Modern Astronomy:
An Introduction to Astronomy

Presented by
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School of Physics

Spring 2018

THE UNIVERSITY OF SYDNEY

This course is an introduction to modern astronomy, showing what we know about our place in the Universe and how we know it.

1. The Universe: a guided tour
2. The Sun and planets
3. The birth of stars
4. The evolution of stars
5. Stellar graveyards: white dwarfs, neutron stars and black holes
6. Miscellany: Binaries, clusters and variables
7. Our galaxy: putting the pieces together
8. Galaxies: normal galaxies to quasars
9. Cosmology: the universe as a whole
10. Modern astronomy: exoplanets, the "new astronomies", dark energy...

There is a course web site, at

http://physics.usyd.edu.au/~helenj/IntroductiontoAstronomy.html

where I will put

- PDF copies of the lectures as I give them
- lecture recordings
- copies of animations
- links to useful sites

Please let me know of any problems!

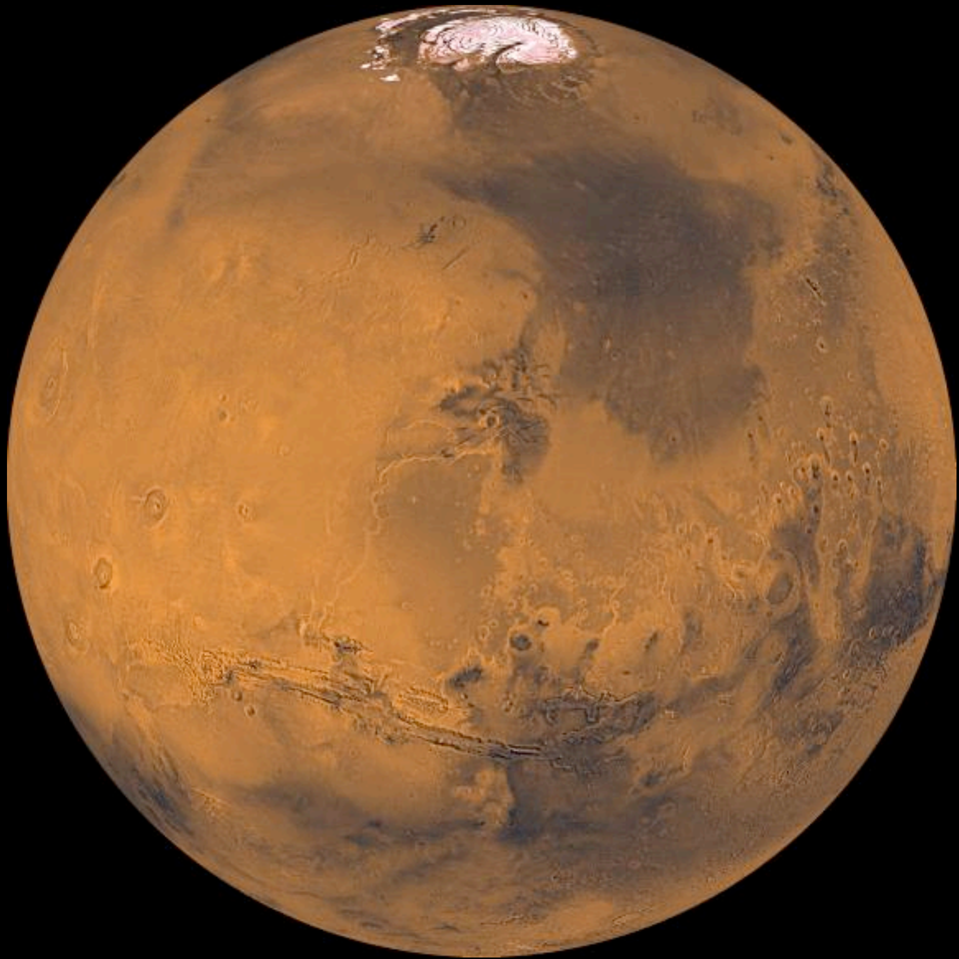
Lecture 1:
The Universe: a guided tour

In tonight's lecture

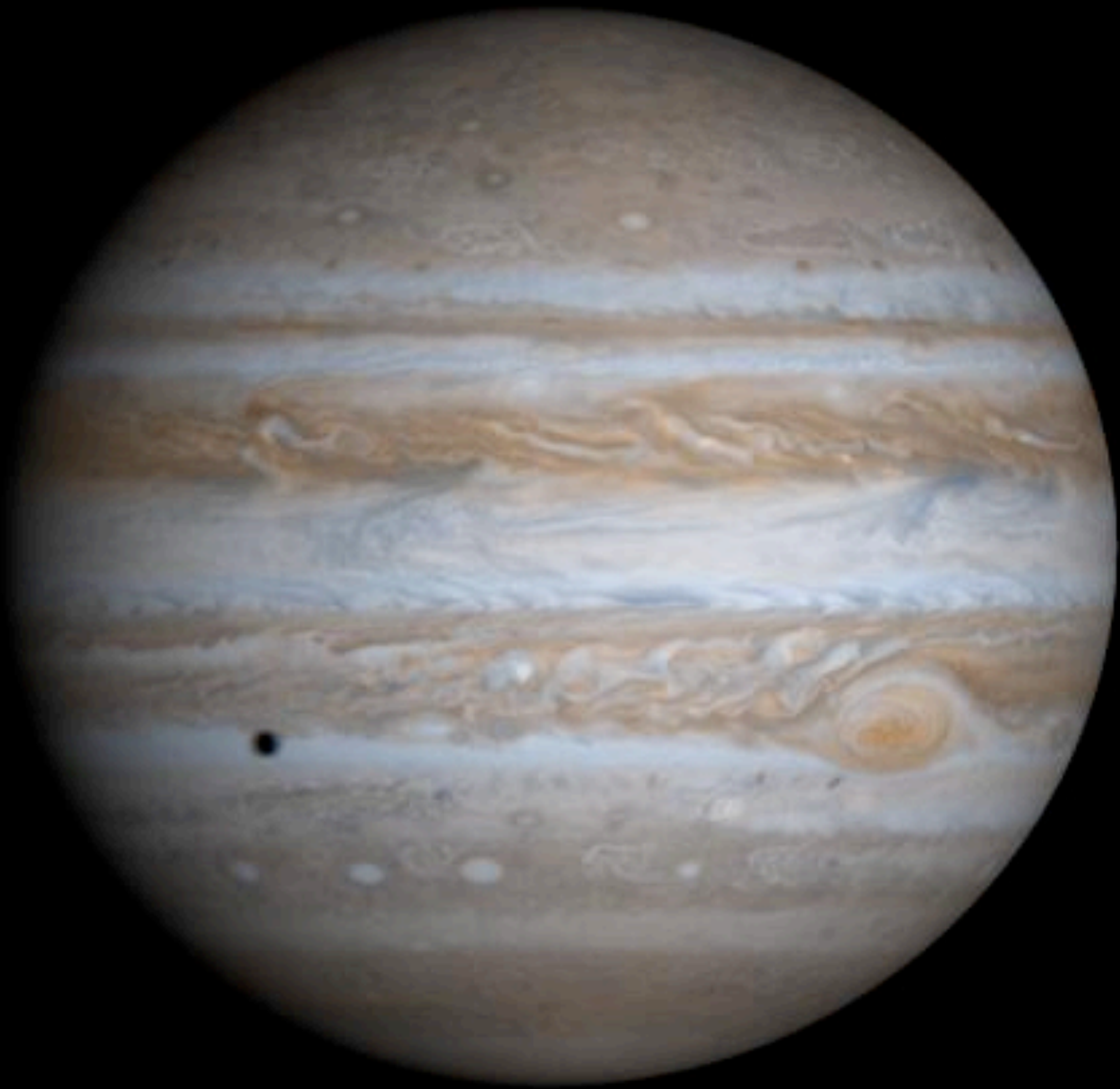
- A quick tour
  – *set the scene of where we are*
- The scales of astronomy
  – *just how big is the universe?*
- Electromagnetic radiation
  – *how do we find out about the universe?*

A quick tour

We are on a small planet...



... orbiting with ~~eight~~ seven other planets...



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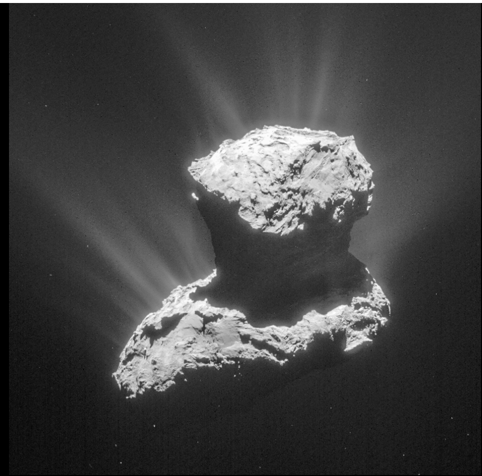
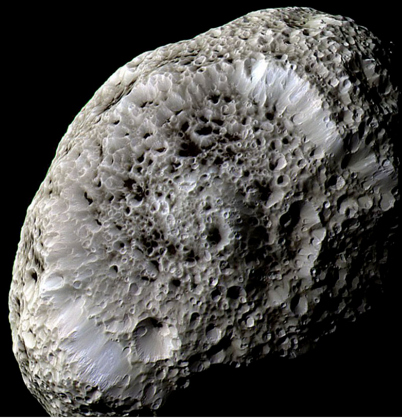
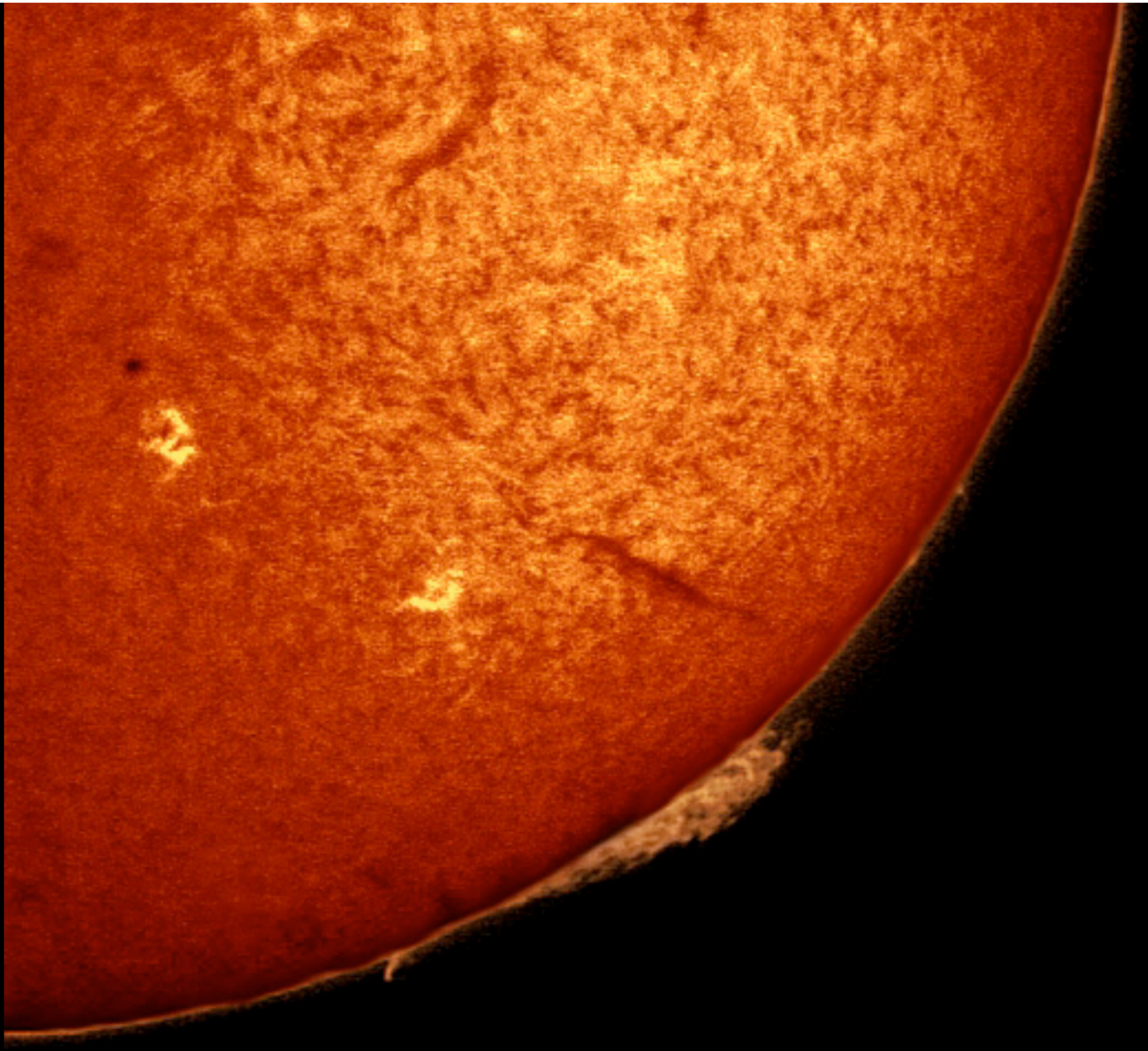
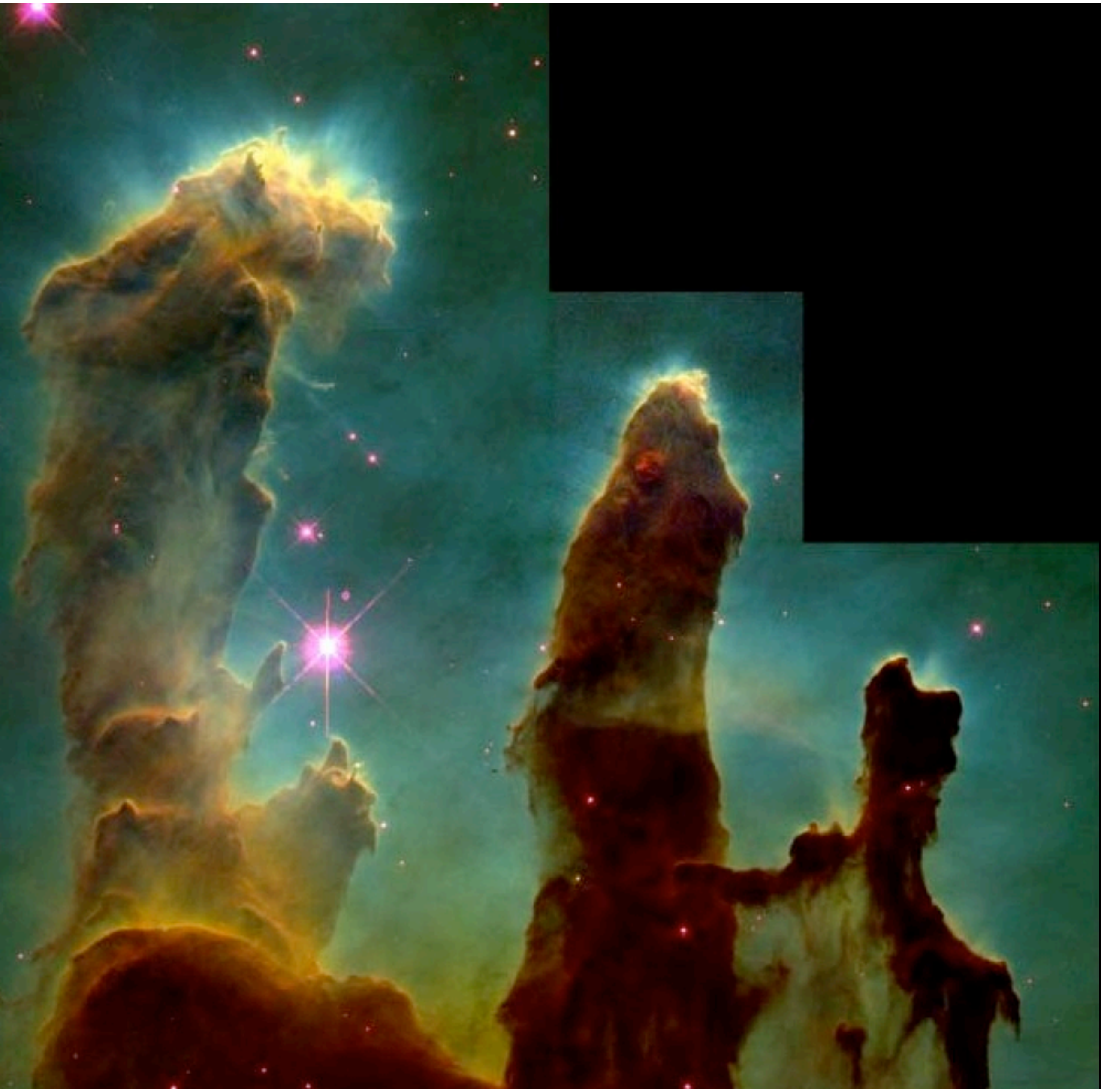




... and a host of smaller bodies...



...around a medium-size orange-yellow star...



...which was born out of the interstellar gas about 5 billion years ago...


...which was born out of the interstellar gas about 5 billion years ago...
© Y.Beletsky & I.Chilingarian


...which was born out of the interstellar gas about 5 billion years ago...


...in a young
cluster of stars.

...in a young
cluster of stars.

Our Sun will eventually expire in a fiery conflagration

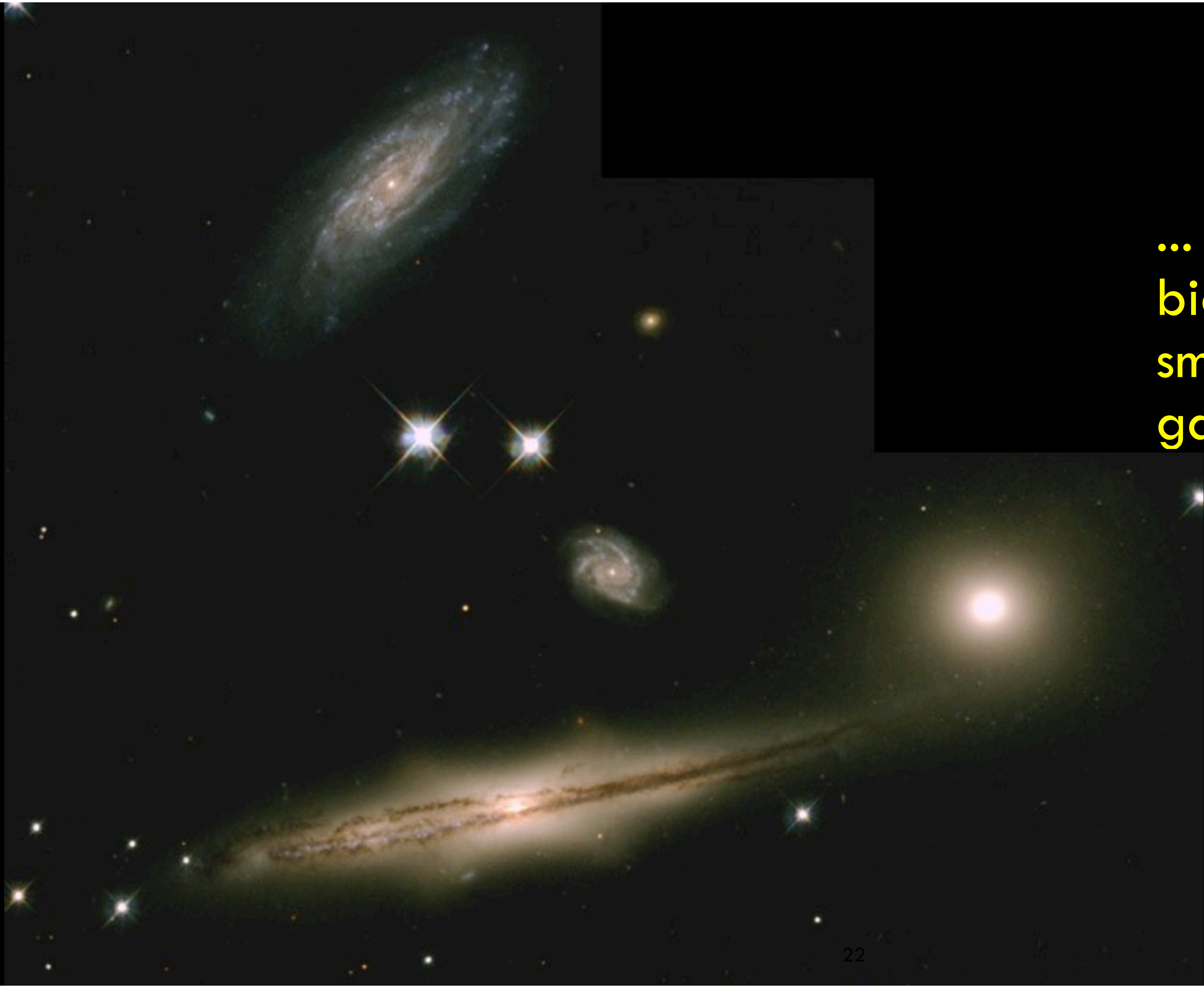
Our Sun will eventually expire in a fiery conflagration

...leaving only a white dwarf behind, doomed to cool slowly into a black cinder.


Our Sun is one of billions
of other stars

Our Sun is one of billions of other stars

Our Sun is one of billions of other stars, about two-thirds of the way out along a spiral arm in a galaxy rather like this one...



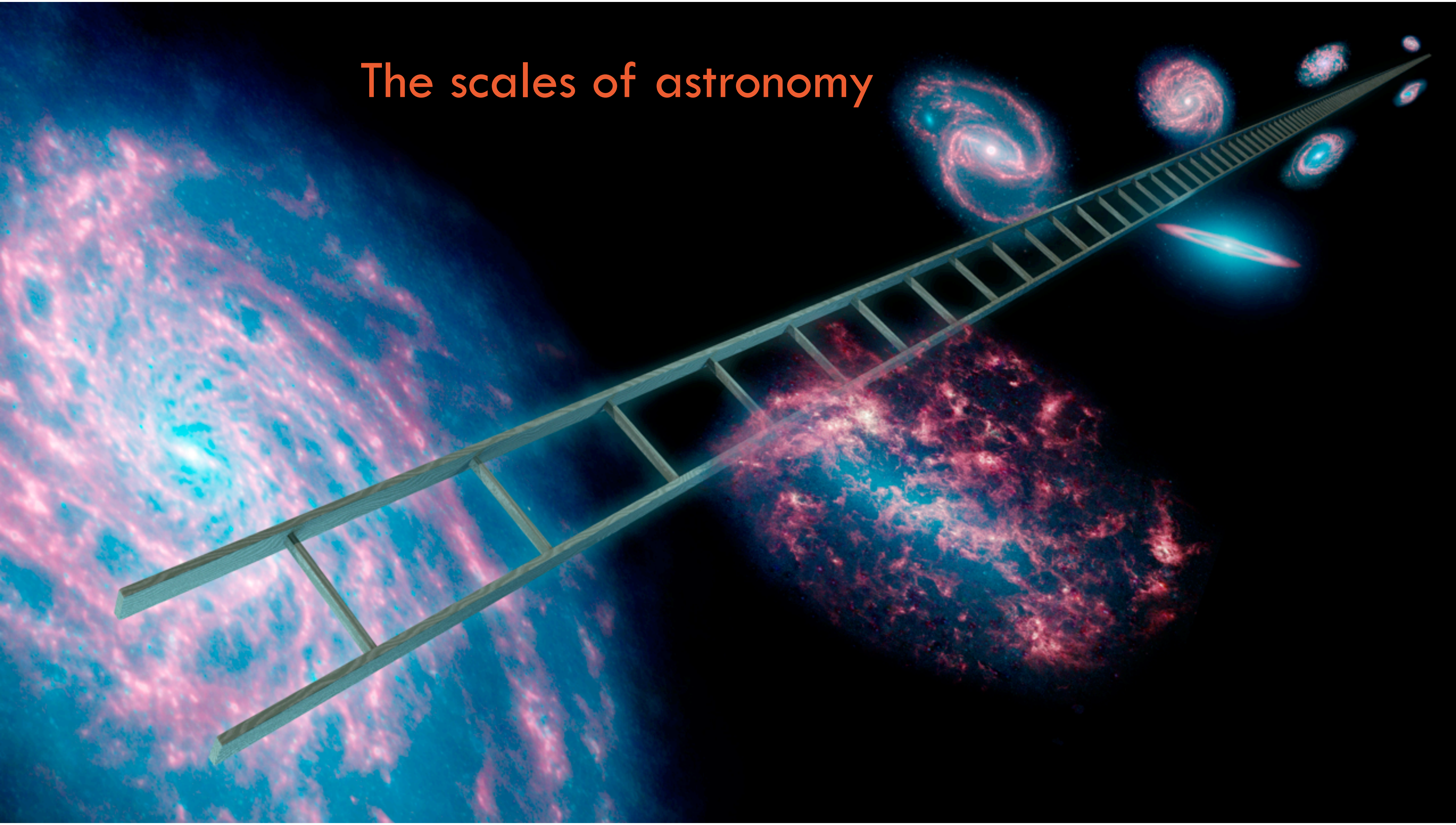
... which is one of the biggest galaxies in a small group of galaxies...

... which is in turn part of a much larger group called the Local Supercluster...


... which is just one of billions of clusters of galaxies...


… which are part of large
sheets and bubbles of
galaxies in the universe.

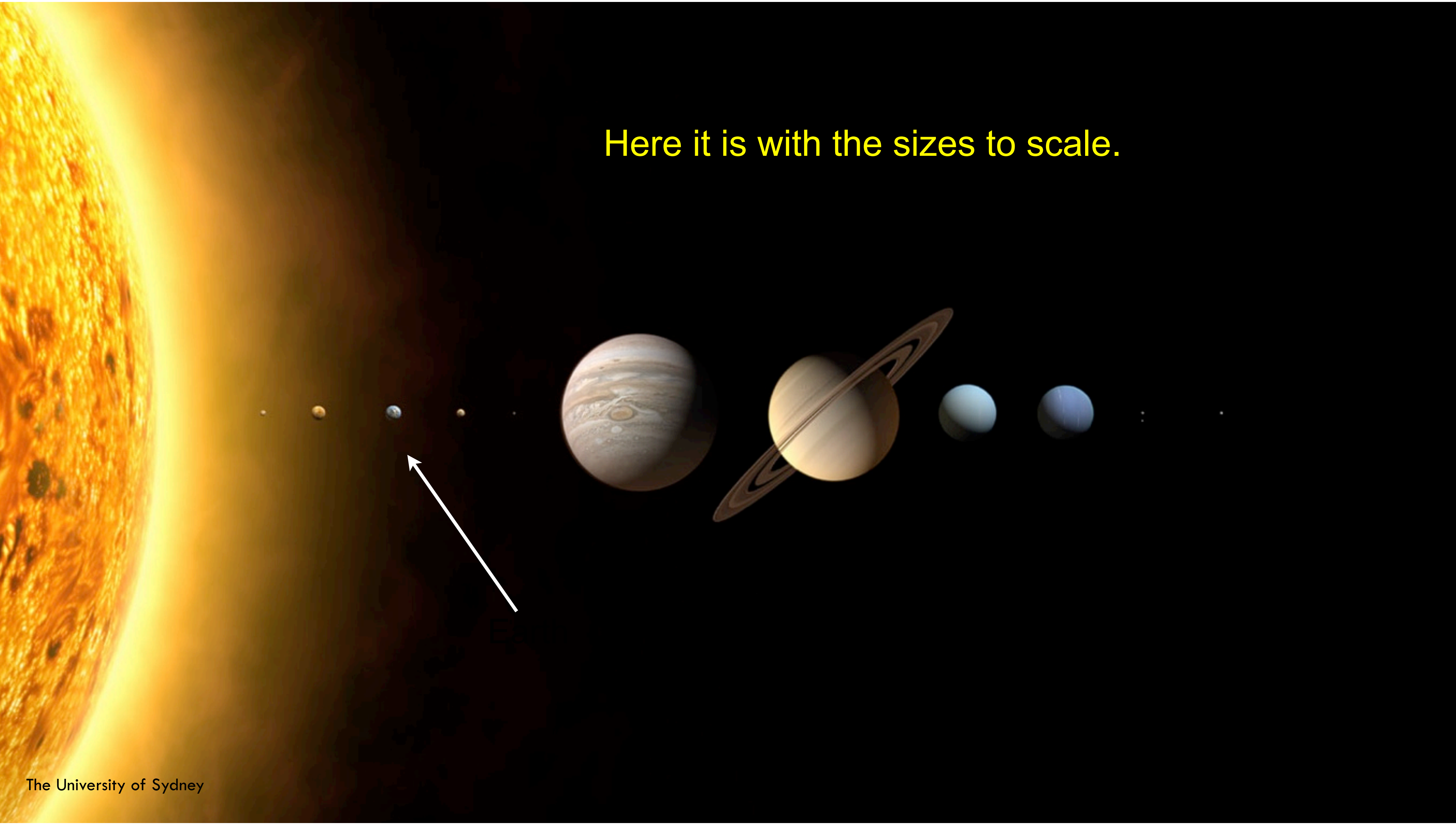
[redacted]


The scales of astronomy

"Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the street to the chemist, but that's just peanuts to space."

– Douglas Adams, The Hitchhiker's Guide to the Galaxy (1978)

Space is really big. Start with the solar system. This is a view you often see, but it totally misrepresents the relative sizes of the planets.

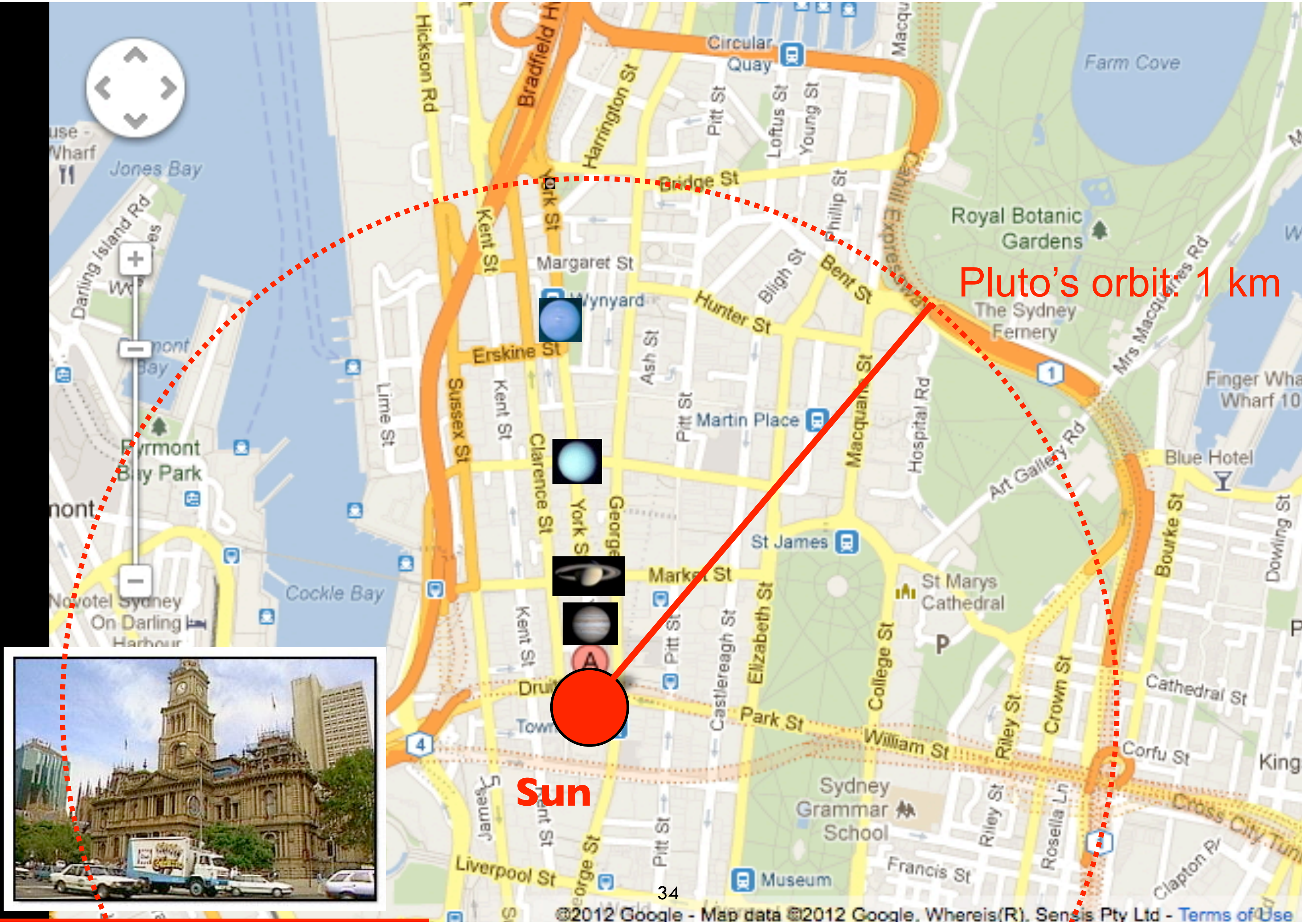

Here it is with the sizes to scale.
The University of Sydney

This shows the relative sizes of the planets, and how small the Earth is. But this shows us nothing about the scale of the orbits: the solar system.

The best way to visualise the distances is with a scale model.

http://solarsystemdrive.com/

Object	Size	Distance from Sun
Sun	23 cm (soccer ball)	-
Mercury	0.08 cm (pinhead)	10 m
Venus	0.2 cm (peppercorn)	18 m
Earth	0.2 cm (peppercorn)	25 m
Mars	0.1 cm (pinhead)	38 m
Jupiter	2.4 cm (walnut)	130 m
Saturn	2.0 cm (macadamia)	238 m
Uranus	0.9 cm (peanut)	478 m
Neptune	0.8 cm (peanut)	749 m
Pluto	0.04 cm (pinhead)	983 m


Pluto's orbit: 1 km
Sun
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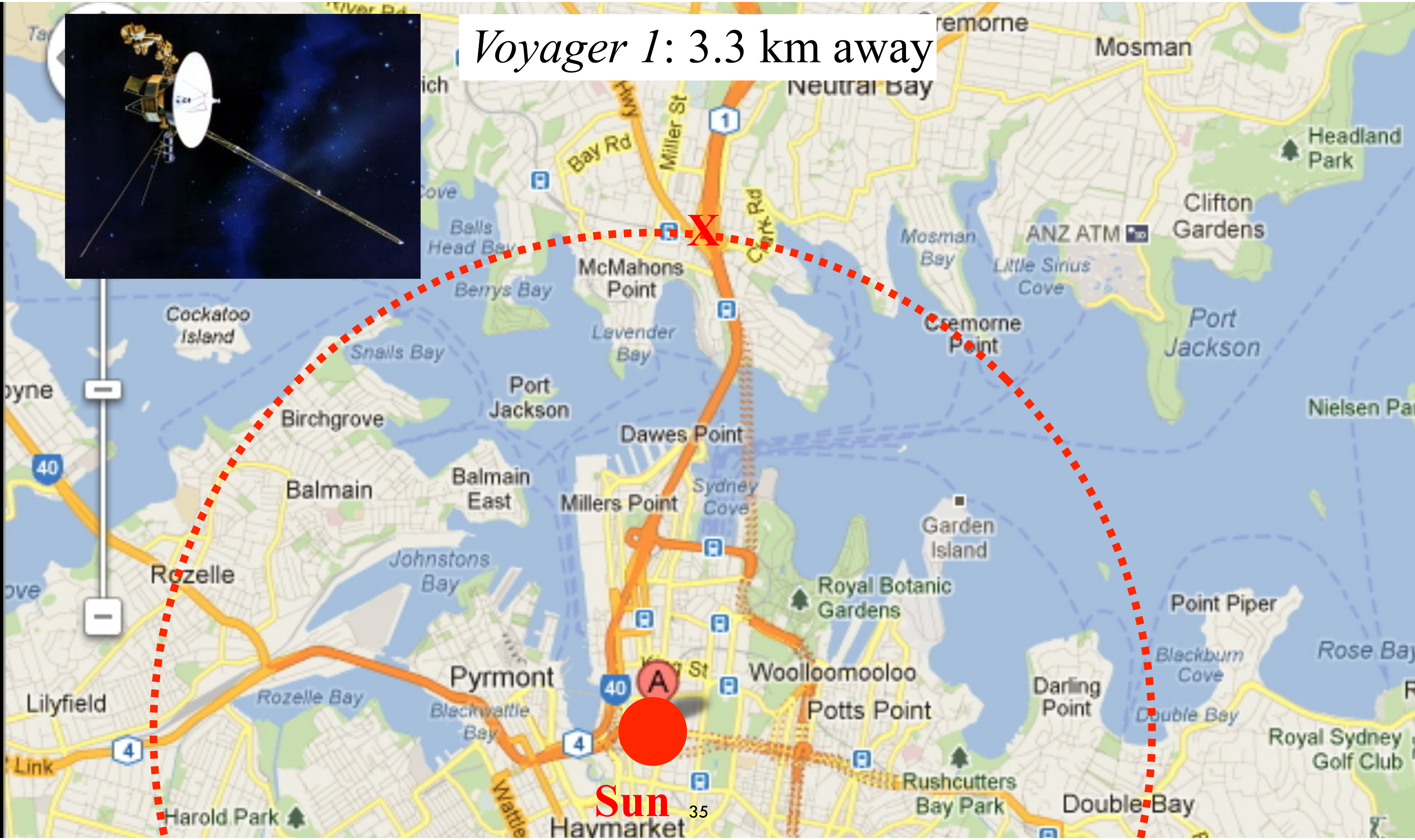
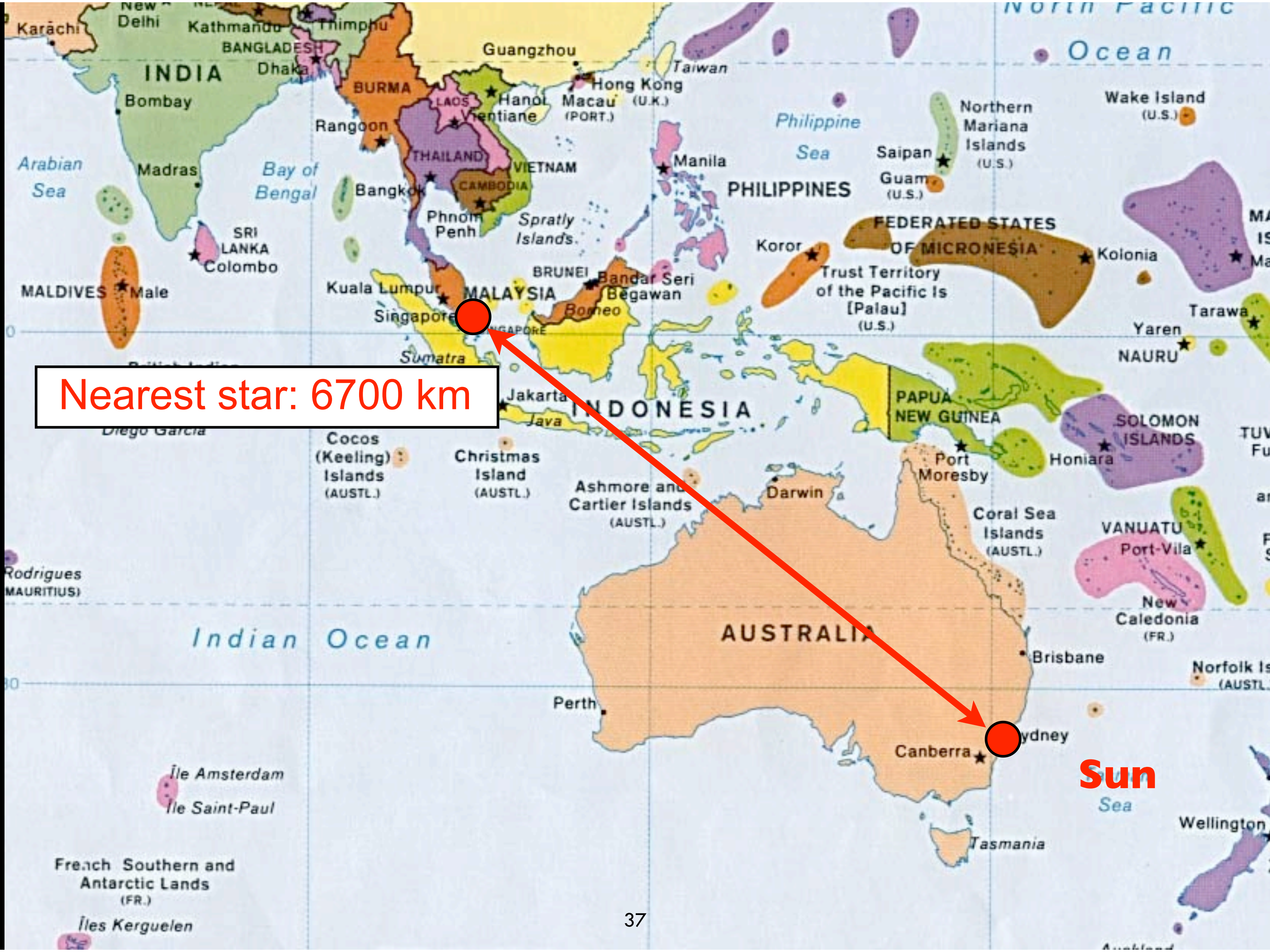


Voyager 1: 3.3 km away
X
Sun
Mosman
Neutral Bay
Headland Park
Clifton Gardens
ANZ ATM
Mosman Bay
Little Sirius Cove
Cremorne Point
Port Jackson
Nielsen Par
Bay Rd
Miller St
Clark Rd
Balls Head Bay
McMahons Point
Berrys Bay
Lavender Bay
Cockatoo Island
Snails Bay
Port Jackson
Birchgrove
Dawes Point
Balmain
Balmain East
Millers Point
Sydney Cove
Garden Island
Johnstons Bay
Rozelle
Royal Botanic Gardens
Point Piper
Rose Bay
Blackburn Cove
Lilyfield
Rozelle Bay
Pyrmont
Blackwattle Bay
King St
Woolloomooloo
Potts Point
Darling Point
Double Bay
Royal Sydney Golf Club
Rushcutters Bay Park
Double Bay
Harold Park
Haymarket
Link


One light year: 1600 km
Sun
Timor Sea
Gulf of Carpentaria
Great Barrier Reef
Indian Ocean
Great Australian Bight
South Pacific Ocean
Ningaloo Reef
WESTERN AUSTRALIA
NORTHERN TERRITORY
SOUTH AUSTRALIA
QUEENSLAND
NEW SOUTH WALES
VICTORIA
A.C.T.
Darwin
Katherine
Kununurra
Broome
Port Hedland
Tennant Creek
Alice Springs
Monkey Mia
Meekatharra
Geraldton
Perth
Kalgoorlie
Esperance
Albany
Margaret River
Coober Pedy
Broken Hill
Adelaide
Mt. Gambier
Melbourne
Canberra
Sydney
Coffs Harbour
Bourke
Brisbane
Toowoomba
Surfers Paradise
Gladstone
Mackay
Townsville
Cairns
Palm Cove
Port Douglas
Kuranda
Cape York Peninsula
Cape Tribulation
Whitsunday Island
Fraser Island
Sunshine Coast
Gold Coast
Kakadu National Park
Litchfield National Park
Kimberley Ranges
Bungle Bungle National Park
Gibson Desert
Uluru National Park
Ayers Rock
Simpson Desert
Nullarbor Plain
Wave Rock
Kalbarri National Park
Nambung National Park
Kangaroo Island
Great Ocean Road
Wilsons Promontory National Park


Nearest star: 6700 km
Sun
INDIA
Bombay
Madras
Karachi
Delhi
Kathmandu
Thimphu
BANGLADESH
Dhaka
Arabian Sea
Bay of Bengal
SRI LANKA
Colombo
MALDIVES
Male
BURMA
Rangoon
LAOS
Vientiane
Hanoi
THAILAND
Bangkok
CAMBODIA
Phnom Penh
VIETNAM
Guangzhou
Hong Kong (U.K.)
Macau (PORT.)
Taiwan
Spratly Islands
Manila
PHILIPPINES
Philippine Sea
BRUNEI
Bandar Seri Begawan
MALAYSIA
Kuala Lumpur
Singapore
Sumatra
Borneo
INDONESIA
Jakarta
Java
Diego Garcia
Cocos (Keeling) Islands (AUSTL.)
Christmas Island (AUSTL.)
Ashmore and Cartier Islands (AUSTL.)
Darwin
Koror
Trust Territory of the Pacific Is [Palau] (U.S.)
FEDERATED STATES OF MICRONESIA
Kolonia
Saipan
Guam (U.S.)
Northern Mariana Islands (U.S.)
Wake Island (U.S.)
North Pacific Ocean
PAPUA NEW GUINEA
Port Moresby
SOLOMON ISLANDS
Honiara
NAURU
Yaren
Tarawa
Coral Sea Islands (AUSTL.)
VANUATU
Port-Vila
New Caledonia (FR.)
AUSTRALIA
Perth
Brisbane
Canberra
Tasmania
Norfolk Is (AUSTL.)
Wellington
Rodrigues (MAURITIUS)
Indian Ocean
Île Amsterdam
Île Saint-Paul
French Southern and Antarctic Lands (FR.)
Îles Kerguelen

On this scale, the nearest star, Alpha Centauri, is at a distance of 6,700 km = the distance to Singapore.

There is not a *single object* approaching the size of a soccer ball between here and Singapore.

Remember this scale: we'll refer to it again.

“The chief characteristic of the universe is, I would say, emptiness. There is infinitely more nothing in the universe than anything else.”

– John Updike, *The Poorhouse Fair*

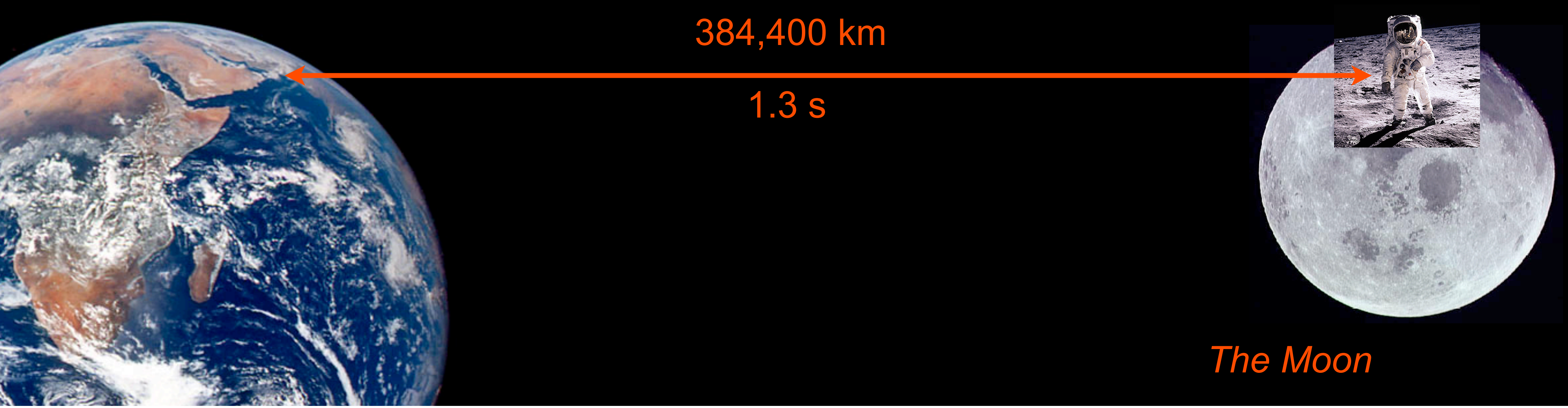
Because of these ridiculous distances, astronomers have defined some special units to make the numbers more manageable:

- An *astronomical unit* (AU) is the average Earth-Sun distance: 1 AU = 149.6 million km

- A *light year* (ly) is the distance light travels in a year: 1 ly = 9,461,000,000,000 km = 63,000 AU

- A *parsec* (pc) is about 3.26 ly; we'll find out where this comes from in a few lectures

The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.



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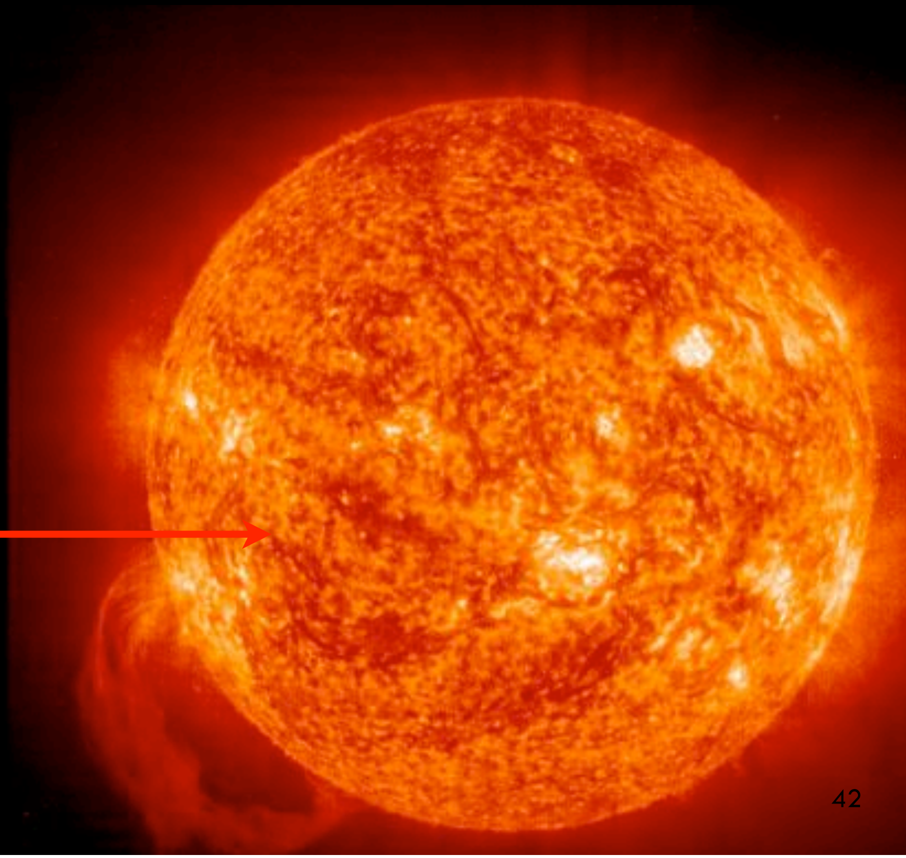
150,000,000 km

8 m



The Sun

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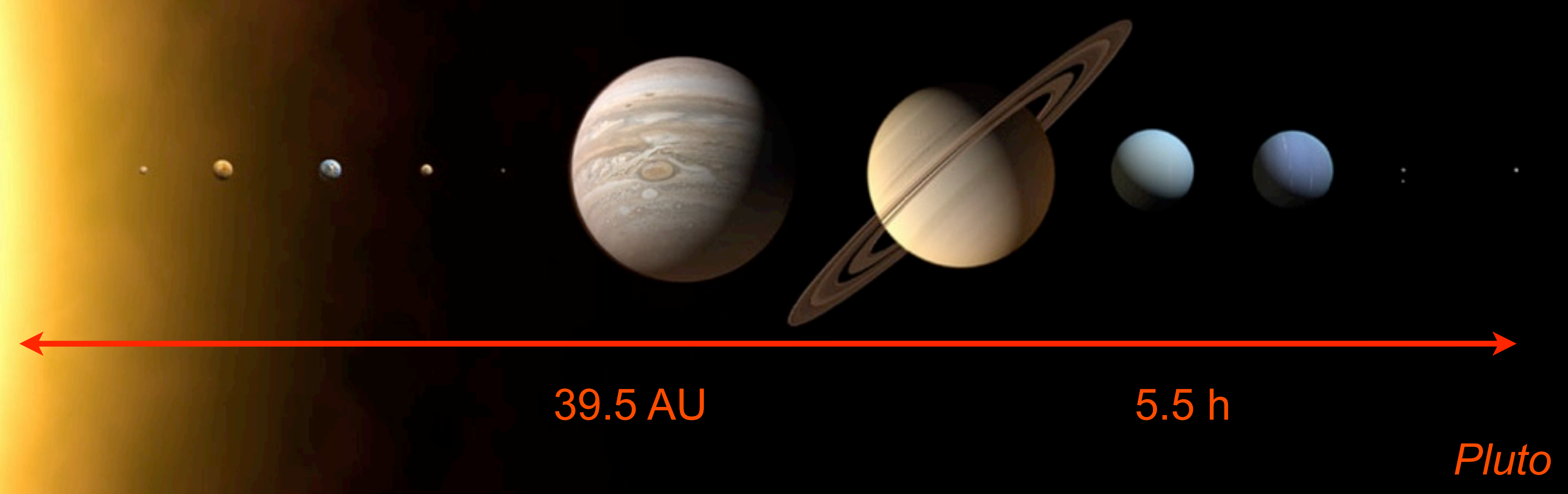

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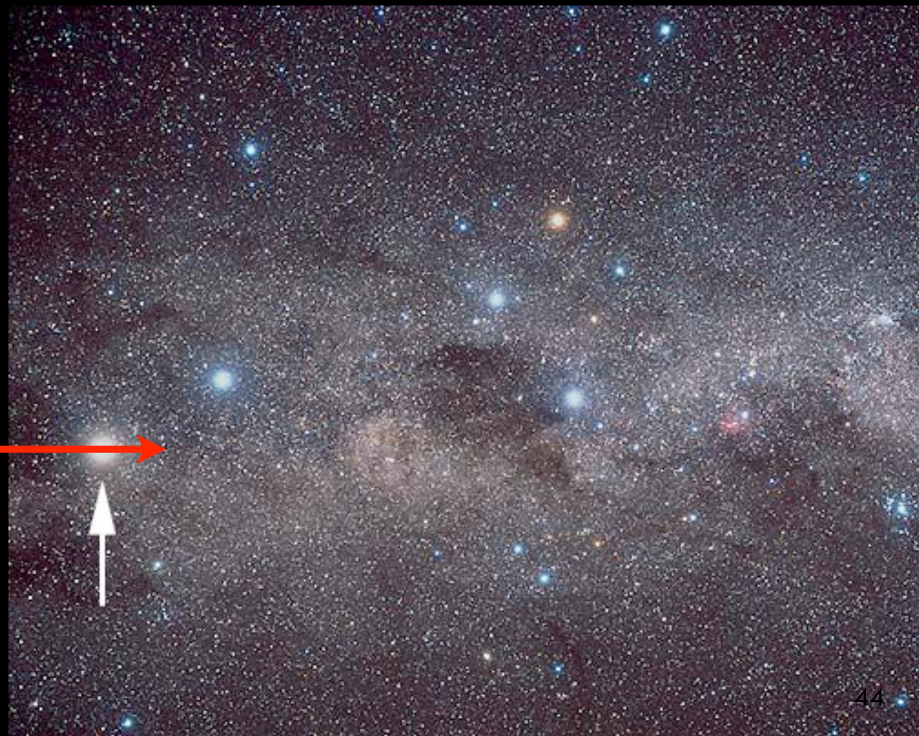
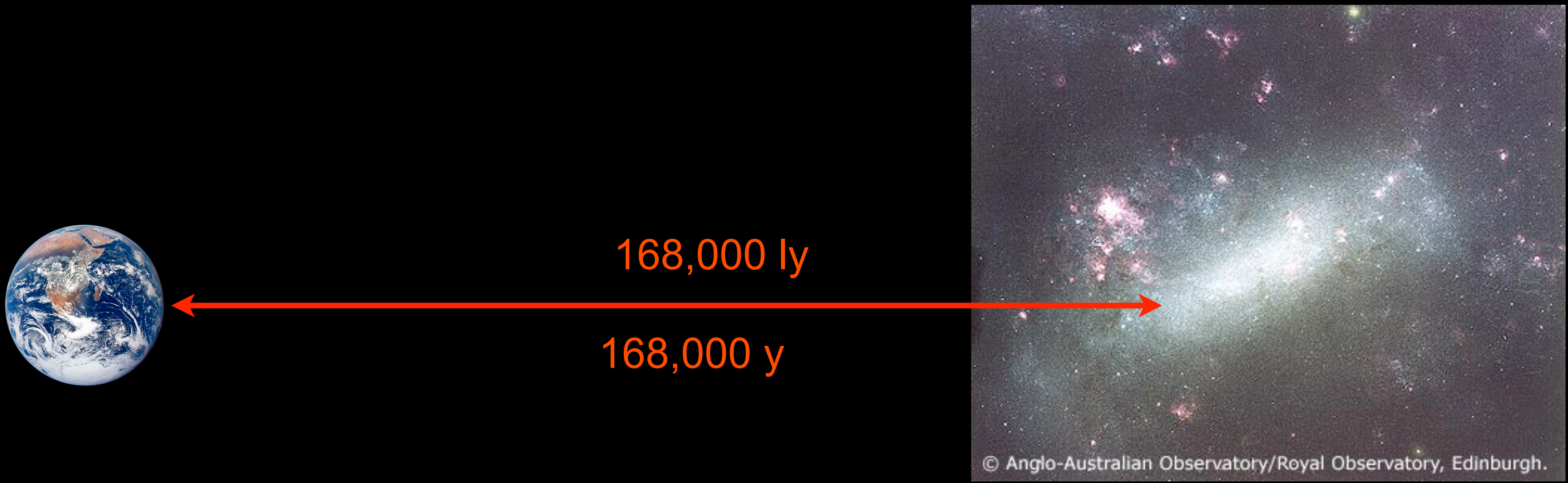
40 trillion km

4.3 y



The nearest star, alpha Centauri

The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.



The Large Magellanic Cloud

The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.

The Andromeda galaxy

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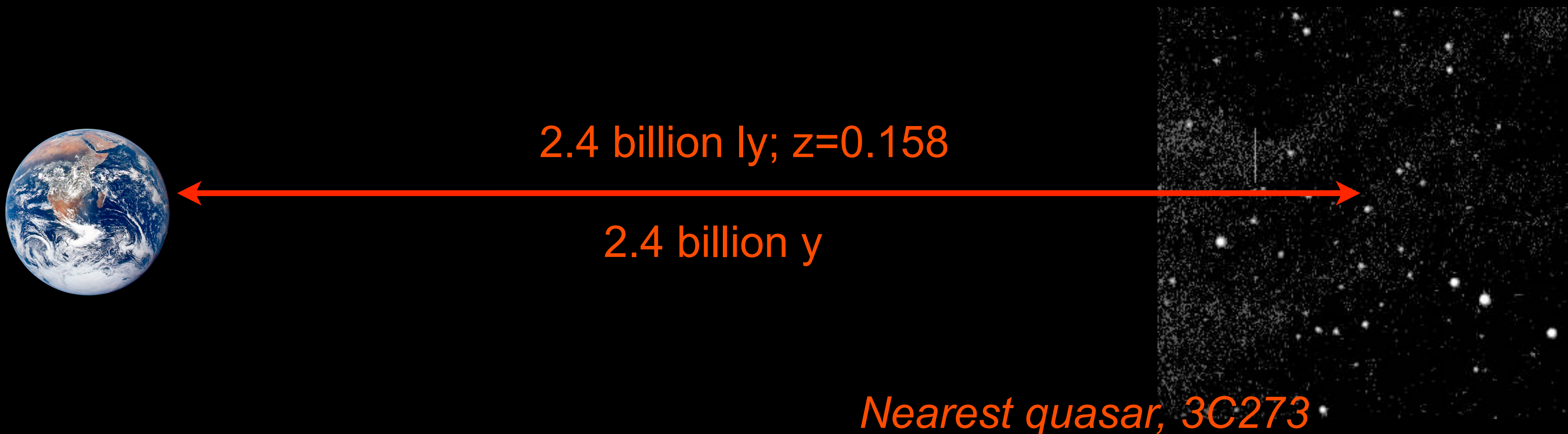

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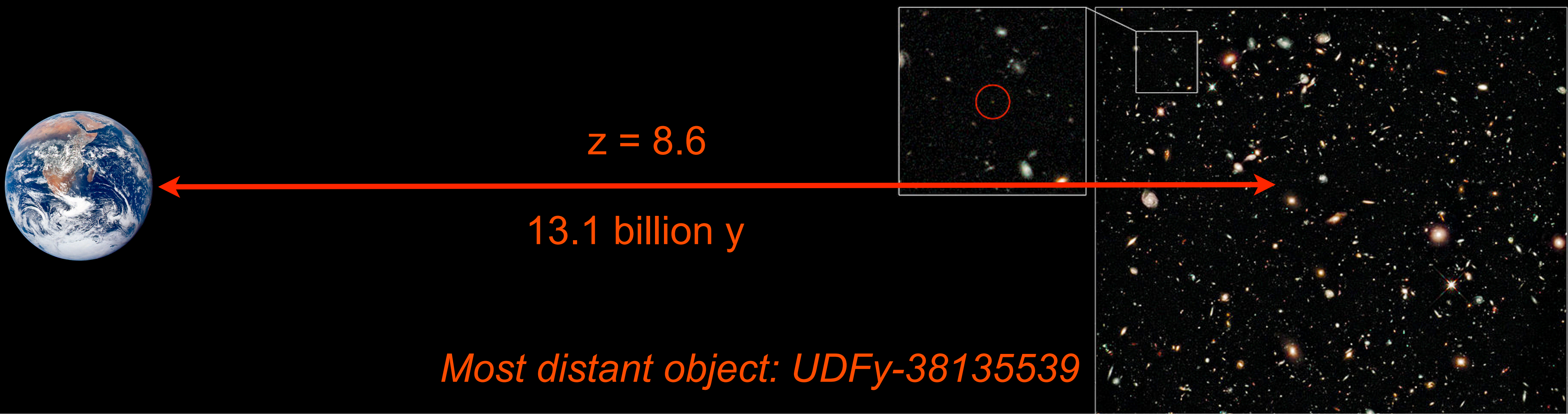
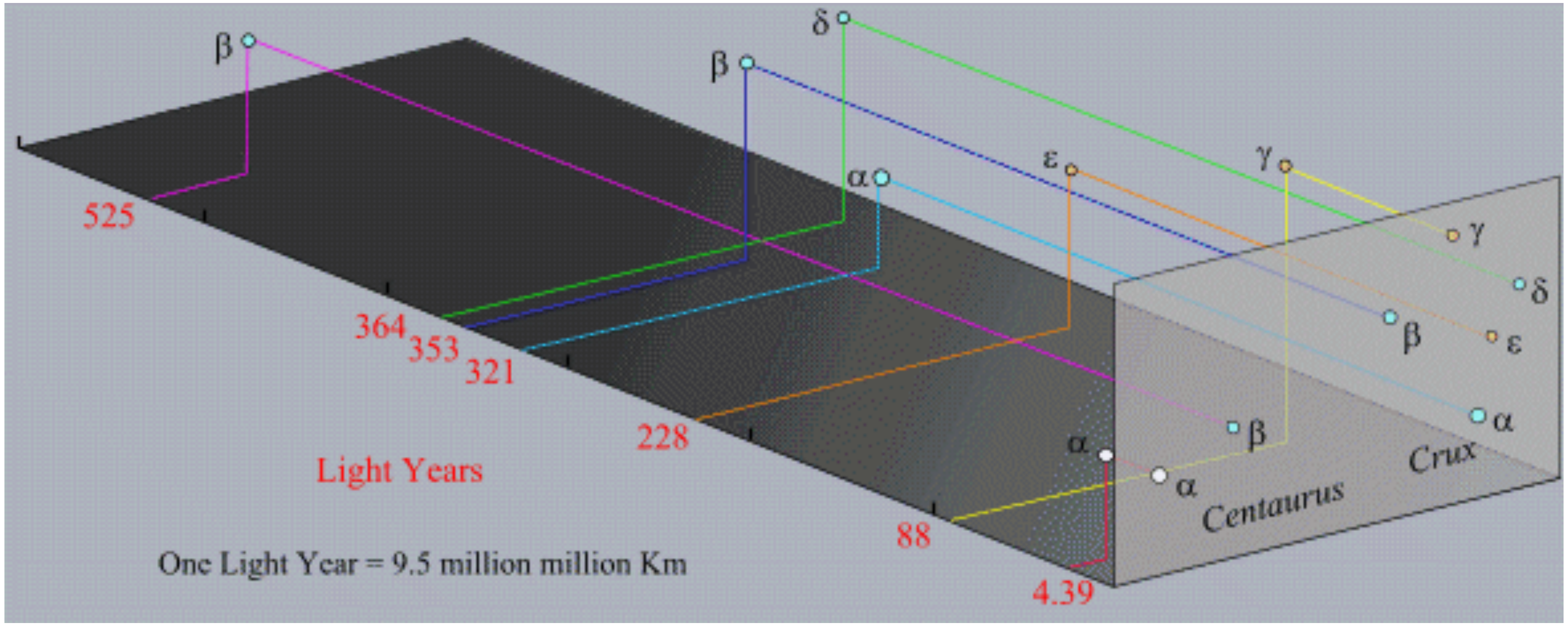
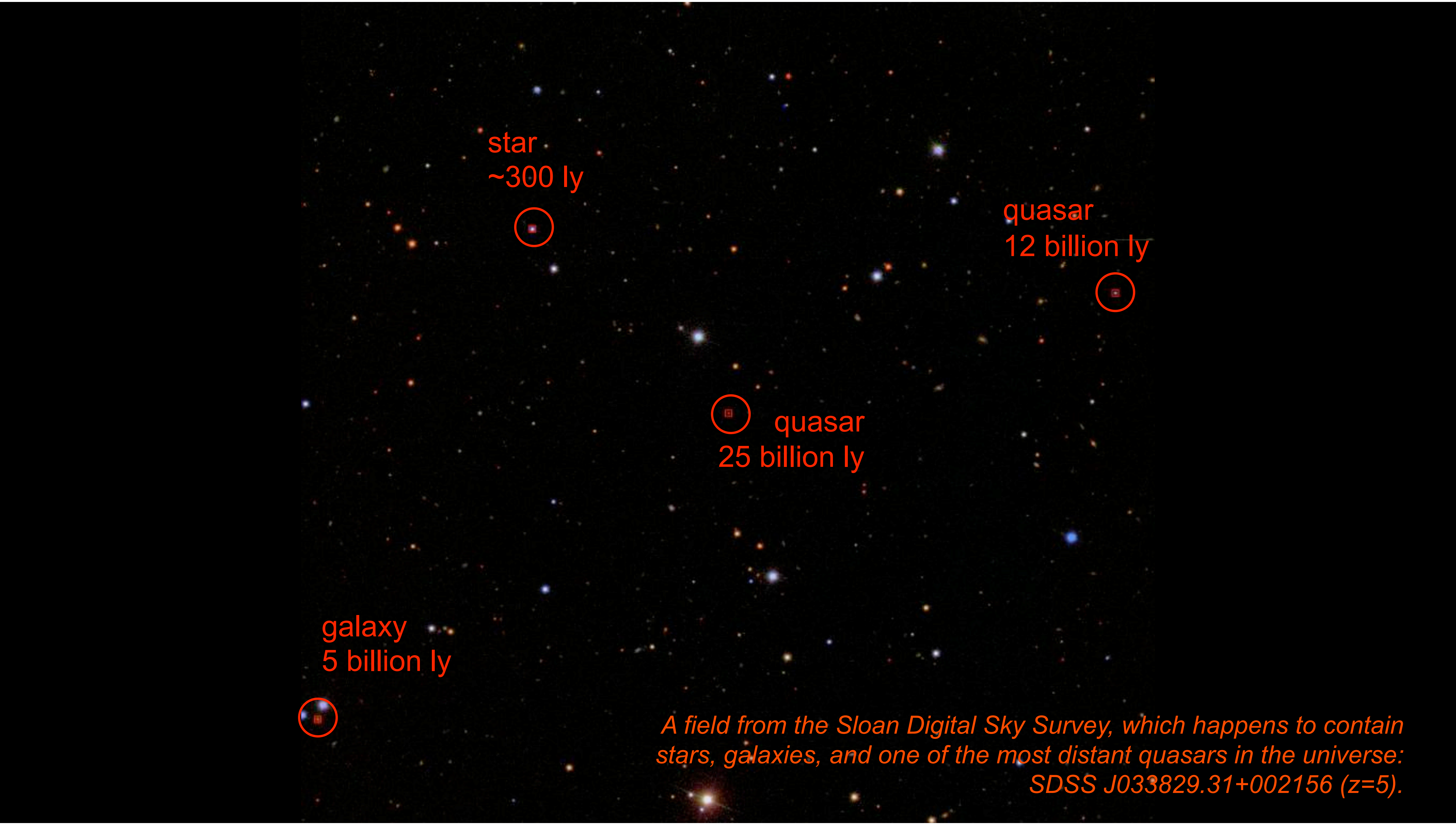


One problem we have is that when we look at the sky, we have no notion how far away objects are.



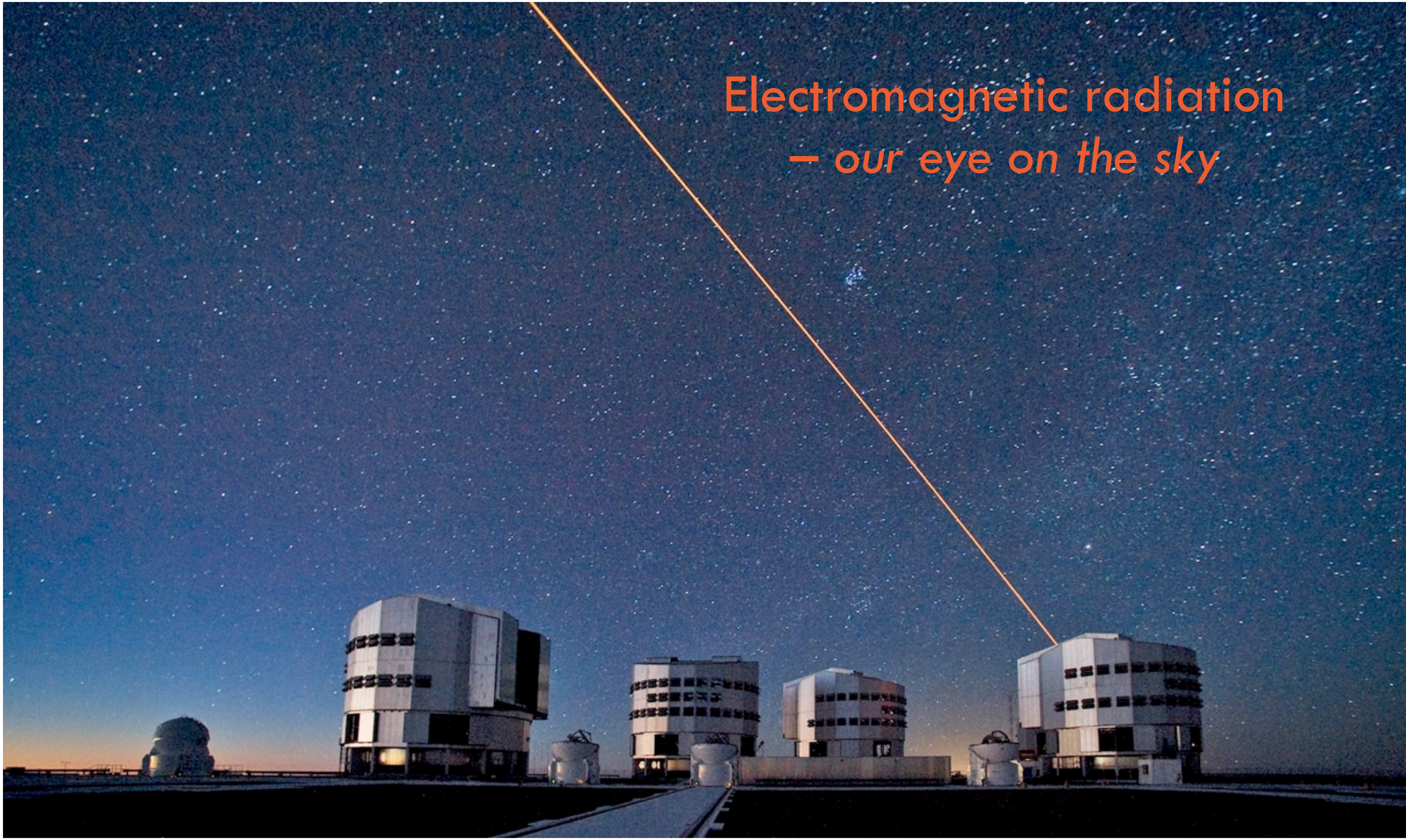
The stars of the Southern Cross and the Pointers have similar brightnesses, but very different distances.

The coloured object is the asteroid Ceres (distance ~3 AU) passing near the galaxy group NGC 3607 (distance 60 million light years)



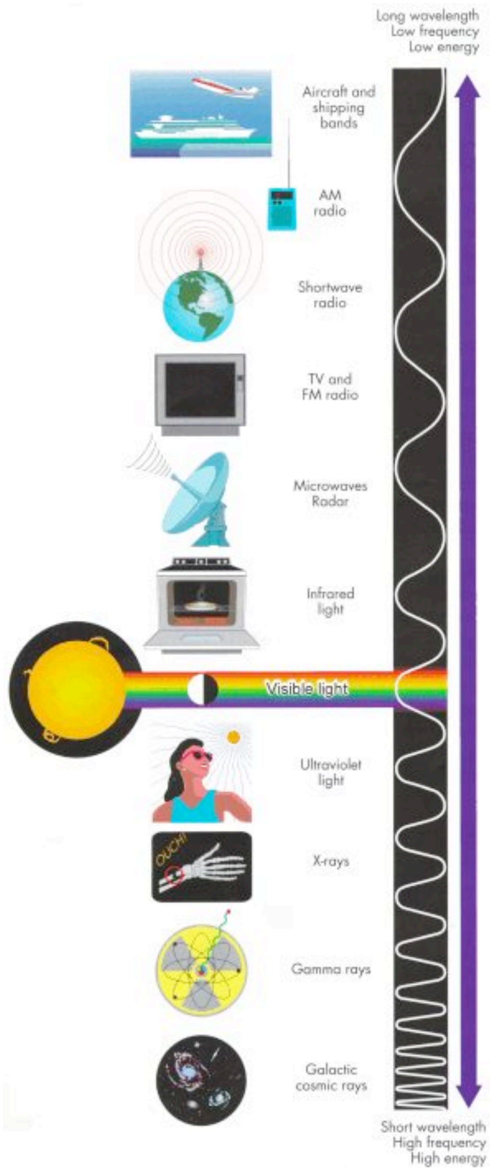
A field from the Sloan Digital Sky Survey, which happens to contain stars, galaxies, and one of the most distant quasars in the universe: SDSS J033829.31+002156 (z=5).

We will be discussing how we find the distances to astronomical objects later in the course.


Electromagnetic radiation
– *our eye on the sky*

Astronomy is not an experimental science: astronomers can't get their hands on their subject matter. Everything we know about the cosmos, we know by *remote sensing*.

Visible light is the most obvious means by which we can observe the universe. But there are many other sorts of radiation we can't see with our eyes: these include radio waves, infrared, ultraviolet, X-rays and gamma rays. Together, all these forms of radiation make up the *electromagnetic spectrum* – the complete spectrum of radiation.



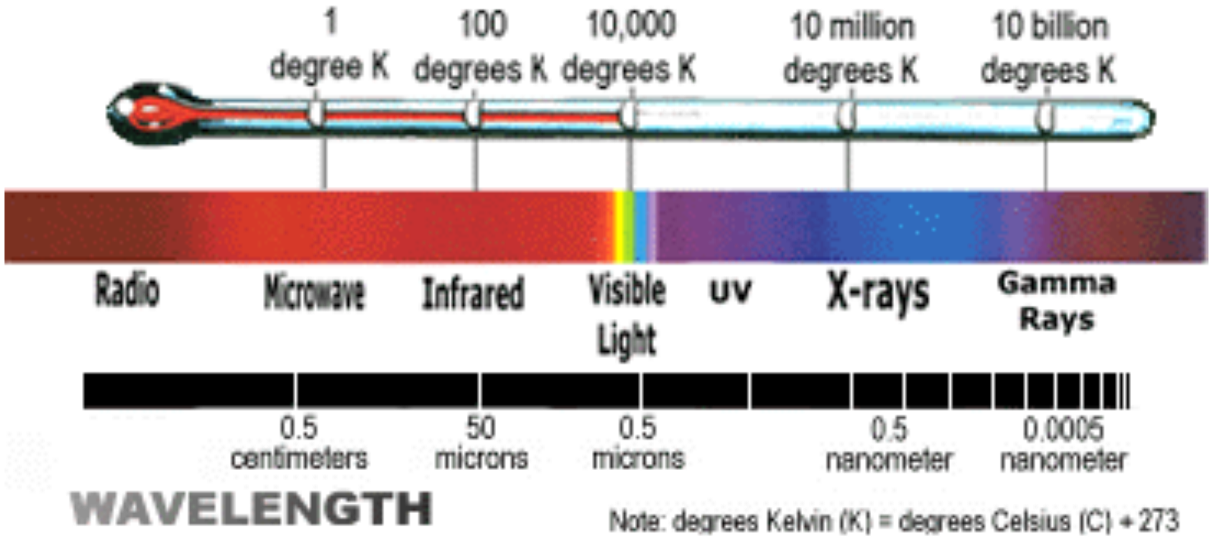
Wavelength	*Frequency*
10 km (shipping)	30 kHz
1 km (aircraft)	300 kHz
300 m (AM)	1000 kHz = 1 MHz
50 m (shortwave)	6 MHz
3m (FM radio)	100 MHz
50 cm (TV)	600 MHz
1 cm (microwave)	
10 micron	
0.5 micron = 500 nm	
100 nm	
1 nm	
0.001 nm = 1pm	

Visible light makes up only a tiny fraction of the electromagnetic spectrum. Our eyes can see less than an octave of the spectrum, from wavelengths of 400 nm to 700 nm. Astronomical observations cover more than *65 octaves* of the spectrum, from low-frequency radio waves to ultra-high-energy gamma rays.

From now on, when we use the word "light", we mean "electromagnetic radiation", not just visible light.

All electromagnetic radiation travels at the *speed of light*, which is usually written as $c = 300{,}000$ km/s.

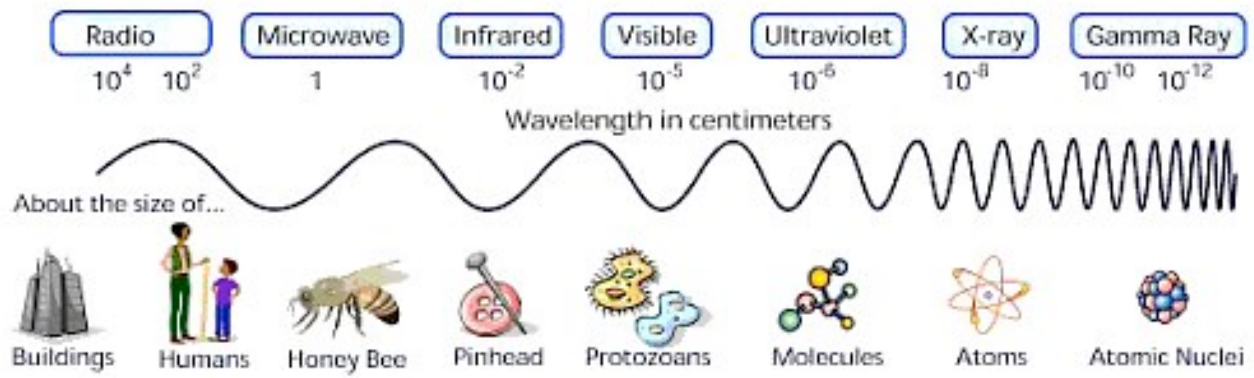
The wavelength at which an object radiates most depends principally on its *temperature*.



Cool objects radiate most at long wavelengths,
hot objects at short wavelengths.

The Sun radiates most at the wavelength of visible light.

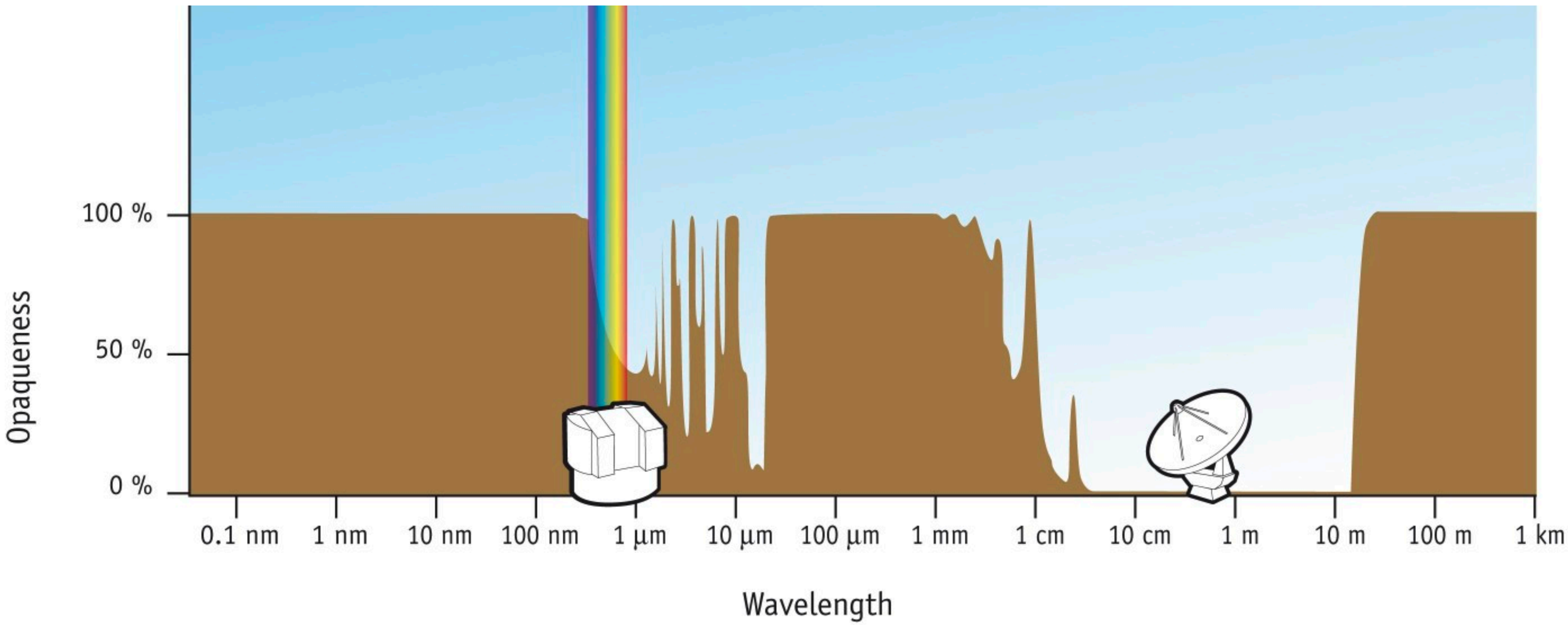
All forms of EM radiation are the same, but they *seem* very different because of the very different scales involved.



Radiation can pass around objects which are much smaller than the wavelength.

Radiation doesn't "see" objects (or holes) which are much smaller than the wavelength – which is why you can see through the door of your microwave, and why you can build a radio telescope out of chickenwire.

The Earth's atmosphere is opaque to nearly all parts of the EM spectrum.

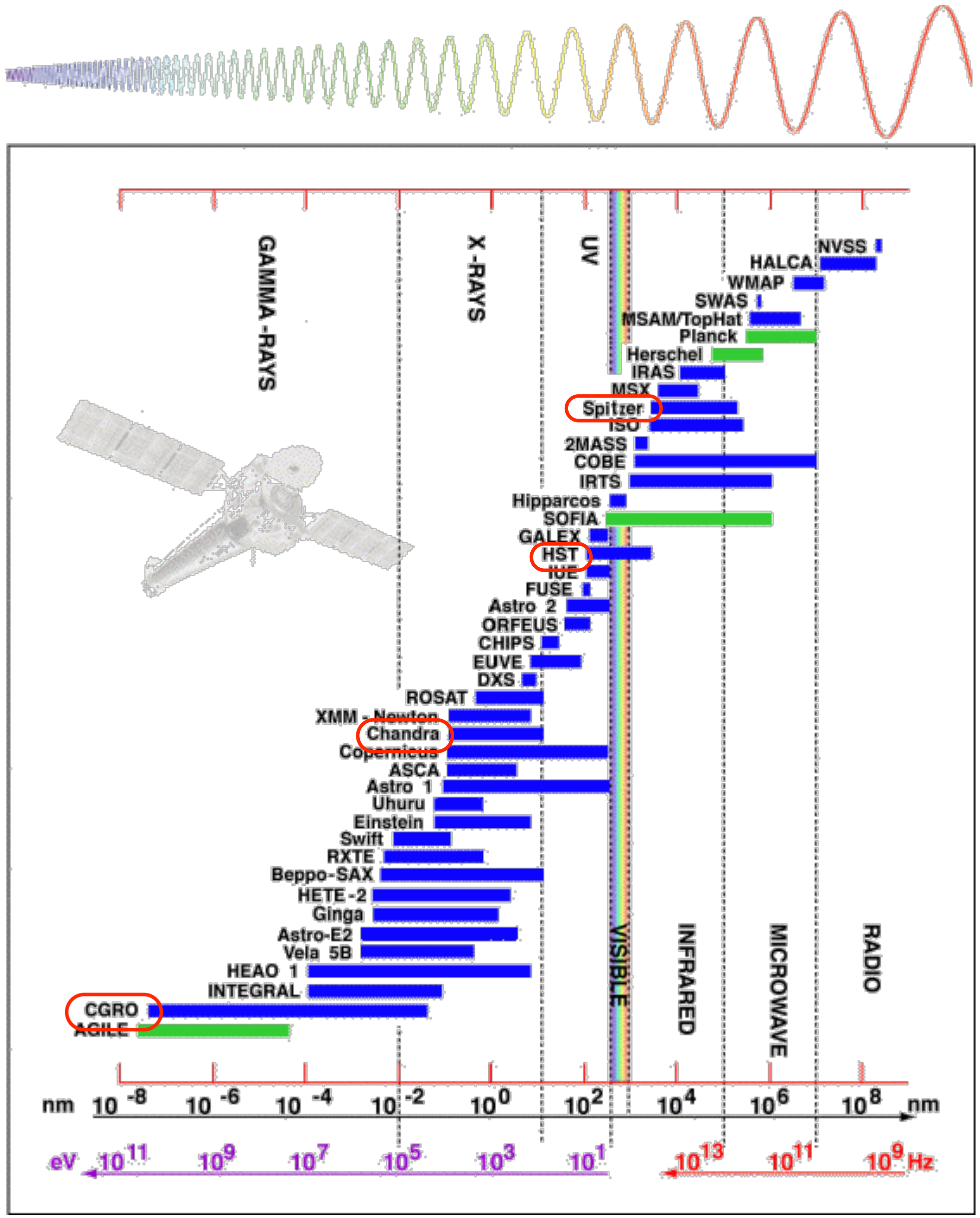


Only visible and radio waves can reach the surface.

So we need to go outside the Earth's atmosphere in order to see many parts of the electromagnetic spectrum. And even for regions which we can see from Earth, like visible light, going into space has advantages, like removing the twinkle the atmosphere produces.

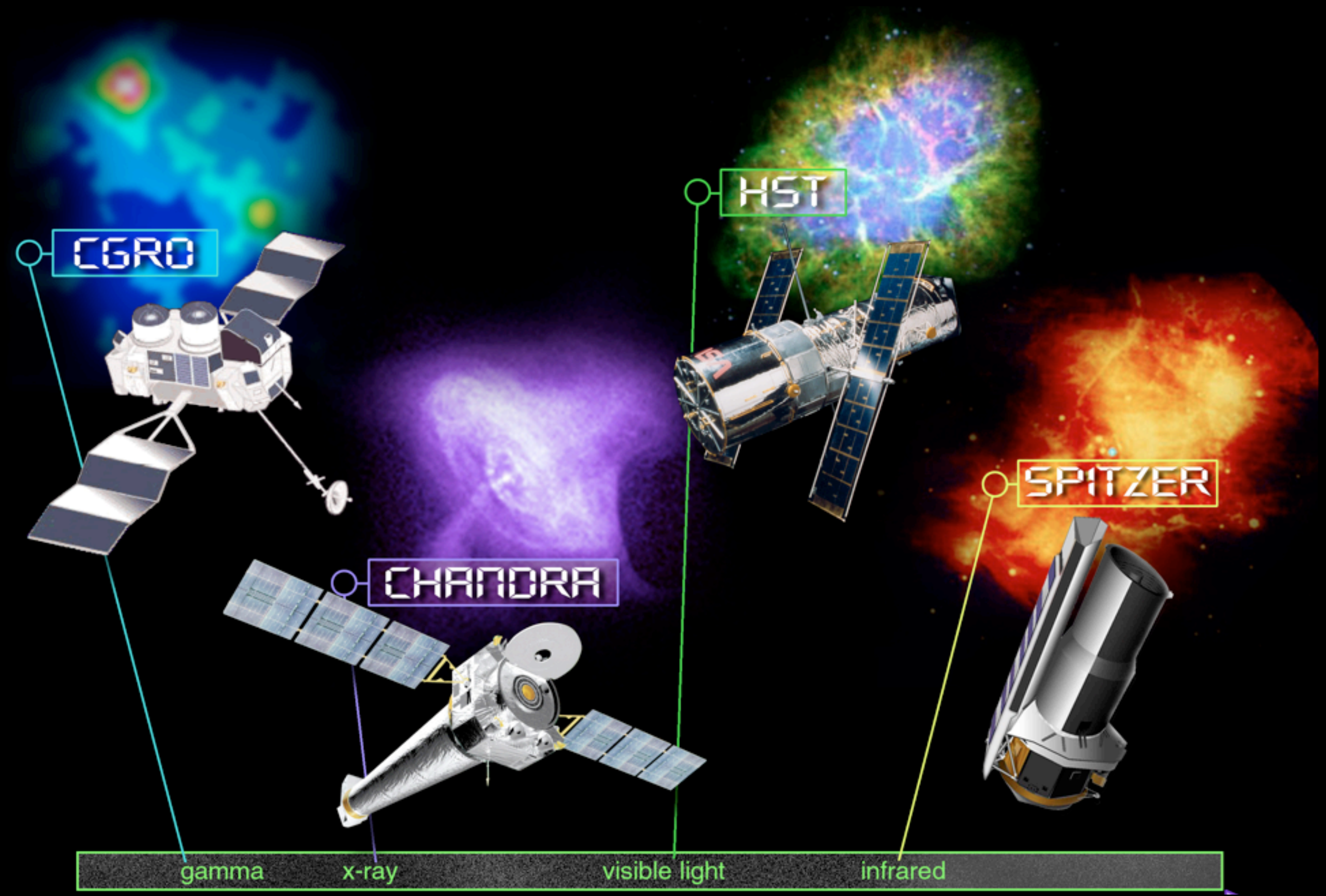
Here are the most important past and present astronomical satellites*

** plus a couple of ground-based missions*



GAMMA-RAYS
X-RAYS
UV
VISIBLE
INFRARED
MICROWAVE
RADIO
NVSS
HALCA
WMAP
SWAS
MSAM/TopHat
Planck
Herschel
IRAS
MSX
Spitzer
ISO
2MASS
COBE
IRTS
Hipparcos
SOFIA
GALEX
HST
IUE
FUSE
Astro 2
ORFEUS
CHIPS
EUVE
DXS
ROSAT
XMM - Newton
Chandra
Copernicus
ASCA
Astro 1
Uhuru
Einstein
Swift
RXTE
Beppo-SAX
HETE-2
Ginga
Astro-E2
Vela 5B
HEAO 1
INTEGRAL
CGRO
AGILE
nm 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} nm
eV 10^{11} 10^{9} 10^{7} 10^{5} 10^{3} 10^{1}
10^{13} 10^{11} 10^{9} Hz

NASA's "Great Observatories" missions



1991–2000

1999–now

1990–now

2003–now

Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

The optical image shows a bright elliptical galaxy obscured by a dark dust lane.

Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

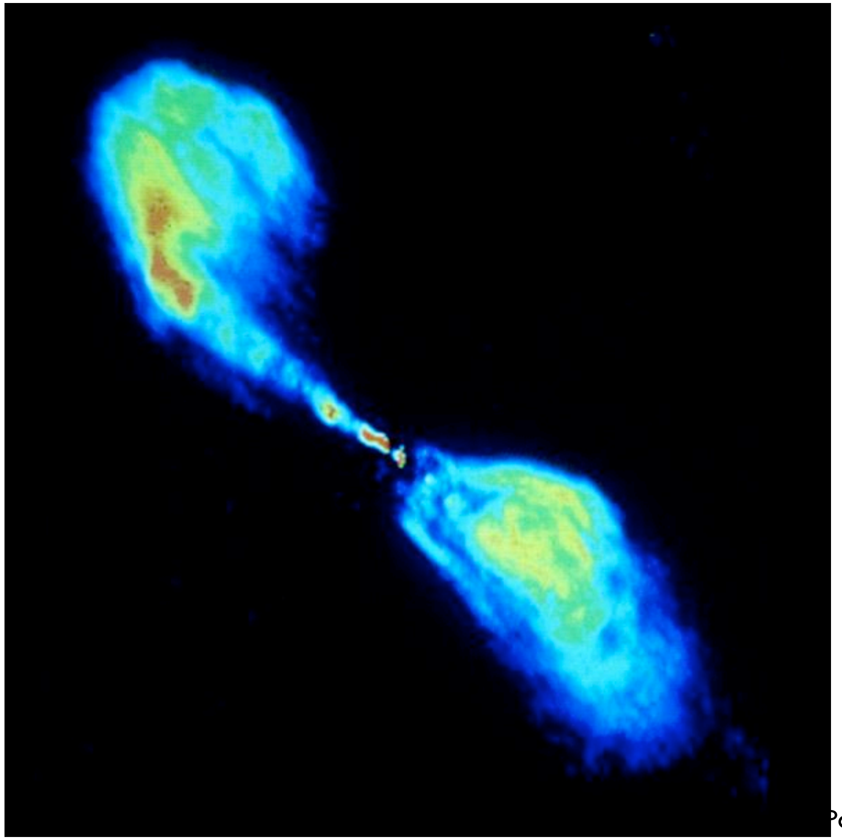
In the ultraviolet image the galaxy has almost disappeared: all we see is the dark dust lane shrouding the bright centre.

Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

The infrared image shows that the dust lane is actually the remains of a spiral galaxy.

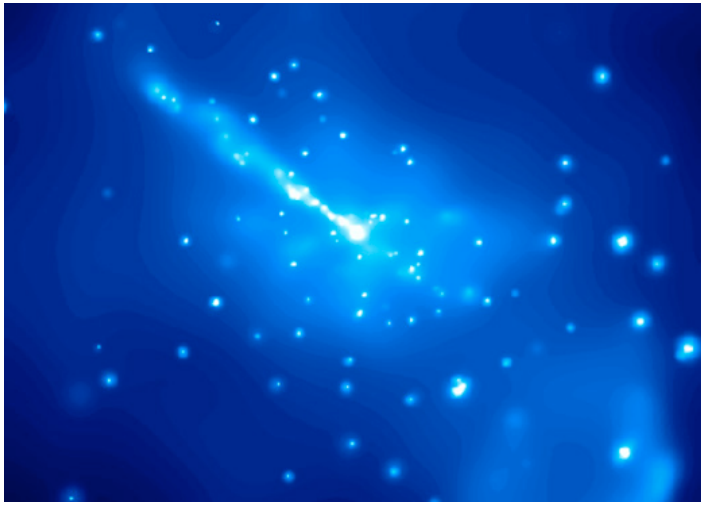
Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

The radio image is a surprise! We see a totally new structure, looking like jets shooting out of the centre and spreading out.



Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

The X-ray image also shows a jet, this time only pointing in one direction. We believe it is emanating from a supermassive black hole at the centre of the galaxy.

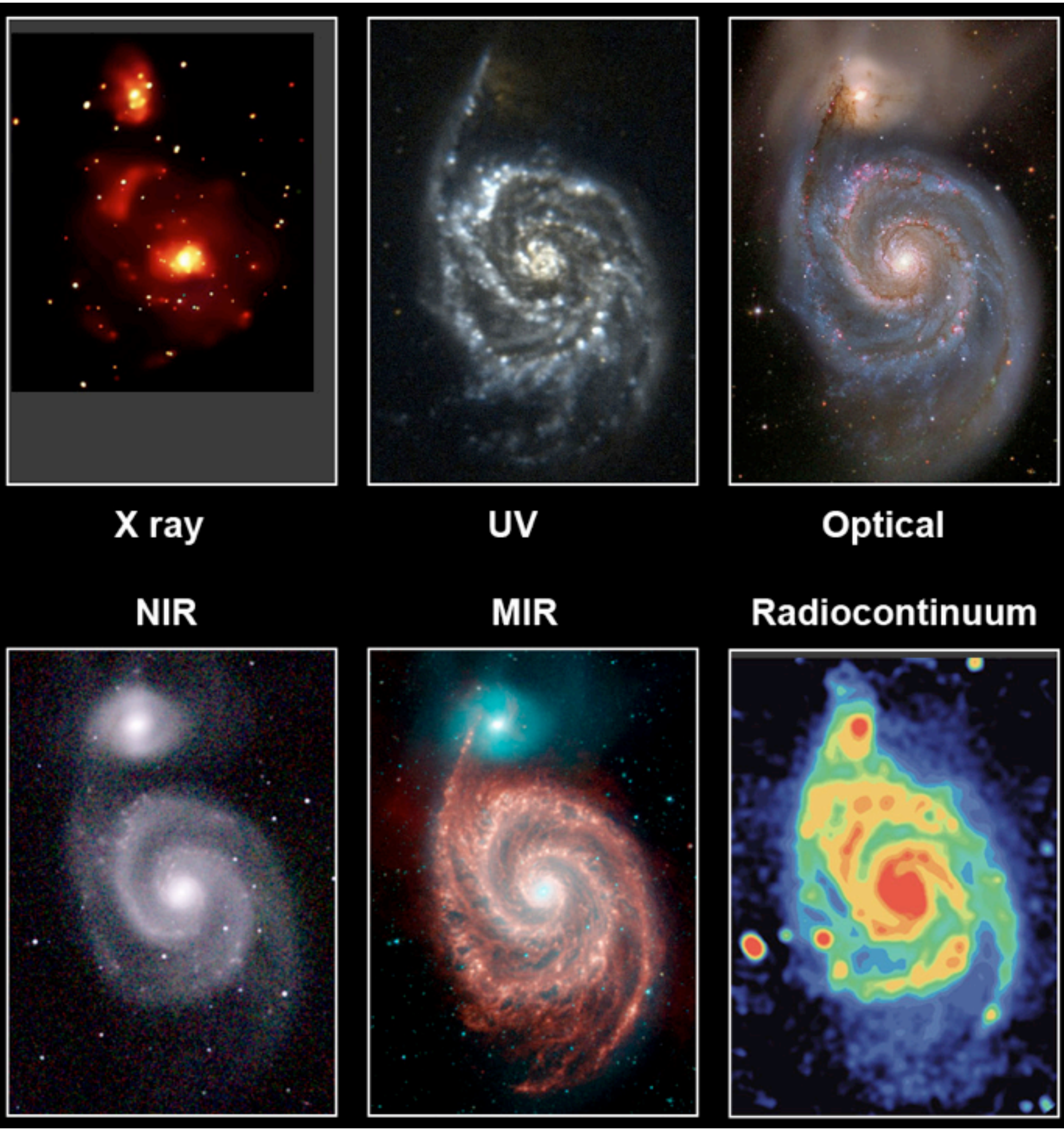


Here are all those images together.

X-ray | ultraviolet | optical | infrared | radio

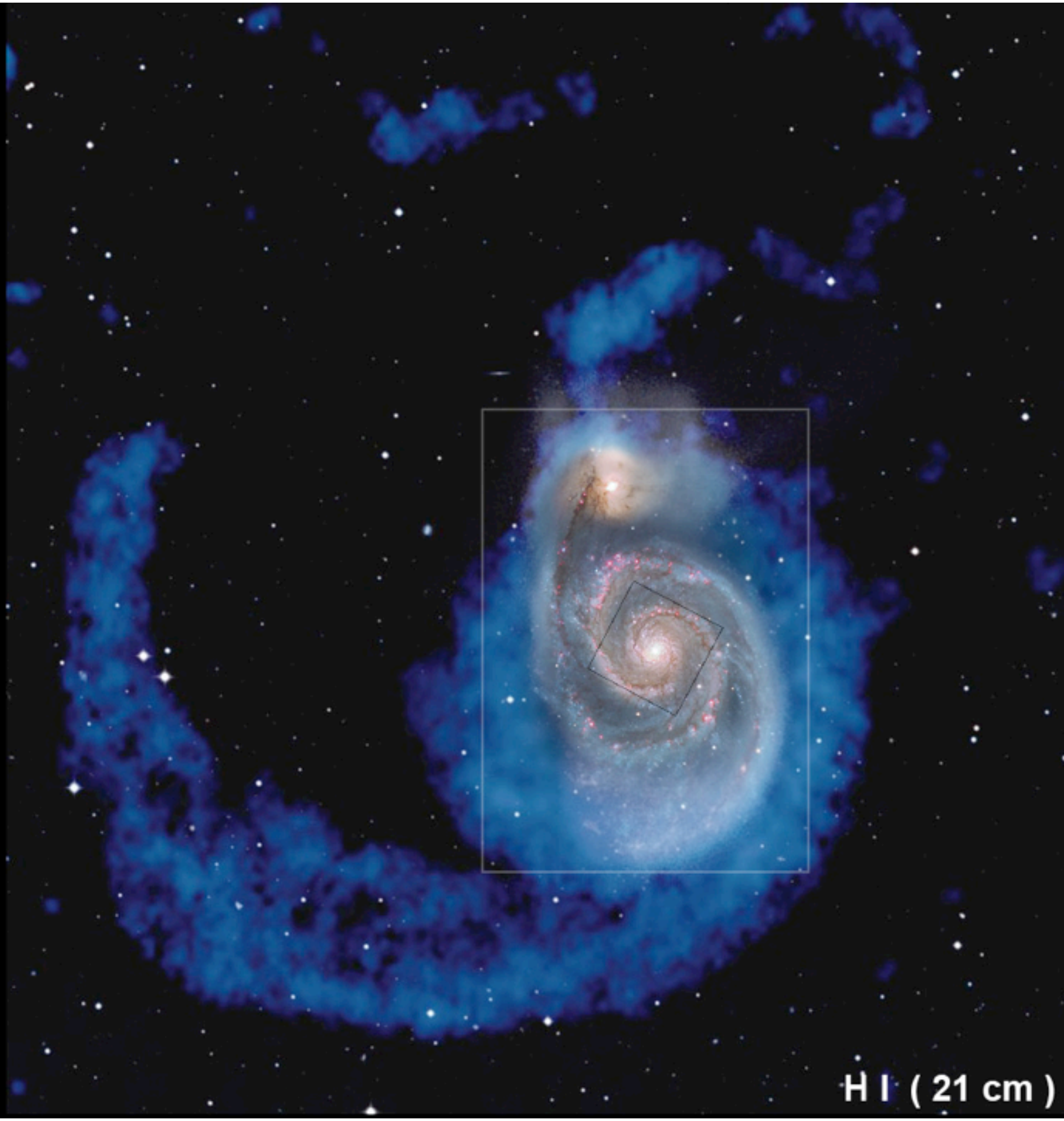
short wavelength ———————————————— long wavelength

Composite X-ray (blue), radio (pink and green), and optical (orange and yellow) image of the galaxy Centaurus A



Another example: the galaxy M51, from X-ray to radio.

Optical



Why do these images look so different?

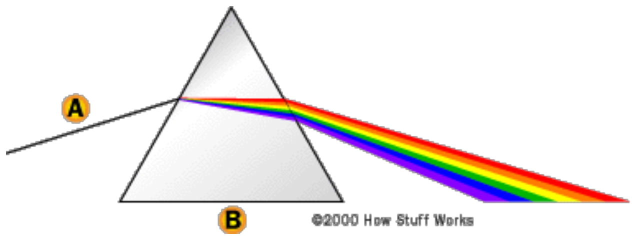
Since objects of different temperatures emit light of different wavelengths, then observing at different wavelengths allows us to “see” objects of different temperatures, which means very different conditions.

Type of radiation	Characteristic temperature	Typical objects emitting this radiation
Gamma-ray	$> 10^8$ K	Neutron stars, accretion disks around black holes
X-ray	10^6–10^8 K	Shocked gas; neutron stars; supernova remnants
Ultraviolet	10^4–10^6 K	Supernova remnants; very hot stars; quasars
Optical	1000–10,000 K	Stars; galaxies; emission nebulae; reflection nebulae
Infrared	10–1000 K	Cool stars; interstellar gas; planets
Radio	< 10 K	Cosmic background; cold interstellar gas; supernova remnants

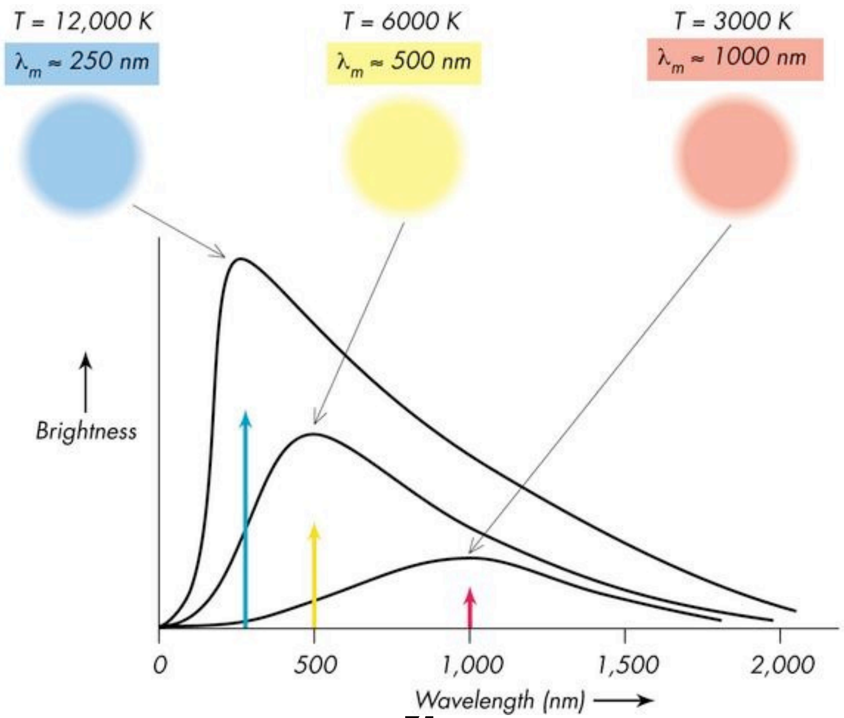
Spectra: separating light

Almost every source of EM radiation produces photons of many wavelengths at once.

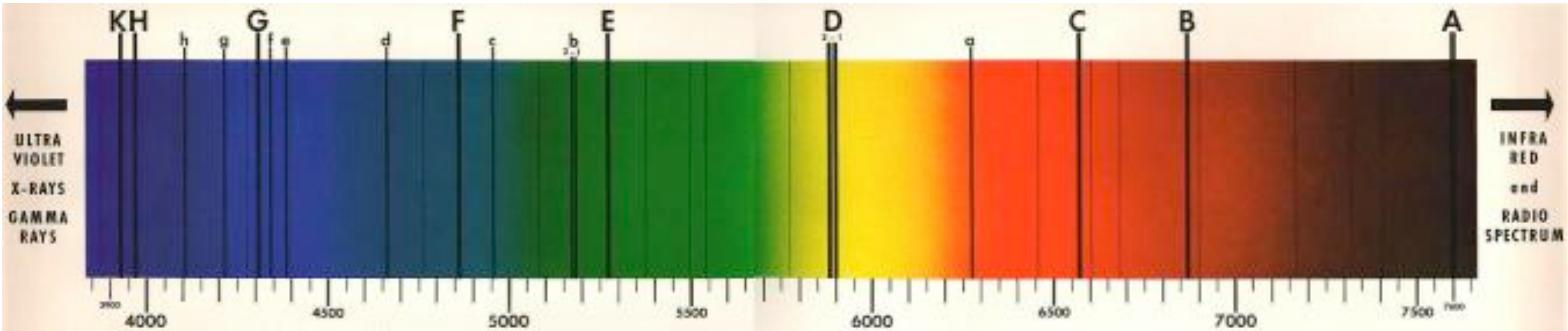
A *spectrometer* is a device for sending light of different wavelengths in different directions.



Many objects when heated show the same shape to their spectrum, called a *blackbody spectrum*. A black body gives off radiation at many wavelengths, but has a strong peak at a particular wavelength. The hotter the object, the shorter the wavelength: *hotter* objects have *bluer* spectra.



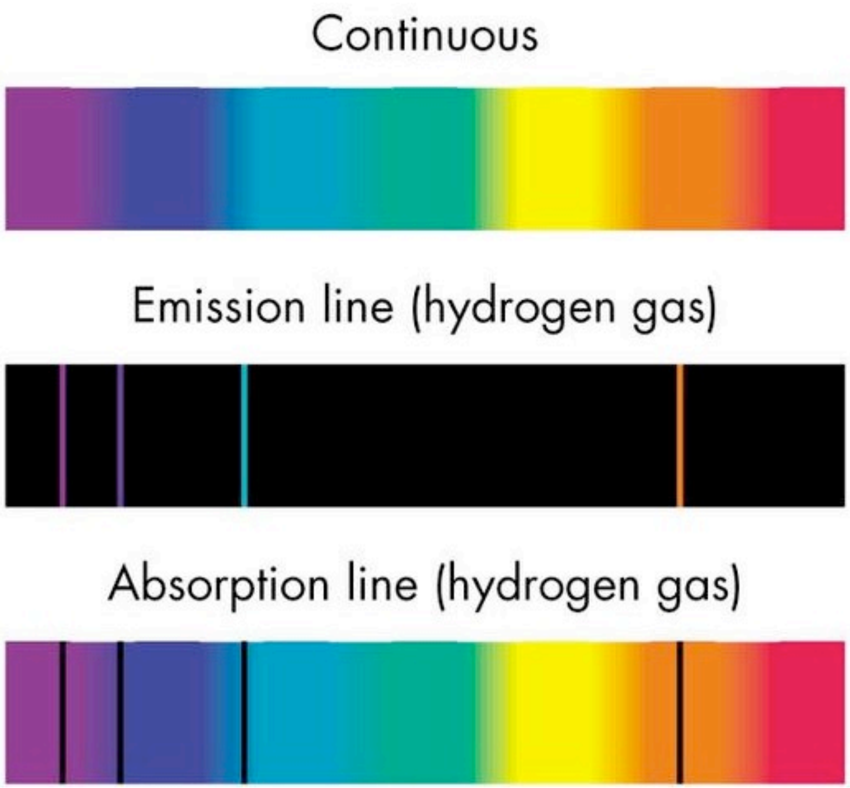
Joseph Fraunhofer, in 1814, discovered that the solar spectrum was not just a continuous band of colour, but was crossed by numerous dark bands, which never changed their position.

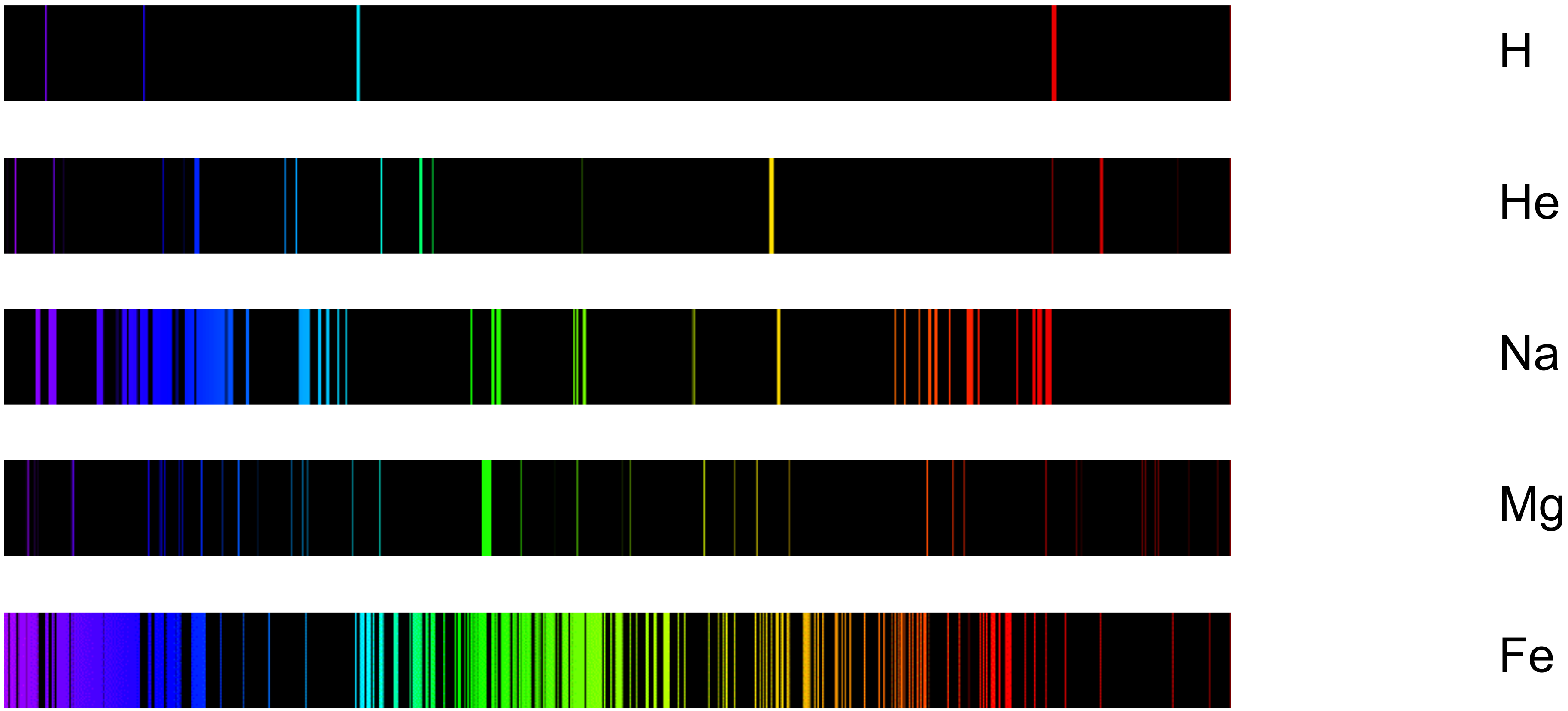


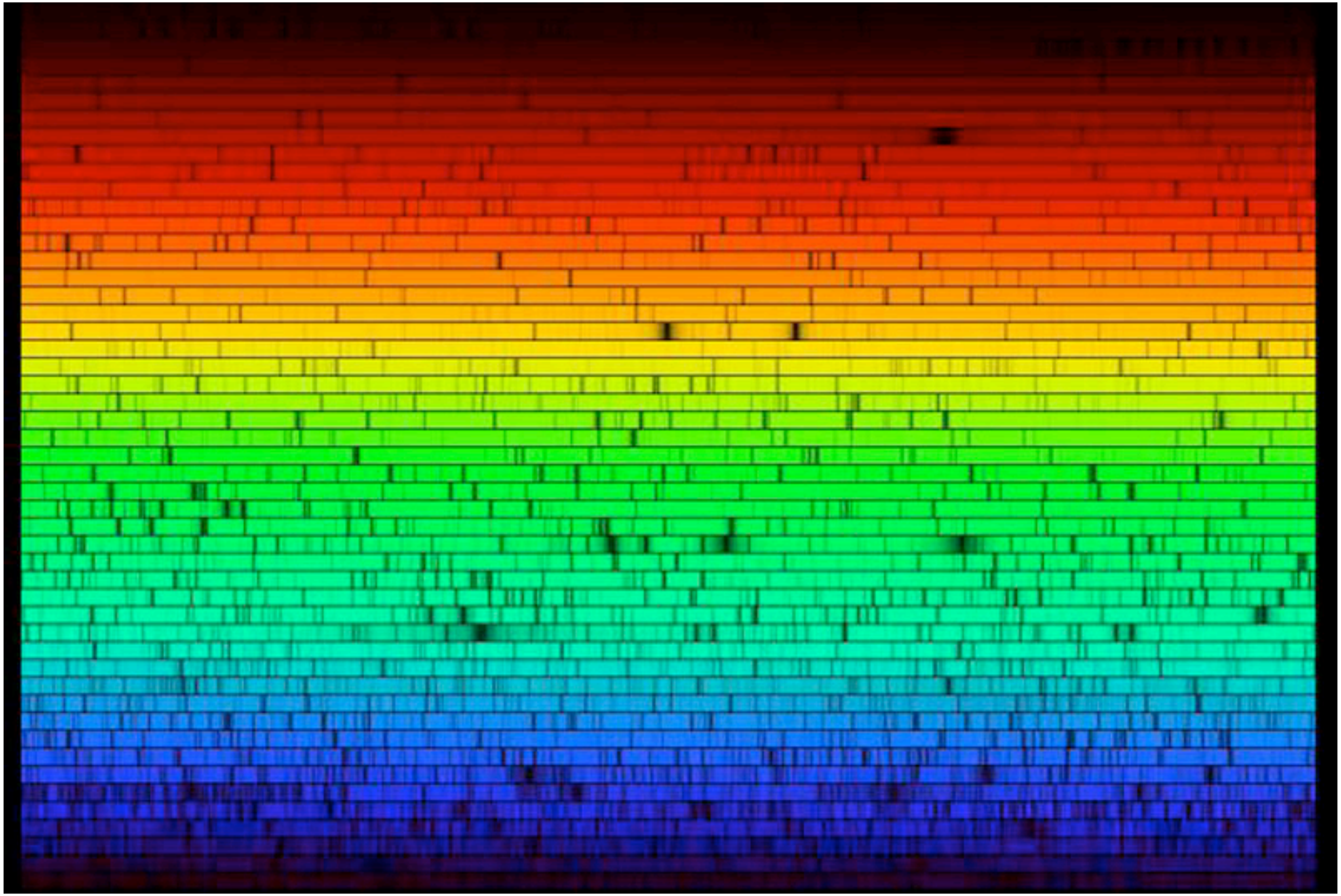
Gustav Kirchhoff, in 1859, discovered that a heated substance produced a series of coloured lines, and that this pattern was unique for each chemical element.

He found that there are three different types of spectra:

- *Continuous* spectrum (hot, high pressure gas or solid)
- Bright *emission* lines (hot, low pressure gas)
- Dark *absorption* lines (cool, low pressure gas)




H
He
Na
Mg
Fe

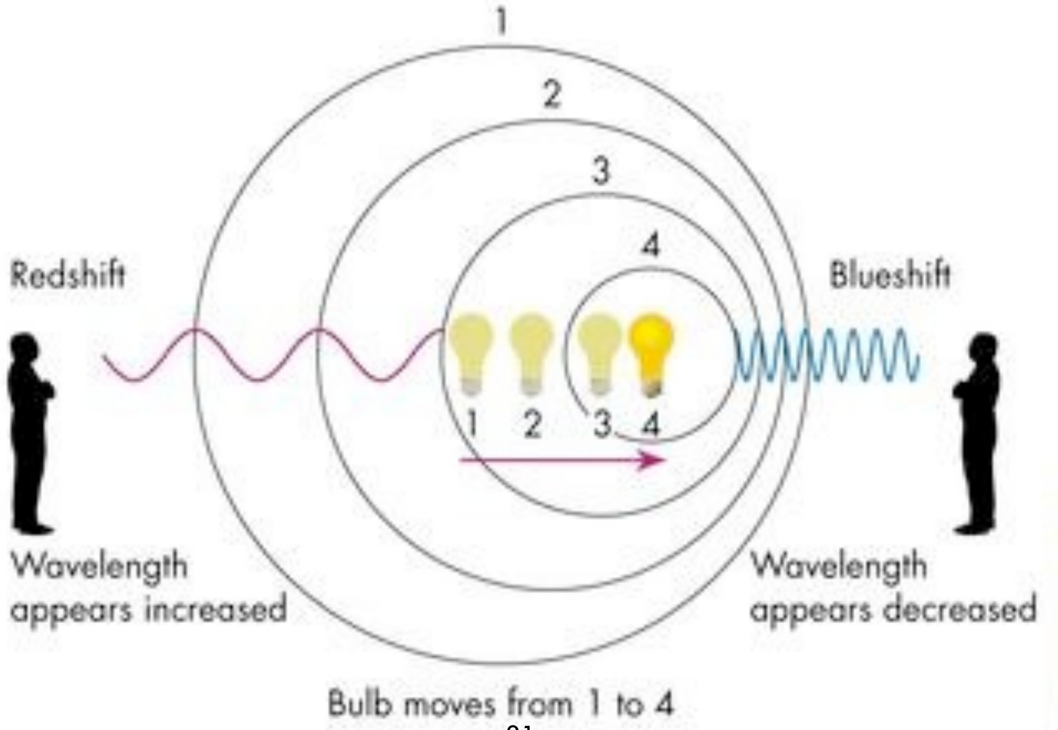


High resolution solar spectrum

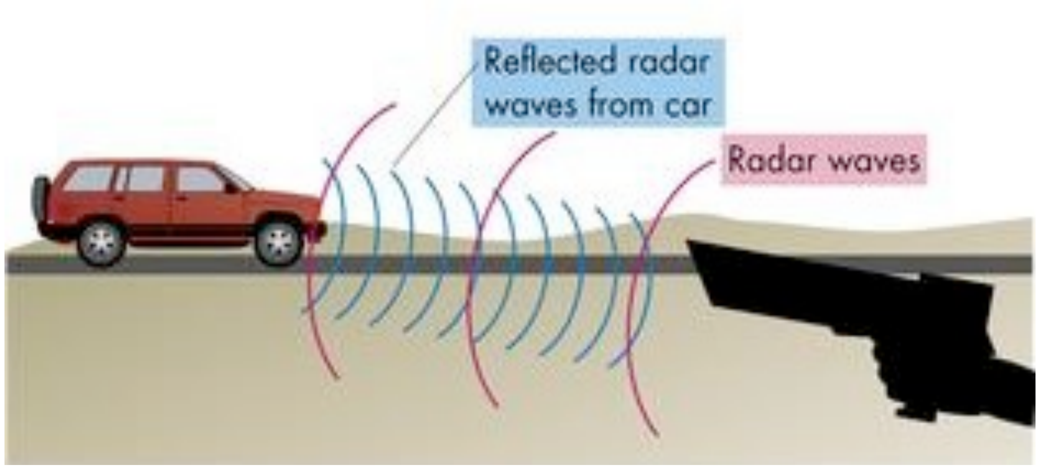
Each element produces a unique fingerprint.

In many ways, this represents the beginning of astronomy as a science. Suddenly it was possible to study the composition of heavenly bodies using nothing but light!

Because light is made of waves, the wavelength will change if the emitting object is moving: the *Doppler effect*. A source moving towards you has a shorter wavelength (*blueshift*), a source moving away has a longer wavelength (*redshift*).



This is how police speed radars work: the shift in frequency gives the speed of the car.



Blueshifted, approaching you

Stationary

Redshifted, receding from you

The amount of shift you get depends on the velocity: faster objects have the spectral lines shifted further from the rest wavelength.

So astronomers have to use a lot of inference to understand what is going on:

- images: *the shape of an object*
- spectra: *what it's made of, how fast it's moving…*
- multi-wavelength images: *how it works*

Case study: Hanny's Voorwerp

In 2007, Hanny van Arkel, a Dutch school teacher and volunteer for the Galaxy Zoo project, discovered a giant green object near an ordinary spiral galaxy.

Nothing like it had ever been seen before.

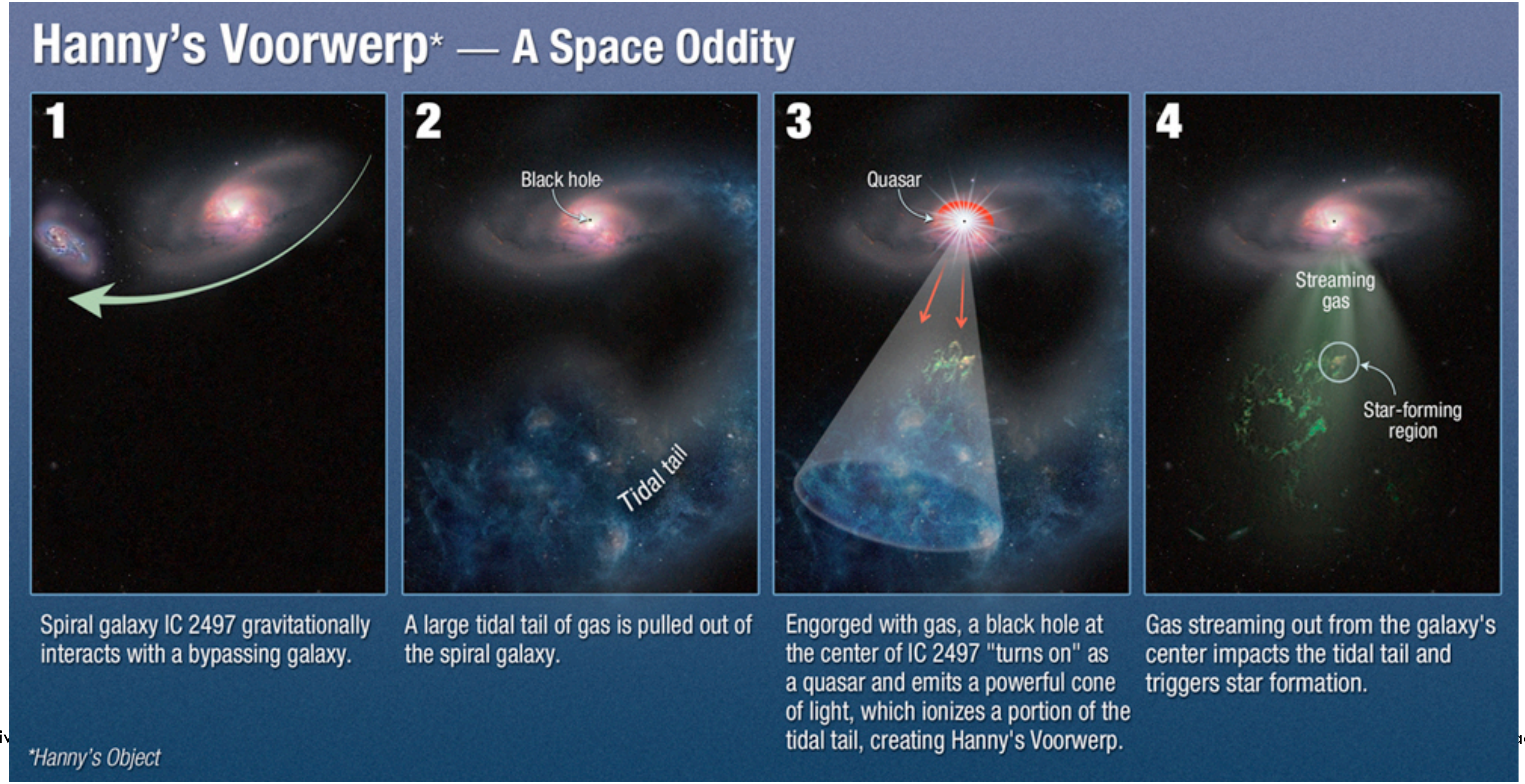
Original SDSS image of Hanny's Voorwerp

Astronomers all over the world used many telescopes at different wavelengths to try to understand it.

Spectra of the object showed that it is at the same distance as the nearby galaxy, and is about the same size. The light is produced by hot glowing gas: the green colour is produced by ionised oxygen atoms.

Hubble image of Hanny's Voorwerp

Our best guess is that the gas, ripped from another galaxy, is glowing because it was illuminated by a quasar which has since switched off.



Next week

... we'll take a look at our Solar System,
and what it's made of.

Further reading

For the whole course:

- For astronomical images, you can't do better than the "**Astronomy Picture of the Day**" website, http://antwrp.gsfc.nasa.gov/apod/astropix.html. Not only does this have a fabulous archive of the most amazing pictures (and a new one every day), each image also has links to many other interesting sites where you can follow up the topic. I've used APOD as the source for many of the images here, mostly because it's so convenient. If you prefer to have your pictures in a form you can hold (and show off to friends), a selection has been published as a book, in "**Universe: 365 Days**" by R. J. Nemiroff and J. T. Bonnell (Harry N. Abrams, 2003), with a follow-up volume called "**Astronomy: 365 Days**" (2006)

- There are many excellent introductory-level texts which cover the material in this course. A good example is "**Horizons: Exploring the Universe**" by Michael A. Seeds (Brooks/Cole, 2000); or the text we use for our first-year introductory astronomy course is "**The Cosmic Perspective**" by Bennett et al. (Pearson, 2010)

- NASA has a site called "**Imagine the Universe**", http://imagine.gsfc.nasa.gov/index.html which is a good place to start for finding out about all things astronomical. It also has excellent links to other places on the Web to find information.

For tonight's lecture:

- **"Imagine the Universe"** has a nice page about the electromagnetic spectrum: http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html

- For more galaxies and other objects in many wavelengths, take a look at IPAC's **"The Multiwavelength Astronomy Gallery"**, http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/ ; or the **"Multiwavelength Milky Way"**, http://mwmw.gsfc.nasa.gov/

- Mike Brown, the discoverer of Eris, has an excellent blog about scale in the Solar System, and how hard it is to depict planetary scales accurately, at http://www.mikebrownsplanets.com/2009/08/planetary-placemats.html

- There's a lovely book on the same topic: **"Sizing up the Universe:** The cosmos in perspective" by J. Richard Gott and Robert J. Vanderbei (National Geographic, 2011). It's like a meditation about size and scale, and the centrepiece is their "Logarithmic Map of the Universe" – a version of which can be found at http://www.astro.princeton.edu/universe/ (though not as pretty). xkcd has a similar idea in the cartoon just called "Height" http://xkcd.com/482/

- The Galaxy Zoo project is a "citizen science" project where members of the public assist in research by classifying galaxies observed in the Sloan Digital Sky Survey: http://www.galaxyzoo.org/. There are other associated projects: classifying features on the Moon (https://www.zooniverse.org/project/moonzoo), finding planets around other stars (https://www.zooniverse.org/project/planethunters), and classifying Hubble galaxy pictures (https://www.zooniverse.org/project/hubble)

- Hanny van Arkel has her own blog, where she talks about the discovery of her *voorwerp*: http://www.hannysvoorwerp.com/

Sources for images used:

- Title image: The barred spiral galaxy NGC 613, taken by ESO's Very Large Telescope. From ESO Press Release, 19 December 2003 http://www.eso.org/public/outreach/press-rel/pr-2003/phot-33-03.html
- Eta Aquarid & Milky Way Reflections: image by Mike Taylor, from APOD 2014 May 9 http://apod.nasa.gov/apod/ap140509.html
- Earth: View of the Earth from space, Eastern hemisphere, from "The Blue Marble: True-color global imagery at 1 km resolution" http://earthobservatory.nasa.gov/Newsroom/BlueMarble
- Valles Marineris hemisphere of Mars: from NASA Planetary Photojournal,http://photojournal.jpl.nasa.gov/catalog/PIA00407
- *Cassini* view of Jupiter: from NASA Planetary Photojournal, http://photojournal.jpl.nasa.gov/catalog/PIA02873
- Asteroid Ida and its moon Dactyl: from Views of the Solar System by Calvin J. Hamilton http://www.solarviews.com/cap/ast/idamnclr.htm
- Callisto (second largest moon of Jupiter): from NASA Planetary Photojournal, http://photojournal.jpl.nasa.gov/catalog/PIA03456
- Hyperion (moon of Saturn): from APOD 2013 Jun 30 http://apod.nasa.gov/apod/ap130630.html
- Comet 67P/Churyumov-Gerasimenko: from the JPL Rosetta site http://rosetta.jpl.nasa.gov/gallery/images/comet-67p/churyumov-gerasimenko
- Comet: Comet Hale-Bopp in 1997, from APOD 2000 December 27 http://antwrp.gsfc.nasa.gov/apod/ap001227.html
- Sun: APOD 2003 July 29 http://antwrp.gsfc.nasa.gov/apod/ap030729.html
- Eagle nebula: APOD 1997 January 19 http://antwrp.gsfc.nasa.gov/apod/ap970119.html
- Star forming region M43, APOD 2015 Jul 10 http://apod.nasa.gov/apod/ap150425.html
- Keyhole Nebula: Hubble Heritage Project, http://heritage.stsci.edu/2000/06/index.html
- Cluster and Starforming Region Westerlund 2 APOD 2015 April 25 http://apod.nasa.gov/apod/ap150425.html
- Open cluster: M11 APOD 2003 January 22 http://antwrp.gsfc.nasa.gov/apod/ap030122.html
- Planetary nebula: The Helix Nebula APOD 2014 Oct 12 http://apod.nasa.gov/apod/ap141012.html
- Cat's Eye Nebula: APOD 2014 Oct 12 http://apod.nasa.gov/apod/ap141012.html
- Artist's interpretation of the white dwarf star H1504+65: from “Naked White Dwarf Shows its Dead Stellar Engine” http://www.space.com/scienceastronomy/mystery_monday_040705.html
- Stars in Scorpius: from APOD 2012 September 12, http://apod.nasa.gov/apod/ap120912.html
- Stars and dust in the Milky Way: from Astronomy Picture of the Day, 2003 September 28, http://antwrp.gsfc.nasa.gov/apod/ap030928.html
- Spiral galaxy: M51, from the Hubble Heritage Project, http://heritage.stsci.edu/2005/12a/index.html
- Group of galaxies: the Hickson Compact Group HCG 87; APOD 1999 September 6 http://antwrp.gsfc.nasa.gov/apod/ap990906.html
- Virgo cluster: APOD 2015 Aug 4 http://apod.nasa.gov/apod/ap150804.html
- Hercules cluster: APOD 2014 June 25 http://apod.nasa.gov/apod/ap140625.html
- Sheets and bubbles of galaxies: from the Illustris Project http://www.illustris-project.org/explorer/
- Distance ladder: from Spitzer mission pages http://www.nasa.gov/mission_pages/spitzer/multimedia/pia15818_prt.htm
- Nine planets: Solar system montage, PIA01341 from the NASA Planetary Photojournal http://photojournal.jpl.nasa.gov/catalog/PIA01341
- Planets and sun to scale: from IAU Draft Definition of “planet” http://www.iau.org/public_press/news/detail/iau0601/
- Scale model of the Solar System: from “The Thousand-Yard Model” by Guy Ottewell http://www.noao.edu/education/peppercorn/pcmain.html

- Updike: quoted in Hirshfeld, “Parallax: The Race to Measure the Cosmos”, p. 68
- Quasar image: from “High Redshift Quasars in the ING Wide Field Survey”, http://www.ing.iac.es/PR/newsletter/news4/science1.html
- Distances of stars in the Southern Cross: from “Distances” by Peter Caldwell, http://users.netconnect.com.au/~astronet/dist.html. Used with permission
- Electromagnetic spectrum: from “Imagine the Universe” http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html
- Wavelength: from “Cool Cosmos”, http://coolcosmos.ipac.caltech.edu/cosmic_classroom/cosmic_reference/emspec.html
- Wavelength as a function of temperature: from Astro11230 by Richard McCray http://cosmos.colorado.edu/cw2/courses/astr1120/text/chapter1/lesson1.html
- Atmospheric transmission from Wikipedia: Space observatory http://en.wikipedia.org/wiki/Space_observatory. Current astronomical missions: from http://nssdc.gsfc.nasa.gov/astro/astrolist.gif. NASA Great Observatories: from Chandra http://chandra.harvard.edu/resources/illustrations/elec_mag_spec.html
- Wavelength scales: from “Cool Cosmos” page, http://coolcosmos.ipac.caltech.edu/cosmic_classroom/cosmic_reference/emspec.html
- Multi-wavelength images of Cen A: from “The Many Faces of Centaurus A”, http://www.mpe.mpg.de/~hcs/Cen-A/cen-a-pictures.html
- Multi-wavelength images of M51: from Angel Lopez-Sanchez http://oldweb.aao.gov.au/local/www/alopez/multiwave.html
- Prism: from "How Stuff Works" http://science.howstuffworks.com/question41.htm
- Blackbody spectrum: from "Explorations" by Thomas T. Arny, Fig. 3.6 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch03/0306.html
- Fraunhofer lines: from "Quantum Physics" by S. Raychaudruri, http://home.iitk.ac.in/~sreerup/BSO203.html
- Types of spectra: from "Explorations" by Thomas T. Arny, Fig. 3.15 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch03/0315.html
- Doppler shifts: from "Explorations" by Thomas T. Arny, Fig. 3.18 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch03/0318.html
- Red and blue shifts: from "Above the Skies: An exploration into our universe through animated spectroscopy", http://hea-www.harvard.edu/~efortin/thesis/html/index.shtml
- Hanny’s Voorwerp: from APOD 2008 June 25 http://apod.nasa.gov/apod/ap080625.html and 2011 February 10 http://apod.nasa.gov/apod/ap110210.html. Explanation sketches from HubbleSite release STScI-2011-01 http://hubblesite.org/newscenter/archive/releases/2011/01/.