Introduction to Astronomy Lecture 7: Our galaxy

– putting the pieces together

Presented by
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Spring 2018

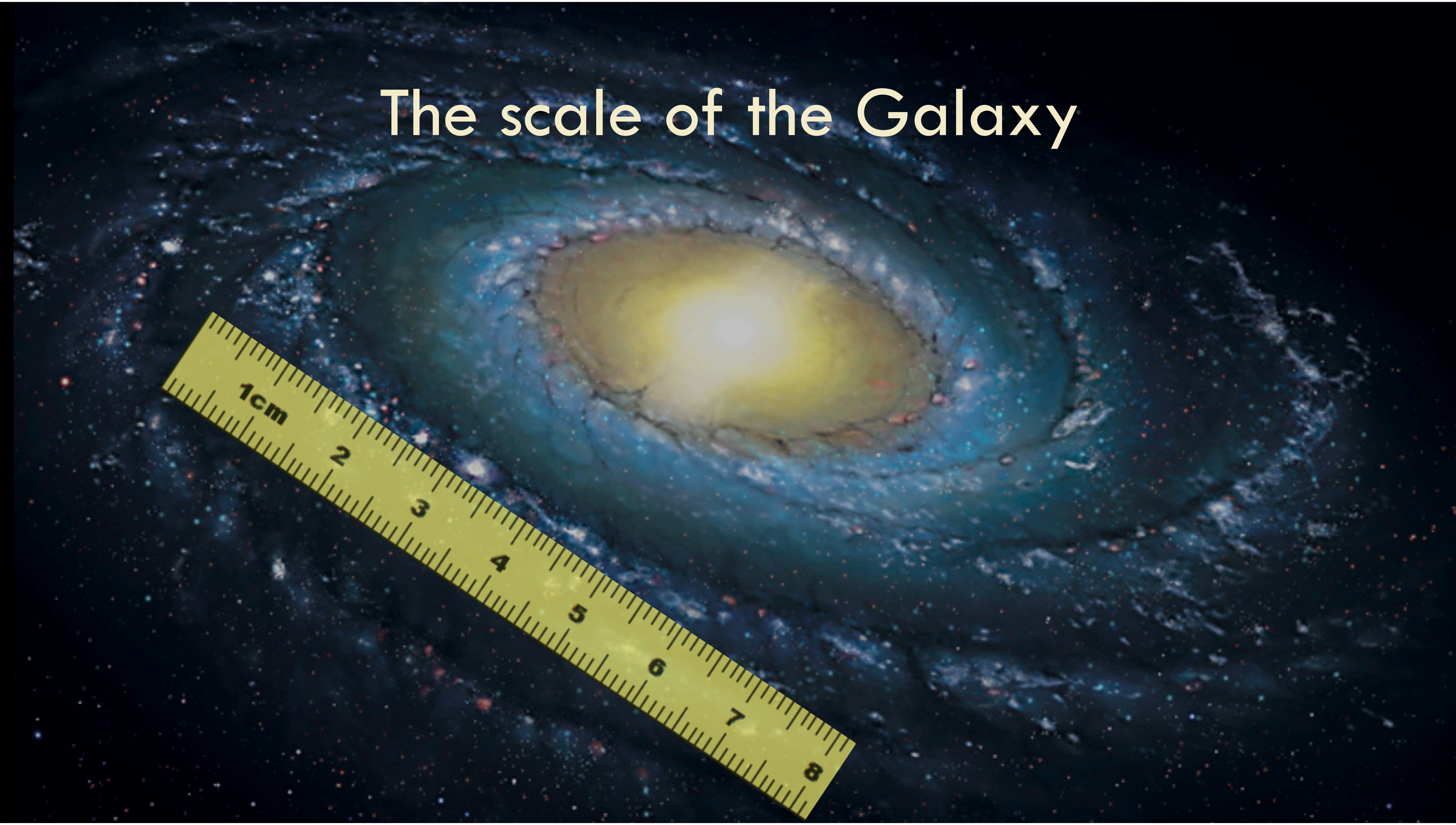
THE UNIVERSITY OF SYDNEY

In tonight's lecture

- The scale of the Galaxy
  – the long, hard journey towards understanding the shape of the universe

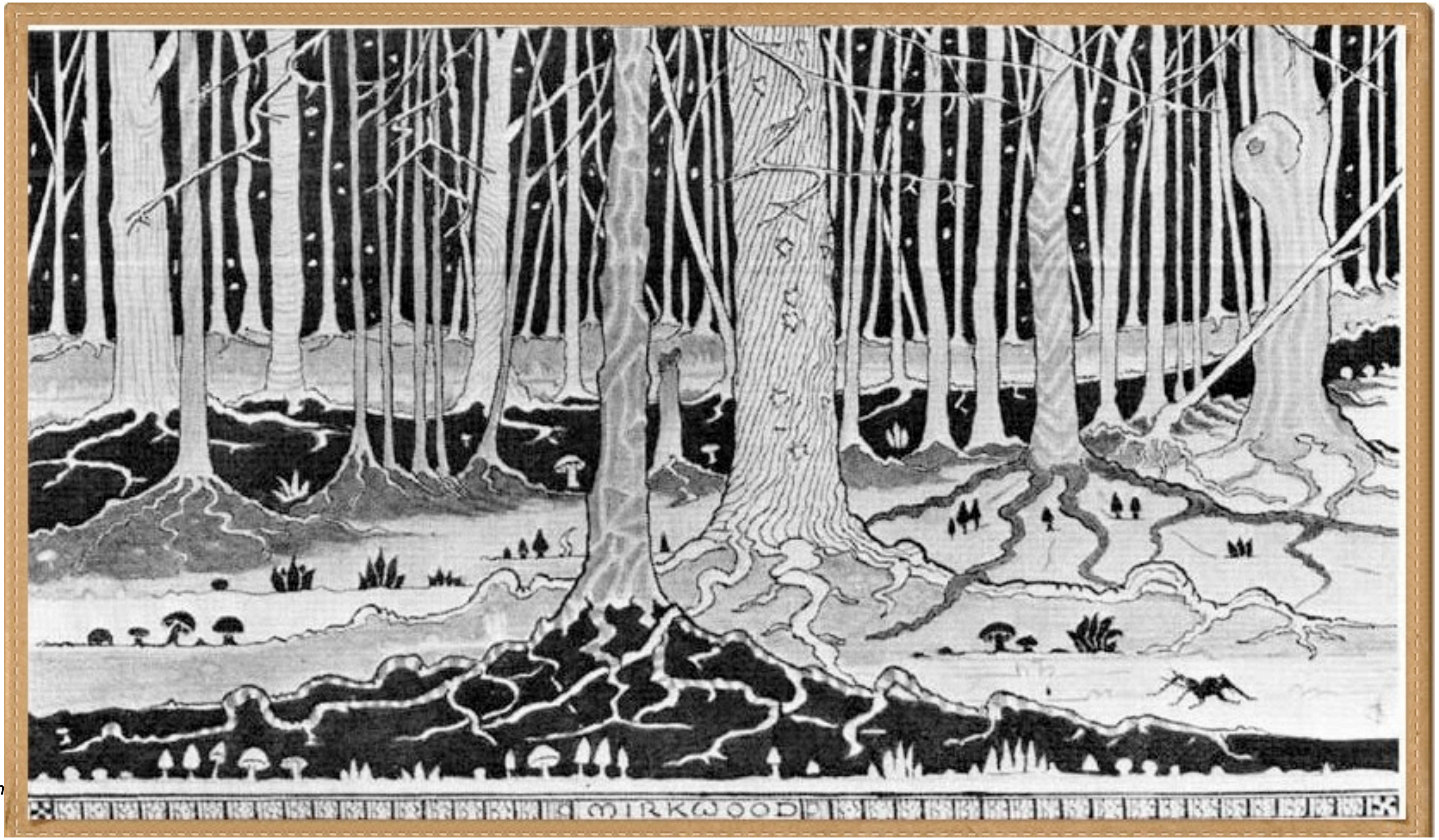
- The structure of the Galaxy
  – the various components that make up our Galaxy and how we discovered them

- The formation of the Galaxy
  – how the Galaxy came into being


The scale of the Galaxy
1cm
2
3
4
5
6
7
8

We’ve already seen how our Sun is one of a multitude of other stars, and that our very existence is intimately related to the cycles of the birth and death of stars.

Trying to understand the *shape* of the collection of stars we call our Galaxy is like trying to map a forest from the inside.



The Milky Way has been know since ancient times: the Greeks called it *galaxias kuklos*, or "Milky Band". The Romans called it *Via Lactea* ("road of milk"); in China and Japan it was called the "*River of Heaven*"

It was seen as a diffuse band of light crossing the night sky, but the nature of it was unknown: it was a kind of backdrop to the stars.

The Milky Way above Easter Island

Many Australian Aboriginal cultures tell of the Emu in the Sky: one of the few astronomies that focussed on the dark spaces instead of the bright stars.

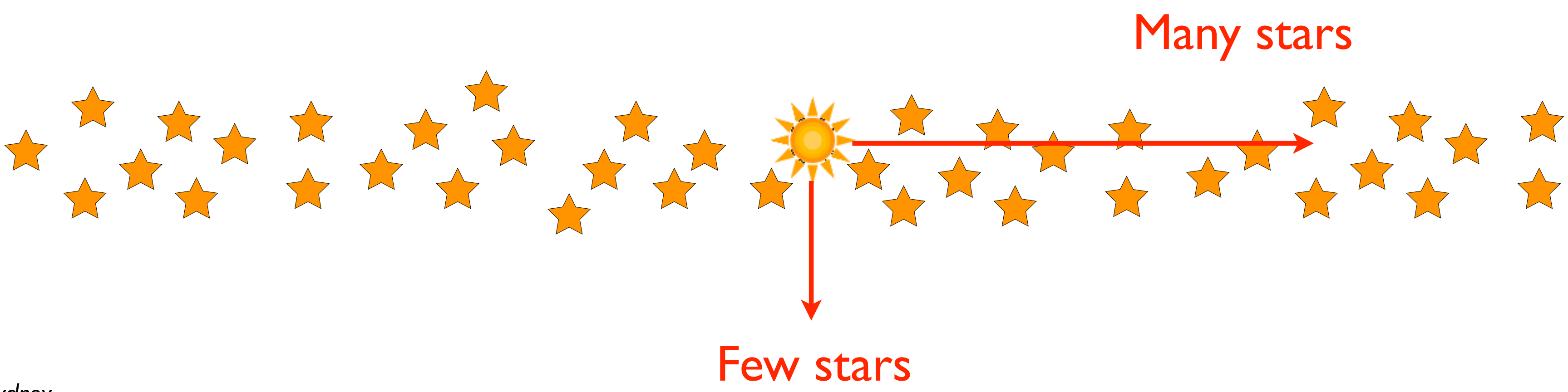
The "Emu in the Sky" engraving, as seen from Elvina Track, Kuringai Chase National Park. Image by Barnaby Norris.

Galileo was the first person to show that the Milky Way was made of stars.

> *"I have observed the nature and the material of the Milky Way... The galaxy is, in fact, nothing but a collection of innumerable stars grouped together in clusters. Upon whatever part of it the telescope is directed, a vast crowd of stars is immediately presented to view. Many of them are rather large and quite bright, while the number of smaller ones is beyond calculation."*
>
> – Galileo Galilei, *The Starry Messenger* (1610)

Galileo made no comment on the other important thing we can observe about the Milky Way: that it only occupies a narrow band across the sky.

If the Universe was spherical, then numerous stars would lie in all directions. The fact that we see lots of stars only in some directions means the Universe is *anisotropic* – different in different directions.

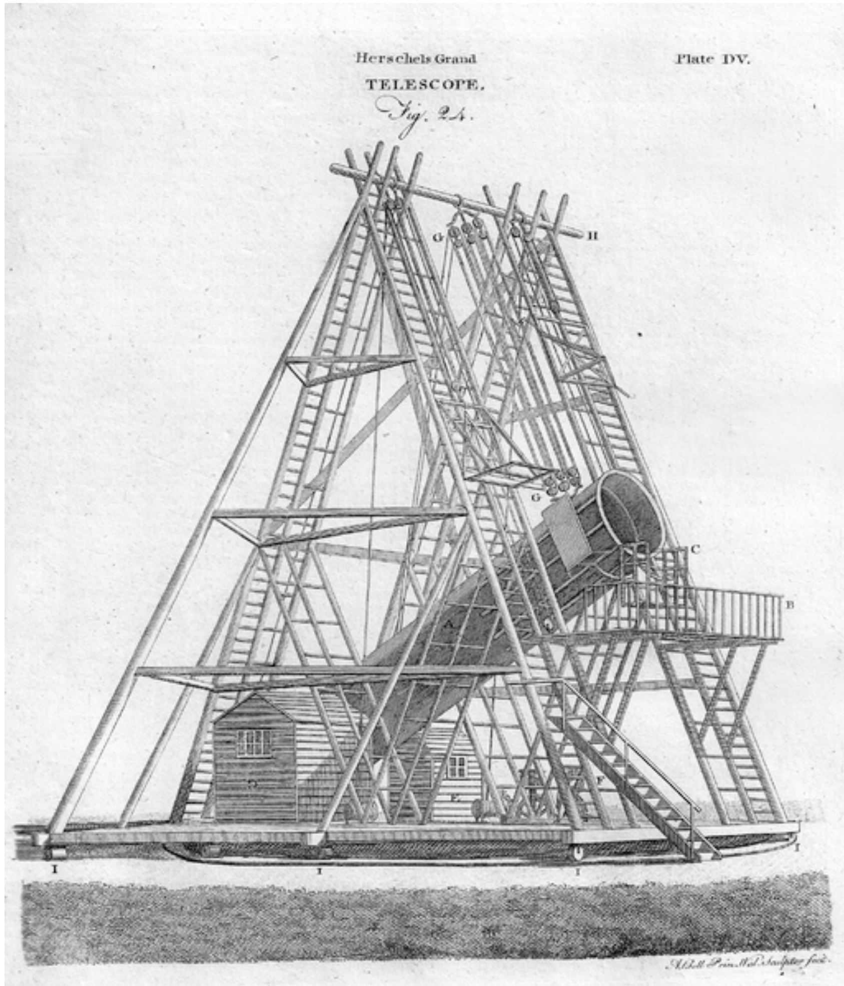


"[The Milky Way is] a vast infinite Gulph, or Medium, every way extended like a Plane, and inclosed between two surfaces."

– Thomas Wright, *An Original Theory or New Hypothesis of the Universe* (1750)

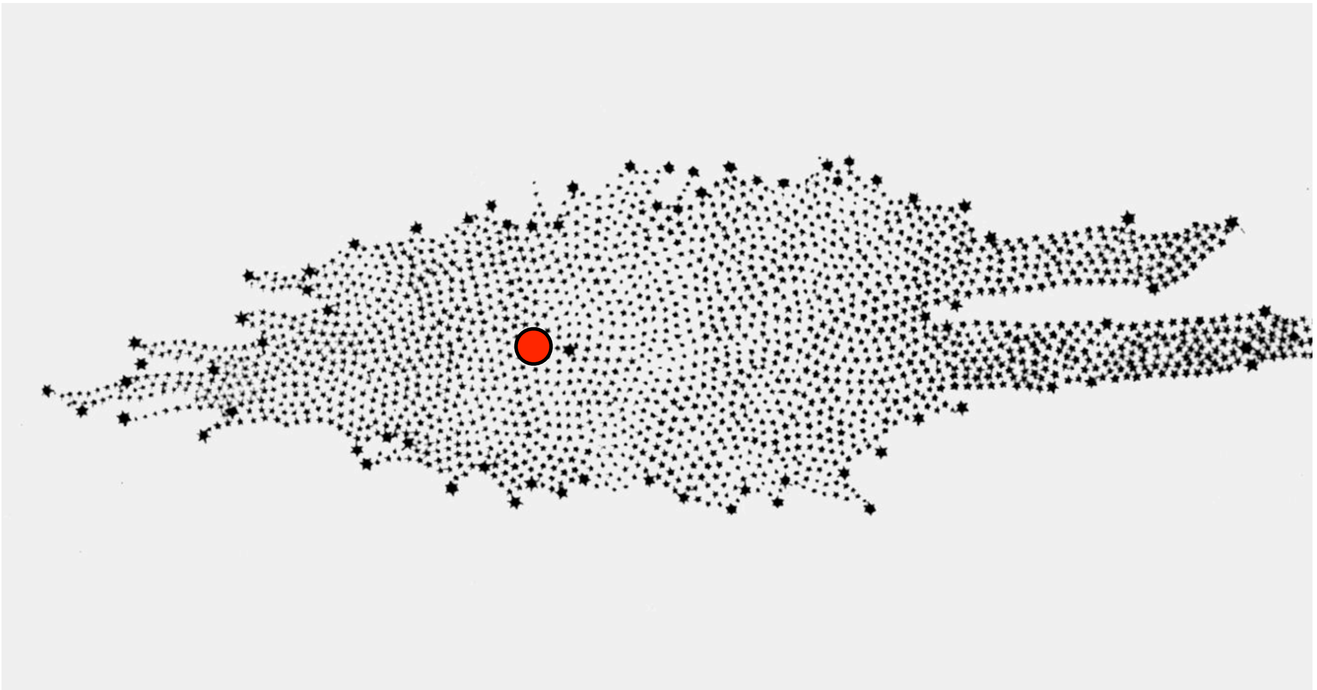
Wright's drawing of the slab-like geometry of the Milky Way.

In 1785, William Herschel used star counts to determine the shape of the layer of stars. He and his sister Caroline counted the number of stars in 683 directions in the sky: between 1 and 588 stars in the 15-arcmin eyepiece field of his Great Forty-Foot telescope.



Herschel's Great Forty-Foot telescope

He then assumed that stars filled the Galaxy uniformly out to some boundary, outside which was emptiness. By counting the number of stars in each direction, he could work out the distance to this boundary. He deduced that the Milky Way is a flattened thick disk, with the Sun nearly at the centre.



Herschel's model suggested that we are very near the centre of the Galaxy. Photographic surveys gave the same answer: there are roughly even numbers of stars in all directions in the band of the Milky Way, so we must be near the centre of a flattened disk about 15 kpc in diameter.

In 1915, a young astronomer named Harlow Shapley was studying globular clusters. He found that the globulars are *not* evenly distributed in the sky. There are very few globulars in the part of the sky we see in summer, but many in the winter sky, towards Scorpio and Sagittarius.

Globular clusters are clusters of stars, containing between 10,000 and a million stars. They are typically a few parsecs in size, and are densest in the centre, where there may be as many as 1,000,000 stars per cubic parsec.

The globular cluster omega Centauri, one of the largest in the Galaxy.

The globular clusters form a great swarm concentrated in the sky towards the constellation of Sagittarius.

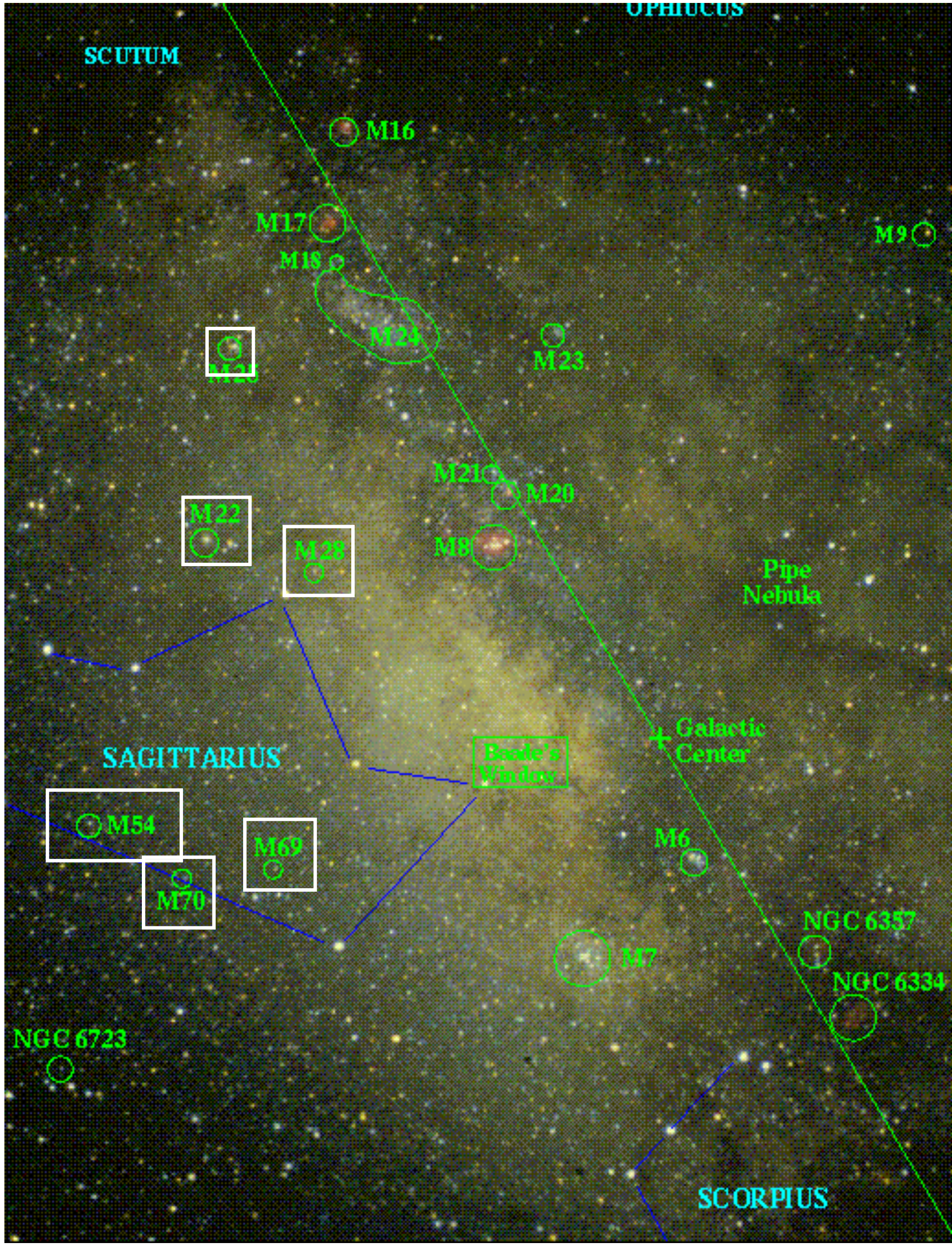
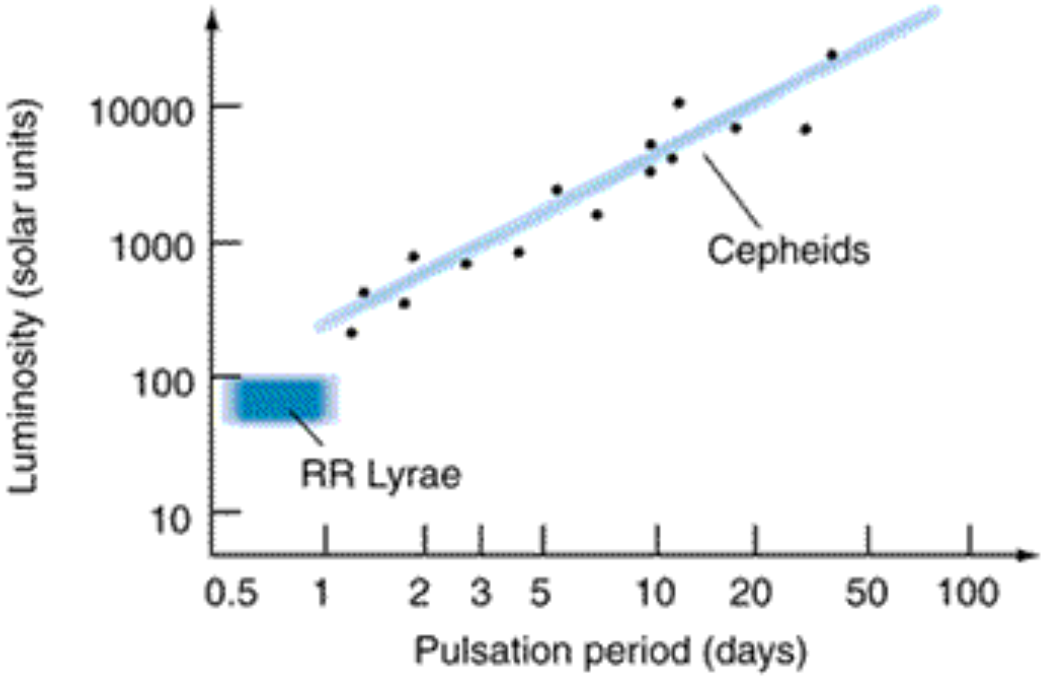
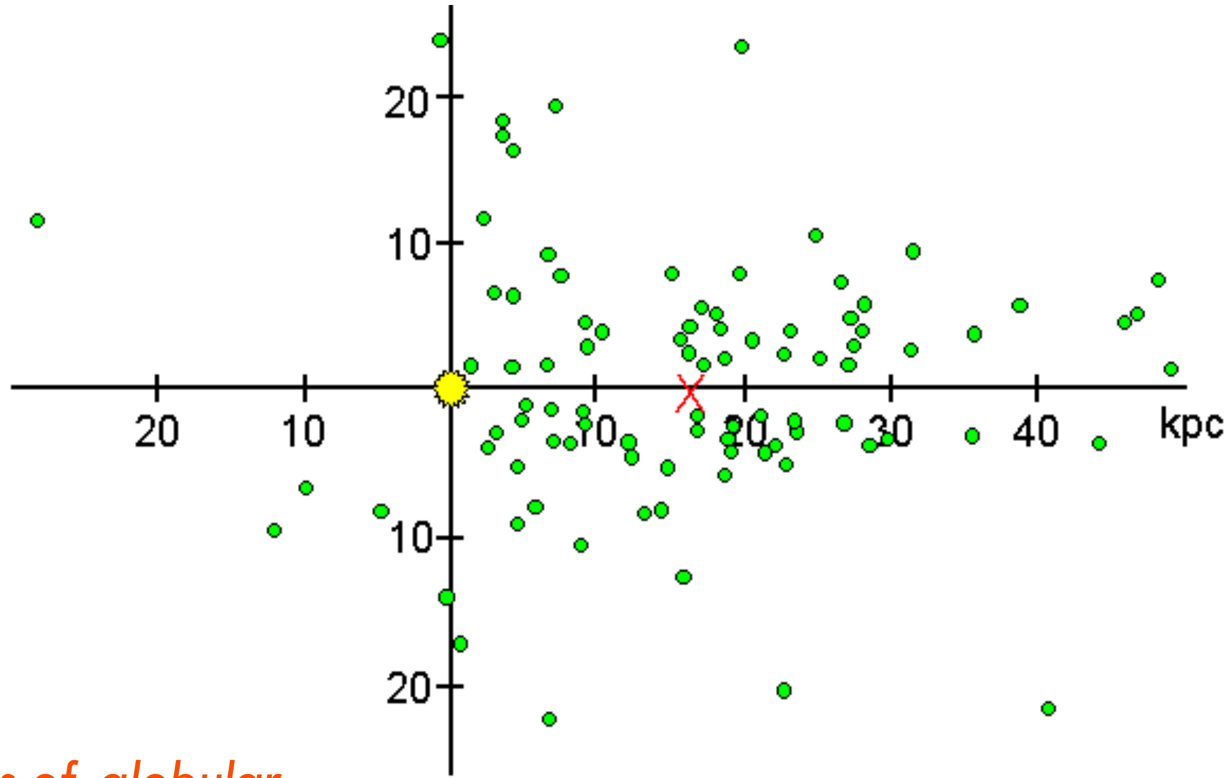


Image of the Galactic centre region. The squares indicate globular clusters.

Shapley needed to measure the *distances* to the globular clusters. Henrietta Leavitt had just published her period-luminosity relation for Cepheid variables; Shapley calibrated the relation using nearby variables, so he could use them as *standard candles*.



When Shapley plotted the 3-dimensional positions of the globular clusters, he found they were centred around a point about 16,000 parsecs away in Sagittarius.



Shapley's plot of the positions of globular clusters: the Sun is the yellow circle.

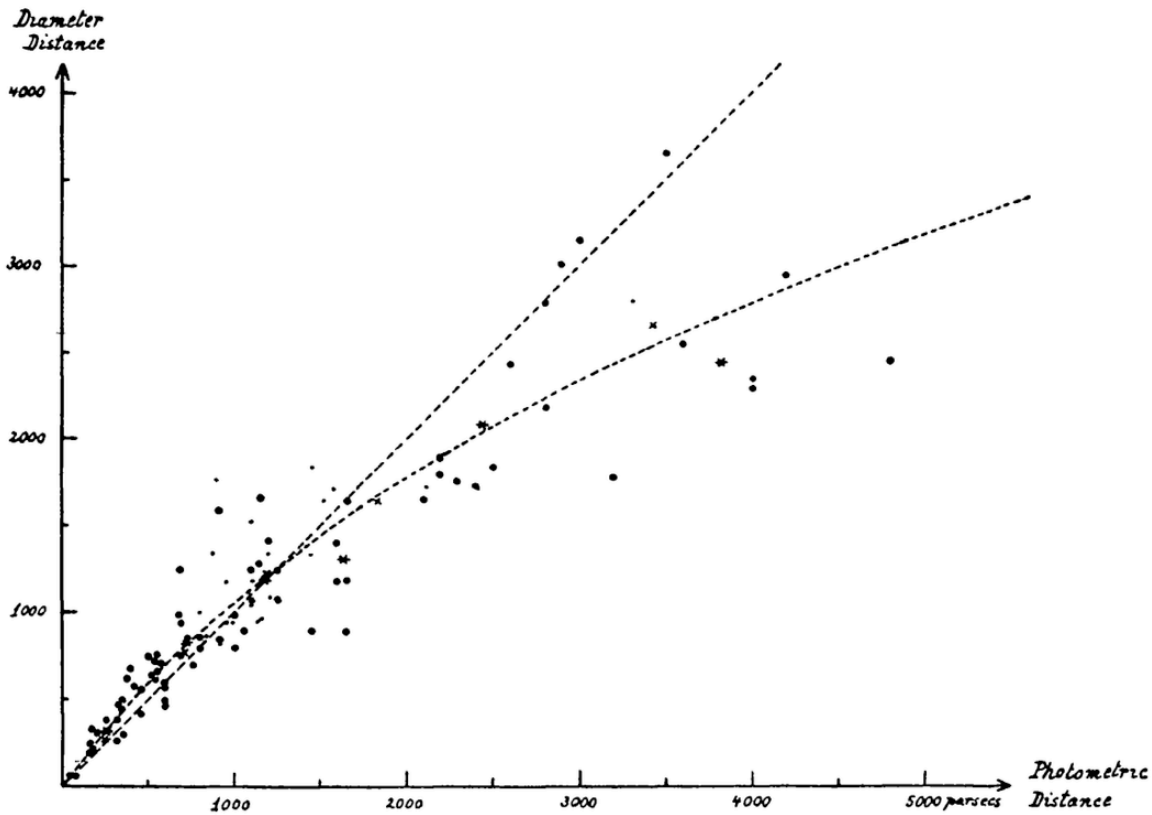
So the globular clusters appeared to be *beyond* the apparent edge of the Galaxy.

Shapley concluded that the Galaxy must extend far beyond the portion that had been mapped, and that the globular clusters must mark the true centre of the Galaxy.

This suggested the Galaxy was much larger than we thought.

In fact, Shapley's measurement of the size of the Galaxy was an *overestimate*. Robert Trumpler showed that more distant clusters were systematically larger than nearby ones, which must mean that their light is being dimmed and hence their distance overestimated.

Trumpler estimated the distance to clusters twice: once using their brightness and once using their size. The two did not agree: stars in the clusters appeared systematically <u>fainter</u> than expected.



He concluded that the light from the clusters was being *dimmed* and *reddened* by dust in the Galaxy, just as light from the Sun gets dimmer and redder as the Sun sinks towards the horizon.

The dark lanes in the Milky Way are thus explained as clouds of dust hiding the light of stars beyond.

The dust consists of tiny (~ few μm) particles of carbon and silicon. Dust grains serve as sites for the formation of molecules and organic compounds.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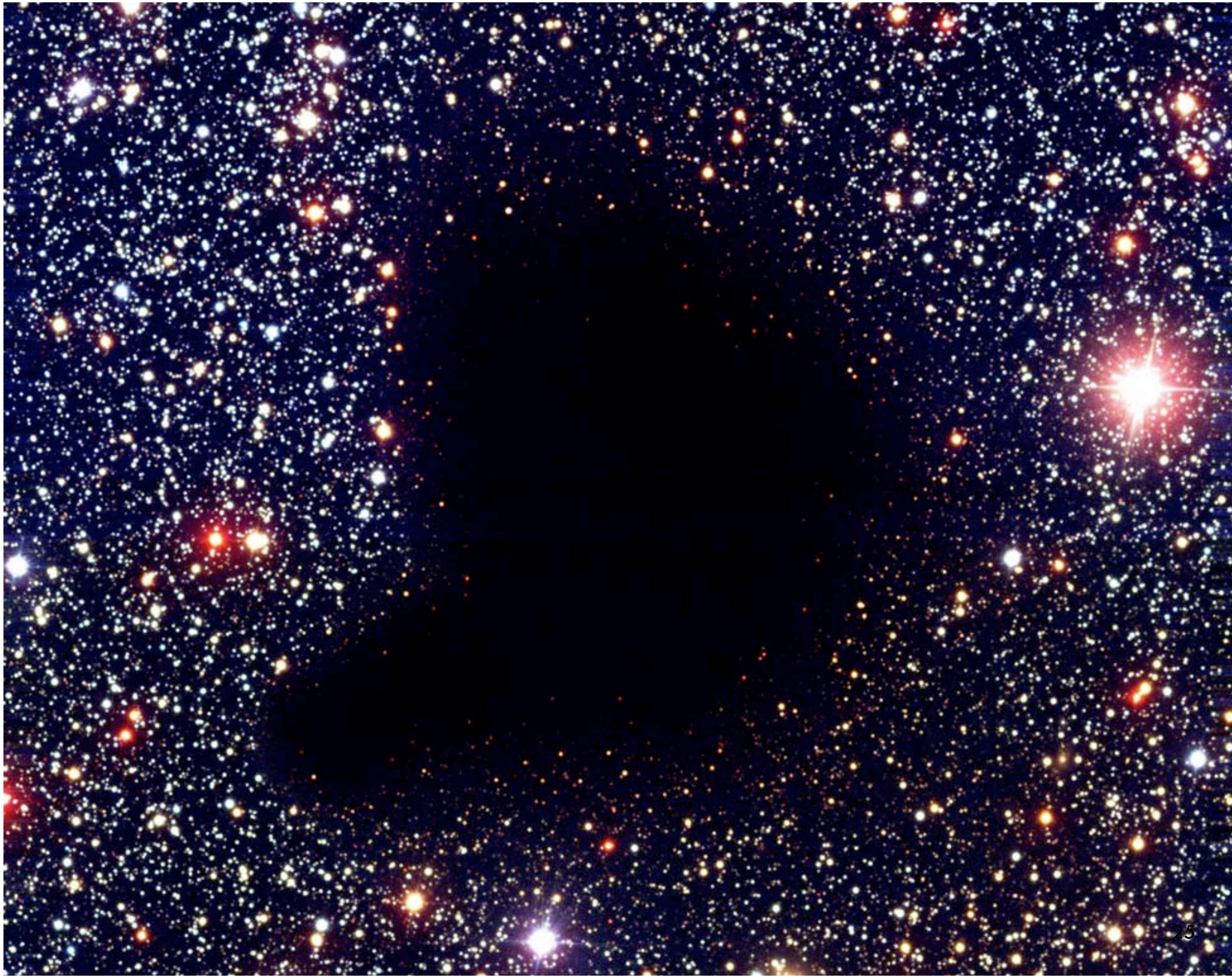
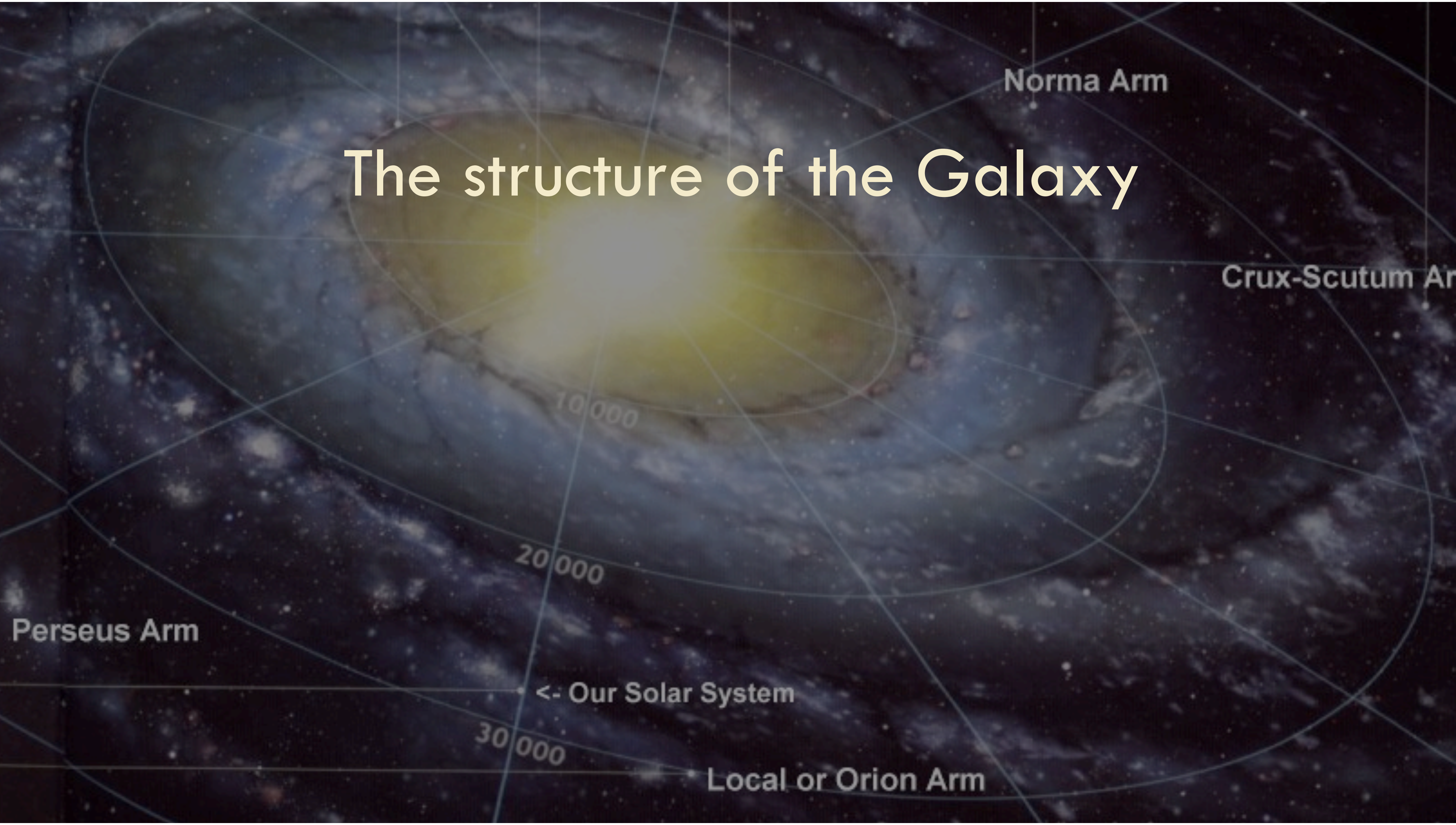
The dark cloud Barnard 68, a likely site of future star formation.



The structure of the Galaxy



While the size of our own Galaxy was being worked out, it was becoming clear that the *spiral nebulae*, which had been known for some time, were in fact other "island universes" – galaxies in their own right.

"The great spirals … apparently lie outside our stellar system."

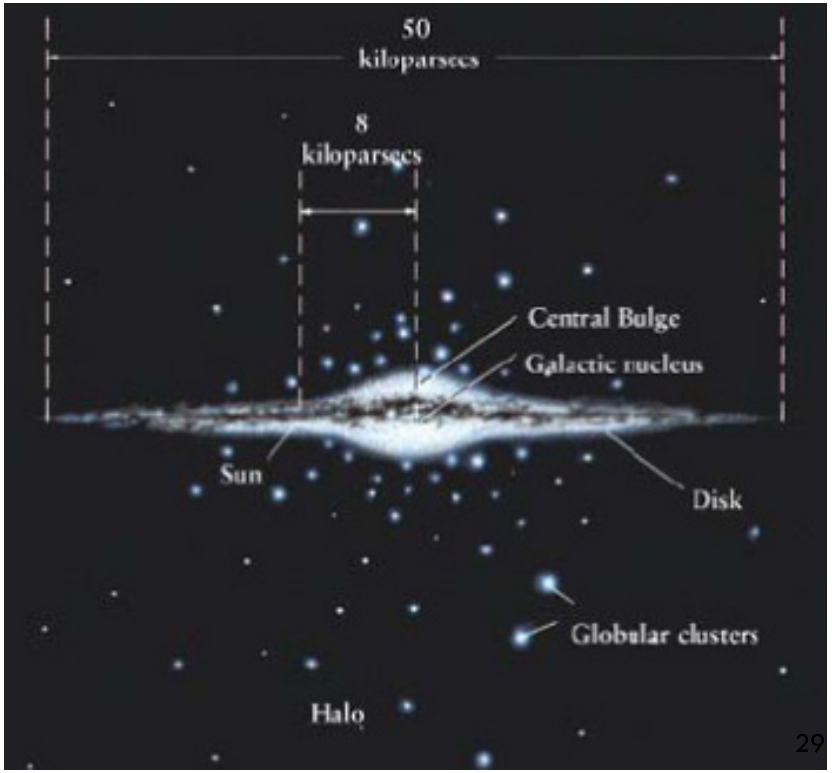
—Edwin Hubble, 1917

We will discuss other galaxies next lecture.

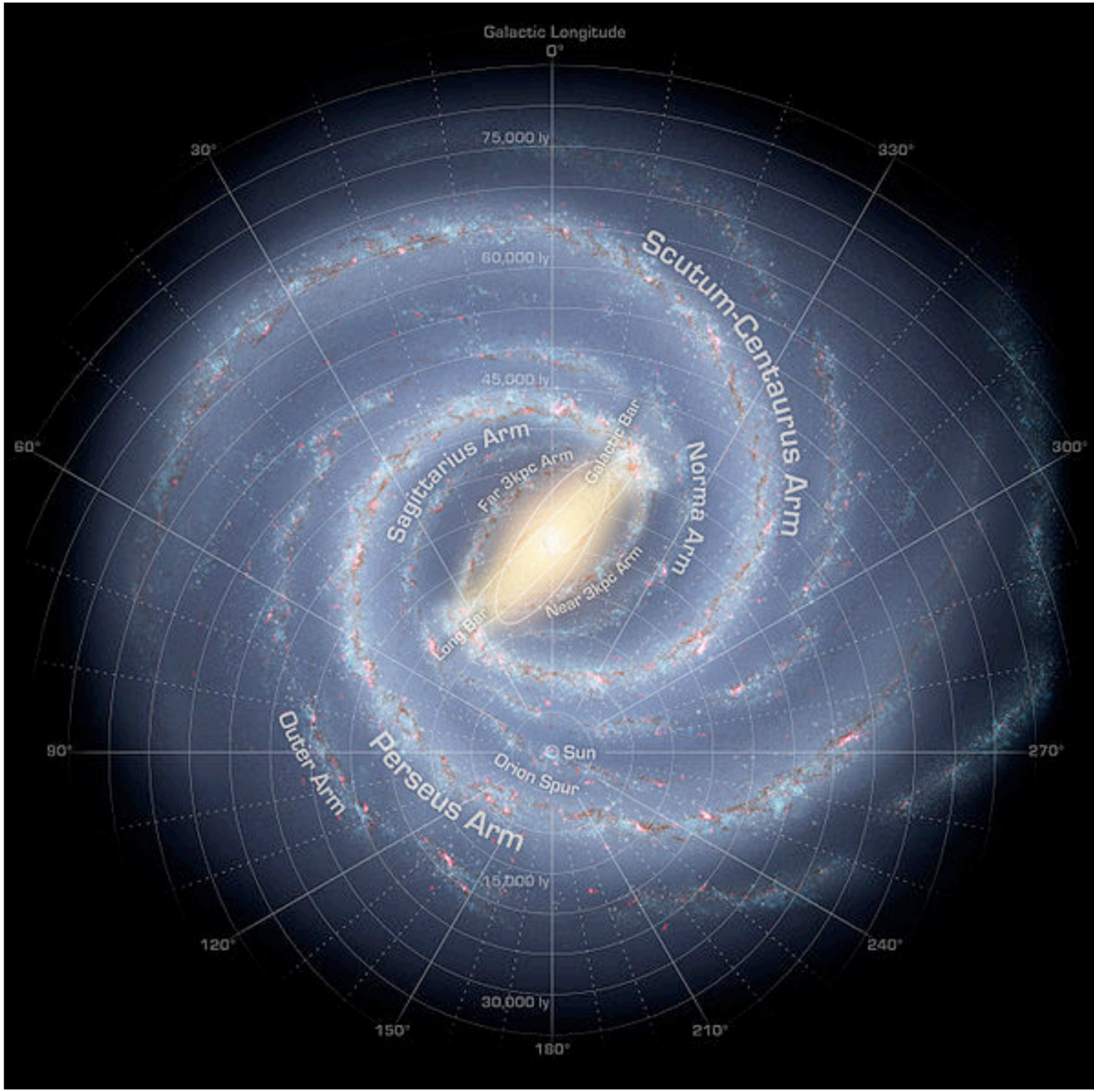
Meanwhile, here is what we now know about the structure of our Galaxy.

Our Galaxy consists of three separate components:

- a *bulge* of old stars in the centre
- a *disk* of stars and gas
- a *halo* of globular clusters



Seen from above, it would look like this.



The total size of the Milky Way is about 25 kpc (75,000 light-years) in radius, with the Sun a little over halfway from the center.

The disk of our Galaxy is shaped like a whirlpool with many spiral arms spanning out from the center of the Galaxy.

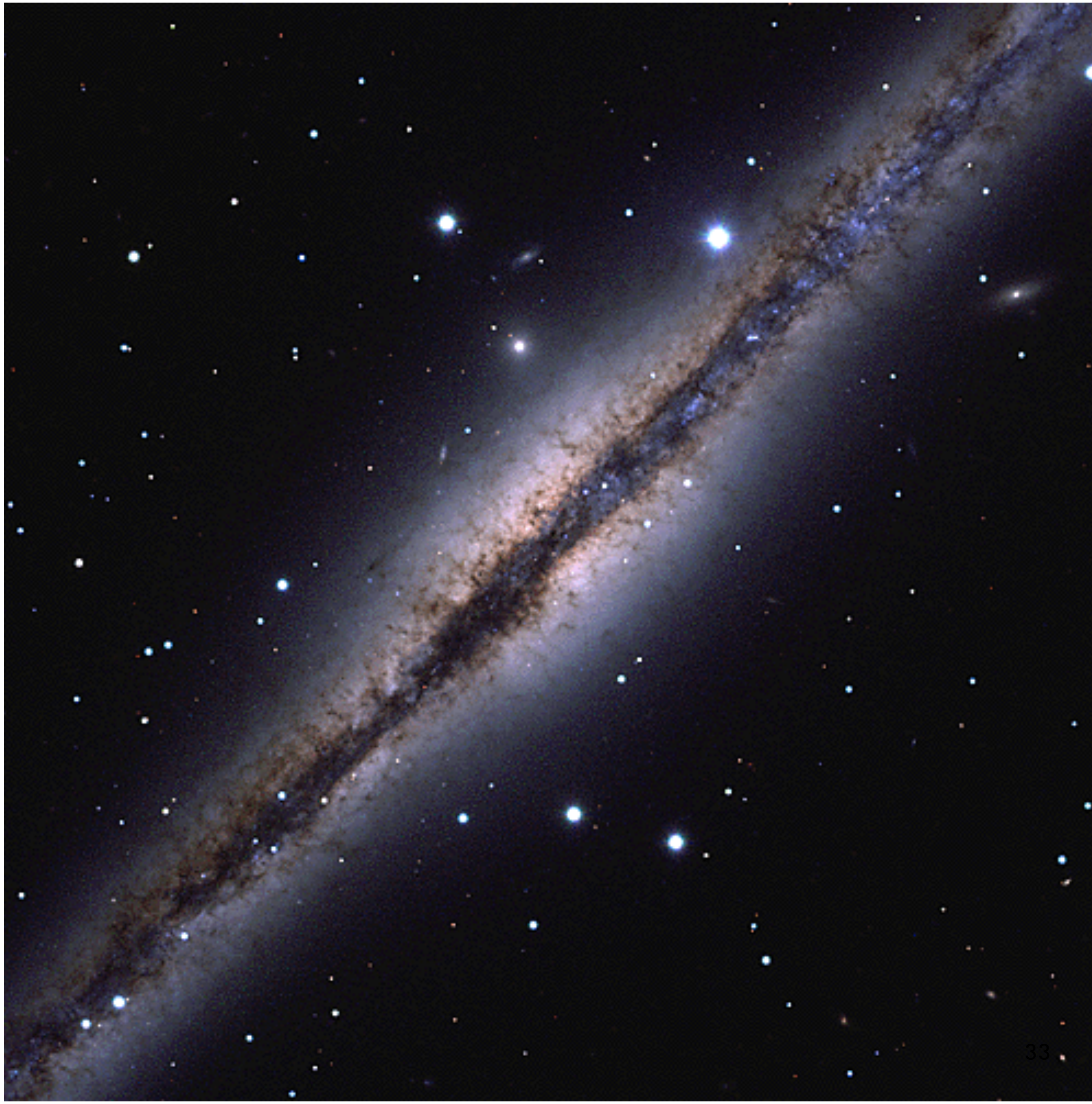
The spiral galaxy NGC 5033

The *disk* contains stars, open star clusters, and nearly all the galaxy's gas and dust. It is the site of most of the star formation in the Galaxy, so the disk is illuminated by bright blue massive stars.

The spiral galaxy NGC 1232

The disk is thin, but the exact width is hard to define because it does not have sharp boundaries.

Stars like the Sun lie within 500 pc above and below the central plane; the youngest stars lie within 50 pc.



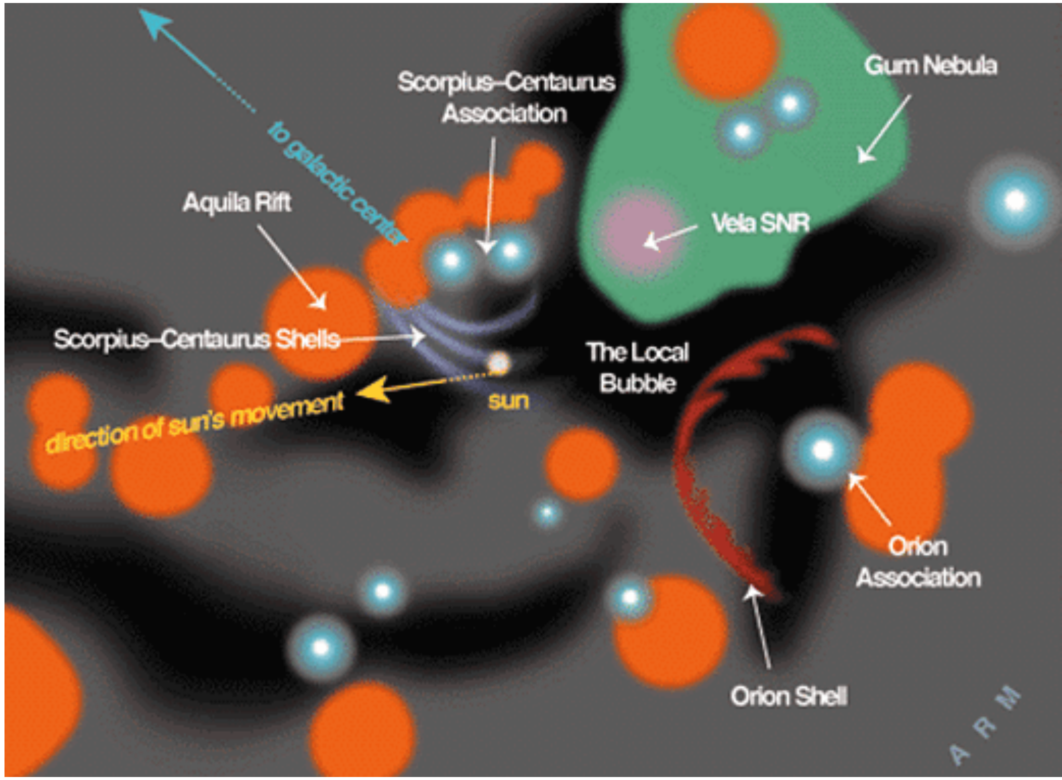
The edge-on spiral galaxy NGC 1232

Gas and dust make up about 15% of the total mass of the Galaxy.

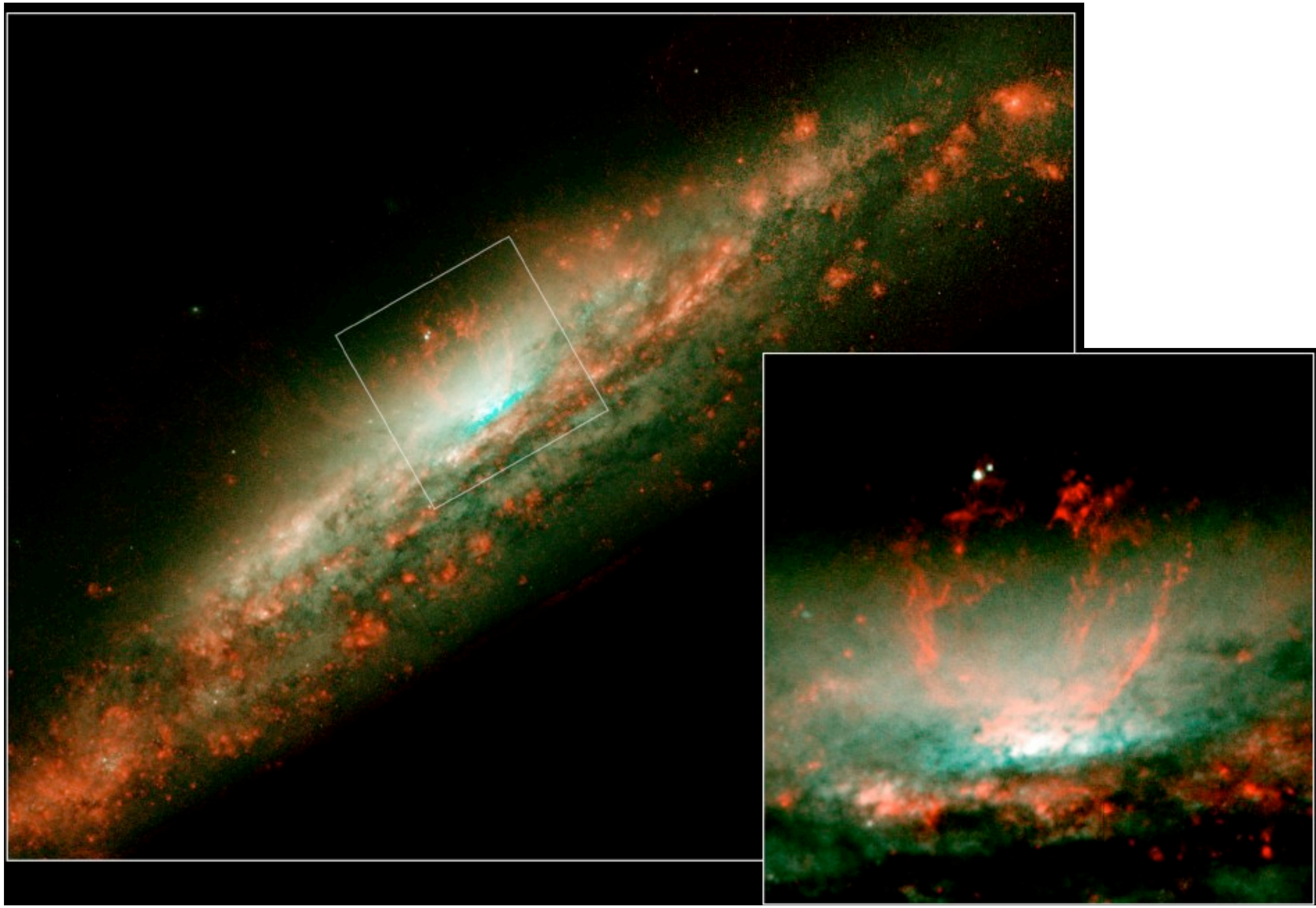
90% of the gas is hydrogen, with the remainder mostly helium.

The typical ISM has densities of less than 1 atom per cubic cm. In dense regions, there can be between 1000 and 1,000,000 atoms per cubic cm, and hydrogen atoms can combine to form molecules: we call these regions *molecular clouds*.

These clouds can contain anything from a few solar masses to over a million solar masses of gas.

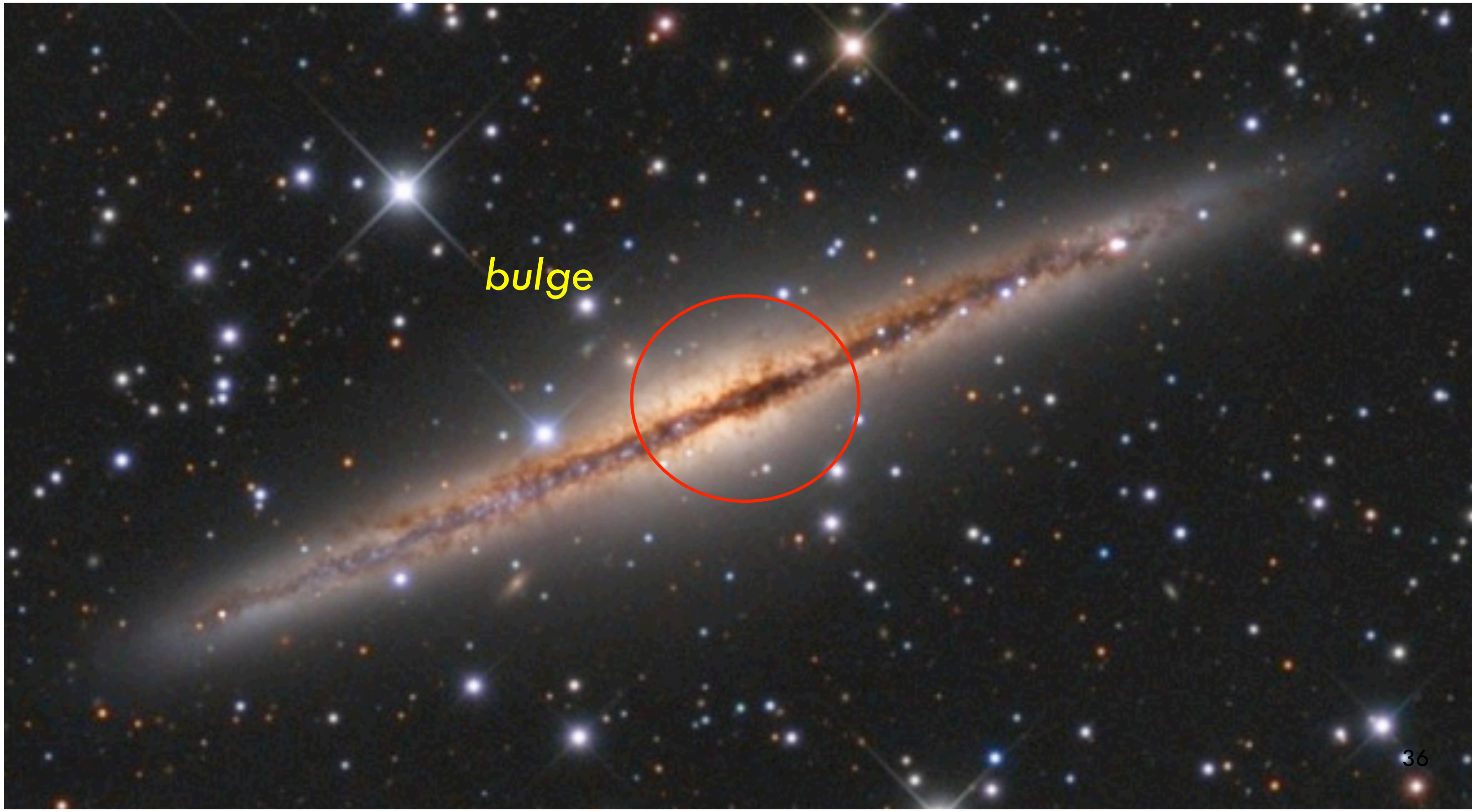


Supernova explosions and winds from hot stars can combine to form enormous bubbles of hot gas, which can even punch right out of the disk of the galaxy.

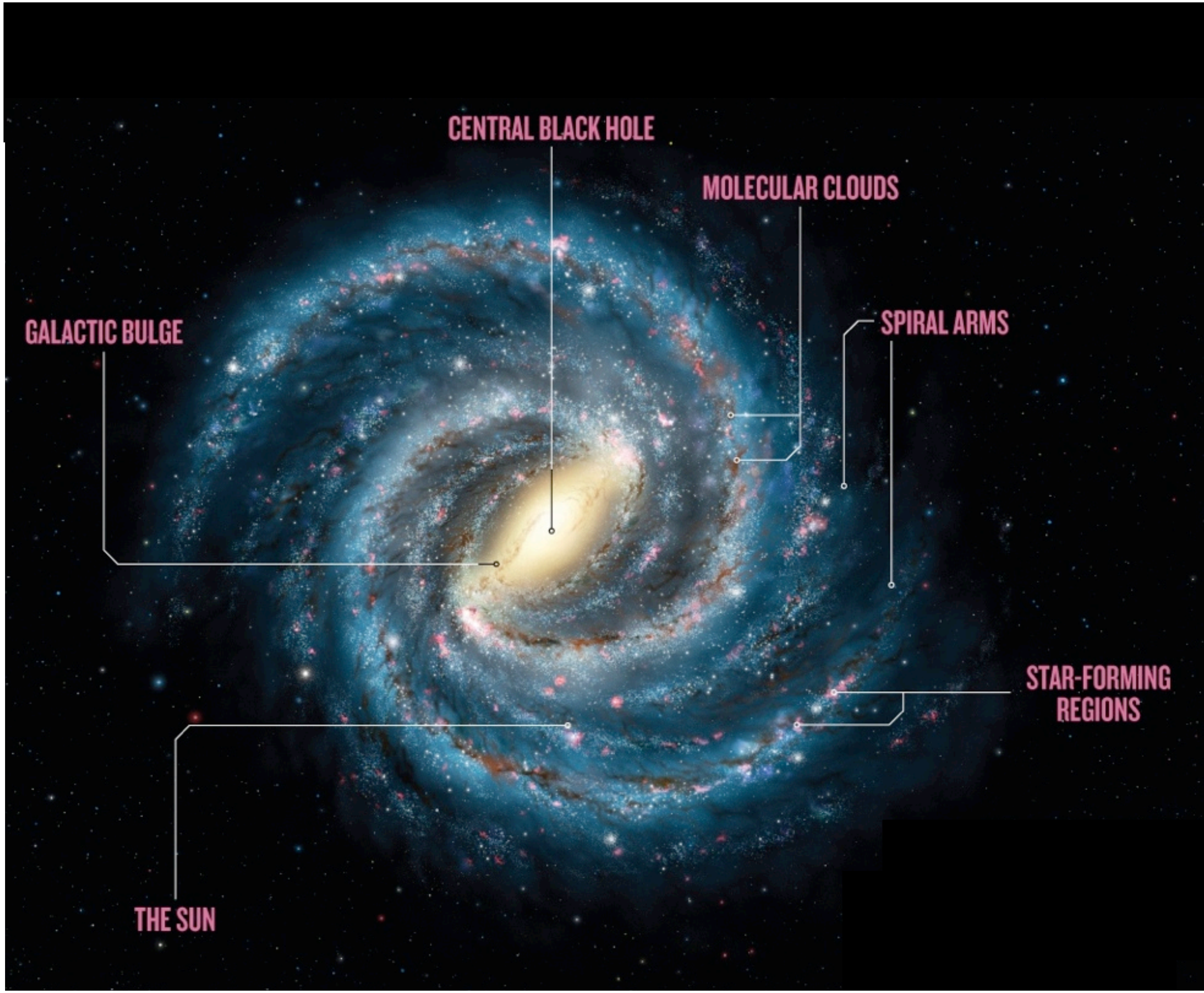


HST images of a bubble of hot gas being expelled from the galaxy NGC 3079.

The *bulge* is the dense cloud of stars that surrounds the centre of the galaxy. It has a radius of about 2 kpc and is slightly flattened. The bulge contains little gas and dust and there is thus little star formation.

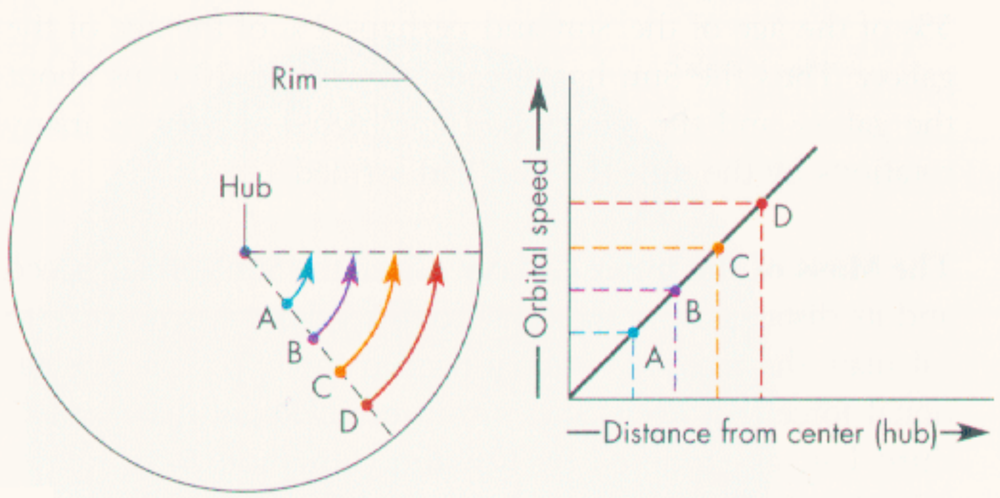


The total number of stars in the Galaxy is about 200 billion; the total mass is about 1 trillion times the mass of the Sun (10^{12} solar masses).



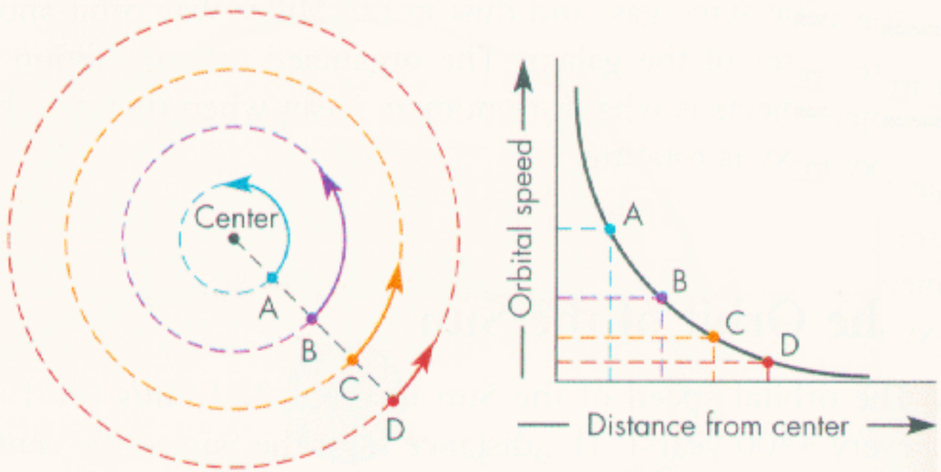
The Galaxy rotates, but *not* as a solid body. The Sun takes about 250 million years to travel around the centre of the Galaxy. Stars closer to the centre take less time, stars further away take more.

This swirling motion, in which the inner parts rotate faster than the outer parts, is called *differential rotation*.



Wheel-like rotation

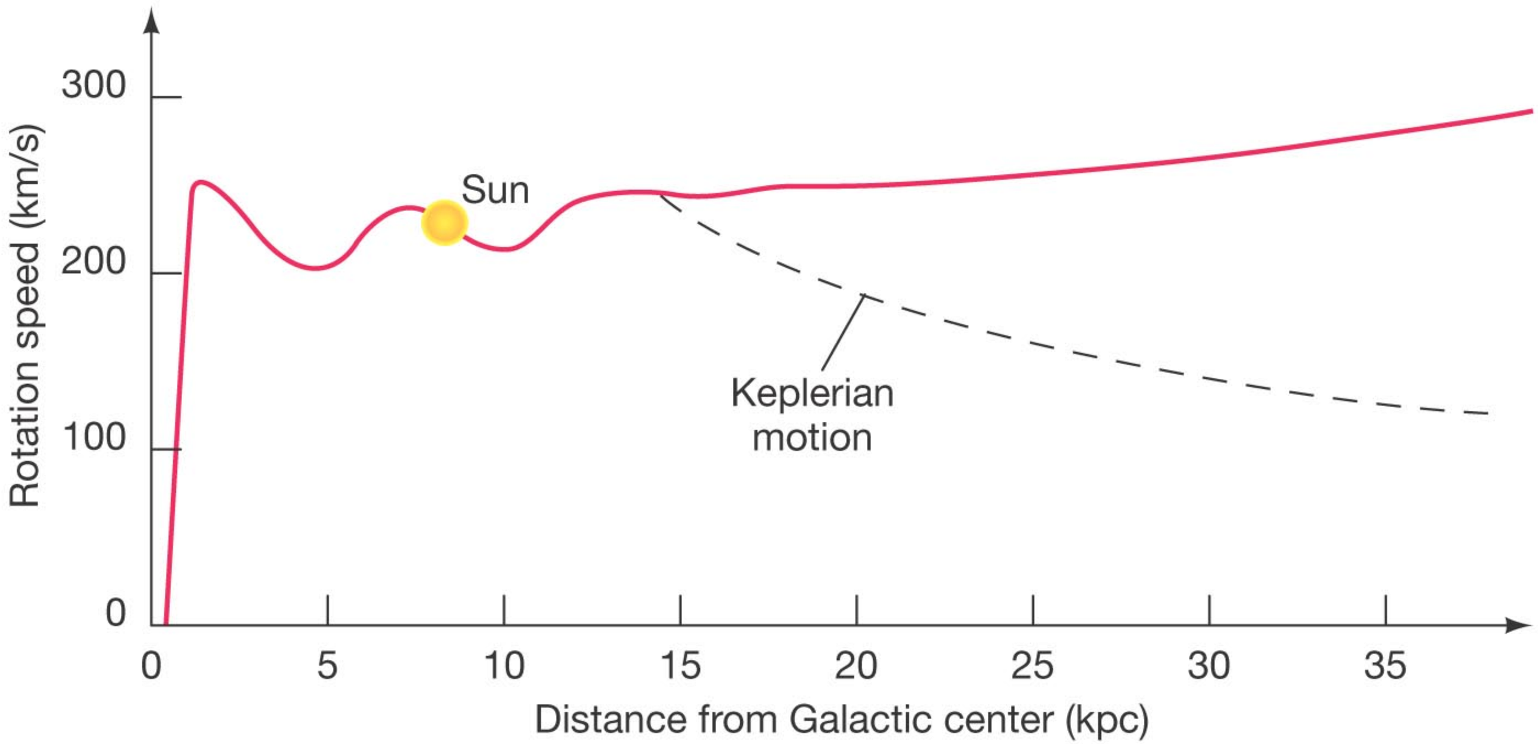
Rotation curve for wheel-like rotation



Planet-like rotation

Rotation curve for planet-like rotation

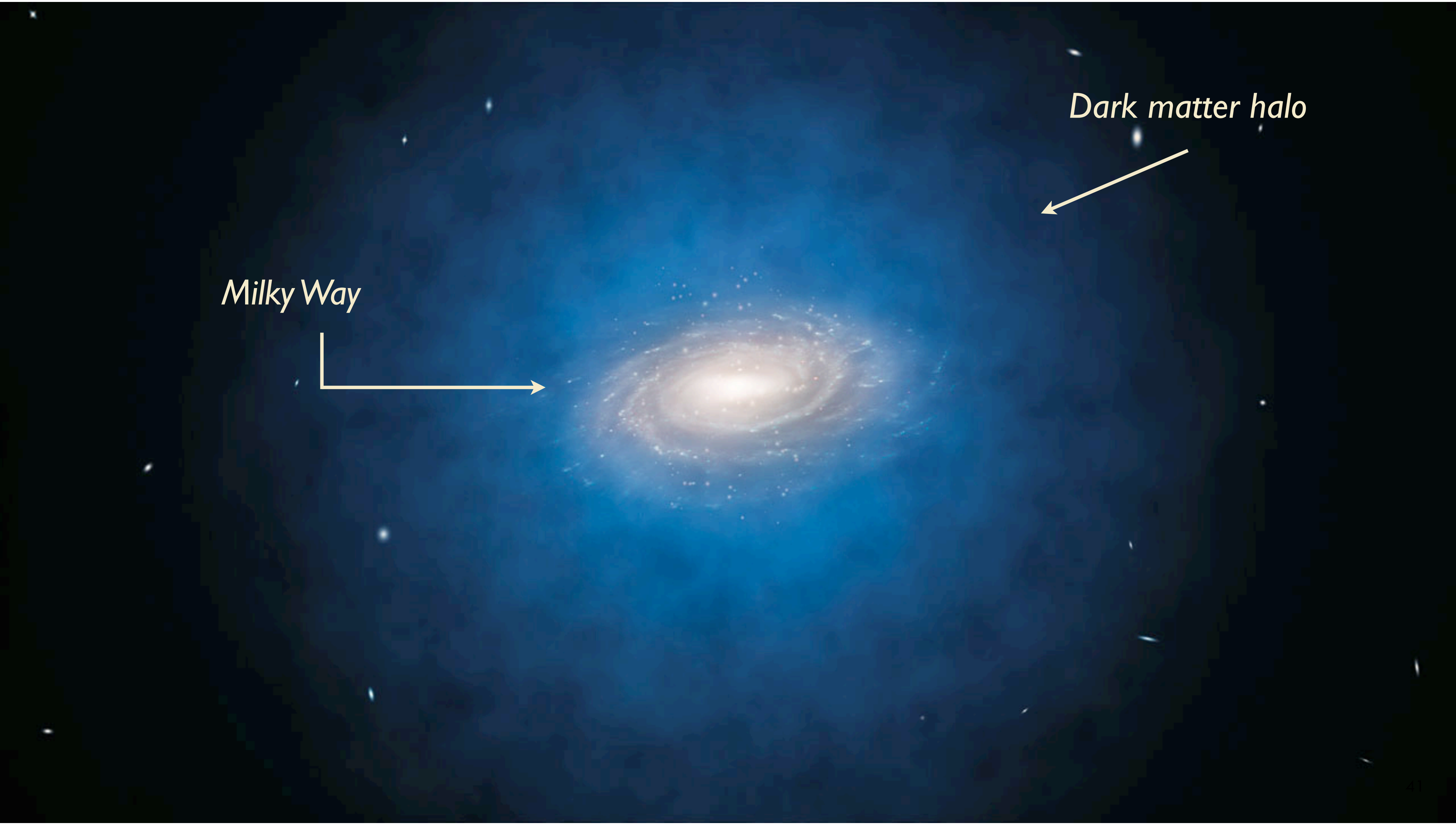
By measuring the velocities of stars at different distances from the Galactic centre, we can derive the mass profile of the Galaxy. Instead of falling off, the rotation curve *increases* with distance from the centre. This means that the mass of the Galaxy increases with increasing distance from the center.



This means that the mass of the Galaxy is several times greater than the sum of the masses of the visible stars and interstellar gas!

We don't know what this matter is. We only know it is there because we can see the effects of its gravity on the orbits of the stars and gas.

We call this the *dark matter problem*, which states that the halo of our Galaxy is filled with a mysterious dark matter of unknown composition and type.


Dark matter halo
Milky Way

What is the dark matter made of?

The two best guesses are:

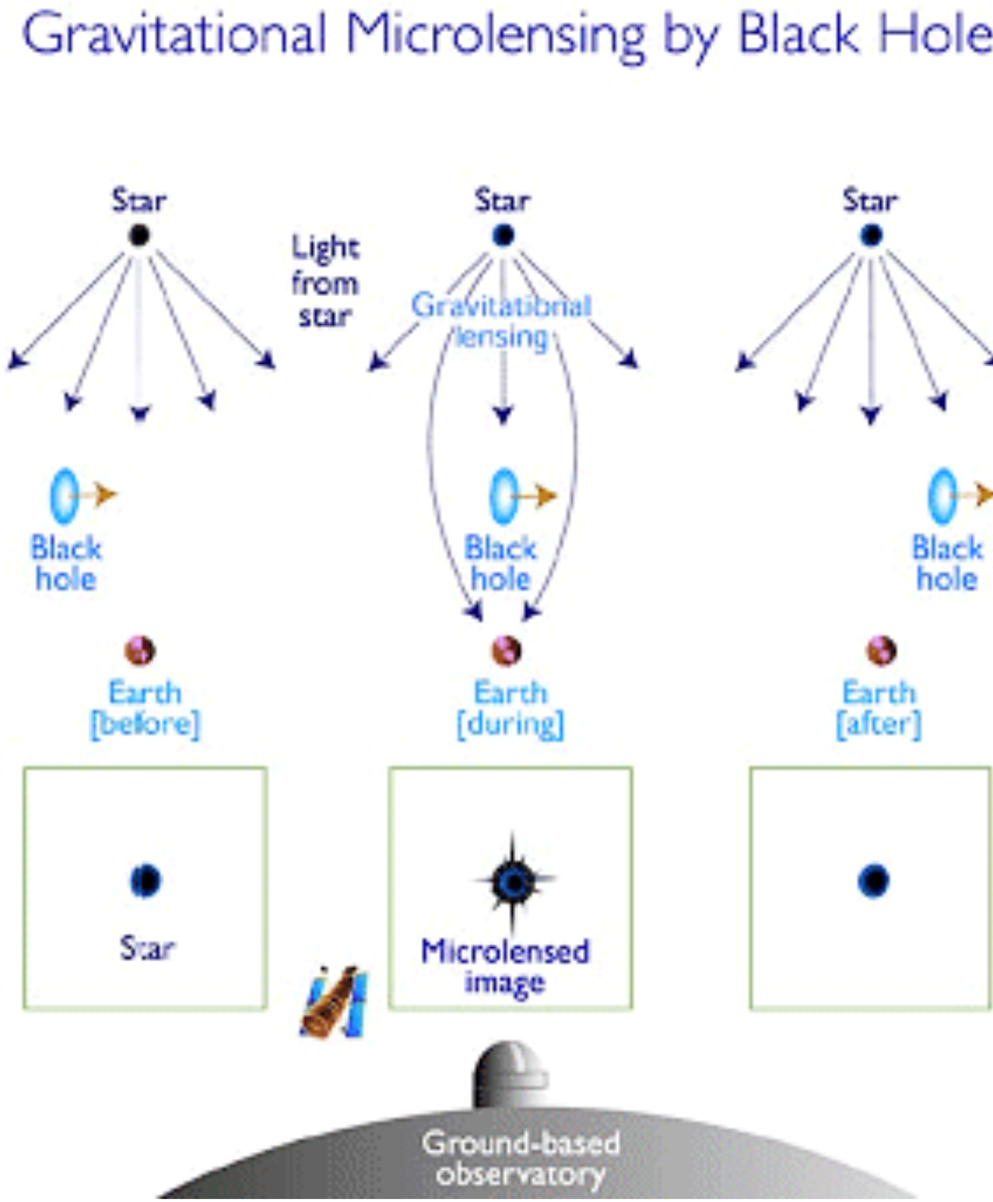
- “invisible” objects like brown dwarfs, planets or black holes, made of ordinary matter – MAssive Compact Halo Objects (MACHOs)

- some kind of exotic matter, like neutrinos, or some undiscovered subatomic particle – Weakly Interacting Massive Particles (WIMPs)

Astronomers have looked for MACHOs in several ways:

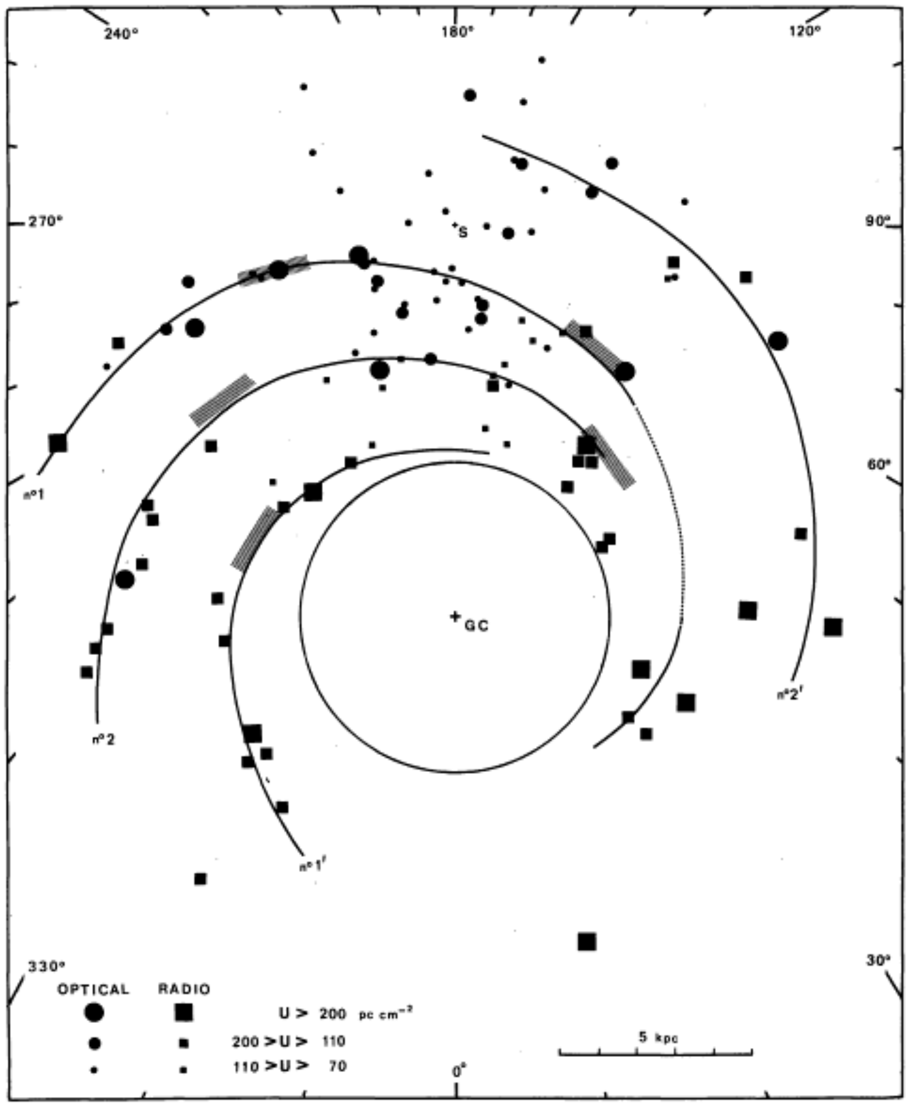
- looking for *microlensing* events, when the light from a star in the bulge is briefly magnified by a MACHO passing in front of it
- taking a census of faint stars using Hubble

MACHOs have been ruled as contributing to more than a tiny fraction of the dark matter in the Galaxy.



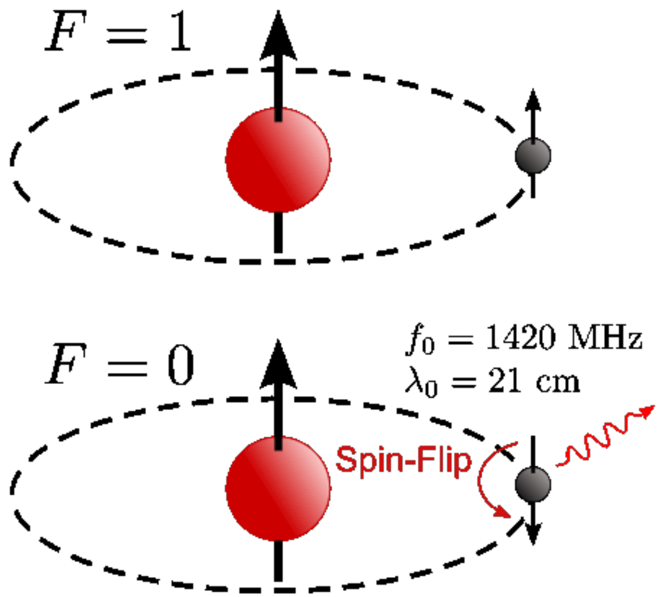
Spiral arms

– How do we find the shape of the Galaxy from inside it?
– We can try looking at the positions of *tracers*, such as young star clusters.

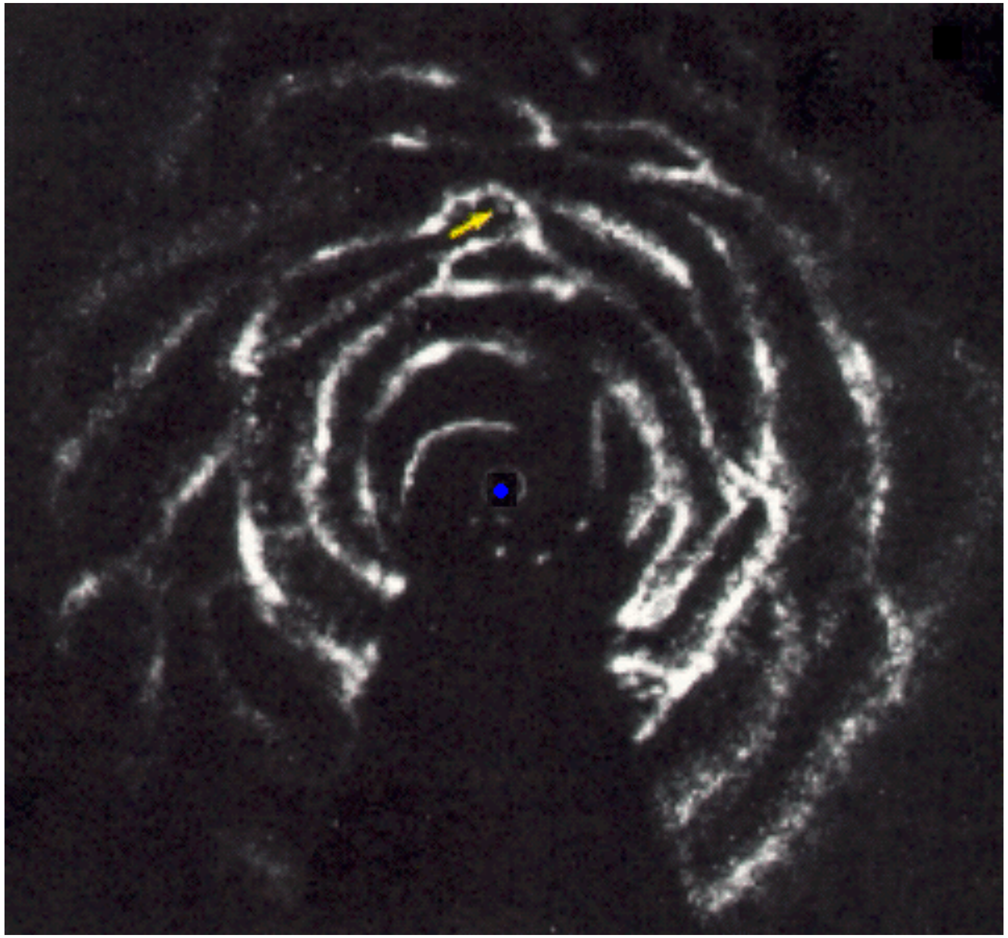


Spiral pattern of our Galaxy derived from H II nebulae around young stars

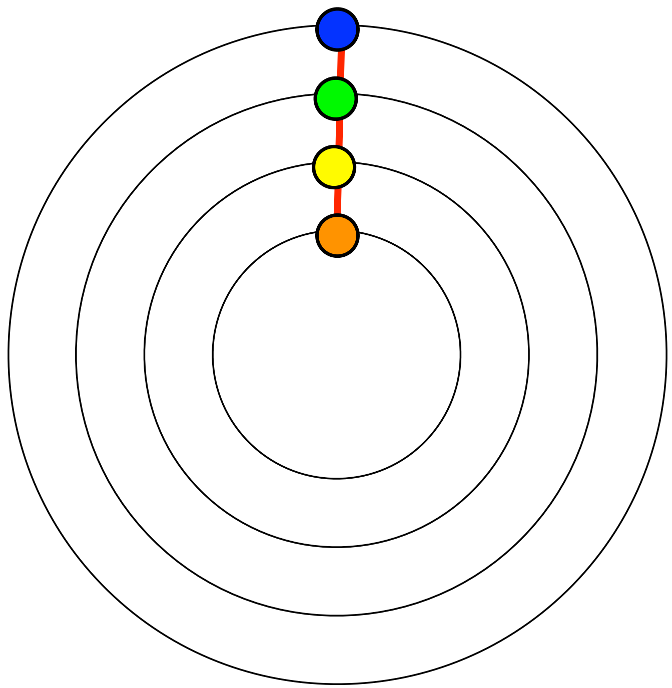
An even better way is to use radio telescopes to trace where the hydrogen gas is. Hydrogen gas emits a photon with a wavelength of 21 cm (frequency 1420 MHz) when the spin of the electron flips over.   This radiation can be seen at great distances, as radio waves are not absorbed by dust.



Maps of neutral hydrogen show the global spiral pattern throughout the Galaxy.



It is actually surprising that we see a spiral pattern, since the Galaxy does not rotate as a solid body. After only a few rotations, the spiral pattern would be wound up very tightly: the spiral pattern would not survive more than a revolution or two.



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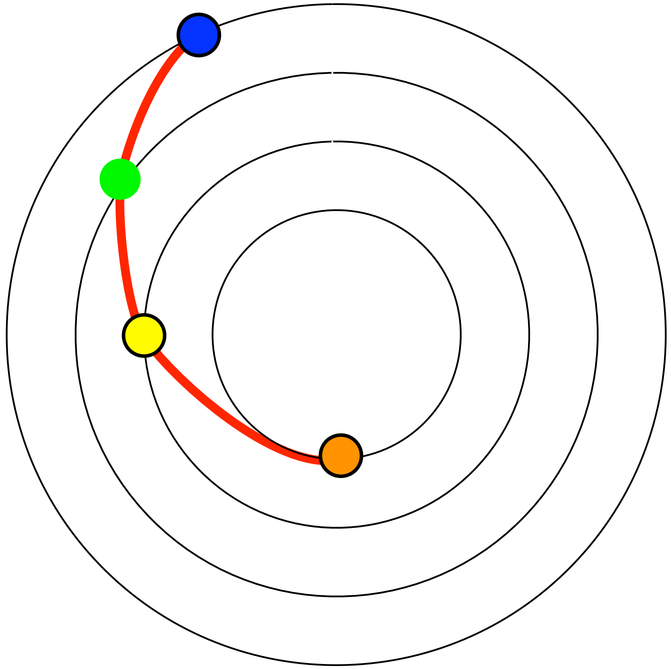

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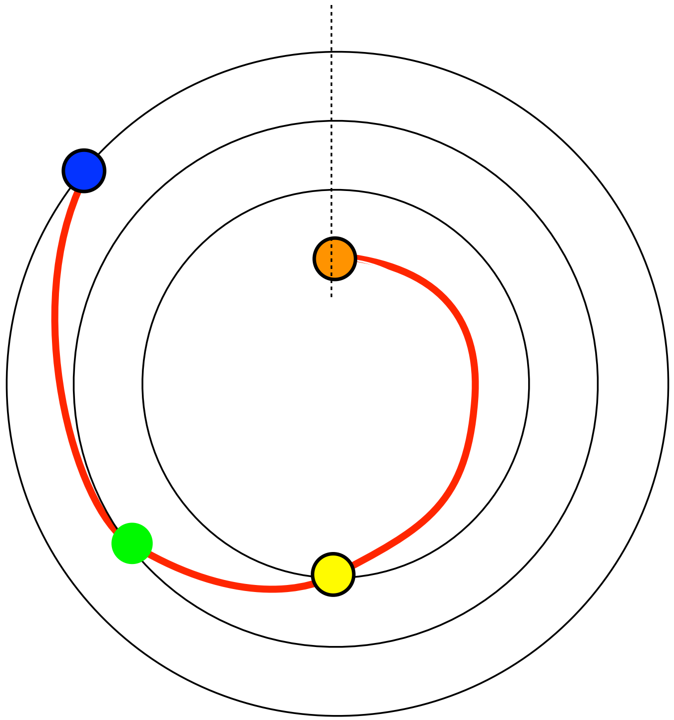

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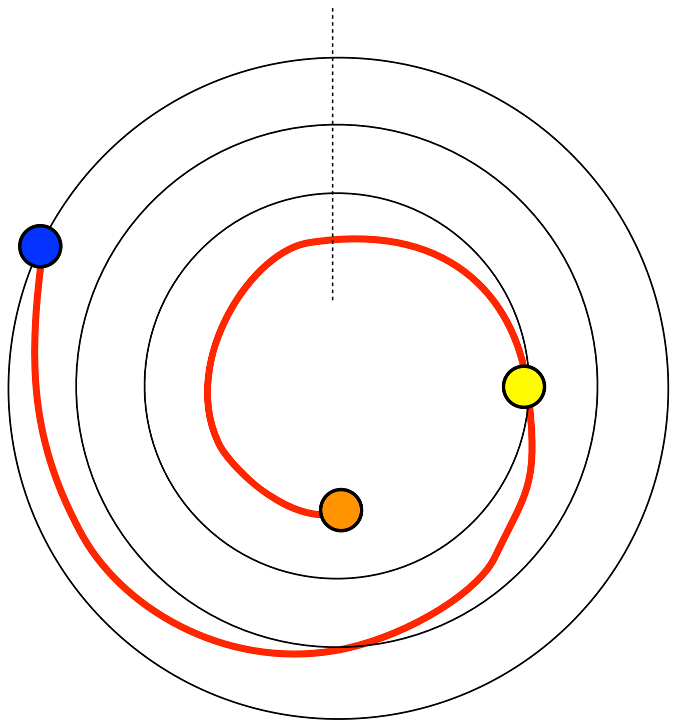
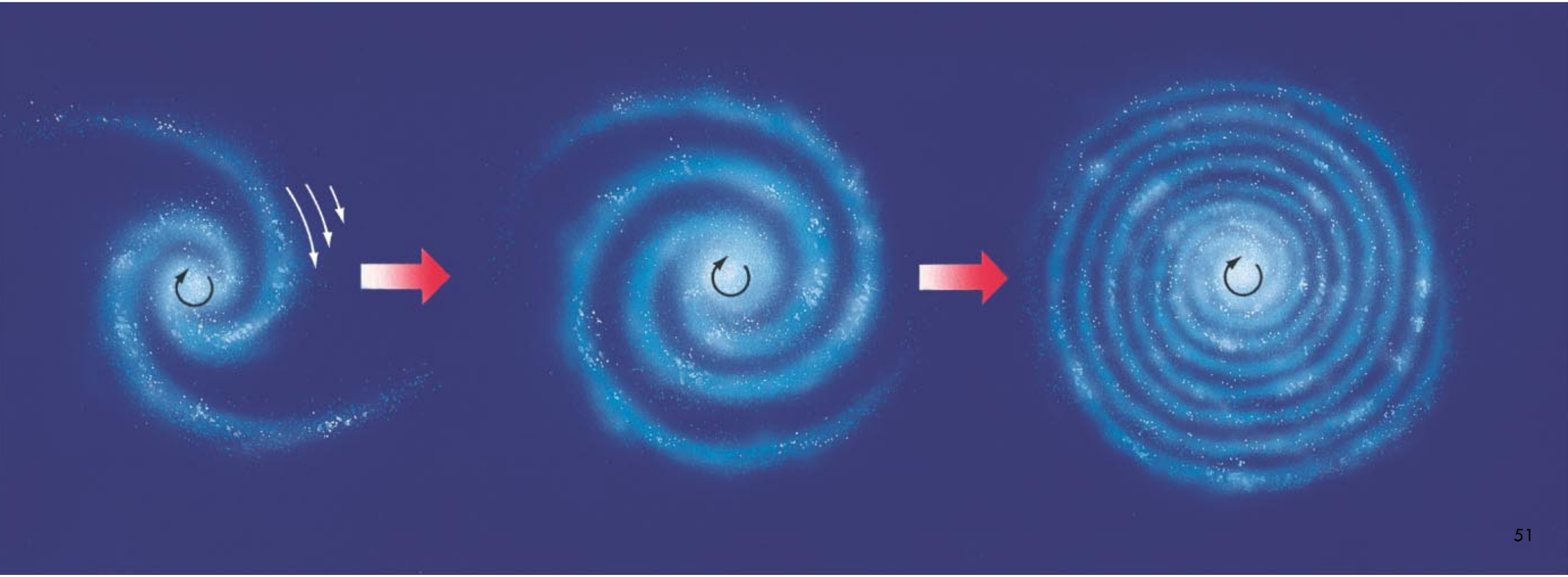


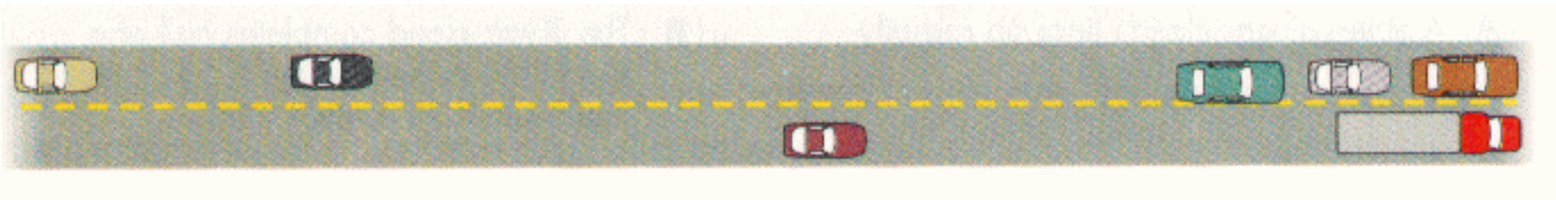
The Sun has been around the Galaxy about 20 times since its birth; if the arms had been around this many times, they would have wound up.

This is known as the *wrapping problem*.



So how does the spiral pattern survive? In fact, the spiral arms are a *pattern* which moves through the stars (or the stars move through the pattern) like a wave through water.

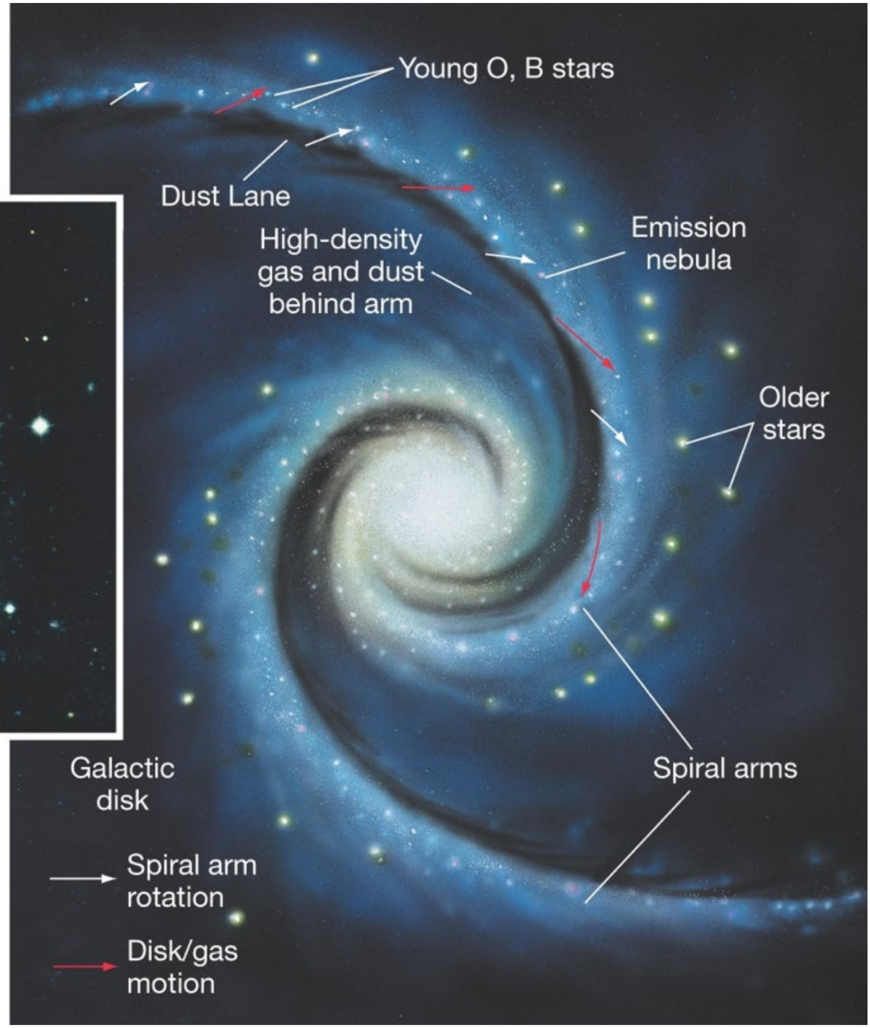
As an example, consider the knot of cars near a slow-moving truck: the knot is always present, and is moving, but at a different speed to the cars themselves.

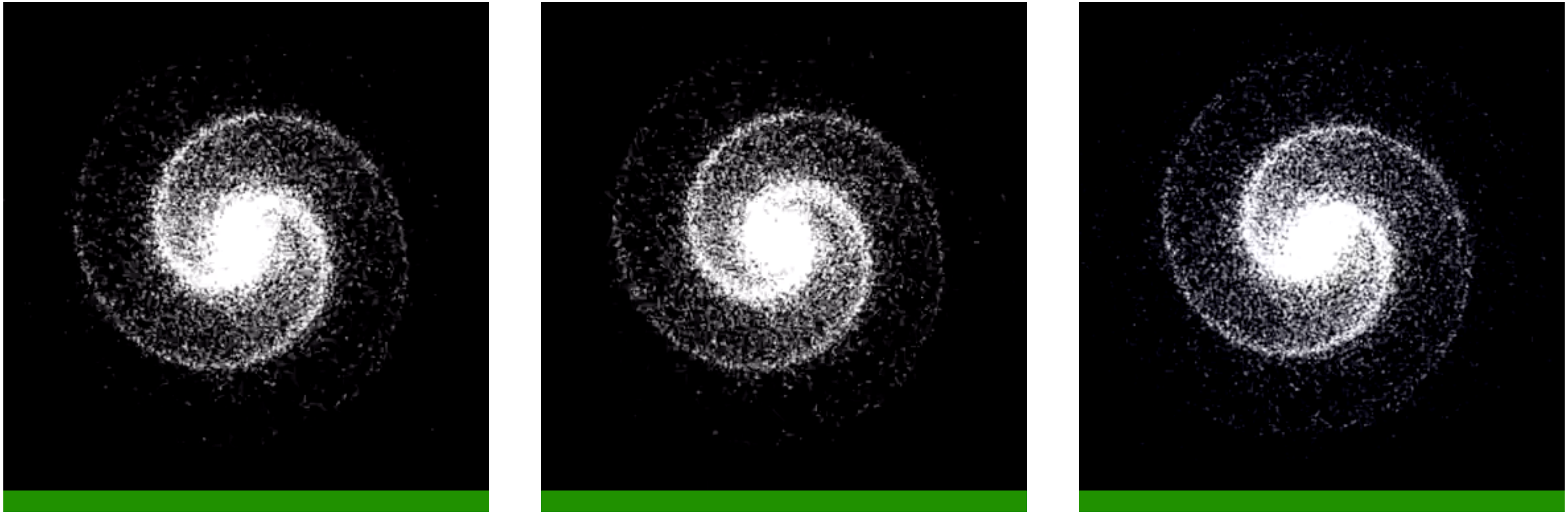


So the spiral arms are regions of greater density: a *density wave*.

Young stars occur in spiral arms because the density wave compresses the gas, which triggers star formation. As the young stars age, they drift out of the spiral pattern.

The pattern rotates, but at a completely different speed to the speed at which the stars rotate.





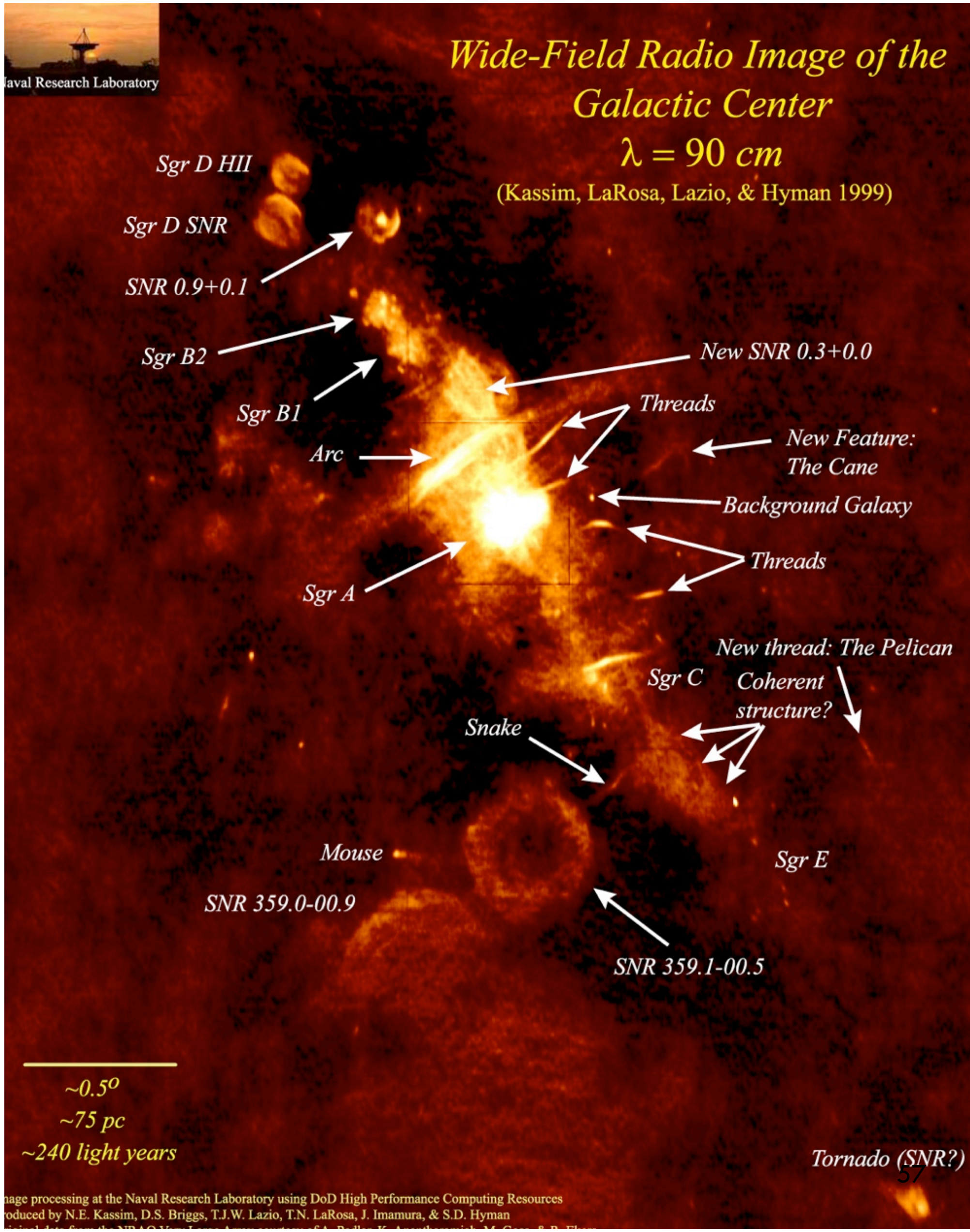
How a galaxy would rotate if it were (a) solid body rotation, (b) differential rotation, and (c) orbits predicted by density wave theory.

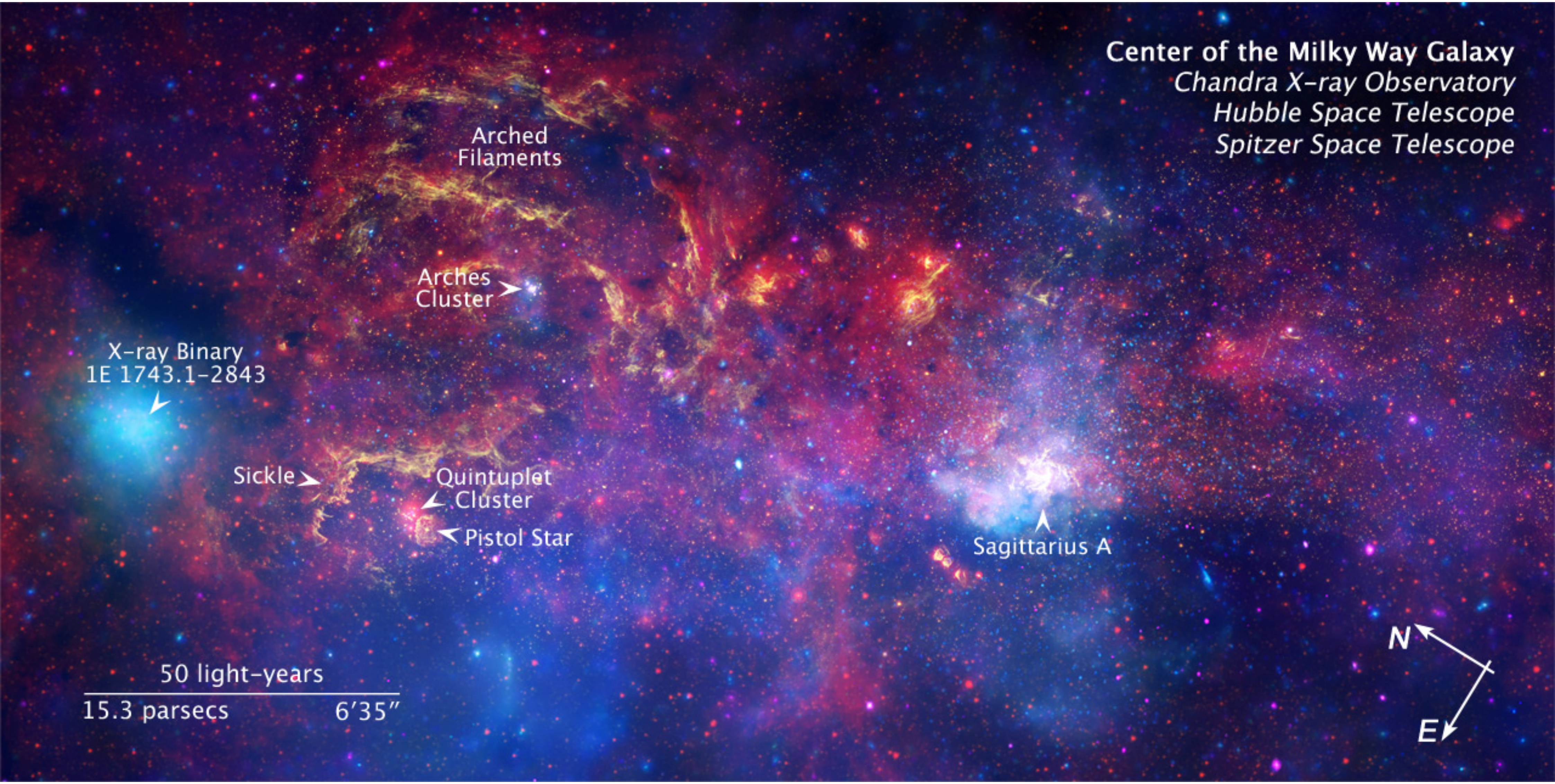
In some cases, the spiral pattern may be caused by gravitational interaction with a companion galaxy.

Spiral pattern galaxy M51 and its companion

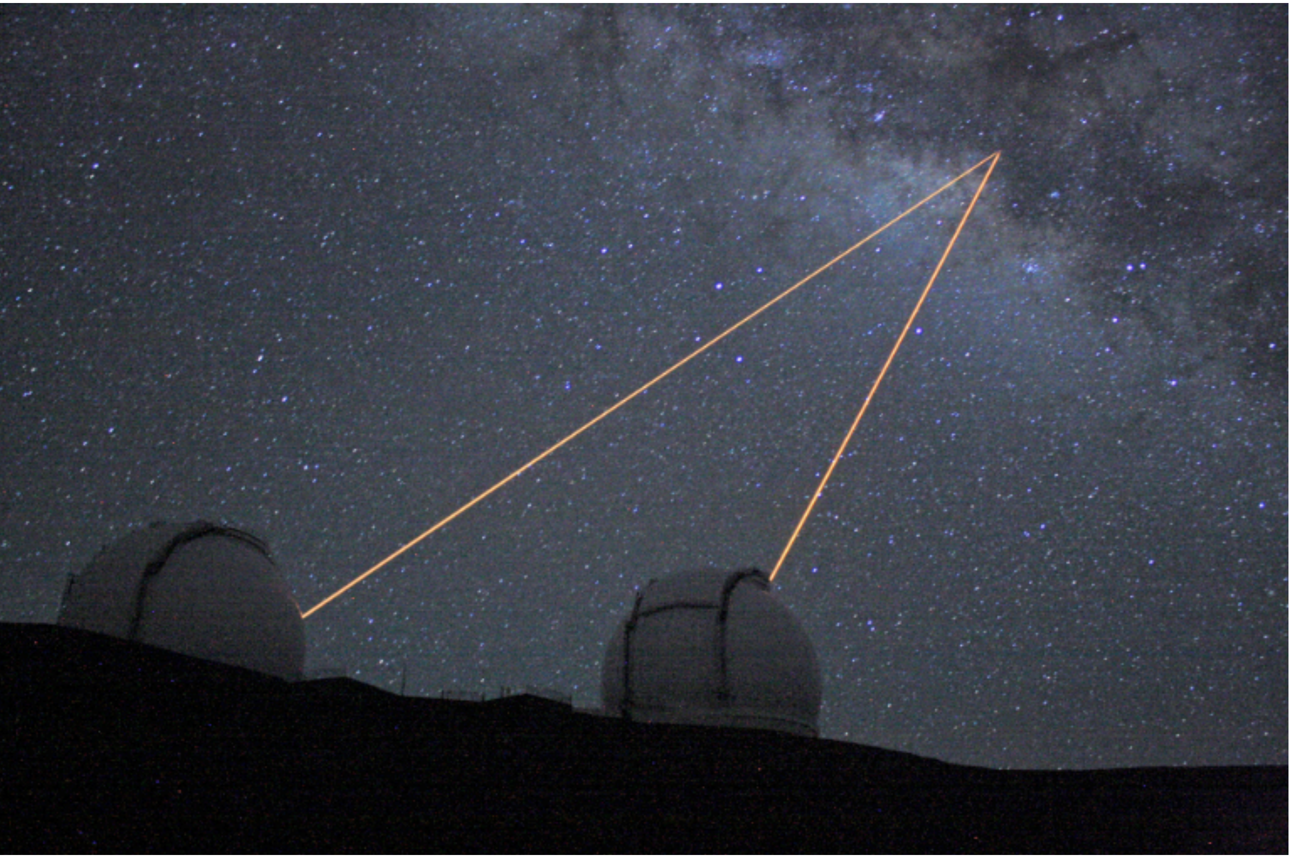
The *centre* of the Galaxy is obscured from us by thick interstellar clouds of gas and dust.

Radio images, however, show a very different and mysterious picture. There are supernova remnants, strange arcs and threads of plasma, plus a very bright source right at the centre of the Milky Way.

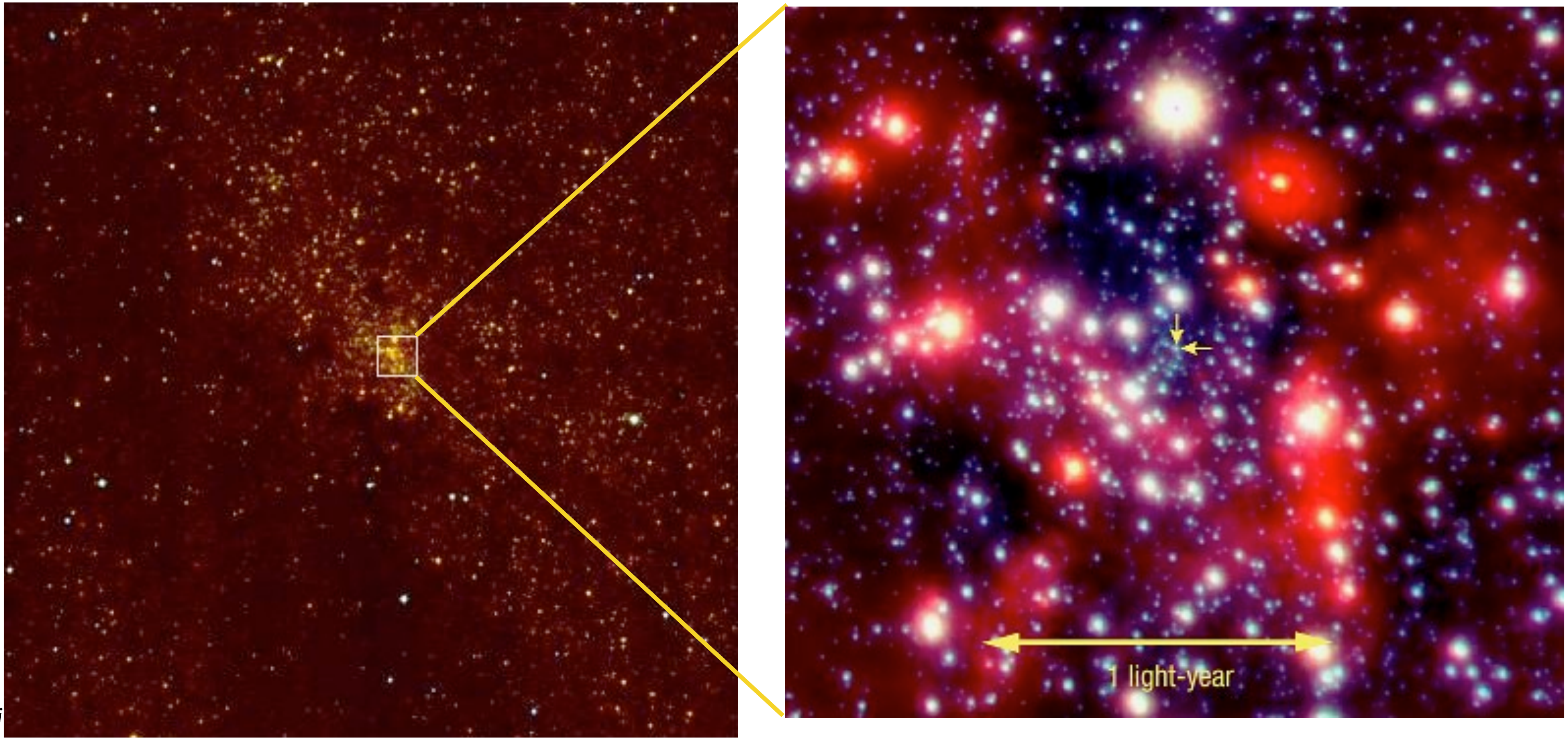


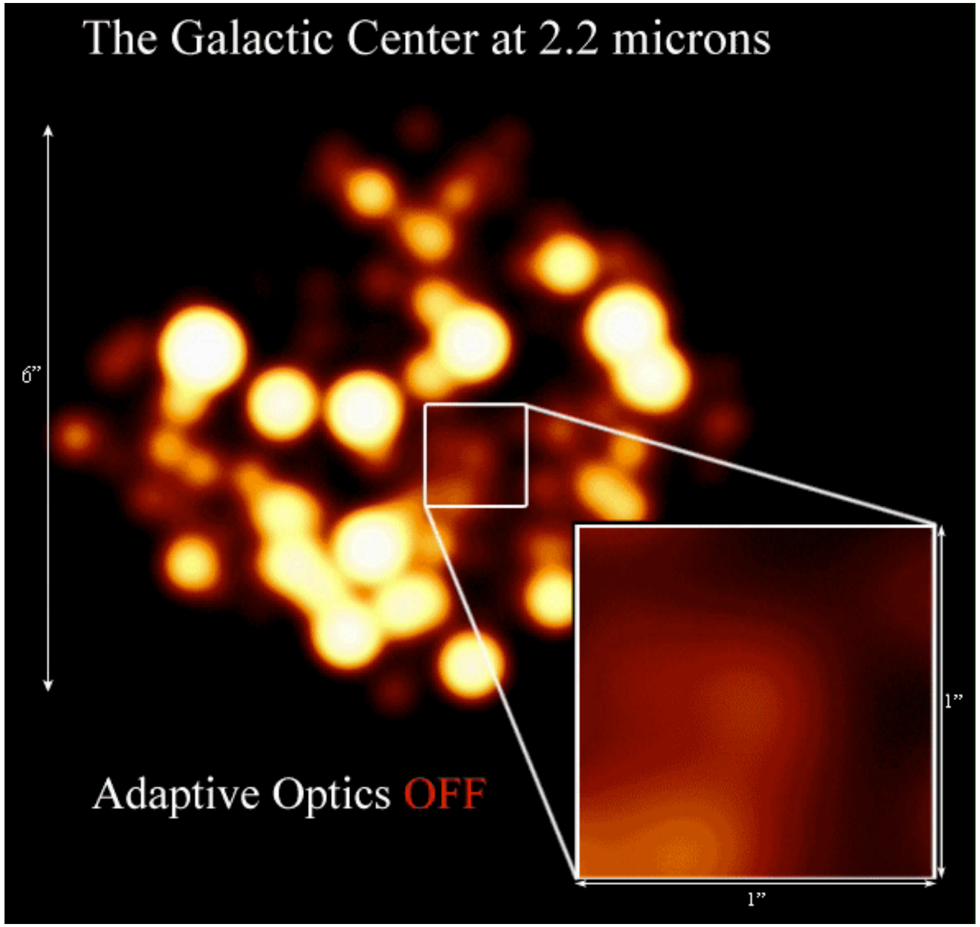

Center of the Milky Way Galaxy
Chandra X-ray Observatory
Hubble Space Telescope
Spitzer Space Telescope
Arched Filaments
Arches Cluster
X-ray Binary 1E 1743.1-2843
Sickle
Quintuplet Cluster
Pistol Star
Sagittarius A
50 light-years
15.3 parsecs
6′35″
N
E

Using laser beams to create artificial stars to correct for the distortion of the Earth's atmosphere, at the distance of the Galactic Center (~25,000 light years), the Keck telescope can separate two objects that are as close as about seven times the size of the solar system.

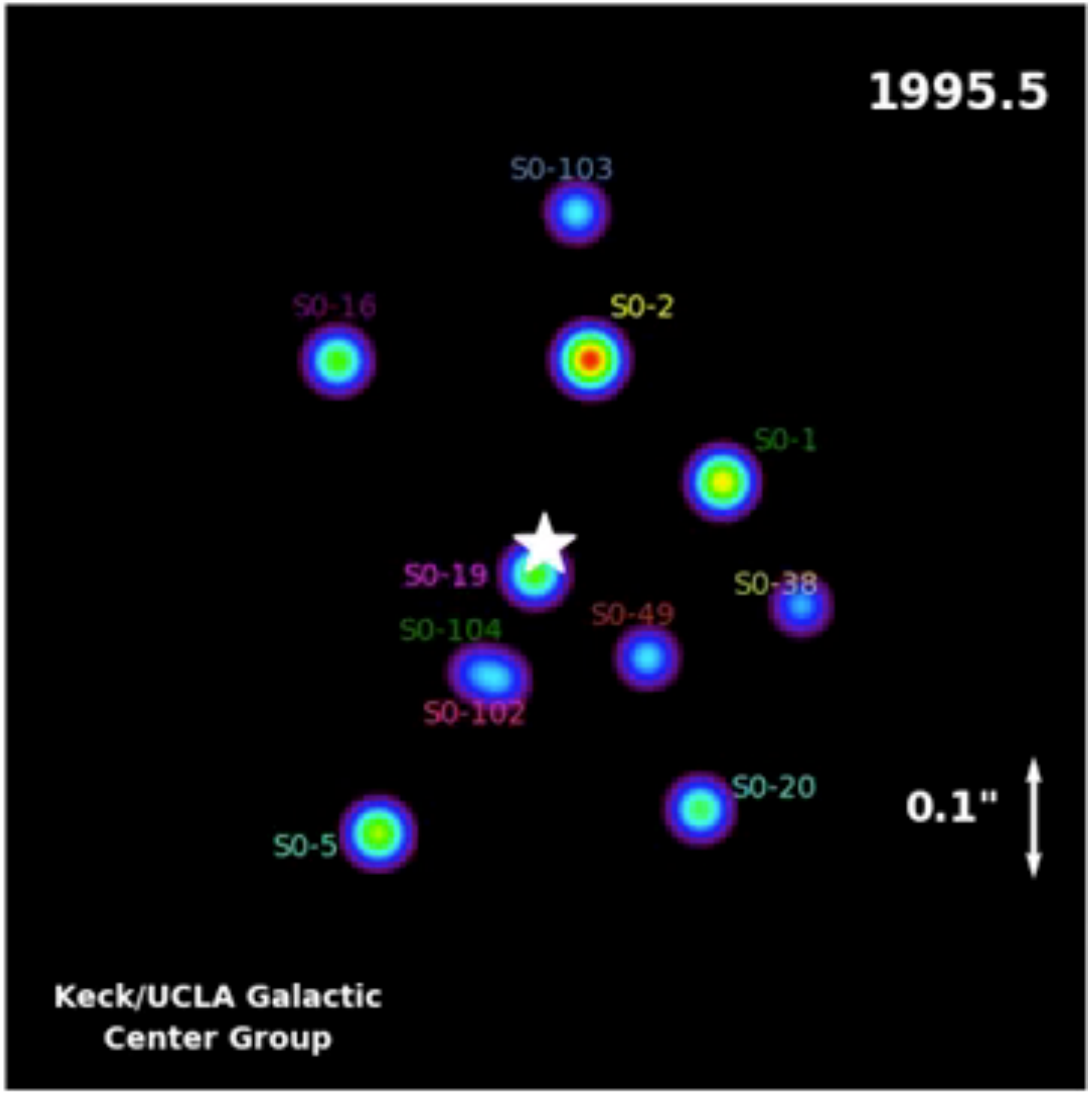


By watching the positions of stars using very precise infrared imaging techniques, astronomers have found compelling evidence that a black hole resides in Sgr A.

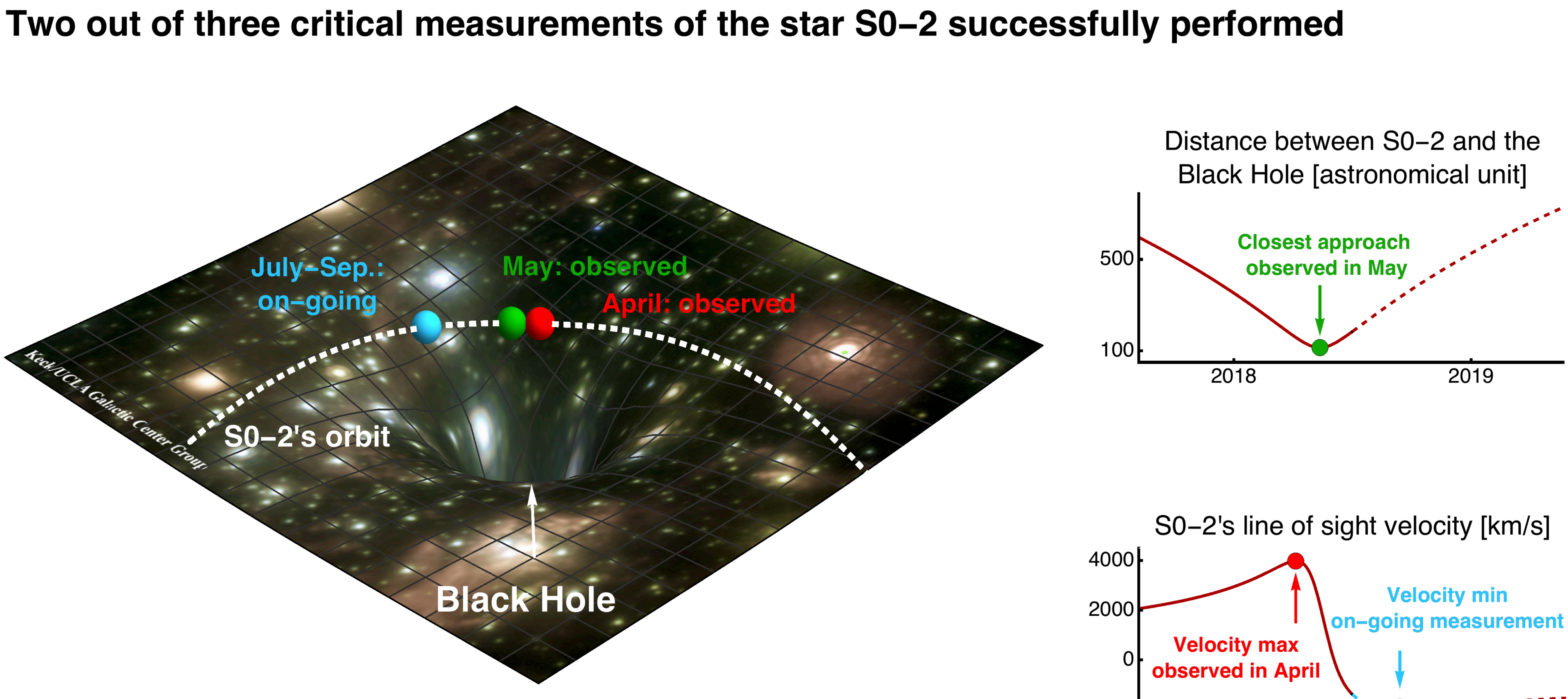



The Galactic Center at 2.2 microns
6"
1"
1"
Adaptive Optics OFF

The stars are moving in orbits indicating that they are orbiting a compact object weighing 2.6 million times the mass of the Sun.

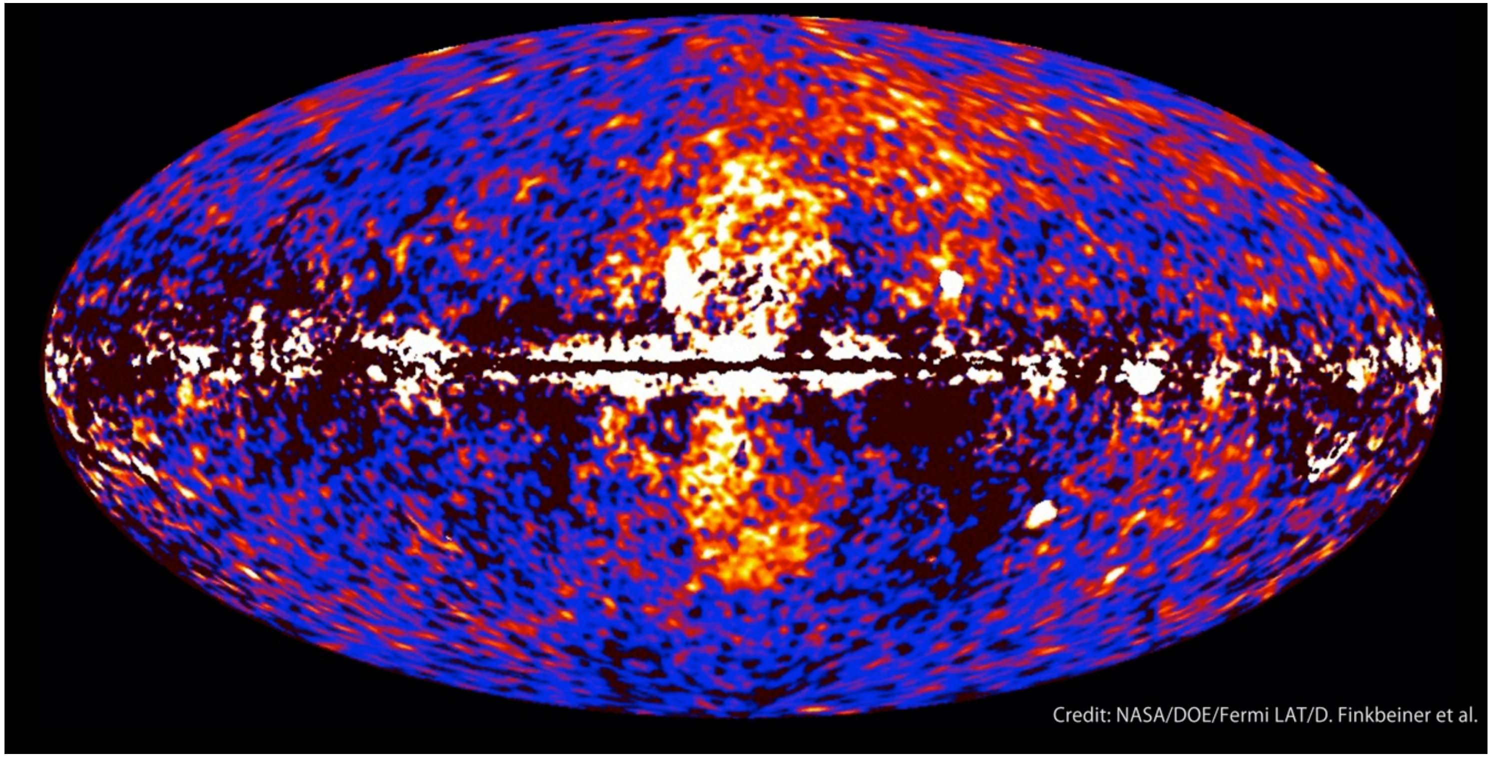


This (northern) summer, star S0-2 reached its closest approach to the black hole – within 100 AU, about 1000 times the event horizon – in May 2018.



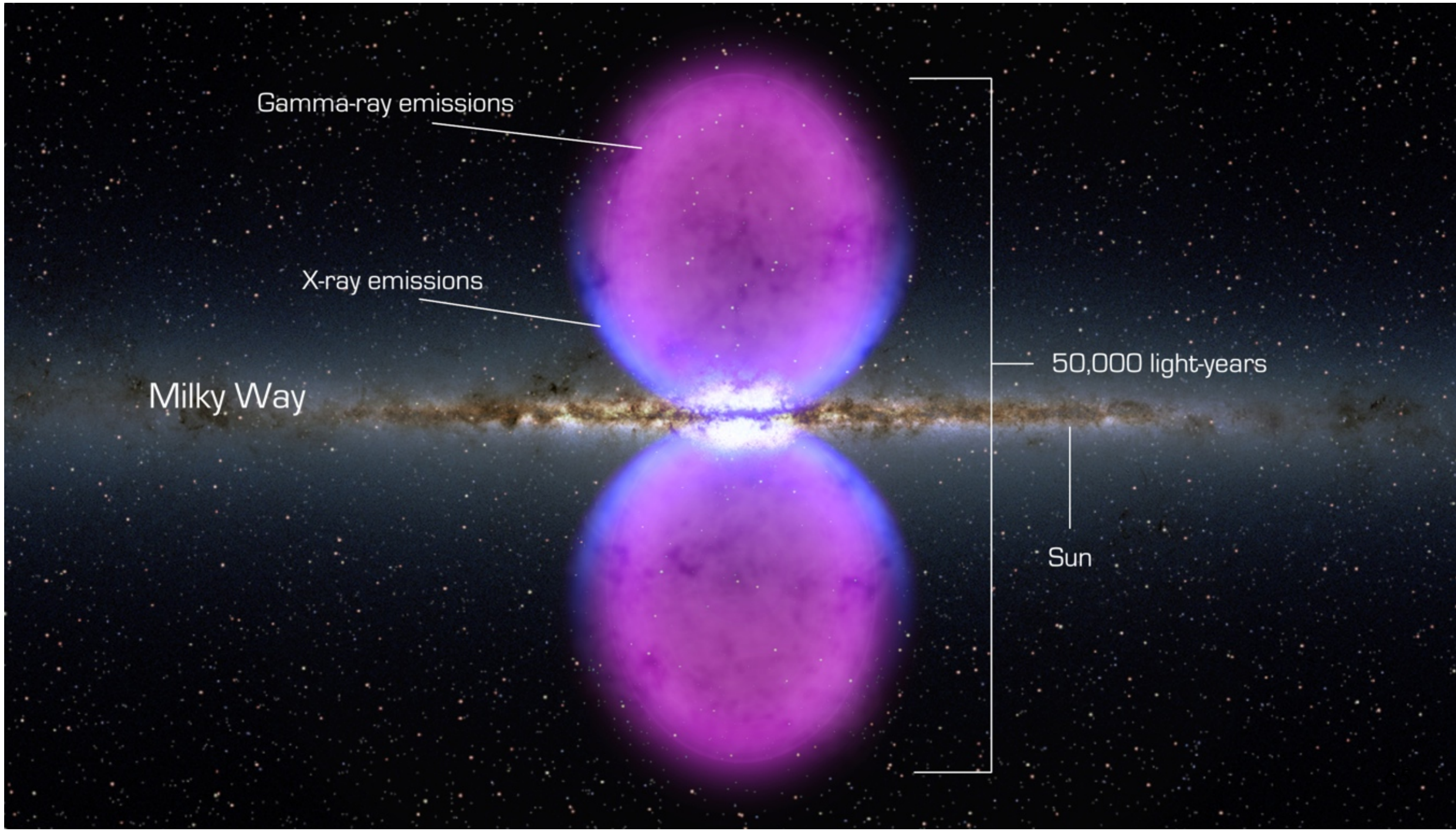
Keck/UCLA Galactic Center Group

The black hole appears to be fairly quiescent at the moment. However, a couple of years ago, the Fermi gamma-ray satellite discovered two giant gamma-ray bubbles extending above and below the Galactic plane.



Newly discovered gamma-ray bubbles extend 50,000 light-years, or roughly half of the Milky Way's diameter

These could be the result of recent activity of the central black hole, some time in the past few million years.



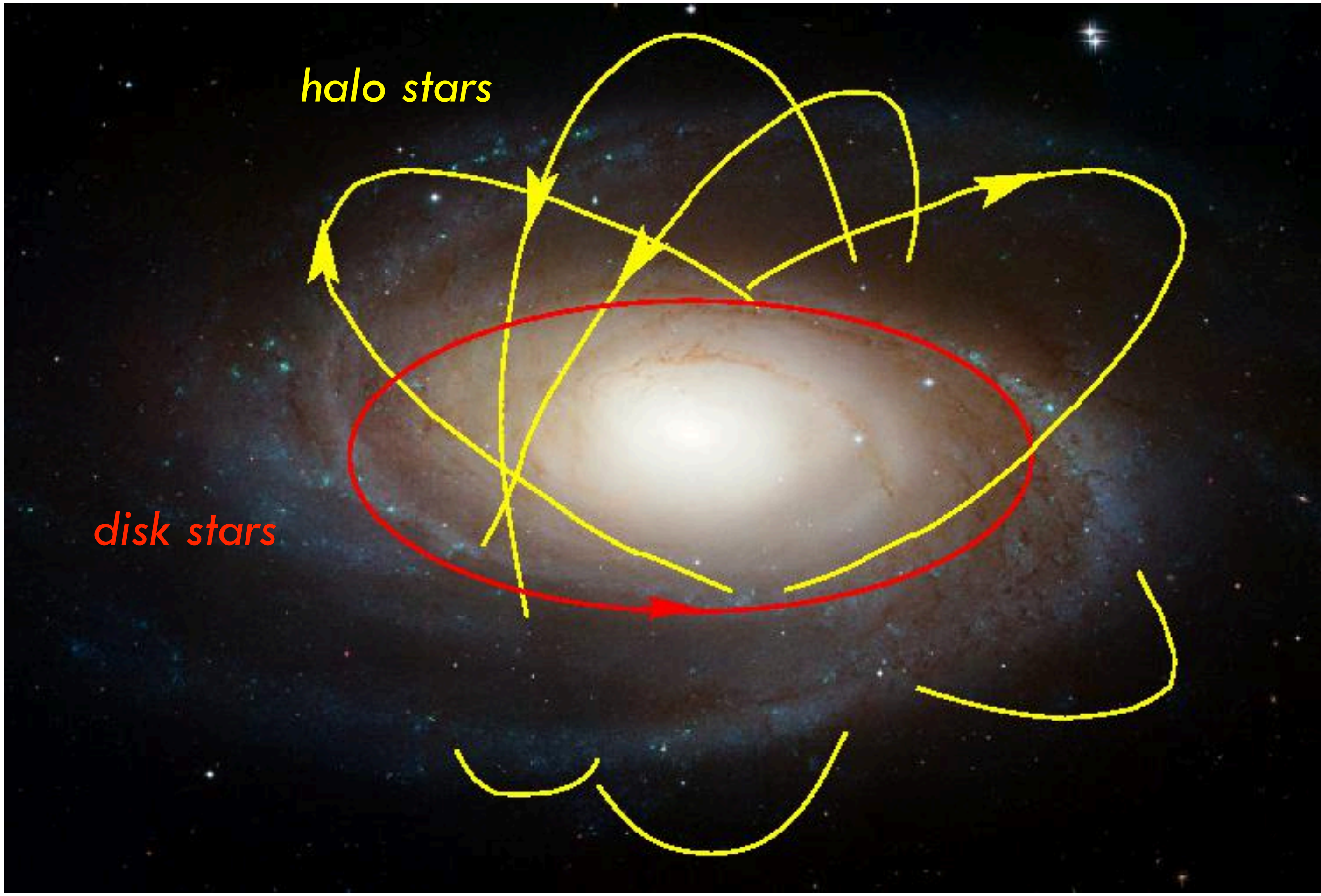
An artist's conception showing the approximate scale of the newfound Fermi bubbles above and below the Milky Way.

The Galaxy consists of two distinct star *populations* – a group of stars within the Galaxy that resemble each other in spatial distribution, chemical composition or age.

We can see the difference at a glance: Population I stars, in the disk, are hot bluish stars, while Population II stars, in the bulge, are much redder.

The spiral galaxy M81, similar to our own Milky Way

The two populations also have very different *motions* in the Galaxy. Disk stars all have circular, low velocity orbits; bulge and halo stars have random, high velocity orbits



Population I stars are associated with gas and dust in the disk and spiral arms. They include many hot, young stars.

Population II stars are distributed in the bulge and halo, and contain no stars younger than about 10 billion years.

Most interestingly, Population I (young disk) stars have relatively high (about 2%) abundance of heavy elements, while Population II (old bulge and halo) stars have much lower (<1%) abundance.

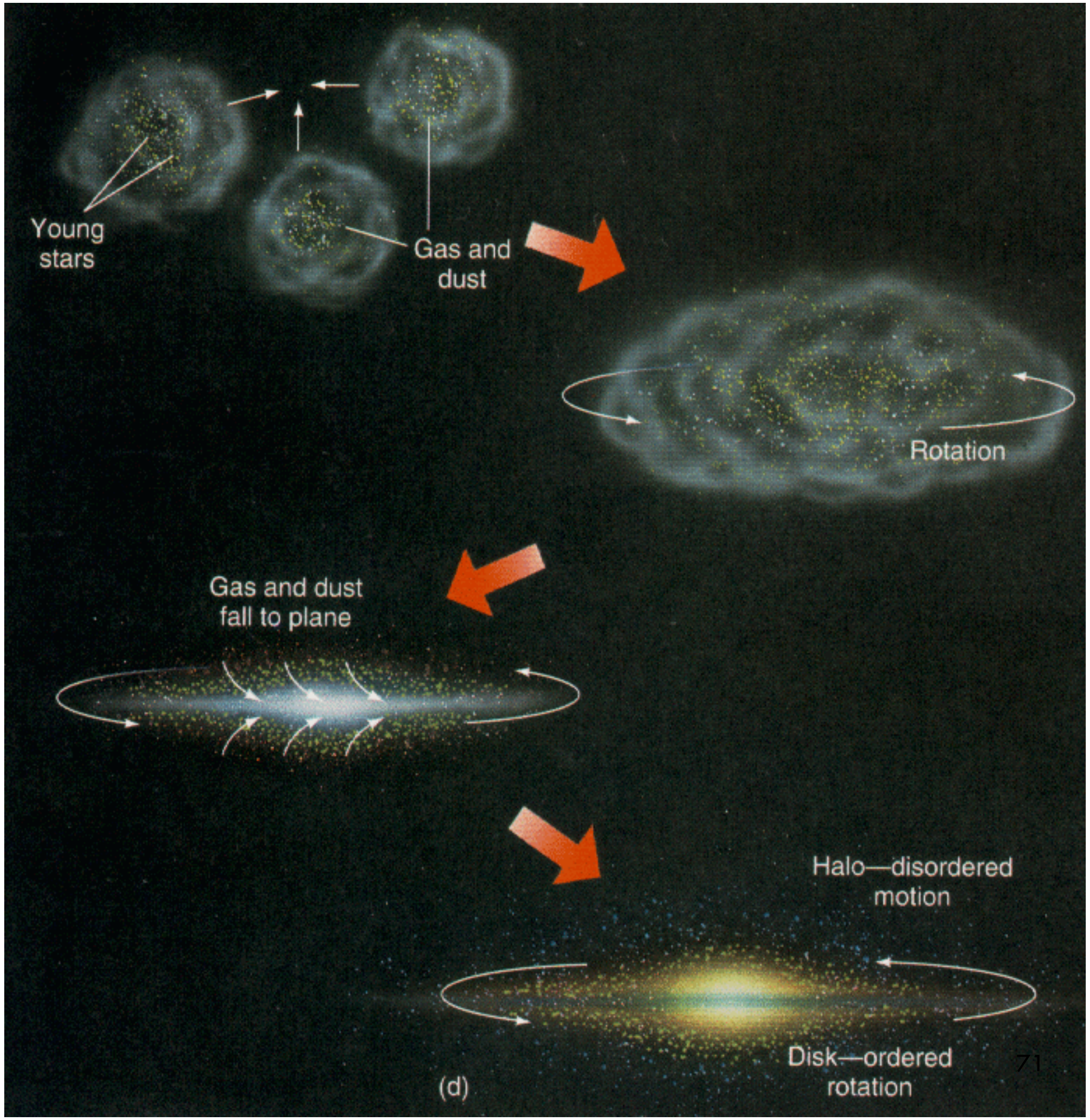
	Population I	Population II
Location	Disk and spiral arms	Bulge and halo
Star motions	Circular, low velocity	Random, high velocity
Ages of stars	Some < 100 million yrs	Only > 10 billion years
Brightest stars	Blue giants	Red giants
Supernovae	Core collapse	Thermonuclear (WD)
Star clusters	Open	Globular
Gas & dust?	Yes	No
Star formation?	Yes	No
Heavy elements	~2%	0.1–1%

The different star populations, and the different components of the galaxy, reflect the order in which the Galaxy formed.

In the first stage, a single gas cloud a few hundred thousand light years across began to swirl and collapse. Small spheres of gas (of about 1,000,000 solar masses) collapsed first: these became the globular clusters. These first clouds were very metal poor, but the first supernovae began to enrich the gas.

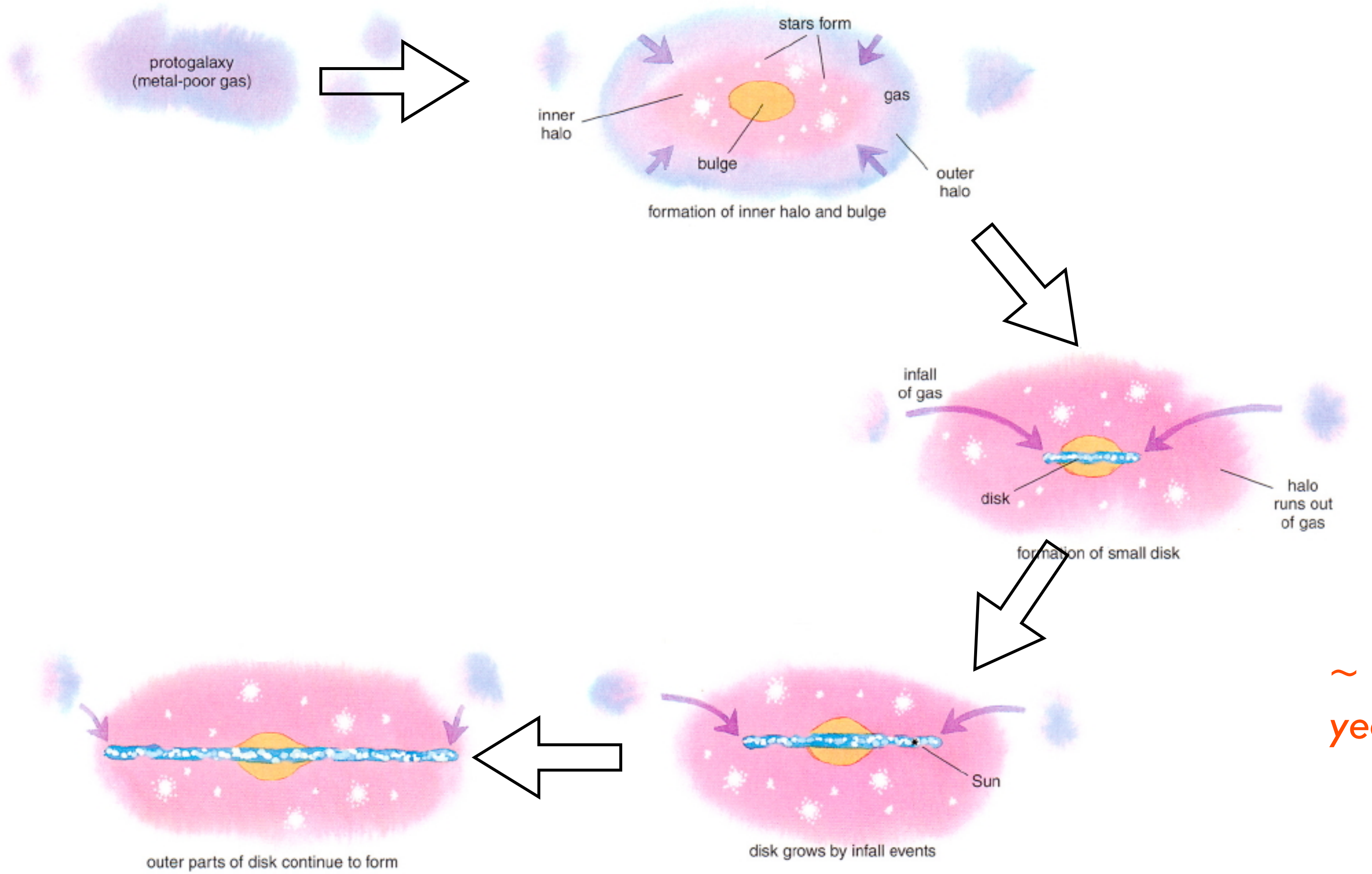
This first stage formed the halo and bulge.

Later, the remaining gas settles into the plane, and a disk begins to form. Small satellite galaxies fall in and accrete onto the edge of the disk.



Big Bang

~ one billion years



~ nine billion years

today

Next week

… we look other galaxies, and the way they live and evolve.

Further reading

- The story of how we found out the shape of the Galaxy is told in a lovely book, "**Minding the Heavens**: The Story of our Discovery of the Milky Way" by Leila Belkora (IoP, 2003).
- The website of the UCLA Galactic Centre group is at http://www.galacticcenter.astro.ucla.edu/. It contains lots of interesting pictures and animations about the great work they are doing.
- *Scientific American* had a cover story devoted to dark matter in November 2010: "**Dark Worlds**" by Jonathan Feng and Mark Trodden. It does a very good job of explaining the various candidates for dark matter and how experimenters are looking for them. There's a copy available at Jonathan Feng's website at http://www.ps.uci.edu/~jlf/research/press/dm_1011sciam.pdf

Sources for images used:

- NGC 6744: image by Don Goldman from APOD 2014 August 8, http://apod.nasa.gov/apod/ap140808.html
- Painting of galaxy: by Mark Garlick, from http://apod.nasa.gov/apod/ap050104.html
- Orion in gas, dust and stars: image by Rogelio Bernal Andreo (Deep Sky Colors), from APOD 2009 Sep 29 http://antwrp.gsfc.nasa.gov/apod/ap090929.html
- Mirkwood: painting by J. R. R. Tolkien, from http://once-upon-a-hobbit.blogspot.com.au/2009/11/mirkwood-forest-of-great-fear.html
- Milky Way over Monument Valley: image by Wally Pacholka, from http://apod.nasa.gov/apod/ap120801.html
- Milky Way above Easter Island: image by Manel Soria, from http://apod.nasa.gov/apod/ap120618.html
- Emu Dreaming, photo by Barnaby Norris, http://www.atnf.csiro.au/research/AboriginalAstronomy/Examples/emu.htm
- Thomas Wright's model for the Milky Way: from http://www.astro.virginia.edu/class/whittle/astr553/Topic01/t1_wright.html
- Herschel's telescope: from Wikipedia http://en.wikipedia.org/wiki/40-foot_telescope
- Herschel's model for the Milky Way: from http://hendrix2.uoregon.edu/~imamura/123/lecture-1/kapteyn.html
- The Galactic Centre annotated: image by William Keel, from http://apod.nasa.gov/apod/ap011229.html
- Trumpler's distances to the globular clusters: from "The interstellar medium: Dust" by Michael Richmond, http://spiff.rit.edu/classes/phys230/lectures/ism_dust/ism_dust.html
- Zimbabwe sunset: photo by Marray Alexander, from APOD http://apod.nasa.gov/apod/ap020621.html
- Barnard 68: from APOD http://apod.nasa.gov/apod/ap120129.html
- Structure of Milky Way: from http://lcogt.net/education/article/milky-way-galaxy
- NGC 5033: image by Adam Block, from APOD 2012 August 17 http://apod.nasa.gov/apod/ap120817.html
- NGC 1232: VLT picture, from http://www.eso.org/public/images/eso9845d/
- NGC 891: image by Bob Franke, from APOD 2010 February 25 http://apod.nasa.gov/apod/ap100225.html
- Overview of Galaxy: from A. Finkbeiner, "Galaxy formation: The new Milky Way", Nature 490 News Feature
- Rotation: from James Schombert, Astronomy 122 http://abyss.uoregon.edu/~js/ast122/lectures/lec25.html
- Dark matter around the Milky Way: from ESO press release 1217: http://www.eso.org/public/news/eso1217/
- Microlensing: from "Black Holes on the Loose" http://science.nasa.gov/science-news/science-at-nasa/2000/ast14jan_1/
- Spiral arms: from Georgelin & Georgelin 1976, "The spiral structure of our Galaxy determined from H II regions", http://adsabs.harvard.edu/1976A%26A....49...57G
- Hydrogen spin flip: from Wikimedia commons https://commons.wikimedia.org/wiki/File:Hydrogen-SpinFlip.svg
- Neutral hydrogen map: from http://abyss.uoregon.edu/~js/images/hi_spiral.gif
- Winding problem and trigerred star formation: from http://physics.uoregon.edu/~jimbrau/BraulmNew/Chap23/6th/23_17Figure-F.jpg
- Truck moving: from James Schombert, Astronomy 122: http://abyss.uoregon.edu/~js/ast122/lectures/lec26.html
- Galaxy rotation movies: from Wikipedia, Density wave theory https://en.wikipedia.org/wiki/Density_wave_theory
- M51: from Wikipedia http://en.wikipedia.org/wiki/Whirlpool_Galaxy

- Centre of the Milky Way: image by Serge Brunier, from APOD http://apod.nasa.gov/apod/ap051004.html
- Stars near the Galactic Centre: from the UCLA Galactic Centre Group http://www.astro.ucla.edu/~ghezgroup/gc/pictures/index.shtml
- Fermi bubble: from NASA, “NASA's Fermi Telescope Finds Giant Structure in our Galaxy” http://www.nasa.gov/mission_pages/GLAST/news/new-structure.html
- Spiral galaxy M81: from Hubblesite http://hubblesite.org/gallery/album/galaxy/pr2007019a/hires/true
- Galaxy formation: from James Schombert, Astronomy 122: http://abyss.uoregon.edu/~js/ast122/lectures/lec26.html
- Formation of the Milky Way: from “The formation and evolution of the Milky Way” by Cristina Chiappini, American Scientist, Nov/Dec 2001, pp. 506-515. Downloaded from http://www.astro.caltech.edu/~george/ay20/Chiappini-MilkyWay.pdf
- M31: image by Robert Gendler, from APOD 2015 August 30 http://apod.nasa.gov/apod/ap150830.html