultimately, the mode in which galaxies have assembled their mass.

9.5 UV Missions

Questions for Luciana Bianchi:
`UVIT` and likely `WSO`, are future UV facilities. In 2012 a Request for Information from NASA asked the UV community for new ideas for space missions in this wavelength range. In your view, what are the main questions that a future UV mission should tackle about galaxy structure and evolution?

`GALEX`'s UV sky surveys have delivered >200 million UV source measurements, and completed our view of the sky across the electromagnetic spectrum. They have also led to unexpected discoveries, and opened new studies of extragalactic environments which are elusive at all other wavelengths, yet easily disclosed by short exposures with a small UV telescope (see Chaps. 5.5.1 and 7.3).

Amazing progress has come from HST imaging. However, it takes >500 HST images (>20,000 with STIS-MAMA) to cover one `GALEX` field. The resolution afforded by `HST` proved to be invaluable for detailed studies, but mapping extended star-forming regions in the local Universe is prohibitive. In addition, most HST large programs, including PHAT (Panchromatic Hubble Andromeda Treasury) and Legus (HST Legacy Extragalactic UV Survey) (see Chap. 1.5.1), have their shortest filter in NUV. FUV measurements are indispensable to characterize the hottest stars, the youngest populations, as well as to trace the faintest star-forming structures, because of the enhanced contrast with the underlying diffuse populations, and with the sky background. GALEX FUV-NUV color, wide field, and deep sensitivity gave us the only panoramic, complete characterization of young stellar populations across large galaxies, and in outermost structures. GALEX UV sky surveys have become the long-awaited UV road-map and help shaping new science priorities and planning of future UV instrumentation.

Future progress in understanding the modalities of star formation in different physical conditions, and massive star evolution at different metallicities, requires high resolution, access to UV, and wide field. Several concepts are being studied to this aim. While on one hand we strives to push our understanding of cosmic evolution to the earliest epochs, we still miss some conspicuous stepping stones. The UV emission of star-burst galaxies is red-shifted into optical-IR wavelengths in distant galaxies. Since you ask me about UV instrumentation, I restrict my discussion to the local Universe, our template for interpreting integrated measurements of distant galaxies. The most striking absence in our UV coverage of nearby galaxies so far is the Magellanic Clouds (MC). They are our closest laboratory for studies of stellar evolution and dust at low metallicity, close enough that individual stars can be easily resolved and hot low-luminosity objects could be accessible; they are conveniently situated with negligible foreground extinction, which is critical for UV studies (Bianchi 2011); they span a huge range of SF intensity (Bianchi 2014), and probe low metallicities which are needed for models of galaxies in the early Universe. Too bright for GALEX UV detectors, the main stellar bodies of LMC and SMC were only surveyed in NUV at the end of the mission (Bianchi 2014; Simons et al. 2014); SWIFT-UVOT also produced a NUV map, at slightly higher resolution than GALEX but with rather shallow magnitude limits (and no FUV). Only in the periphery of LMC and SMC and in the Magellanic Bridge, we have both FUV and NUV data from GALEX (Bianchi 2014). These images show an amazing number of hot star associations and structures not clearly identifiable in optical images (Fig. 9.2), and the potential to identify for the first time hot post-AGB objects outside the Milky Way (Bianchi 2014), as well as to study some types of binaries elusive at other wavelengths. FUV maps of the main portions of LMC and SMC are needed, and NUV maps ~3-4 mag deeper than SWIFT-UVOT data. Photometry in GALEX deep fields of MC regions is crowding limited, given the abundance of hot stars, therefore better resolution is also necessary to reach deeper magnitude limits. Huge time investments with the largest ground-based imagers available are being expended for modern optical surveys of these galaxies; such expensive efforts will provide the necessary corollary data and synergy to the essential UV maps. HST studies at very high spatial resolution are confined to very small, crowded regions such as the Tarantula nebula (30 Doradus) and its ionizing cluster R136 (Sabbi et al. 2013), a unique environment in the Local Group, and do not include FUV coverage.

A long-standing problem that severely limits our characterization of star-forming regions in galaxies (and of individual hot stars), is the [$T_{\rm eff}$,E_{B-V}] degeneracy for hot stars, or [age,E_{B-V}] degeneracy for young star-forming complexes (Bianchi et al. 2011, 2014). In addition, the extinction curve in the UV is known to vary with environment, in a complex way, not yet fully understood. A correct estimate of

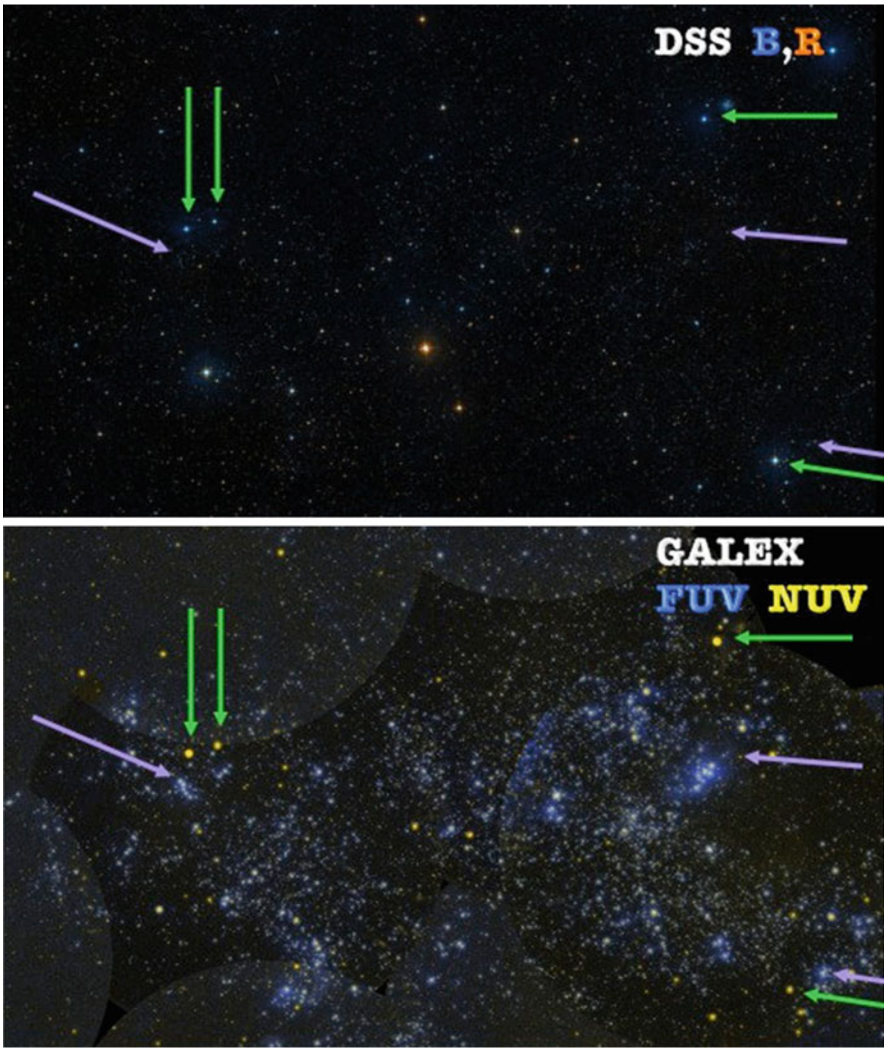

Fig. 9.2 Portion of the Magellanic Bridge seen at optical wavelengths (DSS) and in UV (GALEX FUV, NUV), illustrating the sensitivity of UV to hot stars. FUV imaging only exists for the periphery of LMC and SMC and portions of the Magellanic Bridge, the main stellar body of these galaxies was too bright for GALEX detectors

physical parameters of galaxies can be achieved only when the relation between dust properties and SF will be conclusively constrained, and extinction properly accounted for. Metallicity is another parameter that benefits from UV data, and an essential ingredient to understand galaxy evolution. A substantial number of photometric UV-IR studies addressed UV extinction in global galaxy measurements, but they all depend on fundamental assumptions which are yet to be validated, and that we know do not hold in many environments. UV extinction curves from spectroscopy are limited to a handful of sight lines even in the most studied galaxies such as M31 and M33 (Bianchi et al. 1996; Clayton et al. 2015). While substantially expanding UV spectroscopic studies of extinction by interstellar dust is a compelling need, a broad characterization of entire regions of galaxies can only be accomplished with multi-band UV photometry (Fig. 1.14 in this book).

The above issues can be addressed and solved by an imager with an ad hoc set of UV filters and adequate field-of-view and resolution. Complementary optical data abound from ongoing and upcoming surveys: SDSS, Pan-STARRS, Skymapper, LSST. The filters of `UVIT`[1] on *Astrosat* (Hutchings 2014) (FUV, NUV, optical ranges) will allow us to explore the science potential of such facility for addressing the above questions, but only a limited number of observations of nearby galaxies is expected. A satellite of the SMEX (NASA Small Explorer) class, for example, with today's detector capabilities, could enable the next major revolution in studies of star formation in nearby galaxies, ultimately to clarify how and when galaxies assembled their stellar populations. Such small instrument could fill the "sweet spot" between `HST` and `GALEX`, and in a way it would also replace `HST` after its demise, not merely extending in time our access to UV wavelengths, but expanding our ability to address new questions beyond what `HST` has accomplished, and which `HST` and `GALEX` results have prompted. If we were to start building such a small instrument now, it could be launched not too long after `HST` ceases operations or with almost no gap, in the best of circumstances.

Larger UV telescopes are also being studied, they require a longer development time and can address additional questions. The EUV-UV spectral range contains the highest number of transitions from HI, H_2, and the ground states of several ions (Fig. 9.3), and the most important line diagnostics for stellar atmospheres (Chap. 1.5.1), and for stellar, ISM, and CGM components of galaxies. The World Space Observatory (`WSO`, Shustov et al. (2014), www.wso-uv.org) currently aimed to launch around 2019, could take over from `HST` the niche of high resolution UV spectroscopy (the spectrographs on the 170 cm `WSO` telescope will yield slightly higher efficiency than `HST-COS` according to current design), its `ISSIS` cameras would extend the high resolution, small field-of-view capabilities of `HST` and include a slit-less spectroscopy mode. Unlike `HST`, it will be entirely dedicated to UV.

For extragalactic studies, multi-slit spectroscopy can be very powerful, and several concepts are being considered. Such instruments will likely require a Medium-Class telescope or larger, e.g. `GESE` (Galaxy Evolution Spectroscopic Explorer (Heap et al. 2014)). The NUV-optical range is sufficient for studies of galaxies at redshift $\gtrsim 1$ [e.g. `GESE` Heap et al. (2014), `CASTOR` (Cosmological Advanced Survey Telescope for Optical and UV Research) (Côté and Scott 2014), `Messier` orbiter].

[1]Successfully launched on September 28, 2015, the ISRO-CSA UVIT telescope on ASTROSAT is delivering the first UV images at the time this book goes to press.

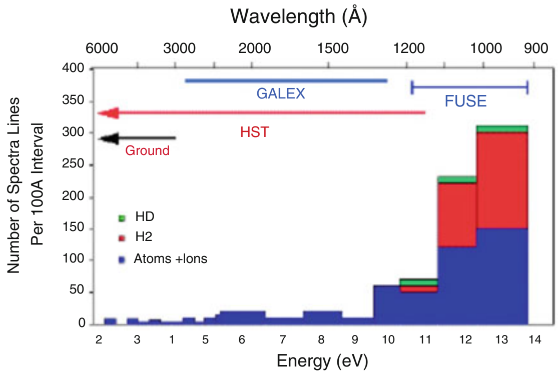

Fig. 9.3 EUV–UV spectral diagnostics power: number of lines per 100 Å interval as a function of wavelength, from the *ground states* of ions of various elements plus molecular hydrogen. Transitions from ground states are relevant for studies of ISM, IGM, stellar winds, etc. The UV range covered by GALEX is approximately also that of IUE, HST UV spectrographs, and WSO (Adapted from an original figure by Edward Jenkins)

Finally, there is still a very relevant but largely unexplored range shortward of Ly$_{\alpha}$, the so-called "Lyman Ultraviolet" (912–1216 Å). FUSE has enormously expanded the reach of spectroscopy at these wavelengths with respect to its precursor (Copernicus, Chap. 1.5.1), but the important results from FUSE also showed that much is left to be done. Questions range from the habitability of exoplanets to the reionization of the IGM to the physics of massive stars, the ISM and IGM. Imaging at these wavelengths is also still lacking and has been proposed to NASA (Green and France 2014, 2015).

As you point out, in 2012 NASA COPAG (Cosmic Origins Program Analysis Group) issued a "UV-Visible Science Objectives and Requirements Request for Information"; the submitted white papers, addressing science drivers for future UV capabilities, can be viewed on the NASA COPAG web site: http://cor.gsfc.nasa.gov/RF\discretionary-I2012/rfi2012-responses.php. Topics span from understanding the ionization of the Universe (McCandliss et al. 2012) to mapping how galaxies assembled their stellar mass, to exoplanets and, last but not least, the time domain. More recent (2015) white papers on science requirements for a UV-optical large mission are being submitted, and are available on the COPAG web site. NASA *Visionary Roadmap* (2013) and 2010 Decadal Survey identified a UV-Optical-IR Surveyor among four flagship-class missions to be considered for the future. Concepts for possible new UV instruments were also presented at a NUVA/ESO meeting in 2013; some of these presentations are published in a special issue of ApSS (N. 354).

9.6 X-Ray Missions

**Questions for Ginevra Trinchieri:
after the success of the `XMM-Newton` and `Chandra` telescopes, in your view, what are the characteristics required to future X-ray missions to enhance our knowledge of galaxy evolution?**

There is no doubt that the main requirement that could help advance our current knowledge in galaxy evolution through X-ray studies is to have deep high spatial resolution images of systems at different values of z.

We are now able to obtain unique information on black hole/neutron star/white dwarf binary systems, to link XRBs to the stellar population, and have been able to investigate some of the open questions related to the origin and evolution of the interstellar/intergalactic medium in galaxies, its chemical composition and its relation to other general properties of galaxies. Relatively large samples of galaxies are now in the archives and are used for statistical studies. Several galaxies at high redshifts have been detected, although just at the high end of their luminosity distribution.

However, observatories operating now, such as `Chandra` and `XMM-Newton`, will soon exhaust their potential for providing great contributions in the field: both suffer from relatively high background, limiting the actual depth of the observations, `XMM-Newton` has a spatial resolution that is too limited to allow us to fully use its larger effective area and `Chandra` suffers from a limited collecting area.

Currently `Chandra` still offers the best quality data for in-depth analysis of individual sources in galaxies: its sub-arcsecond resolution is required to resolve them from the other components that contribute to the X-ray emission. Moreover, sources can be identified and properly subtracted to study diffuse, faint components in confused, crowded areas. In fact, there are many examples in the literature of incorrect results based on poor resolution data, from overestimating the amount of hot halos in early-type galaxies to inferring low metal content in their spectra.

However, real advances now require long dedicated observations, which can be obtained only for a handful of objects, and mostly in the local Universe, if we want to obtain enough photons do go beyond mere detection. Given the complex nature of the emission in galaxies, this is important also for studies of galaxies at high z: while detection can and has been achieved with a handful of photons and/or through more sophisticated techniques (e.g. stacking), the ambiguity remains between emission from a nuclear source (a massive black hole), and the integrated emission of the galactic sources or the more extended hot halos.

The study of galactic sources, begun with `Einstein` and `ROSAT`, has received a boost only after `Chandra`: only with the high spatial resolution could individual sources be detected out to the Virgo distance (hardly a cosmological one!) and the luminosity function be constructed to limiting luminosities similar to those obtained in the local group with Einstein. With these data, new questions could be addressed, such as: are the LMXBs detected in early-type galaxies associated/born in globular clusters (GC) or are they native field binaries? What is the shape of the XLF at the low-luminosity end? What are the implications of the significant dearth of low-luminosity LMXBs in Globular Clusters observed in early-type galaxies? Are ULXs accreting compact sources related to the young stellar population?

Similarly, the investigation of the diffuse emission from hot gas requires high spatial resolution: in faint objects the discrete source population contributes equal amounts of—or even dominates—the hot halo emission. Only after the individual sources have been reliably identified and subtracted, can the real diffuse emission emerge.

We cannot go back in resolution now that we have seen its potential in galaxy studies. Improving the collecting area is however crucial to build on what we have understood so far, and to expand it to more examples and larger volumes.

A second important requirement is to have a relatively broad spectral range with adequate energy resolution. The broad band is important to be able to separate spectrally all unresolved components: plasma and compact sources contribute, to first approximation, in different energy bands. We will be able to obtain the same crude results of the first Einstein data, and separate XRBs from hot gas in galaxies in the local Universe, only applied to galaxies at high z, for which we will not have adequate spatial resolution and too few counts to exploit the spectral resolution necessary to analyze closer examples.

In the local Universe, we still need to properly measure the chemical composition of the hot ISM, in particular in low-luminosity systems. These observations are crucial to give us unique insight into the evolution of the ISM and its interaction with AGN, which are relevant for our understanding of crucial ingredients of current evolutionary scenarios: merging evolution and feedback. Being able to resolve spectral lines, to measure chemical composition and to adequately model the physical properties of the ISM will give us the right tools for a leap forward in our understanding of galaxy evolution.

Last—but not least—galaxies need to be studied in their full complexity, and this can only be done with a multi-wavelength approach. X-rays are a minor component in the overall energy budget, but provide unique information and probe regimes that cannot be probed at other wavelengths.

We should not waste the knowledge we have accumulated so far, and are still accumulating. We need a large collecting area, high spatial resolution observatory operating at high spectral resolution in the soft-to-medium X-ray bands. And we need it before Chandra and XMM-Newton leave us with no window in the high energy output of galaxies.

9.7 Gamma-Ray Missions

Questions for Volker Bromm:
the BAT instrument on-board of SWIFT, connected to a large ground-based efforts and follow-up has largely contributed to the study of Gamma-ray Bursts (GRBs). The detection of high redshift GRBs could provide important cosmological information. Could you tell us why? How can GRBs be studied in the near future? How new observations may constrain theories?

GRBs are indeed very intriguing probes of the state of the early Universe.

The only opportunity to probe individual Population III stars may be to catch them at the moment of their explosive death. This could involve extremely energetic supernova events, such as hypernovae or PISNe, or GRBs. The latter fate depends on whether Population III stars could give rise to suitable collapsar progenitors, involving rapidly rotating massive stars (MacFadyen and Woosley 1999). Since Population III stars are predicted to fulfill both requirements, GRBs are expected to be prevalent at very high redshifts. Indeed, GRBs may play a key role in elucidating primordial star formation, as well as the properties of the early intergalactic medium, given their extreme intrinsic brightness, both of the prompt γ-ray emission, as well as that of the prolonged afterglow.

A number of features render GRBs ideal probes of the epoch of first light (Loeb 2010): (1) Traditional sources to observe the high-z Universe, such as quasars and Lyman-α emitting galaxies, severely suffer from the effects of cosmological dimming, whereas GRB afterglows, if observed at a fixed time after the trigger, exhibit nearly-flat infrared fluxes out to very high z. This counter-intuitive effect arises, because a fixed time interval in the observer frame translates into an increasingly early time in the source frame. Such earlier times in turn sample the rapidly decaying GRB light-curve at the moment of maximal brightness, thus compensating for the cosmological dimming. (2) In the hierarchical setting of cosmic structure formation, earlier times are dominated by lower-mass host systems. The massive hosts required for quasars and bright galaxies therefore are "dying out" at the highest redshifts (Mortlock et al. 2011). GRBs, on the other hand, mark the death of individual stars, which can form even in very low-mass systems. (3) Finally, Population III GRBs would provide very clean background sources to probe the early intergalactic medium. Again reflecting the low masses of their hosts, any proximity effect should be much reduced, as ionized bubbles are confined to the immediate vicinity of the Population III system; the intergalactic medium would thus largely remain unperturbed. In addition, since GRB afterglow spectra can be described as featureless, broken power-laws , any signature imprinted by absorption and emission events along a given line of sight can be easily discerned. The outlook for GRB cosmology, therefore, is bright. Future missions, such as SVOM (Space-based multi-band astronomical Variable Objects Monitor), promise to fully unleash its potential.

Are Population III stars suitable GRB progenitors?

To successfully trigger a collapsar event, the leading contender for long-duration GRBs, a number of conditions have to be met. These are quite stringent, and often difficult to fulfill simultaneously. The first requirement for a collapsar central GRB engine, the emergence of BH remnants, is fulfilled, given the top-heavy Population III IMF. The binary nature of Population III stars may also enable them, if the binary is sufficiently close to allow for Roche-lobe overflow and a common-envelope phase, to expel the extended hydrogen (and helium?) envelope. This may be crucial to prevent the quenching of the relativistic jet, launched by the central engine. What about the additional requirement that the collapsar progenitor retains enough angular momentum? This question ties in with the rate of rotation of Population III stars, where almost nothing is known yet. A first attempt to address this within a fully cosmological context has recently been carried out, indicating that the first stars may have typically been very fast rotators, with surface rotation speeds of a few 10 % of the break-up value. Such high rates of rotation would have important consequences for Population III stellar evolution, possibly enabling strong mixing currents, and for the fate encountered at death. Thus, it is plausible that all requirements for a collapsar central engine were in place in the early Universe. The next question now is: How common were Population III GRBs, and do current or planned missions have a fair chance to detect them?

How frequent were Population III bursts?

Briefly after the cosmological distance scale to GRBs had been established, it was realized that they provide a powerful probe of the cosmic star formation history, extending out to very high redshifts where the first stars are expected to form (Bromm and Loeb 2002; Lamb and Reichart 2000) As a case in point, we now have examples of such bursts at very high redshifts, with the spectroscopically confirmed GRB 090423 at $z \simeq 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009), and a photometrically constrained candidate at $z \sim 9.4$ (Cucchiara et al. 2011). In addition, the radio afterglow of GRB 090423 has been detected with the VLA (Chandra et al. 2010), providing useful constraints on the afterglow energetics and geometry, as well as on the circumburst density. From these observations, we have learned that the afterglow properties of the very high-z bursts are not significantly different from the more local sample.

To explore the likely space of discovery, it is important to construct models of the high-redshift GRB rate (for details, see Bromm and Loeb 2006). Within such models, one typically estimates that of order 10 % of all *Swift* GRBs should originate from $z > 5$, with of order 0.1 Population III bursts per year. Detection of a Population III burst may thus lie just outside of the *SWIFT* capabilities, unless we get lucky. However, the real situation is likely much more complicated. The GRB efficiency could well depend on redshift, or on environmental factors, such as the metallicity of the host system. Since the early modeling of the GRB redshift distribution, significant refinements have been added (Campisi et al. 2011; Daigne et al. 2006; Elliott et al. 2012). It is important, though, to not lose sight of the inherently very uncertain nature of his enterprise.

How Population III stars can probe the Early Universe?

Assuming standard, shocked-synchrotron theory, the properties of Population III afterglows have been worked out (Gou et al. 2004). Consistently, across a wide range of wavelengths, from the near-IR to radio, as well as in the X-ray bands, flux levels are predicted that bring such Population III bursts within reach of existing and planned instruments. A key uncertainty in such modeling is what to assume for the circumburst density (Wang et al. 2012). If we can identify these bursts through rapid follow-up in the near-IR, they will provide us with exquisite background sources to probe the early intergalactic medium. Firstly, we can place constraints on the ionized fraction of the high-z intergalactic medium, as a function of redshift. This would provide a much more discerning picture of the cosmic reionization history, compared to the integral constraint from *WMAP* and *Planck*. In the latter case, by measuring the optical depth to Thomson scattering along the travel path of a cosmic microwave background photon from the surface of last scattering to $z = 0$, we cannot distinguish between models that can be quite different, but happen to yield the same line-of-sight integral. The basic idea is to exploit the absorption strength in the red damping wing of the Lyman-α resonance, which is very sensitive to any residual intergalactic medium neutral fraction. This idea has been tested with the exquisite spectrum taken for GRB 050904 at $z \simeq 6.3$ (Totani et al. 2006). The problem there proved to be the strong local column in neutral hydrogen, which completely overwhelmed any contribution from the general intergalactic medium. Again, the hope is that if we go to Population III bursts, such local contamination would not be a problem, given that the first stars are expected to form in low-mass host systems. Any local damping would then be small compared with the cosmological signal.

A second use of a Population III GRB background source is to scrutinize the degree and nature of metal enrichment in the pre-galactic Universe. The first stars are predicted to form in a highly biased region of the Gaussian random field of density fluctuations, such that their formation sites are strongly clustered. Any Population III burst would then likely explode in a region that already may have been enriched by a small number of supernovae. The diagnostic provided by a high signal-to-noise, near-IR spectrum of a Population III afterglow may allow us to not only measure the overall metallicity at a given redshift. Additionally, we may also be able to distinguish between the abundance pattern from different kinds of explosion, such as a PISN, a hypernova, or a more conventional core-collapse (Type 2) event (Karlsson et al. 2013).

9.8 The New Powerful Ground Based View of Galaxies

The west countries will greatly contribute to the future view of galaxies with the new class of 30m+ ground based telescopes, e.g. the Extremely Large Telescope (`ELT`), and with several survey telescopes, e.g. the Large Synoptic Survey Telescope

(LSST). Both ELT and LSST will be hosted in Chile. The next interview to Joss Bland-Hawthorn will clarify the main goals of these two projects.

Questions for Joss Bland-Hawthorn:
concerning the study of galaxies, in what technical aspect will the new 30m+ compete with the new generation of Space telescopes?

Adaptive optics at optical/IR wavelengths has yet to live up to its promise, with only a few breakthroughs in our understanding of galaxies to date. But my view is that AO science will dominate the extremely large telescope (ELT) era because, without it, the science case for ELTs is much less compelling. AO-corrected ELTs will have higher sensitivity in resolving stars to at least 20 Mpc compared to future space missions (e.g. JWST). This will allow us for the first time to resolve stellar populations over a broad range in absolute magnitude in galaxies that reside in high density regions (e.g. Virgo). Our most detailed studies to date, in particular, our understanding of the initial mass function, come from the low density environment of the Local Group.

Wide-field AO systems armed with multi-object integral field spectrographs will allow us to build up vast 3D spectroscopic surveys of galaxies. We can probe the detailed dynamical and baryonic properties of galaxies across large-scale structure. Do the angular momentum properties align with filaments and sheets? Can we observe the build-up of angular momentum and mass with cosmic time? These surveys will require new photonic OH suppression technology under development at the University of Sydney if we are to chase galaxies to higher redshifts.

For me, the biggest disappointment about the planned instrumentation suites for 30m+ telescopes is the lack of a multi-object, high resolution fiber spectrograph. I have long believed that dwarf galaxies are relics of a past age that predates the reionization era. Within these dwarfs, the star formation events have been few and far between over billions of years. The relatively low levels of pollution means that the products of the first stars may be buried within the stars, although the strongest signals may reside in dwarfs that have already disrupted in the Galactic halo.

What will be the contribution to galaxy understanding of wide field telescopes, as e.g. the Large Synoptic Survey Telescope?

The Large Synoptic Survey Telescope (LSST)is a remarkable project that explores the combination of accurate, deep multi-band photometry and the time domain for the first time in a systematic way. The all-sky survey will detect billions of stars and galaxies and do for both fields what the Sloan Digital Sky Survey has done but taken to another level. Microscopic distortions in galaxy images will tell us about the distribution of dark matter at intermediate redshift across half the sky.

I am very excited by how the LSST will explore the deep connections between particle physics and cosmology. The Standard Model says nothing about dark matter, dark energy or for that matter the hierarchy of fundamental particles. The LSST will probe neutrino masses (cosmology supplies the best limits to date) and non-gaussianity of large-scale structure to ever higher precision. Some experiments will repeat and refine previous work, e.g. distance vs redshift relations using supernovae. But entirely new science will be possible, e.g. combining lensing signals through galaxies and clusters with time delays measured from multiply lensed images opens up more precise probes of dark matter structure and distances to individual sources. While we have an accurate measurement of the mass fraction in dark matter averaged over the observable Universe, there are few reliable constraints on how much dark matter is bound to galaxies, and how much resides between. A deeper understanding of the distribution of baryons and dark matter is essential to progress in the decades ahead.

East Asia countries will also contribute to the future progress of extra-galactic astronomy. The next interview to Norio Kaifu will touch this theme in a broad perspective.

Question for Norio Kaifu:
Could you please provide us a view of the future observing enterprises in East Asia?

For the world community of astronomy and astrophysics in the twenty first century, one of the important keyword is the international coordination, beyond individual cooperation. This is important mainly because the size of leading telescopes inevitably increased, and astronomy needs huge fund and manpower for further evolution. The ALMA, coordinated by the North America (USA and Canada), Europe (ESO) and Japan (now East Asian consortium) is a typical case, and the ALMA can be called as a "world telescope" for the first time in the history of astronomy. The 30-m class Optical/ IR telescopes, TMT, GMT and E-ELT currently under construction, were led by US universities or European community (ESO) respectively, but they also needs close cooperation or coordination with communities of astronomy out of the western world; Korea in the case of 25-m GMT, Japan, India and China in the 30-m TMT, and Brazil as a non-European ESO member in the case of 39-m E-ELT (here I counted Australia as "western" country). The typical example is the SKA, a global coordination by 11 member countries worldwide and several countries showing interests. We see an interesting fact that the community of radio astronomy is relatively "democratic" and global, while the community of optical astronomy looks "centralization-like", tends to be led by a particular organization. Such difference probably came from cultural difference between two communities based on different history of those two astronomical fields; short in the radio, and 400 years long in the optical. In general, the democratic international coordination helps the development of astronomy and technology in developing member countries, as in such coordination system the member countries can claim their contributions to the project through their own engineering, technological and scientific developments, rather than to just contribute money and/or manpower to the construction. I expect such democratic and equal-footing coordination will become common in the international-level large facilities of twenty first century. Japan is now operating the ALMA jointly with Taiwan (ASIAA) and Korea (KASI) as the East Asian Regional Center of ALMA. Japan is also constructing the TMT at Mauna Kea with USA, India, China and Canada, aiming to start operation in early 2020s. As we see here the recent growth of astronomy in the East-Asian region is prominent (see also Chap. 1). In Taiwan the ASIAA (Academia Sinica Institute for Astronomy and Astrophysics) was established in 1993, and joined the SMA (Sub-Mm Array on Mauna Kea led by Smithsonian Astronomical Observatory) and ALMA, as well as construction of its own project like AMiBA, a Cosmic Microwave Background measurement mm-wave array. The National Astronomical Observatory of China (NAOC) was established based on the former Beijing Astronomical Observatory and some others in 2001. The NAOC constructed the LAMOST, a 4-m aperture Schmidt telescope for a massive spectroscopy, and constructing the FIRST, a 500-m diameter spherical-surface radio telescope. Finally the KASI, Korea Astronomy and Space Science Institute, was formally established in 2004 based on the Korean Astronomical Observatory, and successfully completed the KVN, Korean VLBI Network by close cooperation with Japan. The KVN is the first dedicated mm-wave VLBI network in the world, and the KaVA, a combined network with Japanese VERA, is now working as a very powerful tool to observe the AGNs and star forming regions. Based on such rapid evolution of astronomy in East Asia, the coordination among those four leading institutes was organized in 2005 as the EACOA (East Asian Core Observatories Association, by NAOJ, ASIAA, NAOC and KASI), after long-years efforts by myself, Liu Caipin of Purple Mountain Observatory, China, and Se Hyung Cho of KASI. In 2015 the East Asian Observatory (EAO) was formally established by the EACOA institutes, under the leadership of Paul Ho of ASIAA. The EAO will take the operation of the JCMT, an UK15-m diameter sub-mm telescope at Mauna Kea. By adding some other telescopes in near future the EAO could be a proto-type of the East-Asian version of the ESO. The ESO, European Southern Observatory, was established in 1964 as a diplomatic organization by European countries. It can be regarded as a pioneer of equal-footing farm international coordination, though it has been a regional organization concentrated in the European region. The idea "from EACOA to EAO" aims, in some day in future, to establish the ESO-type farm organization in East Asia region (probably not a diplomatic one though), for the well-coordinated joint promotion of large-scale astronomy. In reality the East Asian countries are in different political systems and have difficult historical conflicts, still, we are neighbors, and share common cultures. In fact, many regional collaboration in astronomy have been accumulated; a series of EAMA (East Asian Meeting on Astronomy) since 1990, East Asian Young Astronomers Meeting (EAYAM), East Asian VLBI Network, ALMA EA Research Center, and the EACOA and the newly established EAO as mentioned above. Why do we work for promotion of regional coordination of astronomy in the global cooperation era of twenty first century though? As known well, really good international cooperation is an equal-footing one, supported by high-level science and technology in each member country. Therefore the international cooperation are always activated and supported by international competitions, and also, such cooperative competition tend to work better among the adjacent countries located in the same region than among countries geographically and culturally distant. This is why Europe needed the ESO, and why we have been promoting the EACOA and EAO. In fact, the ALMA is supported by three regional consortiums; North America, Europe, and East Asia. The global coordination in the twenty first century will be very successful, if it is supported by strong astronomy of each nations plus farm regionally coordinated platforms. The SKA may work as a trigger to build a coordination of astronomy among African countries. Astronomy is always and everywhere a huge sauce of curiosity of humankind, toward the Universe, exoplanets and life, history of Milky Way and numerous galaxies and expanding Universe, and even origin of space and matter. Japanese astronomy is still in pretty difficult economic and political situation, but also we feel happy that we are now working in the frontier of human's exploration toward the Universe, as a nation, as a component of East Asia, and as a part of the whole world.

Radio astronomy will contribute very much to the future of view of galaxies. ALMA (Atacama Large Millimeter Array) and SKA (Square Kilometer Array) are only two examples of the present and future efforts in this research area. The next interviews to Françoise Combes and David Moss will clarify the current expectation from ALMA and SKA studies.

Questions for Françoise Combes:
we are today in the ALMA era. This new powerful instrument in the mm(sub-mm) frequencies will enhance our understanding of a wide variety of phenomena. What do you expect to be the major impact from ALMA on the study of galaxies? Will ALMA be able to study distant galaxies?

ALMA will provide considerable progress in sensitivity, spatial resolution, and dynamical range. This will benefit both to the nearby and distant galaxies. For nearby galaxies, it will be possible to resolve the Giant Molecular Cloud (GMC) in small clumps, better determine the CO-to-H_2 conversion ratio by reaching the dynamical state of clouds and the virial ratio, and also reach a scale closer to the star formation. Multi-line studies will be possible, quantifying the physical state of clouds. In nearby nuclei, the feeding of the supermassive black holes will be better understood, as well as the mechanisms of the AGN feedback and molecular outflows. The molecular torus expected to obscure some AGN of Type 2 will be uncovered.

But certainly the most exciting discoveries will be the nature of high redshift sources, and their precise evolution with time. Deep surveys of large selected fields should be observed with wide bandwidth, in order to detect both their continuum, and some of their lines, to reveal their redshift. These surveys will track the distant galaxies without any selection bias. Not only exceptionally bright sources will be studied, but also more normal galaxies, to follow galaxy formation and evolution. With the wide bands, multi-line studies and in particular dense tracers of the brightest sources will be possible. Resolved images and velocity fields of galaxies will yield insights in the dynamical state of the objects, either thick disk with large clumps, of more evolved thinner disks with bulges. The cosmic evolution of cold and dense gas will be obtained, and compared with cosmological models. In the early science, with less telescopes and sensitivity, ALMA has already detected many galaxies at high redshift, and determined some unknown redshifts by line identification, up to z∼6 (Weiss et al. 2013).

Determining the evolution of the cold gas over cosmic times will constrain many unsolved questions: how galaxies accrete their gas? how efficiently is the gas cooling in galaxies, or is it violently ejected by starburst of black hole energy? Why today baryons are mainly found outside galaxies, and why are they so few very massive galaxies? How star formation has been quenched at z∼2, what is the influence of the environment? Why galaxy evolution reveals some down-sizing effect, i.e. the most massive galaxies have formed all their stars very early, while stellar activity is confined to light galaxies today? and the same for black hole evolution?

Questions for David Moss:
SKA will open a new frontier in the study of magnetic fields in galaxies. What will be its contribution?

Observationally, the twenty first Century has already seen some very significant advances in radio astronomy. New telescopes have come into use (LOFAR, JVLA and SKA precursors such as ASKAT and MeerKAT). The precision of measurement of pulsar RMs has increased by use of LOFAR, and spectropolarimetry has become important tool. Magnetic fields have been discovered in high red shift galaxies (the MgII systems, with age about a third that of the present age of the Universe), our knowledge of magnetic arms in nearby spiral galaxies has increased substantially, and magnetized outflows in halos of spiral galaxies that are perpendicular to their discs have been observed.

In its full realization the SKA will be an assembly of several thousand receivers with total area approximately 1 km^2, and baseline extending from South Africa to Western Australia. Unprecedented amounts of data will be generated; synthesis of signals from such a large array will require state of the art analytical techniques, software and computational facilities, and the prospect is stimulating new developments in data processing. The very high resolution and large signal gathering power of such an instrument will certainly advance greatly our knowledge, among other things revealing detailed structure of magnetic fields in the MW and nearby galaxies, leading to a better understanding of how the fields interact with the gas, and their role in star formation and relation to spiral arms.

The SKA will allow much more detailed studies of the relation between magnetic fields and large- and small-scale gas motions. Our general knowledge of magnetic fields within galaxies, and at larger scales, will increase significantly. Also the SKA should allow us to discover more about the early history of magnetic fields at large red shifts, and hence establish more firmly constraints on and mechanisms for the origin of large-scale fields. This in turn will feed into theories of formation of early structures,galaxies and stars, and may thus help to determine early stellar mass functions.

On the modeling side, the speed and capacity of computing systems can be expected to continue to increase. Astrophysicists have always been among the first to exploit improvements in computer resources, and so we can anticipate more detailed and comprehensive modeling, although I suspect that for a long time this will take the form of increasingly detailed DNS in boxes linked to more detailed global solutions for galaxies. This should as a byproduct illuminate better the evolution of helicity, and contribute to our fundamental understanding of dynamo action. With improved modeling, computational facilities and observations, we can hope for better models for magnetic fields for specific rather then generic galaxies. Cosmological simulations that include galaxy formation will develop, and there is scope for attempting to model magnetic field evolution in these early epochs.

Fifty or so years ago the study of magnetic fields was very much a fringe issue for astrophysics (other than solar astrophysics), now it has moved to near centre stage. I recall a comment made in the 1960s by a prominent astrophysicist to the effect that "the larger the uncertainty, the bigger the magnetic field". Things have changed—we have come a long way since then! In short, the future is bright with promise for studies of magnetism in spiral galaxies and in the space between them.

Today's astronomers do not work only with observations provided by larger and larger telescopes, but they also use data provided by others astronomers on the same targets with various instruments. The high level of the web development permitted the creation of enormous databases for the astronomical objects. The Virtual Observatory now tell us what data are available in the word for our galaxies. The next interview to Georges Paturel will disclose the secrets of this new interactive database, and its power for getting fruitful scientific results.

9.9 Investigating Galaxies with Virtual Observatories

Questions for Georges Paturel: ground-based and space missions have produced and will produce an enormous data-base of information about celestial objects and galaxies in particular, and the Virtual Observatories are now the new world archives for astronomical observations. May you describe existing VOs projects and their possible contribution to the understanding of galaxies?

I am not a specialist of Virtual Observatory (VO). During my career I was not involved in it, even if LEDA used resources of external image databases. But the story of Virtual Observatories is an old one. It has been suggested simply to produce a standard language that will allow each database to exchange pieces of information with another database. In this way each database maintains its own data. In particular, the sites of observation could make accessible all their observational archives. There is no need to change the existing sites, no need to transfer all data in a given site. You just open your own data on the Web through the standard language.

I'll explore some difficulties. We must remember that the major difficulty when compiling data from different sources comes from the cross-identification of individual objects. Indeed, a same object can be published under different names (Messier 31, Andromeda galaxy, NGC 224, UGC 454). The coordinates can differ significantly in two different catalogues. In rare cases they could not be sufficient.

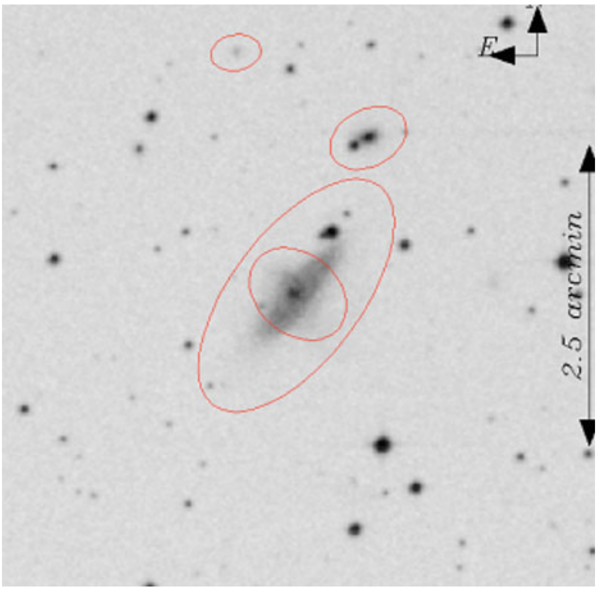

Fig. 9.4 Two galaxies at the same position: a large edge-on galaxy and a small face-on one. The coordinates are not sufficient to identify them. The external shape of the objects or their neighborhood must be used for clarification

An extreme case is provided by the pair of galaxies NGC 3314A and NGC 3314B (see Fig. 9.4). Both are known to be exactly superimposed. To disentangle them, one must use additional parameters (e.g., axis ratio, position angle or HI-radial velocity). When ground-based and space missions will produce billions of new galaxies, the problem of identification will remain the same despite the improvement of coordinate accuracy. *So, we will have to trust the computer identification*. Probably the identification of a galaxy should be based on coordinates, structural parameters (axis ratio, position angle) and environment. Anyway, we will be obliged to accept a few mis-identifications, because some of these parameters depend on the photometric domain (imagine the correlation between radio and optical observations). Probably the same difficulties we had with nearby galaxies will occur with distant ones.

My experience tells me that when managing a very large sample, everything that can happen, happens. For instance, there is an almost perfect continuum between a bright star hiding a small galaxy, and a bright galaxy hiding a small star. At which limit should we say it is a star or a galaxy? There is no answer. The problem of galaxy recognition will be difficult with future very large automatic surveys. The most secure way to recognize an extragalactic object is the value of its redshift. But, we know that automatic redshift may also produce fake measurements. *Again, we will have to trust the automatic galaxy recognition*.

Fortunately, if one returns to the main purpose of a database, i.e. delivering data for scientific research, the problem of having a few mis-identifications may be not so dramatic. It depends on the subject.

The last problem I see concerns the exchange of a large amount of data between two distant places. Imagine a query selecting one hundred million of images. Clearly, the network should be improved, but I am confident that it will be.

Concerning the last part of your question, I find that it is dramatic that so many Virtual Observatories exist (more than fifteen). I would prefer only one, that could help those who accept to enter a free diffusion of scientific material. I fear that many different standard languages appear. Somebody said: "It is so easy to create a standard, that everybody can create its own". One should have started earlier with a simple language that could have been improved progressively.

We have a nice example in Astronomy of a standardization that works very well. This is the FITS format for astronomical files. It works for images, for spectra, actually for any kind of data, thanks to a number of keywords that describe all characteristics of the data contained in the file. Would it be possible to use the same kind of keywords to describe what we want to extract from a given database?

9.10 To Summarize

We are mapping the entire Universe at all wavelengths with unprecedented resolving power, we are collecting petabytes of data, we are planning larger and larger telescopes for the ground and for space, we are constructing a new generation of fast computers for our simulations and models. The man history has never seen a so big investment for the astronomical science. Galaxies are one of the main targets of this enormous scientific effort. The first effects of such enterprise are already under our eyes: our idea of galaxies is changed in less than a century. They are no more frozen as in "The Realm of the Nebulae" but "citizens" with a very eventful life in a complex cosmic web society.

This chapter has attempted to focus our discussion on the projects of the astronomical community that have been planned for the next future to increase our knowledge of galaxies and to solve many of the still open problems about their formation and evolution. The biggest expectations come from the new largest ground and space telescopes, either those already operating and that predicted to work in the near future. Both have been described in our interviews.

Here below our brief summary of the most important aspects emerged in the discussion.

- *The* `Gaia` *mission operating since December 2013 seems to respect the expectation of being the most revolutionary mission for our knowledge of the MW. Data are coming to earth continuously and are of good quality. Parallaxes, proper motions, radial velocities and other data will provide the astrophysical characterization of millions of stars, designing a new view of the MW history and* *consequently of all galaxies. This mission will be also important for mapping the quasar distributions, the baryonic acoustic oscillations and the dark energy, but also for setting the properties of an inertial cosmic reference frame.*

- *With the lunch of the* `JWST` *extragalactic astronomy push its boundaries to the end of the re-ionization era. This telescope will therefore impacts directly on our view of galaxy formation and evolution. The first generation of stars and galaxies are expected to be seen, providing more light for the dark age. However, the bulk of the* `JWST` *activity will be devoted to understand the processes occurred in galaxies between the re-ionization era and redshift* ~ 1 *where galaxies have approximately reached the properties observed today. The spectacular angular resolution and sensitivity of* `JWST` *on nearby galaxies will also secure a major step forward in understanding the dust component of galaxies.*
- *Unfortunately there are almost no planned mid-far IR missions for the near future once excluded* `JWST`*. The* `SPICA` *mission will also lack the peak of the IR emission from galaxies in the redshift range 0–3, missing therefore the peak of the star formation in the Universe.*
- *At the moment the* `GALEX` *NUV-FUV survey has provided the most complete panoramic characterization of the young stellar populations in nearby galaxies, up to the outermost structures. Future progresses could come by coupling high resolution with wide field at all wavelengths. Particularly important will be to fill the gap in the UV coverage of the Magellanic Clouds, which are the closest laboratory for studying stellar evolution and dust at low metallicity. For the next future the* `WSO` *telescope will be entirely dedicated to the UV range with instruments of the level of that now available on* `HST`*. For extragalactic studies the most useful improvement will be the multi-slit spectroscopy at least for the NUV-optical range.*
- *Even in the X-ray domain the most important advancement will be to build high diameters telescopes with a large resolution and field of view. A second step forward will be to increase the broad band, to spectrally separate plasma and compact sources. At the same time high spectra resolution is required to measure the chemical composition of the ISM to adequately model the complex relation between galaxies and their environment.*
- *New telescopes for direct GRBs detection coupled with those required to get the prolonged afterglows could strongly impact our knowledge of the early Universe. The idea is essentially that of detecting the explosions of Population III stars. These can form even in small halos, that should be dominant in early phases of a hierarchical Universe. These data can also provide important information on the enrichment of the IGM. Among the future missions,* `SVOM` *seems promising.*
- *The* `ELT` *will largely contribute to the new galaxy view. Once corrected by the adaptive optics the* `ELT` *images could potentially resolve stars in galaxies up to* $\sim 20\,Mpc$*, which means that we can study the stellar populations in the Virgo cluster. The most detailed studies will be of course devoted to understand the galaxies of the Local Group. A 3D spectroscopic survey of galaxies can reconstruct the build-up of mass and angular momentum with the cosmic time and looks at the alignment with the web filaments and sheets. The* `LSST` *will*

combines deep multi-band photometry with the time domain for the first time in a systematic way. From detailed lensing analyses it will be possible to better understand the distribution of baryons and dark matter.

- *Asian Countries will have in the next decades a strong impact in terms of efforts dedicated to the extragalactic research. A lot of ground and space telescopes for all wavelength ranges are foreseen for the near future. New associations are born among countries to create an east-asian version of ESO. East countries are also partners of many international projects that now involve countries from the whole word. We can say that is one of the keywords to realize a unique democratic world.*
- *The impact of `ALMA` is already clear when you think that more than 50 % of the requests of telescope time cannot be satisfied for the high pressure on its instruments. For the MW and the LG galaxies the possibility of resolving the giant molecular clouds in small clumps with `ALMA` for better determine the Co-to-H_2 conversion ratio will be a significant progress. For external galaxies the most important steps forward will come by following the cosmic evolution of the cold gas.*
- *`SKA` will permit a detailed analysis of the magnetic fields in galaxies at various levels of resolutions, so that important outcomes are expected for the solution of the star formation process. This telescope will also provide useful data about the primordial magnetic fields.*
- *The VOs are an enormous database of astronomical data, that everybody can access from his home computer. We can say that today there are more data available for our galaxies that people who can work on them. The problems are those which affect all databases: the misidentification of the sources, the increasing number of VOs, the standardization of the used language, the organization of the data, and so on. The VO question goes in parallel with the big problem of archiving our astronomical data. Astronomy is a science that needs a very accurate care of the data. Each astronomical event registered by our telescopes and stored in our computers is unique in unique in space and time, and we must have the possibility to retrieve it.*

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Chapter 10
Lights and Shadows on Galaxies Understanding

Contributions by: Mauro D'Onofrio, Roberto Rampazzo, and Simone Zaggia

I've seen things you people wouldn't believe…
attack ships on fire off the shoulder of Orion,
I watched the c-beams glitter in the dark near the Tannhäuser Gates.
All those moments will be lost in time,
like tears in rain.
Blade Runner, Screenplay by **David Webb Peoples**

With this book we neither aimed at tracing a history, even concise, of extragalactic astronomy nor at summarizing the vast panorama of scientific successes in this field of astrophysics. Our wish was to stimulate some distinguished researchers, via interviews in specific fields of extragalactic studies, at expressing their own convictions and perplexities about the progresses achieved in our understanding of galaxies across one century of research, if necessary emphasizing the scientific problems that still remain open. After about fifty interviews, we try in this chapter to delineate a picture underlying the facts and the views emerged from the presentations.

The US of the second decade of twentieth century has been the cradle where a bunch of scientists triggered a debate about the nature of spiral nebulæ, and put into discussion the size of The Galaxy set by Jacobus Kapteyn. The new research field, extragalactic astronomy, very soon reached the rank of a mature scientific branch of astrophysics "on the shoulder of giants" of the caliber of Hubble, Zwicky

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and Baade. However, it was only after WWII that the growth of extragalactic astronomy was overwhelming thanks to big investments in US and later on, for the worse economic conditions, also in some European countries and in Japan. In the last decade of the twentieth century extragalactic astronomy assumed the today physiognomy of highly developed science branch in most of the advanced and emerging economies. The national level institutions and observing facilities characterizing the 1960–1980s decades boosted huge international collaborations and consortia, with hundreds of researchers involved with ground based telescopes located in the best observing sites. Space facilities with a complete wavelength coverage bypassed the limitations imposed by the Earth atmosphere providing a panchromatic view of galaxies. We refer to this as the *Big Science era* of extragalactic astronomy.

10.1 Men, Telescopes and …

As all human disciplines, extragalactic astronomy has been driven by the minds of several brilliant researchers whose works have been mentioned in the previous chapters. Their leadership has proven to be effective either for having fully taken advantage of each technological innovation and for the achievements obtained in several area of astrophysics. However, if we want to understand the origin of the big growth of extragalactic astronomy we should consider at least five equally important factors:

Telescope Performances The art and engineering of telescopes design and construction made enormous progresses. The diameter of the ground-based telescopes improved by a factor of four: from the 100-in. top class telescope at the time of the Great Debate to about 400-in. today. The number of 8–10 m class telescopes is now close to 20, most of which located in top quality observing sites, opened, via panel review, to a large, international community. Enormous the contribution of the 2–4 m class ground based telescopes that have been in operation for many years providing a wealth of data for various types of studies. Surveys (see Chap. 5) were performed with this class of telescopes with dedicated instrumentations. In parallel, the development of active and adaptive optics permitted the ground based telescopes to almost reach their resolution limit, minimizing the gap with the space telescopes orbiting outside the atmosphere. Figure 10.1 shows the growth of the total collecting area of ground based telescopes from the Galileo first sky observations through the "perspicillum" (Mountain and Gillett 1998) up to the beginning of the new century.

Starting with instruments loaded on balloons or manned space missions in the 1960s investigating few bright objects, the extragalactic research has been the driver for the development of the most important space telescopes. From far infrared to high energy wavelengths, space telescopes triggered the growth of extragalactic knowledge displaying galaxy properties unreachable from the Earth surface and

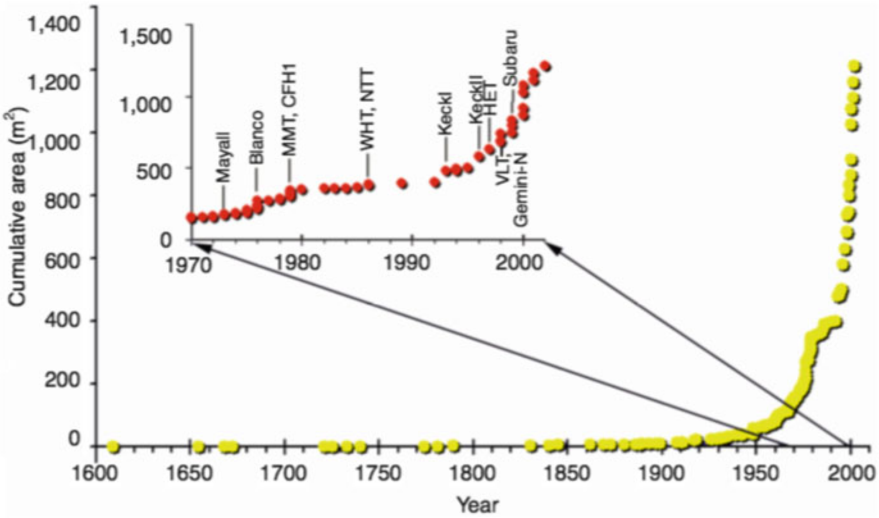


Fig. 10.1 In Mountain and Gillett (1998) published this figure showing the impressive growth of the cumulative telescope collecting areas since the first observations made by Galileo Galilei in 1609–1610 from his house in Padova. In the top panel the last 40 years are zoomed. The date of commissioning of the larger telescopes are indicated

pushing our knowledge to the faintest galaxies at redshifts $z \sim 7$–8 near the end of the re-ionization era.

Detectors Efficiency The digital detectors have progressively substituted the photographic plates since the 1980s. Their enhanced quantum efficiency and multi-wavelength response were preferred despite the smaller field of view. The new generation of astronomical instruments for the ground base and space telescopes exploiting these detectors, have offered an unprecedented detailed panchromatic view of galaxies. Today the CCDs detectors have reached and bypassed the field of view of the Schmidt plates, that dominated the scene of extragalactic surveys like the immensely productive POSS.

In Fig. 10.2 is shown the growth of the CCDs array size at the focal planes of telescopes since 1990, roughly a decade after the CCDs introduction. In the figure Suprime-cam at Subaru is among the first largest IR CCD arrays. The wide field of view is an extremely important factor for the study of nearby galaxies that can be mapped out to their outskirts. Similarly CCD arrays can accommodate tens to hundreds of spectra from new image slicers or from multi-object fiber devices.

Computing Power The exponential growth of computing power is one of the key factors for the progresses achieved in extragalactic research. Today we have the possibility of managing petabyte of data coming from the modern detectors at the telescopes, stocking and retrieving them from data-bases/virtual observatories,

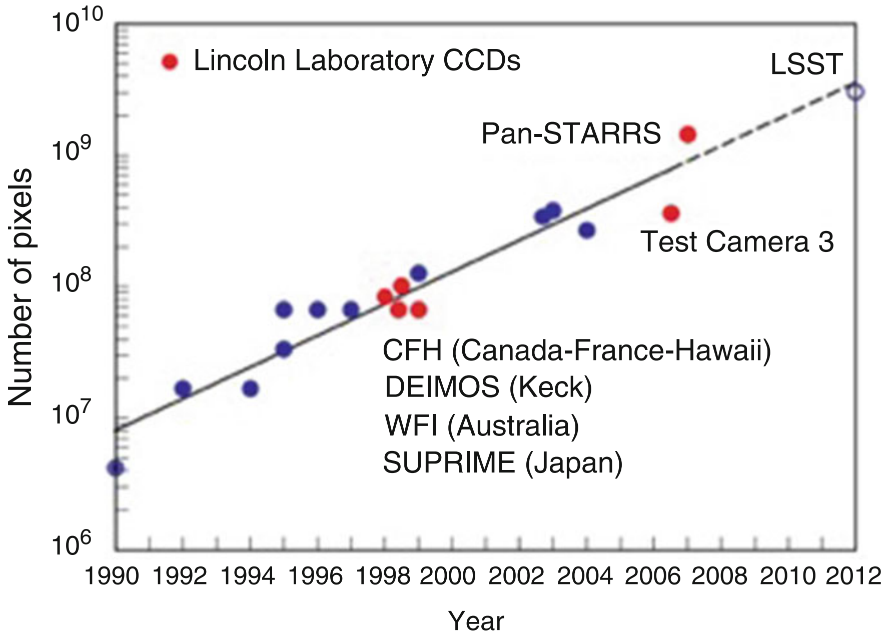


Fig. 10.2 The growth in CCD focal-plane array sizes from 1990. The paper by Burke and collaborators, published in 2007 (Burke et al. 2007) anticipated the size of the CCDs for the Large Synoptic Survey Telescope. `LSST` will have a 3.2×10^9 pixels camera (see Chap. 9)

simulating observations, and testing theories. The same power is used to project telescopes and modeling their tracking and/or multiple-mirrors forms and to control remote observing.

In Fig. 10.3 we see as a function of years the growth in the number of particles used in N-body direct simulations of collisional stellar systems in dense star clusters and in the galactic center as well as in collisionless stellar dynamics (galaxies and large scale structures). The N-body simulations are now associating to each single particle (star) the stellar evolution taking into account mass loss and even SNæ explosions.

Progresses in Physics The enormous progress in all physics disciplines in the past century is obviously the pillar on which is founded our present comprehension of the Universe and of galaxies in particular. For an ample description of the achievements in experimental and theoretical physics of the past century see, e.g. Longair *The Cosmic Century* (Longair 2006). To make just few examples lets think to general relativity, that is the skeleton of our cosmology, or to nuclear and particle physics in relation to our understanding of the star central engines, and to solid-state physics for its direct reverberation on our detectors.

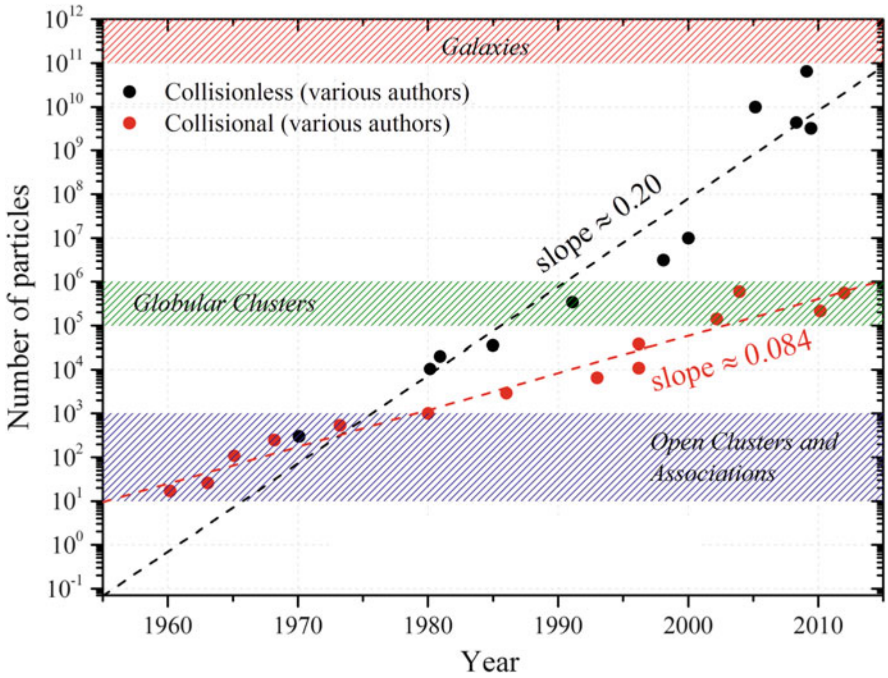


Fig. 10.3 Number of particles used for N-body direct simulations as a function of year. *Red* and *black dots* indicates specific simulation experiments conducted by different authors in collisional and collisionless regimes, respectively [see for a review Dehnen and Read (2011)]. The study shown in this plot has been prepared by Mario Spera (personal communication)

Man Power Finally it is worth to mention the widely increasing number of researchers working in astronomy along the century. The long period of pace after WWII and the economic growth achieved in several parts of the world, have permitted to many young people the study of physics and astronomy, providing new intellectual forces. This can be partly deduced from Fig. 10.4, that shows as a function of year the number of refereed papers appeared on the literature (credit to NASA/ADS) since the Great Debate, that share the keyword "galaxies". Apart from the decrease observed during WWII we see a progressive increase in the number of works that only recently seems to flat to a nearly constant rate.

10.1.1 The Era of Surveys

In this Big Science era the future of extragalactic astronomy is strongly connected with the investments of each country in new telescopes and new surveys. We have largely discussed of this in the book. The efforts done up to now have opened a panchromatic view of our Universe and of galaxies in particular. Much of the present

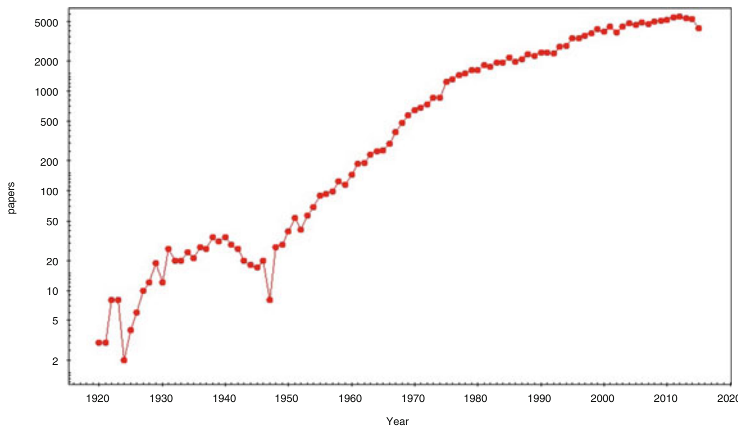


Fig. 10.4 Number of refereed papers with the keyword "galaxies" in the ADS/NASA database as a function of year

understanding of the structure of the Universe and its constituents derives from large surveys [e.g., 2dFGRS (Folkes et al. 1999); SDSS (York et al. 2000); GEMS (Rix et al. 2004); VVDS (Le Févre et al. 2004); COSMOS (Scoville et al. 2007); GAMA (Driver et al. 2009); etc.].

These surveys have clarified the large scale structure of our Universe and have provided a link between the properties of individual galaxies and their star formation history. The major advantages of this research approach are: (1) the large number of objects sampled permits robust statistical analyses; (2) large control samples can be constructed; (3) the broad coverage of galaxy morphologies and environmental conditions; (4) the homogeneity of data acquisition, and data reduction. The current technology has permitted to plan either imaging and spectroscopic surveys. More recently an observational technique has combined the advantages of imaging and spectroscopy (albeit with quite small field of view): the Integral Field Spectroscopy (IFS). The first attempts to use IFS in survey mode observed only few galaxies providing largely incomplete samples. The most famous are: the SAURON survey (de Zeeuw et al. 2002), focused on the study of the central regions of nearby early-type galaxies and bulges of spirals; the PINGS project of a dozen very nearby galaxies (Rosales-Ortega et al. 2010); the Disk Mass Survey (Bershady et al. 2010) that provided high spectral resolution of face-on spirals; the VENGA project (Blanc et al. 2013), also dedicated to face-on spirals; and the SIRIUS project, currently studying ULIRGS at $z < 0.26$ (Arribas et al. 2008). More recently the survey ATLAS^{3D} (Cappellari et al. 2011), CALIFA (Sánchez et al. 2012), MaNGA (Law et al. 2015) and SAMI (Croom et al. 2012) have filled the gap with imaging surveys. These data represent a real breakthrough for the combined analysis of the dynamics and stellar populations, enabling a more detailed reconstruction of the star formation history. However interviews suggest that several fundamental questions have not been answered yet: what is the reason for the declining star formation since $z = 1$–2 in currently star-forming galaxies, and for the quenching of currently passive galaxies? how did the $z = 0$ Hubble sequence get shaped, i.e. what is the origin of today's morphological types? Why did galaxies evolve the way they do between $z = 1$ and $z = 0$, over half of the age of the Universe?

Now we want to spend some words for another survey that will impact our knowledge of galaxies in the near future: the `Euclid` mission. `Euclid` is an ESA mission aimed at mapping the geometry of the dark Universe. The mission will investigate the distance-redshift relationship and the evolution of cosmic structures by measuring shapes and redshifts of galaxies and clusters of galaxies out to redshifts ~ 2, or equivalently to a look-back time of 10 billion years. In this way, `Euclid` will cover the entire period over which dark energy played a significant role in accelerating the expansion of the Universe. In early 2010 ESA's Science Programme Committee recommended `Euclid` and two other M-class candidate missions (PLATO and Solar Orbiter) for the next phase. The final approval arrived in 2012. The launch is planned for 2020.

10.2 MW and the LG: Our Still Unexplored Home

The studies of the MW are living today the most fruitful and exciting period of their history, waiting for `Gaia` results and the future interferometric studies of the galactic center. With the launch of the `Gaia` satellite and the various follow-up programs of observations planned all around the world, the data for a partial 3D tomography of the MW will be soon available. These data will be exploited in the next future to construct a new ample vision of our Galaxy. Interferometric studies will map at high resolution the evolution of the Galactic center under the influence of the BH in SgrA*.

Historical efforts in understanding the MW came from the measures of positions, velocities and proper motions of stars, with considerable successes in modeling the whole dynamics of our stellar system. The first breakthrough, however, began with the analysis of the stellar types. The WWII blackout permitted to Walter Baade to resolve stars in our neighbors M31, M32 and NGC 205, developing the concept of stellar populations in our own Galaxy (Baade 1944). Soon after, the first model of monolithic galaxy formation by Eggen et al. (1962) appeared.
Both the stellar population view and galaxy formation model have changed since then. The flood of observations revealed a much more complex mix between stellar kinematics, metallicities, ages, masses, etc., so that even the concept itself of stellar population has now a very different meaning. The idea of galactic components has progressively lost its utility, for the difficulty of assigning a single star to a given component and of defining their properties in an absolute way. Exemplary were globular clusters in the MW: believed for years to be the prototype of a single stellar population made of coeval stars, they demonstrated to host more than one main

sequence (Piotto 2009), raising the problem of their formation in a single collapse event.

One of the aspects not touched by the interviews is the revival of the optical interferometry starting from the 1970s and its contribution to the understanding of our Galaxy, measuring the diameters of single stars, in separating binaries etc., of extraordinary importance for the study of stellar evolution. Having his founding fathers at the end of XIX and beginning of XX centuries, like Hipoolyte Fizeau (1819–1896), Eduard Stephan (1837–1923), Albert Michelson (1852–1931)—who measured at Mount Wilson the Io's diameter (1".1891) and that of Betelgeuse (50 mas) with Francis Pease in 1920—interferometry for many decades proceeded in parallel, sometimes children of a lesser God, to the main stream of galactic studies performed via classical telescopes. At the beginning of the 70s using intensity interferometry, Robert Hanbury Brown and Richard Twiss at Narrabry Australia started to measure stellar diameters and Antoine Labeyrie in France used speckle interferometry (interference from independent telescopes) to measure the Vega diameters observed with a 12 m baseline with two 25 cm telescopes.

The real jump in interferometry came from the decision worked out in the 1980s within ESO to built `VLTI`, an optical interferometer including the coherent combination of four 8 m units and four 1.8 m ancillary telescopes on Cerro Paranal (Chile) which has been completed in 2001. These kind of instruments will be crucial, together with high resolution cameras to provide a vision of the Galaxy center in the proximity of the radio-source SgrA*. After `AMBER` and `MIDI`, new instruments are going into service like `MATISSE` and especially `GRAVITY` to have the precise astrometry of the Galactic center. We simply mention here the recent achievements like the direct measure, via the stellar motions, of the BH mass associated to SgrA* $M_{SgrA*} = 4 \pm 0.3 \times 10^6 M_\odot$ at the distance of 8 kpc from us reached by Eckart and Genzel (1996, 1997); Eckart et al. (2002); Schödel et al. (2002); Eisenhauer et al. (2003), and Ghez et al. (2000, 2005). Interferometry is still mainly connected to the study of galactic objects (see Fig. 10.5). Due to the high magnitude limit very few (∼50) extragalactic nuclei have been studied at high resolution, namely AGN sources, but the way is traced.

10.2.1 How Are the Neighbours?

After decades of debates the extragalactic distance scale is now built on more solid indicators. A 3D picture of our environment, a "Cosmography of the Local Universe" is really coming. Courtois et al. (2013), authors of this efforts, report "Distances are measured for some fraction of galaxies (∼40 % of normal galaxies within 3000 km s^{-1} decreasing to only a few percent at 10,000 km s^{-1}) and this information can be translated to give maps of peculiar velocities the radial components of deviations from the cosmic expansion." It is astonishing that distances of galaxies with $z \lesssim 0.03$ remain a challenge. On the other side, Andromeda, the only other giant member of the LG, is located 785±25 kpc away from the MW. The

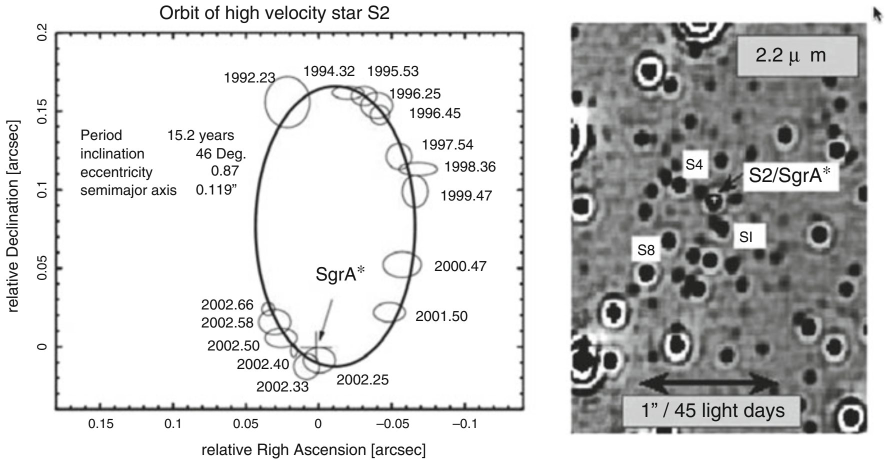


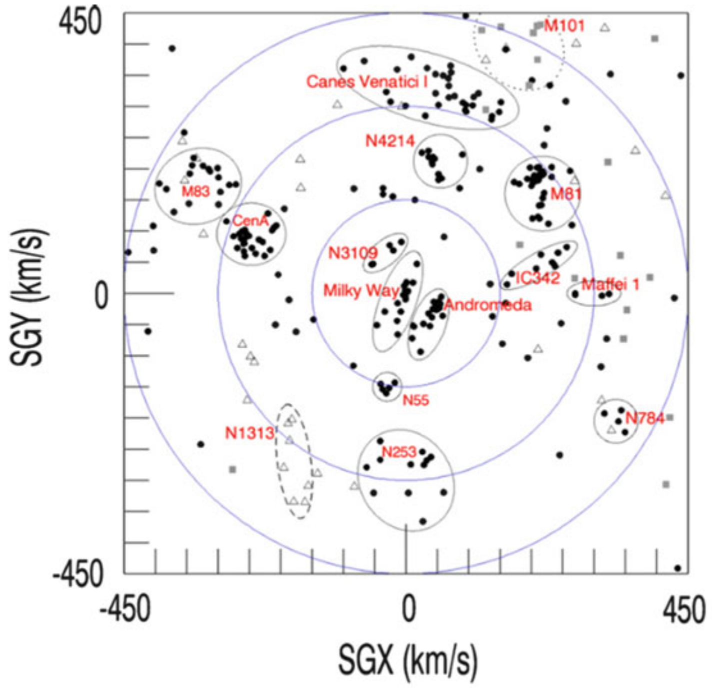
Fig. 10.5 From Eckart et al. (2003). The *left panel* shows the orbit, measured in different periods with UT4 NACO and NTT, of the star S2 close the central BH at the position of the compact radio source SgrA*. The *right panel* shows the image of the 1" area around SgrA cluster. High velocity stars are shown

uncertainty of its distance is 3 times larger than our estimated distance from the Galactic center.

The MW and Andromeda have quite different properties, as well as the plethora of dwarfs which populate the LG. The range of masses in the LG goes from 10^3 to $10^{10.7}\,M_\odot$. Outside the LG environment we largely miss low mass dwarfs. At the same time, interviews underline how our observing facilities proved to be inadequate for a complete picture of the dwarf companions in the LG. The range of galaxy morphologies in the LG does not encompass the whole variety found just beyond it, when Virgo and Fornax clusters are encountered at less than 20 Mpc away.

The LG provides the best evidence of how interrelated can be the galaxies' life in a group. Evidences have been found of past interactions and merging events who have changed the stellar populations of many satellites. Streams of stars surround either the MW and M31, rising questions about influences of dwarfs ingestion in the evolution of both galaxies. However, the arrangement of the MW and M31 satellites has been claimed to be in contrast with the expectations from the hierarchical scenario of galaxy formation (see, e.g. Pawlowski et al. 2014 and Ibata et al. 2014 see also Fig. 10.6).

The interviews about the LG and the cosmography of the nearby Universe, i.e. galaxies that we should know with the best accuracy after one century of research, transmit the impression of a site in construction. Foundations are laid, some pillars and walls appear, the shape of the building is sketched, new bricks are coming, but we are still far from finishing the whole building.



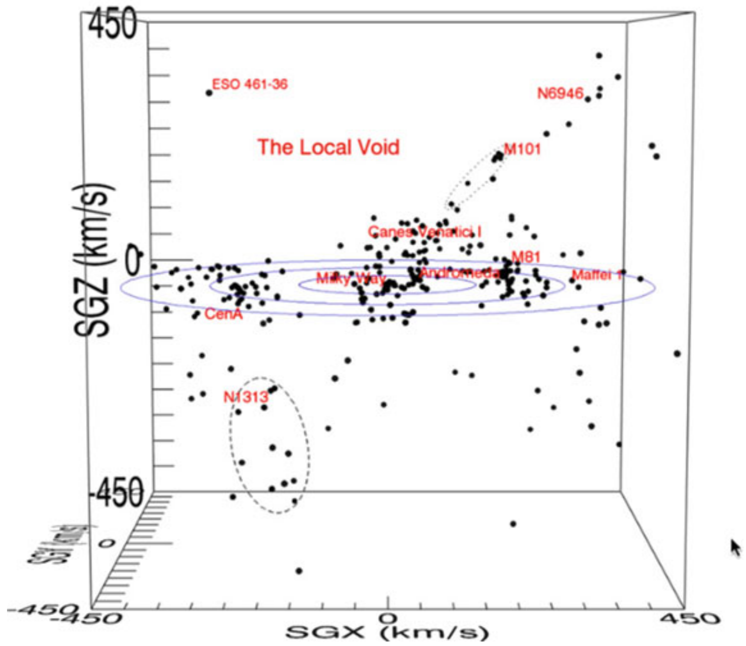


Fig. 10.6 From Courtois et al. (2013). Different projections of galaxies in the vicinity of the LG (courtesy of Helene Courtois)

10.3 Individuals with an Eventful Life

Nebulæ, although named *Island Universes* in the pioneering years, have been soon noticed to display a wide morphological variety and a tendency to cluster. It was so immediately visible to extragalactic astronomers, their "individuality", from one side, and their "social dimension", from the other, both fundamental characteristics to understand their evolutionary paths. The interviews about the LG put into evidence that many member galaxies, including the MW and Andromeda, hide peculiar features, that can be more easily settled into a hierarchical evolutionary framework rather then a monolithic formation scenario. The beginning of the exploration of distant galaxies further increases, if possible, the sense of large uncertainty about the galaxy evolutionary paths.

The notions of interaction, accretion and merging events, key elements in a hierarchical evolutionary scenario, have been developed along several decades both via observations, starting from Fritz Zwicky and continuing e.g. with Francois Schweizer, and simulations, e.g. by Toomre brothers and Joshua Barnes to mention few astronomers. On group scales, strong vs. weak interactions between galaxies, *dry* vs. *wet* (gas rich) accretions, major vs. minor merging, starvation, ram-pressure, harassment, etc. or a combination of them, are external mechanisms thought to affect the evolution of a galaxy. On galactic scales feedback phenomena, from SNe to BHs engines in AGN and/or *secular* evolutionary mechanisms creating/modifying/destroying inner sub-structures like rings and bars, are physical events that, in addition to external ones, can affect individual galaxies on time scales much lower than the Hubble time.

As a direct consequence, the galaxy morphology can evolve under external and internal causes. Many galaxies show (morphologic, kinematic, spectroscopic) features that can be associated to the above mechanisms (the estimated fraction of early-type galaxies showing peculiar features in the nearby universe is near to 50 % Rampazzo et al. 2013).

Like in the biological context, galaxies appear in continuous evolution, so that one of the major problems of extragalactic astronomy is to establish what was the *genealogical tree* of the mature objects we see today. Since researchers start to use genetic algorithm to classify galaxies some questions come natural. Has the evolution made *little experiments*, later abandoned yielding many branch tree (it comes to mind the recent discovery of the *Homo Naledi* in South Africa that suggests this view to paleontologists) or is traced by one time-line? Is the "extinction" of some species part of the galaxy evolution? Many interesting outputs emerged from our discussion on this topic with the interviewed scientists.

10.3.1 *What Remains of Morphological Classifications?*

The galaxy morphological classifications has been considered for long time a way station to understand galaxy evolution. Today the concept of galaxy classification itself is experiencing a strong critical revision.

Big classification systems built by Sandage and de Vaucouleurs up to the end of 1980s and their collaborators pass on a "static" view of galaxies. The addition of the abbreviation "pec" at the end of the morphological classification, to indicate peculiar objects is quite rarely used in those systems. On the other side, the description of galaxy structures reached high levels of details including simulation/evolutionary driven concepts (see e.g. Comerón et al. 2014 and classification of rings). Classical morphological systems applies to giant galaxies, very scanty to dwarfs. For these the concept of morphological classification is still at the daybreak and limited to the LG. Furthermore, dwarfs are very sensible to interactions and feedback processes.

Panchromatic observations show that there is a world enclosed in the addition "pec" in the morphological classification. It is clear that the morphology reflects the mix of the stellar populations emitting in the observed waveband. The star formation may leave dramatic scars in far UV, in apparently passively evolving galaxies in optical, in particular if interaction/accretion episodes triggered the phenomenon (see e.g. Marino et al. 2009, 2011 for early-type galaxies). Deep, wide field images of nearby galaxies directly revealed the residual of gravitational interaction in terms of plumes, tidal tails, arcs, shells etc., in galaxies outskirts, even in the optical bands . The frequency of such faint structures demonstrated to be quite high since their discovery (see e.g the frequency of shells $\approx$20 % in Malin and Carter 1983). Recent deep imaging of Duc et al. (2015) suggest that classical morphological classes is "inadequate" to describe galaxies as a whole.

The idea that galaxy structures could be used for a more robust classification is having hard times. In objects with prominent disks, like S0s and spirals, structures like bars and rings may appear as a consequence of secular evolution and disappear with time. In case of merging events and even simple galaxy-galaxy interactions, according to the impact parameters of the encounter, galaxy structures might be induced, like shells and ripples, X-structures, peanut-shape bulges, collisional rings etc. The spheroidal galaxies, among the more massive and old objects, evolving in size are subject to a number of phenomena, including nuclear jet and feedback. Simulations suggest that some of these are long-lasting structures, sometimes are fragile and may be swept away by hostile environmental conditions (dense environments, ICM, etc.). Summarizing, the combinations of panchromatic and deep observations, assisted by simulations revealed a powerful tandem in suggesting that the morphology should be considered a "transient" in the galaxy life rather then the "brand" of the galaxy.

However there are many, sometime contradictory, tendencies in galaxy classification. From one side the increasing number of galaxies observations produced by surveys pushed the development of automatic approaches to galaxy classification (see e.g. Abraham et al. 2003), Most of the time these approaches are independent from a real morphology evaluation being more connected to relations between morphology and galaxy properties. There is a revival of linking morphology to physical processes that can be traced back to the appearance of the Hubble tuning fork diagram. New schemes of galaxy classification have been proposed, but no one has been widely accepted. In most of the cases are attempts of connecting the physics of galaxy formation with the observed morphologies (see e.g Cappellari et al. 2011; Kormendy and Bender 2012; van den Bergh 1976). Very recently the increasing data-base of galaxy photometric, morphologic and spectroscopic properties and the evidence of galaxy evolution is pushing forward new methods of galaxies classification based on genetic algorithms (see, e.g. Fraix-Burnet et al. 2012).

In our view, interviews convey the idea of progressive abandonment of the classical Hubble view, towards the use of galaxy physical parameters rather than morphological quantities, to catch the evolutionary track of the various generations of galaxies up to the most distant progenitors. Surveys shows that the current gross morphology is set up at $z \simeq 1$, when the Universe has about 40 % of the present age. At higher redshift galaxies are dominated by clumpy chains and irregular structures indicating ongoing interaction episodes (e.g. Cowie et al. 1995; Elmegreen et al. 2007). How and when the morphological evolution occurs and what are the physical processes involved in the galaxy transformation is still an amply debated question today.

10.3.2 What Scaling Relations Are Telling Us?

The frequency with which deep images of galaxies unveil the remnants of past interactions suggests that perturbations are more easily the norm rather then the exception in the life of a galaxy. This means that the galaxies we see today are the results of complex processes at high redshift and that galaxy are likely still assembling. What is the weight of the interaction/accretion/merging phenomena in the economy of a galaxy building?

Despite the morphological variety and the “uniqueness” of single objects set by their peculiar features, well defined scaling relations connecting basic galaxy properties have been found and investigated in the last decades. These were the best fruits of large surveys. Among them, the Kormendy relation (Kormendy 1977) in the r_e–μ_e plane, the mass-radius relation, the mass-metallicity and the velocity dispersion-metallicity relations, etc. Definitely the more investigated relations are the Fundamental Plane, for early-type galaxies, in the (r_e,μ_e,σ_0) plane (Djorgovski and Davis 1987; Dressler et al. 1987) and its counterpart for late-type galaxies the Tully-Fisher relation (V_{max}, L) (Tully and Fisher 1977). Intriguing the scaling relation between the mass of the spheroidal component and that of the central BH, which is suggesting a co-evolution of the two structures. Unfortunately, tracing the cosmic evolution of SBH is quite difficult, mostly for the different methods used to measure SBH masses and for the presence of selection effects and systematic biases.

Despite the large debate, the evolutionary picture offered by scaling relation is still open, alimented by the fact that many scaling relations have a very small scatter. How may we reconcile the existence of such relations formation/evolutionary process of mass assembling within a hierarchical picture? The fact that galaxies are virialized systems, i.e. that they are relaxed objects from a dynamical point of view, by itself does not necessarily imply the existence of scaling relations between the galaxy parameters. The origin of such relations has been amply debated in several papers up to now, but there still no consensus on the solution of this problem. Part of the problem is certainly connected with the dissipative phenomena that occur during the galaxy formation when the baryons exchange energy and angular momentum with the non baryonic component. The intriguing fact is that the star formation process should be in some way connected with the dynamical configuration of the galaxies, so that a well define history of the stellar populations arises (see e.g. D'Onofrio et al. 2011).

10.3.3 The Value of Galaxy Structures

The interviews in this book suggest that the galaxy components (bulge, disk, halo, bar, etc.) evolve with time, more or less rapidly, under secular evolution or external mechanisms. This rises the problem of the utility of this concept when we look at the more distant objects. The current structure of galaxies can be observed up to redshift $z \sim 1$, while at higher redshifts galaxies appear dominated by blobs and disturbed morphologies. These are the prototypes structures of the future galaxy components.

Despite the difficulty of an operational definition of galaxy structure, the analysis of each galaxy component per se has given a lot of information on the process of galaxy formation. In particular the most important link is that found between the stellar population and the galaxy component. It is clear that there is well defined connection between the star formation and evolution and the kinematics and dynamics of a stellar system which determine the final shape.

The galaxy components have been up to now described in their light distribution, kinematics, stellar content, etc. Empirical laws fitting the light profiles of the galaxies exist for the various galaxy structures. However, there is not yet a well founded physical explanation linking these empirical formulæ with a coherent scenario of formation and evolution of the distinct components.

Numerical simulations in a cosmological context have recently started to reproduce the first disk galaxies with morphologies and structures quite similar to the observed ones. The first attempts produced disks to small, but the inclusion of feedback effects has apparently solved this problem giving a new input to these researches (see e.g. Scannapieco et al. 2012). Old N-body simulations, not developed in a cosmological context, were already able to reproduce many features like bars and rings often observed in disk galaxies. They succeeded in this by adding a dark halo component which stabilize the disk against a rapid destruction.

On the theoretical side the density wave theory has successfully explained several properties of the spiral wave structure of galaxies.

Many problems are open in this research field, in particular for constructing a coherent scenario which is able to follow the whole evolution of a galaxy structure across the Hubble time. Progresses can be achieved when a better understanding of several phenomena will be obtained. This will require a more extended comprehension of the star formation process, of the role of magnetic fields, of the migration of the stars in the galaxies, of the feedback processes of stars and nuclei, of the enrichment of the ISM, and so on. Last but not least we should better understand the role of interactions and merging as well as of secular evolution in changing the properties of the galaxy components.

10.3.4 Gas, Dust and Galaxy Evolution

Gas and dust, the dissipative components in the ISM, have assumed since the Hubble tuning fork diagram a discriminating role. Early-type galaxies, devoid of gas on one side, gas rich spirals, with dust-lanes, on the other. This picture has greatly smoothed out with time. Pioneering optical spectroscopy of Phillips and collaborators in 1986 (Phillips et al. 1986) discovered that a large fraction of ETGs have ionized atomic gas in their nuclei. The fraction of ETGs with ionized gas in their nucleus is estimated between 50 and 90 % according to the sample (Annibali et al. 2010; Goudfrooij 1995; Macchetto et al. 1996; Sarzi et al. 2006, 2010; Serra et al. 2008; Yan et al. 2006). The quantity is quite poor, being in mass between 10^6–$10^8\,M_\odot$. Serra and collaborators showed that HI is also present: 10 % of Virgo ETGs and 40 % in field have extended HI disk with masses up to $10^9\,M_\odot$. This fresh hydrogen is the fuel of new stellar generations in otherwise "red and dead" ETGs.

The gas has been detected in very different physical conditions. Hot plasma is revealed by its X-ray emission. Interviews has discussed how it is still unclear its relation with the stellar component in ETGs. Recently infrared space mission and sub-millimeter observations have disclosed the molecular gas windows including the molecular hydrogen, H_2. However, most of the present studies about molecular gas, whose dynamics and energetic link the formation of galaxies, stars and giant planets, rely on observations of low rotation emission lines of CO, while the CO-H_2 conversion factor in different galaxy types, from quiescent to star-bursts, is still poorly understood. Molecular gas is ubiquitous and one of the next challenges will be to map the H_2 content also in shielded regions of the Universe. H_2 rotational transitions in mid infrared (0-0 S(0) at 28.2 μm, S(1) at 17.0 μm etc.) have been detected also in a very high fraction ETGs (34^{+10}_{-8} % in Es and 51^{+15}_{-12} % in S0s Rampazzo et al. 2013). PAHs have also been detected in 47^{+8}_{-7} % of ETGs but only a small fraction (9^{+4}_{-3} %) have PAH ratios similar to that of spirals. Star formation set the abyss between ETGs and spirals, although only 20^{+11}_{-7} % of S0s shows a passively evolving mid-infrared spectrum (Rampazzo et al. 2013), indicating some recent form of (SF and/or AGN) activity.

The dust properties are prevalently studied from their infrared emission. Interviews emphasized, in this respect, the values of both Spitzer and Herschel space missions. We note here that dust-lanes, distinctive features of spirals since Harlow Shapley's observation of spiral galaxies, are frequently found in ETGs. HST data reveal the presence of dust in $\sim$50 % ETGs center (Ramiro et al. 2007). The structure of dust lanes is often irregular and chaotic (see e.g. Ramiro et al. 2007 and references therein) at odds with spirals where they are typically aligned with the disk. Herschel and Spitzer observations permits to estimate a very short upper limit ($<46 \pm 25$ Myr) to the dust grain survival time in the hostile environment of ETGs for amorphous silicate grains (Clemens et al. 2010). The combination of the large frequency with which dust-lanes are detected and the short survival time thus require a frequent dust replenishment. In this respect the origin of dust-lanes in ETGs is still uncertain being possibly connected both with the stellar mass loss or to trace an accretion event.

Gas and dust, although they represent a few percent of the total baryonic mass of a galaxies are relevant for mapping the galaxy evolutionary path. Multi-wavelength observations of the gas and dust components have provided a live view of the galaxy evolution. Extraordinary evidences of direct galaxy on-flight refueling (see e.g. Keel 2004), and of stripping have been observed (see e.g. Arrigoni Battaia et al. 2014 and references therein). Future interferometric observations will image gas and dust tori around SMBHs testing AGN unification models.

The gas and dust link to the stellar component via mass-loss and/or SNæ explosions, and likely with the cosmic web structure or *wet* accretions narrate the history of the chemical enrichment of the galaxy. The physics of such complex inter-relationship between stars and gas/dust has seen along this century several steps forward, due in particular to the possibility of observing these components in their waveband emissions from space satellites. Much work is still necessary to understand the complex stars-dust-gas ecosystem in galaxies.

10.4 First Galaxies and High Redshift Objects

The combination of the HST deep imaging with the use of spectroscopic facilities at the foci of 8–10 m ground based telescopes produced in the last 20 years a sort of *taste* of the high redshift galaxies properties, a *core sampling* of the young Universe. Interviews suggest that a real breakthrough in this research area is expected to came when the JWST, ALMA, Euclid, LSST and the class of 30 m+ telescopes will be fully operative. A connection data vs. simulations and modeling will be even more necessary than has been up to now.

In the current cosmological framework mapping the properties of high redshift galaxies is essential to trace back the connection between the first objects, appeared after the *dark era*, to the present epoch. The inventory today stops at the end of the re-ionization era. The first galaxies at redshifts $z > 1$ were detected thanks to their Lyα emission (Djorgovski et al. 1985) and after the 1990s with the Lyα break technique (see e.g. Steidel et al. 1996). Sub-mm and space-based IR observations have also revealed the existence of obscured galaxies at $z \sim 3$ and beyond, complementing our picture of the cosmic star formation history. The galaxy candidates at redshift $8 < z < 12$ are selected on the basis of their colors and population synthesis models, but in many cases there are not yet spectroscopic confirmations (see e.g. Pritchet 1994).

At $z \gtrsim 1$, the galaxies morphology appear clumpy and compact. Peculiar morphologies, such as tadpole-shaped galaxies, amount to at least 30 % of the sample, while barred and grand design spirals are almost absent. The fraction of peculiar galaxies increases beyond $z = 1.4$ in the HDFs and the bright galaxies are primarily late types with irregular morphologies beyond $z = 0.7$. Selection effects need to be carefully considered, because only the higher surface brightness objects are generally detected and many of them are lensed systems magnified by a closer mass in between.

The advent of very large surveys of high redshift galaxies, such as DEEP2 (Davis 2002), COSMOS (Scoville et al. 2007), Extended Groth Strip (Noeske et al. 2007), and CANDELS (van der Wel et al. 2011), is currently yielding statistics that will aid our understanding of galaxy evolution. Today about 200 galaxies at $z > 1$ have been detected for their CO emission. Notably molecules and dust are observed in some objects with abundances close to solar ones, for lookback times up to 95 % of the age of the Universe, while it was thought that it will take billions of years to sufficiently enrich the gas in heavy elements. Unfortunately the CO-to-H2 conversion factor to obtain the molecular masses is not well determined at high z. For quiescent galaxies like the Milky Way, this factor has been well calibrated, but at higher redshifts the CO gas is denser and warmer. At high redshift, galaxies are forming more stars, and the physical state of their gas, together with is metallicity, is less known. `ALMA` will greatly contribute to the progress in this field.

At $z \sim 1$ the global rate of star formation was up to 10 times larger than today. Increasing in redshift at $z \sim 8$–10 we encounter very different physical conditions in the Universe. The mean density of the Universe was $\sim$1000 times greater than it is now, the CMB radiation was $\sim$10 times hotter and its energy density $\sim$ 10,000 times greater. The Universe was just beginning to become transparent with the onset of the epoch of re-ionization. Clusters of galaxies were almost not separated out from the primeval plasma.

The modern supercomputing technology have produced an increasingly realistic picture of how the cosmic dark ages ended. At its foundation lies the prediction that the first stars, the so-called Population III, were typically massive up to 10–50 $M_{\odot}$. These stars rapidly enriched the IGM of heavy elements and initiated the re-ionization of the Universe.

According to their feedback we have different possible evolutions for the first galaxies. At present the question of the observability of the first galaxies is largely debated since the key factor is the dimension of the first DM halos, and whether these halos hosted high or low mass systems.

10.5 The Formation and Evolution of Galaxies

In the current cosmological framework galaxies started their formation when the gas began to fall into the potential wells of hierarchically growing DM structures dissipating its energy (Fall and Efstathiou 1980; White and Rees 1978). In the hierarchical scenario small and low mass objects come first, whereas larger and more massive objects appear later on. First cosmological simulations did not considered the contribution of baryons, being the BM/DM ratio very small. They simply described the mass assembly history of the DM halos. When the BM was added to halos, suitable prescriptions were assumed for the gas cooling and heating, for the star formation, for the chemical enrichment, for the energy feedback by SNæ explosions and AGN (the central BH). Later on the morphological transformation of disks into ellipticals as a consequence of mergers was taken into account, and the population synthesis techniques started to simulate luminosities, magnitudes and colors of the stellar content, etc.

The current models of galaxy formation and evolution can be grouped in semi-analytical (SAMs) and hydrodynamical (HDMs). Modern SAMs (see e.g. De Lucia et al. 2006) are very sophisticated codes, relatively easy to use, and often publicly-available together with their outputs. Using the SAMs, the importance of the various physical processes can be easily tested and gauged. The weakness is that the physics is somewhat controlled by hand and the codes are largely parameterized. The HDMs (see e.g. Springel 2010) split in two categories according to the numerical technique in use: the cell-based in the modern version with adaptive meshes to follow a large range of scales and the particle-based in the modern version of smoothed particle hydrodynamics. The difficulties here are connected to the resolution of the simulations, that should be good enough to model the star formation process on small scales and at the same time respect the cosmological constraints on large scales.

Historically the hierarchical scenario of galaxy formation substituted the monolithic scenario in which the massive early type galaxies (ETGs) formed at high redshift by rapid collapse and a single prominent star formation episode, followed by slow decline to quiescence. Over the years this view changed. In the revised monolithic scheme a great deal of the stars in massive ETGs are formed very early-on at high red-shifts and the remaining ones at lower red-shifts. Today we have also an hybrid mode of galaxy formation and evolution named early hierarchical, quasi monolithic (Merlin et al. 2012), which incorporates the advantages of the monolithic scheme with those of the hierarchical scheme. Even the hierarchical scheme has been amended with two complementary alternatives known as *dry* mergers (fusion of gas-free galaxies to avoid star formation) and *wet* mergers (the same but with some stellar activity).

As we said the building up of the massive galaxies was nearly completed at redshifts earlier than $z \sim 2$. Taking into account the efficiency of the star formation process and the duty-cycle of the gas component (cooling-SF-enrichment-heating-cooling-etc.) it is estimated that only $\sim$20 % of the initial baryons are converted into stars. The star formation history of galaxies largely depends on the total mass: while the more massive systems have a single episode of SF, the less massive ones experience several bursts of SF. The environment however play a non secondary role. The observed downsizing is considered in contradiction with the hierarchical scheme of galaxy formation. However, recent works have pointed out the difference between "formation" time of the stars in the galaxies and its "assembly" time, which makes the observed trend of shorter star formation histories for more massive galaxies not anti-hierarchical.

Given the complexity of the galaxy formation process, it is not surprising that none of the developed models are able to fully explain the variety of observed galaxy properties. A number of "problems", shared by all SAMS and HDMs, have been recently pointed out: (1) the number densities of low-to-intermediate mass galaxies are systematically larger than observational estimates. Efficient stellar feedback is able to bring the low mass end of the galaxy mass function in agreement with observational results in the local Universe, but does not appear to be able to solve satisfactorily the problem at higher redshift. (2) Low-to-intermediate mass galaxies tend to be too passive with respect to observational measurements. (3) Massive galaxies have predicted metallicities that are too low with respect to observational measurements. The solution of these problems are likely connected to the parallelism between mass growth and halo growth, and to a better understanding of the SF process as well as of the feedback and gas recycling scheme.

Observations have shown that the SFR of galaxies is connected with the galaxy mass. The modern interpretation of the color-magnitude diagram (see e.g. Peng et al. 2010) is related to such relation where galaxies are segregated in two distinct regions, the so-called main sequence dominated by red and quenched objects and the blue region dominated by star forming galaxies. In the middle there is the so called *green valley*, which is almost empty of galaxies in evolved environments, and can be crossed in the two directions when galaxies quench and rejuvenate (see e.g. Mazzei et al. 2014a,b).

The details of the SFH also depend on the IMF, i.e. from the distribution function of all stars formed together in one "event". The IMF of a whole galaxy is a different issue, as it is deduced from the field population of stars in a galaxy, and this field population has many different ages and metallicities. A lot of work has been done in this area, often resulting in contrasting conclusions. The difficulties arise because the theoretical form of the IMF can never be measured: there is never an instant of time in which the full function is assembled. For galaxies the determination of the IMF can only be based on the interpretation of the integrated star light. A model predicting the form of the IMF simply does not exist, so in general the IMF is assumed. Observations seem to favor a top-heavy IMF. Whether or not the IMF is a universal function is presently unknown. What is clear is that the IMF is related to the dark matter problem because a top-heavy IMF yields dark stellar remnants which behave dynamically like cold dark matter. Thus, a massive E galaxy which formed with a high SFR $> 1000\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ would contain as much mass in dark stellar remnants as in shining stars. Consequently from the dynamical M/L ratio, assuming a universal invariant IMF, one could wrongly conclude that the massive galaxy contains dark matter.

10.5.1 The Assembly of ETGs: A Crucial Test for Models

Elliptical galaxies have been considered for long time the prototypical example of galaxies originated in a single collapse event. This view started to change around the 1970s when evidences accumulated demonstrating that their shape could not be explained with a single spheroid flattened by rotation, dust-lanes were observed along their minor axes, counter-rotating stellar and gas components were discovered, and fine structures reminiscent of past accretion/merger events were revealed (see e.g. Bertola and Capaccioli 1975; Bertola and Galletta 1978; Bertola et al. 1990; Schweizer et al. 1983; Schweizer and Ford 1984). S0s share most of the kinematic and morphological peculiarities of Es. So often elliptical are associated to S0s to form the vast class of ETGs. During the last decades, many characteristics of the ETGs luminosity profiles as (it cuspy vs. *core* nuclei) or their *boxy* vs. *discy* isophotal shape have been credited to separate ETGs produced by nurture (*wet* vs. *dry* merger/accretion) vs. nature scenarios (Bender et al. 1989; Lauer 2012; Lauer et al. 1991, 1992).

S0s posses by definition a disk apparently at odds with elliptical. Indeed the borders, as usual in nature, are not so precise: Es may have host a discs and rotate as fast as S0s. The ALTLAS^{3D} team investigate nearby ETGs suggesting that inner ($\lesssim 1\ r_e$) kinematic properties may distinguish between true Es from S0s. True Es are slow rotators, but represent only a small fraction (18 %) of ETGs. Fast rotators, S0s plus a significant fraction of morphologically classified Es, are the vast majority of ETGs and have kinematic properties similar to spirals. These led the team and other researchers to propose various modifications of the Hubble tuning fork, introducing a third parallel arm for S0s/fast early-type rotators (see e.g. Cappellari et al. 2011; Kormendy and Bender 2012; van den Bergh 1976).

HST work (ACSVCS/FCS) on Virgo and Fornax galaxies provide a view that the structure of ETGs—both on nuclear and global scales—changes in a continuous and regular way from the brightest cluster members to galaxies almost a factor 1000 less luminous (or massive). Laura Ferrarese suggests that this was quite a drastic departure from the view compartmentalized early-type galaxies in disjoint populations, each claimed to be characterized by distinct structural properties. A continuity in structural properties also implies a continuity in the processes that have, through cosmic time, affected and shaped ETGs we observed today.

When ETGs assembled? Likely at very high redshift, but the full formation process it is not yet clear (Cox et al. 2008; De Lucia et al. 2011; Khochfar et al. 2011; Mihos 2004). There are evidences that a significant fraction of ETGs at high redshift have signatures of interaction and/or merger morphologies and star formation activity (Treu et al. 2005). However in the more massive ETGs, the measured [α/Fe] ratios, encoding information about the timescales of the star formation history, have super-solar values suggesting a relatively short timescales for the galaxy formation (Annibali et al. 2007; Chiosi et al. 1998; Clemens et al. 2009; Granato et al. 2004; Salim and Rich 2010), challenging a hierarchical scenario.

A high fraction of nearby ETGs show signatures of interaction/accretion/merging, sometimes very recent, phenomena. What is the weight of these phenomena in the ETGs evolution? Morphological peculiarities are sometimes accompanied by *rejuvenation* signatures in ETGs which have been detected both in the galaxy central regions and even in outskirts, as clearly shown by GALEX (Marino et al. 2011; Rampazzo et al. 2007; Salim and Rich 2010; Thilker et al. 2010), These observations suggest that there have been different phases of the galaxy assembly/evolution. A fair upper limit to the contribution of recent rejuvenation episodes is $\sim$25 % of the total galaxy mass (Annibali et al. 2007), but episodes are possibly much less intense than that (see e.g. Panuzzo et al. 2007).

There is another aspect of the evolution of S0s likely tied to the environmental conditions, raised by Spitzer and Baade that questioned the possible origin of S0s as evolving spirals in 1951 (Spitzer and Baade 1951). This hypothesis about the evolution of S0s, according to our interviews, is still an unsolved question. The idea of an evolved morphology is mostly supported by the studies of the population of galaxies in clusters at increasing redshifts. Here, the number of S0s is seen to decrease with redshift in favour of Spirals. However, the mechanisms which have operated the morphological transformation are not clear yet. The main actors, at least for galaxies in dense environments, are believed among others the spoiling of gas by ram-pressure stripping or its evaporation due to an hot IGM. In the field these processes are likely less important, so that S0 galaxies should originate even from secular evolution or from merging events (for more details see, e.g. D'Onofrio et al. 2015).

At the end of this excursus about the problem of the origin of ETGs we need mention the subject of fossil groups, not touched by interviews. Fossil groups are considered dynamically evolved environments where the dominant galaxy, an elliptical, has accreted the most massive surrounding galaxies via dynamical friction. Mulchaey and Zabludoff introduced this concept investigating the giant elliptical NGC 1132 whose X-ray temperature, metallicity, and luminosity of the halo are similar to those of a galaxy group (Mulchaey and Zabludoff 1999). Jones et al. (2003) provided a definition for fossil groups: they have a spatially extended X-ray source with an X-ray luminosity from diffuse, hot gas of $L_{X,bol} \geq 10^{42} h_{50}^{-2}\,\mathrm{erg\,s^{-1}}$ and a gap of $\Delta m_{1,2} \geq 2.0$ magnitudes between the brightest galaxy and the second brightest galaxy in the group. From one side the X-ray condition discarded "normal" elliptical with X-ray halo, the other condition imposes that the elliptical dominates the group. Analyzing the data set produced by the Millennium simulation (Springel et al. 2005), Dariush and collaborators suggested that fossil groups assembled their dark matter halos early, accumulating 80 % of the present-day mass about 4 Gyr ago (Dariush et al. 2007). The gap in magnitude in the parent galaxies populations and the lack of substructure in fossil groups raised a debate as a possible challenge to the ΛCDM paradigm, similar to the missing satellite problem on the LG (e.g. Sales et al. 2007 and references therein).

We believe that the link between the low and high redshift ETGs will be an observational and simulations gym in the future for understanding galaxy evolution.

10.6 The Today's Great Debates

This book started considering the different views of the pioneers of extragalactic astronomy around the 1920s. Many of the questions they sketched about one century ago, still preserve their freshness. The technological and scientific jumps extended our horizons in space and time. Panchromatic observations sometimes open totally unexpected views, real breakthrough in understanding of galaxies opening astronomers eyes to new visions. Some interviews emphasized, however, the "resilience" of some (still unsolved) problems. The most relevant example is that formerly called the *missing mass problem*, raised by Zwicky (1937) studying the mass-to-light ratio (M/L) of galaxies in Coma, revitalized by Vera Rubin in the 1970s (Rubin and Ford 1970) with the study of the optical rotation curve of galaxies, and today generalized as the"dark matter problem".

10.6.1 The Dark Matter Puzzle

Pros and cons for the existence of DM can be found. However, this problem will be definitively solved only when the DM will be detected or a new physical framework will be able to fill the gap between particle physics and general relativity.

The antagonists of the DM hypothesis have in general pointed out that the current cosmological framework fails in reproducing several observed properties of galaxies (see e.g. Kroupa 2012; Kroupa et al. 2010, 2012). The main concerns are expressed for the dwarf objects: (1) the class of tidal dwarfs, that should not be surrounded by a DM halo, appears not different from the class of primordial dwarfs, that should be dominated by the DM halo; (2) the number of massive dwarfs around us is too small with respect to the predicted one; (3) the arrangement of the dwarf satellites around the MW and M31 cannot fit the idea of being DM substructures; (4) the downsizing, i.e. the fact that the most massive galaxies have already produced all their stars and now are quenched systems, while the dwarfs are still forming stars today, is anti-hierarchical. Other doubts concern the inability of simulating galaxy disks of the correct size and stability without introducing strong feedback effects, the highly significant matter under-density on scales of 10–300 Mpc, the frequency of the merging events, and so on.

The DM supporters on the other hand claim that there are no alternative to this hypothesis (see e.g. Einasto 2014). `WMAP` made precise measurements about the fraction of barions (4.6 %) and dark matter (26 %) present in the Universe. The CMB measurements do not favor the presence of baryonic DM, whose existence is clear from the M/L of galaxies and clusters, from the rotation curves of galaxies, from the lensing of galaxies and quasars, from the cosmic web structure, etc. The large scale structure of the Universe can be very well reproduced with the cold DM.

From a theoretical point of view the DM is well inserted in the standard cosmological model, now represented by the ΛCDM scenario, while the few antagonist theories such as MOND (Modified Newtonian Dynamics; see e.g. Milgrom 1983a,b,c) and TeVeS (Tensor-Vector Scalar gravity; see e.g. Bekenstein 2004) still have some difficulties or are not yet written for the cosmological context.

10.6.2 The Cosmological Context

In the ΛCDM cosmology the Universe contains three main components in cosmic proportions: Dark Energy (DE, 70 %), Dark Matter (DM, 25 %), and Baryonic Matter + Neutrinos (BM, 5 %). The DM candidates are the so-called Weak Interacting Massive Particles (WIMPs), non relativistic particles born in the early Universe with a mass in the energy range GeV-TeV. Numerical simulations have shown the growing of primordial perturbations of bigger and bigger mass under the action of gravitation. The cold nature of the DM is mostly supported by the properties of the CMB radiation. Warmer forms of DM are not able to create the fine structure observed in the cosmic web. The shape of the angular power spectrum of CMB temperature fluctuations is sensitive to the whole set of cosmological parameters. The detailed analysis of the CMB spectrum from various missions, such as `WMAP` and `Planck`, have provided a determination of the cosmological parameters with unprecedent accuracy, so that we currently say that we are in the era of "Precision Cosmology". The DE or the cosmological constant is responsible of the accelerated expansion of the Universe. The acceleration was actually detected by comparing distant and nearby supernovae (Perlmutter et al. 1999; Riess et al. 1998).

The large scale structure of the Universe, i.e. the cosmic web, is quite easily interpreted in this cosmological framework. The dominant elements of the cosmic web are chains/filaments of galaxies and clusters. The space between filaments is almost devoid of galaxies and these regions are called cosmic voids. Superclusters are the high-density regions in this network. The linear shape of filaments can be explained only when galaxies and clusters already form inside filaments. A widely accepted explanation of the large-scale structure of the Universe is intimately related to its microscopic structure on elementary particle scales: the initial seed of fluctuations at the Planck epoch which determined the asymptotic growth of irregularities in the expanding Universe.

The proper end of this book, as its motivation, is based on our creed that some fundamental pages about the nature of galaxies have still to be written. Many problems are unsolved since the early times, but there are many possibilities for young scientists to emerge in spite of the assembly lines which characterize the work of astronomers in the *Big Science era*. We therefore look forward hoping that a protracted epoch of peace will open minds toward new scientific enterprises in extragalactic astronomy, disclosing the mysteries of this fascinating astrophysical branch.

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