



# An Introduction to Astronomy

Helen Johnston  
School of Physics  
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...*




# Mankind set to cross the final frontier

September 10, 2012

☆ Read later

Voyager 1, launched 35 years ago with messages of love from the Earthlings, is on the brink of history with a move into interstellar space, writes Richard Gray.

 Tweet 75

 Recommend 225

 +1 17

 Share

 Pin it

 Email article  Print



This artist's rendering provided by NASA shows the Voyager spacecraft. Photo: AP/NASA

It will be one of the most important milestones in human history as, for the first time, an ambassador for mankind moves beyond the confines of our solar system.

NASA scientists are preparing for the moment, any day now, when the first of two spacecraft launched in the late 1970s crosses the invisible boundary that marks the start of "interstellar space".

## Blogs

NEAR-FUTURE WAR STORIES IN ...

“ Multiplayer is the key to *Call of Duty's* success, but ... ”



Posted in: [Screen Play](#)

Date: Sep 11, 2012, 4:32AM

## Compare & Save

Deals Compare Popular

6 of 1

### Compare Plans & Deals

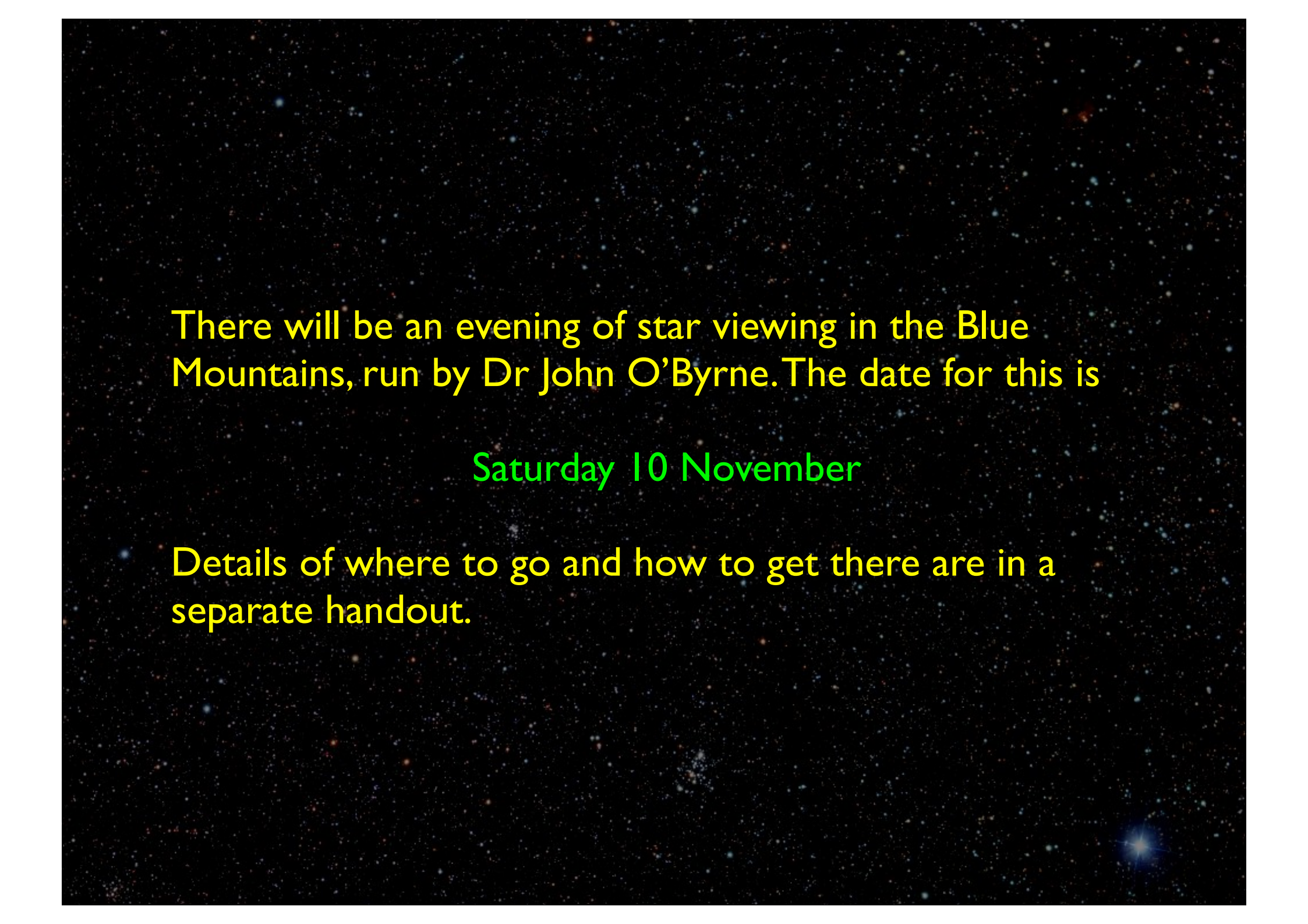
The most popular Android phone on the market right now...

Compare Now



Deals powered by WhistleOut

whistle

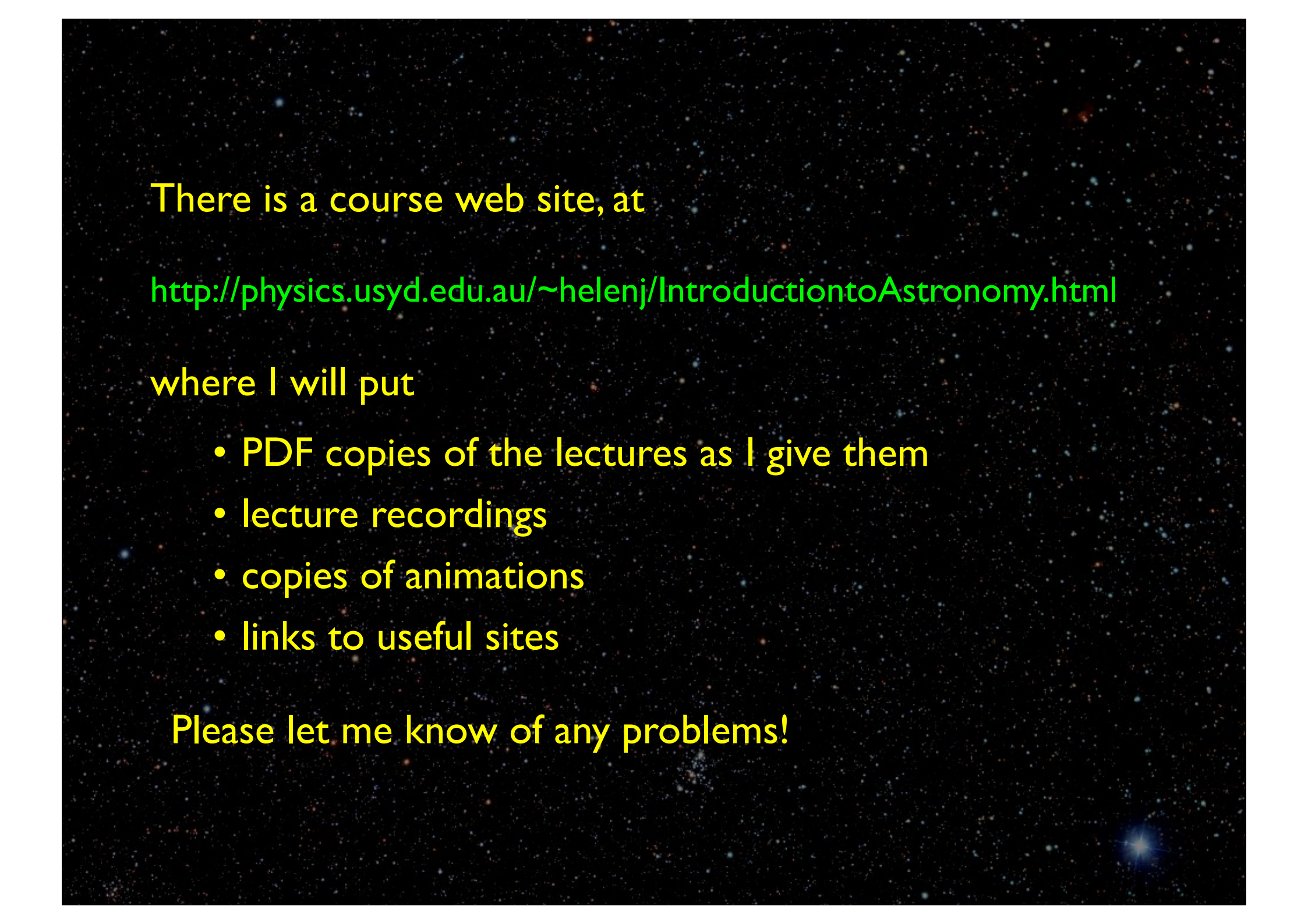


There will be an evening of star viewing in the Blue Mountains, run by Dr John O'Byrne. The date for this is

Saturday 10 November

Details of where to go and how to get there are in a separate handout.





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!



# Introduction to Astronomy

## Lecture I:

# The Universe: a guided tour

University of Sydney  
Centre for Continuing Education  
Spring 2012



# Outline

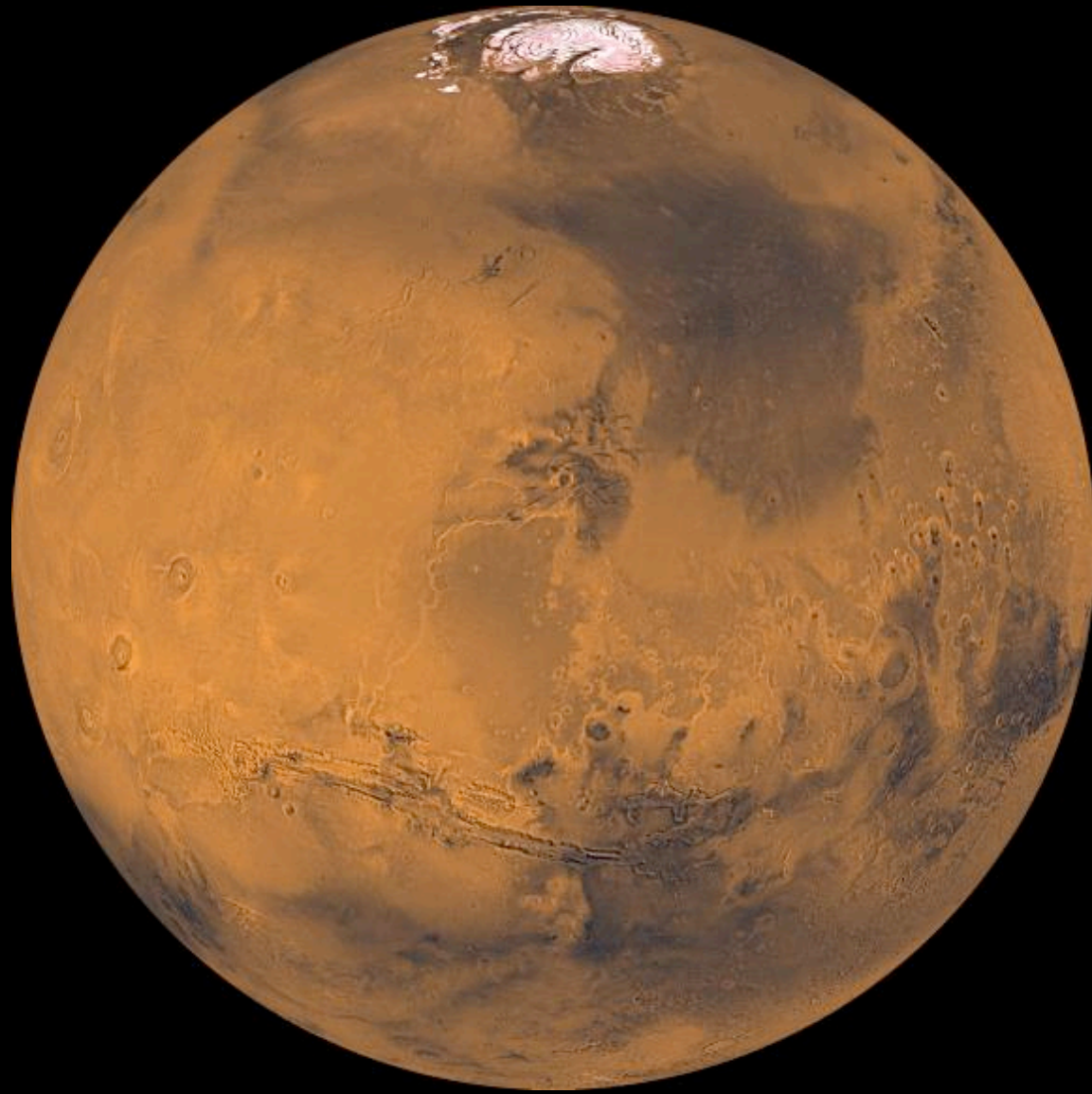
- A quick tour
  - *set the scene of where we are*
- The scale of astronomy
  - *just how big is the universe?*
- Electromagnetic radiation
  - *how do we find out about the universe?*

# A quick tour

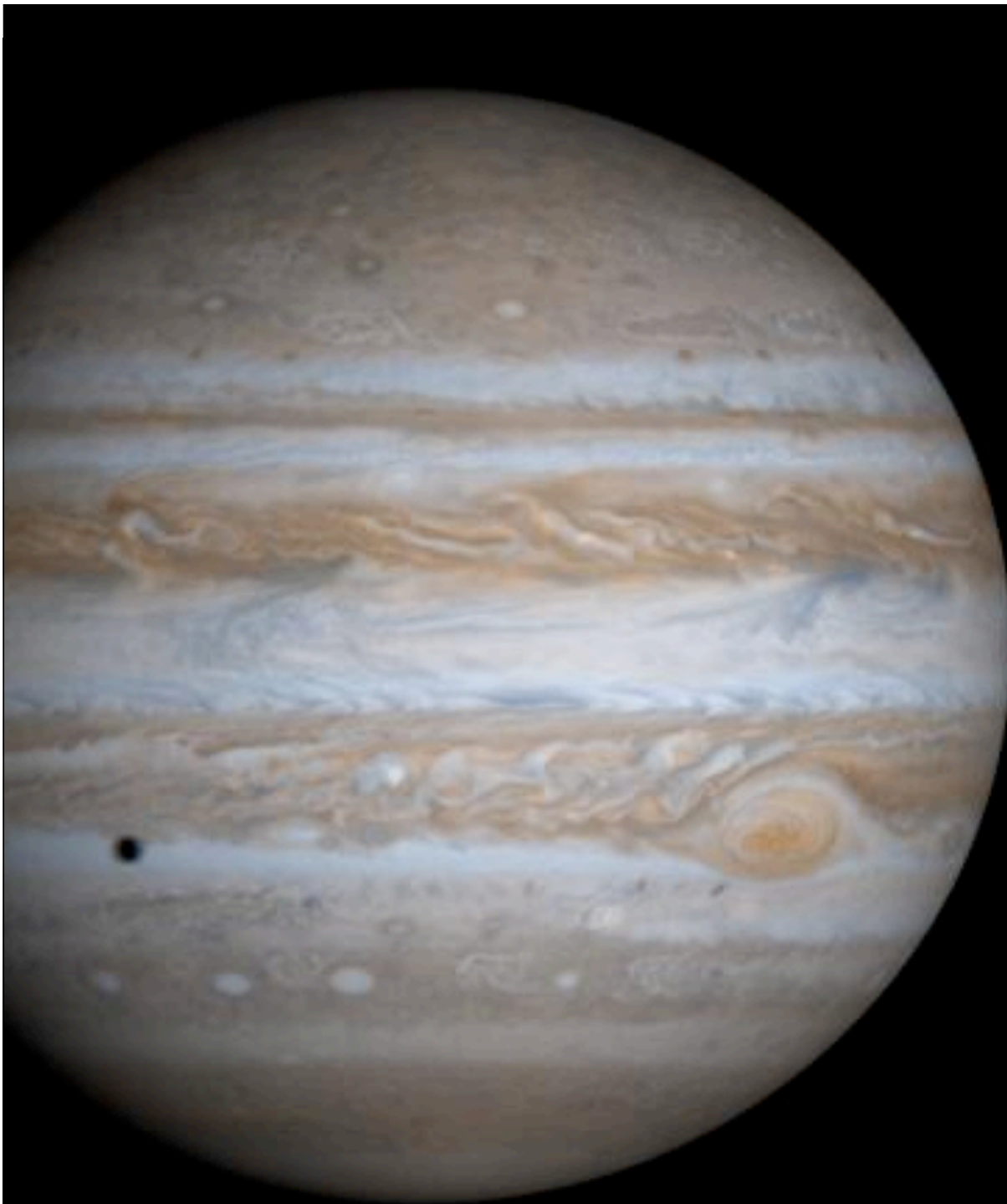


We are on a  
small planet...





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

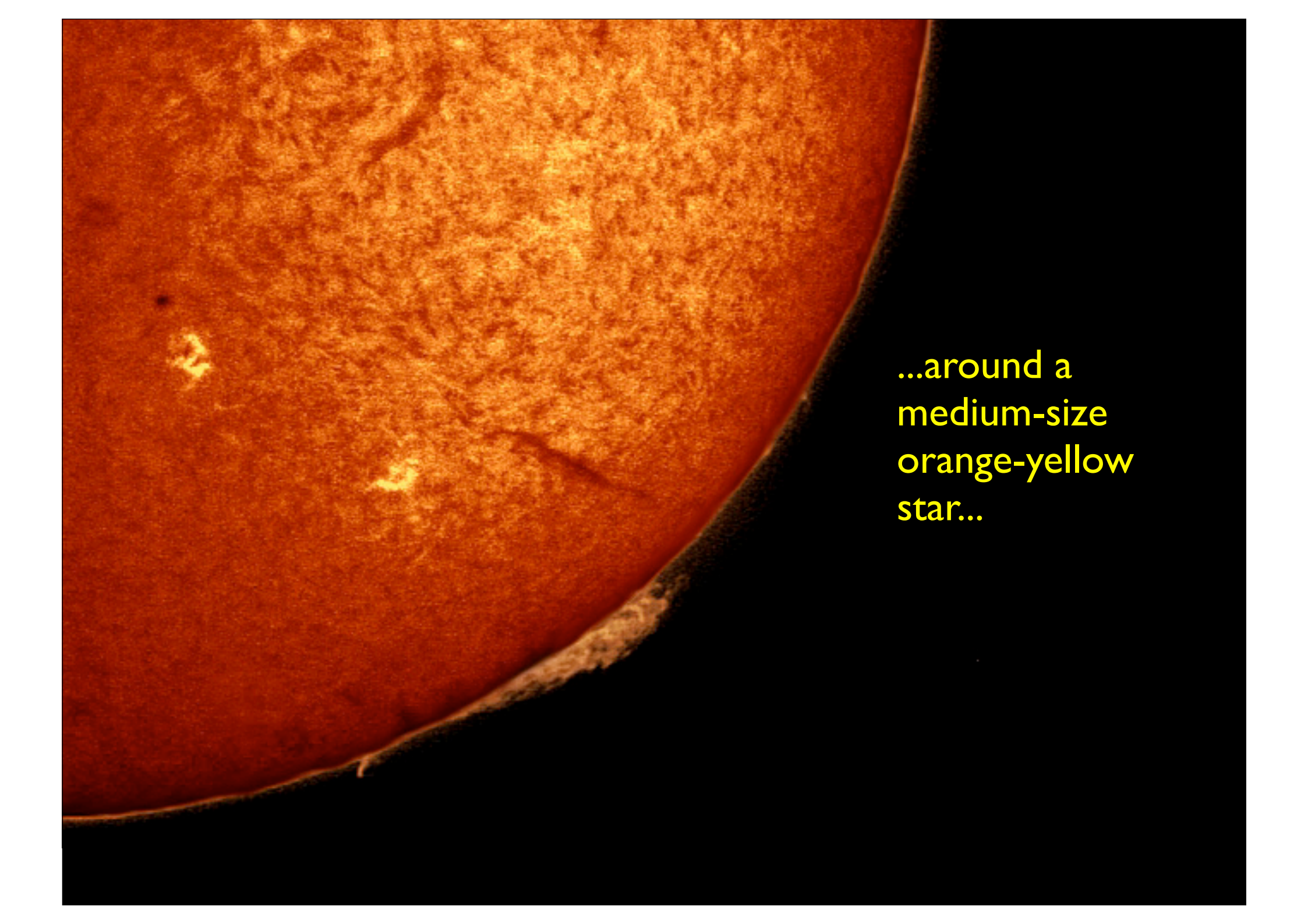


... orbiting with eight  
seven other planets...





... 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...





...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, spilling its  
gas back into interstellar  
space...





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

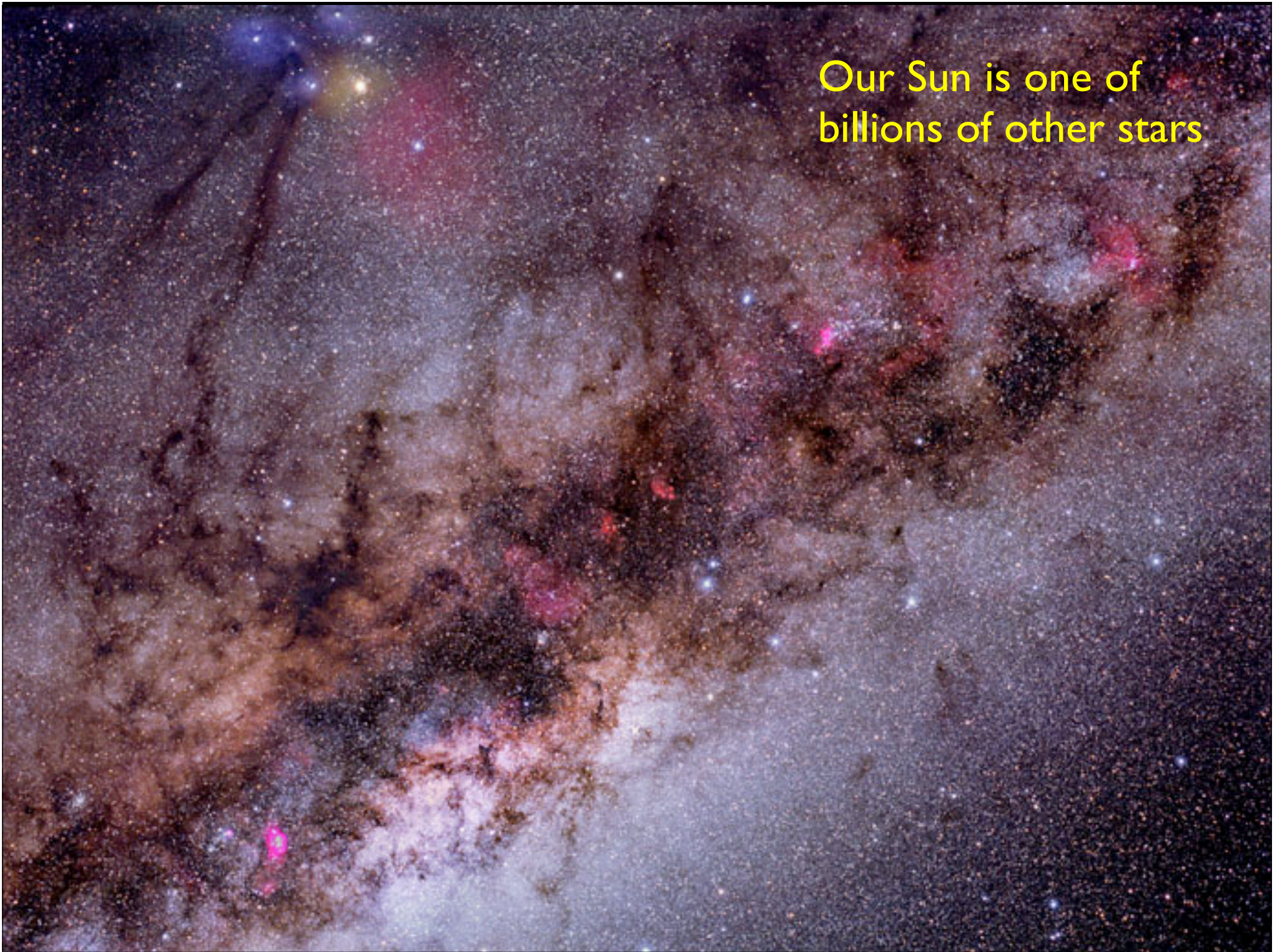


Our Sun is one of  
billions of other stars






Our Sun is one of  
billions of other stars





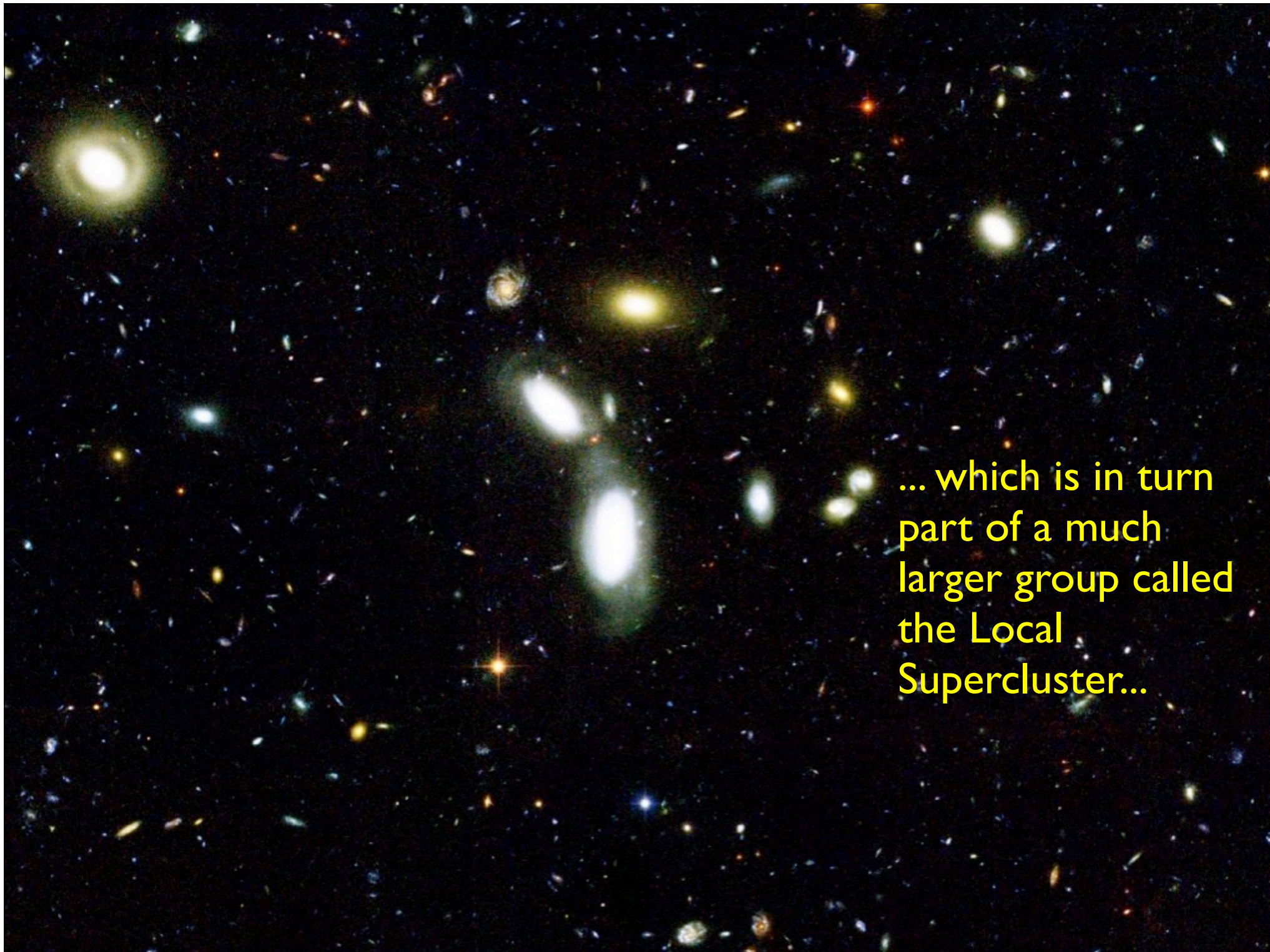


Our Sun is one of  
billions of other stars,  
about two-thirds of the  
way out along a spiral  
arm in a galaxy rather  
like this one...

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



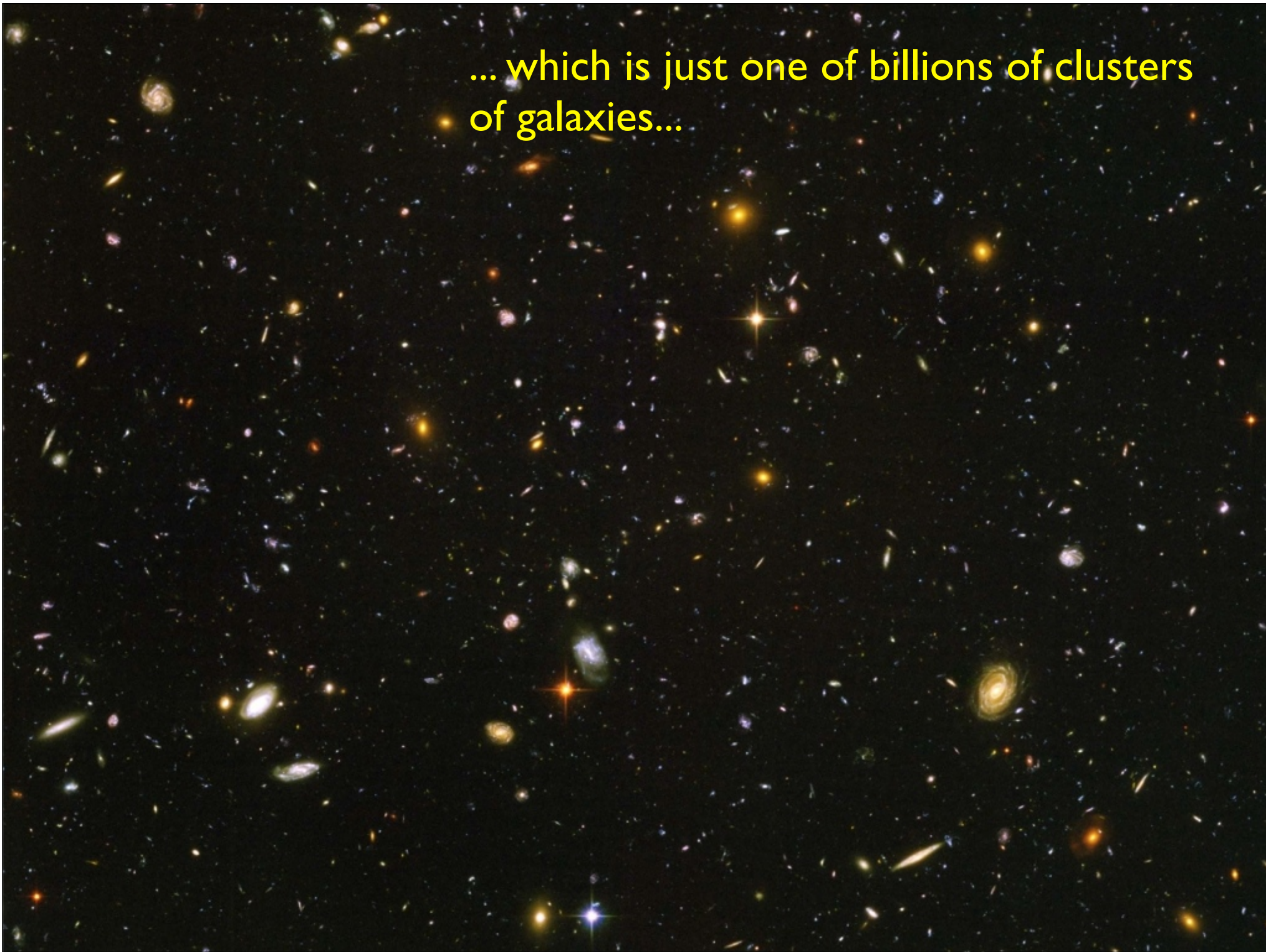




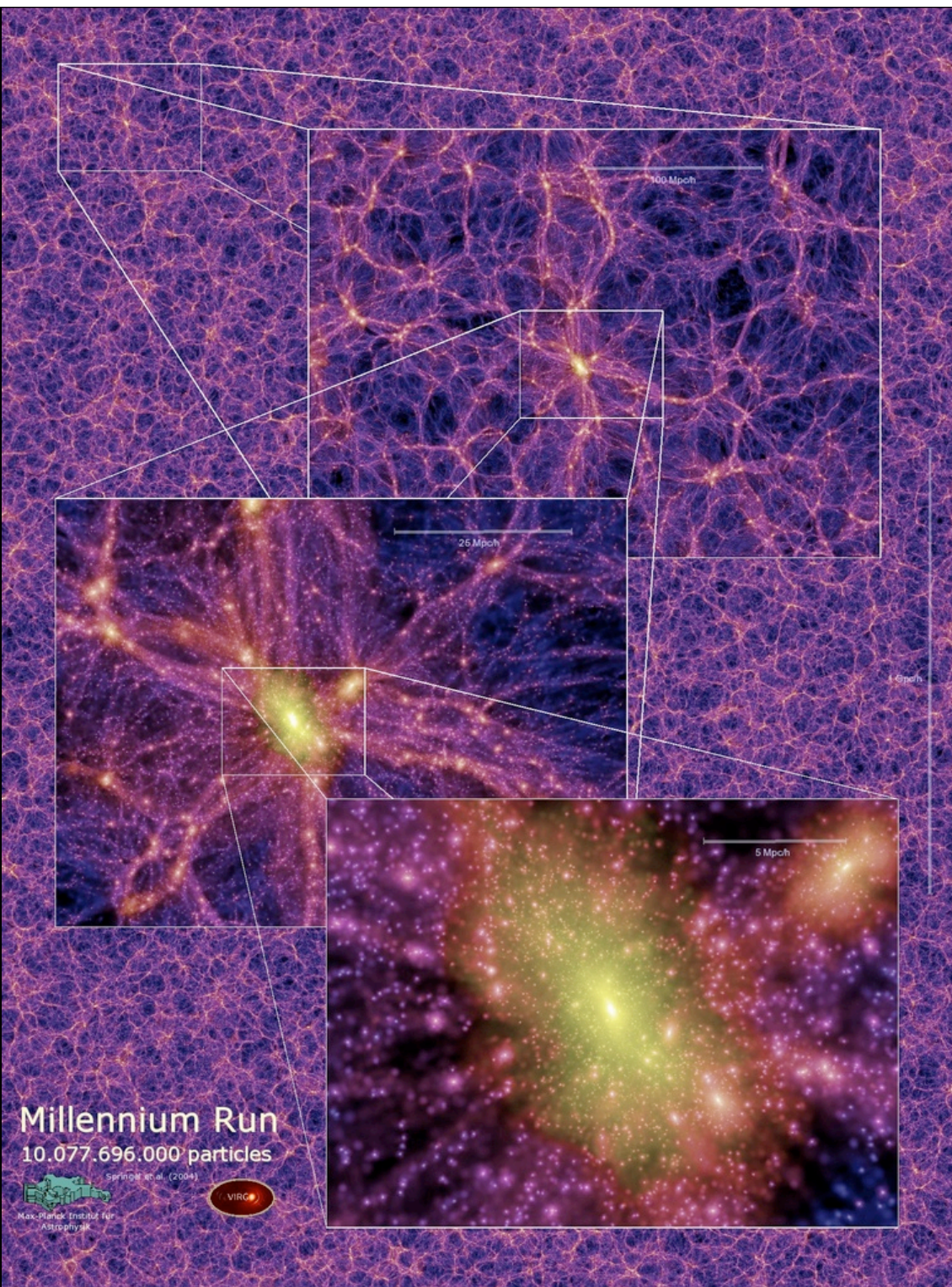
... which is in turn  
part of a much  
larger group called  
the Local  
Supercluster...



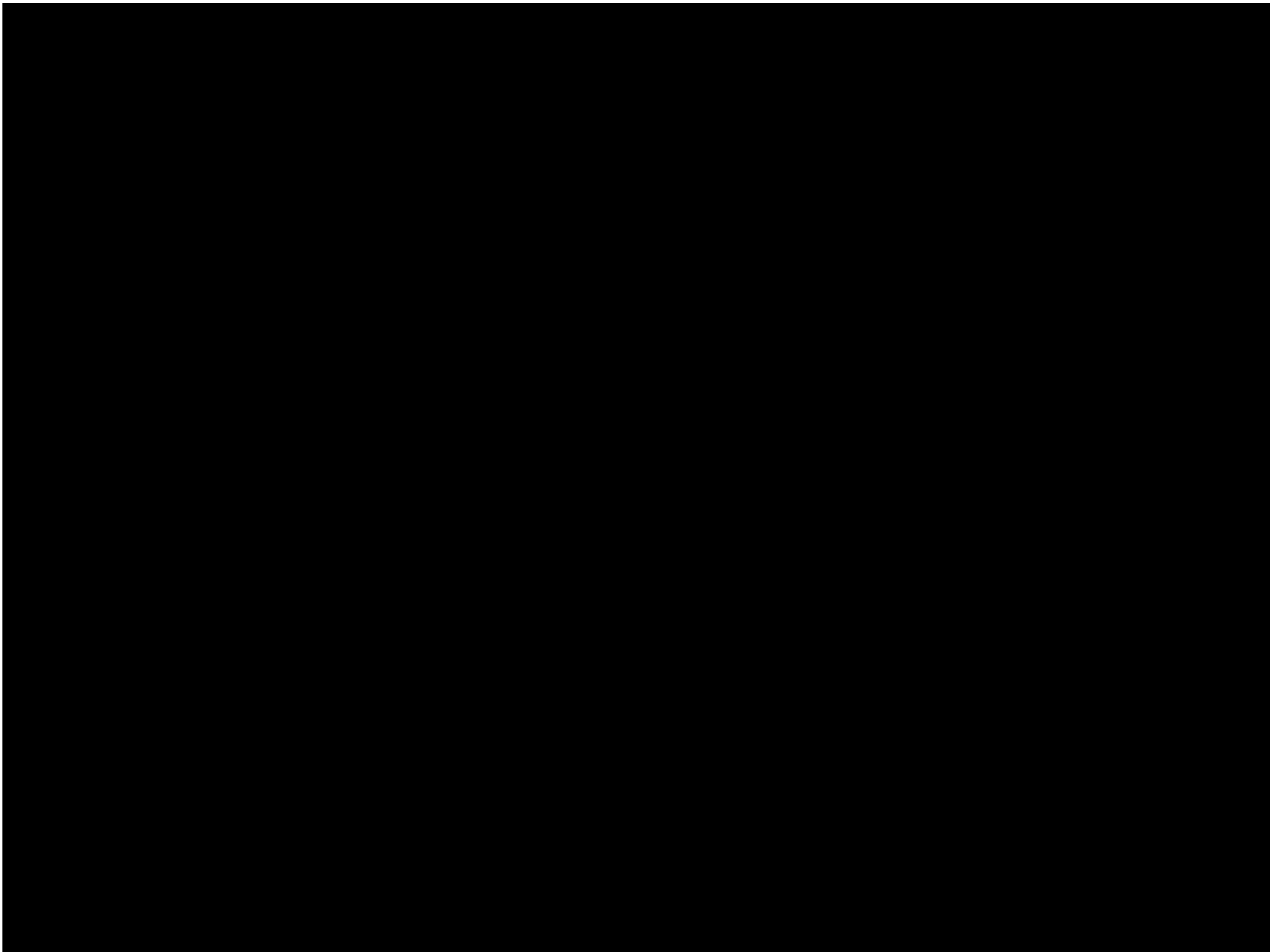
... which is just one of billions of clusters  
of galaxies...







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

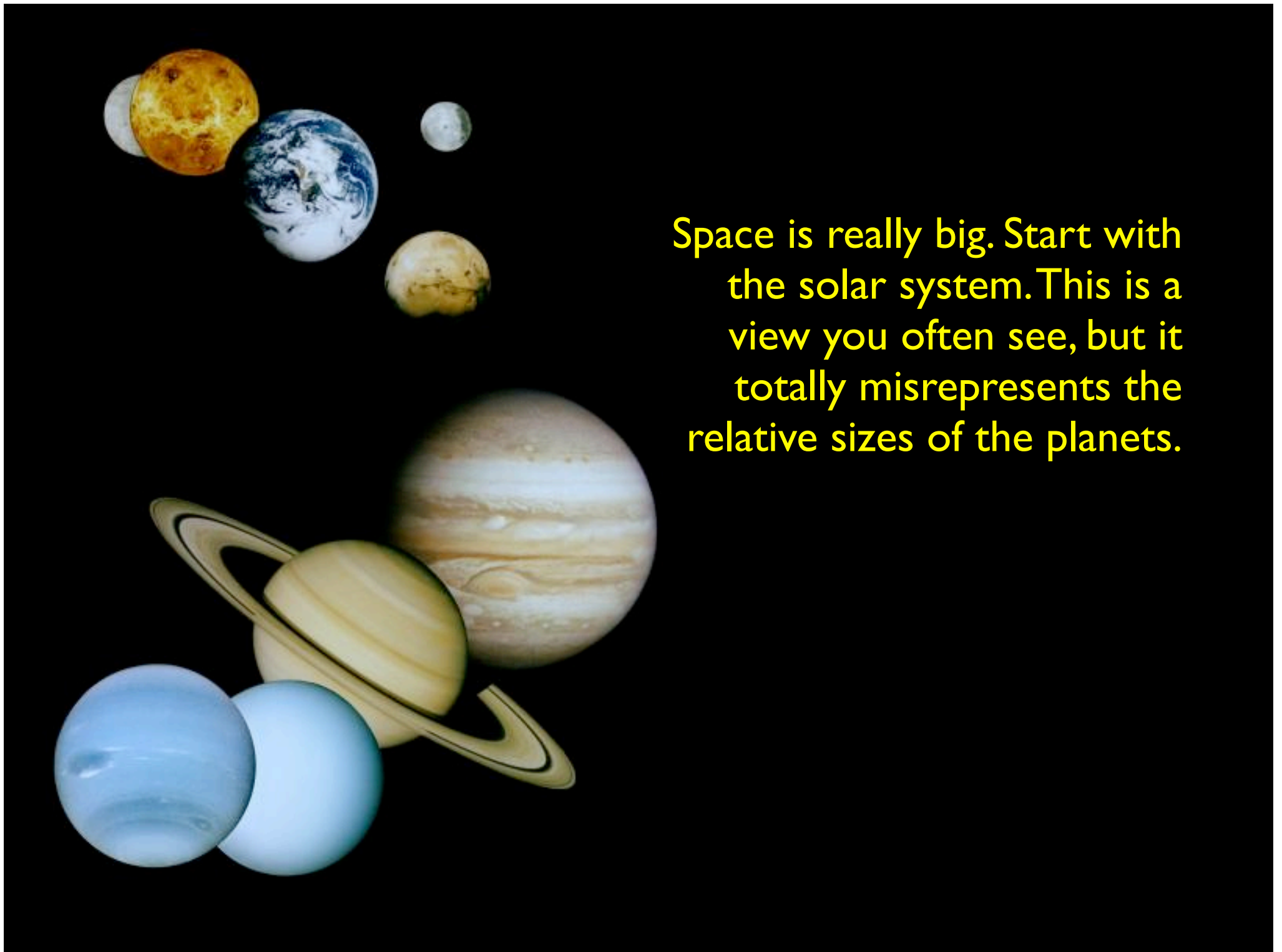




# The scales of astronomy

*“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.”*

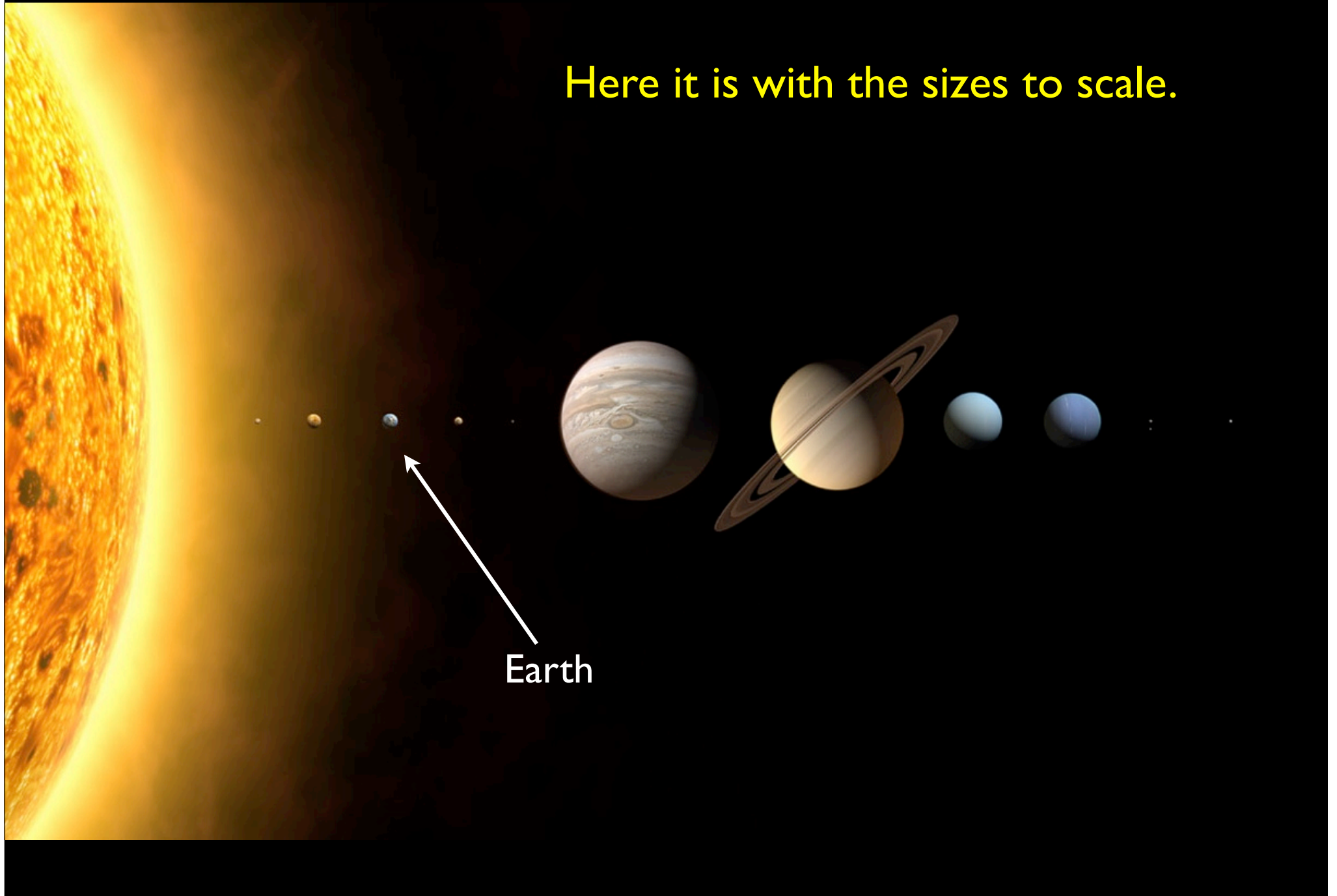
*– Douglas Adams, The Hitchhiker’s Guide to the Galaxy (1978)*

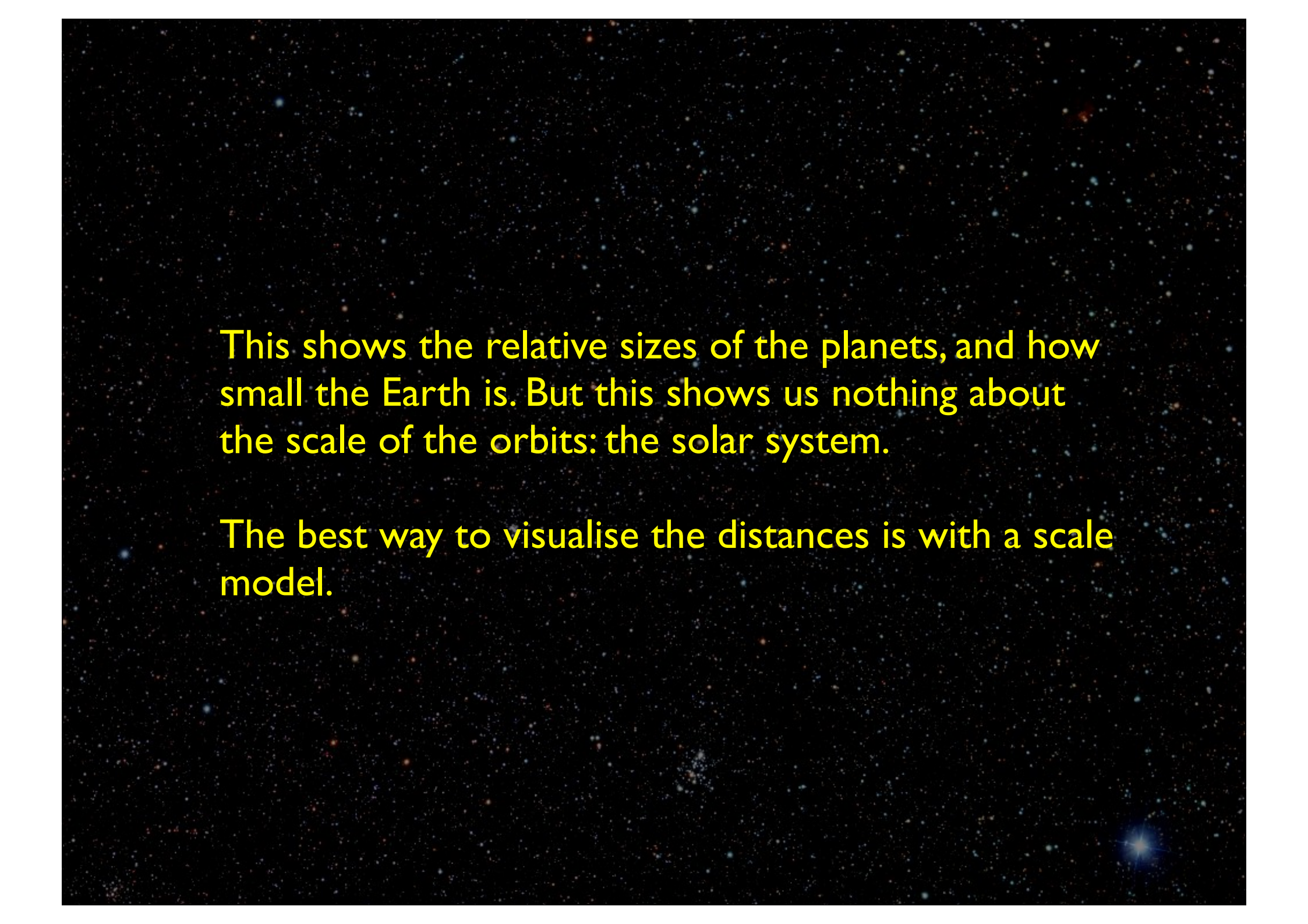


Space is really big. Start with the solar system. This is a view you often see, but it totally misrepresents the relative sizes of the planets.



Here it is with the sizes to scale.





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.

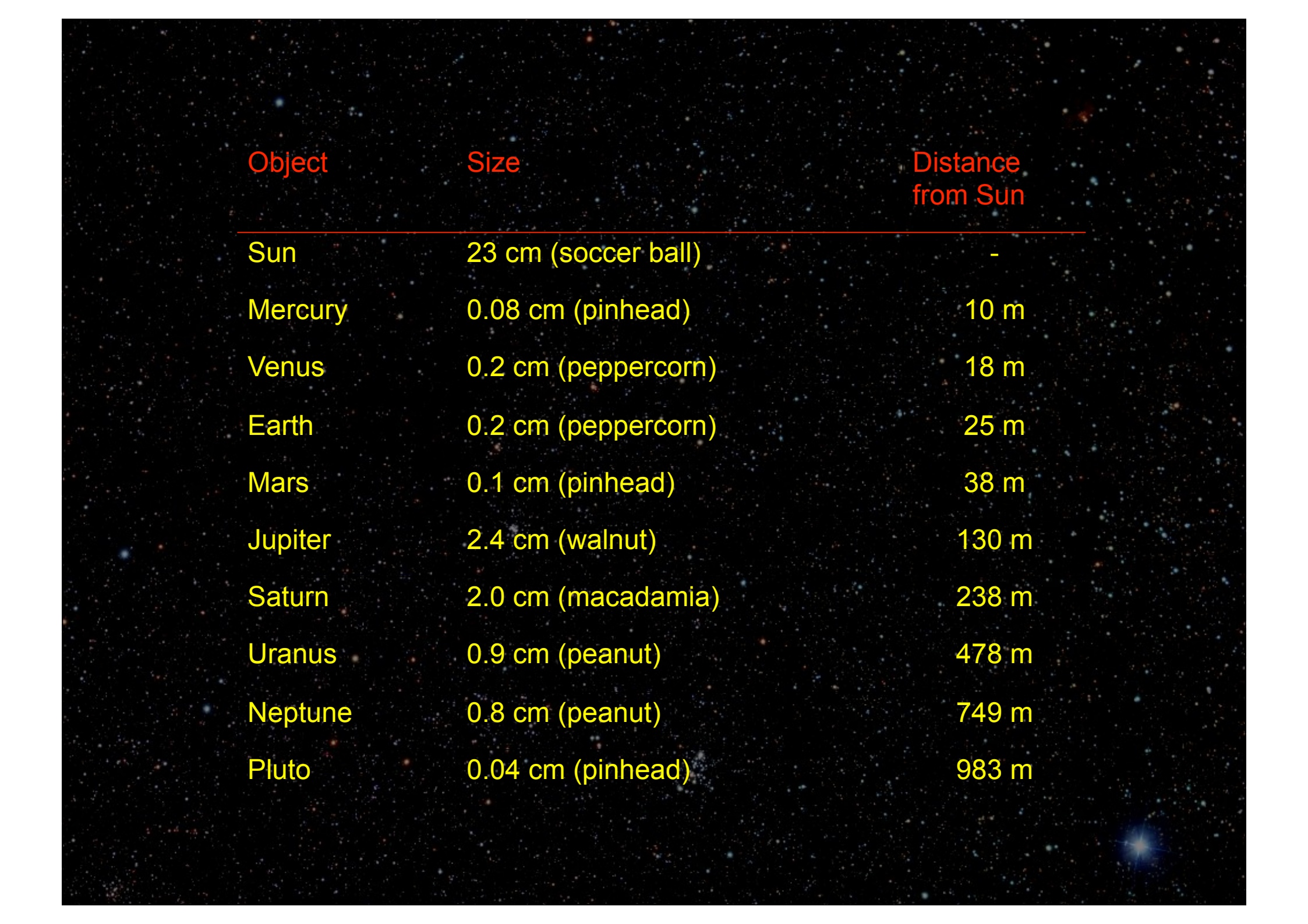
The best way to visualise the distances is with a scale model.





<http://solarsystemdrive.com/>

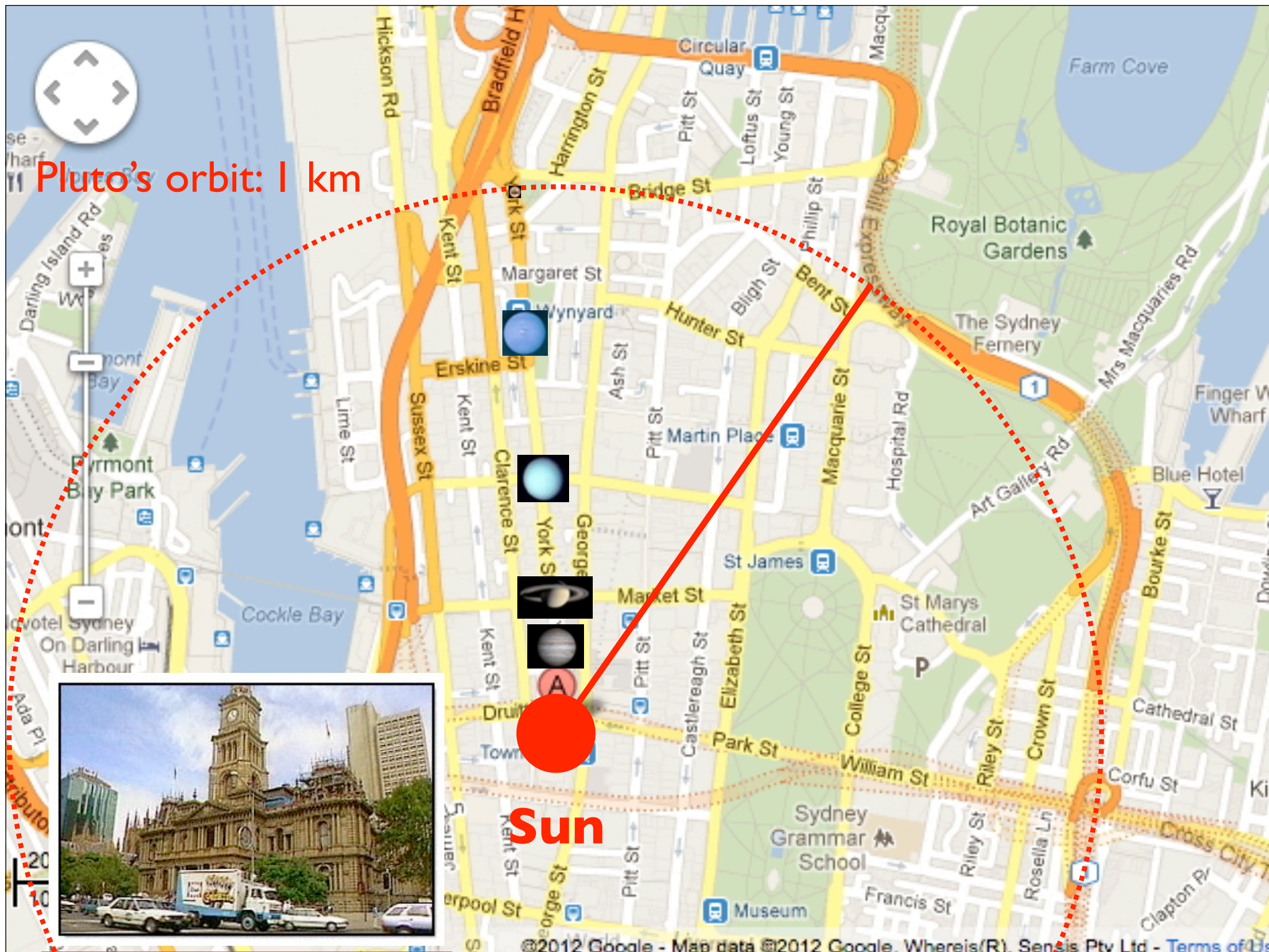




Object	Size	Distance from Sun
Sun	23 cm (soccer ball)	-
Mercury	0.08 cm (pinhead)	10 m
Venus	0.2 cm (peppercorn)	18 m
Earth	0.2 cm (peppercorn)	25 m
Mars	0.1 cm (pinhead)	38 m
Jupiter	2.4 cm (walnut)	130 m
Saturn	2.0 cm (macadamia)	238 m
Uranus	0.9 cm (peanut)	478 m
Neptune	0.8 cm (peanut)	749 m
Pluto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

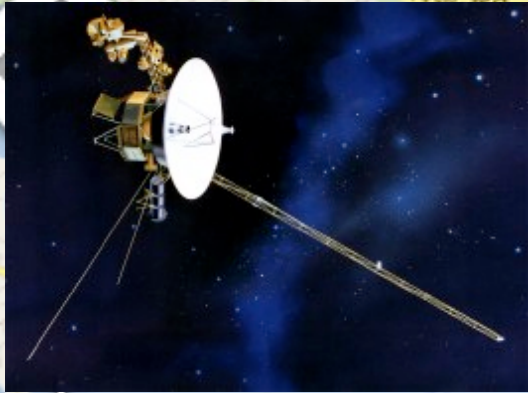


Pluto's orbit: 1 km

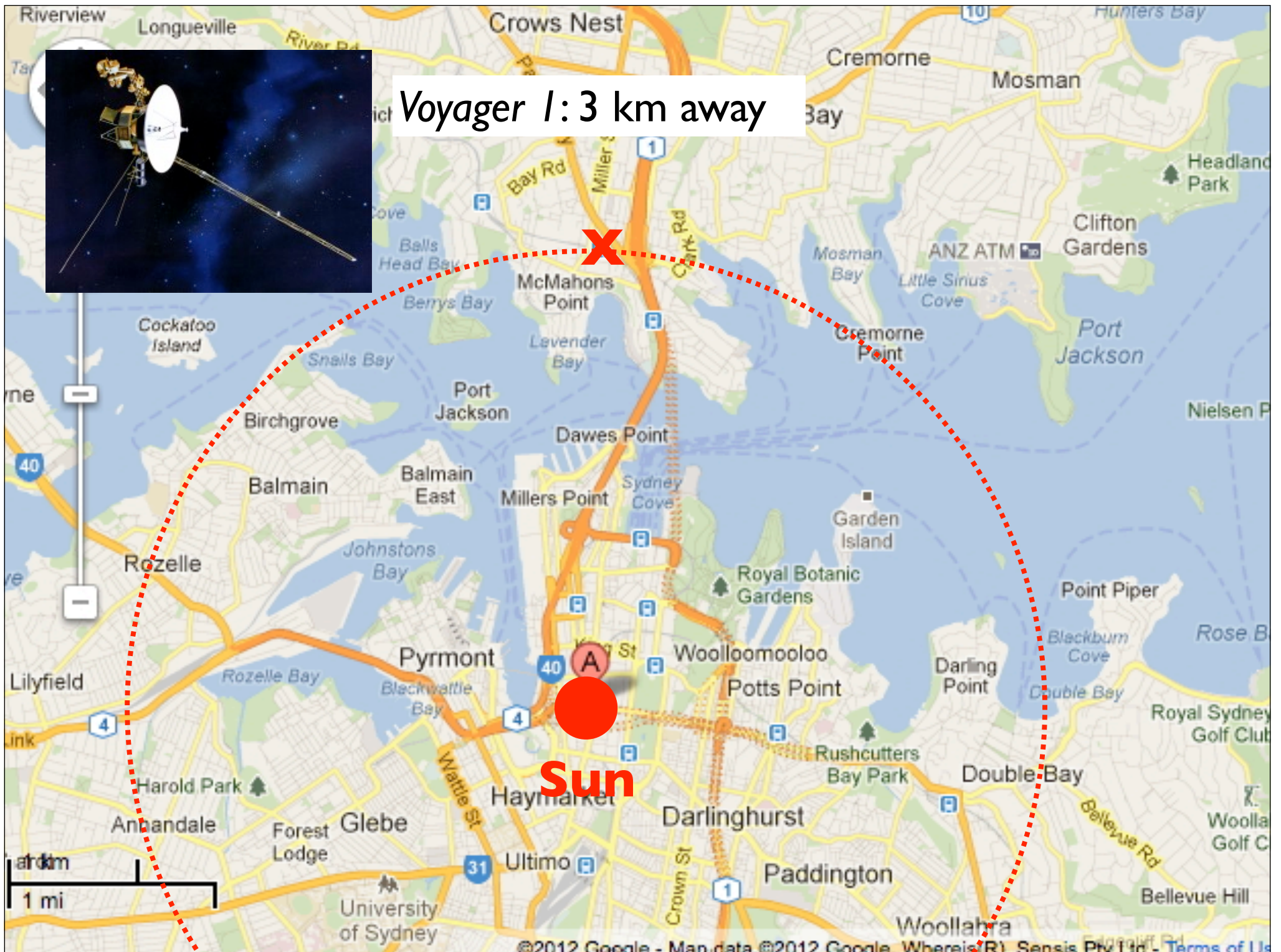


Sun





Voyager 1: 3 km away



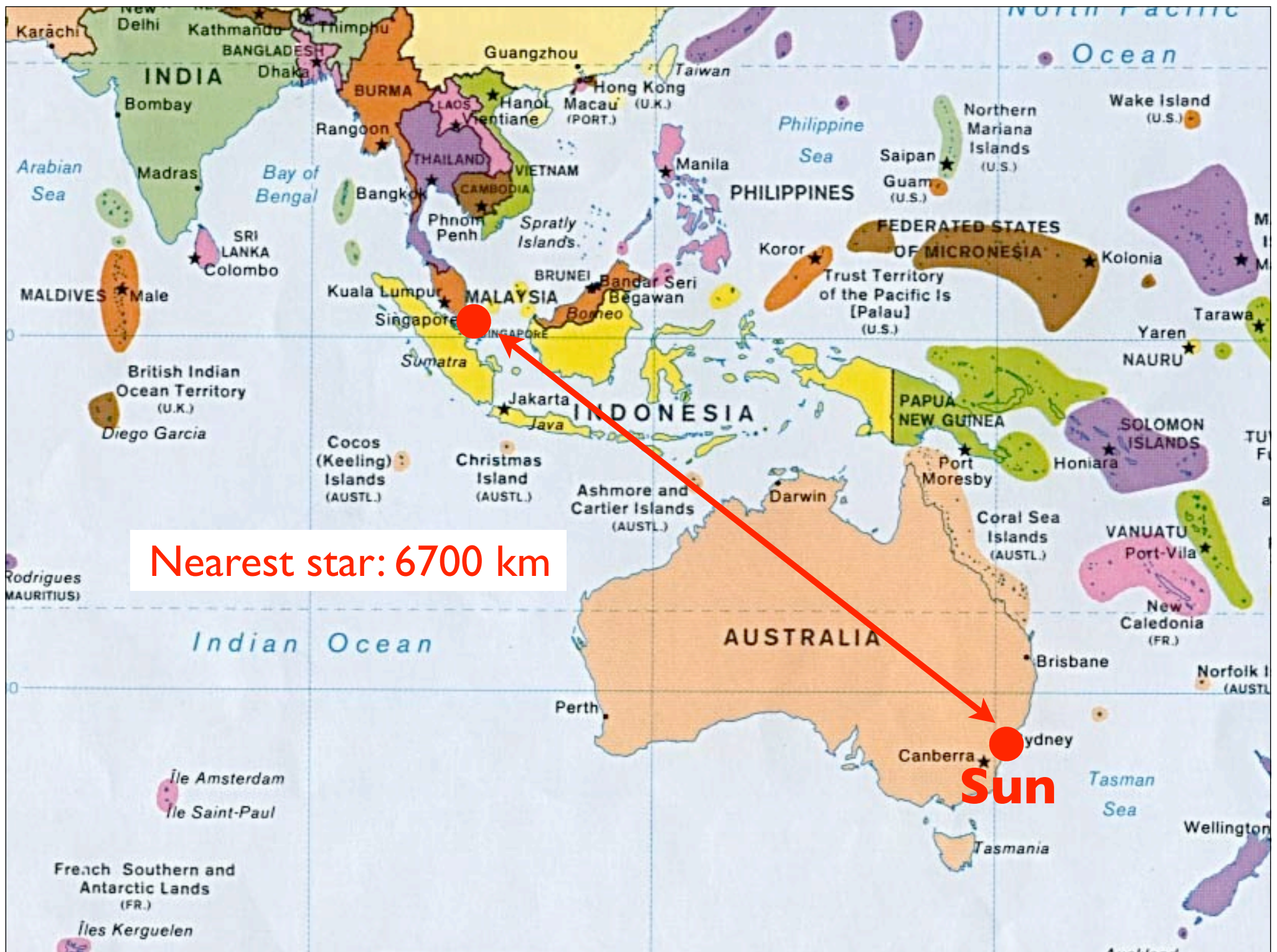




One light year: 1600 km

Sun

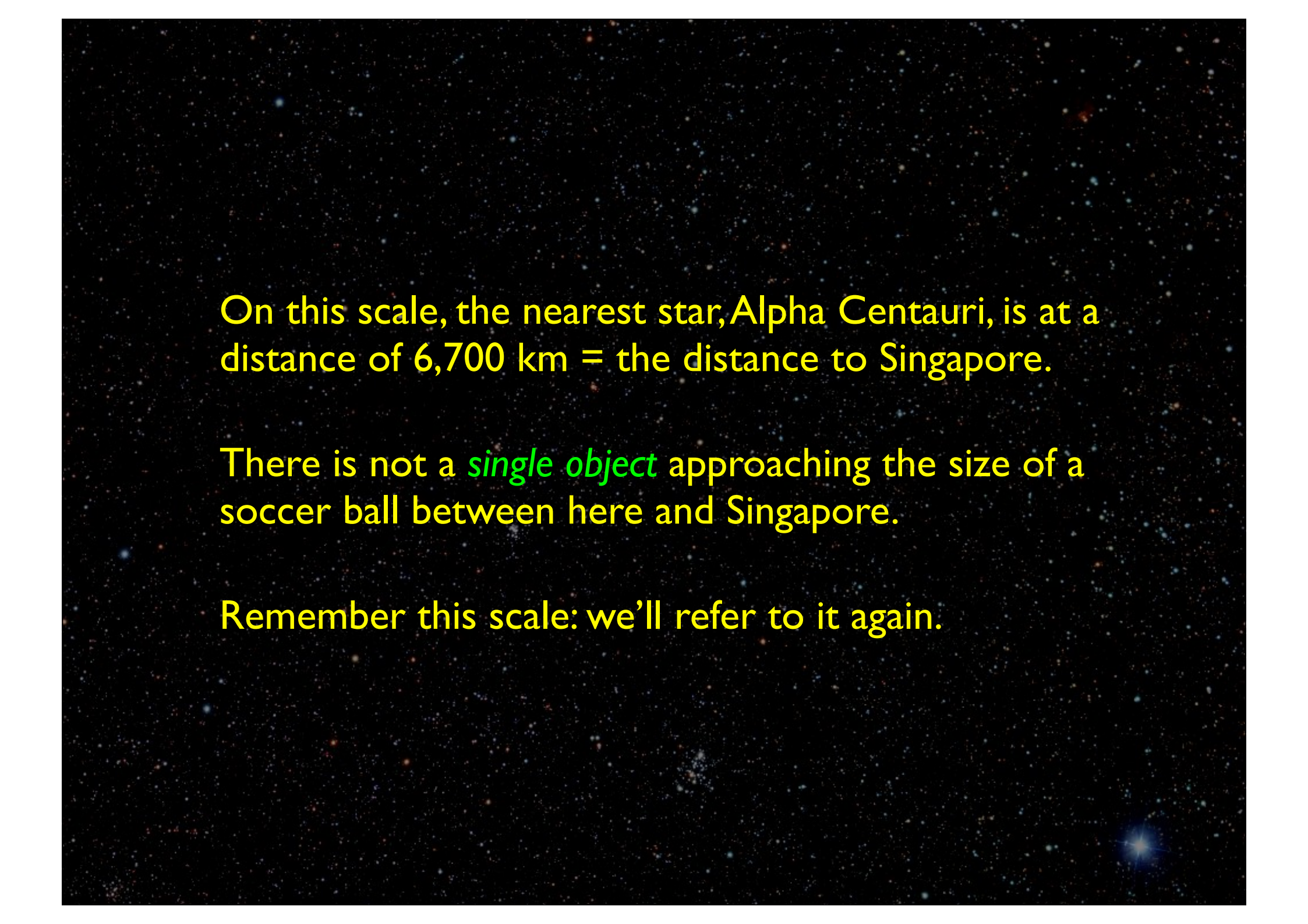




Nearest star: 6700 km

Sun



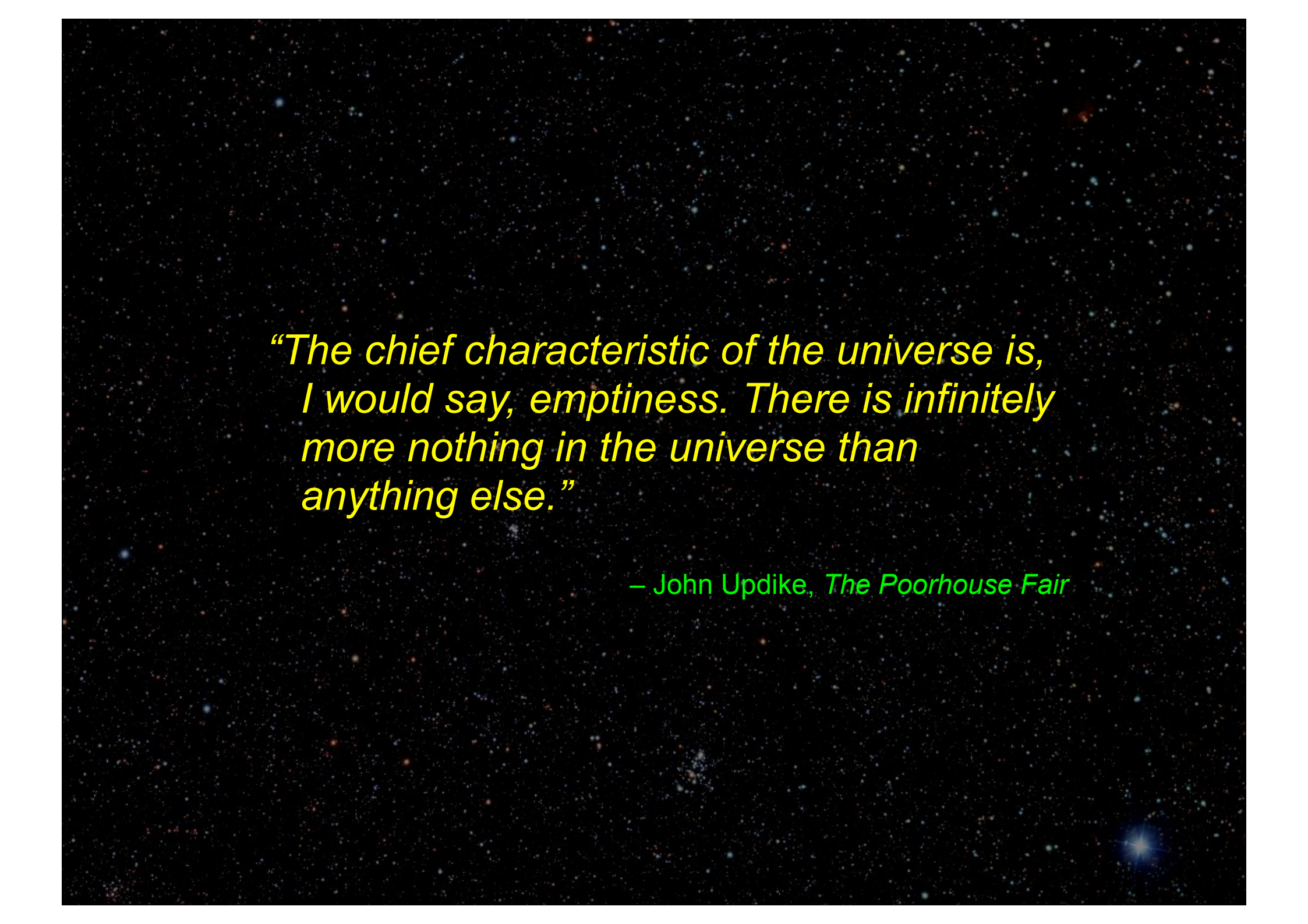
A deep space photograph showing a vast field of stars against a black background. The stars vary in brightness and color, with some appearing as distinct points of light and others as faint, diffuse clouds. The overall scene is a dense, star-filled expanse of the universe.

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:

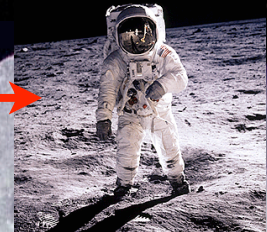
- An *astronomical unit* (AU) is the average Earth-Sun distance:  $1 \text{ AU} = 149.6 \text{ million km}$
- A *light year* (ly) is the distance light travels in a year:  
 $1 \text{ ly} = 9,461,000,000,000 \text{ km} = 63,000 \text{ AU}$
- A *parsec* (pc) is about 3.26 ly; we'll find out where this 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.

384,400 km

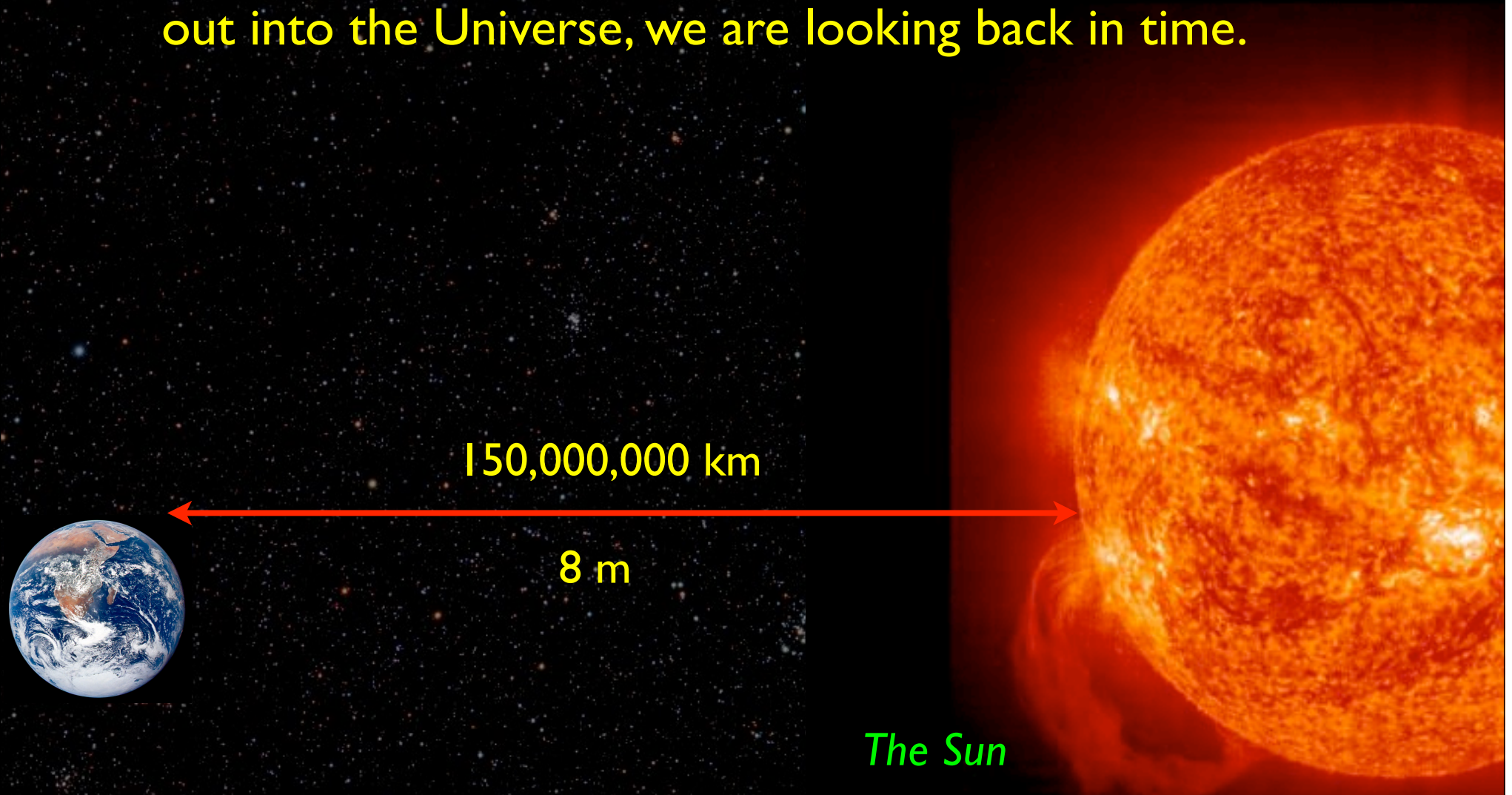
1.3 s



The Moon

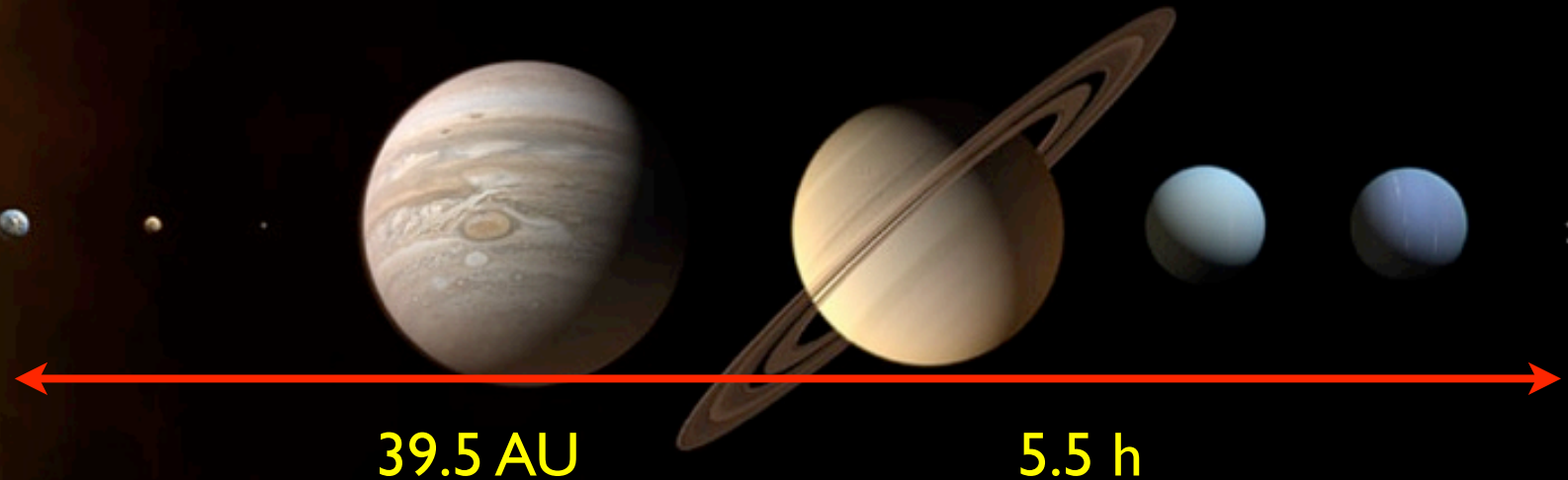


The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.





The 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.



*Pluto*



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.



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.



168,000 ly

168,000 y



© Anglo-Australian Observatory/Royal Observatory, Edinburgh.

*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.



2,000,000 ly

2 million y



*The Andromeda galaxy*



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.



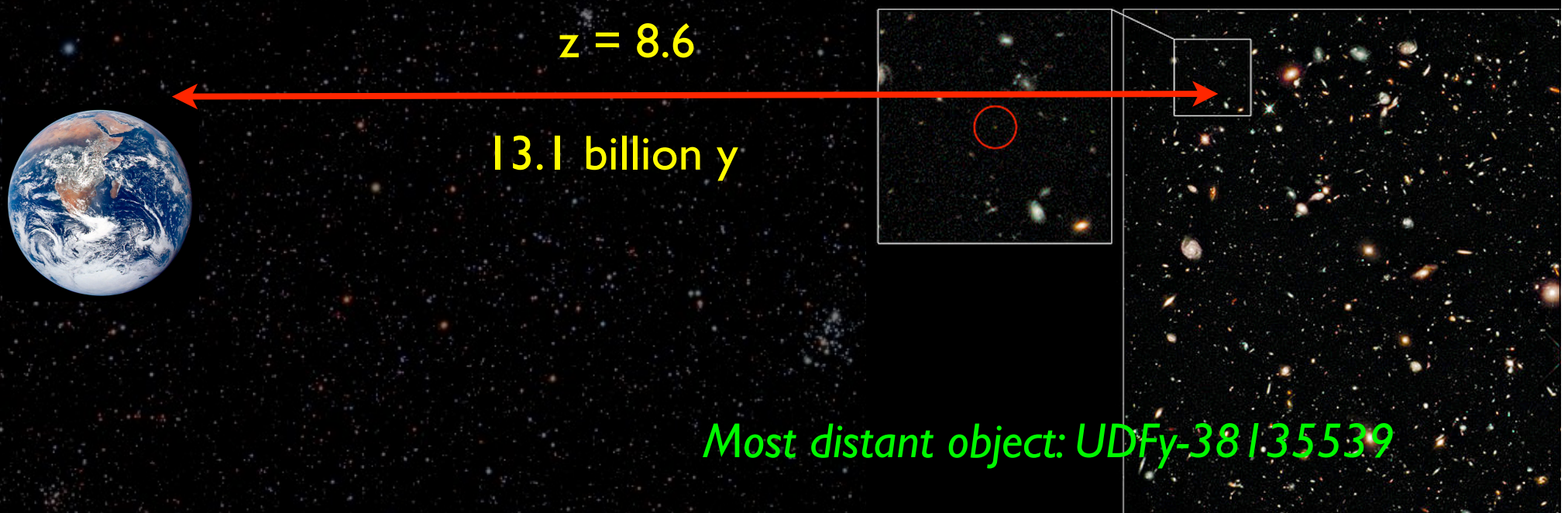
2.4 billion ly;  $z=0.158$

2.4 billion y

Nearest quasar, 3C273

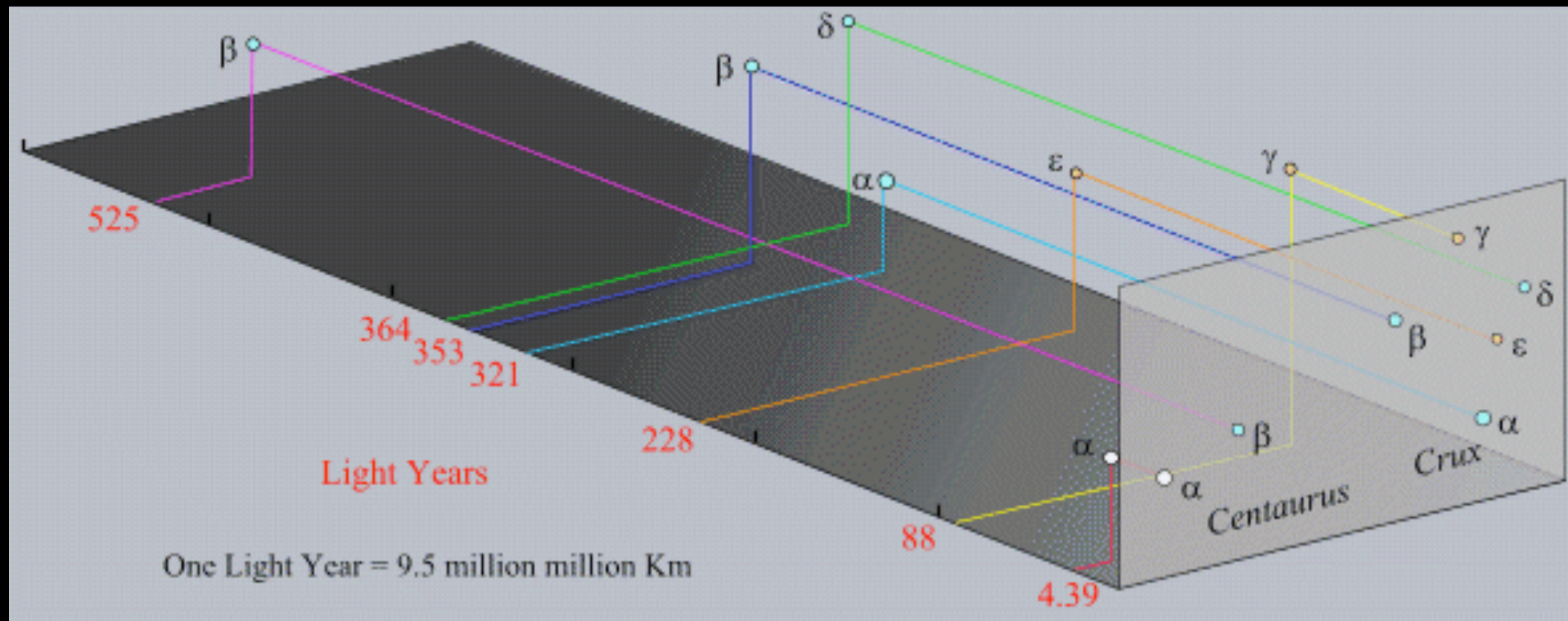


The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.





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)*



star  
~300 ly



quasar  
24 billion ly



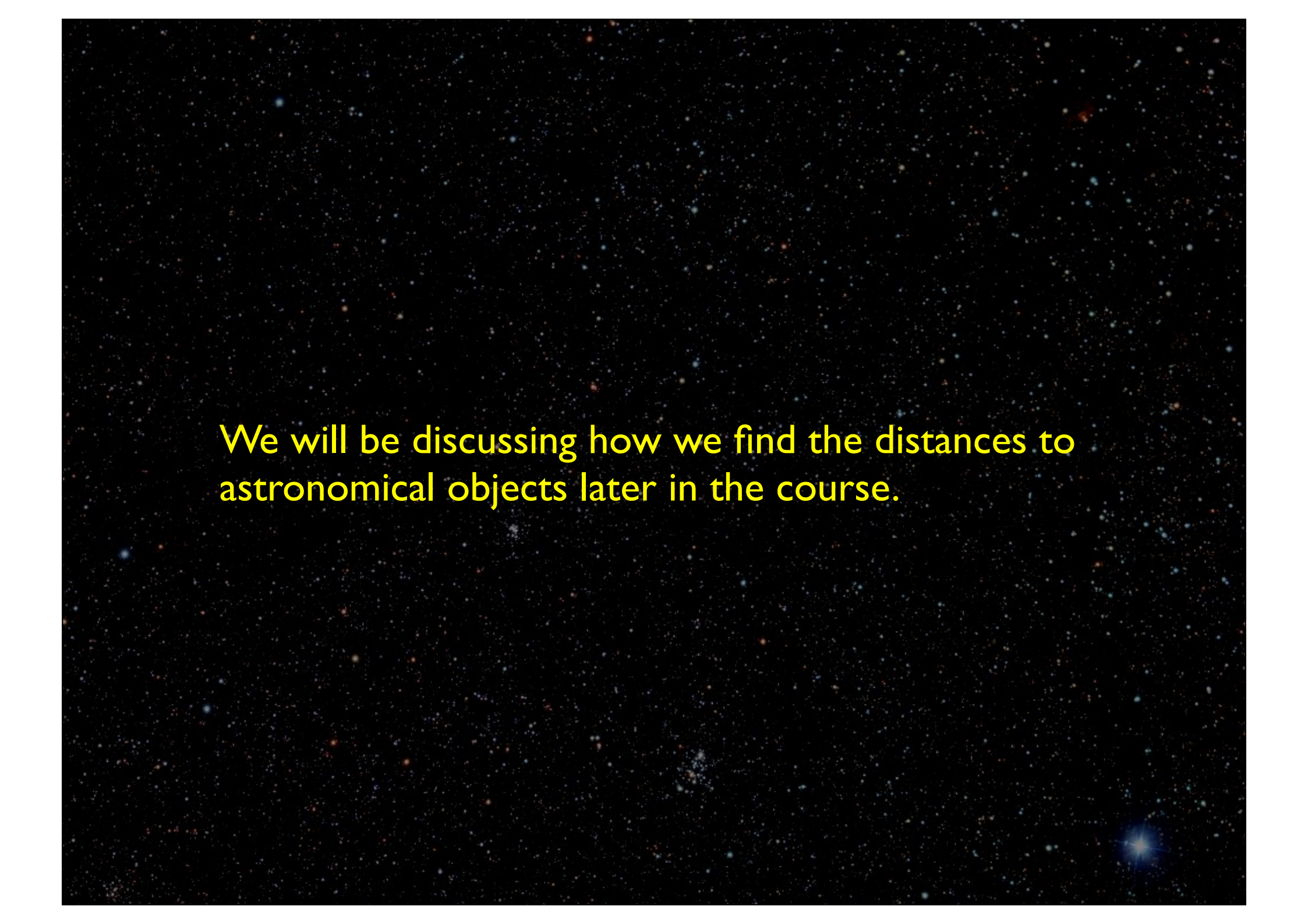
quasar  
155 billion ly

galaxy  
7 billion ly



*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).*



A deep-field astronomical image showing a vast field of stars and distant galaxies against a black background. The stars appear as small, colorful dots in various colors like blue, red, and white. Some faint, diffuse structures resembling galaxies are visible in the background.

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

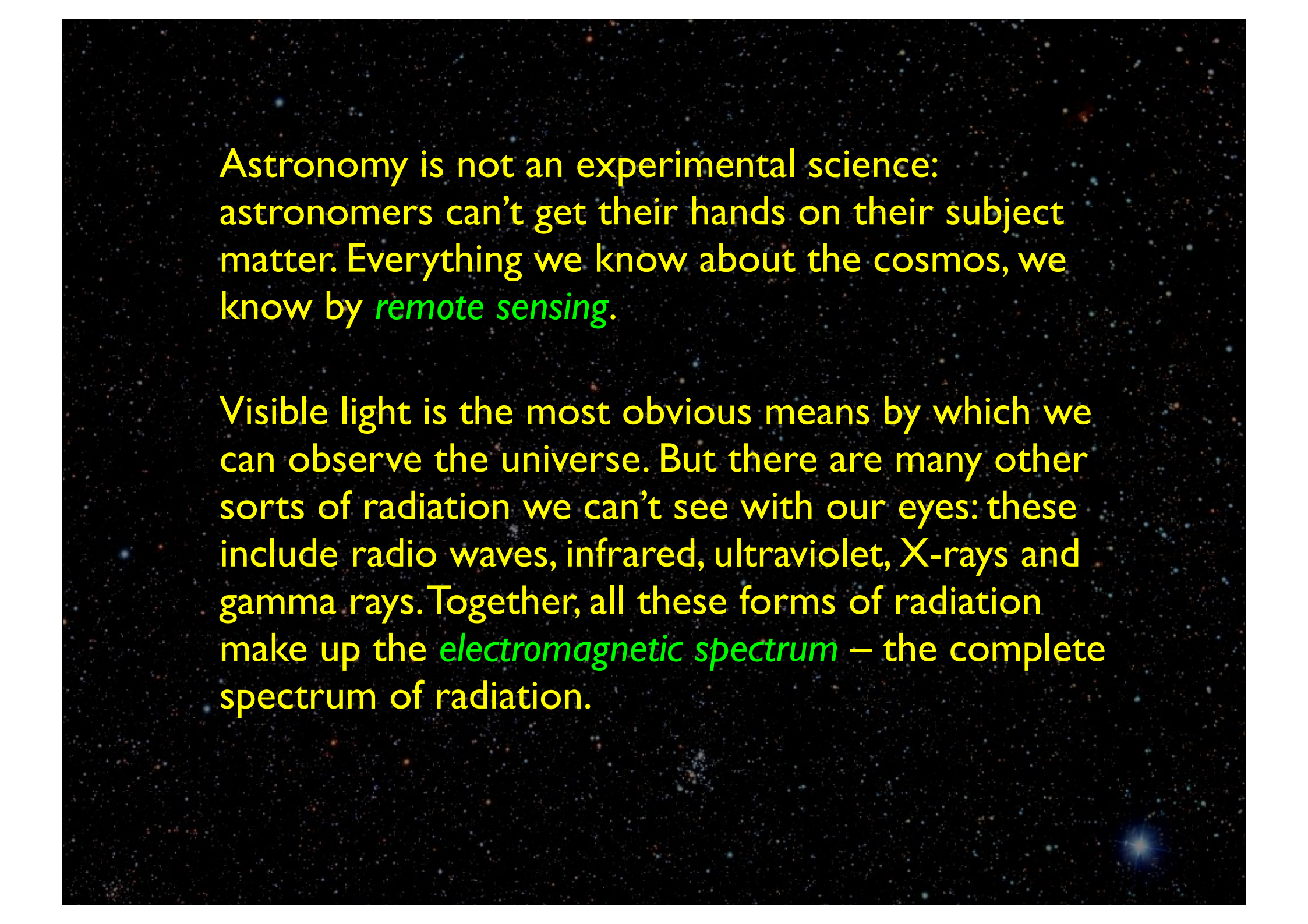


A deep space photograph showing a vast field of stars of various colors (blue, orange, white) against a black background. The text 'Electromagnetic radiation' is overlaid in a large, bold, yellow font.

# Electromagnetic radiation

*– our eye on the sky*

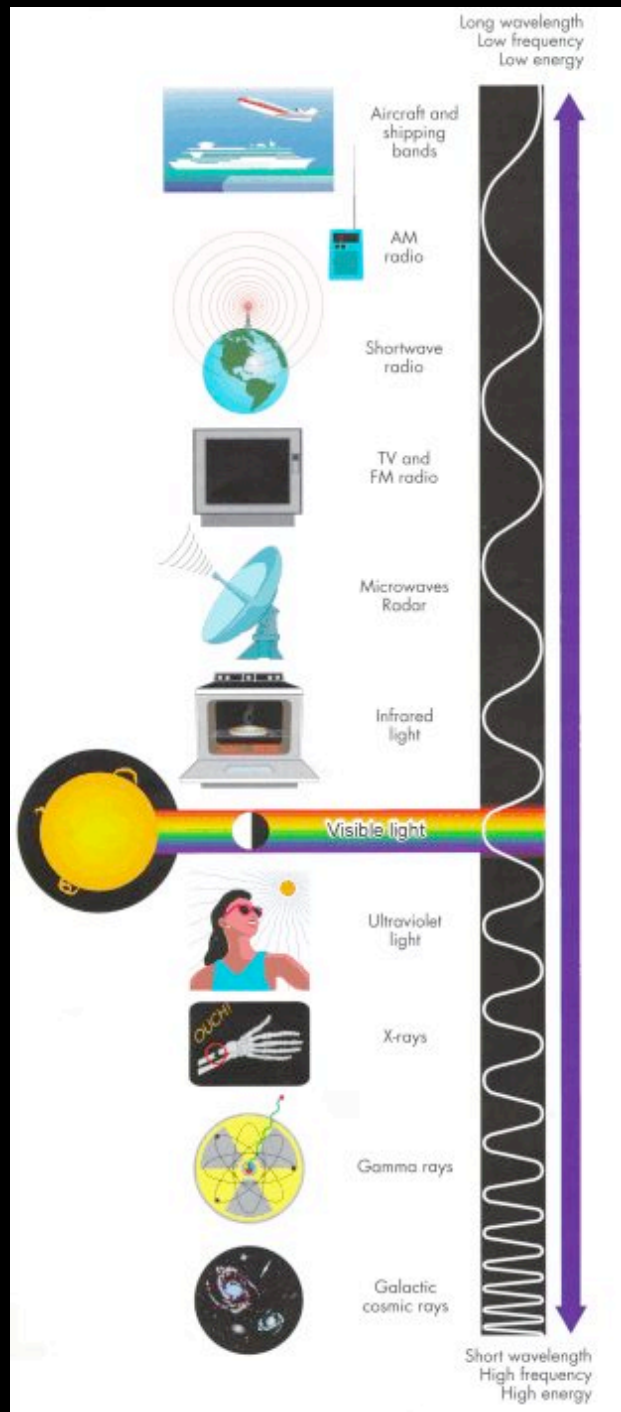




Astronomy is not an experimental science: astronomers can't get their hands on their subject matter. Everything we know about the cosmos, we know by *remote sensing*.

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

10 km (shipping)

1 km (aircraft)

300 m (AM)

50 m (shortwave)

3m (FM radio)

50 cm (TV)

1 cm (microwave)

10 micron

0.5 micron = 500 nm

100 nm

1 nm

0.001 nm = 1 pm

## Frequency

30 kHz

300 kHz

1000 kHz = 1 MHz

6 MHz

100 MHz

600 MHz



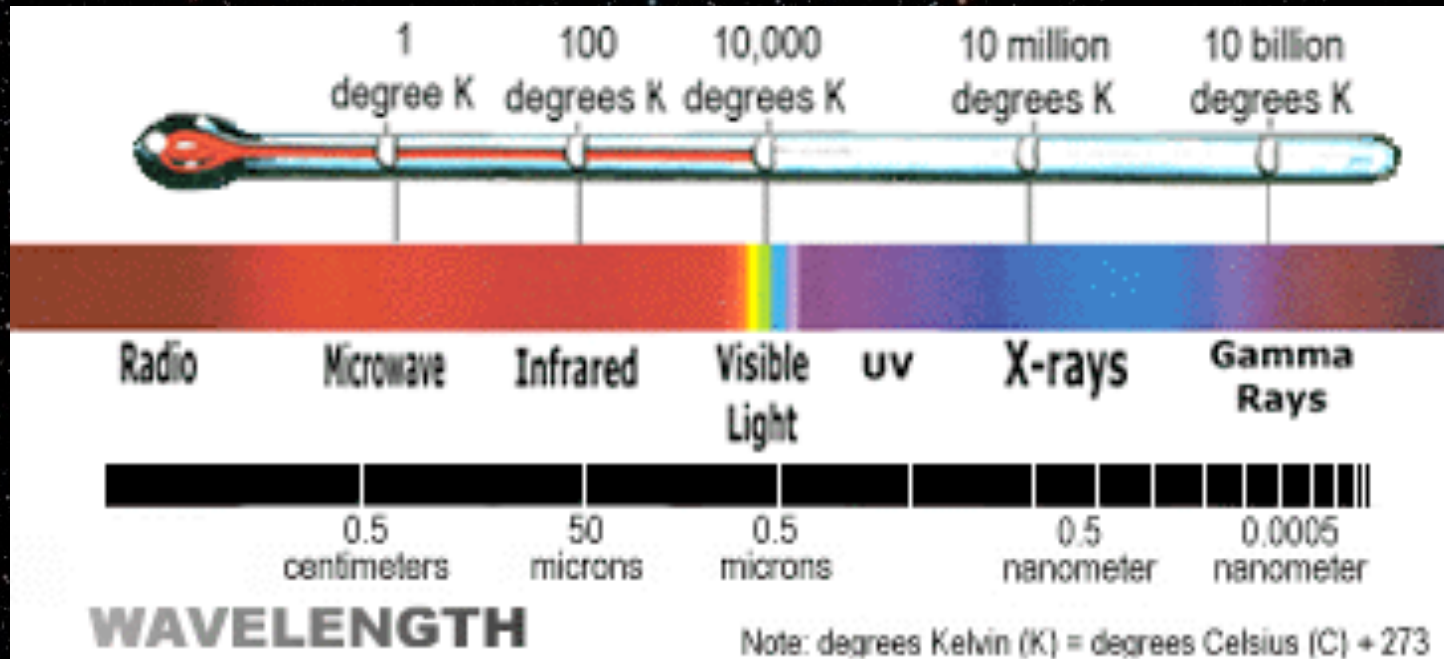
Visible light makes up only a tiny fraction of the electromagnetic spectrum. Our eyes can see less than an octave of the spectrum, from wavelengths of 400 nm to 700 nm. Astronomical observations cover more than *65 octaves* of the spectrum, from low-frequency radio waves to ultra-high-energy gamma rays.

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  $c = 300,000 \text{ km/s}$ .



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

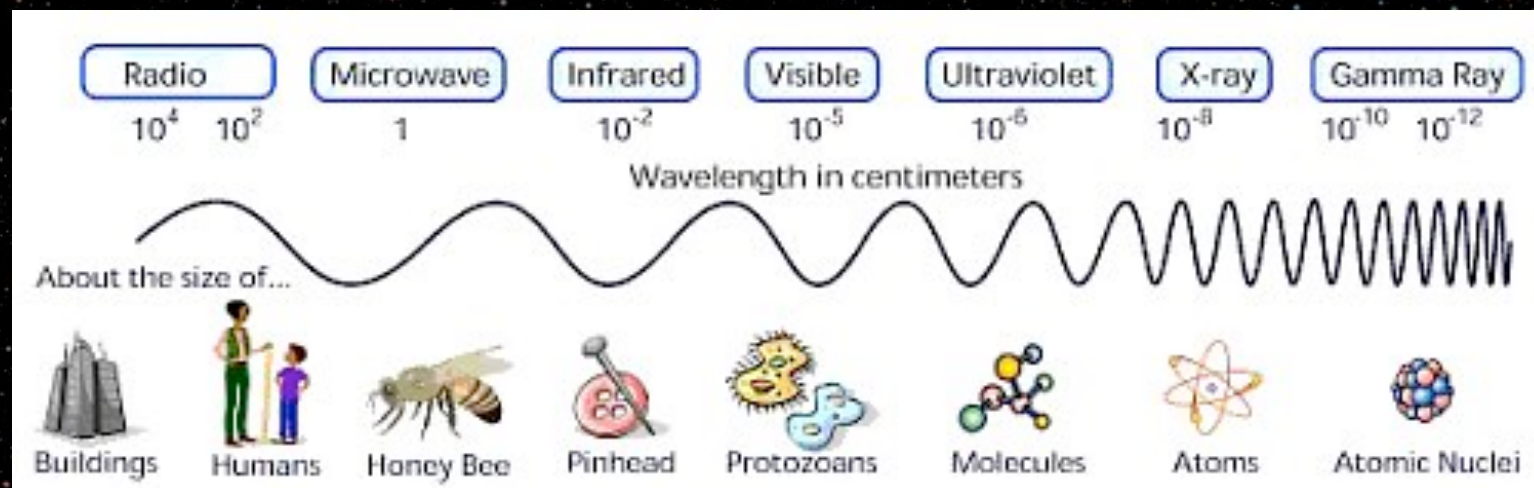


Cool objects radiate most at long wavelengths,  
hot objects at short wavelengths.

The Sun radiates most at the wavelength of visible light.



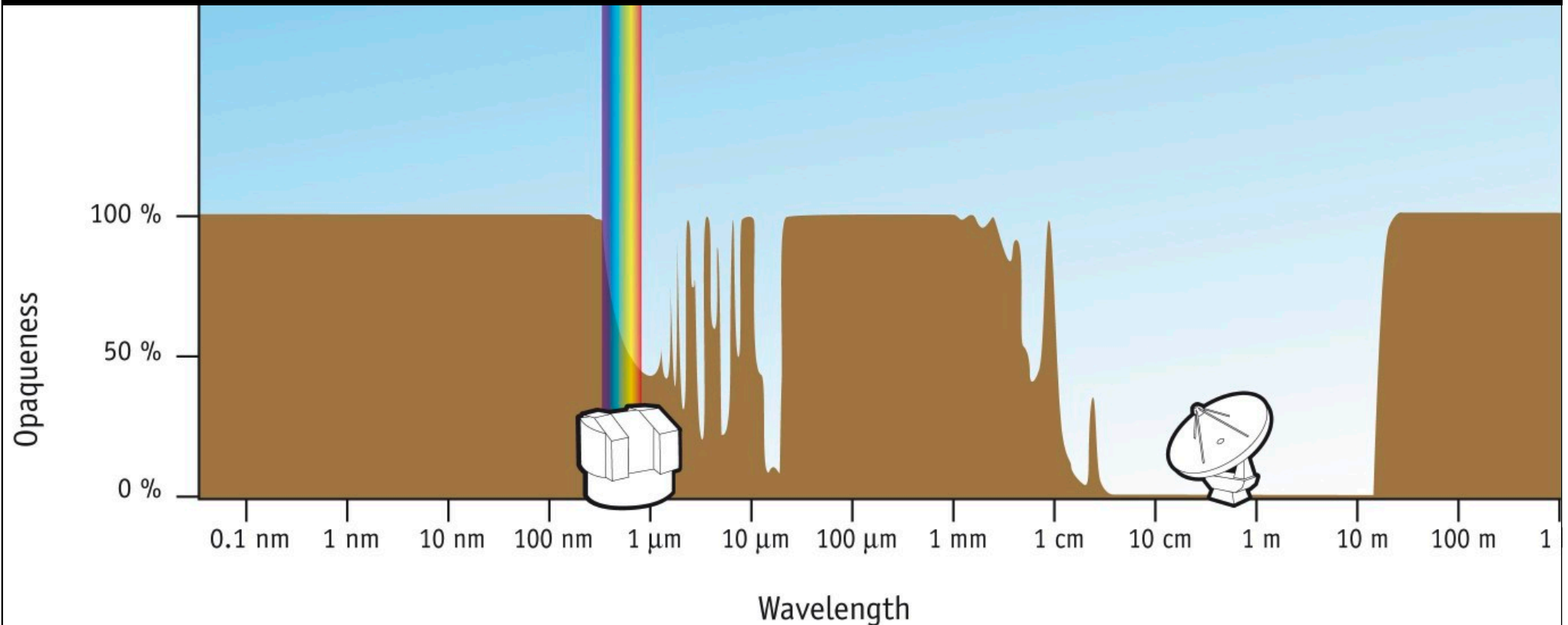
All forms of EM radiation are the same, but they *seem* very different because of the very different scales involved.



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

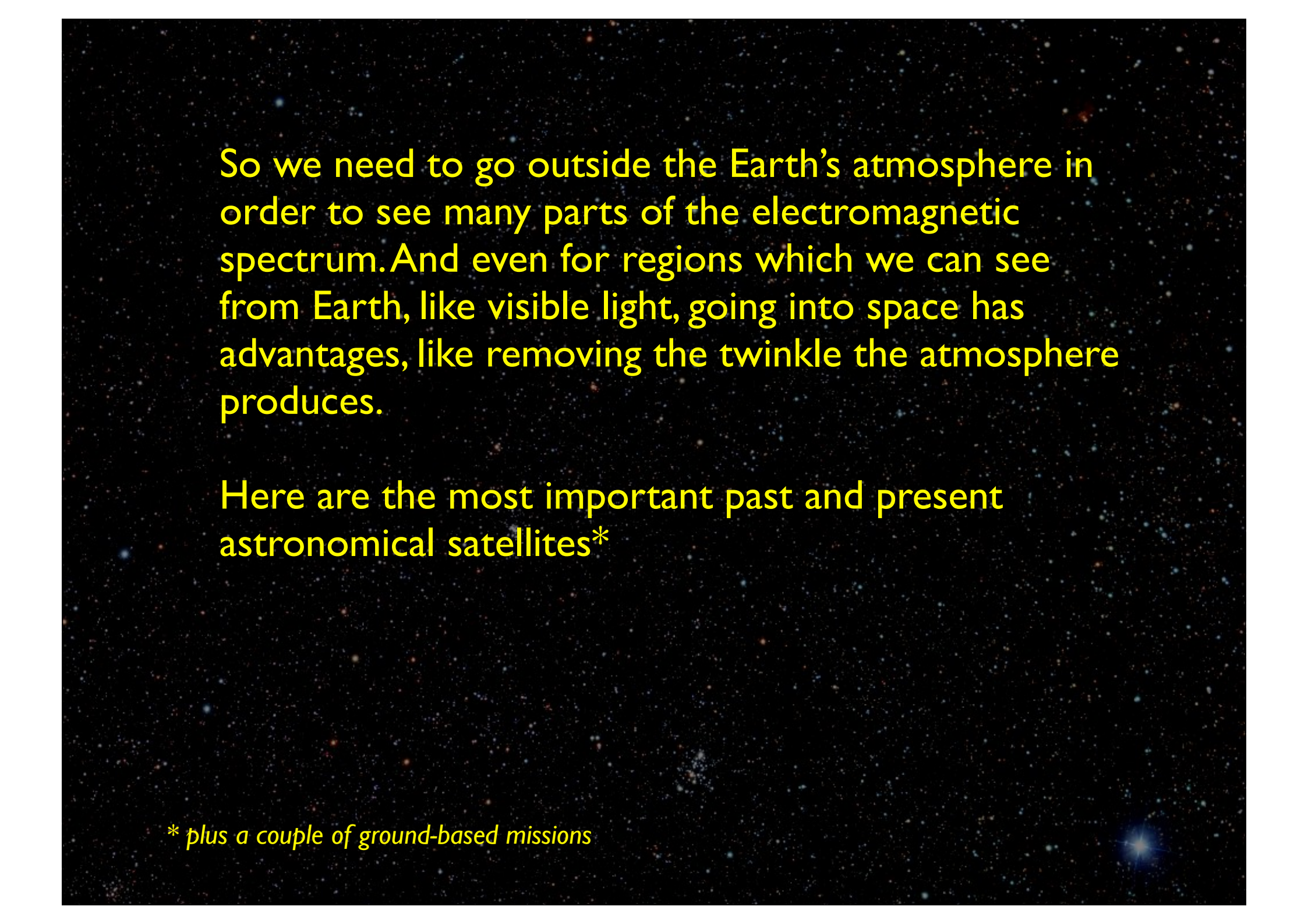


The Earth's atmosphere is opaque to nearly all parts of the EM spectrum.



Only visible and radio waves can reach the surface.

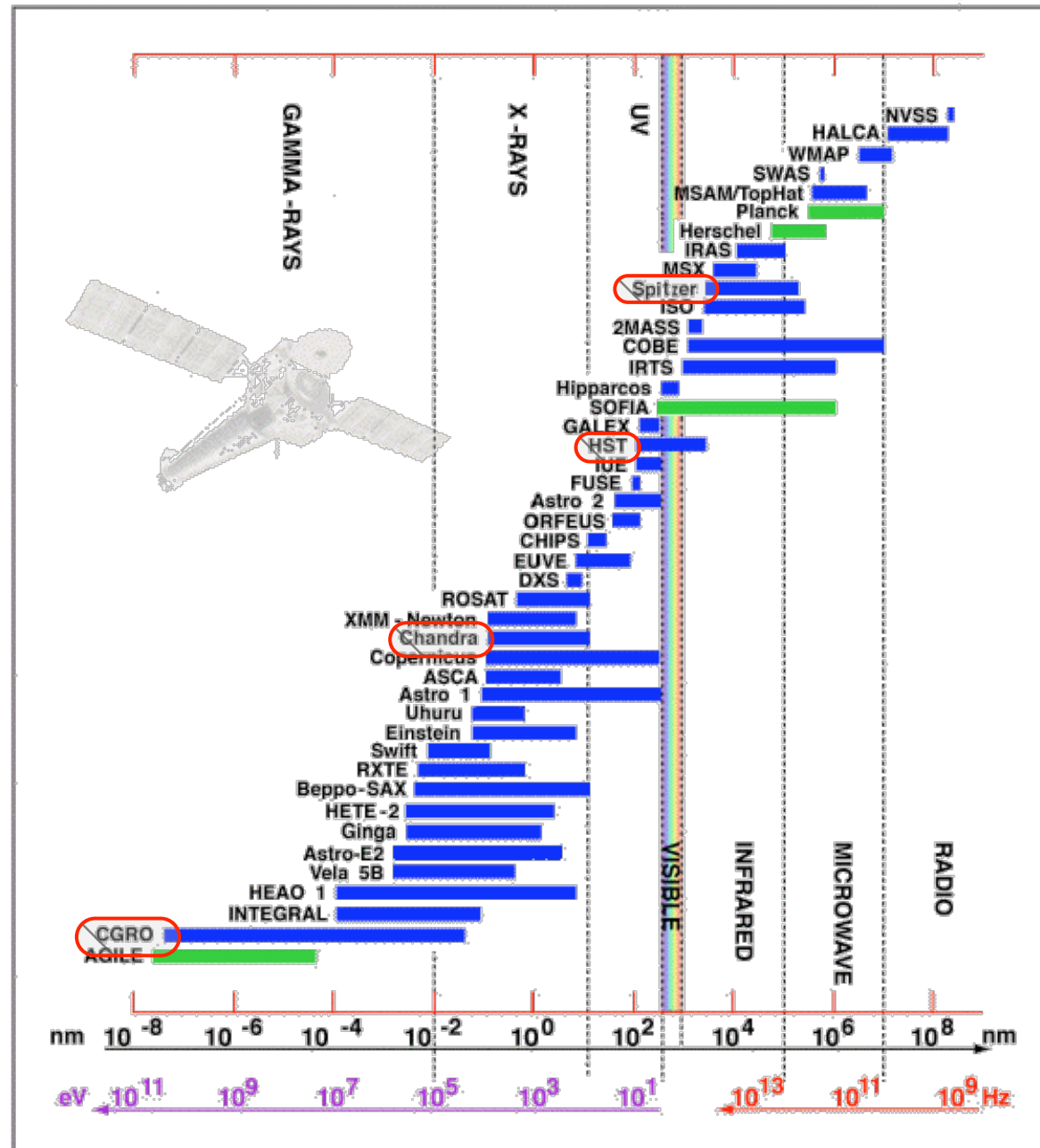
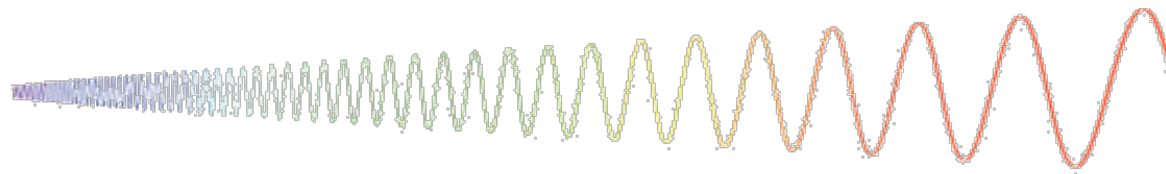




So we need to go outside the Earth's atmosphere in order to see many parts of the electromagnetic spectrum. And even for regions which we can see from Earth, like visible light, going into space has advantages, like removing the twinkle the atmosphere produces.

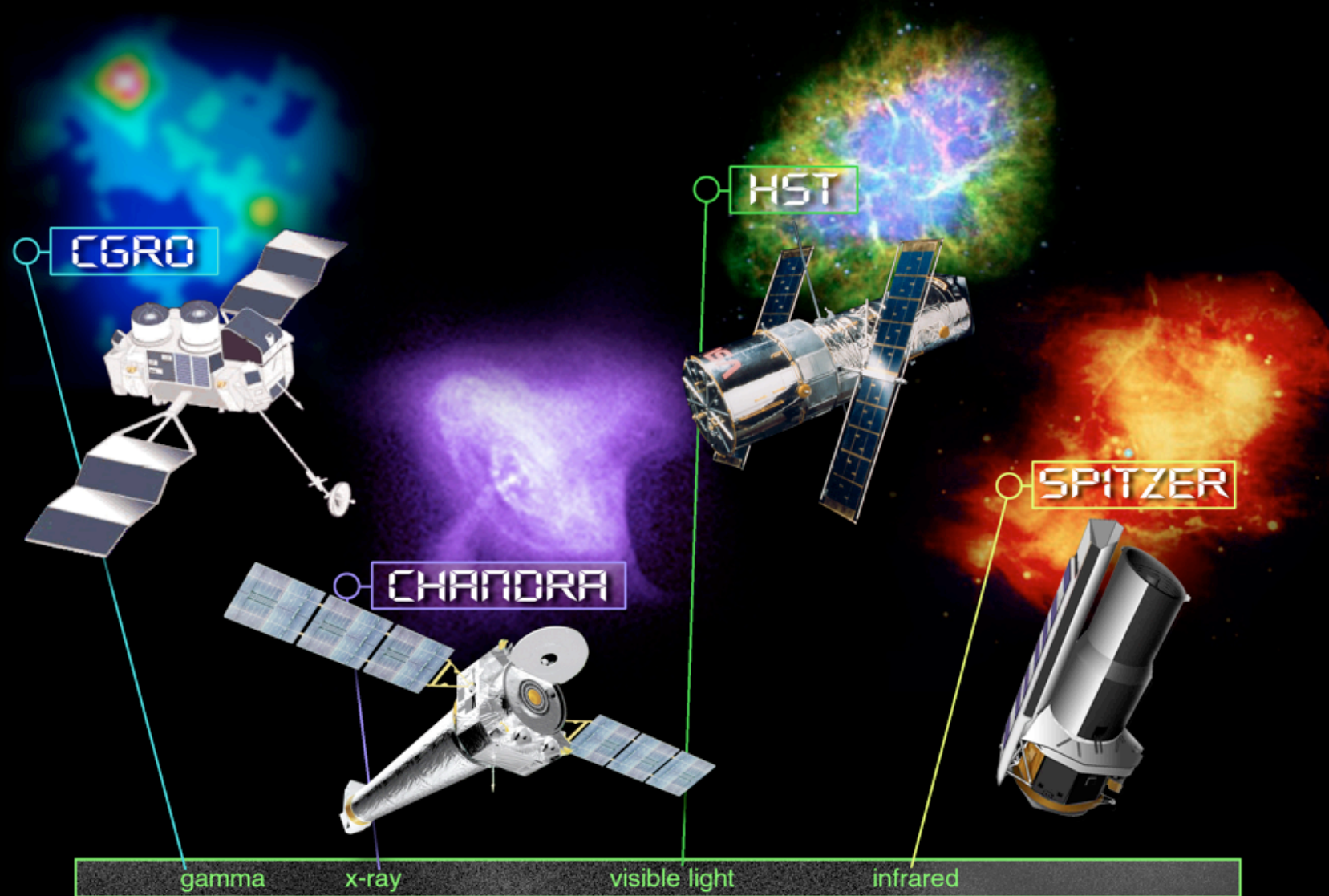
Here are the most important past and present astronomical satellites\*

*\* plus a couple of ground-based missions*





# 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.

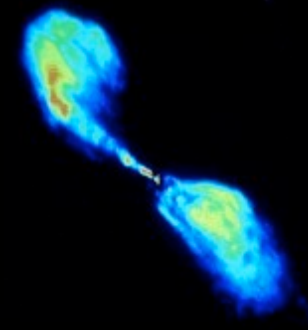
The **infrared** image shows that the dust lane is actually the remains of a spiral galaxy.





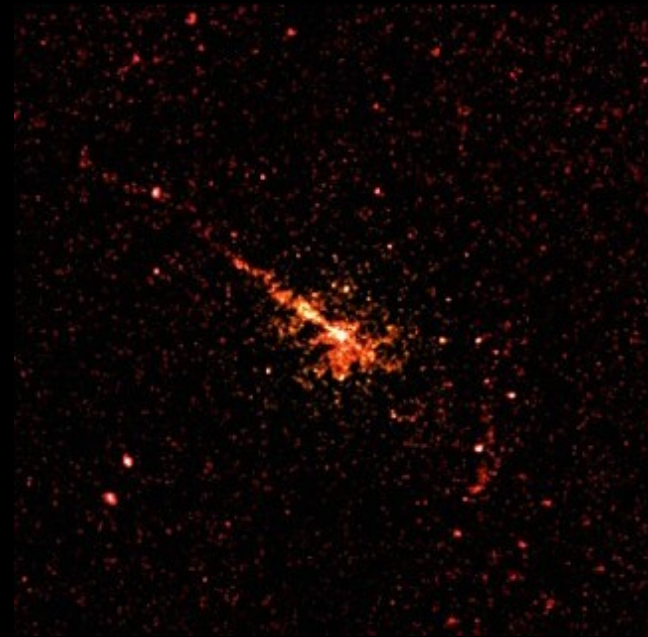
Astronomy has been revolutionised by the ability to observe the sky at different wavelengths. Here is the galaxy Centaurus A at different wavelengths.

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.

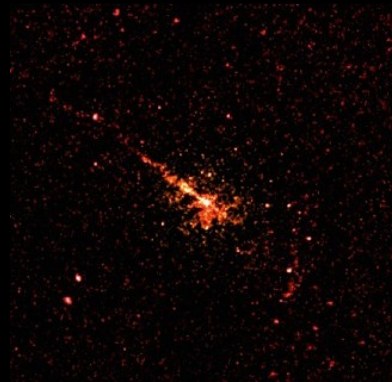
The X-ray image also shows a jet, this time only pointing in one direction. We believe it is emanating from a supermassive black hole at the centre of the galaxy.



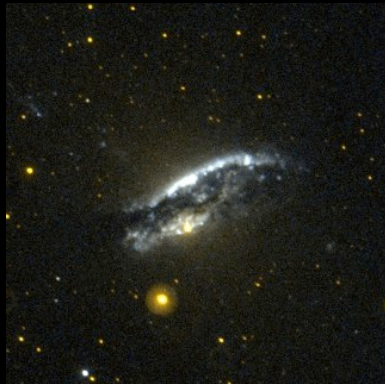


Here are all those images together.

X-ray



ultraviolet



optical



infrared



radio



short  
wavelength



long  
wavelength

## 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	$> 10^8 \text{ K}$	Neutron stars, accretion disks around black holes
X-ray	$10^6\text{--}10^8 \text{ K}$	Shocked gas; neutron stars; supernova remnants
Ultraviolet	$10^4\text{--}10^6 \text{ K}$	Supernova remnants; very hot stars; quasars
Optical	$1000\text{--}10,000 \text{ K}$	Stars; galaxies; emission nebulae; reflection nebulae
Infrared	$10\text{--}1000 \text{ K}$	Cool stars; interstellar gas; planets
Radio	$< 10 \text{ K}$	Cosmic background; cold interstellar gas; supernova remnants



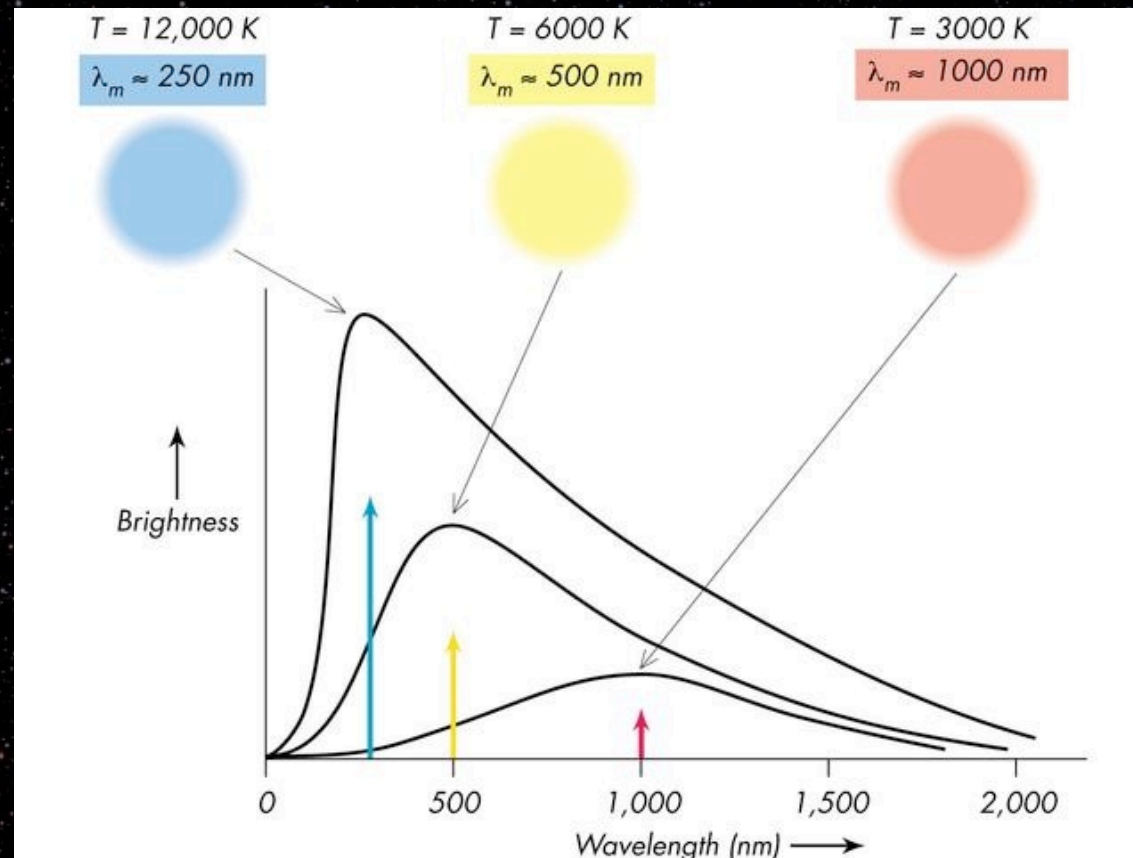
# Spectra: separating light

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.

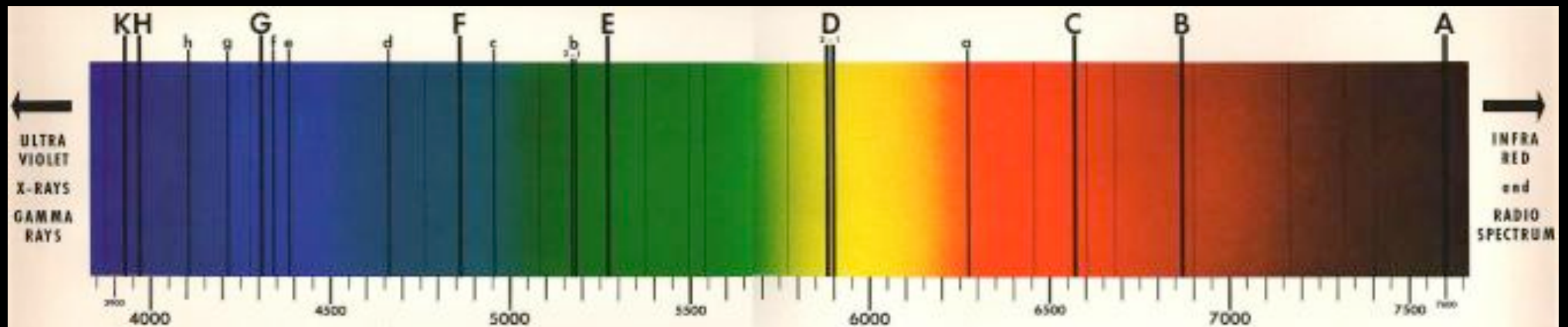


Many objects when heated show the same shape to their spectrum, called a *blackbody spectrum*. A black body gives off radiation at many wavelengths, but has a strong peak at a particular wavelength. The hotter the object, the shorter the wavelength: *hotter* objects have *bluer* spectra.





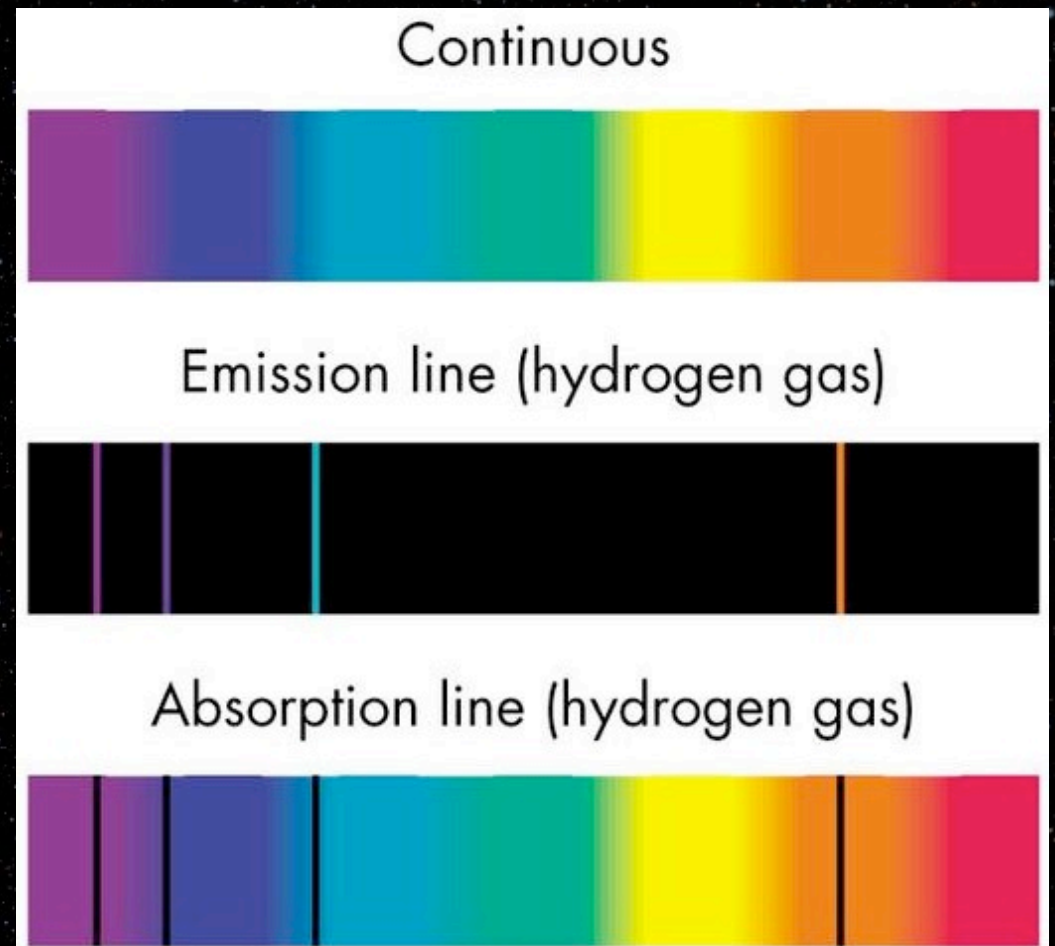
Joseph Fraunhofer, in 1814, discovered that the solar spectrum was not just a continuous band of colour, but was crossed by numerous dark bands, which never changed their position.



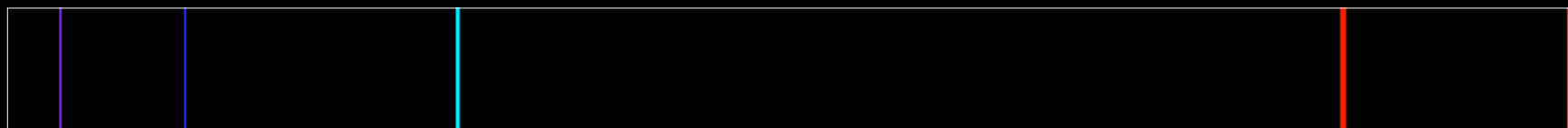
Gustav Kirchhoff, in 1859, discovered that a heated substance produced a series of coloured lines, and that this pattern was unique for each chemical element.

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)



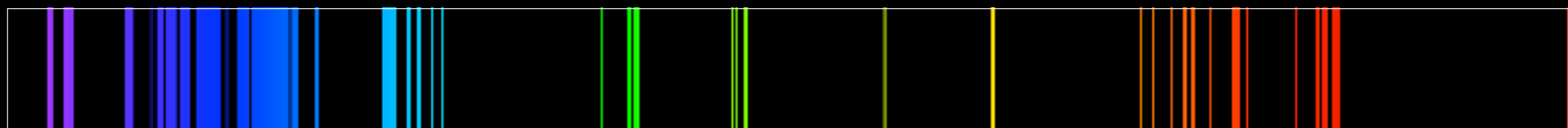




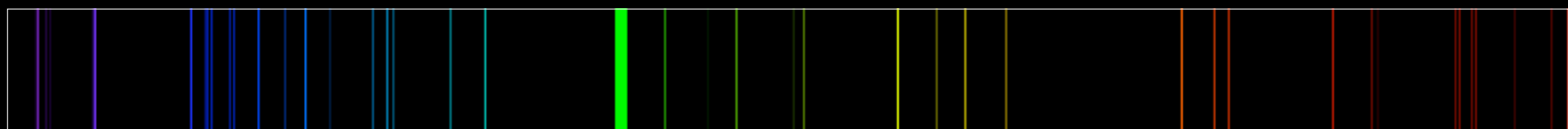
H



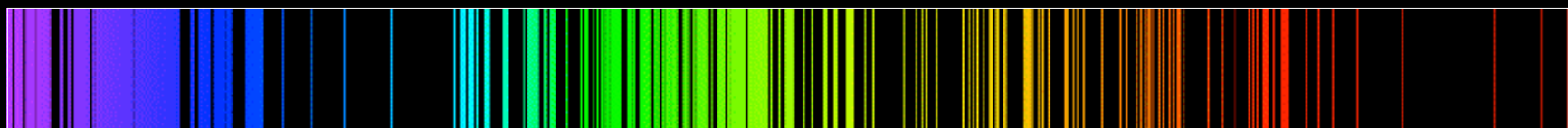
He



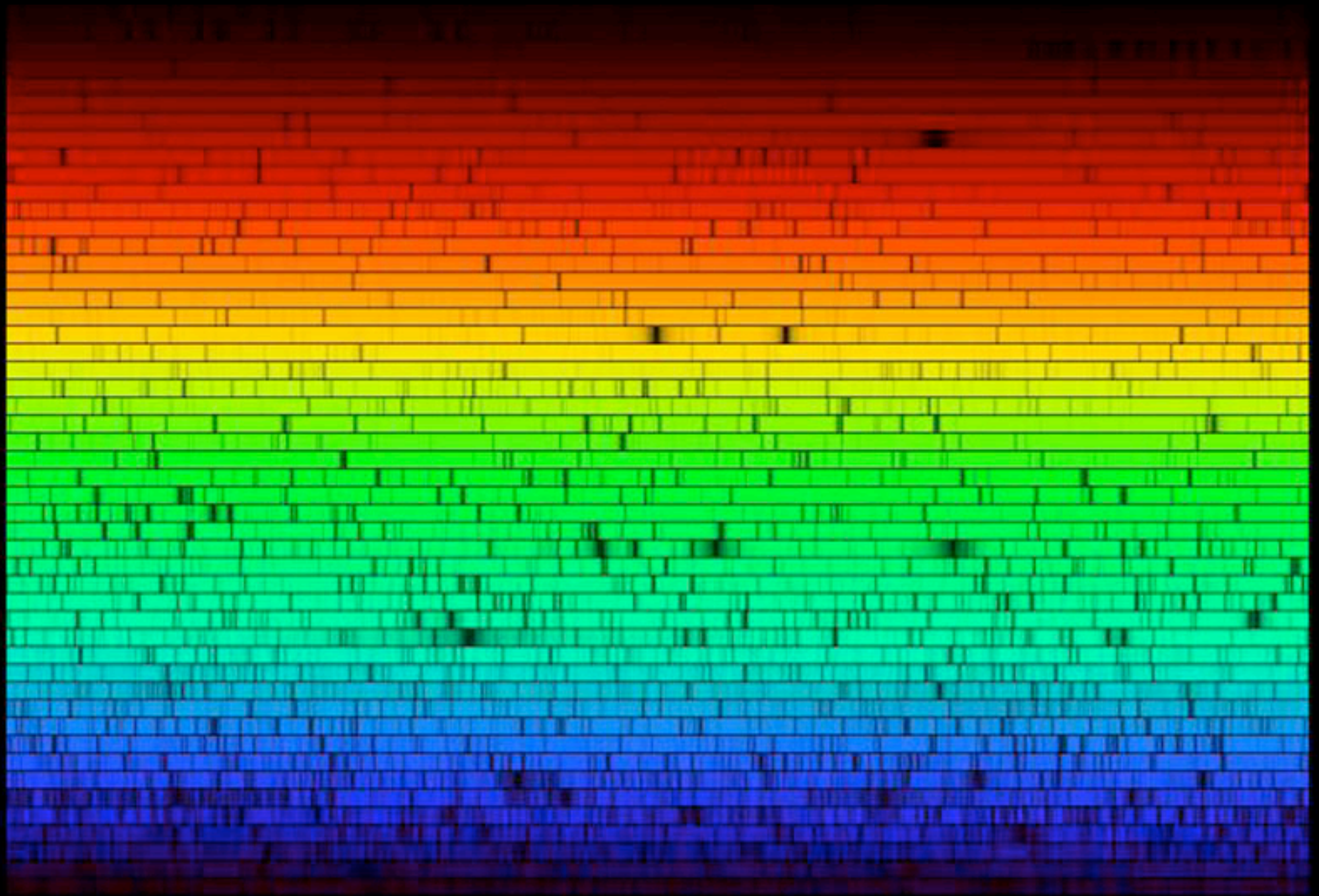
Na



Mg



Fe



*High resolution solar spectrum*

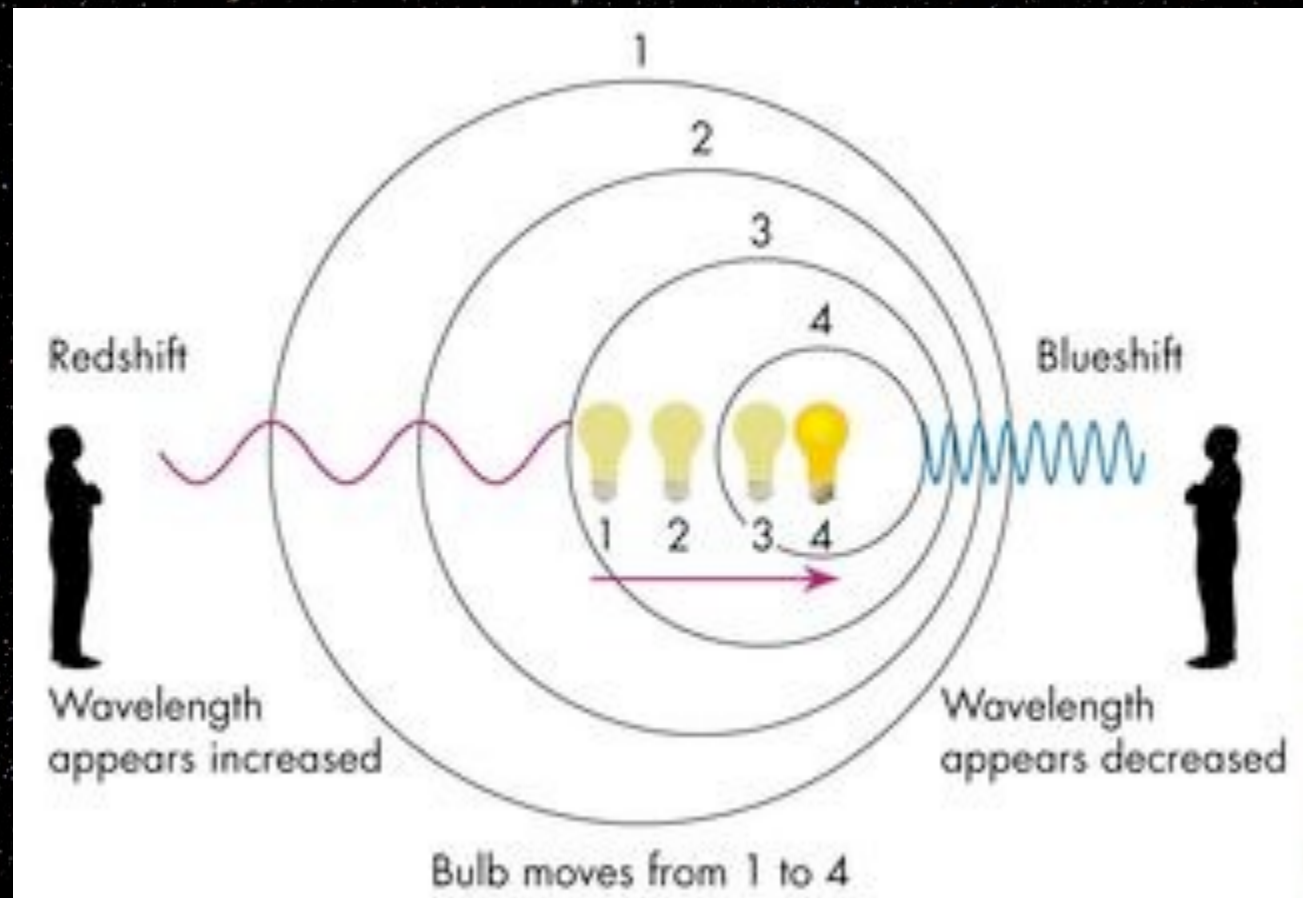




Each element produces a unique fingerprint.

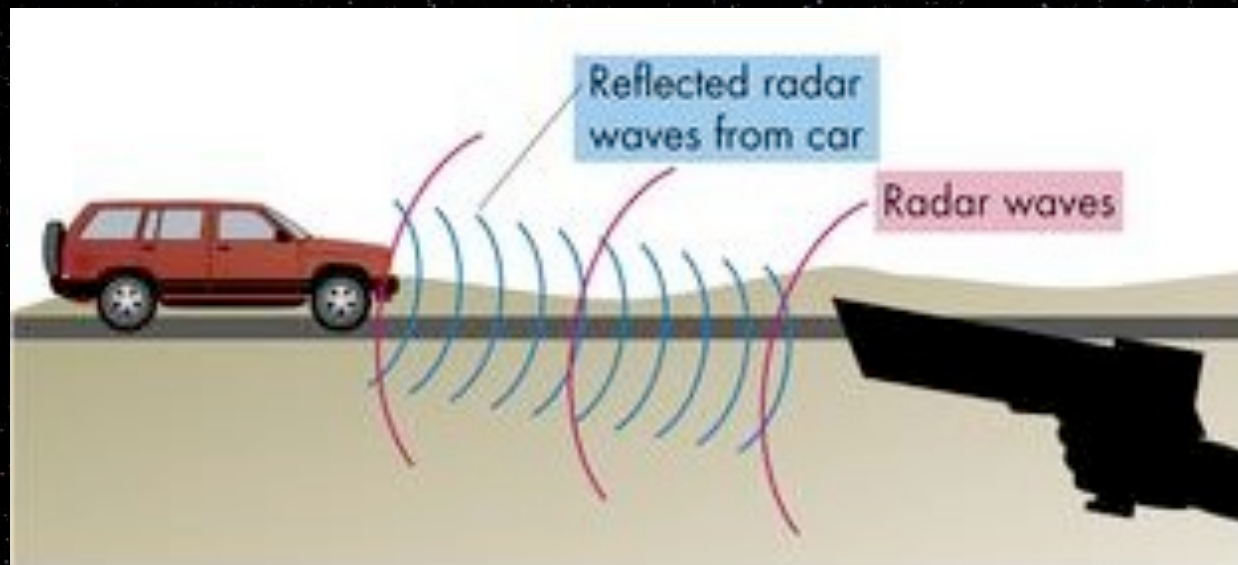
In many ways, this represents the beginning of astronomy as a science. Suddenly it was possible to study the composition of heavenly bodies using nothing but light!

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



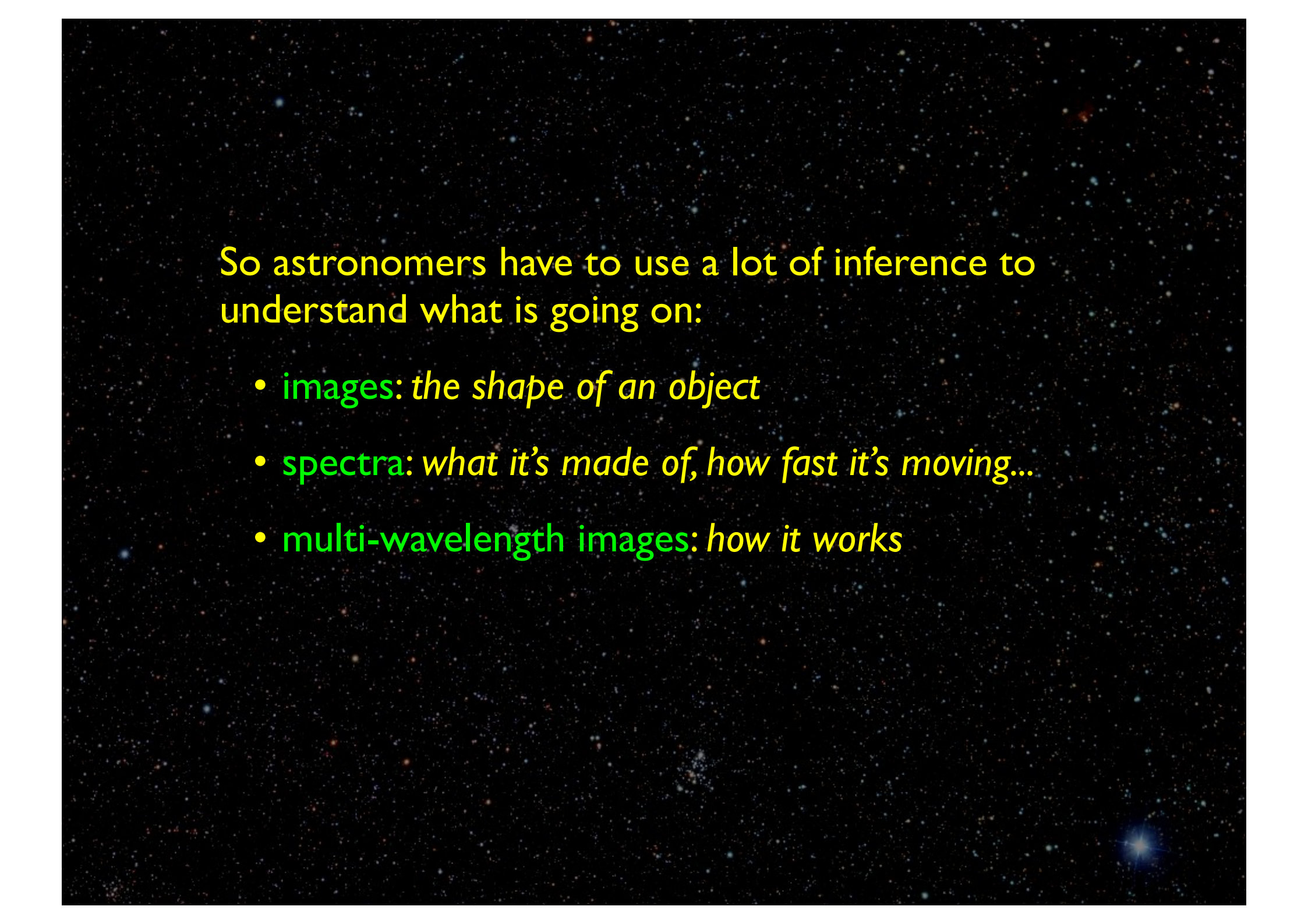
Stationary



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*



A Hubble Space Telescope image of Hanny's Voorwerp, a glowing nebula. The central part of the nebula is bright and pinkish-red, while the surrounding gas is a deep green. The nebula is set against a dark background of space.

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.

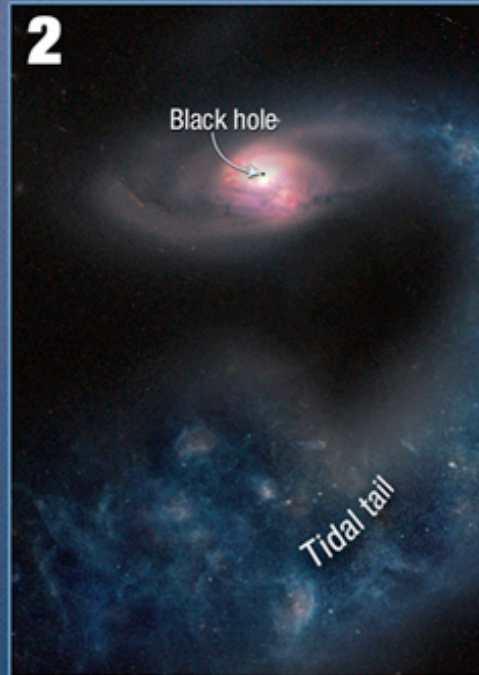
*Hubble image of Hanny's Voorwerp*

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.

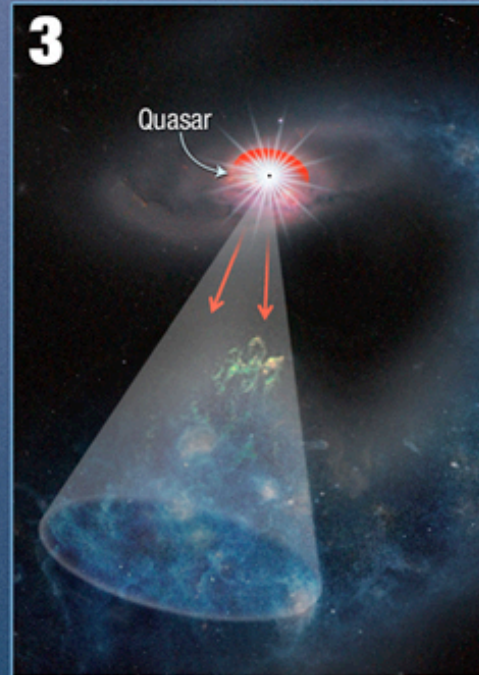
## Hanny's Voorwerp\* — A Space Oddity



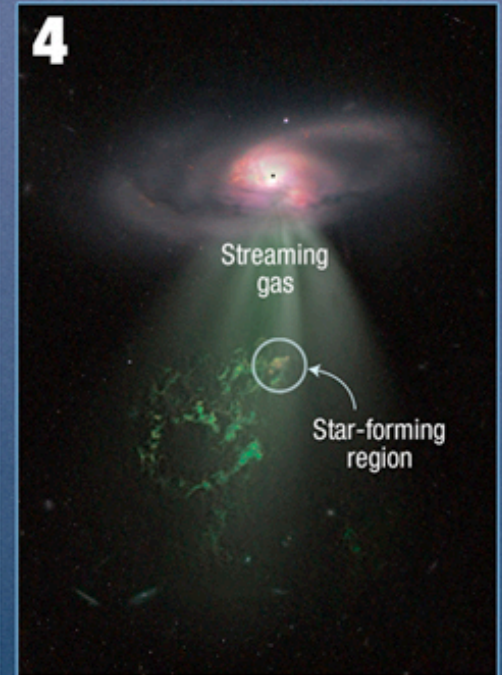
Spiral galaxy IC 2497 gravitationally interacts with a bypassing galaxy.



A large tidal tail of gas is pulled out of the spiral galaxy.



Engorged with gas, a black hole at the center of IC 2497 "turns on" as a quasar and emits a powerful cone of light, which ionizes a portion of the tidal tail, creating Hanny's Voorwerp.



Gas streaming out from the galaxy's center impacts the tidal tail and triggers star formation.



# 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\\_11/emspectrum.html](http://imagine.gsfc.nasa.gov/docs/science/know_11/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/](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 centerpiece 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/>



## For tonight's lecture:

- 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>
- 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/idamnc1r.htm>
- Callisto (second largest moon of Jupiter): from NASA Planetary Photojournal, <http://photojournal.jpl.nasa.gov/catalog/PIA03456>
- 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>
- M17: The Omega Nebula in Sagittarius APOD 2003 April 25 <http://antwrp.gsfc.nasa.gov/apod/ap030425.html>
- Keyhole Nebula: Hubble Heritage Project, <http://heritage.stsci.edu/2000/06/index.html>
- NGC 281: Star formation around the open cluster IC 1590 APOD 2003 April 7 <http://antwrp.gsfc.nasa.gov/apod/ap030407.html>
- Open cluster: M11 APOD 2003 January 22 <http://antwrp.gsfc.nasa.gov/apod/ap030122.html>
- Planetary nebula: The Helix Nebula NGC 7293 APOD 2003 May 10 <http://antwrp.gsfc.nasa.gov/apod/ap030510.html>
- Cat's Eye Nebula: APOD 2002 March 24 <http://antwrp.gsfc.nasa.gov/apod/ap020324.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](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>



- Galaxies: Galaxies in the Hubble Deep Field South, in Fornax; APOD 2003 June 25  
<http://antwrp.gsfc.nasa.gov/apod/ap030625.html>
- Billions of clusters: Hubble Ultra Deep Field, from Hubblesite <http://hubblesite.org/newscenter/archive/releases/2004/07/>
- Sheets and bubbles of galaxies: from the Millemium Simulation <http://www.mpa-garching.mpg.de/galform/millennium/>
- 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/](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/known\\_11/emspectrum.html](http://imagine.gsfc.nasa.gov/docs/science/known_11/emspectrum.html)
- Wavelength: from "Cool Cosmos", [http://coolcosmos.ipac.caltech.edu/cosmic\\_classroom/cosmic\\_reference/emspec.html](http://coolcosmos.ipac.caltech.edu/cosmic_classroom/cosmic_reference/emspec.html)
- Wavelength as a function of temperature: from Astro I 1230 by Richard McCray  
<http://cosmos.colorado.edu/cw2/courses/astro1120/text/chapter1/lesson1.html>
- Atmospheric transmission from Wikipedia: Space observatory [http://en.wikipedia.org/wiki/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](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](http://coolcosmos.ipac.caltech.edu/cosmic_classroom/cosmic_reference/emspec.html)
- Multi-wavelength images of Cen A: from "Cool Cosmos"  
[http://coolcosmos.ipac.caltech.edu/cosmic\\_classroom/multiwavelength\\_astronomy/multiwavelength\\_museum/cenA.html](http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/cenA.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. Raychaudhuri, <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/>.