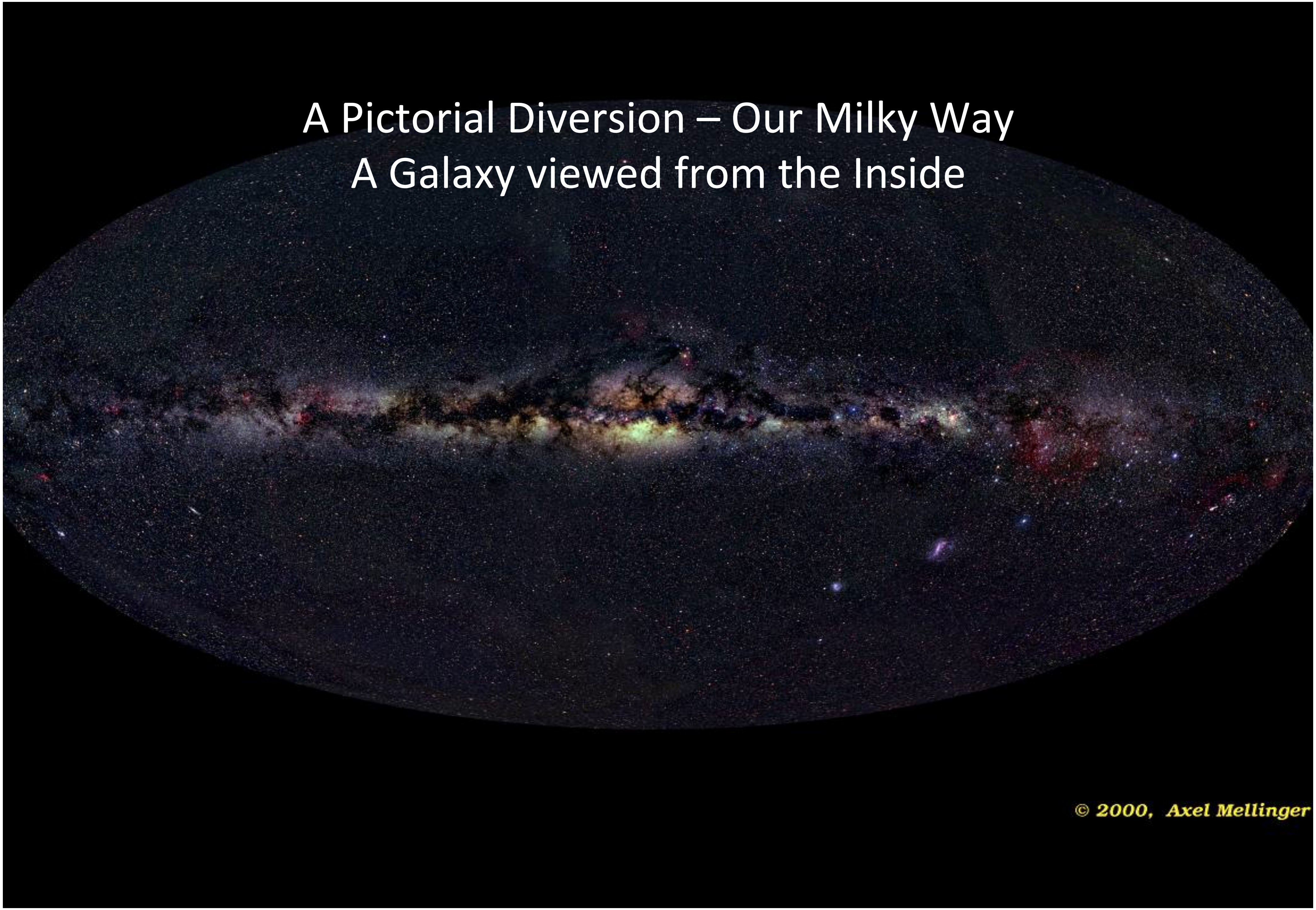
PHYS2160 – Astronomy

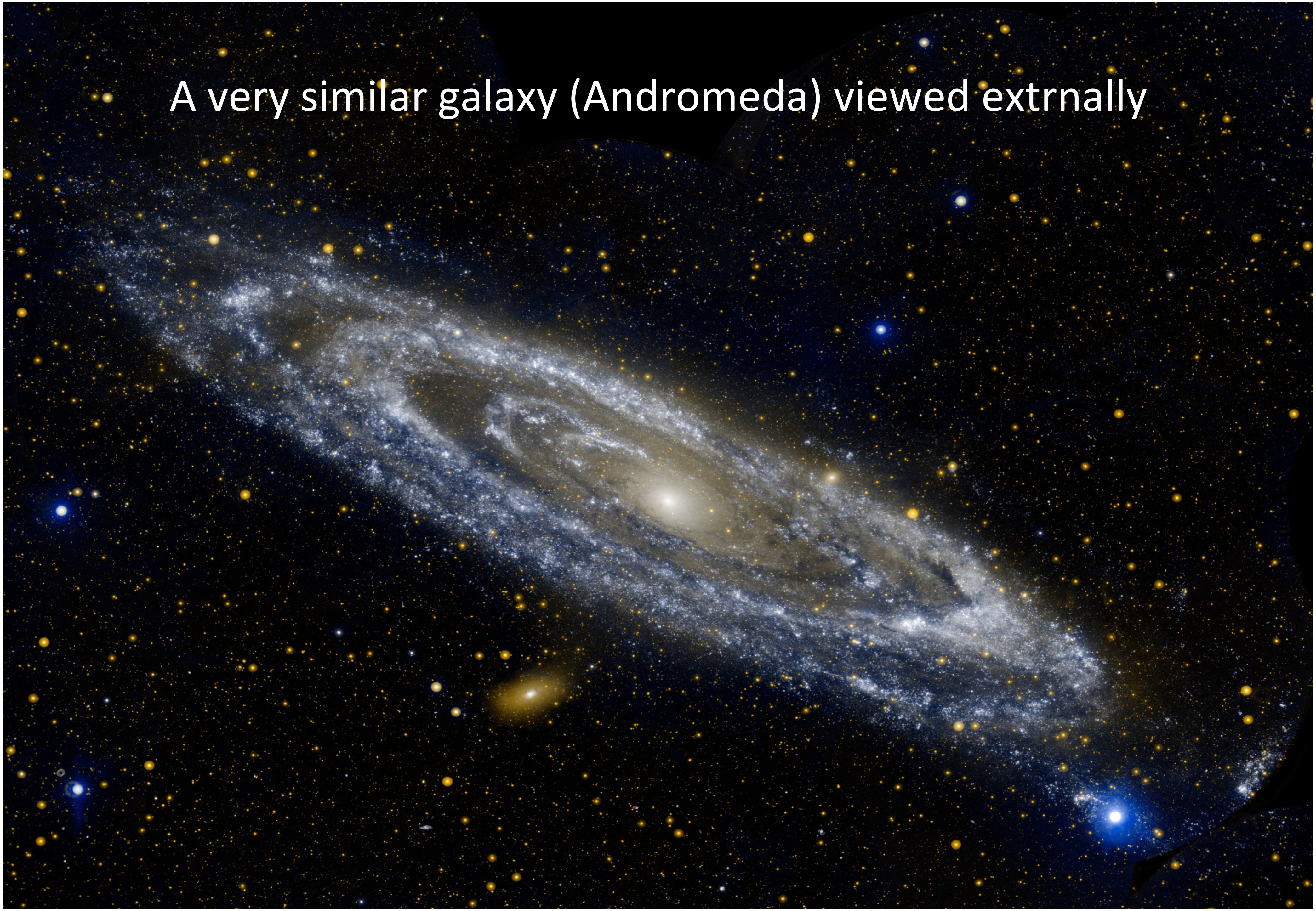
- This course will cover much of basic astronomy, and will be presented by two lecturers
- Chris Tinney (Weeks 1-6) will cover "Part I" – our Galaxy (the Milky Way), other galaxies (spiral, elliptical, active and starburst galaxies, and quasars), the cosmic distance scale and the size and age of the Universe.
- Sarah Martell (Weeks 7-12) will cover "Part II" – Galaxies at High Redshift and their Evolution (galaxy number counts, cluster and field galaxy evolution; redshift surveys; gravitational lensing), Cosmology (Models and observations; the Big Bang; Inflation and Grand-Unified Theories; galaxy formation; the cosmic microwave background; dark matter models; cold dark matter scenario).
- Lectures
  - Tuesday, 11am, Old Main Building 151
  - Wednesday, 1pm, Old Main Building 150
- Website (for Part I)
  - http://www.phys.unsw.edu.au/~cgt/PHYS2160_-_Part_1
- Website at School of Physcs
  - https://www.physics.unsw.edu.au/courses/phys2160-astronomy
- Assessment
  - 1 assignments worth 15% of final mark
  - In-session exam (during Thursday lecture of Week 6) worth 35% of final mark

PHYS2160 – Astronomy

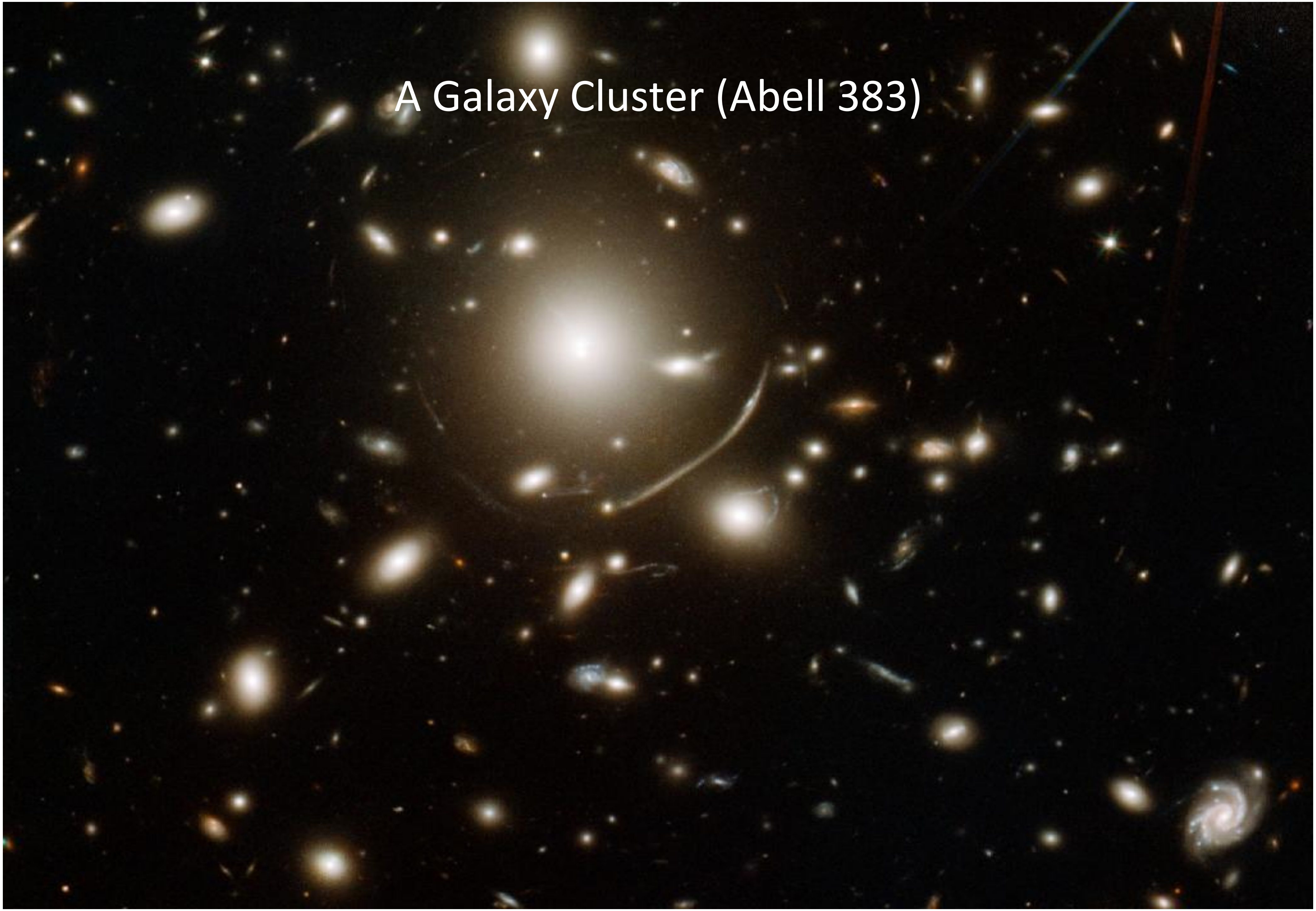
- By the end of this course you should have a better understanding of
  - how our Milky Way galaxy works;
  - how the stars and gas and dust are distributed in it;
  - how spiral galaxies are generally different from elliptical galaxies;
  - how studies of the distribution of galaxies throughout the universe, and searches for the most distant galaxies and quasars tell us about how the universe formed and how galaxies evolve;
  - how measuring the distances to galaxies with ever more precision has told us both how old the universe is, how big it is and how much stuff it has in it – including the fact that the stuff you and I are made from makes up only ~4% of the Universe with the rest being a combination of dark matter and dark energy.

A Pictorial Diversion – Our Milky Way
A Galaxy viewed from the Inside

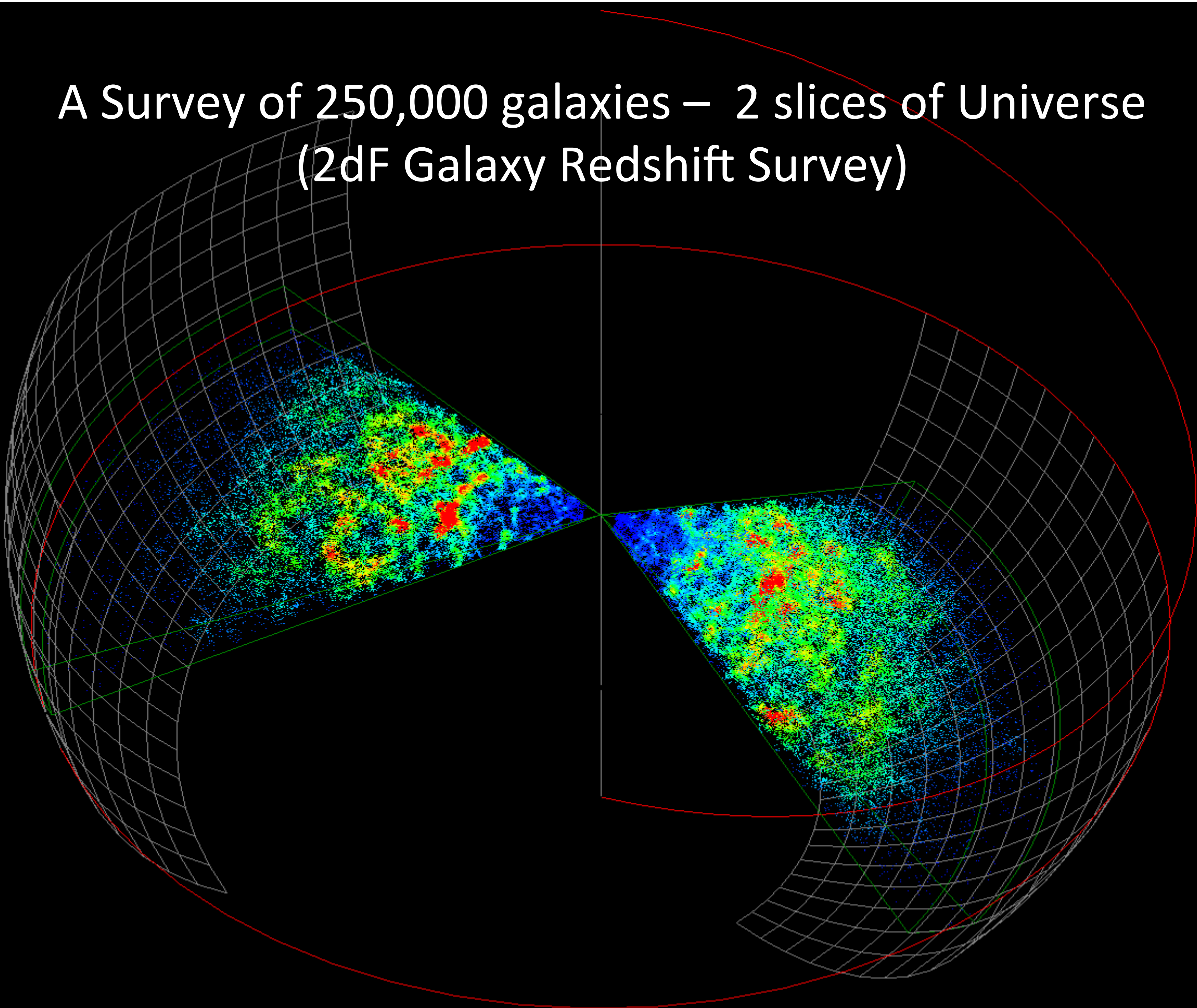


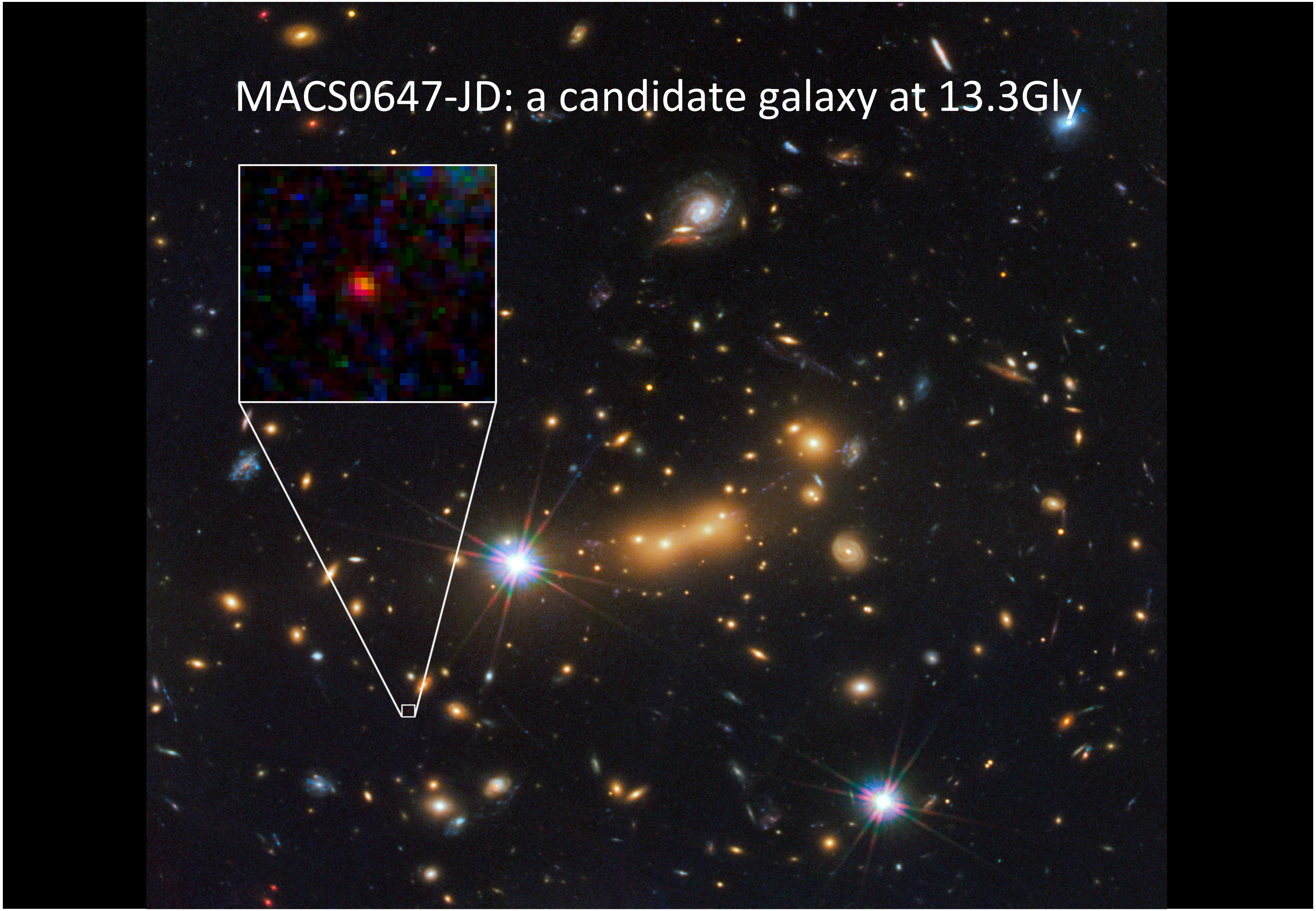

A very similar galaxy (Andromeda) viewed extrnally

A Galaxy Cluster (Abell 383)

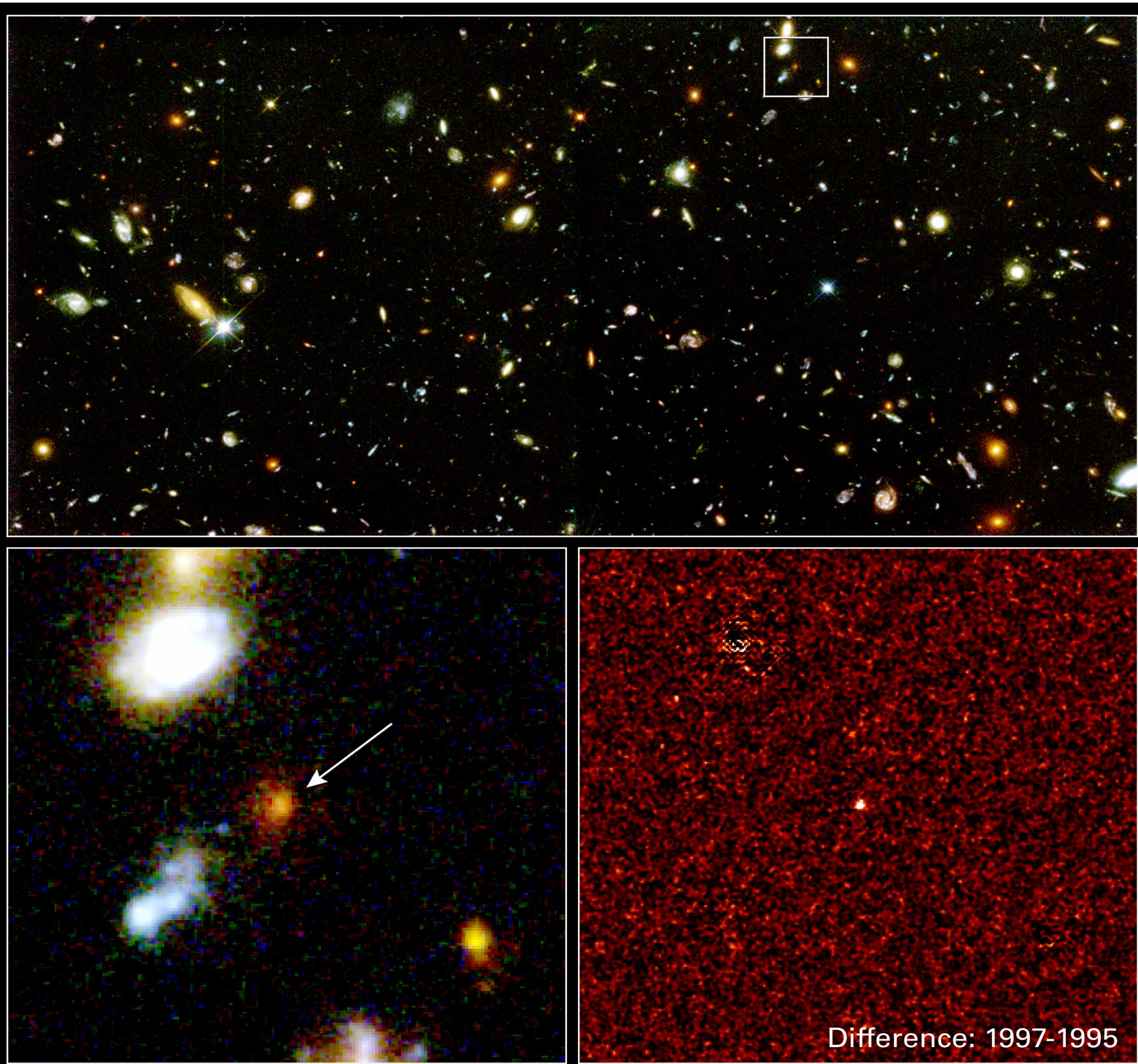


A Survey of 250,000 galaxies – 2 slices of Universe
(2dF Galaxy Redshift Survey)



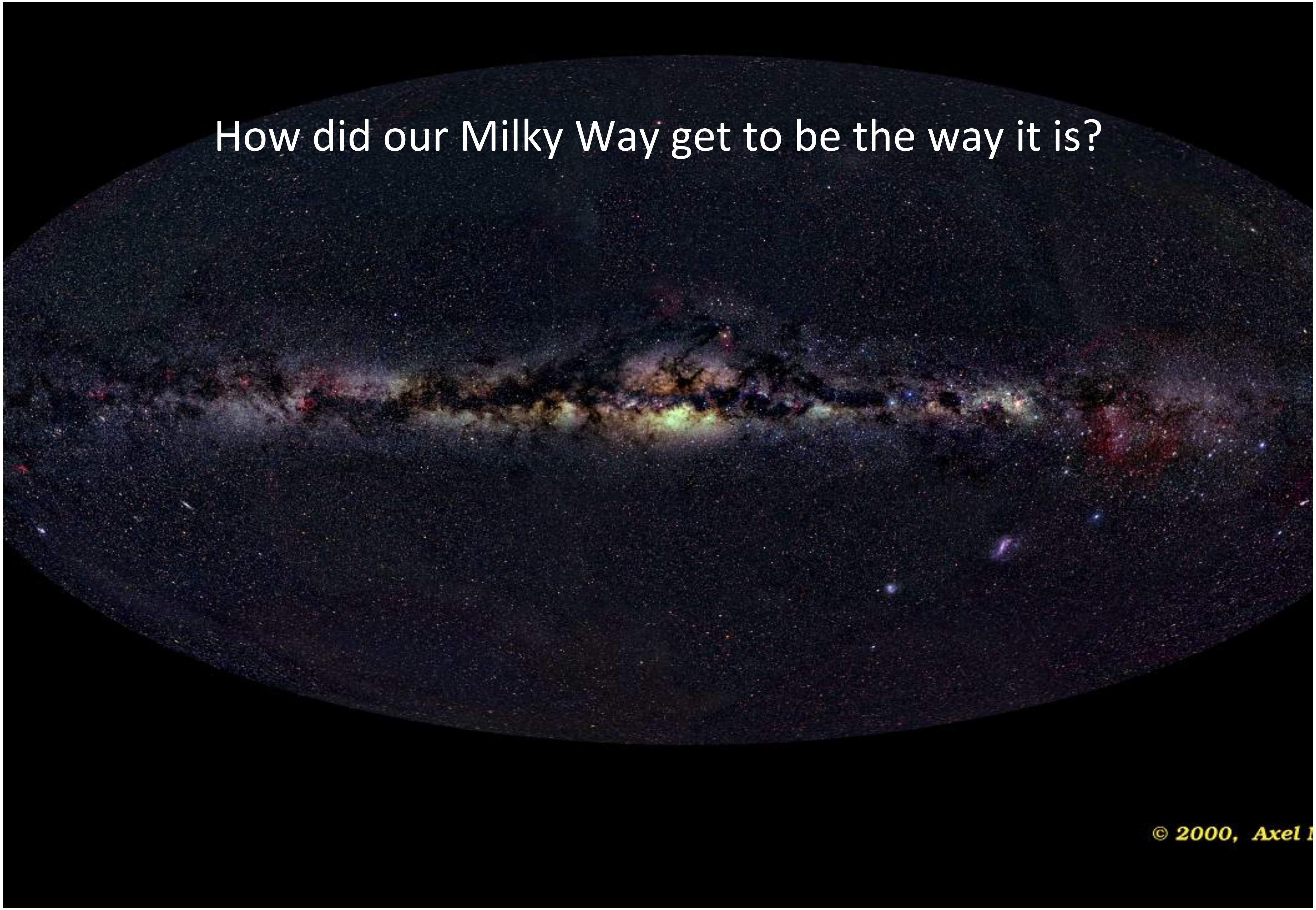

MACS0647-JD: a candidate galaxy at 13.3Gly

SN1997ff
z~1.7 or 10Gly –
one the of Sne that
revealed Dark Energy



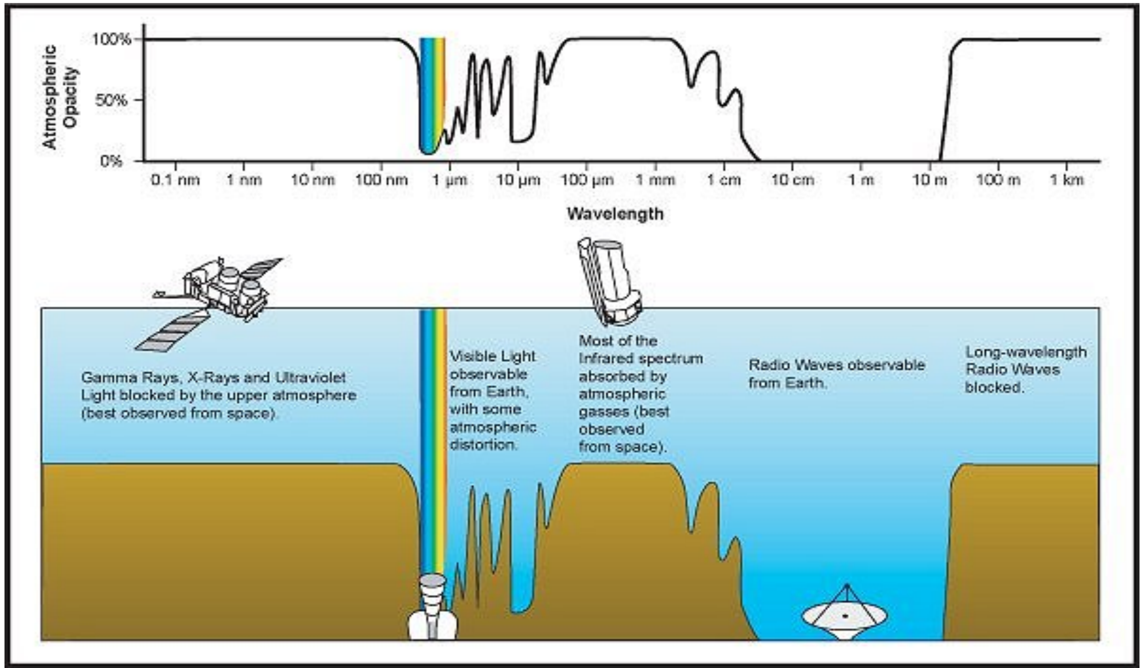
Distant Supernova in the Hubble Deep Field
Hubble Space Telescope • WFPC2

NASA and A. Riess (STScI) • STScI-PRC01-09


How did our Milky Way get to be the way it is?
© 2000, Axel

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

Electromagnetic radiation (i.e. photons) provides pretty much all the information astronomers can access about the Universe beyond our Solar System.



coolcosmos.ipac.caltech.edu

From the ground, there are limited regions of this spectrum that we can access

UV/Optical-to-Mid-infrared (300nm – 15um)

Radio – (1mm – 10m)

Everything else has to be done from space

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

Define some quantities

Apparent brightness, or flux, *f* is the total energy received per unit time per unit collecting area integrated over a given energy range

Common units for *f* are the

Janky (Jy) = 10^{-26} W m^{-2} Hz^{-1} (common in radio astronomy) or

erg cm^{-2} s^{-1} (an optical astronomy flux scale.)

In optical astronomy we more commonly use the logarithmic "magnitude" system, where the flux ratio f_1/f_2 between two objects related to the magnitude difference between m_1 and m_2 as follows:

$$m_1 - m_2 = -2.5 \log10 (f_1/f_2)$$

Beware the minus sign! *Larger* magnitudes means *fainter* objects.

This system is admitted to be a historical hangover – arising from the fact our eye registers light on a logarithmic scale. However it has some useful features

f ratio factor of 10 => 2.5 mag, *f* ratio factor of 2 => 0.753 mag

f ratio factor of 10% => 0.1 mag, *f* ratio factor of 1% => 0.01 mag

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

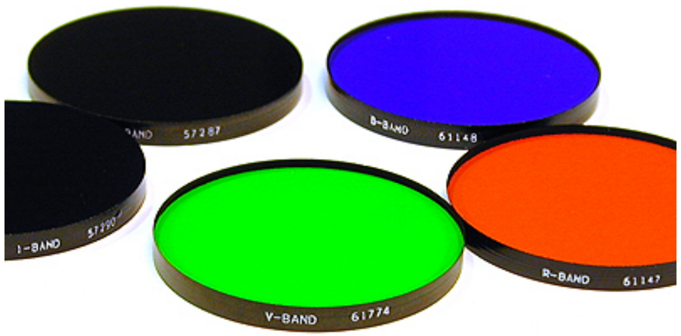
The previous flux and magnitude definitions referred to energy "integrated over a given energy range". What does that mean?

Band[1]	$\Delta\lambda$ μm	λ_{eff} A0	F_0 Janskys
U	0.325–0.395	0.366	1,181
B	0.39–0.49	0.44	4,520
V	0.50–0.59	0.542	3,711
R	0.565–0.725	0.638	3,180
I	0.73–0.88	0.787	2,460
J_{CIT}	1.16–1.35	1.22	1,568
H_{CIT}	1.49–1.80	1.63	1,076
K_S	2.00–2.30	2.15	650
K_{CIT}	2.02–2.43	2.19	674
L_{CIT}	3.24–3.73	3.45	281
L'	3.52–4.12	3.80	235
M	4.5–5.05	4.75	154

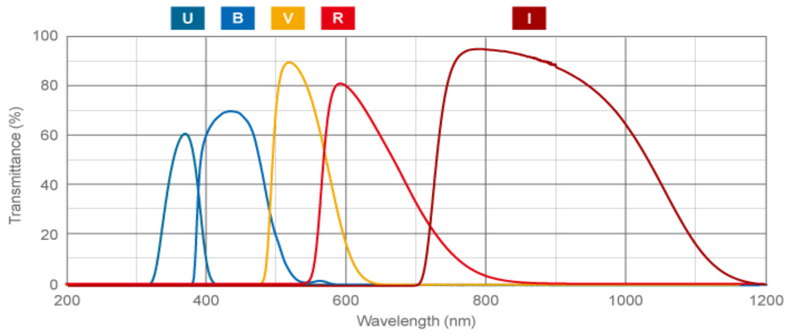
Usually, it means you have done your observations through a standardised filter, chosen to cover useful wavelength ranges, and defined your "zero point" using a standard A0 star – Vega.

For each filter, there will be a flux F_0 that corresponds to zero magnitude in that filter.

Table adapted from Reid & Hawley (2005, p20, above) summarising filter band-passes and zero-point fluxes for some common filters. Figure below.



Example optical filters



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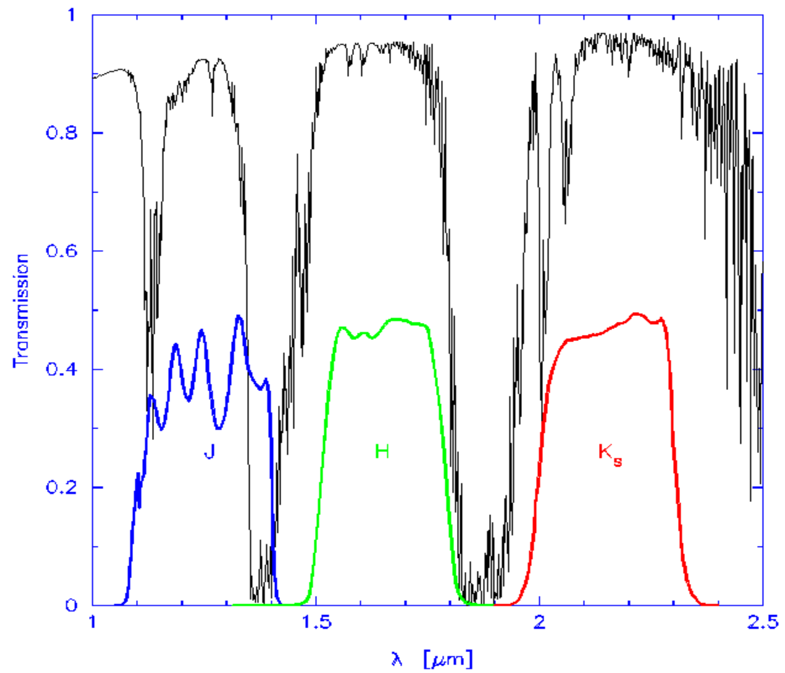
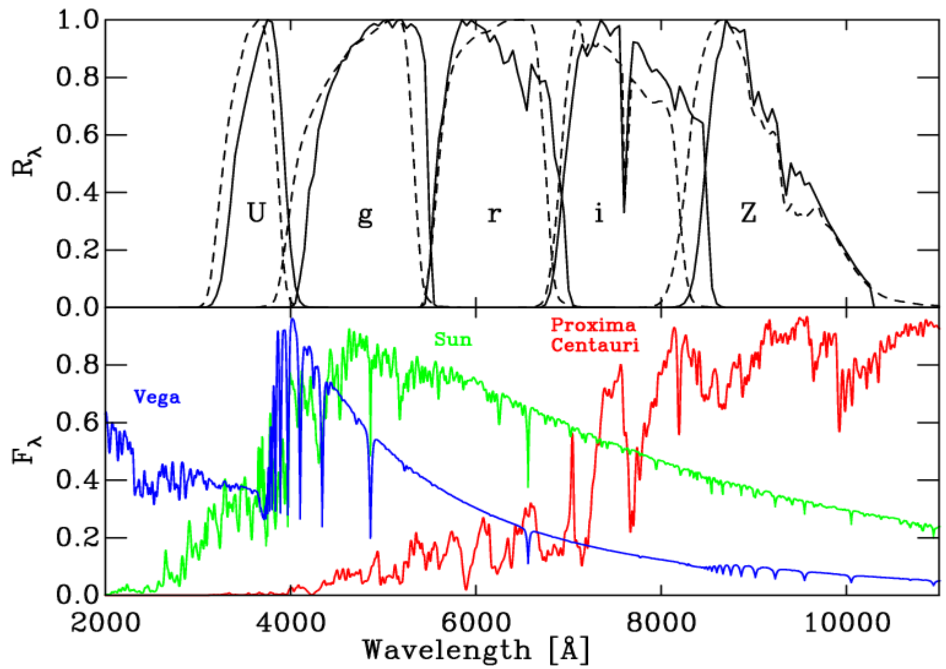
"Useful" here can mean either that it's a wavelength range that sits in a gap in the atmospheric transmission (e.g. in the infrared), or because it probes useful quantities in the stars in question





Vega 9600K Sun 5800K Prox Cen 3000K

Near-infrared filters (colours) tuned to match gaps in sky transmission (black line)

UgriZ optical filter system (black solid) showing how they probe spectral differences for different types of stars (Bell et al. 2012, arXiv:1206.2361)

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

More quantities

Luminosity (L) and flux (*f*) in a given band-pass are related by distance (d)

$$L = f \,.\, 4\pi d^2$$

If you integrate the total flux from an object over all wavelengths, you get the *bolometric luminosity* L_{bol}, meaured in units with dimensions of energy per unit time (e.g. erg s^{-1}, J s^{-1}, or W)

We also define the magnitude version of luminosity the *absolute magnitude* M, which is the magnitude a star would have if it were at a standard distance, chosen to be 10 parsecs (10pc).

1pc = 3.26 light years = 3.086×10^{16}m

…. we'll come back to why this unit of the parsec is what it is later.

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

More quantities

From the previous equation defining the magnitude scale, this gives us

$$m - M = 2.5 \log[\,(L/10^2) / (L/d^2)\,] = 5 \log d - 5$$

This difference m-M is known as the *distance modulus*.

Some examples – in the V (or "visual") passband the Sun has $m_\odot = -26.78$, $M_\odot = 4.82$.

The Sun's total (or bolometric) luminosity is

$L_{bol} = 3.86 \times 10^{33}$ erg s^{-1},

$m_{bol\odot} = -26.85$, $M_{bol\odot} = 4.75$.

Some easily observed objects in the sky

m(Venus) = -4.4, m(Sirius) = -1.4, m(alpha Cen) = -0.27

The faintest objects currently detected are at ~30th mag in the Hubble Space Telescope Ultra-Deep Field … 10^{12} times fainter than alpha Cen.

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

Why the parsec? The *only* fundamental distance measure in astronomy is trigonometric parallax. It is used to define our fundamental unit of distance – the parsec

For the *very* small angle π

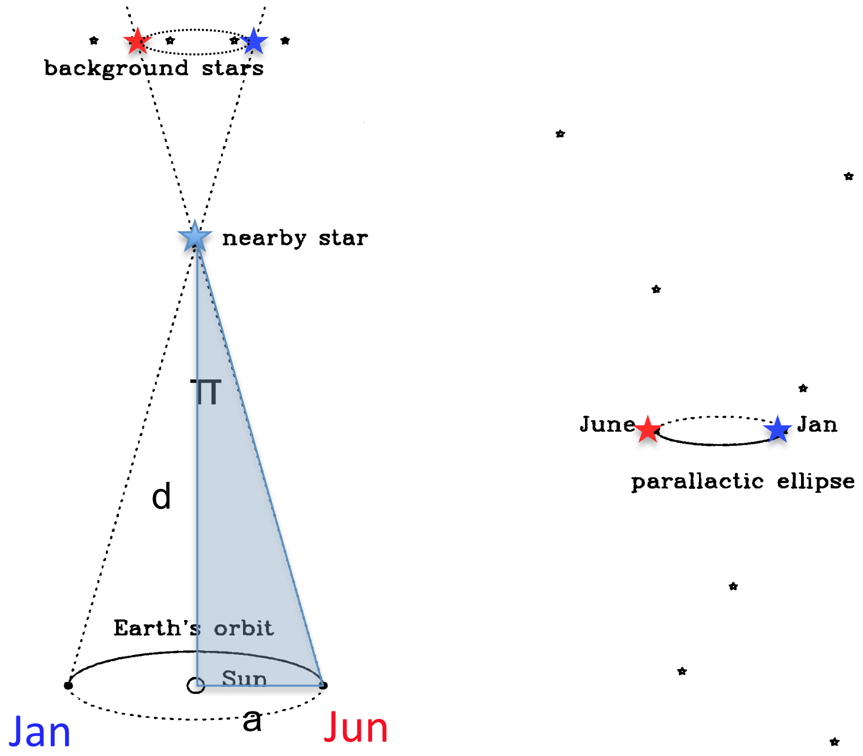
$$\pi = \mathrm{Tan}(\pi) = a/d$$

For scale – the nearest star to the Sun as a parallax π of 0.75”

[cf. 1degree(°) = 60 arcminutes(’)
= 3600 arcseconds (“)]

We define our basic distance unit, the parsec (pc), as the distance at which an object has a parallax of 1”.

Current limits for parallax measurement are about 0.001” (or 1 milliarcsecond or 1mas)



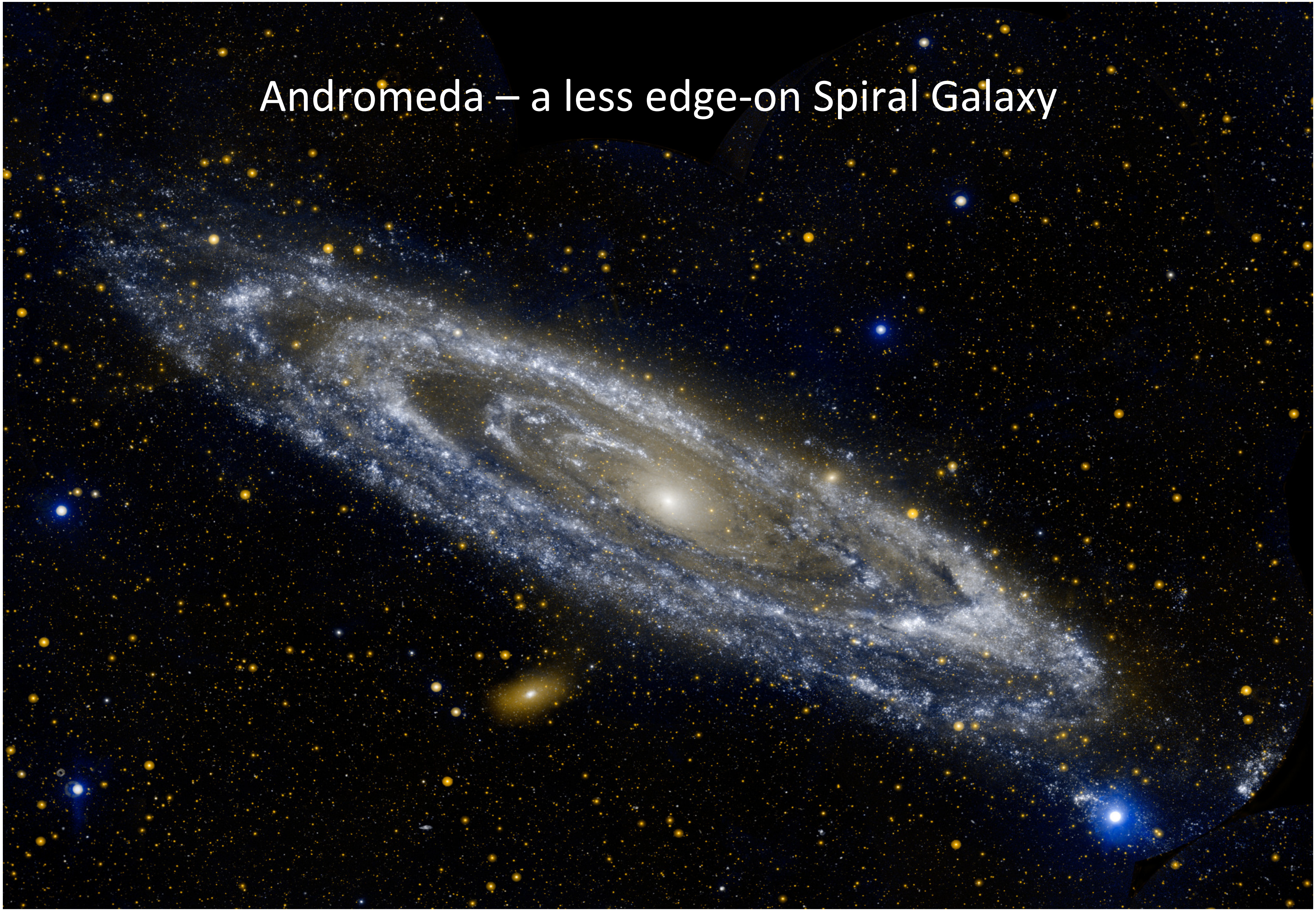
PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

Our Galaxy

When we look up at the night sky, its hard to get a global picture of what the Galaxy looks like … because we are viewing it from the inside.


Our Galaxy
Similar view – but higher in the sky – of the central part of our Galaxy


An external edge-on Spiral Galaxy


Andromeda – a less edge-on Spiral Galaxy

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How (from our position inside the Galaxy) did we work out the Galaxy has this shape?

Early astronomers counted stars in different directions on the sky and concluded that they were the same in all directions, so we must lie in the centre of the visible Universe.

William Herschel (1738-1822) built some of the world's first truly large large telescopes, and used them to make two critical discoveries. First - that there are a great many "fuzzy patches" called nebulae, many of which we know today as "galaxies". And second, he recognised that we live in a huge collection of stars – the Milky Way.

Herschel tried to measure the approximate distance to as many stars as possible, using the rough approximation that all stars are equally bright. Although we know that assumption to be wrong, it did allow him to estimate the approximate distances to several hundred stars. Most of those stars are located in a circular band around the sky, suggesting that we are located in a disk of stars, with the plane of the disk aligned with the hazy Milky Way. His measurements suggested that the thickness of the disk was about one-tenth its diameter.

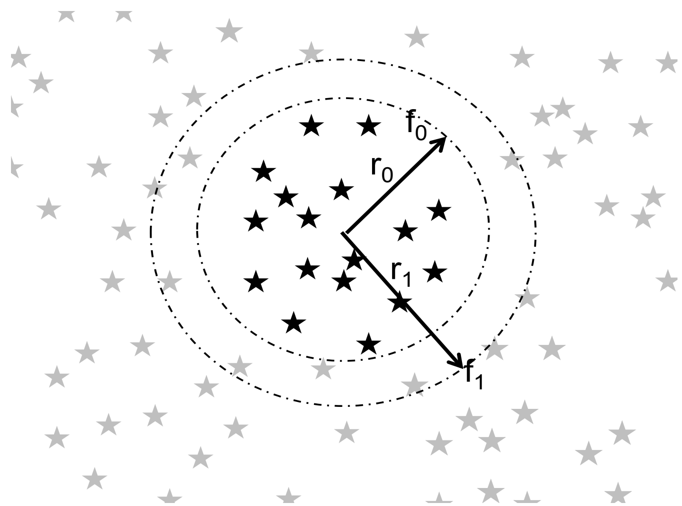
An impressive result for someone using just eyes as a detector!

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

Indeed you can make quite a bit of progress even when you don't know the distances to stars.

If you assume all stars have the same luminosity and are uniformly distributed, then its easy to see that you expect the number of stars brighter than a given flux to scale as that flux limit to the power -3/2.

Imagine observing all the stars out to the distance limit r_0 set by a limiting flux f_0. The number of stars in that sphere of space will be $N_0 = 4/3\pi\ \rho\ r_0^3$, where ρ is the space density of stars. If the flux limit is halved (to see fainter and more distant stars) then the distance limit for detection becomes $r_1 = \sqrt{2}\, r_0$, so the volume (and so the number of stars N_1 at flux limit $f_1 = f_0/2$) increases by $(f_1/f_0)^{3/2}$



Actual star count experiments (e.g. work by Kapteyn starting in 1906 by counting numbers of stars as a function of brightness) do not see this – star counts grow much more slowly than the 3/2th power, telling us that the universe is not uniformly filled with stars. And indeed the 'thinning' out is also not uniform, confirming the idea that the Galaxy is a flattened disk.

(Actual stars are not all the same brightness … but this doesn't matter in this case. Why? See next page)

But where does the Sun lie in this disk? At the centre? At the edge?

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

Let $n(L)$ be the number density of stars with luminosity L. Assume $n(L)$ is spatially uniform. The observed brightness is

$$f_o = \frac{L}{4\pi r_o^2}$$

The number of stars with luminosity L with apparent brightness $f > f_o$ is

$$N_L(f > f_o) = n(L)\frac{4}{3}\pi r_o^3$$

Substitute for r_o from the first equation above, to get

$$N_L(f > f_o) = n(L)\frac{L^{3/2}}{3(4\pi)^{1/2}} f_0^{-3/2}$$

The *total* number of stars with $f > f_o$ is then

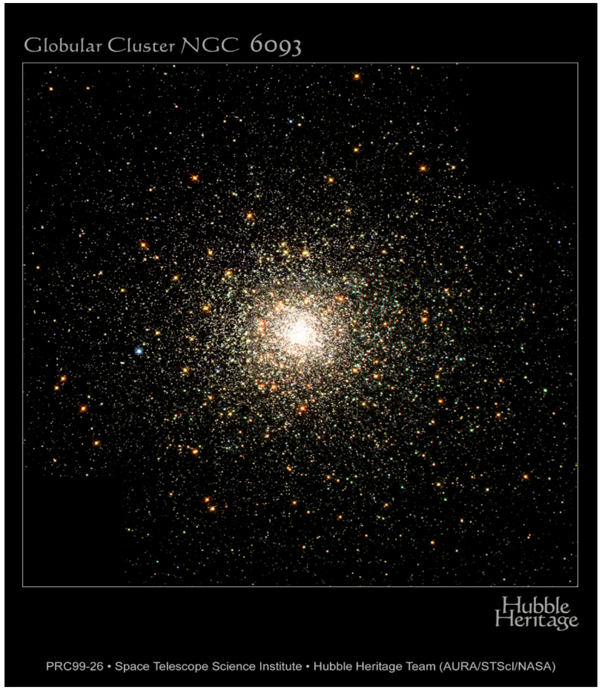
$$\begin{aligned} N(f > f_o) &= \int_0^\infty N_L(f > f_o)dL \\ &= f_0^{-3/2}\int_0^\infty \frac{n(L)L^{3/2}}{3(4\pi)^{1/2}}dL \\ &= Af_o^{-3/2} \end{aligned}$$

Thus, if we see 1000 stars down to a limiting brightness f_o, we should see $1000 \times 4^{3/2}$ down to $f_o/4 = 8000$ stars.

Tutorial exercise to reproduce, understand and explain this.

But where does the Sun lie in this disk? At the centre? At the edge?

PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals



Globular Clusters

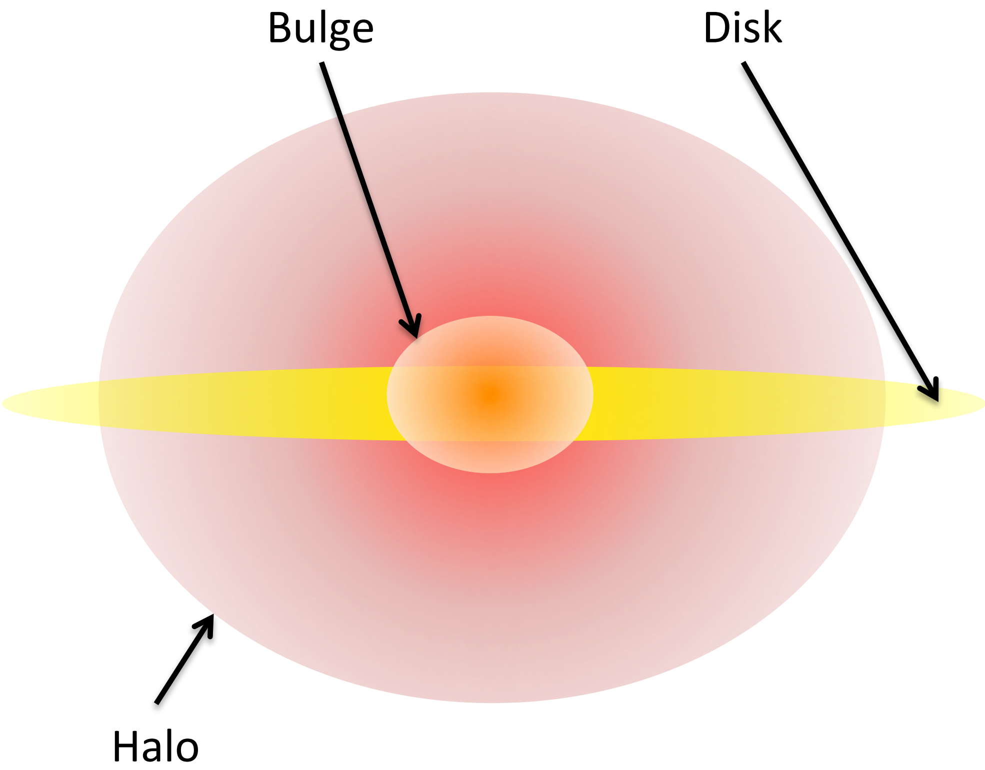
- Spherical agglomerations of 10^5-10^6 stars
- Among the first nebulae seen by Herschel.
- Around 200 associated with Galaxy
- Lie at great distances from the Sun, so can be seen even when they reside on the other side of the Galaxy.

You can estimate distances to them using a variety of techniques (assuming same size, comparing magnitudes of certain types of *variable stars*). From 1914 onwards Shapley studied globular clusters and found them to be highly asymmetric relative to the position of the Sun. He therefore used them to define a position for the Galactic Centre, which has the Sun far from the centre of the Galaxy.

The reason Shapley & Kapteyn got such different answers is that star counts can not probe to the centre of the Galaxy. *Extinction* by clouds of dust along the plane of the Galaxy obscures the Galactic Centre, and means star counts just can't probe the whole Galaxy's structure.

Globular clusters reveal the Sun lies ~8kpc from the Galactic Centre (8.3±0.3kpc is a recent determination by Gillessen et al. 2009, ApJ, 692, 1075)

The Schematic Milky Way Galaxy



Disk – stars (young and middle-aged like Sun), gas, dust

Central Bulge – stars (but largely hidden from view in the MW).

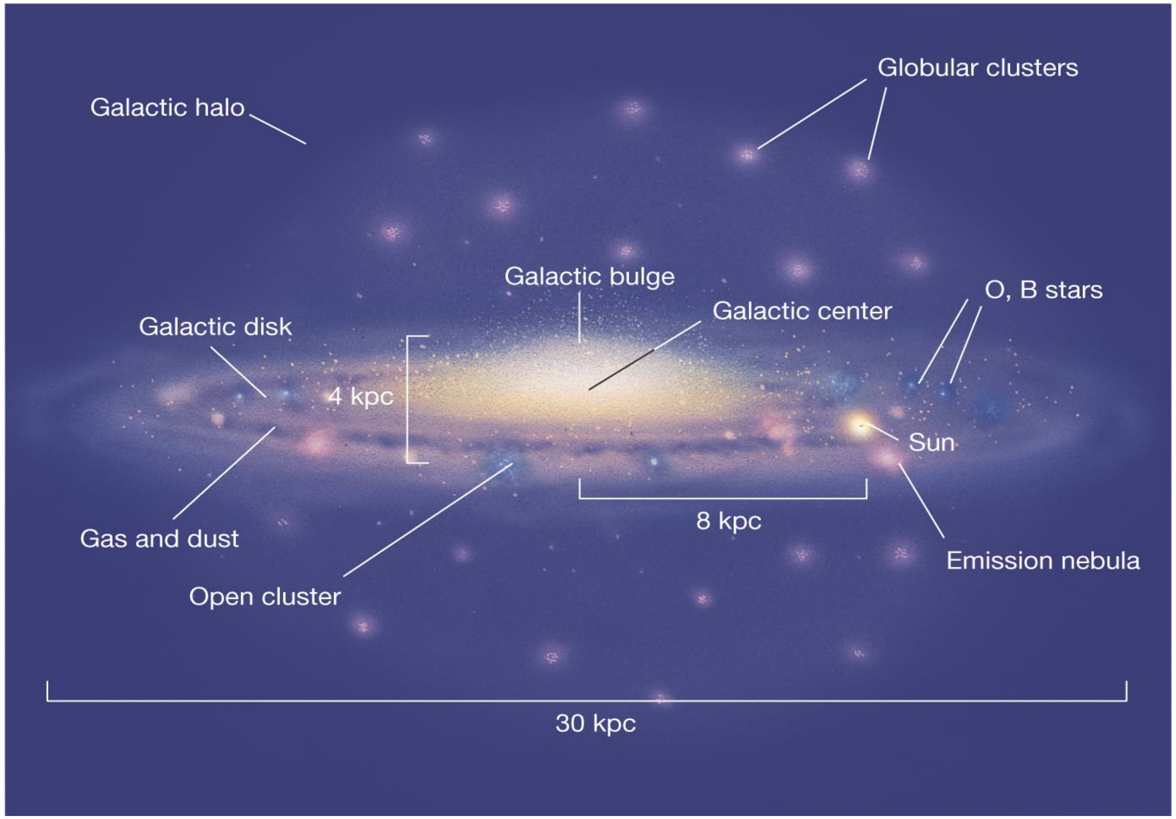
Halo – globular clusters and old stars (which are asymmetric relative to the Sun)

The Sun orbits at 8kpc with velocity 220 km s^{-1}.

Galactic 'year' ~230 Myr.

Mass of Galaxy ~ $6x10^{11}M_{\odot}$.

The Slightly-less Schematic Milky Way Galaxy



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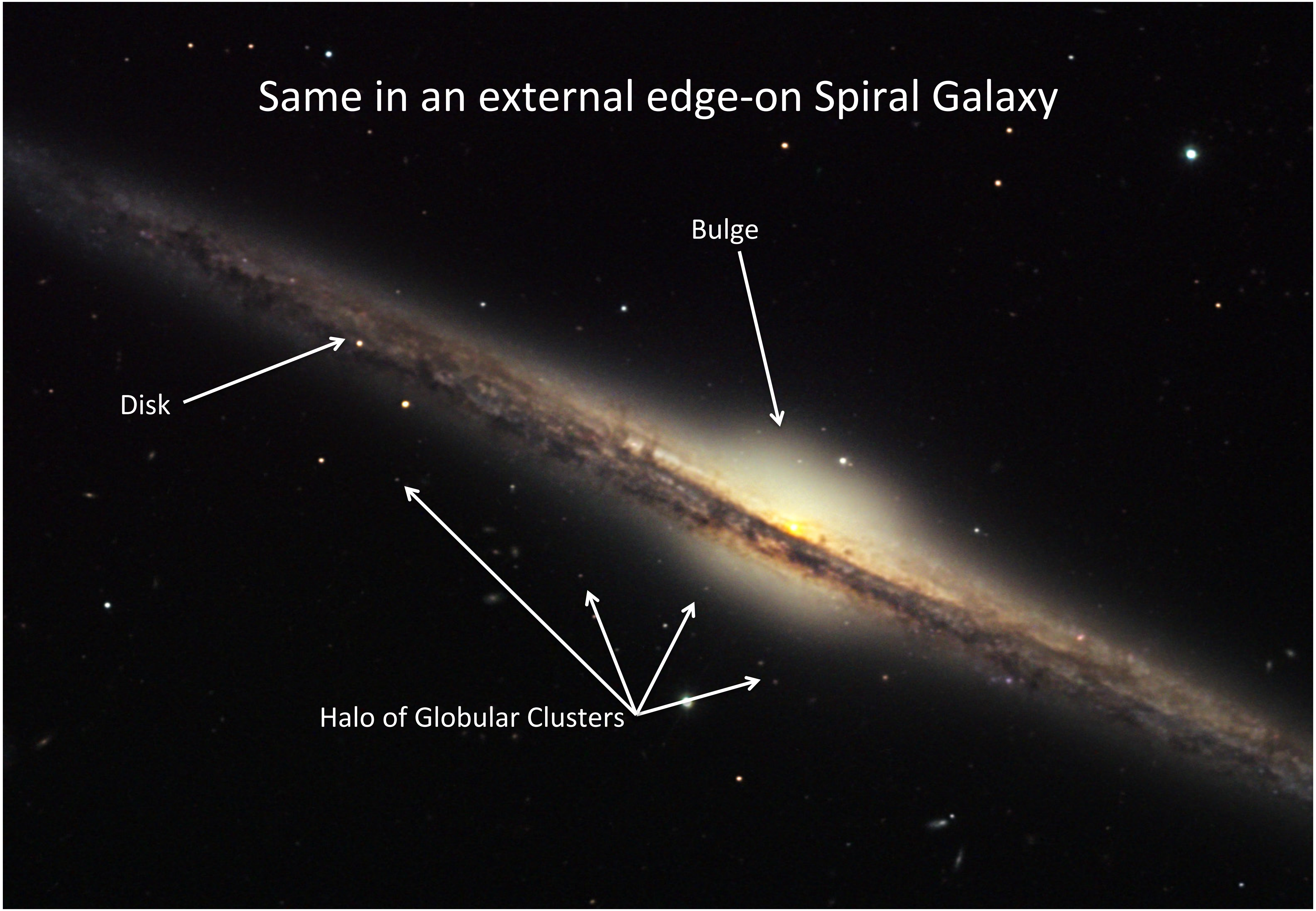
Same in an external edge-on Spiral Galaxy
Bulge
Disk
Halo of Globular Clusters

Are you interested in contributing to the improvement of teaching in Physics? Ensuring that the opinions of students are heard?
Become a course representative.

What's a course representative?

•A student who acts as a liaison between the students in a course and the School of Physics Teaching Committee. This may include meeting with the Committee to provide general feedback; or passing on student problems or complaints.

•We would like one representative from every undergraduate physics course.

How to nominate:

•Send an email with your name, student number and course code to Sue Hagon s.hagon@unsw.edu.au by Sunday 2 August. If more than one student nominates in a course, we will organize a vote.

UNSW Science Student Research Expo

http://www.science.unsw.edu.au/svrs

View this email in your browser

UNSW AUSTRALIA

Student Research Expo

Science Postgrad Research Competition - July 30

Never Stand Still | Science

July 30: Postgrad Research Competition

Join us in Leighton Hall from 1pm on **Thursday 30th July** for our annual Student Research Extravaganza.

Come and watch 80 PhD students from across all schools in the faculty compete in the 1 minute thesis competition and view the poster displays while enjoying delicious free food.

Learn More | RSVP

Summer Vacation Research

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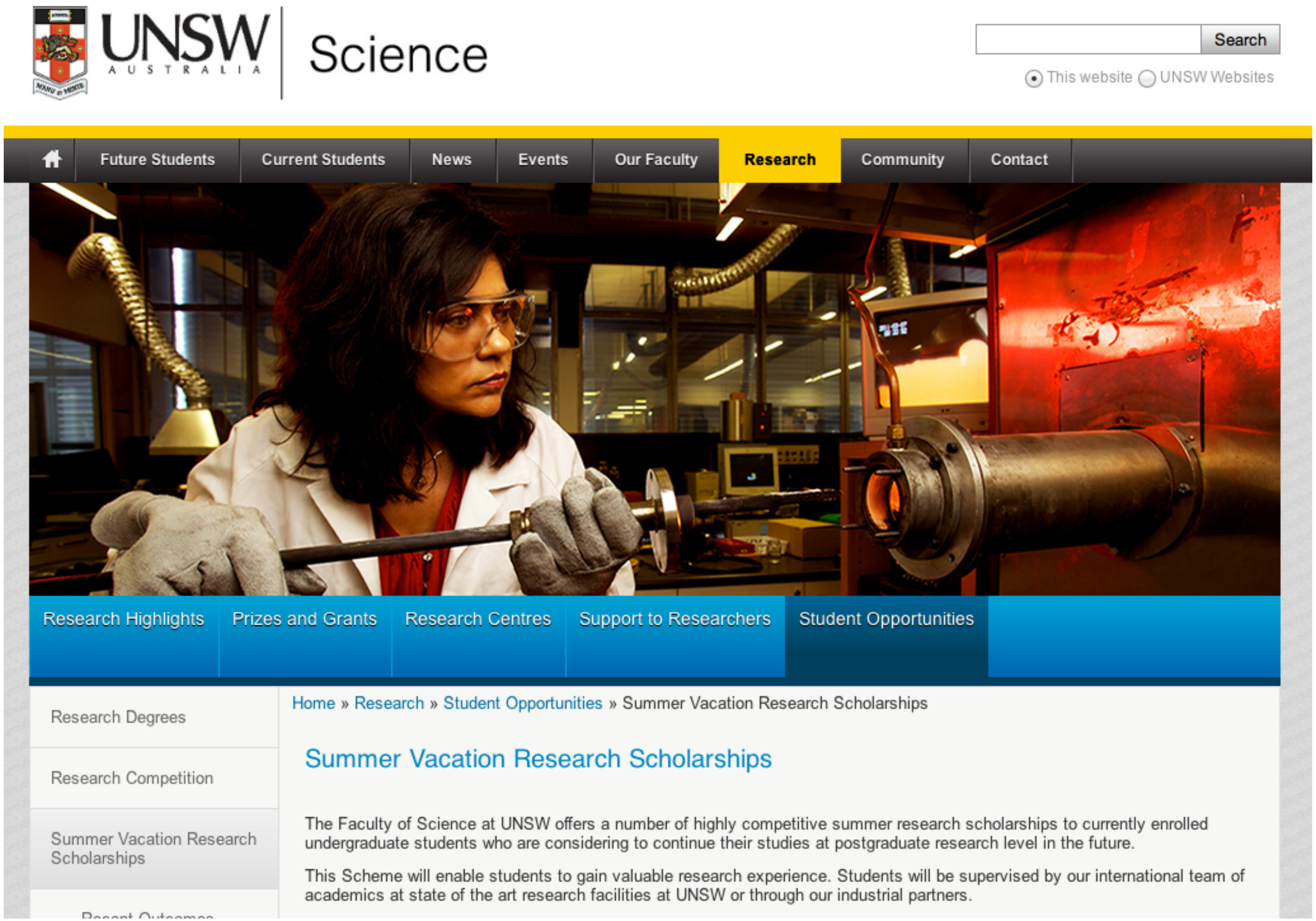


PHYS2160 – Lecture 1 – Our Galaxy: Fundamentals

- References
  - Reid, I.N. & Hawley, S. “New Light on Dark Stars”, Springer, 2005
- Bibliography
  - Shu, F. The Physical Universe, Chapter 12, p255-258 (can be found on google books)
  - Reid, I.N. & Hawley, S. “New Light on Dark Stars”, Springer, 2005, Chapter 1-1.2, 1.3.2, 1.5-1.5.1

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	$=$	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	$=$	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	$=$	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	$=$	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	$=$	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	$=$	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	$=$	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	$=$	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	$=$	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	$=$	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	$=$	1.496	$\times$	10^{11}	m
Parsec	pc	$=$	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

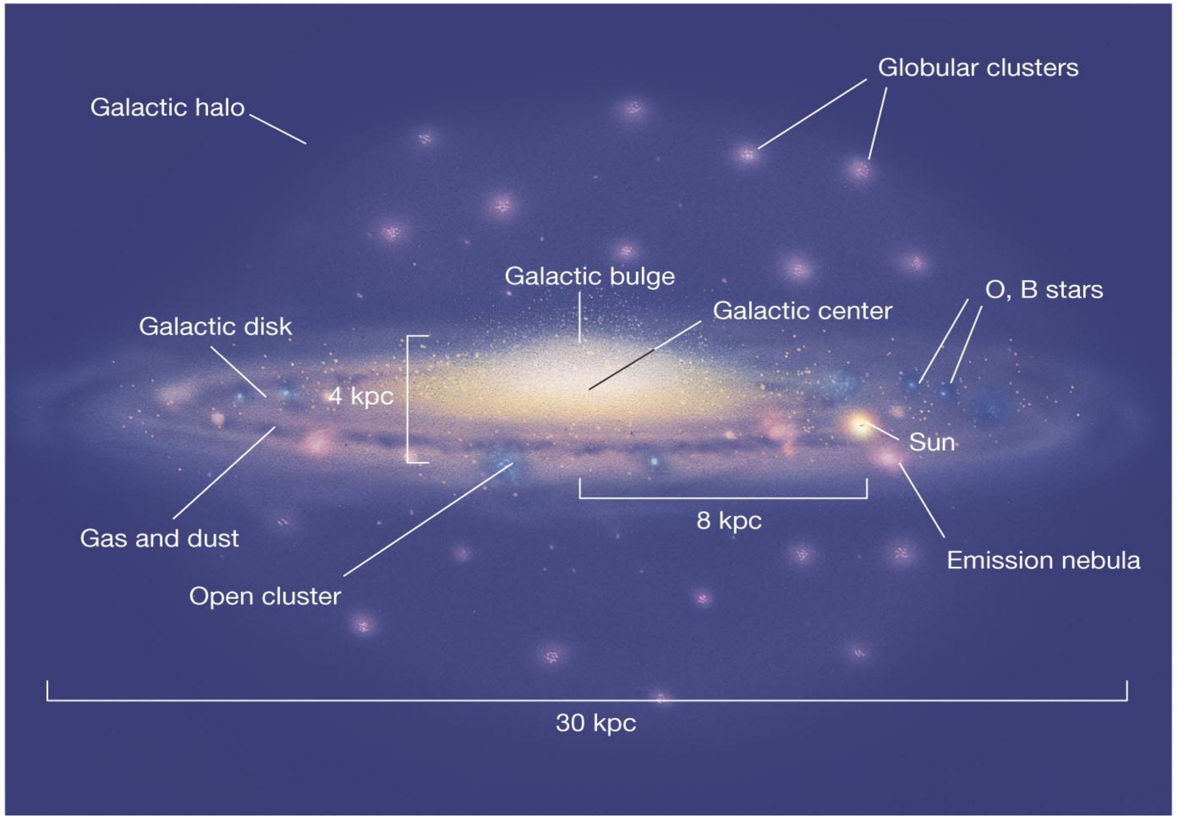
Distance modulus	$m - M$	$=$	$5 \log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	$=$	$2.5 \log \frac{f_1}{f_2}$
For small recession velocities	v/c	$=$	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$

PHYS2160 – Lecture 2 – The Milky Way

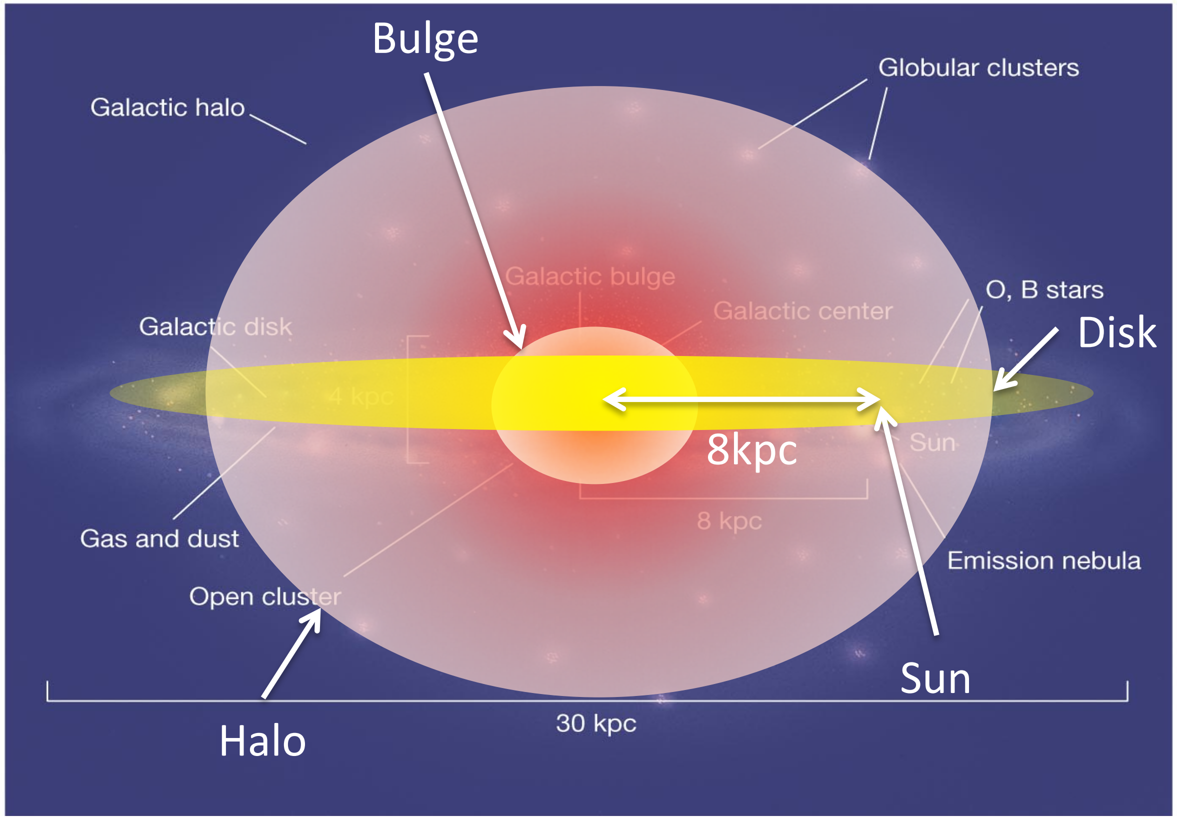
Last time

- flux, luminosity and distance
- apparent magnitude (or more usually just “magnitude”), absolute magnitude & distance modulus
- flux/luminosity in a given bandpass vs bolometric (or “total integrated”) flux/luminosity
- trigonometric parallax and definition of the parsec as a fundamental distance unit
- star counts as a way to probe the properties of a population of stars
- basic picture of the Milky Way

PHYS2160 – Lecture 2 – The Milky Way



PHYS2160 – Lecture 2 – The Milky Way



Disk – stars (young and middle-aged stars like Sun), gas, dust

Central Bulge/Spheroid – stars (but largely hidden from view by the disk of the Milky Way).

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The Sun orbits at 8kpc with velocity 220 km s^{-1}.

Galactic 'year' ~230 Myr.

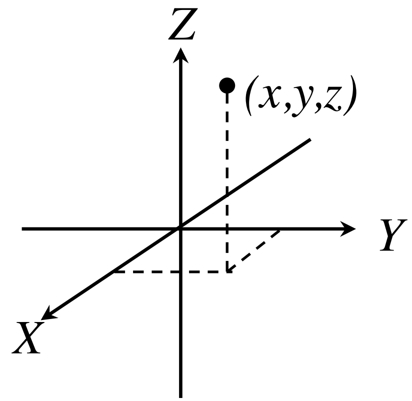
Mass of Galaxy ~ $6\times10^{11}M_{\odot}$.

PHYS2160 – Lecture 2 – Milky Way

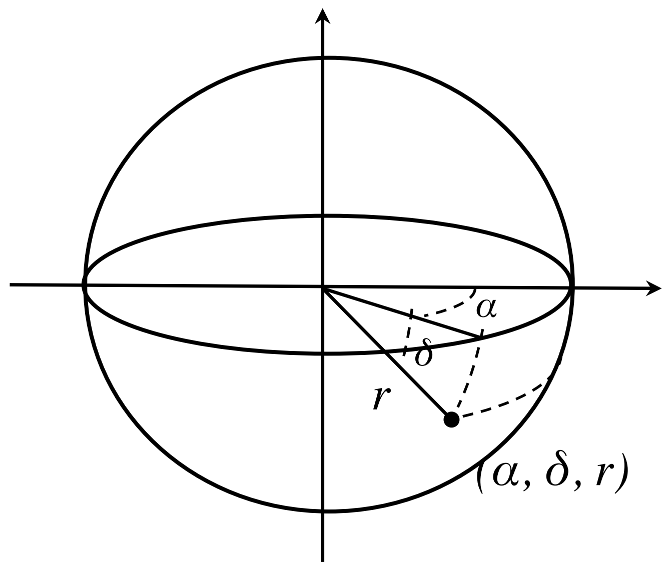
Co-ordinates

The Cartesian (x,y,z) three dimensional co-ordinate system (that we all know and love) is not very useful in astronomy.

We observe the Universe projected onto a sphere at enormously large distances, so a spherical-polar co-ordinate system makes much more sense.



We can easily measure the pair of angles – (α, δ) in the example below – to very similar levels of precision, and be left with the separate problem of how to measure the distance (r)



We most commonly use an Earth-based co-ordinate "equatorial" system where the place that defines the co-ordinate α – known as "right ascension" – is based on the Earth's equator, and the axis that defines the δ co-ordinate – known as "declination" – is based on the Earth's axis of rotation.

It's basically a celestial projection of the longitude/latitude system used to navigate on the surface of the Earth.

PHYS2160 – Lecture 2 – Milky Way

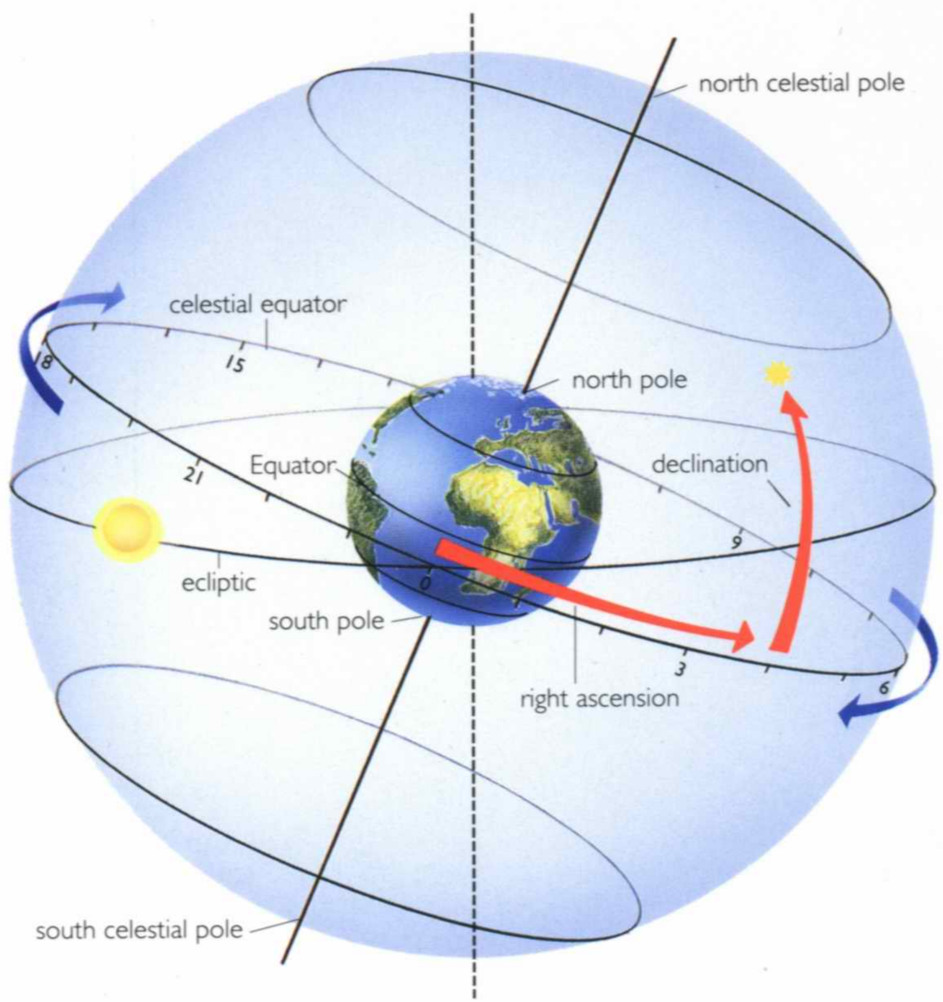
Co-ordinates

In this co-ordinate system, the stars have (more-or-less) fixed co-ordinates, and the whole system *appears* to rotate above us.

As noted before measuring (α, δ) to the same levels of precision is straightforward. Typically getting precisions of 0.1” (1/1,296,000th of a full circle) is straightforward, and to 0.001” (1 milliarcsecond or mas) is doable with effort.

Measuring distances to objects in the Universe to better than 10% is typically quite hard to do.

(α, δ) can be reported in units of decimal degrees or in radians, but are more commonly reported in sexagisamal notation – Hours:Minutes:Seconds for α and Degrees:Minutes:seconds for δ.



PHYS2160 – Lecture 2 – Milky Way

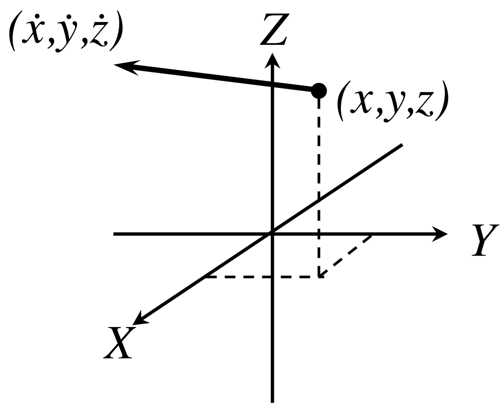
Velocities

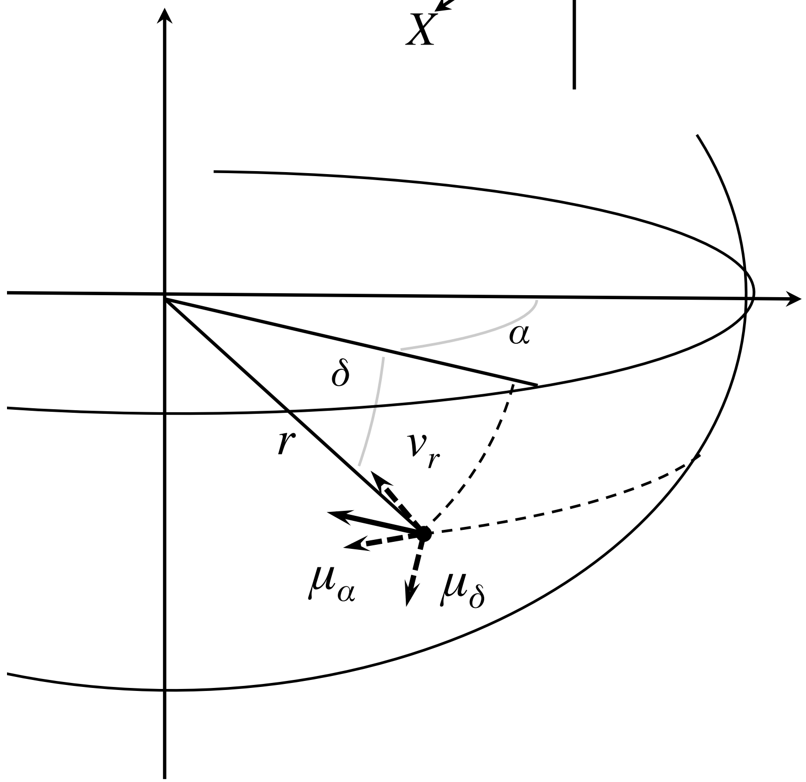
Just as we can define a velocity vector for any particle in a three dimensional space …

So we can define one in our equatorial co-ordinate system (α, δ, r). The relevant velocities are $\mu_{\alpha,} \mu_{\delta,} v_r$

The first two are angular "proper motions" across the sky (i.e. velocities in the plane tangent to the celestial sphere at that point, and aligned with the right ascension and declination directions at that location on the sky) and a "radial velocity", which is the velocity towards or away from us along the line of sight.

$\mu_{\alpha,} \mu_{\delta}$ are straight forward to measure, by taking pairs of observations separated in time …





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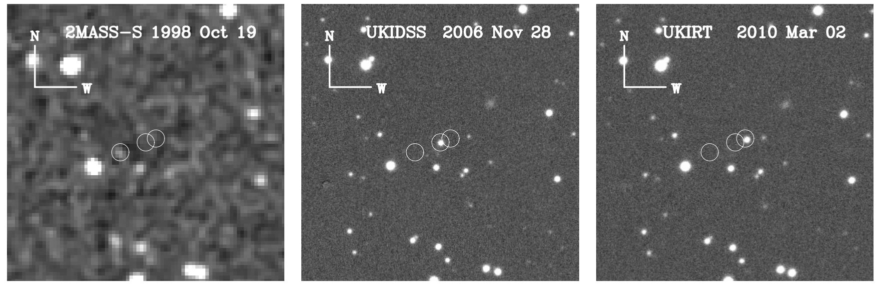
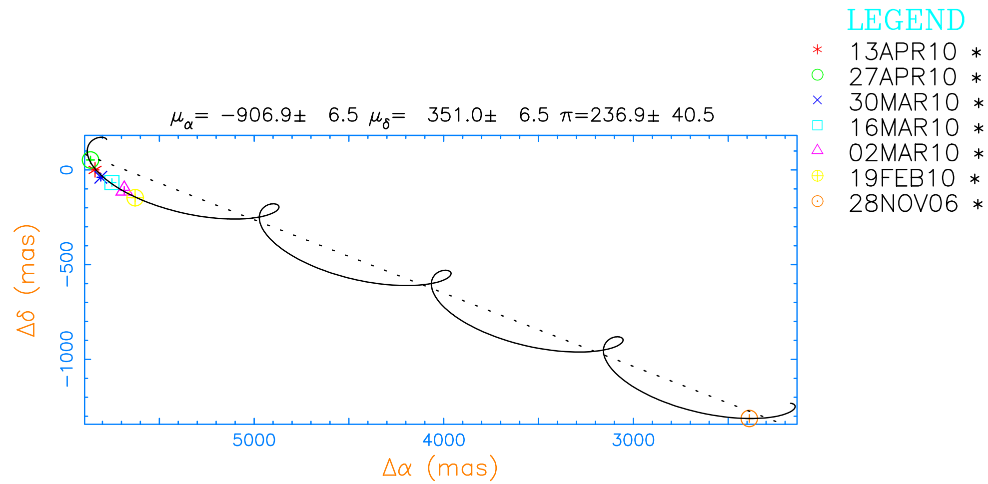
Proper motions

For example - at right are three images of the very cool “brown dwarf” UGPS0722 from 1998 to 2010. Three circles highlight the object’s at each epoch. Additional observations (below) allow one to perform a solution for both proper motion *and* parallax.



Proper motions are typically expressed in arcsec/yr or sometimes as millarcsec/yr = mas/yr



Lucas et al. 2010 MNRAS, 408, 56. http://arxiv.org/abs/1004.0317v2

The orthogonal proper motion components in the right ascension and declination directions can be combined in quadrature to give the total amplitude of the proper motion. So in the case of UGPS0722

$$\mu^2 = \mu_\alpha{}^2 + \mu_\delta{}^2$$

$$\mu \;\;= \sqrt{(906.9^2 + 351.0^2)} = 972.4 \; mas/yr$$

The total proper motion is 0.972”/yr. (These data are how the parallax mentioned last time are measured. In this case the object lies just 4.2pc away.

The fastest known object (measured by apparent proper motion) is Barnard’s Star at 10.37”/yr at a distance of 1.834pc.

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Tangential Velocity

If the proper motion *and* distance is known, then one can determine the physical velocity of the object (in the tangential plane of the sky) using

$$v_T = 4.74\ \mu\ /\ \pi$$

for v_T in units of km/s, if μ has units of arcsec/yr and π has units of arcsec.

Radial Velocity

Radial velocities are determined using the Doppler shift to provide the velocity along the line of sight.

If you know the rest wavelength of a spectral line as obtained in the laboratory here on Earth (λ_{rest}), and then observe the same spectral line in an astronomical object at a different wavelength (λ_{obs}) then the difference between those observations is the Doppler shift and provides the relative line-of-sight velocity

For $\Delta\lambda = \lambda_{rest} - \lambda_{obs}$ then $v_r = c\ \Delta\lambda\ /\ \lambda_{obs}$

Where *c* is the speed of light. It is always quoted in the sense that motions toward you (called "blue shifted" because λ_{obs} is smaller [and so bluer] than λ_{rest}) are +ve, and motions away ("redshifted") are -ve. Total space velocity V is then just the sum of all three components of the space velocity

$$V^2 = v_r^{\ 2} + v_T^2 = v_r^{\ 2} + v_\alpha^2 + v_\delta^2$$

The measurement of positions, velocities and brightnesses form the core of much of modern astronomy.

PHYS2160 – Lecture 2 – Milky Way

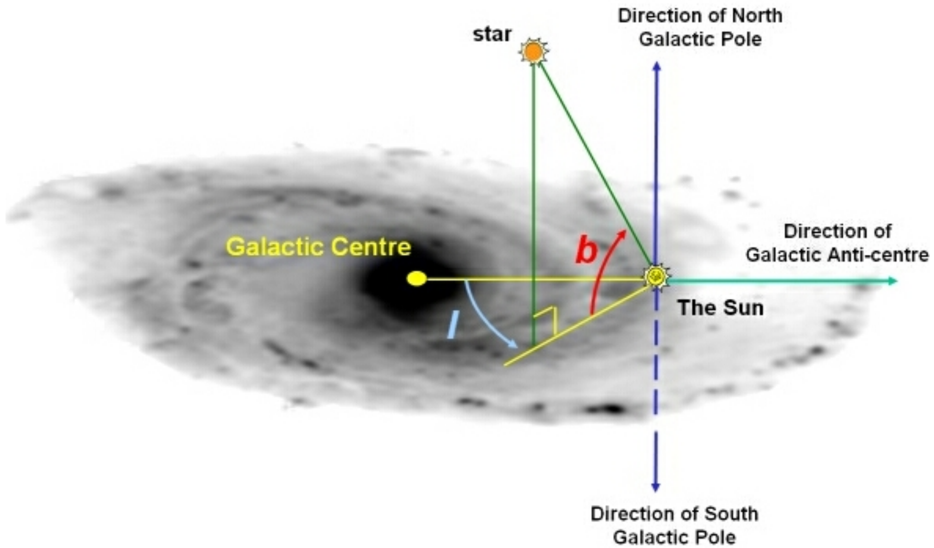
Galactic Co-ordinates

Just as one can define an *equatorial* spherical-polar co-ordinate system based on the orientation of the Earth (because it's useful), so one can define a *Galactic* spherical-polar co-ordinate system based on the orientation of the Galaxy.

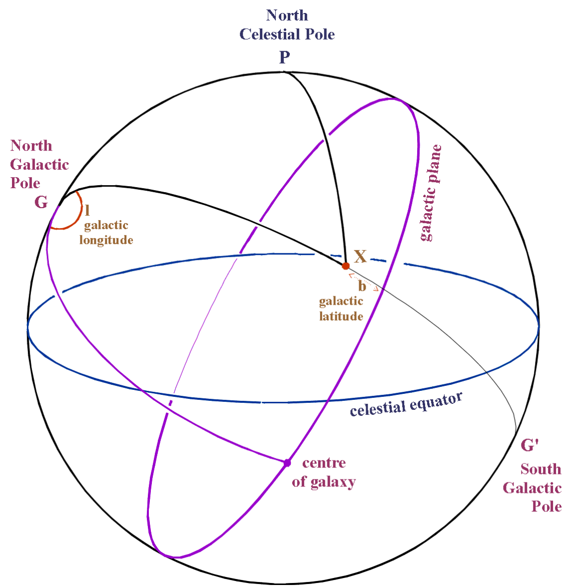
Galactic co-ordinates are centred on the Sun, and defined by two angles

- *l* is the Galactic longitude defined to be zero in the direction the Galactic centre
- *b* is the Galactic latitude defined to be zero in the galactic plane

The Galactic centre direction lies in the constellation of Sagittarius at α = 17h45m40.04s, δ = -29° 00' 28.1"



Galactic co-ordinates viewed from outside Milky Way



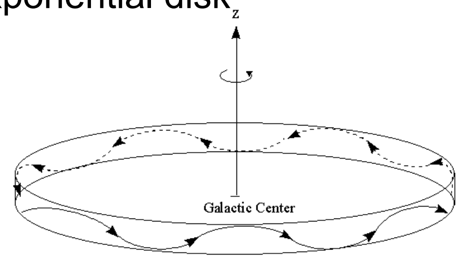
Galactic & equatorial co-ordinates viewed from the Earth

PHYS2160 – Lecture 2 – Milky Way

The Disk (1)

Geometry: Flattened structure of material (stars, gas, dust) that orbits the centre of the Milky Way on predominantly circular orbits. Its density is reasonably well parameterised as an exponential disk in both the radial and vertical directions

$$\rho(r,z) = \rho_0 \, exp(-r/r_d) \, exp(-z/h_d)$$



The radial scale length is r_d = 3.5±0.5kpc, so at the Sun's 8kpc radius its density is only ~10% of that at the Galactic centre, placing us well into the outer regions of our Galaxy. The characteristic scale height h_d is around 330pc for older stars like the Sun. The Sun lies within about 30pc of the mid-plane of the disk.

Gas and Stars : As well as a dense population of stars, the Disk also contains a significant reservoir of gas. It is this gas that is responsible for on-going star formation in the Milky Way.

The gas and dust disk has a significantly lower scale height (around 160pc) than the disk of older stars (330pc), as do the very young stars currently forming from this gas and dust.

It is also this gas that is slightly concentrated by travelling spiral density waves to produce the spiral arms, that are the dominant visual feature of most galaxy disks. These density waves are believed to trigger gravitational instabilities in dense clouds of gas, which in turn initiate the formation of young stars. It is these bright, hot young stars which produce the clearly visible spiral arms.

Young hot stars trace out the spiral arms in M51 (HST)

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Galaxies are almost entirely "collisionless" systems as far as stars are concerned

The mass of stars in the Milky Way disk within the inner 3.5kpc (one scale radius) is about $10^{10}M_{\odot}$.

If we assume the average mass of a star is about $0.5M_{\odot}$, than that implies some 2×10^{10} stars. To get a number density lets assume they occupy a volume given a cylindrical disk of radius 3.5kpc and thickness 2×330pc … so

$$n_* \sim 2\times10^{10} / (\ \pi(3500\text{pc})^2 \times 2 \times 330\text{pc}\ ) \sim 1\text{pc}^{-3}.$$

Or a mean distance between stars of $d=1/\sqrt[3]{n_*} \sim 1$pc.

Ignoring gravity for the time being, the mean free path for a star to make a direct collision with another star will be

$$l \sim 1/(n_*\,\sigma)$$

Where σ is the geometric cross-section for collision. For a solar radius star $\sigma = \pi(2r_{\odot})^2$, which means $l \sim 4.8\times10^{30}$m $= 1.5\times10^{14}$pc. That's a very large number compared to the size of the galaxy!

Or put another way, given the average random velocities of stars relative to each other of about 20km/s, this corresponds to a mean time between direction collisions of 2.4×10^{26}s or 7.6×10^{18}yr – almost a billion times longer than the age of the Universe.

In practice, gravitational focussing (i.e. nearby stars attracting each other) increases this cross section by a factor of ~1000. But this is not enough to change the fact that collisions in a disk are incredibly rare.

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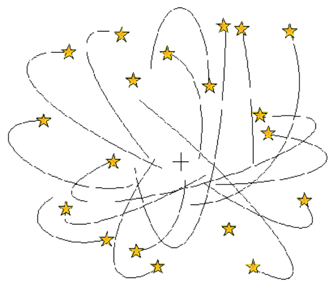
The Bulge/Spheroid and the Stellar Halo

Geometry: predominantly spherical "cloud" of stars on randomly distributed elliptical orbits. Stellar density that falls off as ~ $1/r^3$.



Stellar Halo : is revealed by (1) globular clusters, and (2) as a population of "high velocity" stars in the solar neighbourhood (Since Halo stars are on predominantly "radial" orbits they are "left behind" by the circularly orbiting stars of the disk, including the Sun).

Stars in globular clusters and the halo (and the bulge) are old (ages in the range 10-14Gyr) and have much lower "metallicities" than that seen for stars in the Solar neighbourhood.

Metallicity is "astronomer speak"(i.e. historical and a bit silly) for the relative abundance of heavy elements in a star, compared to the amount of hydrogen. The elements in the Universe heavier than Li have all been formed in the cores of stars, and returned to the interstellar medium via stellar winds or supernovae explosions.

So very old stars will tend to have lower metallicities because their formation material has been through less cycles of enrichment. Metallicity is usually paramatrised via the Fe/H abundance ratio written as [Fe/H], which refers to the logarithmic Fe/H ratio relative to that of the Sun.

A star with [Fe/H] = -4.0 (i.e. Fe abundance 1/10,000th that of the Sun) is considered quite metal poor, and the current record for the lowest metallicity star known is ~ [Fe/H] < -7 (Keller et al. 2014, Nature, 506, 463). The overall density of this Halo population is *very* small compared to that of the disk (~1/10000th) at the Galactic radius of the Sun.


ulge" is readily apparent – the "Halo" is not. It's
ily seen via Globular clusters, and "high velocity"
stars near the Sun.

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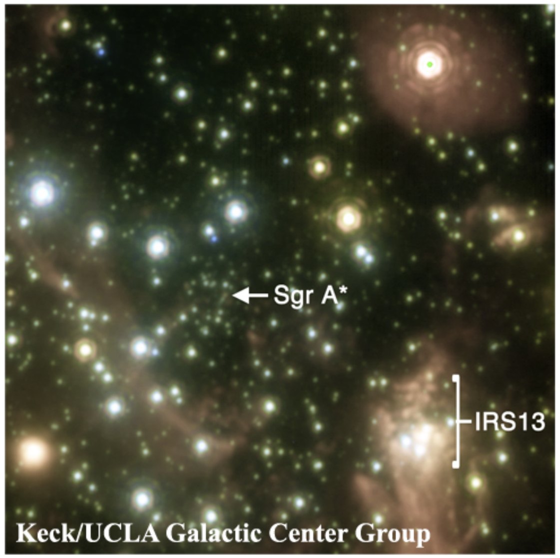
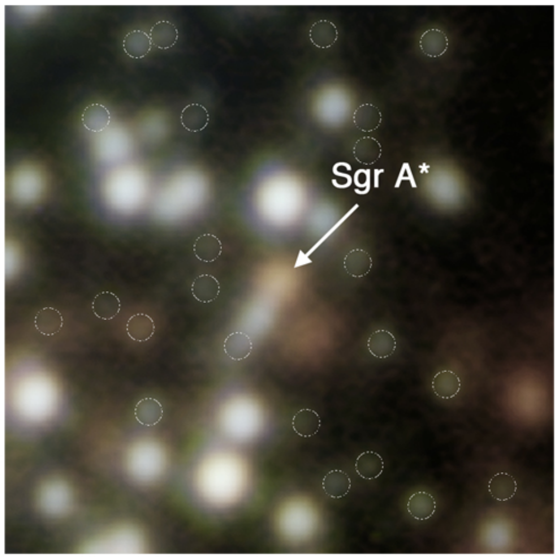
The Bulge/Spheroid and the Stellar Halo

Bulge / Spheroid : similar geometry (and density profile) to the Halo, but is much more obvious in the Galactic central region because its density is much higher. It is not clear whether it and the Halo are the same population (i.e. the halo is an outer extension of the bulge), or distinct ones. Similar bulges are seen in almost every spiral galaxy.

It is believed that many (if not most) galaxy bulges are host to a massive black hole …

In our own Galactic centre, the use of very high resolution imaging techniques at infrared wavelengths allows the stars near the Galactic centre to be monitored. These proper motions allow the orbits of objects to be tracked, which reveals the presence of a dark, compact, massive object at the Galactic centre.





Left: An HKL-band colour mosaic of the region around the black hole at the Galactic centre: H(1.8 μm) = blue, K'(2.2 μm) = green, L'(3.8 μm) = red.

Right: Blow-up of the 0.8”×0.8” region around the position of the supermassive black hole (labelled Sgr A*).

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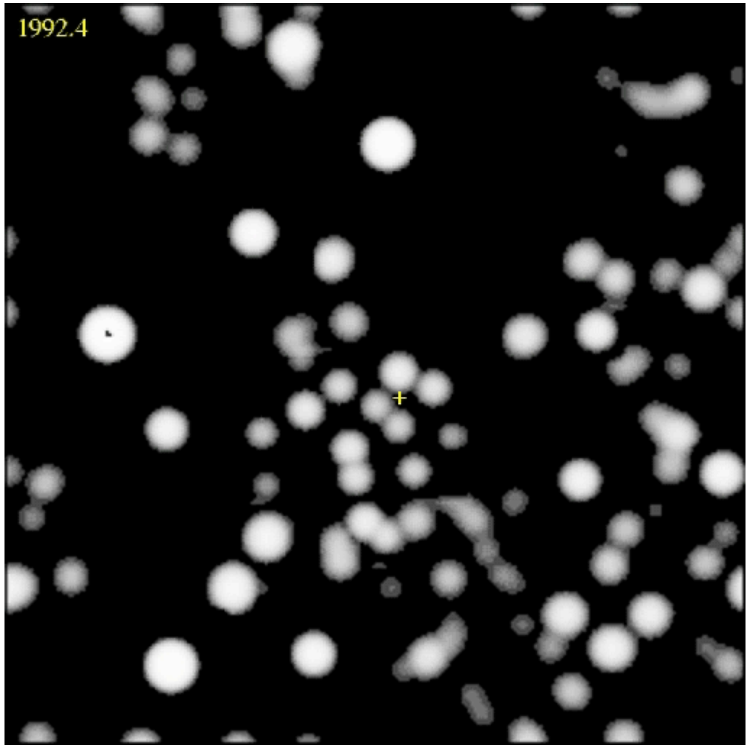
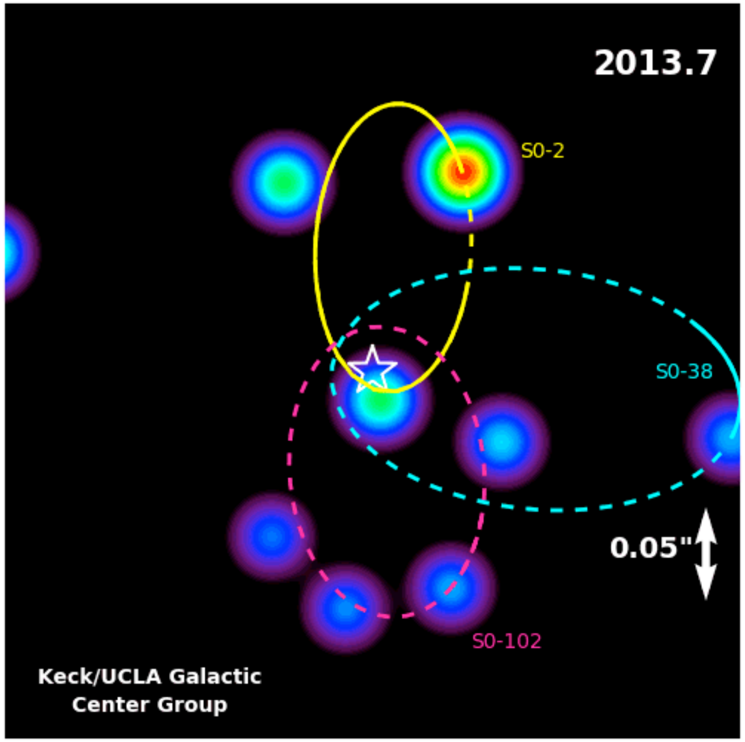
Early data : 1992-1998



Later data!



A 2.2 micron animation of the stellar orbits in the central parsec. Images taken from the years 1995 through 2011 are used to track specific stars orbiting the proposed black hole at the centre of the Galaxy.

PHYS2160 – Lecture 2 – Milky Way

Astrometric positions and orbital fits for 2 stars, within the central 0."8 ×0."8 of the Galaxy, that show significant deviation from linear motion for measurements obtained at the Keck telescopes between 1995 and 2012.

Positions are plotted in the reference frame in which the central dark mass is at rest. Overlaid are the best fitting simultaneous orbital solutions, which assume that all the stars are orbiting the same central point mass.

These two stars have orbital periods of ~ 16 and ~ 11 years.

These orbits, and a simple application of Kepler's Laws, provide the best evidence yet for a "supermassive" black hole, which has a mass of $4 \times 10^6 M_\odot$.

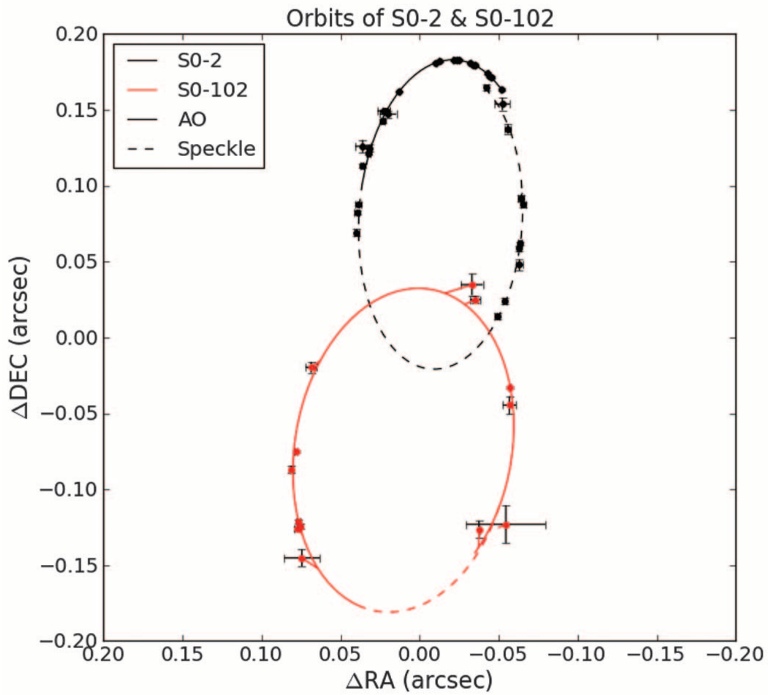


Fig. 2. The orbits of S0-2 (black) and S0-102 (red). RA, right ascension; DEC, declination. The data points and the best fits are shown. Both stars orbit clockwise. The dashed lines represent the parts of the orbits that have been observed with Speckle data; the solid lines indicate AO observations. The data points for S0-2 range from the year 1995 to 2012, and S0-102's detections range from 2000 to 2012. The connecting lines to the best fit visualize the residuals. Although the best-fit orbits are not closing, the statistically allowed sets of orbital trajectories are consistent with a closed orbit. S0-102 has an orbital period of 11.5 years, which is 30% shorter than that of S0-2, the shortest-period star previously known.

from Meyer et al. 2012, Science, 338, 84

Our Milky Way has a fairly *small* black hole at its centre … as we will see later, other galaxies have much larger ones, and it may well be that almost all galaxies harbour black hole at their centre.

PHYS2160 – Lecture 2 – Milky Way

The Disk (2) - Rotation

The Galactic disk does not rotate as a solid body, but rather differentially rotates – it rotates faster at smaller Galactic radii. This can be observed in even the Solar Neighbourhood by looking at the mean motions of stars in the disk.

If we assume we are a 'standard of rest', then stars exterior to us are seen to lag behind, while those interior to us advance ahead. Stars at the same Galactocentric radius have the same velocity and appear not to move.

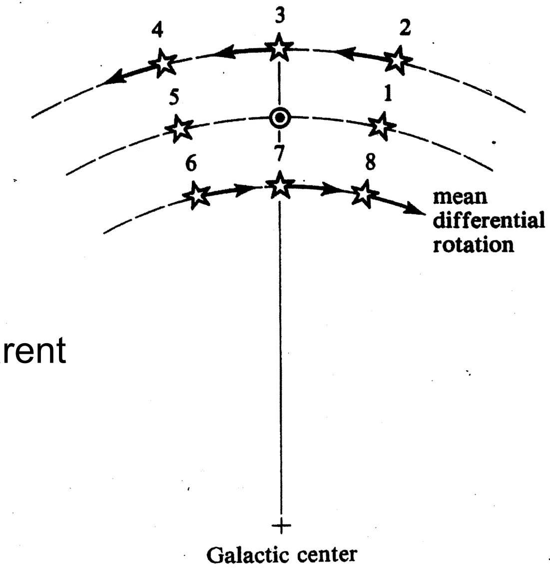


Figure 12.9. The pattern of motions to be expected for the differential mean motions of stars within a few thousand light-years of the Sun.

Fig 12.9 from Shu

In practice, stars do not have perfectly regular, circular orbits. So while they do tend to stay near the same Galactocentric radius, they do move both radially and above and below the disk. The result is an apparent "random" fluctuation in motion compared to the "bulk flow" of the disk – what are known as *peculiar velocities*.

We define a "Local Standard of Rest" (or LSR) in our Galactic co-ordinate system which is the velocity an "ideal" star would have were it to have no peculiar velocity. (The Sun's peculiar velocity relative to the LSR is ~13km/s.)

How can we measure the extent of that differential rotation?

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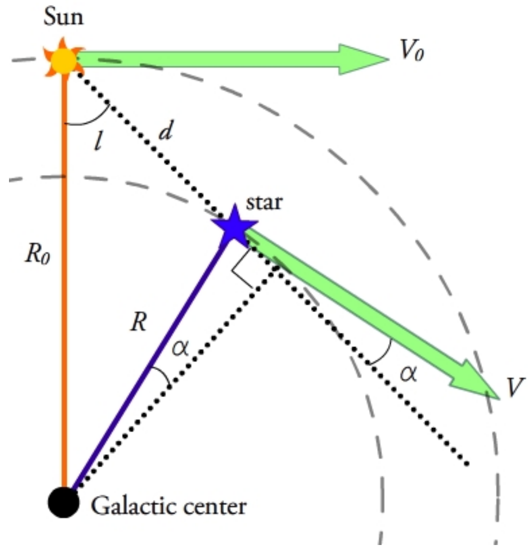
The Disk (2) – Oort's Constants

Consider a star in the mid-plane of the disk with Galactic longitude l at a distance d from the Sun.
Assume that both the star and the Sun have circular orbits around the centre of the Galaxy at radii of R and R_0 from the Galactic centre, and rotational velocities of V and V_0 respectively. The motion of the star observed from the position of the Sun along our line of sight (i.e. its radial velocity $V_{obs,r}$), and motion of the star across the plane of the sky, (or transverse velocity $V_{obs,t}$), are then:



$$V_{\text{obs, r}} = V_{\text{star, r}} - V_{\text{sun, r}} = V\cos(\alpha) - V_0\sin(l)$$
$$V_{\text{obs, t}} = V_{\text{star, t}} - V_{\text{sun, t}} = V\sin(\alpha) - V_0\cos(l)$$

Where α is the angle the star's velocity makes to the line of sight. For circular motions, we can convert those linear velocities to angular ones ($v = \Omega r$), to get

$$V_{\text{obs, r}} = \Omega R\cos(\alpha) - \Omega_0 R_0\sin(l)$$
$$V_{\text{obs, t}} = \Omega R\sin(\alpha) - \Omega_0 R_0\cos(l)$$

From the geometry in the figure, one can see that the triangles formed between the galactic center, the Sun, and the star share a side or portions of sides, so the following relationships hold and substitutions can be made:

$$R\cos(\alpha) = R_0\sin(l)$$
$$R\sin(\alpha) = R_0\cos(l) - d$$

to get

$$V_{\text{obs, r}} = (\Omega - \Omega_0)\, R_0\sin(l)$$
$$V_{\text{obs, t}} = (\Omega - \Omega_0)\, R_0\cos(l) - \Omega d$$

What we really want, however, is that expression in terms of observable quantities (l,d) rather than angular velocities.

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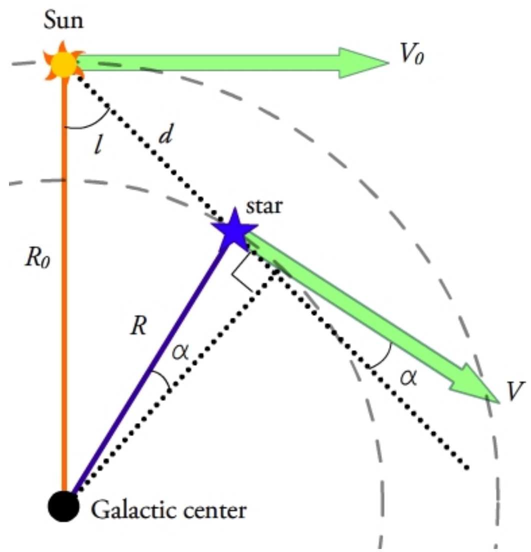
The Disk (2) – Oort's Constants

To do that we take advantage of the Taylor expansion in Ω-Ω_0 about the position R_0.
Recall that for a function f near value a, one can write

$$f(a)+\frac{f'(a)}{1!}(x-a)+\frac{f''(a)}{2!}(x-a)^2+\frac{f^{(3)}(a)}{3!}(x-a)^3+\cdots.$$



So using just the first two terms we can expand $\Omega(r)$, and rearrange to get

$$(\Omega-\Omega_0)=(R-R_0)\,\frac{d\Omega}{dr}|_{R0}+\ldots$$

And in addition as long as we are studying local stars (so $d \ll R$ and R_0).

So

$$R-R_0=-d\cdot\cos(l)$$

$$V_{\text{obs, r}}=-R_0\frac{d\Omega}{dr}|_{R0}d\cdot\cos(l)\sin(l)$$

$$V_{\text{obs, t}}=-R_0\frac{d\Omega}{dr}|_{R0}d\cdot\cos^2(l)-\Omega d$$

Using the sine and cosine half angle formulae ($sin(2A)\ =\ 2\ sin\ A\ cos\ A$, $cos(2A) =\ 2\ cos^2 A - 1$) these velocities may be rewritten as functions of $2l$:

$$V_{\text{obs, r}}=-R_0\frac{d\Omega}{dr}|_{R0}d\frac{\sin(2l)}{2}$$

$$V_{\text{obs, t}}=-R_0\frac{d\Omega}{dr}|_{R0}d\frac{(\cos(2l)+1)}{2}-\Omega d=-R_0\frac{d\Omega}{dr}|_{R0}d\frac{\cos(2l)}{2}+\left(-\frac{1}{2}R_0\frac{d\Omega}{dr}|_{R0}-\Omega\right)d$$

We can write the velocities in terms of the measurable quantities and two coefficients A and B :

$$V_{\text{obs, r}}=Ad\sin(2l)$$
$$V_{\text{obs, t}}=Ad\cos(2l)+Bd$$

$$A=-\frac{1}{2}R_0\frac{d\Omega}{dr}|_{R0}$$
$$B=-\frac{1}{2}R_0\frac{d\Omega}{dr}|_{R0}-\Omega$$

PHYS2160 – Lecture 2 – Milky Way

The Disk (2) – Oort's Constants

So we have the "Oort constants" A and B expressed in terms of angular rotation velocities. These can then be transformed into linear velocities by differentiating $\Omega = v/r$ and substituting

$$A = -\frac{1}{2} R_0 \frac{d\Omega}{dr}|_{R0} \qquad \Rightarrow \qquad A = \frac{1}{2}\left(\frac{V_0}{R_0} - \frac{dv}{dr}|_{R0}\right)$$

$$B = -\frac{1}{2} R_0 \frac{d\Omega}{dr}|_{R0} - \Omega \qquad\qquad B = -\frac{1}{2}\left(\frac{V_0}{R_0} + \frac{dv}{dr}|_{R0}\right)$$

<u>What is the physical meaning of these 'constants'?</u>

- A is a measure of the *shear* (i.e. how much angular velocity changes with radius) in the Solar Neighbourhood.
- If A is positive, then this implies the Galaxy's angular velocity is *decreasing* with *increasing* Galactocentric radius in the Solar Neighbourhood.
- If A is zero, then there is no shear and one would have solid body rotation (i.e. $V = \Omega R$). In which case, B can be seen to just be the magnitude of the angular velocity.
- B describes the angular momentum gradient in the solar neighbourhood, and is also referred to as vorticity.

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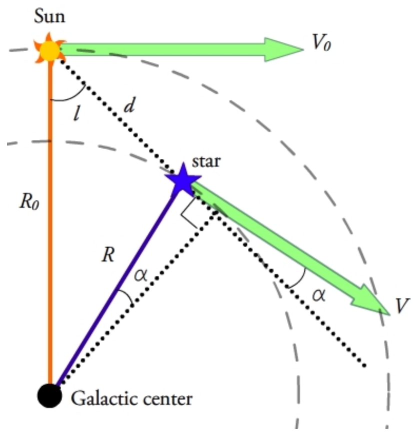
The Disk (2) – Oort's Constants



As noted above …

$$V_{\text{obs, r}} = Ad\sin(2l)$$
$$V_{\text{obs, t}} = Ad\cos(2l) + Bd$$

Which can be rearranged to give A and B solely in terms of measurables (radial velocity, tangential velocity, distance, longitude)

$$A = \frac{V_{\text{obs, r}}}{d\ \sin(2l)}$$
$$B = \frac{V_{\text{obs, t}}}{d} - A\ \cos(2l)$$

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The Disk (2) – Oort's Constants

So, if you can measure distances, radial velocities and longitudes, and plot $V_{obs,,r}/d$ as a function of l, you can determine A and B observationally.

$$A = \frac{V_{\text{obs, r}}}{d \sin(2l)}$$

$$B = \frac{V_{\text{obs, t}}}{d} - A\cos(2l)$$

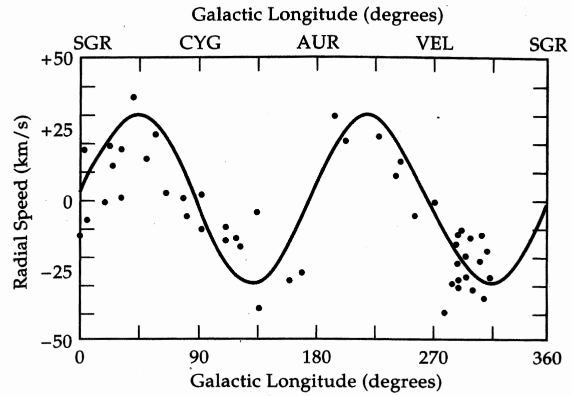

Figure 19–8 Observed galactic rotation. The radial velocities of nearby Cepheids are plotted as a function of galactic longitude. These are motions with respect to the LSR. The solid curve is the expected motions in the Oort model.

Using Cepheids (a class of stars for which distances can be measured – more on this later) you can apply an Oort model and start to understand the *observed* differential rotation of the Galaxy. A is indeed found to be non-zero, which tells us that the Galaxy is differentially rotating, and not rotating as a solid body.

Modern values for A and B (Feast et al. 1997)

A = 14.8 ± 0.8 km/s/kpc
B = -12.4 ± 0.6 km/s/kpc

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The Disk (2) – Oort's Constants

One can then take potential models for the rotation curve of our Galaxy (e.g. solid body, Keplerian, flat), determine what their Oort constants would be, and ask whether they agree with what we see (which is A = 14.8 ± 0.8 km/s/kpc, B = -12.4 ± 0.6 km/s/kpc).

For example if orbits in the local neighbourhood followed Keplerian orbits

$$v = \sqrt{\frac{GM}{r}}$$ which implies $$\frac{dv}{dr} = -\frac{1}{2}\sqrt{\frac{GM}{R^3}} = -\frac{1}{2}\frac{v}{r}$$

One can show that the Oort constants would be …
… which for the known Galactic rotation and solar position would give A~20km/s/kpc and B~-7km/s/kpc. So this doesn't match what we see.

$$A = \frac{1}{2}\left(\frac{V_0}{R_0} + \frac{v}{2r}|_{R_0}\right) = \frac{3V_0}{4R_0}$$

$$B = -\frac{1}{2}\left(\frac{V_0}{R_0} - \frac{v}{2r}|_{R_0}\right) = -\frac{1V_0}{4R_0}$$

What if the rotation curve was flat (ie. V independent of radius, or equivalently dv/dr = 0? This gives

$$A = \frac{1}{2}\left(\frac{V_0}{R_0} - 0|_{R_0}\right) = \frac{1}{2}\left(\frac{V_0}{R_0}\right)$$

$$B = -\frac{1}{2}\left(\frac{V_0}{R_0} + 0|_{R_0}\right) = -\frac{1}{2}\left(\frac{V_0}{R_0}\right)$$

and substituting the known solar rotation velocity and radius into that gives A~14km/s/kpc and B~-14km/s/kpc, which is remarkably close to the measured values.

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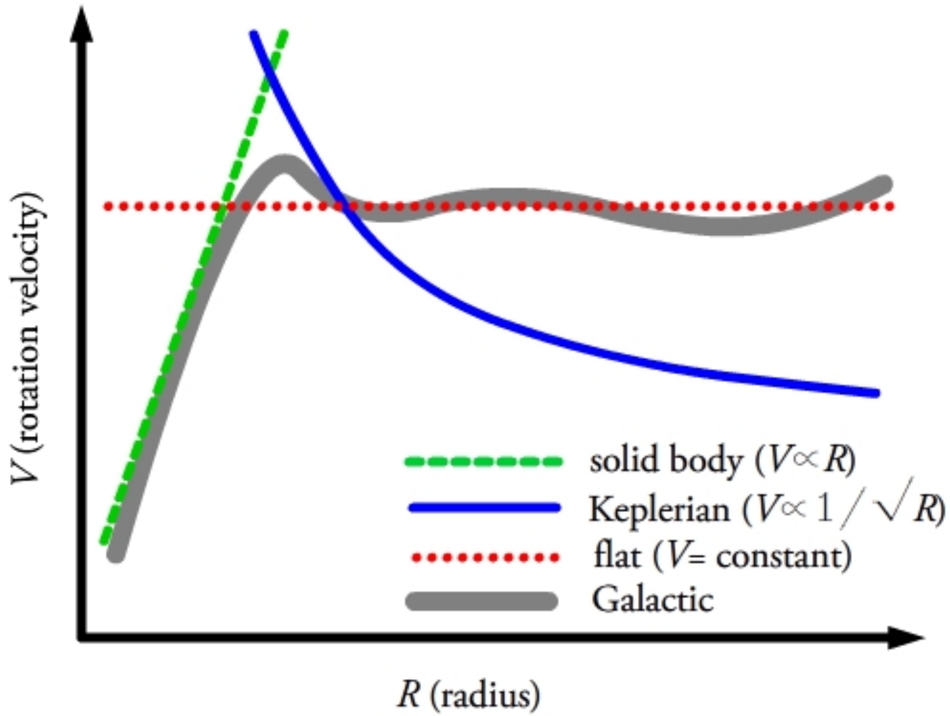
The Disk (2) – Oort's Constants

So the Oort constants provide insight into the nature of the Galactic rotation curve (at least in the Solar Neighbourhood) … the rotation curve is more similar to a flat one, than to a Keplerian one.

This is an insight we will come back to next time … when we look at Galactic rotation curves for the whole Galaxy (and for other galaxies)



Are you interested in contributing to the improvement of teaching in Physics? Ensuring that the opinions of students are heard?
Become a course representative.

What's a course representative?

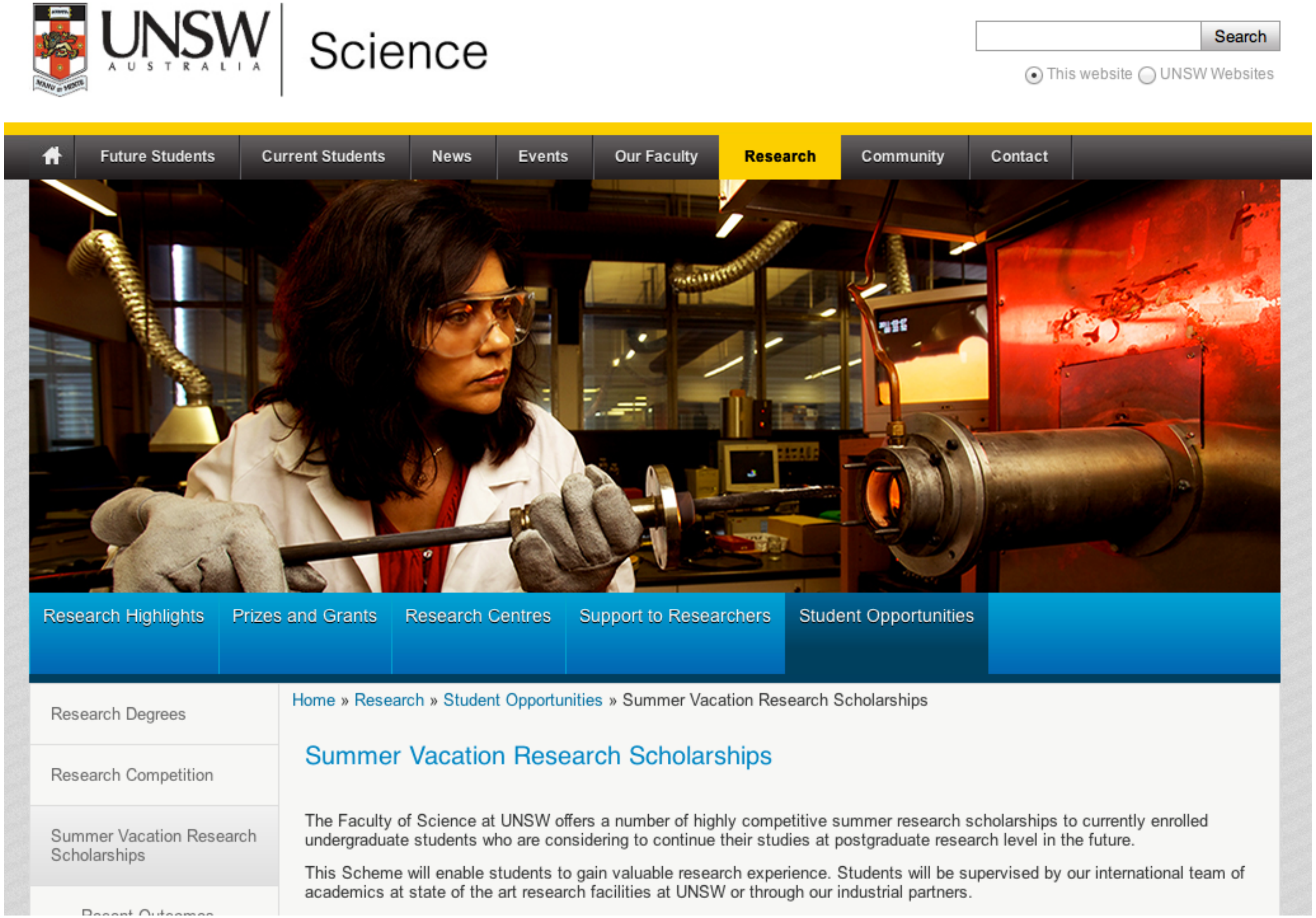
- A student who acts as a liaison between the students in a course and the School of Physics Teaching Committee. This may include meeting with the Committee to provide general feedback; or passing on student problems or complaints.
- We would like one representative from every undergraduate physics course.

How to nominate:

- Send an email with your name, student number and course code to Sue Hagon s.hagon@unsw.edu.au by Sunday 2 August. If more than one student nominates in a course, we will organize a vote.

Summer Vacation Research

http://www.science.unsw.edu.au/svrs



UNSW Science Student Research Expo

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Science Postgrad Research Competition - July 30

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Tomorrow!

July 30: Postgrad Research Competition

Join us in Leighton Hall from 1pm on **Thursday 30th July** for our annual Student Research Extravaganza.

Come and watch 80 PhD students from across all schools in the faculty compete in the 1 minute thesis competition and view the poster displays while enjoying delicious free food.

Learn More I RSVP

Free food. Real Science

PHYS2160 – Lecture 2 – Milky Way

- References
  - Feast, M.; Whitelock, P. (November 1997). "Galactic Kinematics of Cepheids from HIPPARCOS Proper Motions". MNRAS 291: 683. arXiv:astro-ph/9706293.
  - Website of Andrea Ghez's Galactic Centre group at UCLA : http://www.astro.ucla.edu/~ghezgroup/gc/
  - Also copies of the movies in this Lecture are available at the PHYS2160 Part I Materials page.
- Bibliography
  - Shu, F. The Physical Universe, Chapter 12 (can be found on google books)

Useful constants, units, and formulae:

Gravitational constant	G	=	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	=	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	=	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	=	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	=	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	=	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	=	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	=	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	=	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	=	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	=	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	=	1.496	$\times$	10^{11}	m
Parsec	pc	=	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	=	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	=	$5\log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	=	$2.5\log\frac{f_1}{f_2}$
For small recession velocities	v/c	=	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	=	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	=	$h\nu$
Frequency and wavelength	c	=	$\nu\lambda$

PHYS2160 – Lecture 3 – The Milky Way (2)

Last time

- Equatorial & Galactic co-ordinate systems. Proper motions & Velocities
- Milky Way components (disk, spheroid, stellar halo)
- Differential rotation & Oort Constants
- First evidence that the Galactic rotation curve is flat in the solar neighbourhood.

And in case you hadn't noticed "Milky Way" ≡ "Galaxy" . And as opposed to "galaxy" which just refers to any galaxy.

PHYS2160 – Lecture 3 – Milky Way (2)

Stars

A detailed exploration of the complex physics of stars is beyond the scope of this course. However its worth noting a few aspects of how stars work, because this impacts on how we interpret the workings of our Milky Way, other galaxies and the Universe in general.

Stars are spheres of gas held together by self-gravity, and balanced against collapse by pressure gradients supported by the energy generated by nuclear fusion reactions.

It is a useful approximation to consider the *interiors* and the *atmospheres* of stars separately.

– The *atmosphere* (or more specifically the *photosphere*) is the part of the star from which emerges the photons we actually see.
– The *interior* is the rest of the star.

Photons are generated in the core (by nuclear reactions) strongly interact with the matter in the interior and are absorbed and remitted repeatedly as they percolate on a random walk through progressively less dense layers – as a result they are in thermodynamic equilibrium.

Near the surface, however, the photon mean free path becomes comparable to the length scale of the atmosphere and the photons decouple, eventually escaping from the star.

PHYS2160 – Lecture 3 – Milky Way (2)

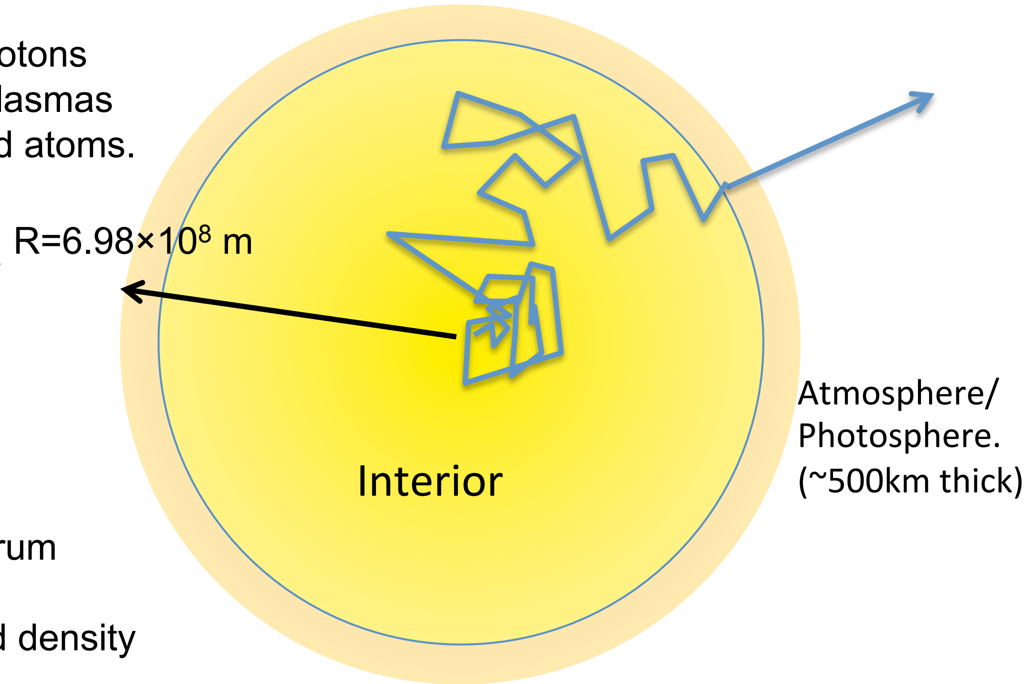
Stars

Using the Sun* as an example, $M=1.99\times10^{30}$ kg, $R=6.98\times10^{8}$ m
so mean density is just 1.4×10^{3} kg/m^3 = 1.4 g/cm^3. Central density 1.6×10^{5} kg/m^3.
Surface temperature is 5778K and central temperature is 1.57×10^{7}K.

The temperatures present at the surfaces of a star (~3000-40,000K) mean that the photons escaping the surface are passing through plasmas containing neutral, singly- or multiply-ionised atoms.

As a result the opacity of the *atmospheric* material depends strongly on wavelength. If the wavelength is the same as a strong electronic transition, the opacity will be high. At other wavelengths the opacity will be relatively low.

The result is the formation of a stellar spectrum that can be rich in features – these reflect the elemental composition, temperature and density of the atmosphere.



* http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

PHYS2160 – Lecture 3 – Milky Way (2)

Stars

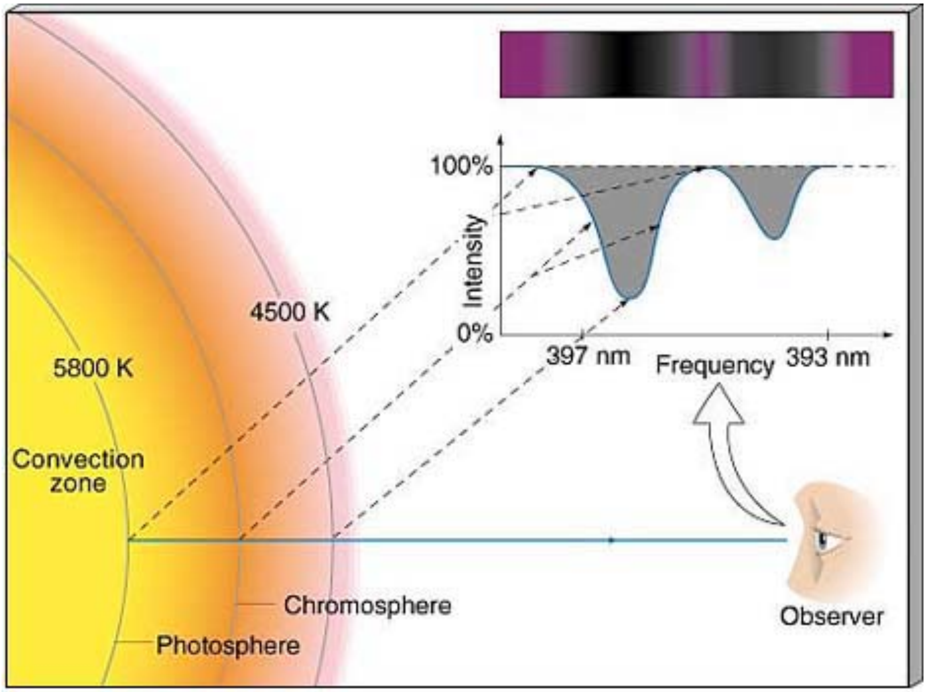
A useful way to think about this is that when we look at a star, we are "peering down into its atmosphere". How far we see will depend on the opacity at that wavelength.

If the opacity is high (for example in the core of a strong atomic transition) we won't see very far, and so will observe the outer, and cooler (and so darker) layers of the star.

If we observe away from that line, we will see to deeper layers, where the star is hotter (and so brighter).

This absorption can be quantified by the *optical depth*, τ

$$I_{obs} = I_{unabs}\, e^{-\tau}$$



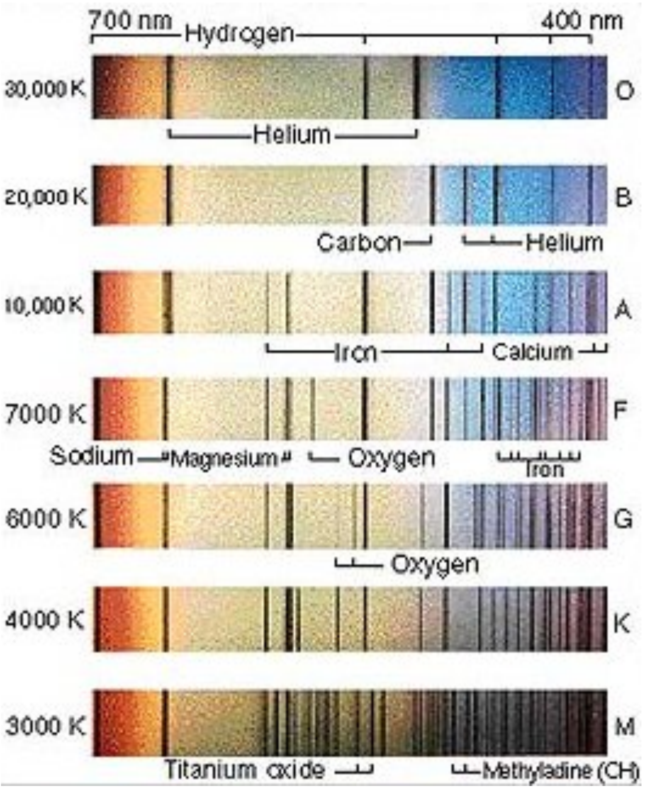
Thought about in this way, we can see why stars can also be seen with spectral lines in emission – due to having tenuous outer regions (the chromosphere and corona) where there is a temperature inversion. (Strictly the "atmosphere" is the combination of the "photosphere" with these hotter layers above).

PHYS2160 – Lecture 3 – Milky Way (2)

Stars

The specific atoms and ions and transitions that are prominent in the stellar spectrum will therefore depend on the combined temperature and density of the atmosphere at $\tau \sim 1$.

This physics gives rise to the "spectral type" classification sequence given to stellar spectra. (To remember "Oh Be A Fine Girl/Guy Kiss Me")



Stars: spectral types

Spectral Type	Colour	Temperature (K) Surface / core	Spectral characteristics
M	Red	3000	Molecular lines (e.g. TiO, vanadium oxide), very strong neutral metal lines
K	Orange	4000	Strong Ca lines, strong neutral metal lines, ± TiO, extremely weak hydrogen lines
G	Yellow	6000	Ca^+ lines strong, ionised metal lines weakening, neutral metal lines weakening, CH strong, hydrogen lines very weak
F	White	8000	Ionised (e.g. Fe^+, Mg^+, Si^+) and neutral metal lines, hydrogen lines weakening
A	White/blue	10 000	Hydrogen lines strong, ionised metal lines strong, weak neutral metal lines
B	Blue/UV	25 000	Strong He lines, strong hydrogen lines, Mg^+ and Si^+ lines
O	Blue/UV	50 000	Strong He^+ lines, weak He and hydrogen Balmer lines, Si^{3+}, O^{2+}, N^{2+} and C^{2+} lines

PHYS2160 – Lecture 3 – Milky Way (2)

Stars

The physics of stellar interiors is governed by four key equations

- Hydrostatic equilibrium
- Conservation of Mass
- Radiative Transfer
- Conservation of Energy

Which form a linked set of differential equations involving density, temperature, opacity and energy generation as a function of radius. These can be solved if you know (1) how the pressure reacts to the local conditions (the “Equation of State”) and (2) how the opacity does the same.

These models tell us the equilibrium configuration a star will reach as a function of its bulk properties (primarily its mass, but to a lesser degree the distribution of elemental abundances or “metallicity”). In particular models predict the luminosity (L) and radius (R) of the star.

Then you can lay a model for the same equations over the top (paying much more attention to the opacity and the radiative transfer as a function of wavelength) to create a model of the emergent spectrum of the star as a function of those bulk properties.

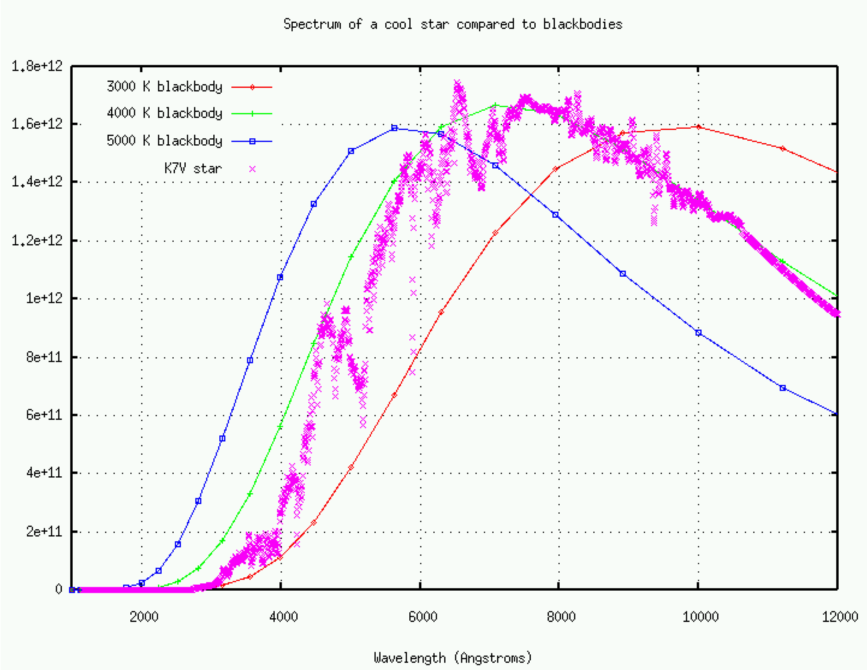
PHYS2160 – Lecture 3 – Milky Way (2)

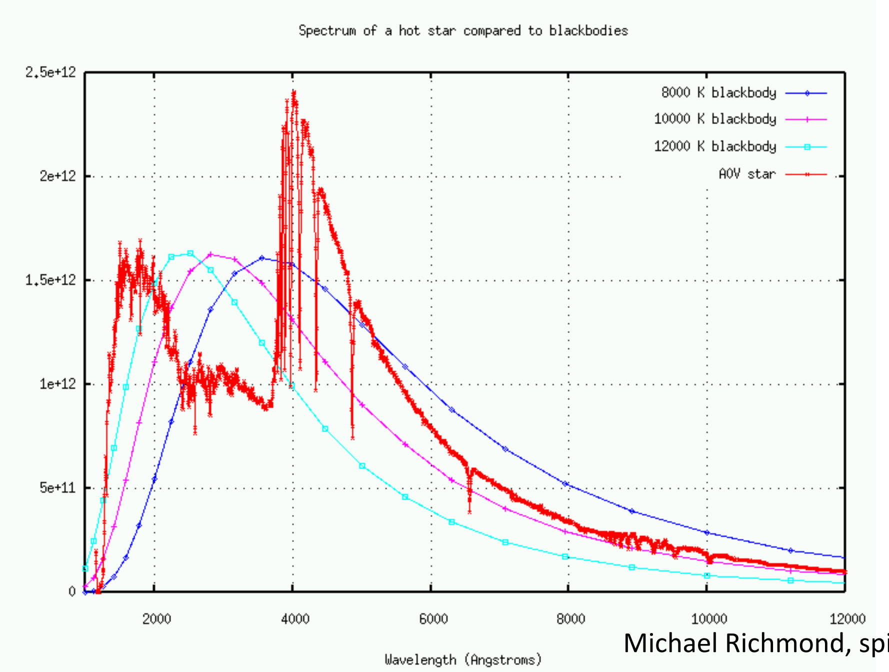
Stars

The Luminosity and Radius of an object tell us what its temperature will be. For a blackbody they actually *define* that object's temperature. A helpful quantity to bear in mind when thinking about stars of different masses, radii and luminosities is the *effective temperature* (T_{eff}) that a blackbody of the same radius (R) and luminosity (L) would have.

$L = 4\pi r^2 \ \sigma T_{eff}^4$ where σ is the Stefan-Boltzman constant.

While stellar spectra are not true blackbodies (they have all those spectral absorption lines after all), this is nonetheless a helpful approximation in many cases.





Michael Richmond, spiff.rit.edu

PHYS2160 – Lecture 3 – Milky Way (2)

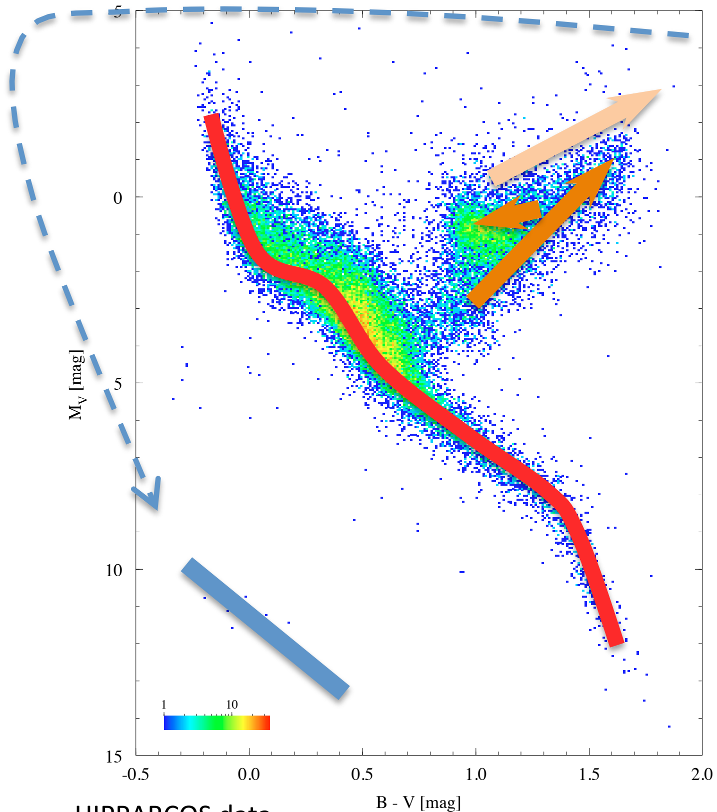
Populations of stars

The when looking at large numbers of stars, its helpful to examine them in a "Hertzsprung-Russell" diagram – a plot of stellar luminosity vs effective temperature. These can be examined either as theoretical constructs, or (more usefully) as observational diagrams of colour (as a proxy for temperature) vs absolute magnitude (as a proxy for luminosity).

The H-R diagram can often be interpreted as an evolutionary diagram for how stars evolve as they age. That is, imagine you start with a population of different masses at one time, in which case different stars will evolve to different locations in the diagram, with more massive stars evolving faster.

Obvious features are the **main sequence** (the sequence of hydrogen burning stars) and the **giant branches** (stars burning H in a shell about their core, burning He in their core, burning He in a shell).

Less obvious are the **white dwarfs** (degenerate remains of highly evolved stars) and the **subdwarfs** (very metal poor stars).

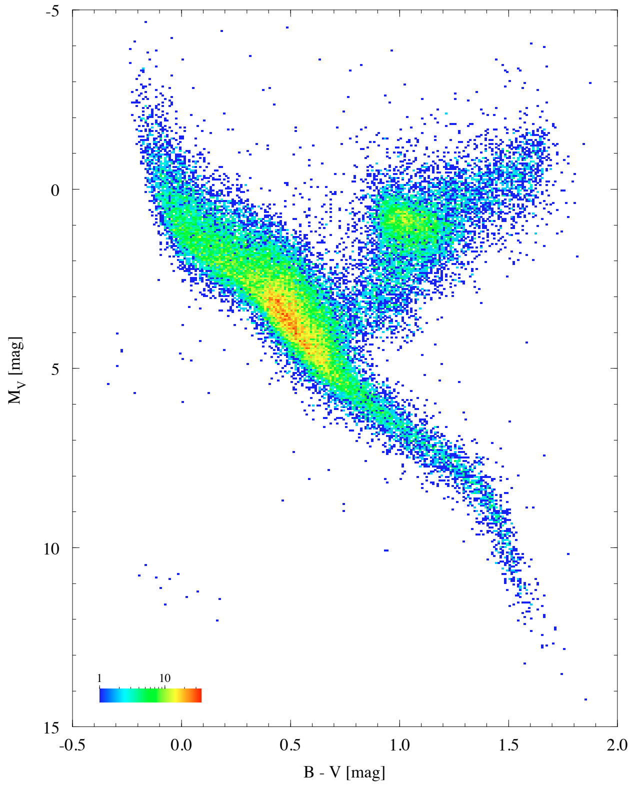


HIPPARCOS data
www.rssd.esa.int/index.php?project=HIPPARCOS&page=HR_dia

PHYS2160 – Lecture 3 – Milky Way (2)

Populations of stars

An observed H-R diagram



HIPPARCOS data for stars
in the Solar Neighbourhood

A theorist's H-R diagram

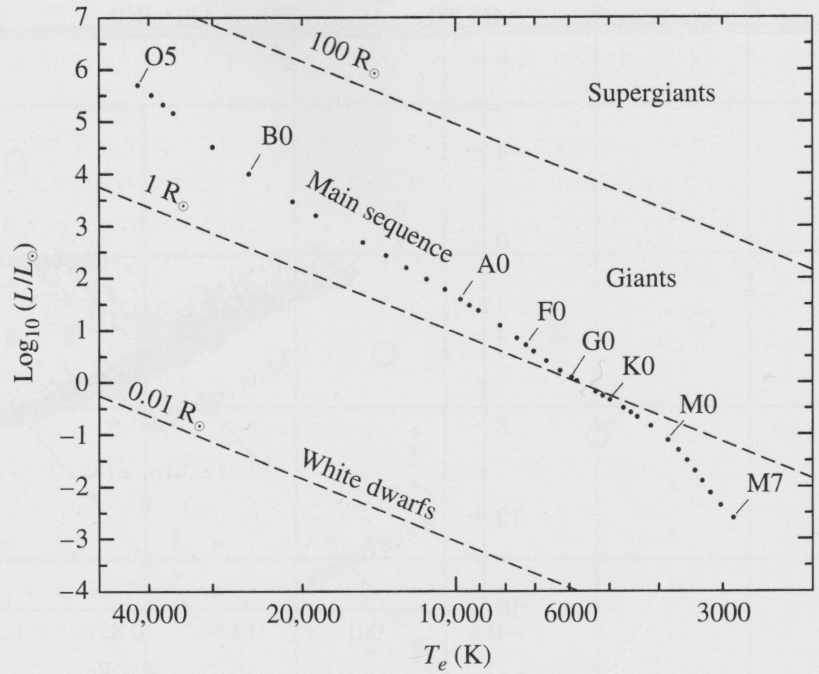
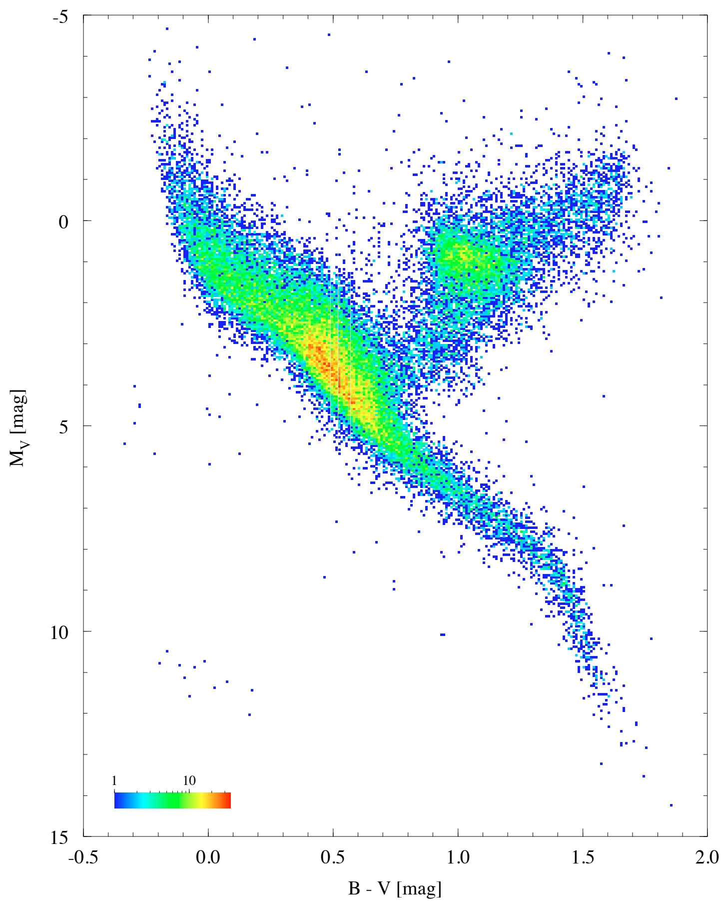


FIGURE 6.23 The theorist's Hertzsprung–Russell diagram. The dashed lines indicate li
stant radius.

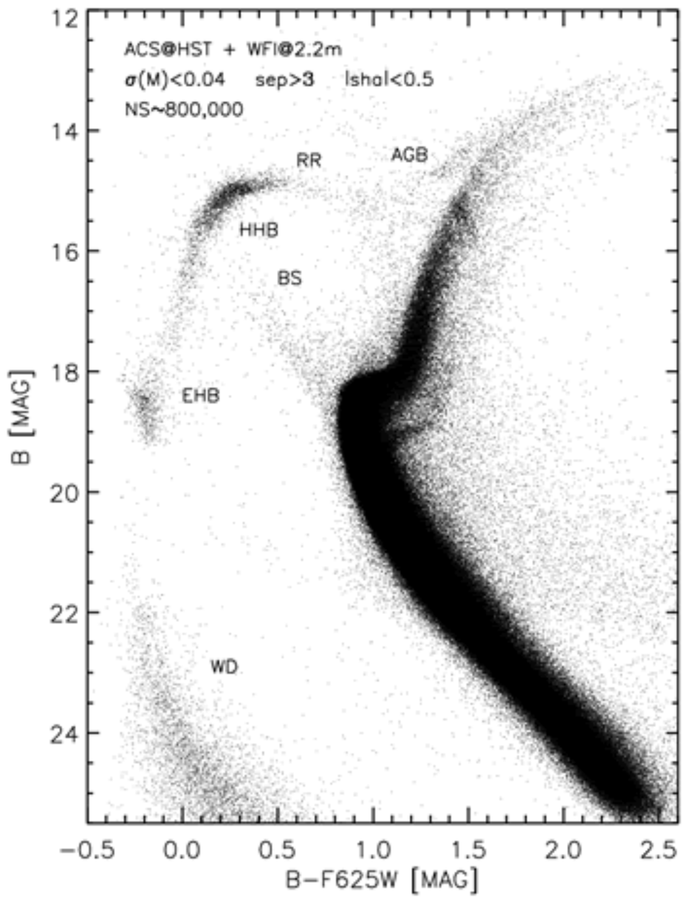
PHYS2160 – Lecture 3 – Milky Way (2)

Populations of stars

Mixed populations of stars



A single cluster of stars (Omega Cen) all at the same distance and similar age.



PHYS2160 – Lecture 3 – Milky Way (2)

Stars

Some useful scaling relations for stars on the main sequence ....

$R \sim M^{0.8}$ for $M < 1.0 M_\odot$;
$M^{0.57}$ for $M > 1.0 M_\odot$;

$L \sim M^{2.3}$ for $M < 0.4 M_\odot$;
M^{4} for $0.4\, M_\odot < M < 2.0 M_\odot$;
$M^{3.5}$ for $2\, M_\odot < M < 20 M_\odot$

Main Sequence Lifetime ~ $10\text{Gyr}\, (M/M_\odot)^{-2.5}$

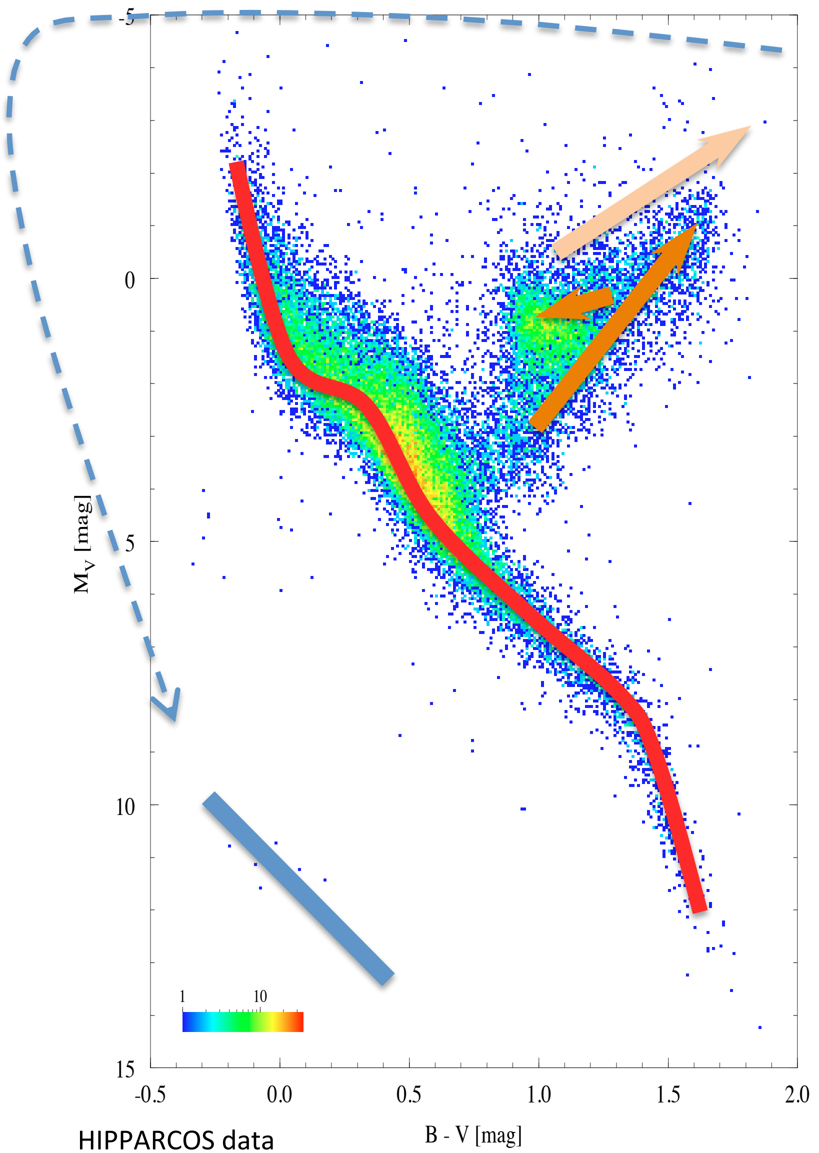
So, at masses below about 0.3$M_\odot$, stars will stably sit on the main sequence for 200Gyr (more than 10 times current age of the Universe).

PHYS2160 – Lecture 3 – Milky Way (2)

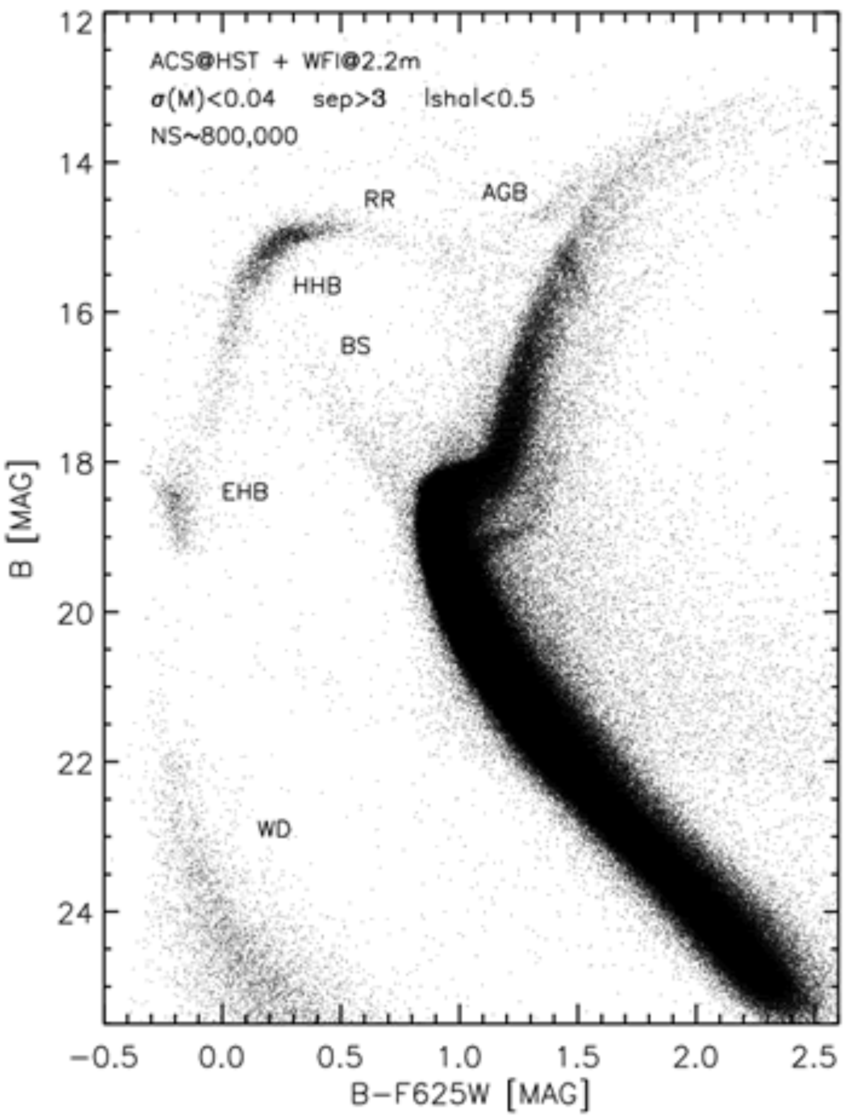
Stars

At masses above 8M$_\odot$, the stellar core collapses in free-fall after Fe burning exhausted (because its core mass exceeds the Chandreskar limit of 1.4M$_\odot$). That collapse is eventually stopped by neutron degeneracy and a neutron star forms. The resulting 'bounce' releases a shockwave of neutrinos which deposits so much energy into the remaining envelope that it is detonated, returning vast amounts of processed stellar material to the Interstellar Medium (ISM). This is called a "Type II Supernova" (or SN - plural Sne). *How long does it take before a 10M$_\odot$ does that?*

At masses in between, the stellar core exhausts its H and contracts. It becomes hotter causing the outer shells to puff up and expand – the star expands and becomes more luminous but cooler as it ascends the "Giant Branch". Eventually the core contracts enough to start He burning and the star moves sideways onto the "Horizontal Branch". Eventually He in the core is exhausted, and the core contracts again – He burning starts in a shell (with some H burning in a shell outside that) and the star ascends the "Asymptotic Giant Branch". The burning in these shells is unstable and this instability causes the star to pulse. These slow pulsations (together with the exhaustion of H and He supplies in the core) eventually cause star to shed its envelope back to the interstellar medium, while the core collapses into a compact (and very hot) "white dwarf". This is the ***other*** way in which stellar material is returned to the ISM



HIPPARCOS data
www.rssd.esa.int/index.php?project=HIPPARCOS&page=HR_dia



PHYS2160 – Lecture 3 – Milky Way (2)

More on Metallicities

You'll recall we said last time that metallicities are measured as the numerical abundance of atoms of an element relative to hydrogen, and then measured as this ratio relative to that in the Sun.

$$[Fe/H] = \log[\, n(Fe_{\star})/n(H_{\star}) \;/\; n(Fe_{\odot})/n(H_{\odot}) \,]$$

so that a star with [Fe/H]=4 has 1/10,000th the metallicity of the Sun.

One can also use a mass fraction, which simply compares the total mass of all elements other than H and He, with that total mass in the Sun. In this parameterisation X is the total mass fraction in H, and Y the total mass fraction in He. For the Sun we have …

$$X_{\odot} = 0.73,\; Y_{\odot} = 0.25,\; Z_{\odot} = 0.02$$

These two forms of expressing metallicity can be related if we assume there is a fixed relationship between the abundance of Fe and the total metallic content (M) of a star via a constant of proportionality (i.e. [M/H] = A [Fe/H]) in which case it can be shown that

$$\log[\, (Z/X) \,/\, (Z_{\odot}/X_{\odot}) \,] = A\,[Fe/H]$$

PHYS2160 – Lecture 3 – Milky Way (2)

Galactic Stellar Populations

Pop I: When astronomers first began looking more closely at the structure of the Milky Way, they first noticed the stars of Disk. These are far and away the most common stars near the Sun, and so these got the (somewhat boring) name “Population I”. These Pop I stars

- Had a vertical scale height in the disk of around 330pc, and appeared to rotate as a disk
- Had spectra revealing similar metallicities to the Sun

Pop II: The stars in globular clusters, and the local stars of the halo population (revealed as “high velocity stars”) were seen to have different properties, and became known as Pop II stars.

- They appeared as sub-dwarfs in H-R diagrams (cf. two pages back)
- When spectra were taken they appeared to be lower in metallicity
- And of course the local examples tended to have very different kinematics to the disk

These facets come together in a consistent picture if you think of the Pop II stars as being a population formed earlier in the Galaxy’s history, when the average metallicity in the interstellar medium (ISM) from which stars form, was much lower. And Pop I stars have been formed from material enriched by subsequent generations of stars. It also suggests an evolutionary sequence from an “old” spherical geometry for the ISM to a “current” disk-like geometry. The dividing line between Pop I and Pop II is often drawn at $Z=0.01$ (i.e. less than 1% of the heavy element abundance of the Sun).

Pop III: this evolutionary sequence suggests that there must have been a “first” Pop III burst of stars that were formed when there were no elements heavier than Boron in the Universe. No example has ever been found. The most metal poor star found so far has [Fe/H]<-7 (see Keller et al. ref in last lecture)

PHYS2160 – Lecture 3 – Milky Way (2)

Measuring Metallicities

Spectra allow one to measure the strength of the metal lines (for example data for F stars from the SEGUE survey – www.sdss3.org/surveys/segue2.php)

Note that while the key CaI line at 3933A gets weaker at lower metallicity, so does the overall level of the "noisy" opacities covering the whole spectrum.

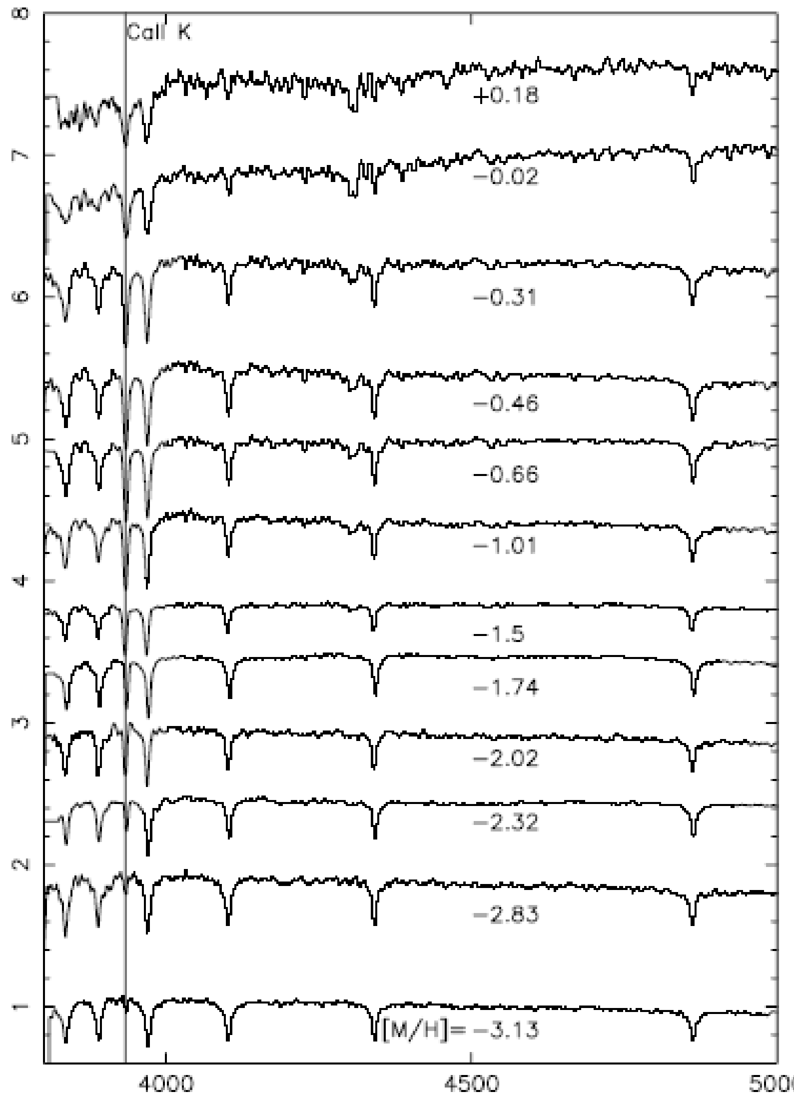


Figure 7. F star metal sequence—a set of SEGUE F stars, selected to show the range of metallicities sampled by the F subdwarf, F/G, spectrophotometric standard and reddening standard categories. All 13 stars have similar effective temperatures, near 6500 K, but the strength of the Ca K line at λ3933 indicates metallicities ranging from less than 0.001–1.5 times Solar.

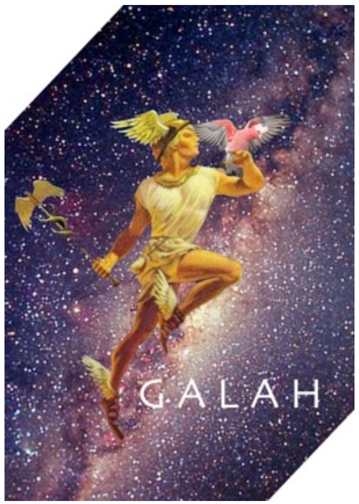
PHYS2160 – Lecture 3 – Milky Way (2)

Measuring Metallicities

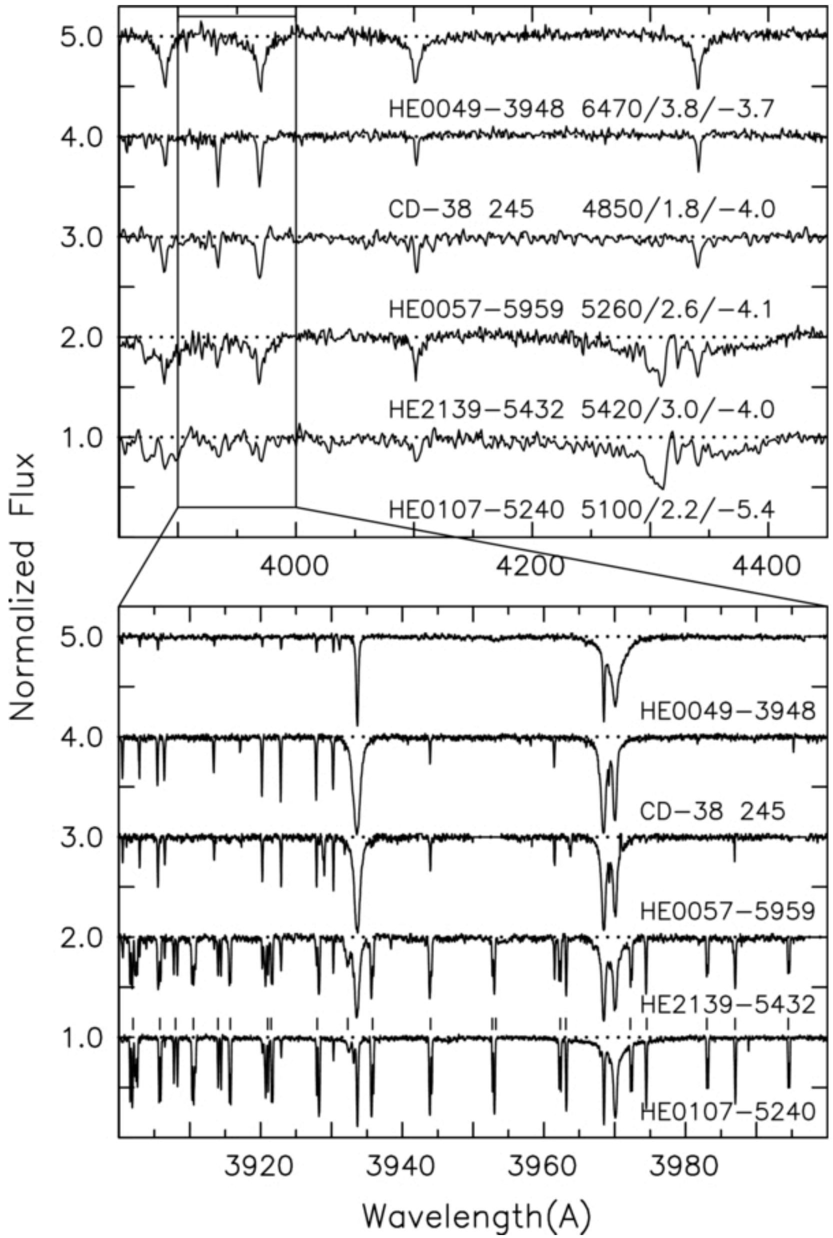
To get a more detailed answer, you have to do some detailed modelling of the stars' properties – Temperature, Gravity ($\log(g)=\log(GM/r^2)$) and [Fe/H]

This sort of data is used to probe the properties of the Population II stars (e.g. to the right is from Norris et al. 2013) – as well as the detailed properties of the Pop I system of the Galaxy.

A major survey to do the latter has just started here in Australia. GALAH will eventually probe the detailed properties of a million Southern stars.



http://www.mso.anu.edu.au/galah/home.html



PHYS2160 – Lecture 3 – Milky Way (2)

- References
  - Norris et al. 2013 "THE MOST METAL-POOR STARS. I. DISCOVERY, DATA, AND ATMOSPHERIC PARAMETERS", ApJ 762 25. http://arxiv.org/abs/1211.3157
  - GALAH Survey Website http://www.mso.anu.edu.au/galah/home.html
  - SEQUE Survey Website http://www.sdss3.org/surveys/segue2.php
- Bibliography
  - Shu, F. The Physical Universe, Chapter 11
  - Zeilick & Gregory Ch 15

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Mass of moon	M_{moon}	=	7.3	×	10^{22}	kg
Astronomical unit	AU	=	1.496	×	10^{11}	m
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For small recession velocities	v/c	=	$\Delta\lambda/\lambda$
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Energy and frequency	E	=	$h\nu$
Frequency and wavelength	c	=	$\nu\lambda$

PHYS2160 – Lecture 4 – The Milky Way (3)

Last time

- Brief background on stars, interiors, atmospheres and evolution (main sequence, giant branches, AGB & Sne return material to the ISM)
- Luminosity, Effective Temperatures, Lifetimes. Spectral Types
- Population I and Population II

This Time

- The Interstellar Medium
- Extinction
- How the ISM collapses into stars and planets
- Stars and Planets

PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium (ISM) – Shu Ch 11, ZG Ch 15

is the gas (roughly 99%) and dust (roughly 1% - condensed molecular material containing silicates, graphite, silicon carbide, polycyclic aromatic hydrocarbons, water ice …) in the space between the stars. Typical sizes range from just a few molecules up to ~1μm (much smaller than the dust in your house!)

ISM was discovered as “stationary” absorption lines in the spectra of spectroscopic binary stars (Hartmann 1904) – that is stars where the velocities of the two stellar componentises varied, but there was a third component that did not move..

Total dust mass is small, but its impact on astronomy is significant – it stops us seeing the Galactic centre in visible light, or seeing the dense regions where stars form. This is primarily because it produces Rayleigh scattering, which has an efficiency that scales as 1/λ (though there is also some actual absorption of photons, and remission at longer wavelengths as well). The impact of this iis known as extinction, and has the property that blue light is more subject to extinction than red light.

Can parameterise this as an ‘extra’ *extinction* term added into the estimation of distance.

$$m - M = 5 \log d - 5 + A_\lambda.$$

PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium (ISM) – Major Components

The major components we'll concern ourselves with are the **Molecular Clouds** (the dense, cold locations where stars form), the **Cold Neutral Medium** (easily seen in our galaxy and other galaxies in radio lines at 21cm wavelengths and so a good tracer of the dynamics of galaxies), and **HII regions** (*really* easily seen in the optical and near infrared and often associated with massive star formation).

Table of Components of the ISM

Component	Frac. Volume	Scale Height (pc)	T (K)	Density (cm^{-3})	H state	Primary observations
Molecular clouds	< 1%	80	10-20	10^2—10^6	H_2	Radio and infrared molecular emission and absorption lines
Neutral Medium						
Cold (CNM)	1—5%	100—300	50-100	20—50	HI	HI 21 cm line absorption
Warm (WNM)	10—20%	300—400	6000-10000	0.2—0.5	HI	HI 21 cm line emission
Warm Ionized (WIM)	20—50%	1000	8000	0.2—0.5	HII	Hα emission and pulsar dispersion
H II regions	< 1%	70	8000	10^2—10^4	HII	Hα emission and Radio recombination lines
Coronal gas Hot Ionized Medium (HIM)	30—70%	1000-3000	10^6—10^7	10^{-4}—10^{-2}	ionized (even metals)	X-ray emission; absorption lines of highly ionized metals, primarily in the ultraviolet

PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium (ISM) – Calculating Extinction

The observed flux intensity (I_{obs}) will be related to the unabsorbed flux intensity (I_{unabs}) by

$$I_{obs} = I_{unabs}\, e^{-\tau_\lambda}$$

where τ_λ is the *optical depth*, which is defined as the integral of the number density of absorbers along the line of sight, times the cross sectional area of the particles $\sigma_\lambda = \pi a^2$ and their *extinction coefficient* Q_λ. (There is a tutorial problem that will look at derivation of this exponential form).

$$\tau_\lambda = \sigma_\lambda \int_0^L n(l)\, dl = \pi\, a^2\, Q_\lambda \int_0^L n(l)\, dl$$

If we have a uniform density distribution along the line of sight ($0 \rightarrow L$), (i.e. $n(l) = n$) then the integral reduces to

$$\tau_\lambda = \pi a^2\, Q_\lambda\, n\, L$$

We can then relate the magnitude difference observed to the flux ratio I_{obs}/I_{unabs}

$$\Delta m = 2.5 \log\,(I_{obs}/I_{unabs}) = 2.5 \log(e^{-\tau\lambda})$$

$$= 2.5 \times 0.434 \times \tau_\lambda = 1.086\, \tau_\lambda = A_\lambda.$$

We find that the optical depth (which is dimensionless) ends up having a numerically similar value to the extinction (measured in magnitudes, which is just a flux ratio and therefore also dimensionless).

The extinction, therefore tells us about the product of the path length through clouds, the space density of the absorbing particles, their cross-section, and their absorption coefficient.

PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium – Nebulae

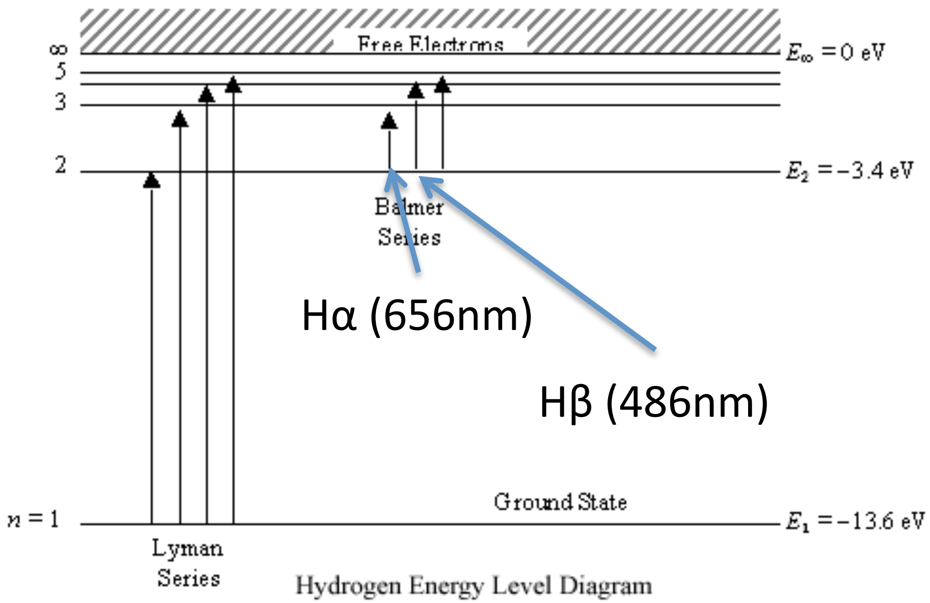
Nebulae – literally “clouds” (from the Latin). Some are seen primarily in emission, and some in absorption.

- *Dark nebulae* : opaque clouds, blocking light from behind. (e.g. Coalsack). Extinctions A_V > 25 (i.e. more than 10 orders of magnitude of absorption) are not uncommon
- *Reflection nebulae* : are seen in scattered light illuminated from one side. Since scattering efficiency ∝ 1/λ, blue light is scattered more efficiently, so reflected light will appear to be bluish (e.g. Pleiades).
- *HII regions* : seen primarily in atomic emission lines (especially H_α at 656nm). These are typically produced when gas is photo-ionised by ultraviolet photons (i.e. E= $h\nu$ > 13.6eV or λ<91.2nm) most commonly from nearby hot O-type and B-type stars (i.e. stars with T_{eff}>20000K, which emit significant UV flux).

  When an electron and a proton recombine, the system will “cascade” down to the ground state producing a characteristic recombination spectrum.

  The “HII” refers to the nebula containing singly ionised H (“HI” means neutral H), which emits photons as electrons and protons recombine.

  The division between the ionised and neutral gas is often very sharp, at a distance from the ionising source called the Strömgren radius – as a result these regions are often known as Strömgren spheres.



PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium – Nebulae – Examples

The Coalsack Nebula – a dark cloud between us and a rich field of background stars. Note there's also a HII region in the same field … can you spot it?)

PHYS2160 – Lecture 4 – The Milky Way (3)

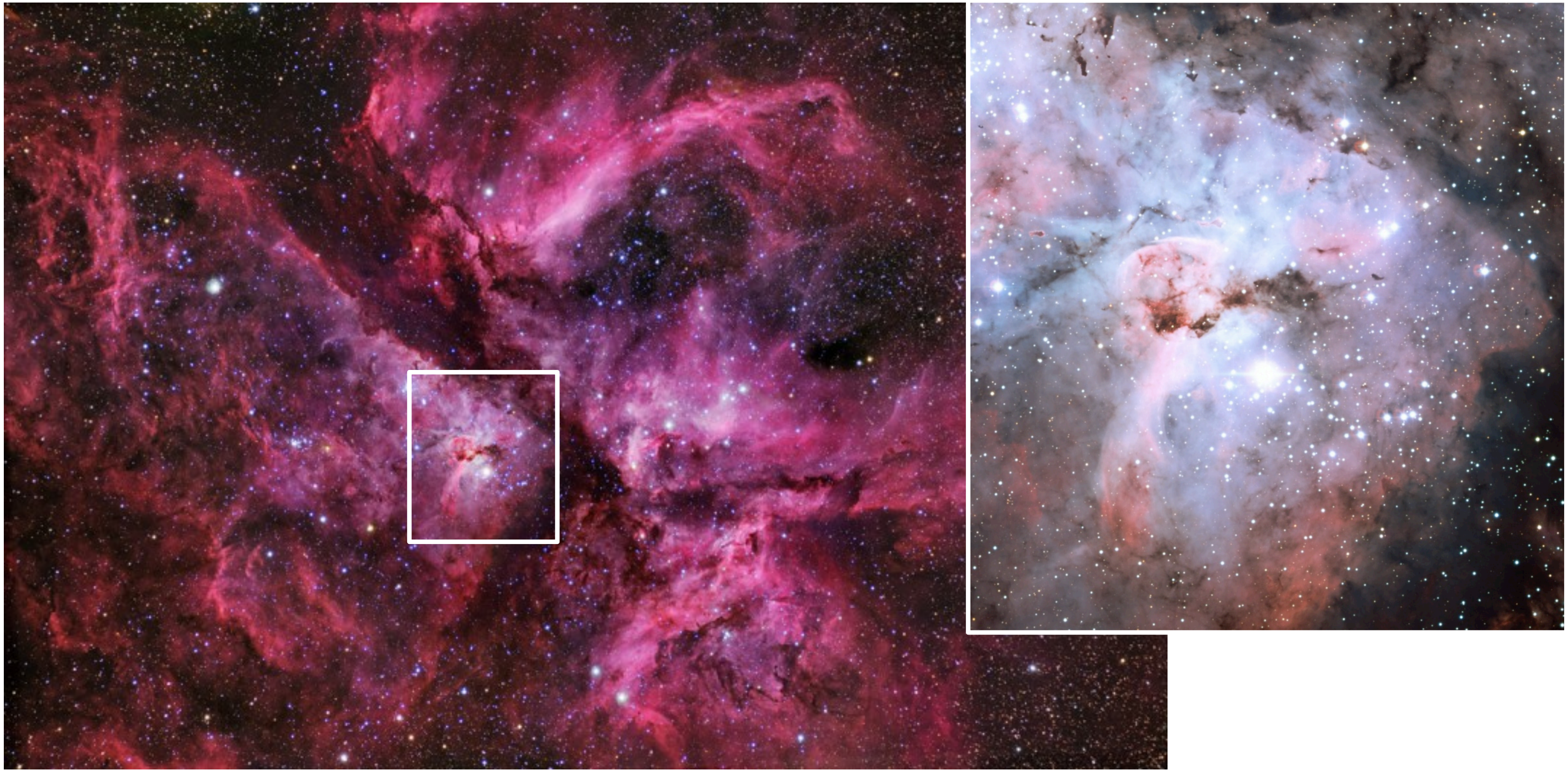
The Interstellar Medium – Nebulae – Examples

Reflection Nebulae : The Pleiades (left) and the Ophiucus star forming region (right). Which bit of the Ophiucus image is a reflection nebula? Which is a dark nebula? What else?

PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium – Nebulae – Examples

HII Regions : The Great Carina Nebula. Spot the ionising stars?



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The Interstellar Medium – Strömgren Spheres

Consider a pure H cloud of uniform density, surrounding a hot star. Let N_* be the number of photons with energy >13.6 eV (i.e. ionisation energy of H). Assume every photon ionizes one H atom. Let R by the the number of recombinations of the resulting protons (p) and electrons (e-) per unit volume per unit time.

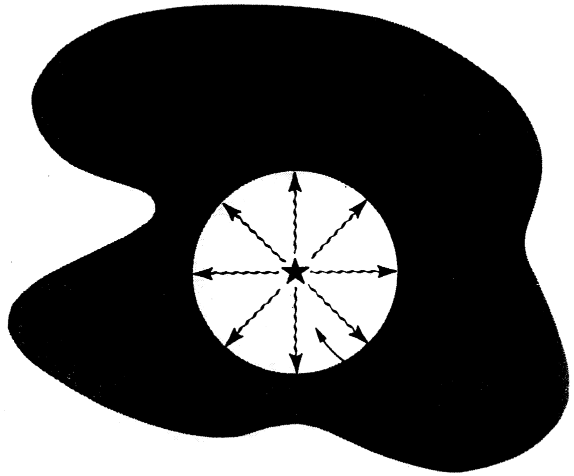


Figure 11.8. A hot and bright star embedded in a cloud of cold atomic hydrogen gas (HI) or cold molecular hydrogen gas (H_2) will ionize a roughly spherical region around itself (HII region). The size of this HII region under equilibrium conditions is given by Stromgren's requirement that the total number of recombinations occurring inside the HII region per unit time equal the total number of ionizing photons emitted per unit time by the central star.

In equilibrium, the number of recombinations and ionizations balance, so

$$4/3\pi\, r^3\, R = N_*$$

The recombination rate scales with n_p and n_e, and these densities will be equal for charge neutrality

$$R = \alpha\, n_p n_e = \alpha\, n_e^2$$

where α is the recombination coefficient (which depends on the T of the plasma). (Note that recombination here means only recombination to *excited* states of H, since recombination to the ground state just results in another ionizing photon. Recombinations to other states produce photons with e<13.6eV, and these can then escape the nebula.) The radius of the resulting ionized sphere is then

$$r = [\, 3N_* \ / \ (4\pi\alpha\, n_e^2)\,]^{1/3}$$

For a typical HII region $\alpha \approx 3\times10^{-13}\,\mathrm{cm^3/s}$, $n_e \approx 10\,\mathrm{cm^{-3}}$, $N_* \approx 4\times10^{46}\,\mathrm{s^{-1}}$ (for an O5 star), which implies $r \approx 2\mathrm{pc}$.

PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium – More Nebulae

- *Planetary nebulae* : compact regions with higher gas densities excited by the UV flux from a very hot white dwarf. Gas in these higher density regions is excited by collisions between electrons, ions and atoms, resulting in substantially different spectra from HII regions.

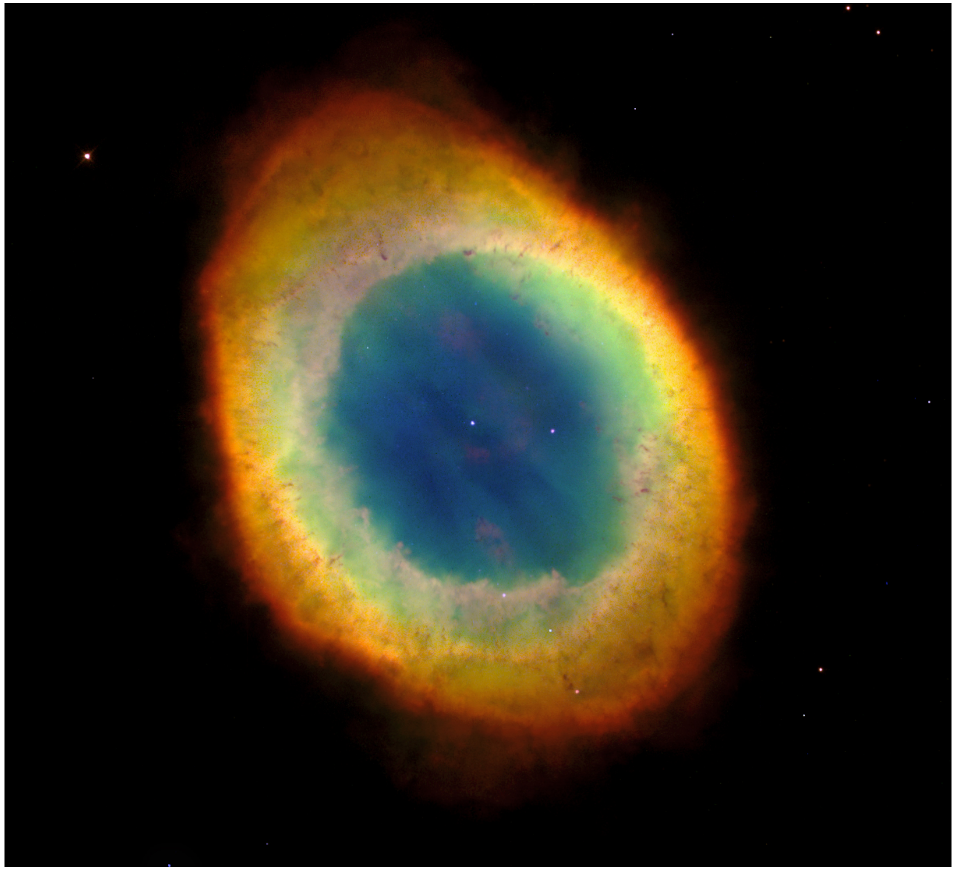
  The shells of gas illuminated (which have arisen from mass loss as the white dwarf shed its envelope after the AGB phase as discussed last lecture) typically expand with velocities of tens of km/s

- *Supernovae remnants* : The gas ejected and swept up by supernova explosions. Gas is ejected at high speed and driven into the the interstellar medium. The resulting shock wave results in very high densities, which excite/ ionise gas to millions of K, resulting in an emission nebula. These temperatures are sufficiently hot to result in X-ray emission.

PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium – Nebulae – Examples

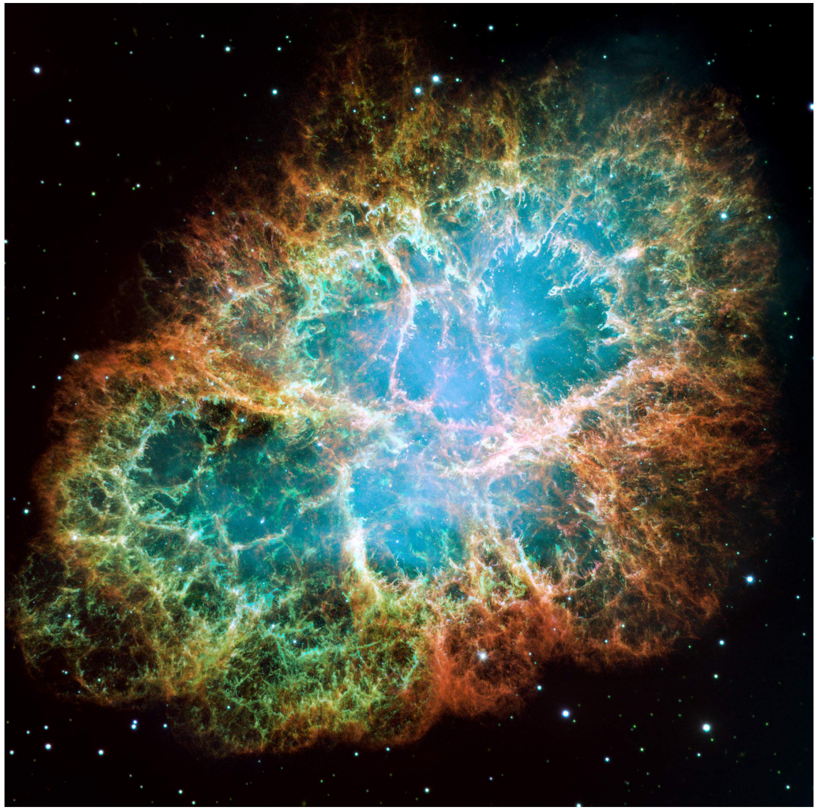
Planetary Nebulae: The Ring Nebula – a “classical” planetary (left), The Cat’s eye (HST) showing they can be much more complicated, reflecting the complex mass ejection pulses of the AGB … (right)

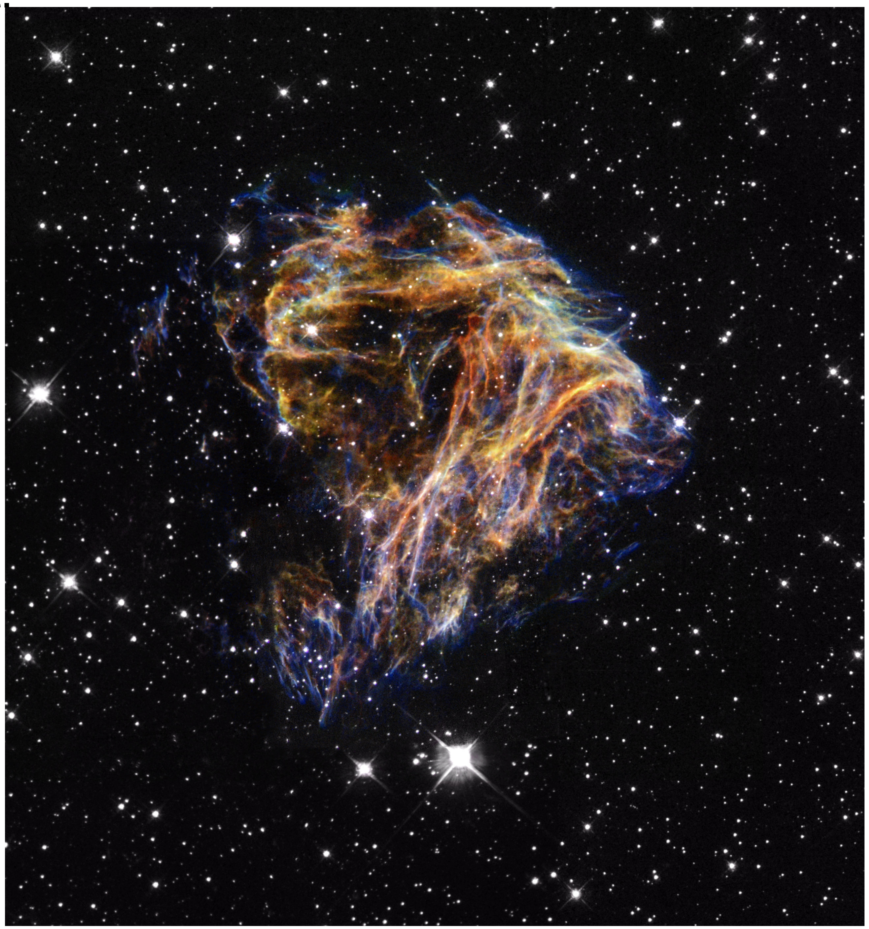


PHYS2160 – Lecture 4 – The Milky Way (3)

The Interstellar Medium – Nebulae – Examples

Supernova Remnants : The Crab (left) a young compact remnant from SN1054, and N49 in the Magellanic Cloud (right) an old, extended remnant.





PHYS2160 – Lecture 4 – The Milky Way (3)

Star Formation – Gravitational Collapse

Stars form in molecular clouds – randomly shaped agglomerations with an essentially chaotic density distribution. Even in this densest part of the ISM (10^2-10^6 cm^{-3}) density is tiny compared to (say) the Earth's atmosphere (10^{19} cm^{-3}).

Jeans Criteria - *when does a clump of the interstellar medium become gravitationally unstable?*
Consider a spherical cloud of ideal gas with radius *r*, total mass *M* and mean particle mass *m*. The cloud will have gravitational energy E_{gr}

$$E_{gr} \approx GM^2/r$$

A small radial compression of the cloud (*dr*) will produce a decrease in its gravitational energy of

$$dE_{gr} = GM^2/r^2\ dr$$

at the same time the volume will decrease by $dV = 4\pi r^2 dr$, and the thermal energy will grow by $dE_{th}=PdV$

Using the ideal gas equation PV = nkT (where n is the number of particles in the volume), we get

$$dE_{th} = nkT\ 4\pi r^2 dr = 3\ M/m\ kT\ dr/r \qquad \text{(have substituted M=volume.n.m))}$$

The cloud will be unstable to collapse if the the absolute value of the decrease in gravitational energy dE_{gr} is greater in absolute value than the increase in thermal energy dE_{th}. From this we can derive a series of **Jean's criteria** for total cloud mass, radius and density (see Tutorial Problems).

$$M_J = 3kTr/(Gm) \qquad r_J = GmM/(3kT) \qquad \rho_J = 3/(4\pi M^2)\ [3kT/(Gm)]^3$$

From this we can find that a cloud of H_2 of $1000M_\odot$ at 20K has a a Jean density of $\rho_J \approx 3\times10^{24}$ gcm^{-3} or $n(H_2) \approx 1cm^{-3}$ – if the density exceeds this, the cloud will be unstable and collapse

PHYS2160 – Lecture 4 – The Milky Way (3)

Star Formation – Gravitational Collapse

$n(H_2) \approx 1cm^{-3}$ is significantly less dense than the 10^2-10^6cm^{-3} densities mentioned earlier. Why don't all molecular clouds collapse immediately?

Real clouds are not spherical. They don't have uniform density. They have chaotically distributed density distributions and are turbulent. And they are threaded by magnetic fields.

If we consider a smaller clump (say $1M_\odot$ or 10^3 times less massive) within the cloud with the same density, then Jeans density will by 10^6 times larger.

So the 'peaks' of the density distribution (i.e. the most dense regions) will tend to collapse first.

This gravitational instability leads to the formation of protostars

PHYS2160 – Lecture 4 – The Milky Way (3)

Star Formation – Protostars and Accretion Disks

The inner regions of this collapsing region will eventually form a hydrostatically supported core – a “protostar”. This will continue to accrete material, growing in mass.

But what if the material being accreted comes from a region of the ISM that has some net angular momentum? That angular momentum will be conserved. Imagine a region of collapsing material 1pc across, that has a rotation across it equivalent to a 1km/s difference. If this material collapses down under gravitational instability to being just 1au across, then the product 1pc.1km/s is conserved meaning the rotational velocity at 1au must be ~200,000km/s=0.66c!

To actually collapse to 1AU (let alone the surface of the protostar ~0.005AU) angular momentum has to be dissipated. Until that happens the materials will remain in orbit about the star. The result is the formation of an accretion disk, in which viscous and magnetic processes transport material in and angular momentum out.

Meanwhile, the central temperatures and pressures continue to rise. Above the minimum temp for H fusion (~3 million K) fusion reactions can begin and the star “turns on”.

(Below the hydrogen burning minimum mass (0.08M) this is never triggered. These objects “brown dwarfs” continually radiate energy and cool, which means they fade with time becoming both fainter and colder. Gas giant planets do the same thing of course (cool), so like brown dwarfs, their intrinsic luminosity is a function of time.)

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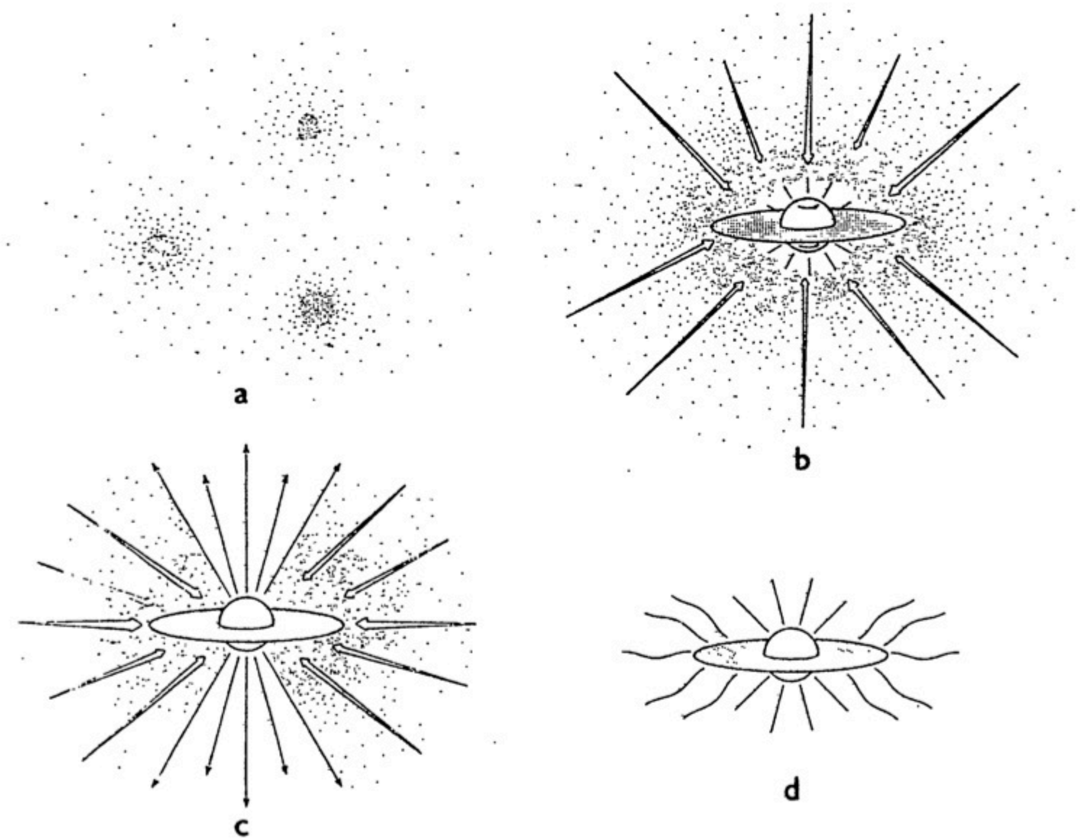


Star Formation – Protostars and Accretion Disks

The "canonical" sketch

a Globule of material in the ISM become gravitationally unstable.

b A protostar core forms, with material accreting via an accretion disk

c The accretion disk generates a polar outflow.

d Nuclear burning initiates which causes the star to dissipate the accreting material leaving only a naked disk, that eventually itself dissipates.

PHYS2160 – Lecture 4 – The Milky Way (3)

Star Formation – Protostars and Accretion Disks

Detailed 3D simulations give a picture for just how complex this process is in detail. See, for example, animations by Matthew Bate, Exeter
http://www.astro.ex.ac.uk/people/mbate/Animations/

"The following calculation models the collapse and fragmentation of a 500 solar mass cloud, but resolves the opacity limit for fragmentation, discs with radii as small as 1 AU, and binary and multiple star systems. The calculation produces a cluster containing 183 stars and brown dwarfs, including 40 multiple stellar systems (i.e. binaries, triples and quadruples) to allow comparison with stellar observations."

Animation available on the PHYS2160 Part I Materials page.


Matthew Bate, Exeter http://www.astro.ex.ac.uk/people/mbate/Animations/

PHYS2160 – Lecture 4 – The Milky Way (3)

Planet Formation within Accretion Disks

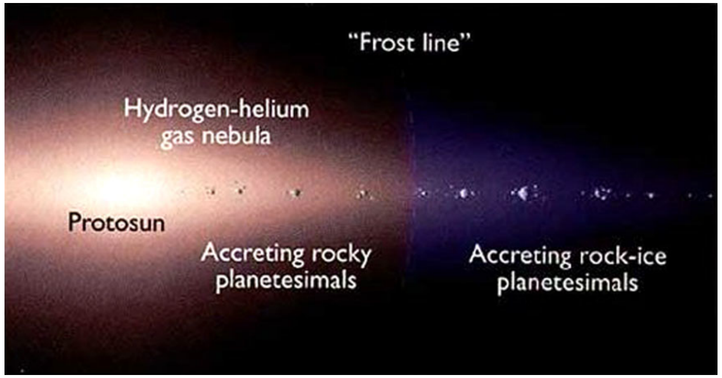
Traditional theories of planet formation seek to explain:

1. Terrestrial planets. Rocky or icy planets have composition very different from disc gas. These must have formed from collisional growth of dust or ices in the nebula.

2. Giant planets. In principle, these could form:
    1. **Via core accretion**. A core of ~10 Earth masses is formed as for terrestrial planets, then accretes an envelope of gas. (This is currently the model most likely to have produced the solar system. Exoplanet detections can be made consistent)
    2. From gravitational instabilities in the protoplanetary disc.
    3. Like stars – i.e. from fragmentation during collapse of molecular cloud cores.

Core Accretion "Stages"

1. Settling and growth of dust grains in disk
2. Pebbles and boulders to km-sized planetismals
3. Planetismals to planet-sized bodies / giant planet cores
4. Ice accretion onto giant planet cores
5. Gas accretion onto icy planet cores



The last stages suggest giant planets should only form in the *outer* regions of accretion disks beyond the "ice line" or "frost line".

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Exoplanets – How to find them

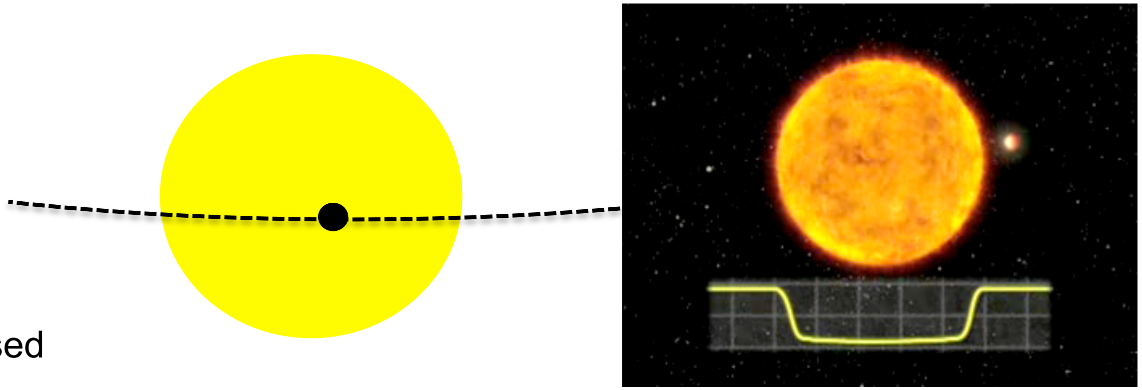
First planet around another star discovered in 1995 (51 Peg b). Now almost >1000 confirmed, and thousands more solid candidates from the Kepler satellite. Two main ways of finding them are transits and radial velocity (or “Doppler wobble”)

<u>Transits</u> – measure relative radius of the planet and star. Very strong bias/cost against long period.

Depth ~ $(R_p/R_{star})^2=(d_p/d_{star})^2$

$R_{jupiter}$ = 71,000km => Depth ~0.01

=> Depth for Earth ~ 1 ppm !

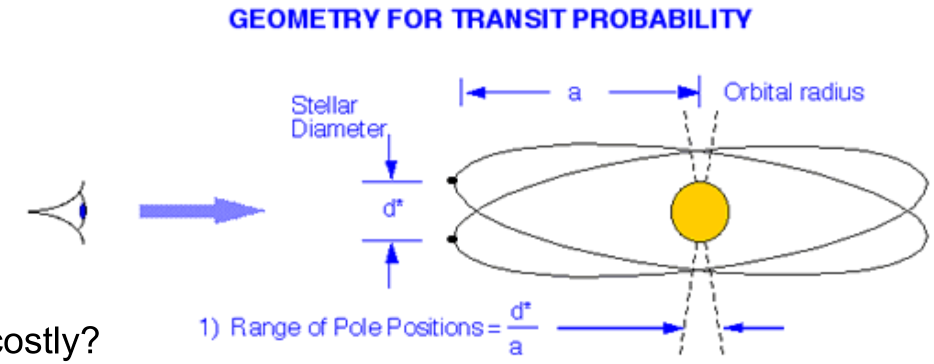


1% photometry fromground is easy, 0.1% is hard. 1ppm is impossible – you need a space-based telescope (like Kepler or COROT).

Likelihood of transit ~ d_{star}/a, but $P^2M_{star}=a^3$ (Kepler’s third law) so

Likelihood ~ $d_{star}/(P^{2/3}\,M^{1/3})$

1.2% for Mercury, 0.5% for Earth, 0.09% for Jupiter



Q: Why might finding long period systems be *very* costly?

PHYS2160 – Lecture 4 – The Milky Way (3)

Star Formation – Exoplanets – How to find them

Doppler Wobble – Planet and star move about barycentre of system, so unseen planet will cause star to "wobble", which can be seen as a periodic radial velocity variation. For a planet with inclination to line of sight i, mass m_2, eccentricity e, period P and orbiting star of mass m_1,

$$K_1 = \frac{2\pi \sin i}{P\sqrt{1-e^2}}\left(\frac{m_2}{m_1}\left[\frac{G\,(m_1+m_2)\,P^2}{4\pi^2}\right]^{\frac{1}{3}}\right)$$

$$= \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{m_2}{m_1}(m_1+m_2)^{\frac{1}{3}} \frac{\sin i}{\sqrt{1-e^2}}$$

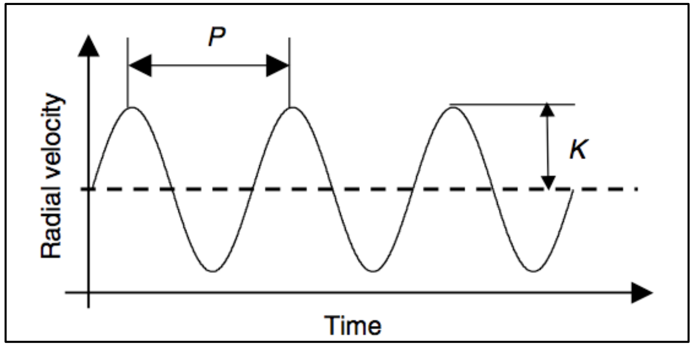


Figure 11 – Plot of radial velocity vs. time for the host star indicating how the period, P, and radial velocity semi-amplitude, K, can be determined from the data. (**Image Credit**: *Planetary Systems and the Origins of Life*, Cambridge University Press, 2007)

And if $m_2 << m_1$, (planet much smaller than star) we can further simplify to

$$K_1 = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{m_2 \sin i}{m_1^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

Jupiter induces wobble of ~12m/s over a 12 year period in the Sun, while Earth induces ~100 mm/s. These are challenging velocity precisions to reach over long period of time.

BUT all parameters are modulo "*sin i*" term. Since an elliptical orbit always projects to an ellipse on the sky, this degeneracy can never be removed from radial velocity data alone.

Good simulator of Keplerians at http://astro.unl.edu/naap/esp/animations/radialVelocitySimulator.html

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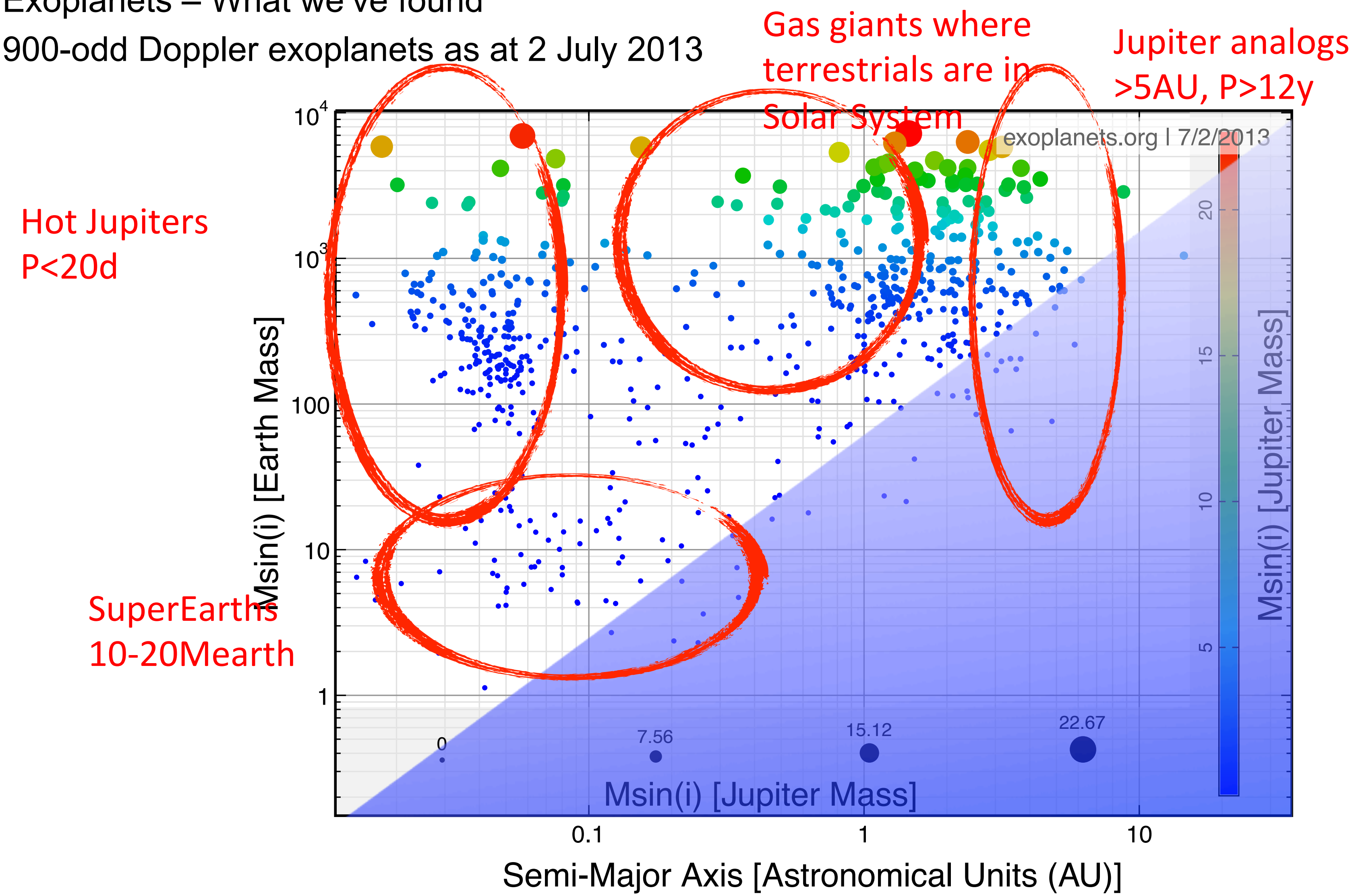
Exoplanets – What we've found

900-odd Doppler exoplanets as at 2 July 2013



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Star Formation – Exoplanets – What we find

Significant number of exoplanets are found in orbits *they shouldn't be in* under basic "core accretion" model. Gas giants inside ~2au should not be able to form there …

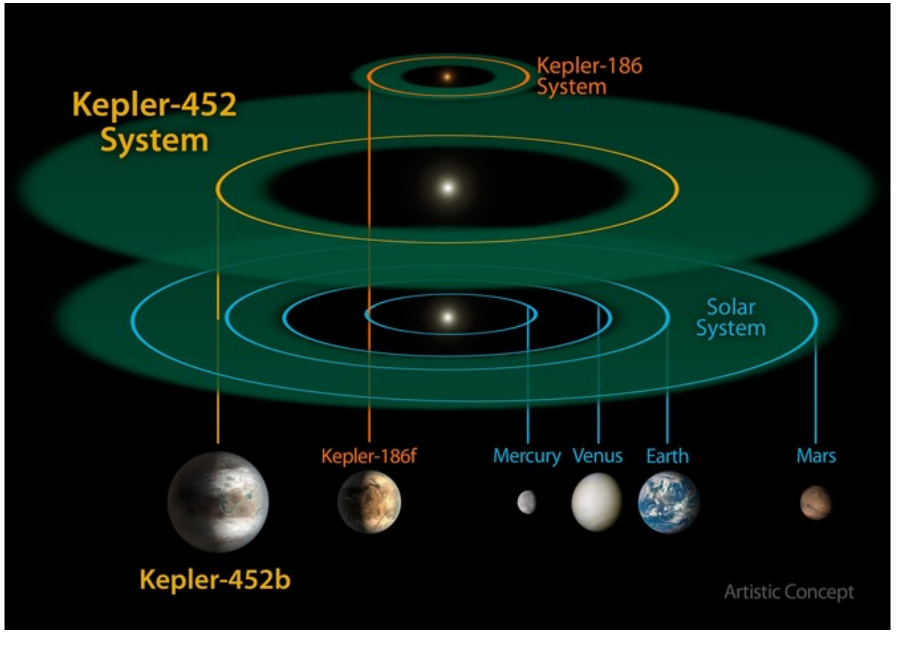
The current working solution is that they did form at larger radii, but *migrated* in to smaller radii due to interactions between the forming gas giant and the gas disk, which exert torques on the planet and so remove angular momentum and so move them to smaller radii.

Only a *very few* examples yet found of planets low enough in mass and at the right orbital separation from the host star to be habitable.

See, e.g., Kepler 22 (http://en.wikipedia.org/wiki/Kepler-22), and GJ677C (e.g. 2 Feb 2012 news item at http://www.phys.unsw.edu.au/~cgt/cgt/Homepage.html)

Or Kepler 452b announced 2 weeks ago (http://www.nasa.gov/ames/kepler/kepler-452-and-the-solar-system)

Sadly our best option for finding these systems (Kepler) failed a while ago (see e.g. https://theconversation.com/the-end-of-kepler-that-would-be-universally-bad-15953 and links therein), though it has been zombified as the K2 mission (http://keplerscience.arc.nasa.gov/K2/) , and there's more light on the horizon in the form of the NASA TESS mission (http://tess.gsfc.nasa.gov)



PHYS2160 – Lecture 4 – Milky Way (3)

- References
- Bibliography
  - Shu, F. The Physical Universe, Chapter 11
  - Zeilick & Gregory Ch 15

Useful constants, units, and formulae:

Gravitational constant	G	=	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	=	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	=	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	=	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	=	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	=	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	=	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	=	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	=	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	=	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	=	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	=	1.496	$\times$	10^{11}	m
Parsec	pc	=	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	=	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	=	$5 \log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	=	$2.5 \log \frac{f_1}{f_2}$
For small recession velocities	v/c	=	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	=	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	=	$h\nu$
Frequency and wavelength	c	=	$\nu\lambda$

PHYS2160 – Lecture 5 – The Milky Way (4)

Last time

- Interstellar medium components – HI, H_2 and HII regions.
- Dust and Extinction and Optical Depth
- Stromgren spheres
- Making stars.
- Jeans Criteria for cloud collapse. Plus complications – turbulence, magnetic fields, angular momentum
- Angular Momentum → Accretion disks → Planetary formation
- Exoplanet detection via transits and radial velocity ("Doppler Wobble")
- The planets we find don't necessarily look like the Solar System → Solar System may not be representative. In particular migration of giant planets clearly takes place.

This Time

- Radio wavelength emission mechanisms – Synchrotron, Bremstrahlung, HI 21cm, CO millimetre
- Galaxy rotation curves from the gas
- Dark matter. Searches for dark matter
- Formation models for the Galaxy

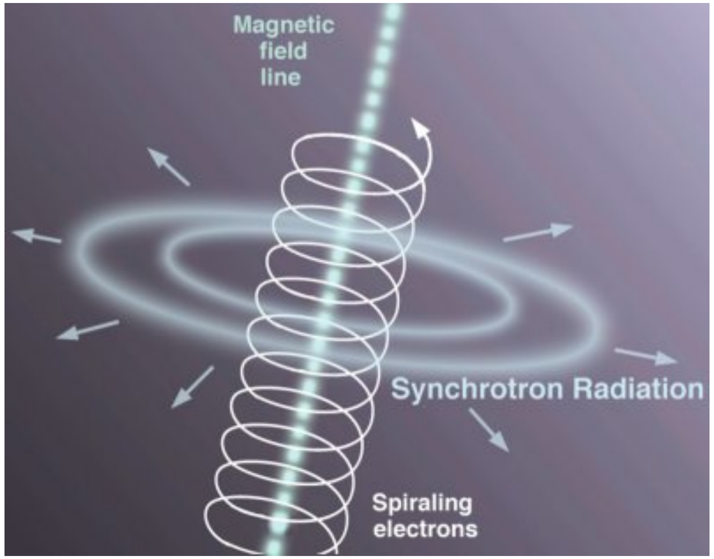
PHYS2160 – Lecture 5 – Milky Way (4)

Synchrotron Radiation

A relativistic electron moving with velocity vector $\mathbf{v}$ in a magnetic field $\mathbf{B}$, is subject to a force

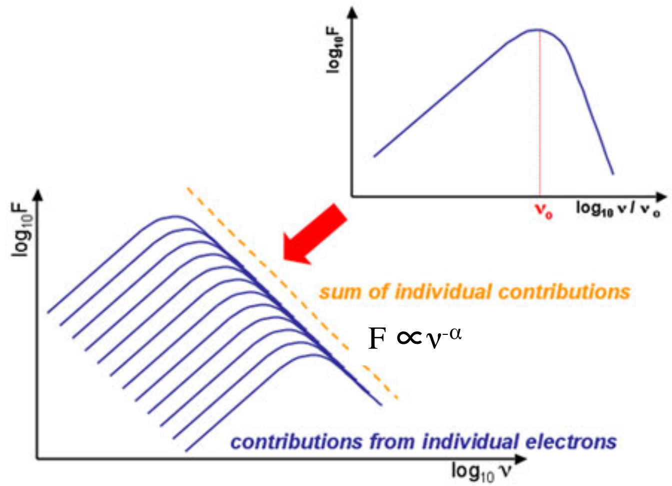
$$-e\mathbf{v}/c \times \mathbf{B}$$

and so will spiral around the magnetic field lines. This acceleration causes the electron to radiate photons along the instantaneous direction of motion.



Such radiation is detected from many classes of astronomical object (though was first encountered in terrestrial particle accelerators) and is often referred to as "non-thermal" emission – the detailed shape of the emission spectrum is a function of the energy distribution of the electrons (rather than a temperature.)

Synchrotron radiation is detected at radio wavelengths and typically has an integrated power law spectrum of form $F \propto \nu^{-\alpha}$, where α is a power law index in the range 0.5-2 (so flux increases as frequency decreases).



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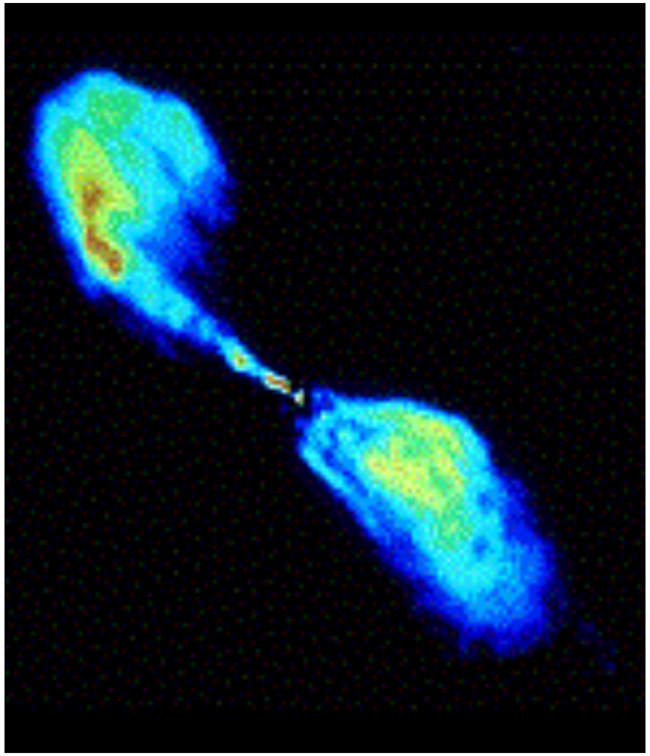
Synchrotron Radiation



Centaurus A (also known as NGC 5128) is a peculiar galaxy in the constellation of Centaurus. The false colour image is a radio one from the VLA showing its synchrotron emission. The image on the left has the optical light from the galaxy superimposed.

PHYS2160 – Lecture 5 – Milky Way (4)

Thermal Bremstrahlung Radiation

Consider an electron in a HII region travelling past an ion. The Coulomb interaction deflects the electron changing its kinetic energy, and this energy loss is emitted as photons.

The electron kinetic energies are generally low, so the resulting photons emitted lie in the infrared or radio. Integrating this process over many electrons with many possible energies, the emission spectrum from an ensemble of particles will form a continuum.

This form of radiation is sometimes called "thermal" emission. The name "bremstrahlung" comes from the German phrase "braking radiation". It is also known as "free-free emission".

The inverse process can also happen (i.e. an electron absorbs a photon in the vicinity of an ion). This process is then known as "free-free absorption".

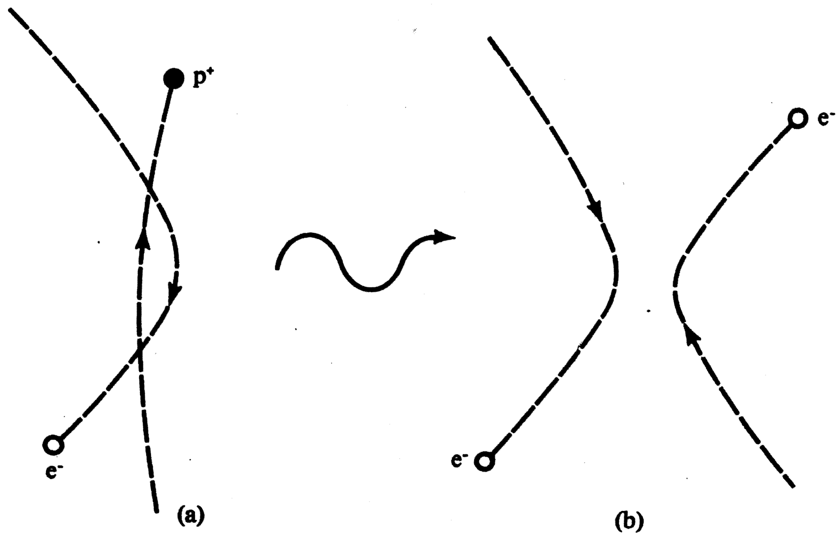


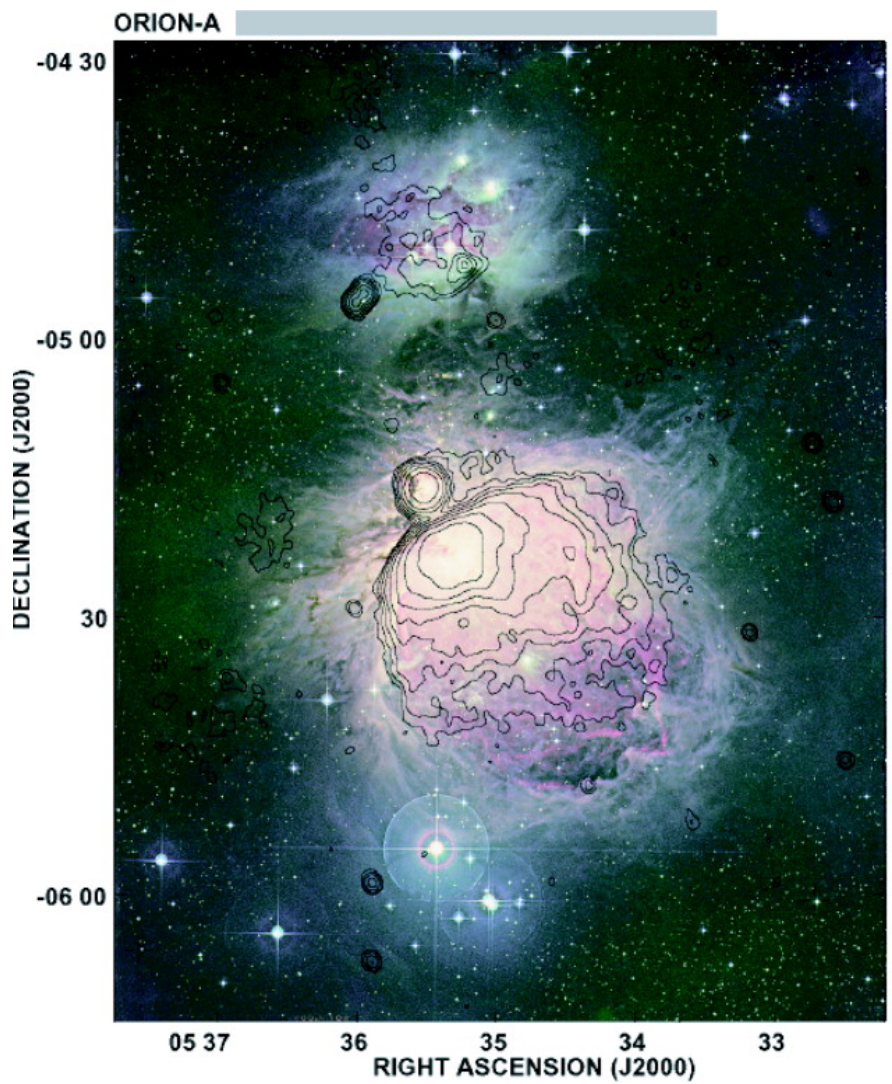
Figure 11.14. The microscopic mechanism responsible for producing thermal radio continuum (free-free emission). (a) A free electron is momentarily deflected by the electric attraction of a passing ion (usually a proton in an HII region). In the acceleration process, the electron radiates a number of photons. The energy carried off by photons of different frequencies (speed of light divided by wavelength) is a pretty flat distribution at radio frequencies, because the encounter time is short compared to the period of vibration of radio waves. (b) When two free electrons deflect one another by their mutual electric repulsion, no net radiation emerges. The oscillatory parts of the electric field associated with accelerating electrons (see Fig. 2.9) exactly cancel when we have two electrons possessing equal but opposite motions.

PHYS2160 – Lecture 5 – Milky Way (4)

Thermal Bremstrahlung Radiation

Overlay of VLA 330 MHz radio contours on a UK Schmidt optical photograph of the Orion region. The radio emission is dominated by thermal bremsstrahlung from hot gas ionized by the central stars of the nebula.

(Subrahmanyan et al., 2001, AJ, 407, 121).



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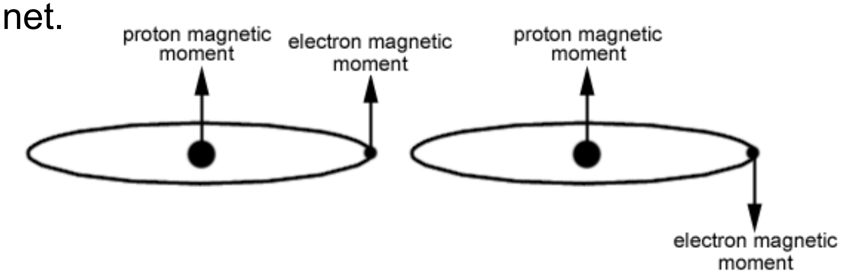
Seeing Gas – HI : The 21cm Spin Flip Transition

As noted earlier *most* of the ISM is very cold (~10-100K) so H will be in either its atomic (HI) or molecular (H_2) form. Gas in this state is too cold to emit at optical wavelengths. However in 1945 Van de Hulst predicted that atomic hydrogen should be detectable using a 21cm line from HI (and this was discovered experimentally in 1951).

What produces this radiation? Both the proton (*p*) and the electron (e^-) in a hydrogen atom have an intrinsic charge and an intrinsic spin, which combine to generate an intrinsic dipole magnetic field (measured by their *magnetic moment*) – much like a bar magnet.



There are two allowed orientations of these two magnetic moments – either aligned or anti-aligned. When aligned, the *p* and e^- are less tightly bound. And the reverse holds. This means there are two possible quantum states for the hydrogen atom, even when in its electronic ground state – a phenomenon known as *hyperfine splitting*. The transition between these two states in known as a spin-flip transition, and has very low energy (corresponding to a frequency of 1.420406Ghz or ~21cm).

Collisions in the ISM are responsible for changing the hyperfine state of H atoms, at a rate of about one transition every 400 years. Spontaneous emission (never seen in the laboratory) occurs about once per atom every few million years.

As a result, quite long path lengths are require to integrate up enough H atoms to actually see the 21cm line. On the other hand, the line is rarely optically thick, so it probes structures as far as the other side of the galaxy. And building receivers to detect radiation at 1.4Ghz is relatively straightforward, so a lot of our knowledge of the state of the structure of our Galaxy and other galaxies comes from HI observations.

PHYS2160 – Lecture 5 – Milky Way (4)

HI : The 21cm Spin Flip Transition

Kalberla & Kerp, Annu. Rev. Astron. Astrophys. 2009. 47:27–61

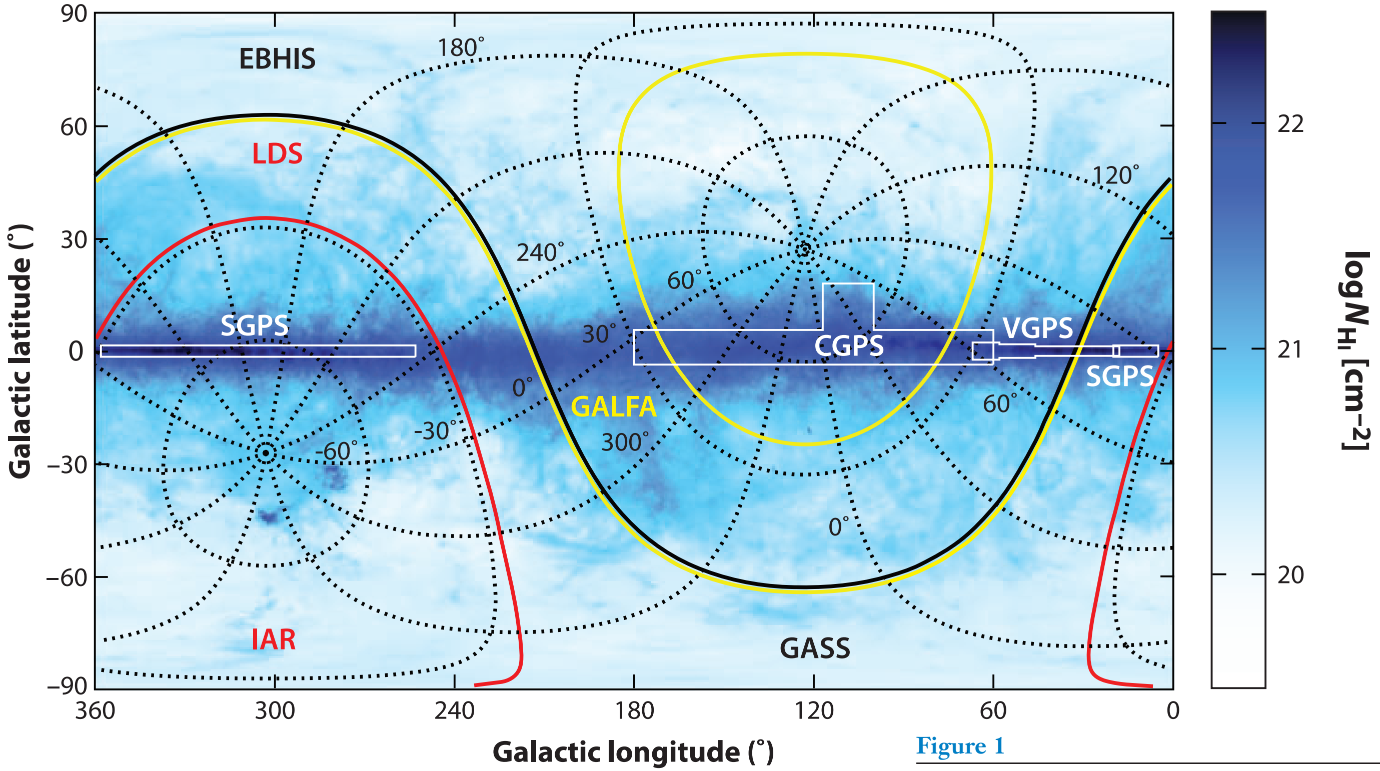


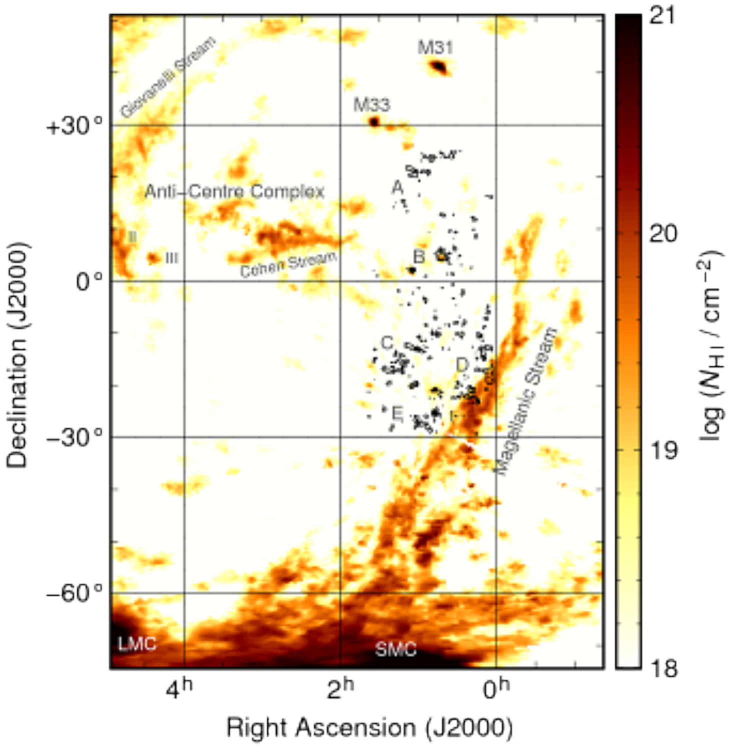
Figure 1

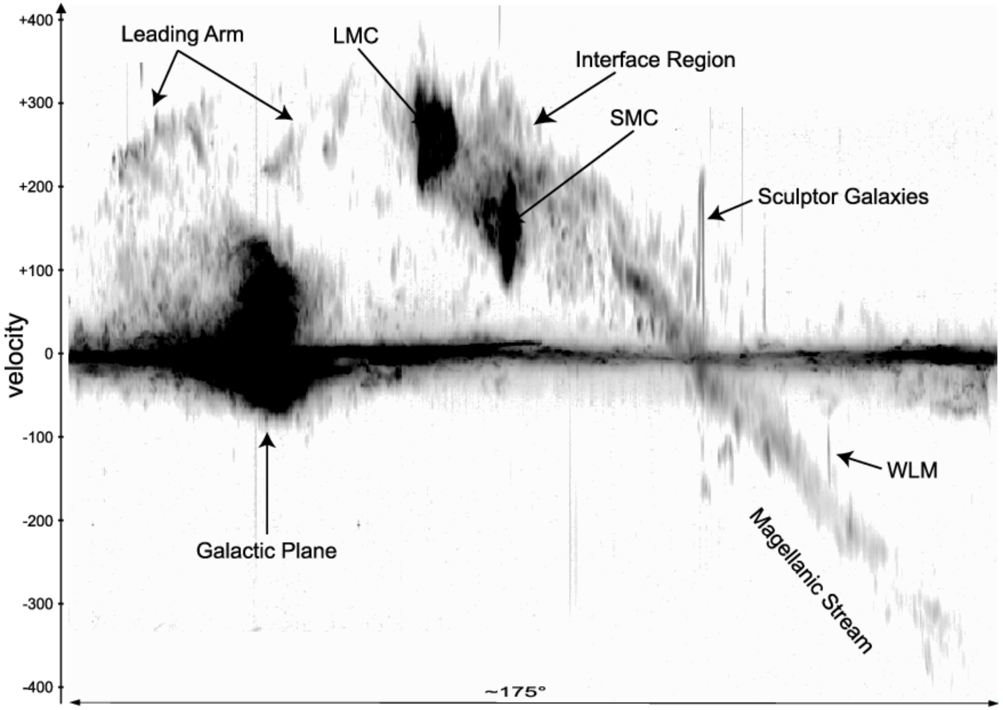
Overview of the sky coverage of different surveys. The Leiden-Argentine-Bonn (LAB) survey merges the Leiden-Dwingeloo Survey and Instituto Argentino de Radioastronomía surveys at $\delta = -27.5° \pm 2.5°$ (*red line*). The Galactic All-Sky Survey and Effelsberg-Bonn HI Survey cover the northern and southern sky, separated by the black line. The Arecibo Galactic ALFA survey coverage is $-2° < \delta < +38°$ (*yellow lines*). The Galactic plane survey consists of Southern Galactic Plane Survey, Canadian Galactic Plane Survey, and VLA Galactic Plane Survey. The background image displays the total volume density of the 21-cm line emission from the LAB survey. This figure was kindly provided by B. Winkel.

PHYS2160 – Lecture 5 – Milky Way (4)

HI : The 21cm Spin Flip Transition

As well as total flux density, we can look at velocity information in the data (e.g. right - Brüns et al. 2005, A&A, 432, 45-67) which shows a survey of a strip of the sky along the line of the Magellanic Stream. Velocity information allows the separation of the Galaxy and Magellanic components.





PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – More on Galactic Kinematics

We saw earlier how we can use data on the radial and tangential velocities of nearby stars to probe the structure of the Galaxy disk using the Oort constants.

We can also use an extension of those techniques to interpret velocity data from *gas* (e.g. HI). In this case we can see *much* further through the Galaxy, though we only detect information on the velocity along the line of sight.

Starting (as before) from

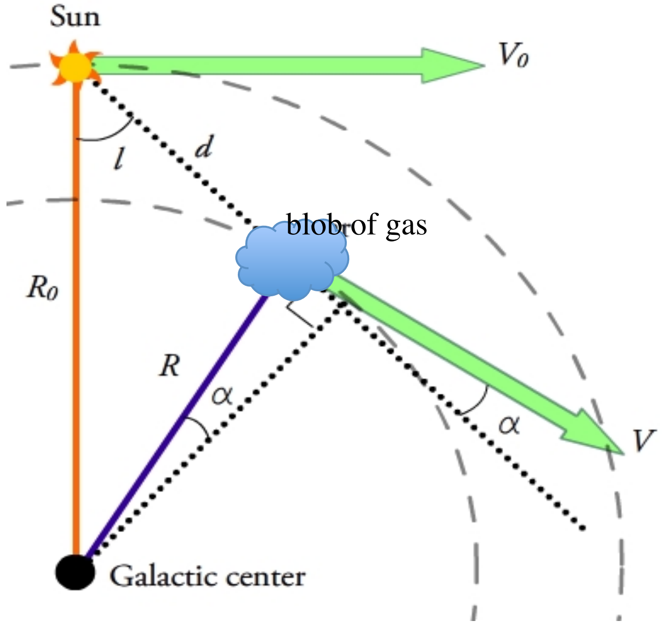
$$V_{\text{obs, r}} = V_{\text{star, r}} - V_{\text{sun, r}} = V\cos(\alpha) - V_0 \sin(l)$$

we get

$$V_{obs} = V - V_0 = V \cos \alpha - V_0 \sin l$$

We can see that the *maximum* value of the velocity we can see along the line of sight will come from the gas lying at α=0 (i.e. at the location where the tangent to the circular velocity is completely along the line of sight. Some trigonometry (see the tutorial problem set) allows one to determine that the maximal radial velocity $v_{r,max}$ obeys

$$v_{r,max} = 2\,A\,R_0\,(\sin l)(1 - \sin l)$$



While the detailed flux emission along a line of sight will depend on the integrated column density along that line of sight (which we don't know), determining the *maximum* velocity is straightforward. By determining the maximum velocity as a function l, we can determine AR_0. And if we know R_0, we then have a *independent* way of determining the Oort constant A.

PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – Measuring the Maximum Velocity

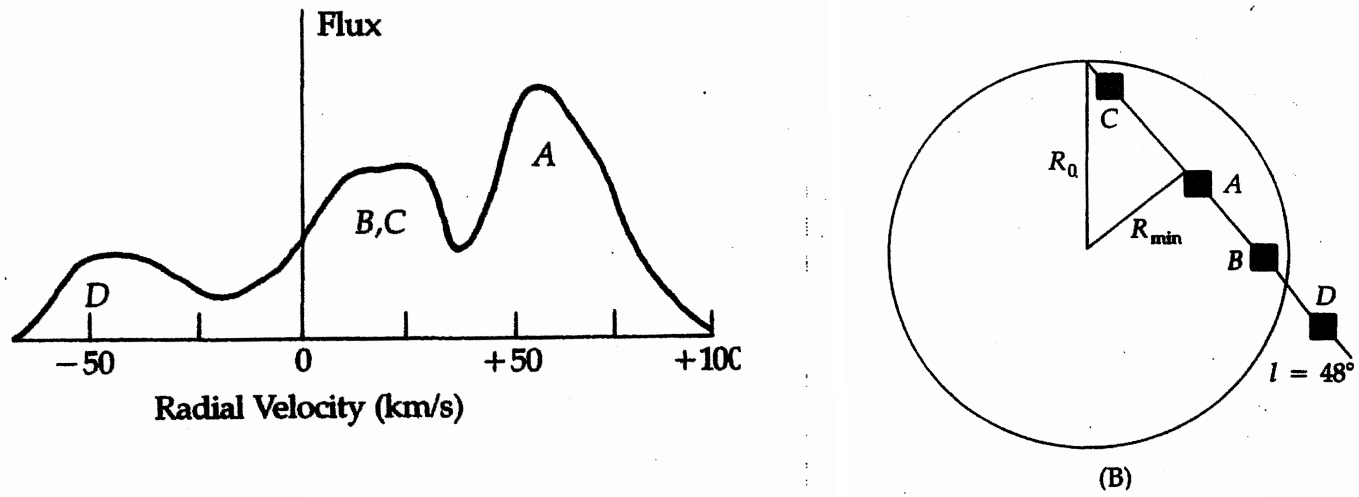


Figure 20–2 Line profiles and Doppler shifts. (A) Line profiles from an umber of H I clouds at longitude 48°. (B) The line-of-sight geometry for the profiles in (A).

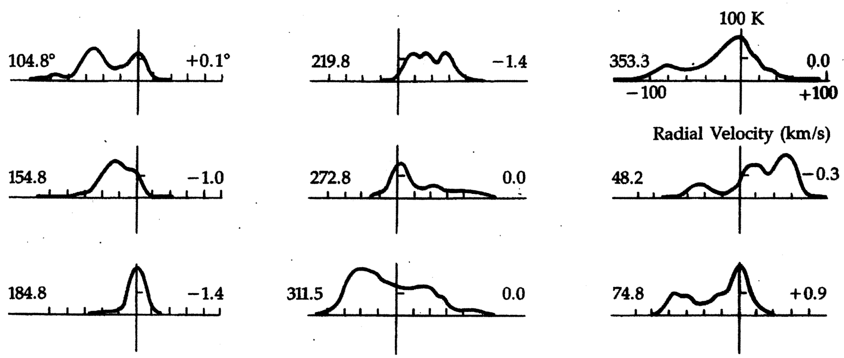
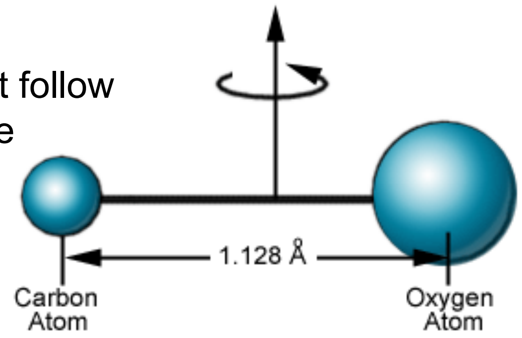


Figure 20–1 Line profiles at 21 cm in the galactic plane. These emissions come from regions spanning the galactic equator. Galactic longitude is indicated on the left of each profile; galactic latitude, on the right. The flux is calibrated in units of the antenna temperature. *(Adapted from diagrams by F.J. Kerr and G. Westerhout)*

PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – H_2: Molecular gas via CO

Consider a diatomic molecule such as CO, or O_2, or H_2. They can spin and they can vibrate. These rotational or vibrational modes are quantized, and must follow a set of quantum mechanical rules. The energies associated with vibration state transitions correspond to infrared wavelengths, while rotational transitions produce lines at radio wavelength.



However, because H_2 contains two identical atoms it has no permanent electric dipole moment, and so has no rotational quantum states. Moreover, its vibrational states cannot be excited by the temperatures present in molecular clouds. So we cannot observe H_2 directly.

Fortunately, CO *is* present in molecular clouds and it does have a dipole moment, with a base rotational transition (J = 1 to 0) resulting in a spectral line at 115.2712 GHz, and a sequence of transitions at longer wavelengths – the J = 2 to 1 transition gives a line at 230.5424 GHz. This 2-1 transition near 3mm was the first to be widely used to probe the molecular clouds of our Galaxy in the 1980s.

These maps show us that star formation happens in the denser molecular clouds (not in HI clouds)

They also show us that it is the molecular gas clouds which trace out the spiral arms in our Galaxy (the arms can also be seen in HI, but are much weaker and more difficult to interpret). *The spiral arms are features of the gas component of the Galaxy.* They are also traced out by young and massive (i.e. recently formed) stars. But they are not seen in older populations of disk stars.

PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – CO tracing H_2 in the Milky Way

e.g. Dame et al. (2001), ApJ, 547, 792 http://www.cfa.harvard.edu/mmw/MilkyWayinMolClouds.html .

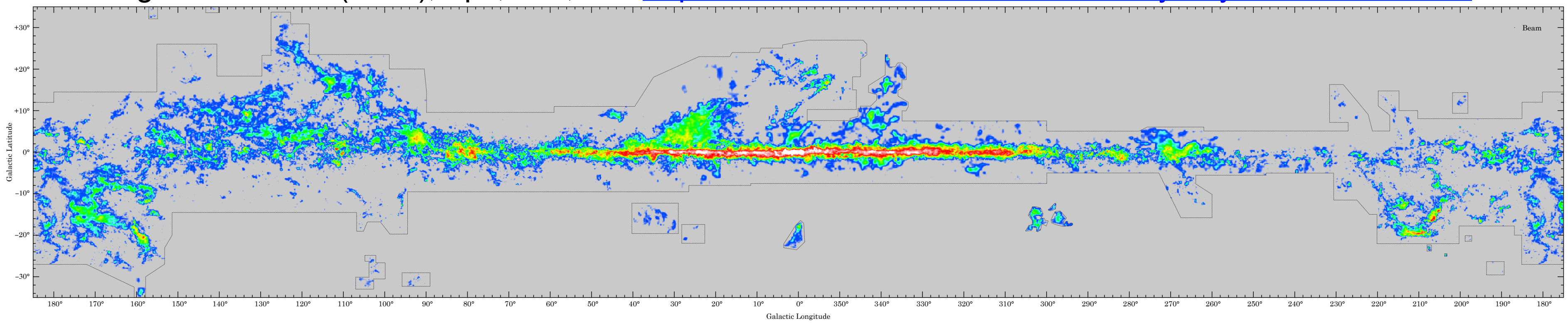
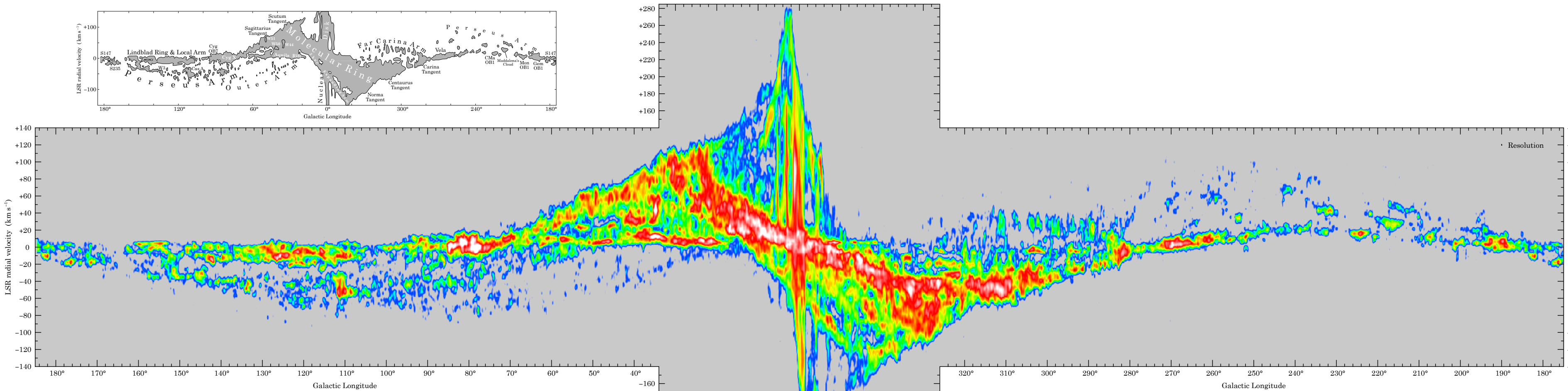


FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.



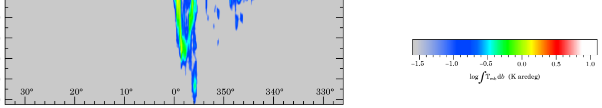
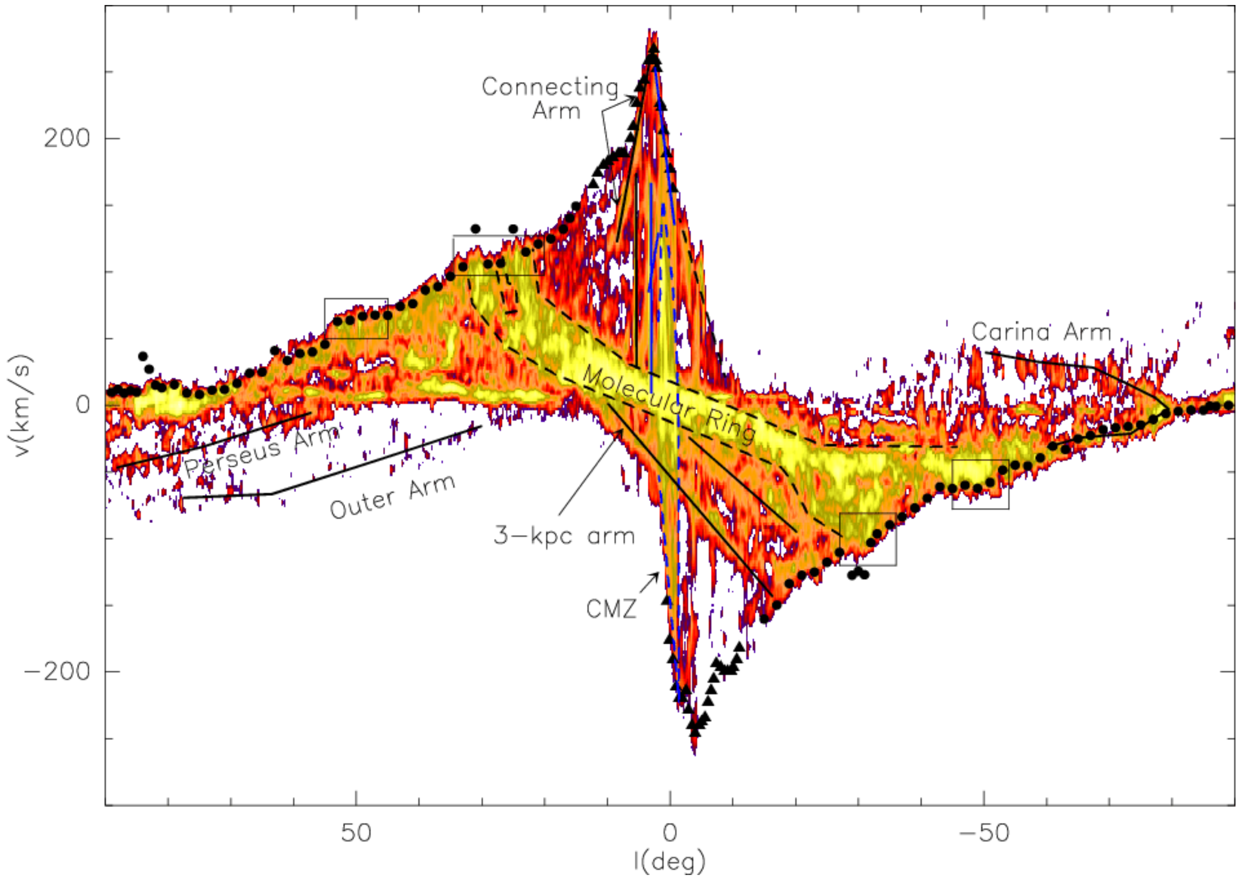


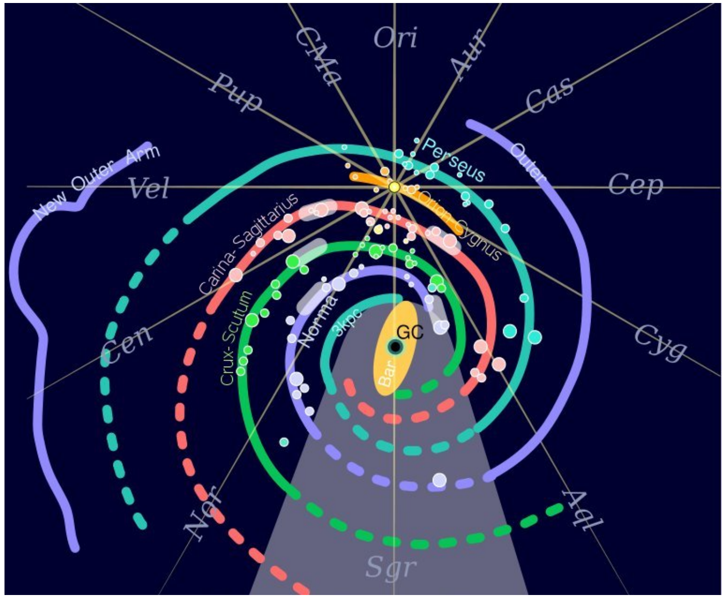
FIG. 3.—Longitude-velocity map of CO emission integrated over a strip ~4° wide in latitude centered on the Galactic plane (see §2.2)—a latitude range adequate to include essentially all emission beyond the Local spiral arm (*i.e.*, at $|v| > 20$ km s^{-1}). The map has been smoothed in velocity to a resolution of 2 km s^{-1} and in longitude to a resolution of 12′. The sensitivity varies somewhat over the map, since each component survey was integrated individually using moment masking at the 3-σ level (see §2.2).

PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – CO tracing H_2 in the Milky Way

Detailed analysis finds correlated structures that can be associated with spiral arms (e.g. Rodriguez-Fernandez & Combes, A&A 489, 115, 2008).

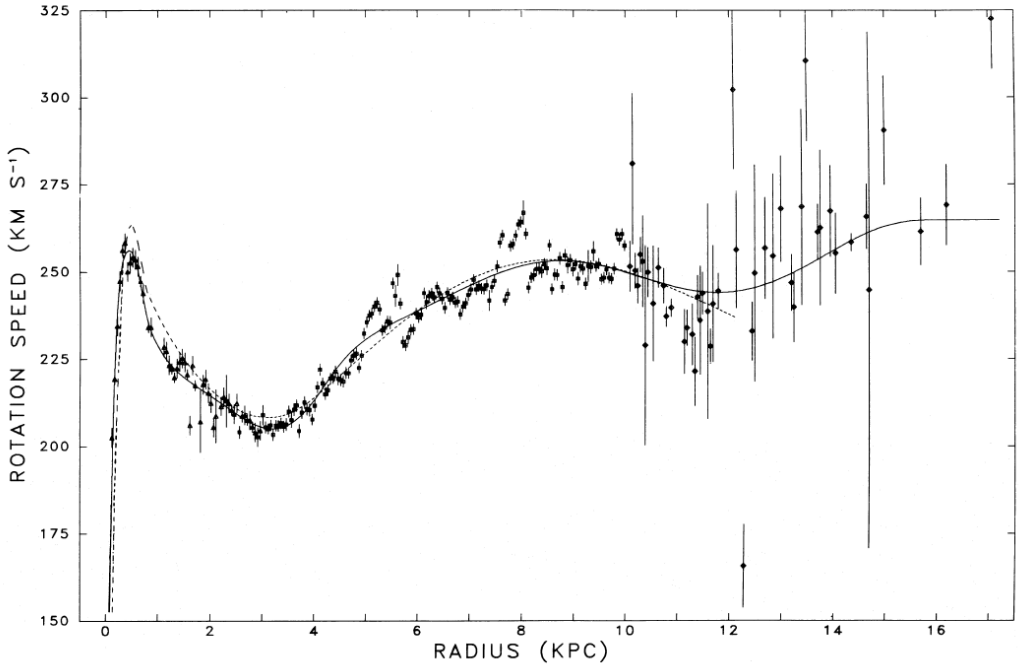




PHYS2160 – Lecture 5 – Milky Way (4)

Rotation Curves – The Dark Matter Halo

Using HI and CO astronomers have been able to trace the Galaxy's rotation curve in towards the Galactic centre, and beyond the radius of the Sun.



It came as a great surprise to astronomers to discover that the rotation curve of the Galaxy is essentially constant beyond R_0 (e.g. figure above from Clemens (1985) ApJ, 295, 422). The fact that the curve does *not* drop off as $\propto R^{-1/2}$ (i.e. Keplerian motion) suggests there is a significant amount of mass beyond R_0.

This is especially surprising as most of the **luminosity** of the Galaxy is produced by matter residing inside the solar radius R_0.

PHYS2160 – Lecture 5 – Milky Way (4)

Rotation Curves – The Dark Matter Halo

What does $V(R)$=constant mean? To see, assume $V(R)=V=constant$. Then from the equation for the centripetal force on a particle at radius r, and from Newton's laws of gravity, we have for a particle with mass m and mass interior to the circular orbit M_r

$$mV^2/r = GM_r m/r^2$$

(We use r for a spherically symmetric mass distribution here, rather than R for a cylindrical rotation in the Galactic plane. However to obtain the rotation curve within the plane we need only set r=R). Solving for M_r and *differentiating* wrt r we get

$$dM_r/dr = V^2/G$$

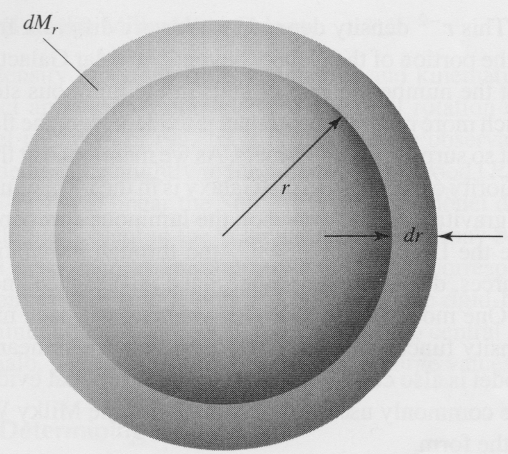


FIGURE 10.25 A spherically symmetric shell of mass dM_r having a thickness dr and located a distance r from the center. The local density of the shell is ρ.

We can obtain another expression for dMr/dr for a spherical mass distribution $\varrho(r)$ using conservation of mass,

$$dM_r = \varrho\, 4\pi r^2\, dr$$

$$dM_r/dr = \varrho\, 4\pi r^2$$

And equating these

$$\varrho(r) = V^2/(4\pi G r^2)$$

PHYS2160 – Lecture 5 – Milky Way (4)

Rotation Curves – The Dark Matter Halo

This simple argument shows that a flat rotation curve requires a spherical mass density that drops as r^{-2}.

Recall that this is a *much* slower drop off than the $r^{-3.5}$ distribution of both the bulge population at the Galaxy's centre and the stellar halo.

The figure to the right shows a model for the contributions of the known components to the rotation curve (the 'Bulge' here combines the bulge and stellar halo).

There must be some source of non-visible, non-luminous matter making up this halo.

This "**dark matter halo**" is composed of a material that remains unidentified to this day.

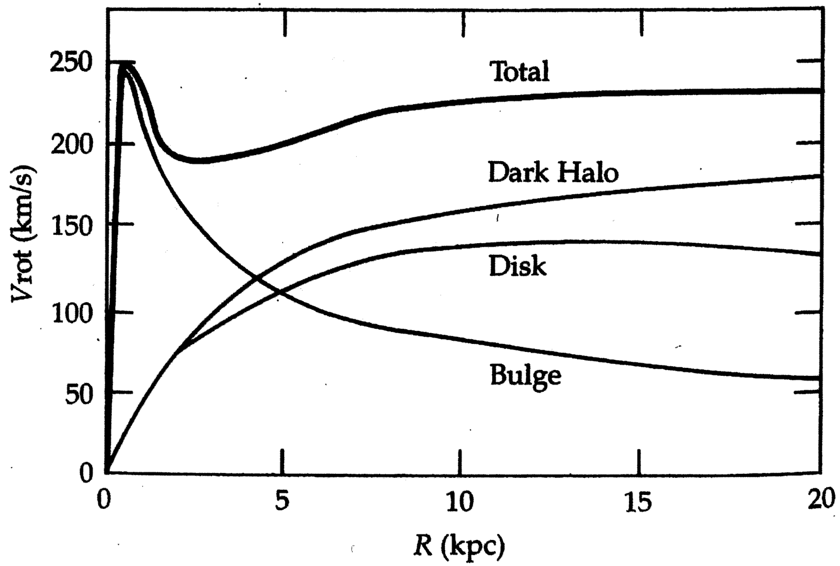


Figure 20–8 A model of the mass distribution of the Galaxy, as represented by rotation curves for each component. The Sun's distance is assumed to be 8.5 kpc. The line marked "Total" should match the observed rotation curve. *(Adapted from a diagram by P.C. van der Kruit)*

PHYS2160 – Lecture 5 – Milky Way (4)

Models for the Formation of the Milky Way

Two models dominate thinking on how the Milky Way formed and evolved – however, this remains an active area of research to this day …

Eggen, Lynden-Bell & Sandage (ELS) Model first proposed in 1962 in which there was a rapid dissipationless collapse of a proto-Galactic nebula. The oldest stars formed early in the collapse on nearly radial trajectories, producing highly elliptical orbits above and below the plane. These earliest stars are metal poor (Population II) as the interstellar medium has not had time to become enriched by the products of stellar nucleosynthesis.

Later, the collapse slowed and became dissipational as energy was converted into random motions in the clouds. The (small) angular momentum in the initial cloud meant that it began to rotate more rapidly as it contracted. The combination of increased dissipation and increased angular speed led to the formation of the disk from which Population I stars began to form (and continue to be formed to this day).

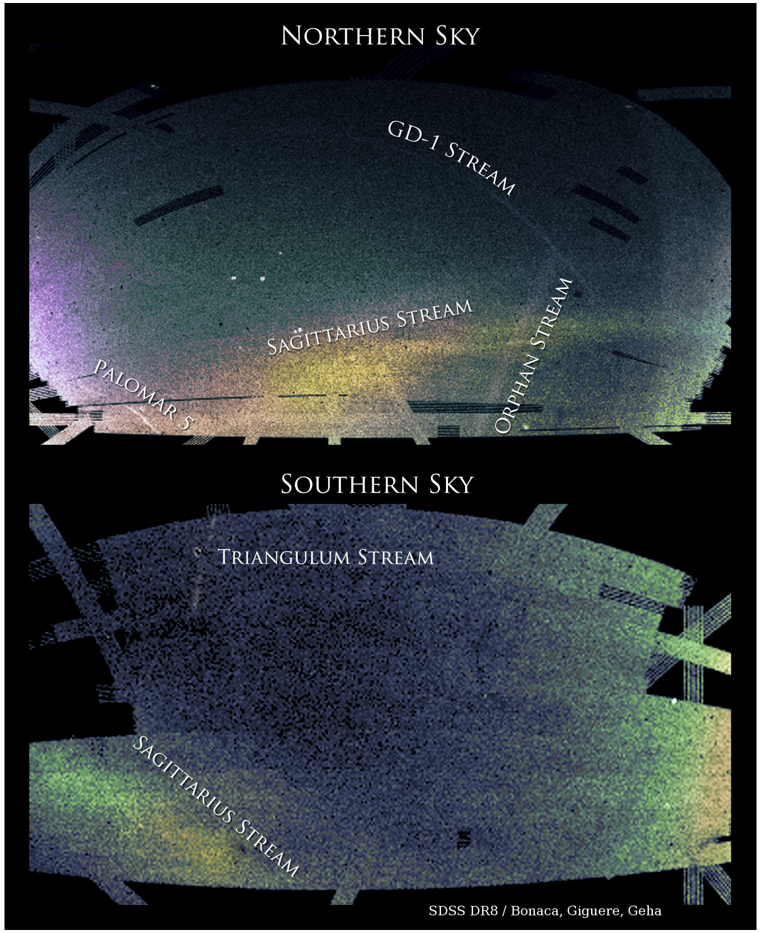
Unfortunately there are some problems – ELS predicts the globular clusters to form early in the rapid collapse (on timescales of 10^8 years). Observations of globular clusters though, show them to have a spread of ages (~2Gyr) and a spread in metallicities. The disk has also been found to have at least two separate components – a *thick* disk and a *thin* disk (we live in the thin disk – the thick disk hosts stars with a scale height several times larger than the thick disk, and quite different elemental abundances).

PHYS2160 – Lecture 5 – Milky Way (4)

Models for the Formation of the Milky Way

Hierarchical Merger Model (sometimes Searle & Zinn or 'SZ').

Galaxy building appears to have been a 'bottom up' merger process (as well as a 'top down' collapse). Indeed, galaxy formation theories for *other g*alaxies are today dominated by the model that all galaxies form via the accretion of smaller units into larger and larger units.



SZ proposed the Galaxy was built up as a chaotic accretion of individual small (or "dwarf") galaxy units (10^7-$10^9 M_\odot$). Each of these had its own star formation history, leading to a dispersion in the resulting cluster and stellar population properties in the Galaxy. While most accretion takes place in the first 2-3Gyr, some accretion of components takes place to this day.

Indeed, in the last decade or so, several 'streams' have been uncovered in large sky surveys that appear to be the remains of dwarf galaxies that have been disrupted by repeated passages through the Milky Way – especially the Sagittarius stream (image to right from http://www.astro.yale.edu/abonaca/research/halo.html)

In reality both processes are likely to have played a role. Unravelling the Milky Way's complex history remains an active area of research right now (e.g. GALAH survey presented in last slide of Lecture 3 – ask Sarah Martell about this in Part II).

PHYS2160 – Lecture 5 – Milky Way (4)

- References
  -
- Bibliography
  -
  -

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	$=$	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	$=$	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	$=$	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	$=$	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	$=$	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	$=$	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	$=$	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	$=$	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	$=$	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	$=$	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	$=$	1.496	$\times$	10^{11}	m
Parsec	pc	$=$	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	$=$	$5 \log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	$=$	$2.5 \log \frac{f_1}{f_2}$
For small recession velocities	v/c	$=$	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$

PHYS2160 – Lecture 6 – Galaxy Types

Last time

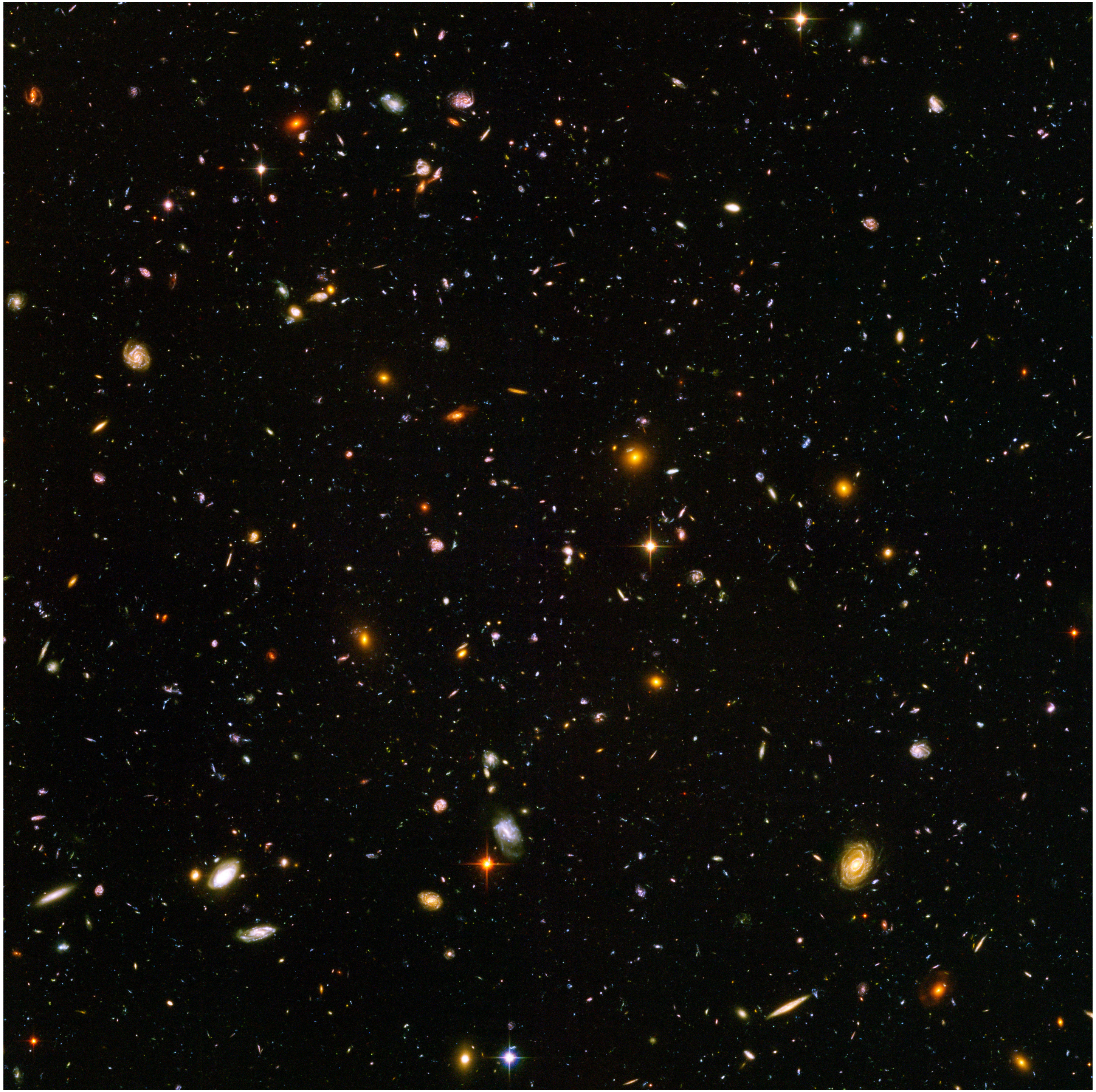
- Radio wavelength emission mechanisms – Synchrotron, Bremstrahlung, HI 21cm, CO millimetre
- What they trace.
- Galaxy rotation curves from gas
- Dark matter in the Halo
- Formation models for the Galaxy

This Time (this lecture is best viewed in PDF on a device or printed in colour)

- Galaxy Types
- The Hubble Galaxy Classification “Tuning Fork”
- Spiral Galaxies
- Density Waves

If you take really deep images of the sky, you find its not “full of stars” …. its “full of galaxies”. And in an amazing ranges of types.

Galaxies are the visible building blocks of the universe – much as stars are the visible building blocks of galaxies.



HST Ultra Deep Field

11d of exposure on one location

This image is about 6000x6000 pixels in size.

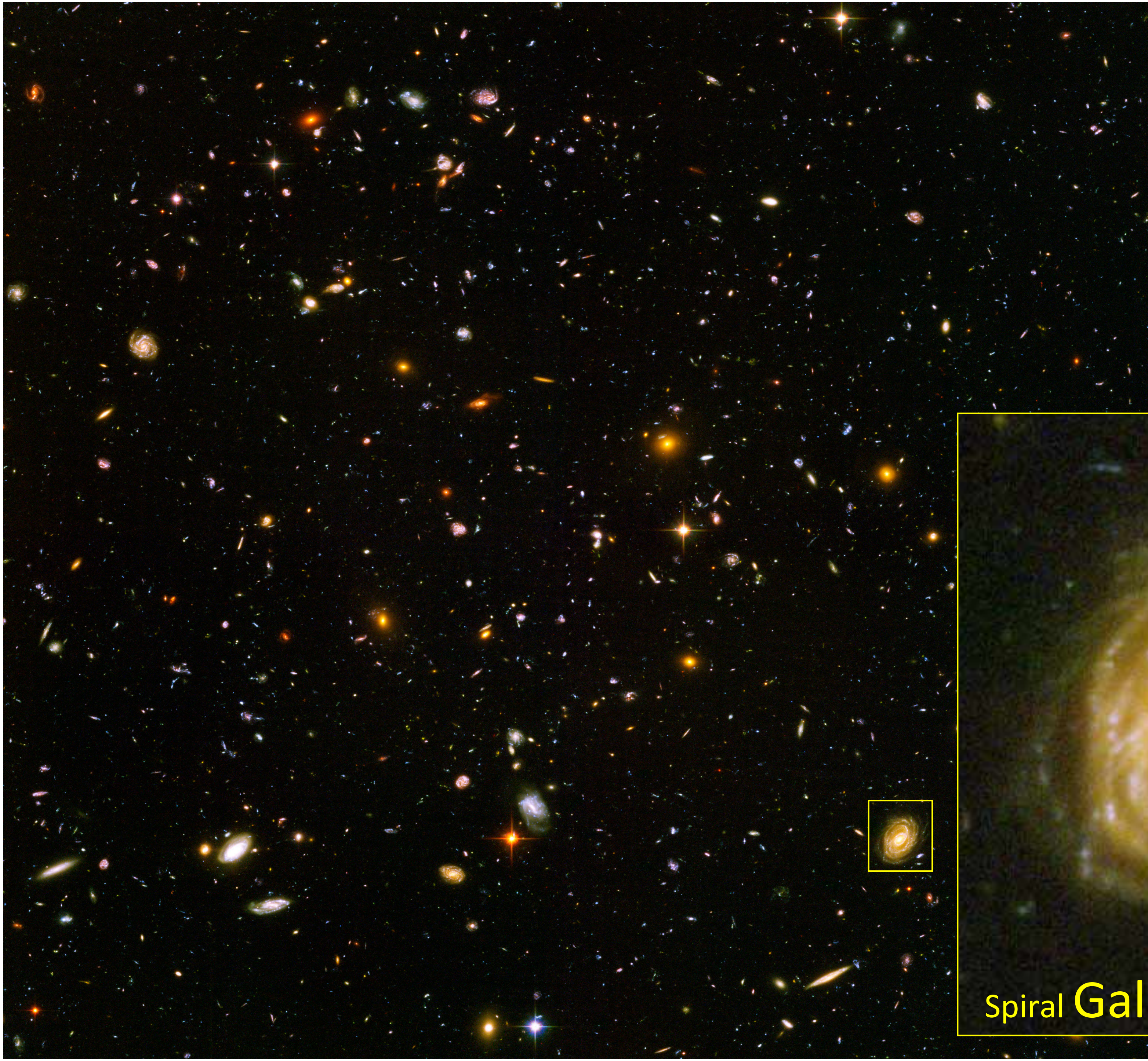
http://www.spacetelescope.org/static/archives/images/large/heic0611b.jpg

HST Ultra Deep Field

11d of exposure on one location

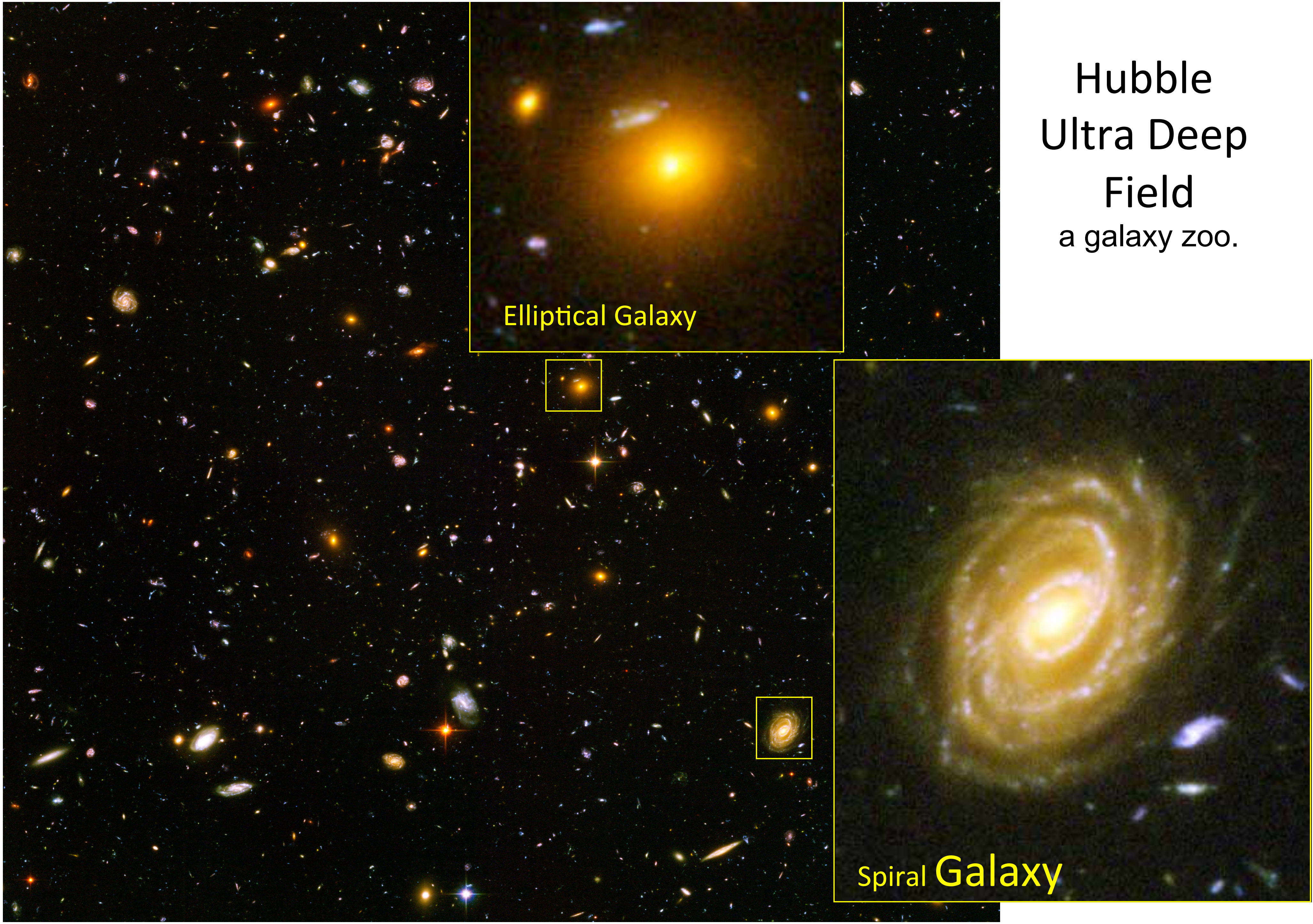
Expanded to ~1800 x 1600 pixels

http://www.spacetelescope.org/static/archives/images/large/heic0611b.jpg



Hubble Ultra Deep Field

a galaxy zoo.

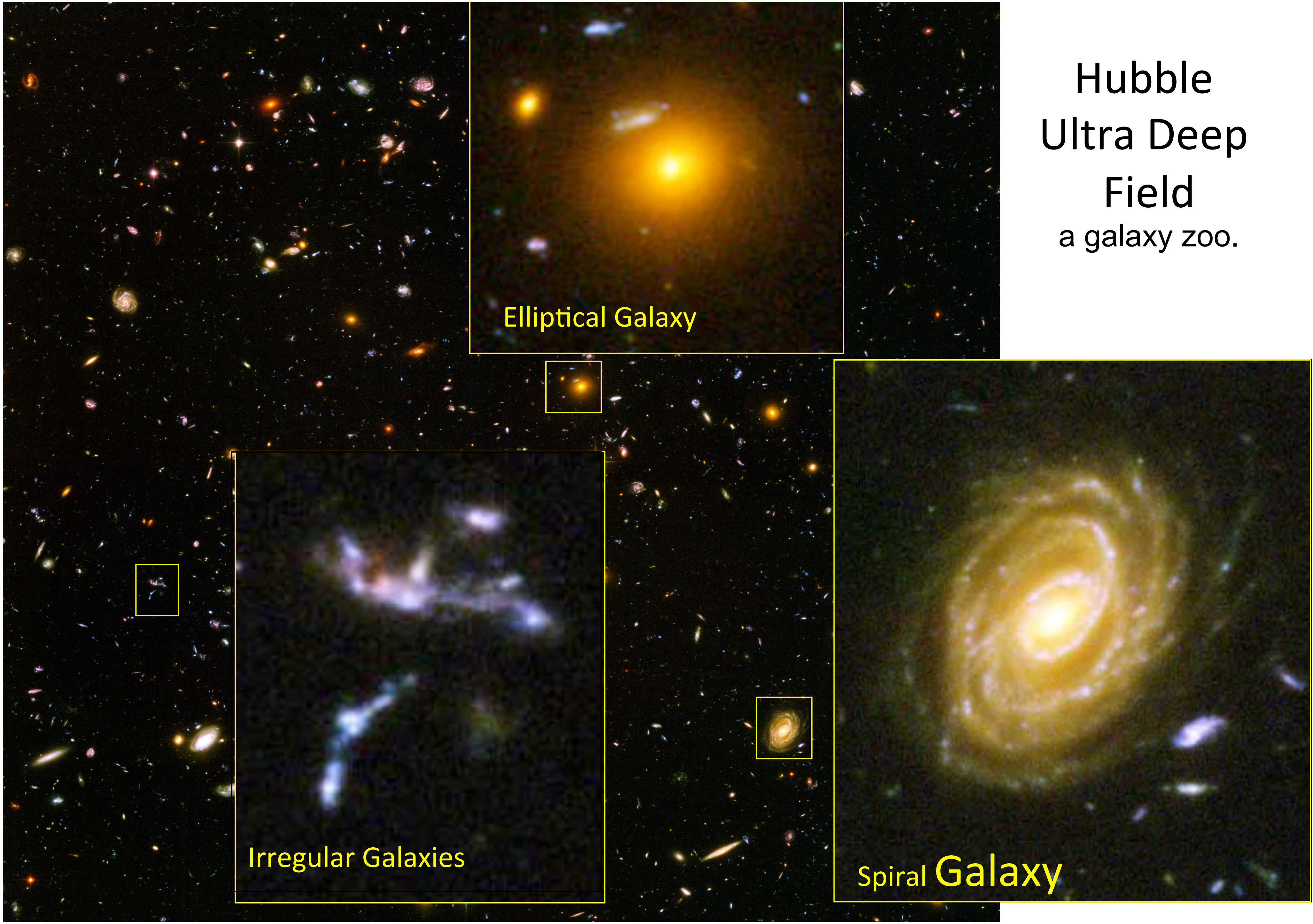


Hubble Ultra Deep Field

a galaxy zoo.

Hubble Ultra Deep Field

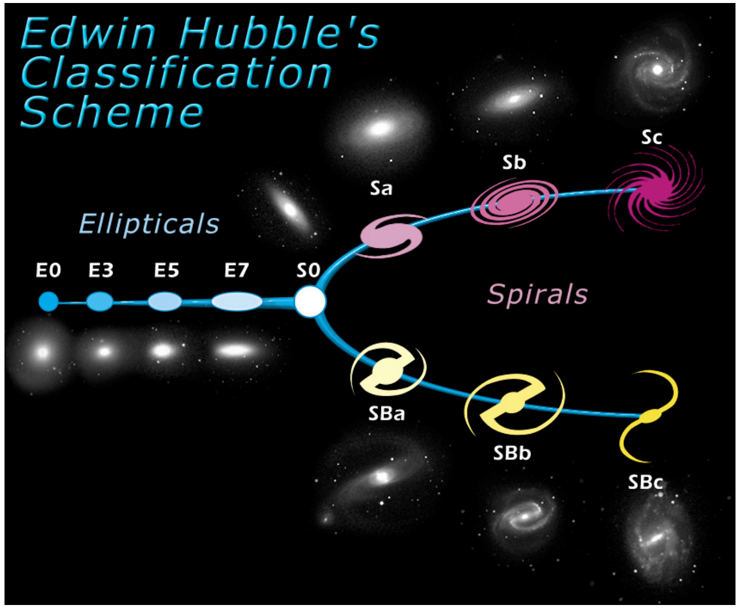
a galaxy zoo.



PHYS2160 – Lecture 6 – Galaxy Types

Hubble's galaxy classification scheme

Edwin Hubble pioneered the classification of galaxies, recognising a shape sequence into which galaxies fell.



There are two basic types of "regular" galaxies

- Spirals (~70% of all galaxies)
  - Barred (Sba – SBc)
  - Unbarred (Sa – Sc)
- Ellipticals (~20%) (E0-E7)

Plus

- Irregulars, which don't fit onto this "tuning fork" diagram

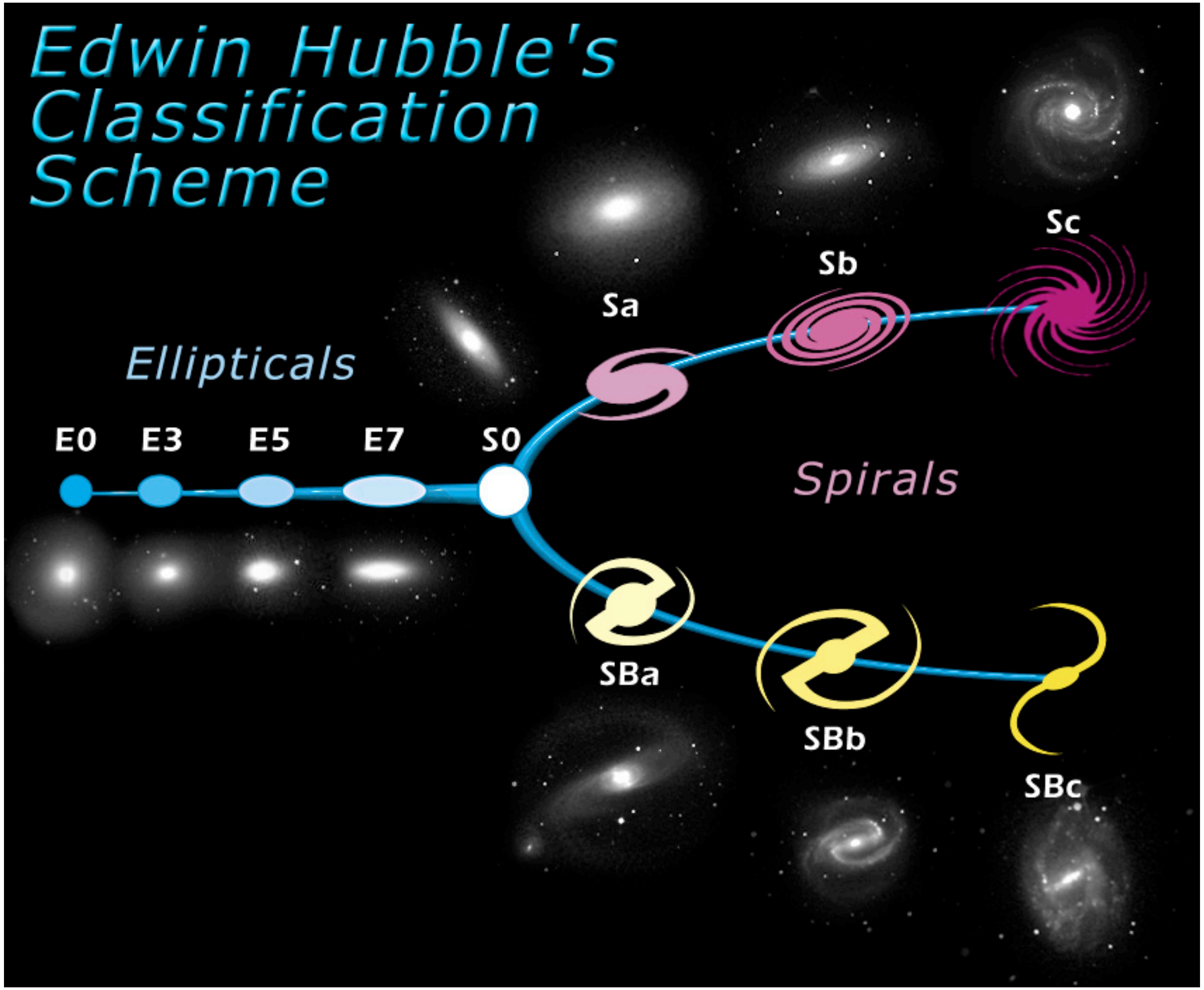
"Regular" galaxies can be thought of a being composed of two components – a central "bulge"/spheroid component, and a flat disk (containing spiral arms). Galaxies can be purely one or the other, or a combination.

Ellipticals ≡ purely bulge systems

Spirals ≡ disk systems with or without a bulge (called spirals because of the ubiquitous spiral patterns in their disk)

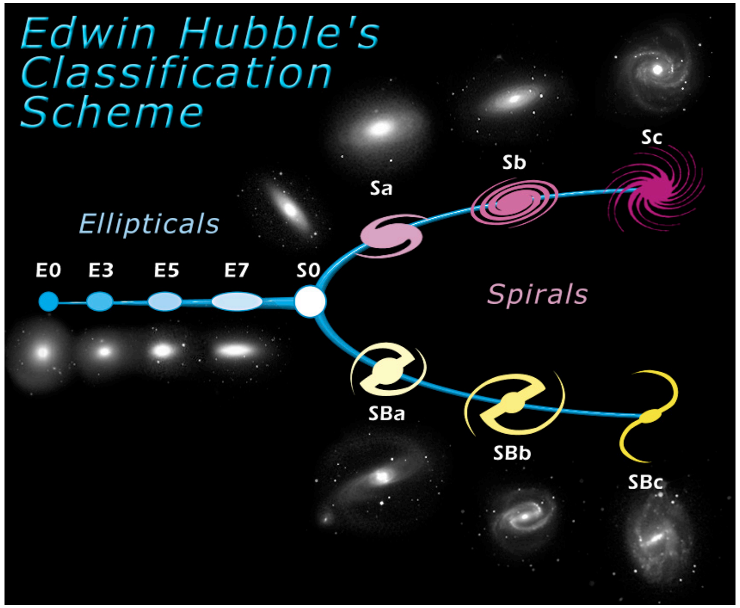
Another way to look at this is as a ratio of the random to rotational velocities. Random velocities lead to elliptical galaxy-like systems, while rotational velocities lead to disk systems.

PHYS2160 – Lecture 6 – Galaxy Types



http://skyserver.sdss.org/dr1/en/proj/advanced/galaxies/tuningfork.asp

PHYS2160 – Lecture 6 – Galaxy Types - Ellipticals

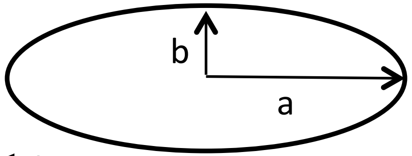


Hubble's galaxy classification scheme

Elliptical galaxies are featureless and elliptical in shape, and display a monotonic decrease in brightness away from their centre.

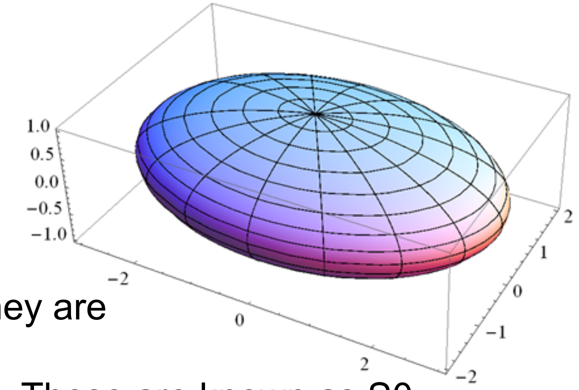
Classified by Hubble as En ($0 \leq n \leq 7$) where n parametrises axial ratio

$$n = 10\times(a-b)/a$$



Projection will cause $n_{observed} < n_{true}$.

It turns out this historical scheme (though still widely used) is not perfect as many elliptical galaxies are now known to be triaxial. That is they are not oblate spheroids (i.e. spheres flattened along just one axis), but are actually flattened along more than one axis!

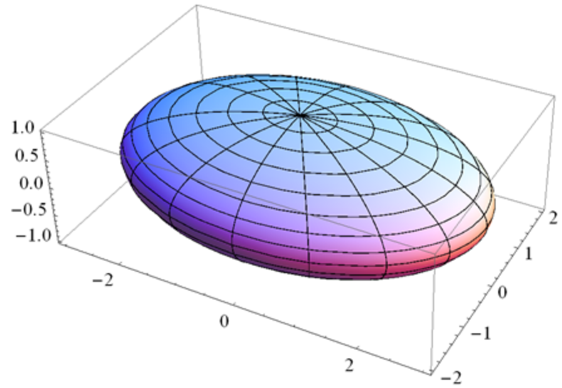


S0 or Lenticular Galaxies – No elliptical galaxies are seen with $n > 7$. They are unstable at such high levels of flattening. More flattened systems *are* seen, but they have a central condensation and a disk without spiral arms. These are known as S0 galaxies and are a transition class from Ellipticals ➝ Spirals. (Barred S0s also exist and are known as SB0)

PHYS2160 – Lecture 6 – Galaxy Types - Ellipticals

Triaxiality

Can be observed in multiple ways – but most notably by *isophotal rotation*.

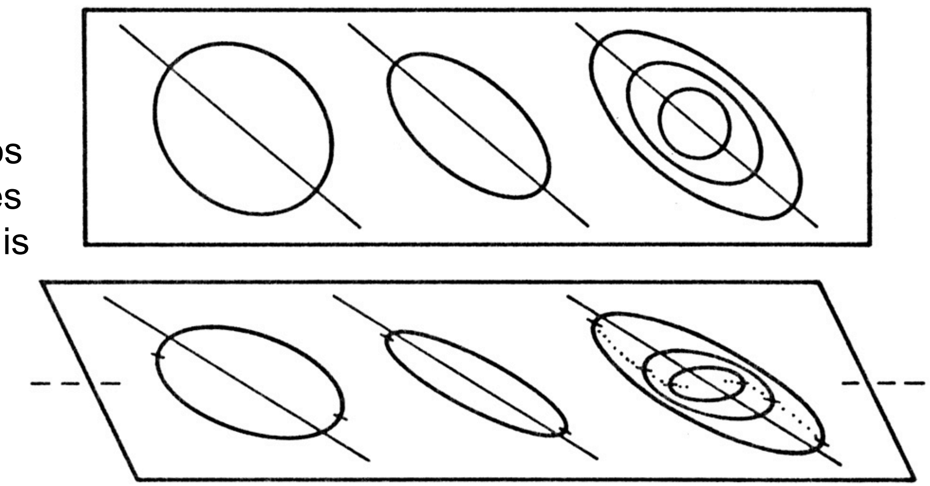


Light distribution for elliptical galaxies can be quite well modelled via a De Vaucoleurs law (where r is the distance from the galaxy centre, and L0 and r0 are fitting parameters)

$$L(r) = L(0) \exp[-(r/r_0)^{1/4}]$$

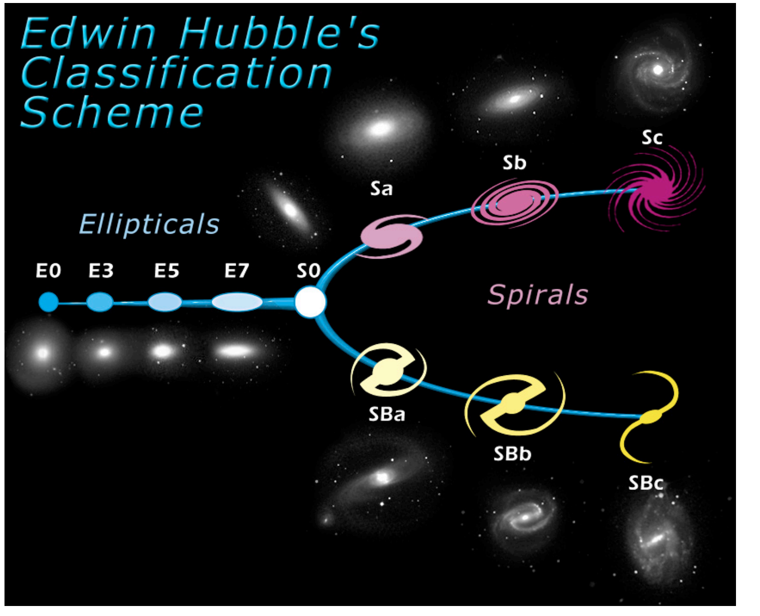
This can be generalised to an elliptical, rather than spherical distribution. If the galaxy is an oblate spheroid, then different isophotes (i.e. contours of equal brightness) will project onto the sky as ellipses with their axes aligned.

If the galaxy is *triaxial*, then the isophotes will be aligned in reality, but will have different axial ratios as a function of brightness. When these isophotes are projected at an angle onto the sky, the result is an apparent twisting of the isophotes.



(For more on this see the detailed explanation at
http://ned.ipac.caltech.edu/level5/March02/Kormendy/Kormendy3_3.html#3.3.1)

PHYS2160 – Lecture 6 – Galaxy Types – Spirals



Hubble's galaxy classification scheme

Spiral galaxies are classified in a morphological sequence Sa to Sc and Sba to SBc. The "B" distinguishes barred from non-barred galaxies. In barred galaxies, the nucleus appears to be extended, with the spiral arms extending from the end of the bar.

The a-c sequence corresponds to decreasing tightness of the spiral winding. This tightness of the winding is seen to correlate closely with the size of the galaxy bulge.

Sa and Sba galaxies have large central bulges, while Sc and SBc galaxies have small (or no) bulge.

More detailed observations have since led to the additional classifications (and complexity), including Sd/SBd types, and the realisation that some galaxies have small central bars (as our own does) making the B a less distinctive feature than a simple "on/off" classification. **S0 or Lenticular galaxies are** an additional type that resemble spiral galaxies (i.e. they are highly flattened and appear to rotate) but have no spiral arms.

One can create an empirical light distribution for a spiral (by averaging in circles to remove the spiral structure) which reveals a radial fall-off much steeper than for an elliptical (and consistent with the exponential scale length observed in our own Galaxy)

$$L(r) = L(0) \exp[-(r/r_0)]$$

PHYS2160 – Lecture 6 – Galaxy Types – Spirals

Measuring Velocities

In addition to measuring brightness distributions, spectroscopy of galaxies can provide information on their structure.

How spectrographs work – instead of taking a 2-D image of the sky, we stop the sky down to a 1-D slit, then disperse the image by wavelength in the direction perpendicular to the slit.

The result is an image with spatial information in one direction and spectral information in another

In Spiral galaxies - the *velocities* of absorption or emission lines tell us about the velocity curve of the galaxy.

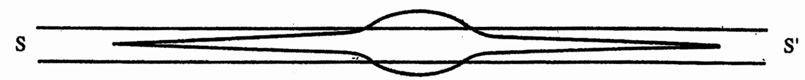


Figure 43. The measurement of a galactic rotation curve. The image of the major axis of the galaxy is aligned along the spectrograph slit SS'.

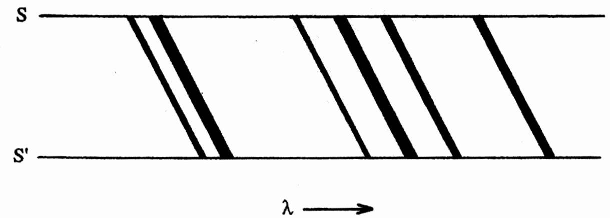


Figure 44. The spectrum of a uniformly rotating galaxy.

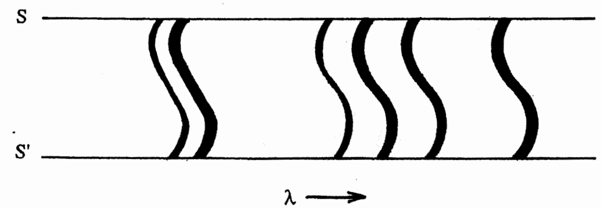


Figure 45. The spectrum of a differentially rotating galaxy.

PHYS2160 – Lecture 6 – Galaxy Types – Spirals

Measuring Velocities

An actual 2-D image from a spectrograph (rotated by 90deg from the schematic on the previous page) … we can see

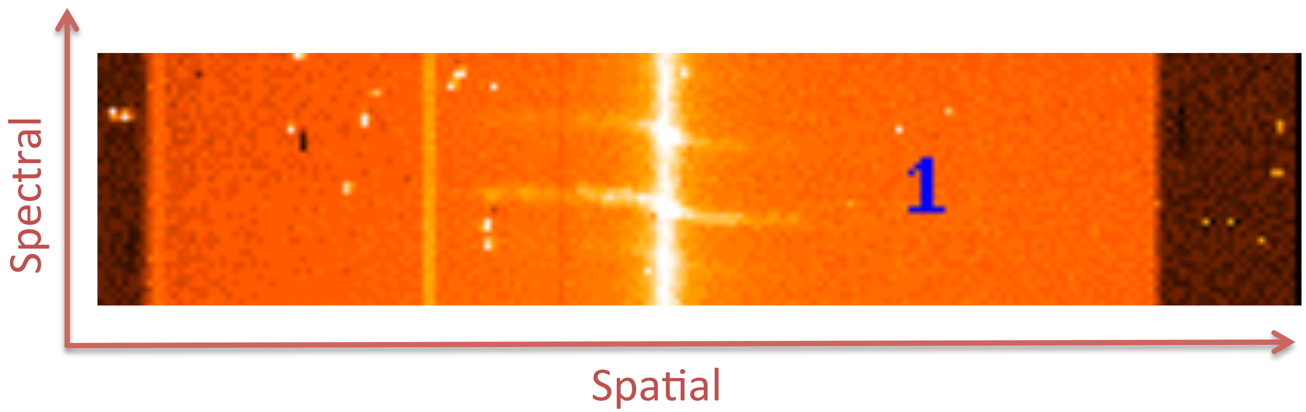
1 – emission lines from the galaxy itself. Note how their position shifts in wavelength as a function of spatial position along the slit. This tells us the rotation curve! And in this example we can see the curve is flat at large galactic radii!

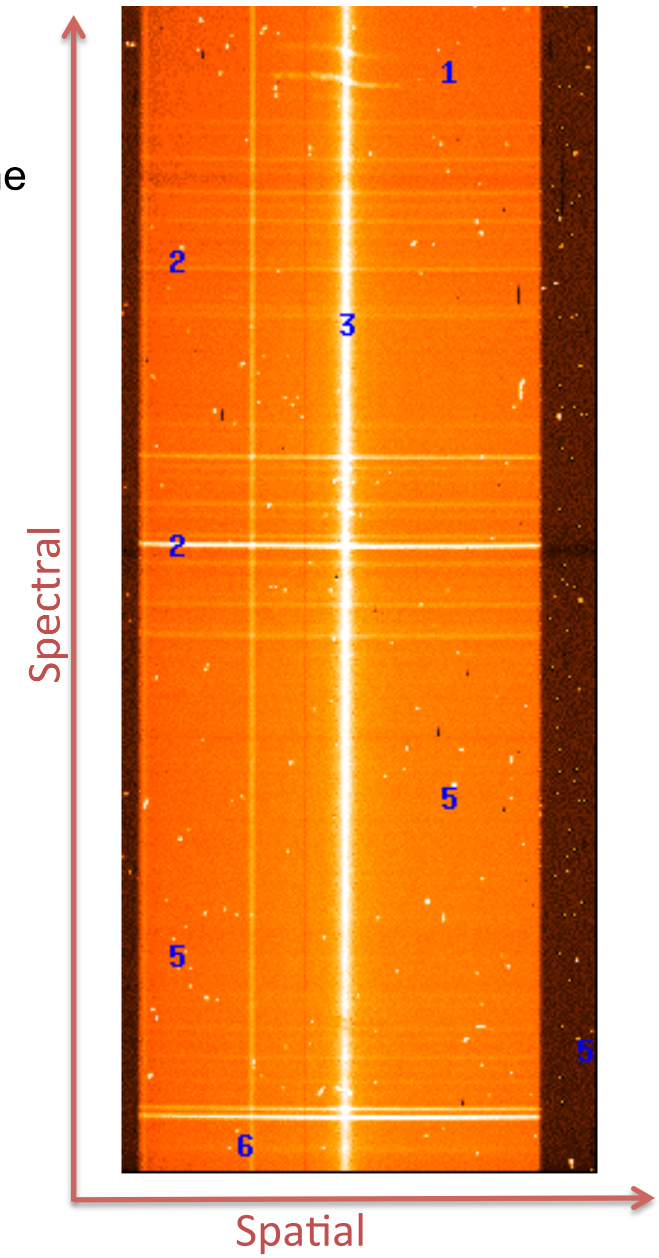
2 – night sky emission lines from the terrestrial atmosphere.

3 – bright light from the galaxy core

5 – bright spots due to cosmic rays collected by the CCD.

6 – there is a star near the galaxy that happens to have fallen on the slit as well.





PHYS2160 – Lecture 6 – Galaxy Types - Ellipticals

Measuring Velocities

In Elliptical galaxies – because there is no net rotation, we do not see a single velocity as a function of radial position. And we don't tend to see emission lines. But we do see the Integrated absorption lines of all the stars along ech line of sight through the galaxy.

The *widths* of these absorption lines, tell us about the velocity structure (and in particular the velocity dispersion) along lines of sight through the galaxy.

This in turn provides information on the total mass of the galaxy.

The combination of line widths and velocity structure driven by rotation can tell you about the relative contributions of the bulge/spheroid and the disk in the galaxy.

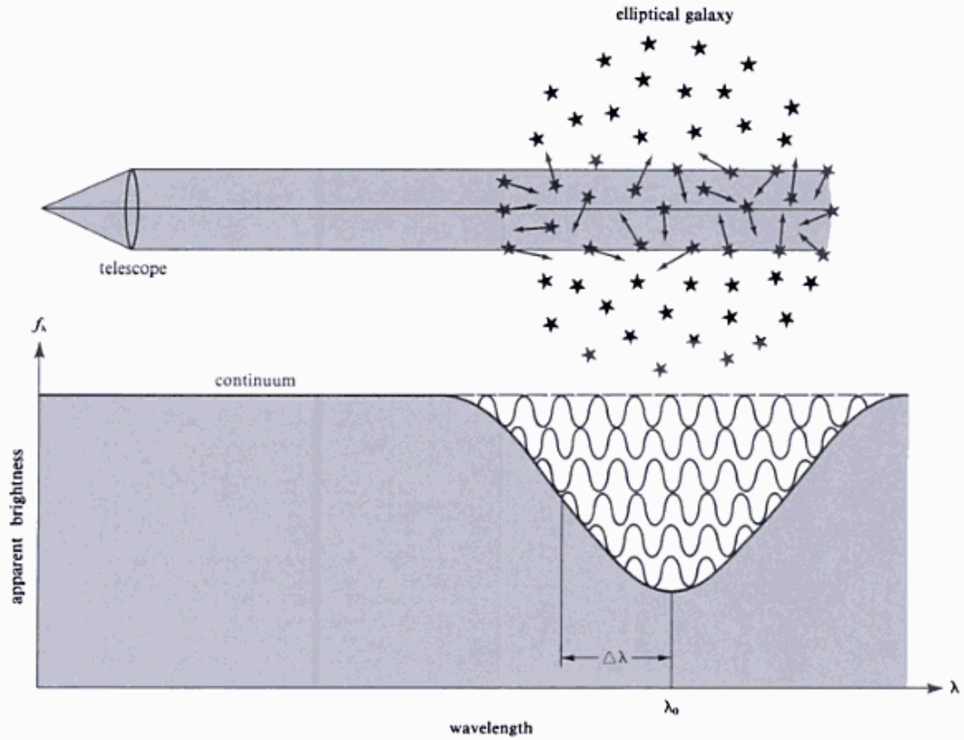
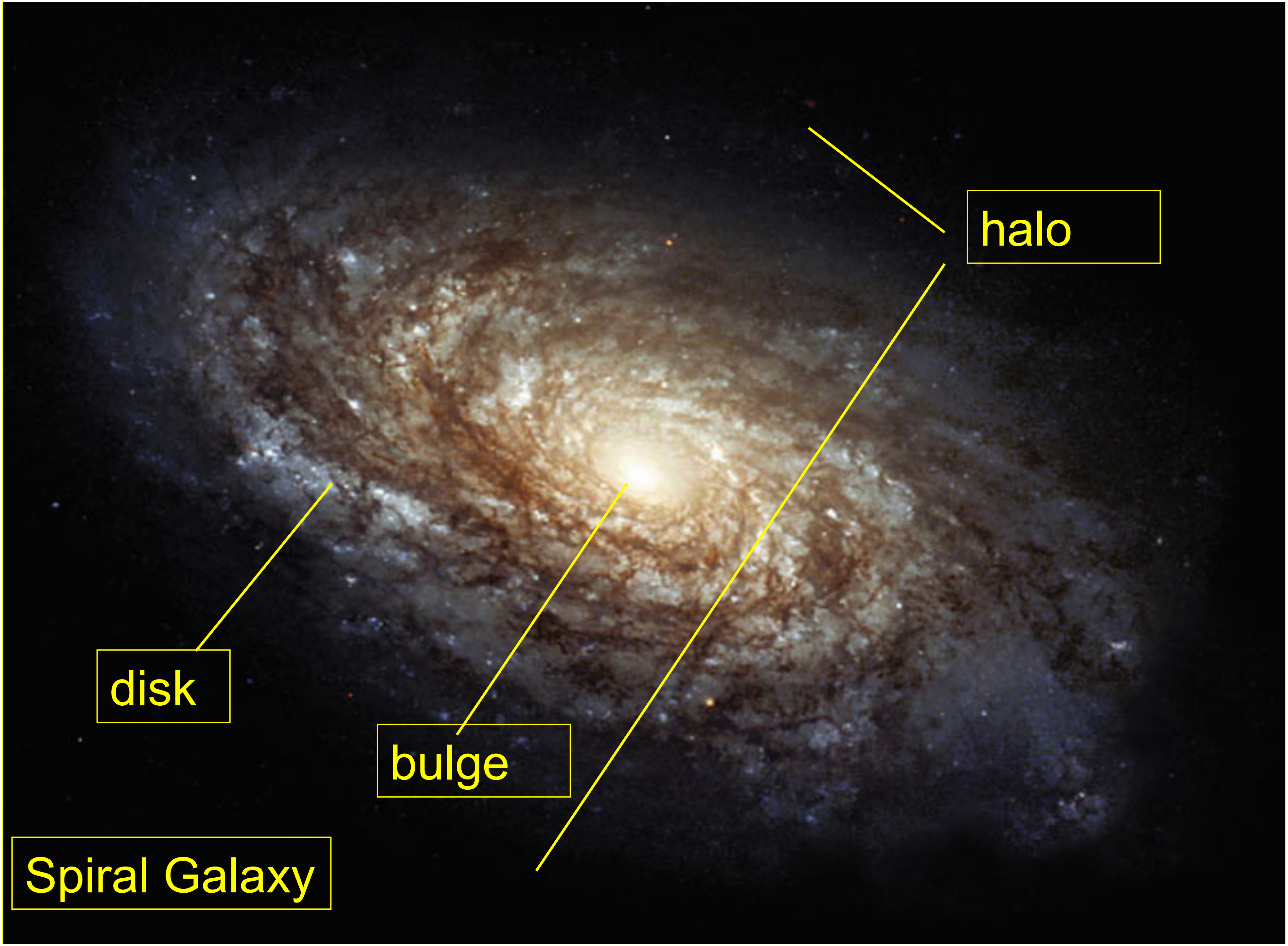


Figure 13.14. The broadening of a spectral line by the velocity dispersion of stars in an elliptical galaxy. In the top diagram, a telescope collects light from all stars within a cylinder through galaxy. Each star may possess a narrow spectral line at the rest wavelength λ_0, Doppler-shifted to a different wavelength λ because of its component of velocity along the line of sight. The superposition of billions of such line profiles produces the broadened spectral line seen in the bottom diagram, in which the line width $\Delta\lambda$ is proportional to the velocity dispersion V of the stars in the galaxy.

Physical Universe, Shu, Fig 13.14


halo
disk
bulge
Spiral Galaxy

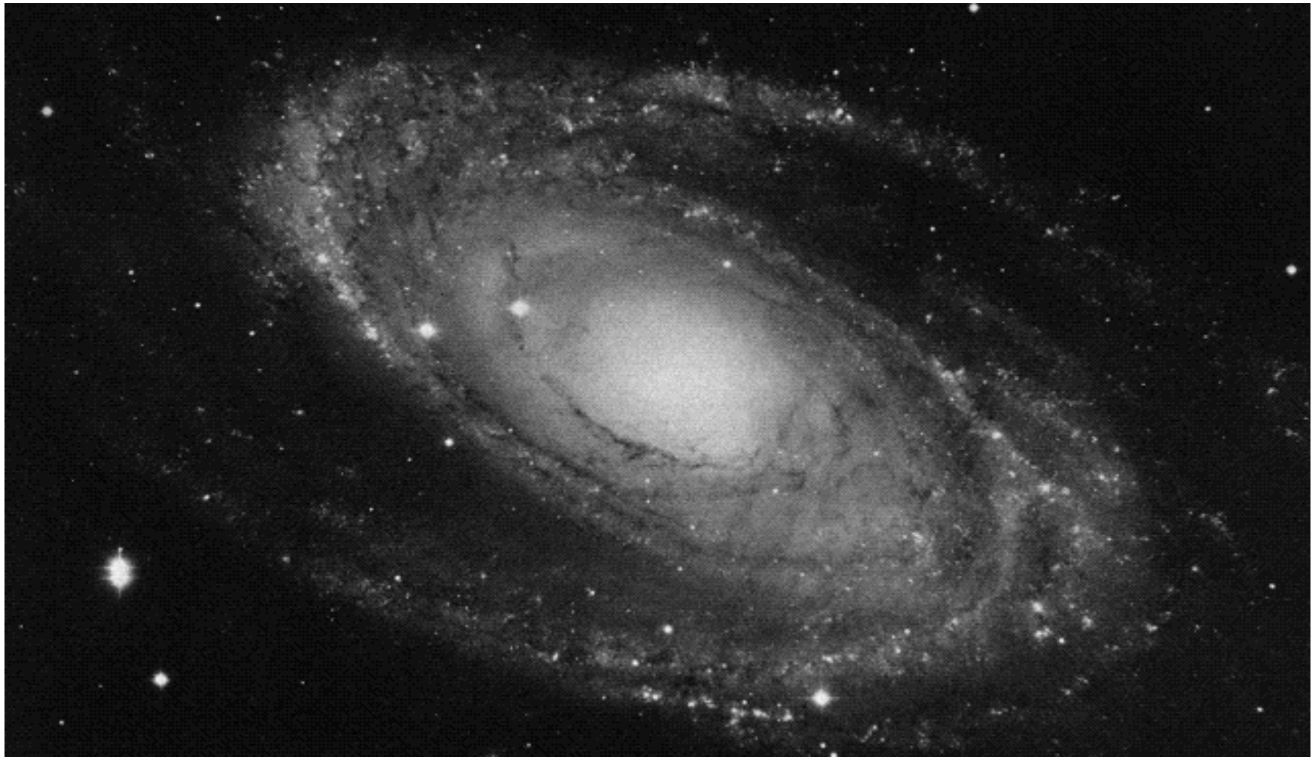
Disk Component:
stars of all ages,
many gas clouds

Type *Sa* Galaxy

Spheroidal Component:
bulge & halo, old stars,
few gas clouds

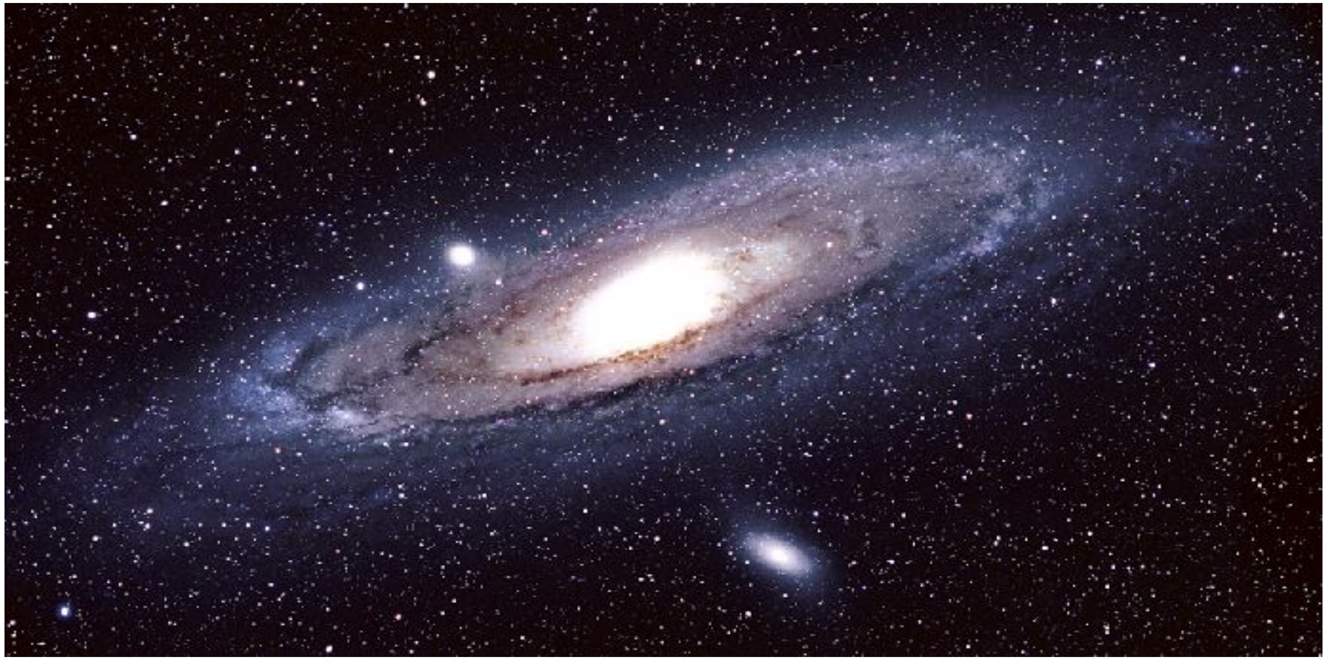
Sa Galaxies:

- Dominant nuclear bulge
- Tightly wound spiral pattern
- Few (but some) newly formed stars, HII regions or other evidence of active star formation



Sb Galaxies

• Moderate nuclear bulge
• Intermediate spiral pattern
• Some evidence for massive young stars, HII regions, star formation



Type *Sc* Galaxy

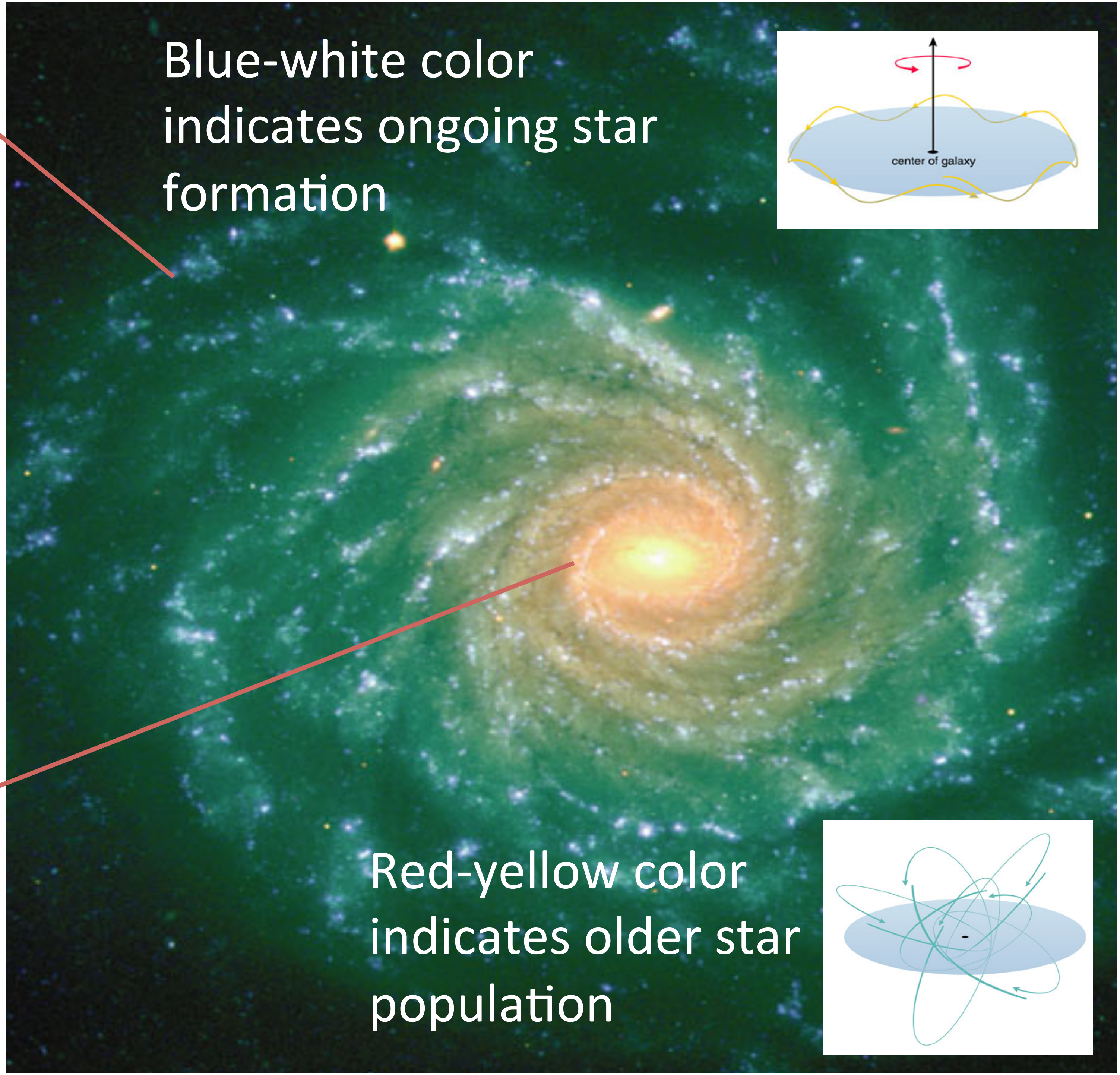
Sc Galaxies

(Some classify Messier as as Type Sd)

- Small to nearly non-existent nuclear bulge
- Open spiral pattern
- Active star-formation

Disk Component:
stars of all ages,
many gas clouds

Spheroidal Component:
bulge & halo,
old stars,
few gas clouds

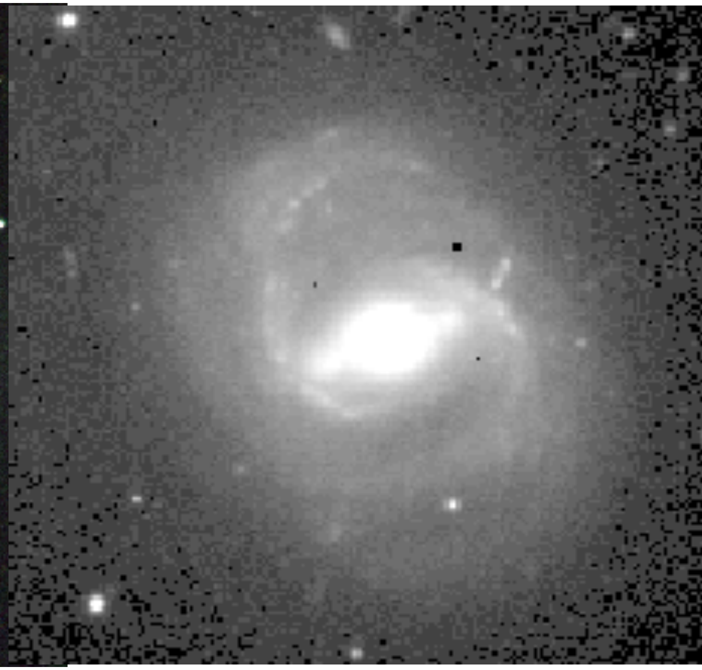


Barred Spiral Galaxy

Has a **bar** of stars across the bulge

Barred Spiral Types

SBa



SBb

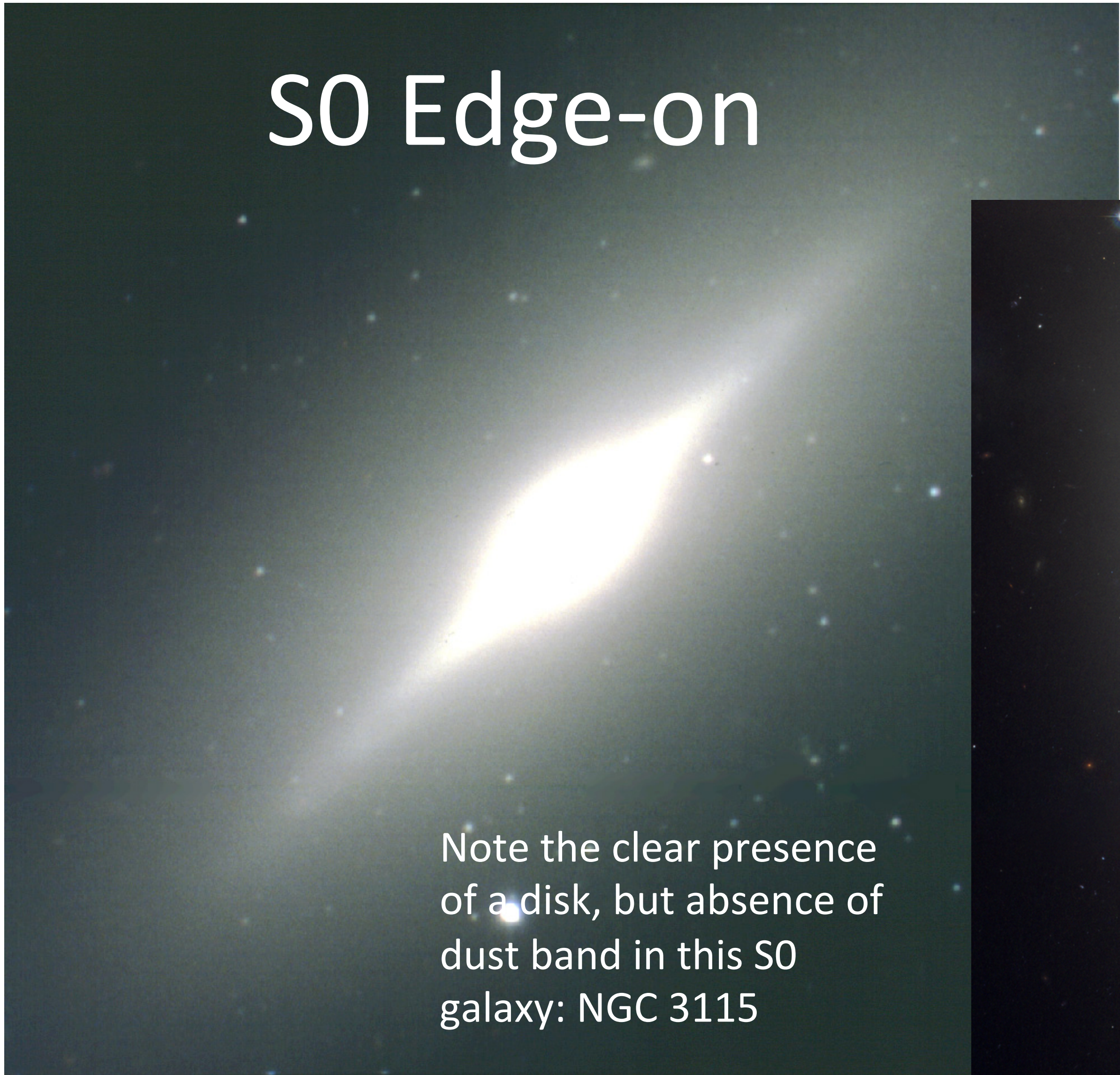
SBc

S0 Lenticular Galaxy

Has a disk like a spiral galaxy but essentially no gas and no active star formation (though it may retain dust)

They are intermediate between spiral and elliptical)

S0 Edge-on

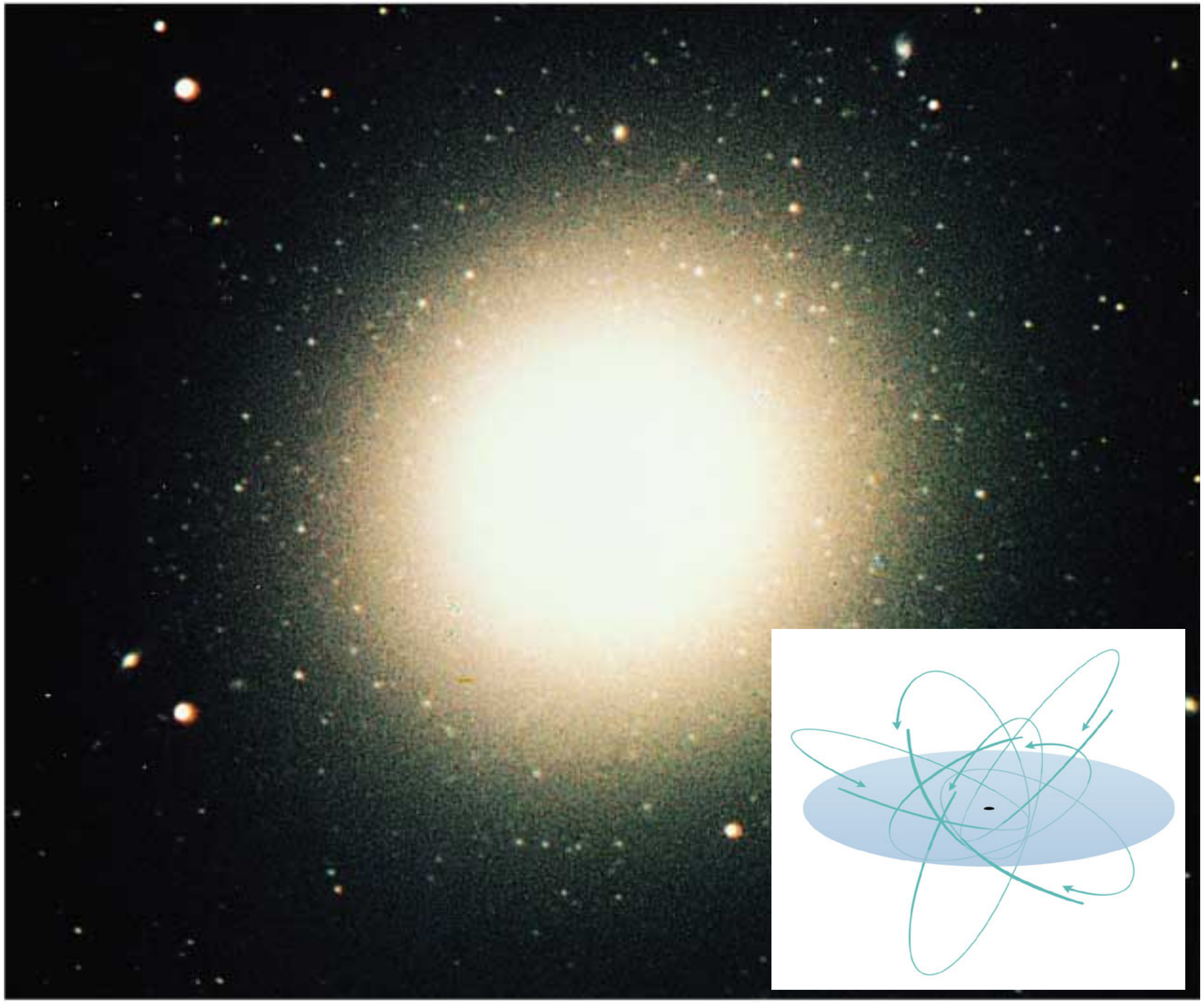


Note the clear presence of a disk, but absence of dust band in this S0 galaxy: NGC 3115

NGC 5866 is an S0 in Draco which does retain dust.

Elliptical Galaxy:

All spheroidal (aka “bulge”) component, no disk



Elliptical Galaxy:
All spheroidal component, virtually no disk component

Red-yellow color indicates older star population

Irregular Galaxies

Irregular I Galaxy

Blue-white color indicates ongoing star formation

PHYS2160 – Lecture 6 – Galaxy Types – Spirals

Density Waves and Spiral Structure

How do spiral galaxies form (and maintain) their spiral structure?

The differential rotation we know exists in the Galaxy tells us that the angular velocity near the Galaxy centre is much greater than near the edges. This in turn means that the outer regions will undergo many fewer rotations in a given period of time than the inner regions. Imagine a structure was imprinted at start time on the stars and gas. It would then get "wound up" as the disk rotated (remember rotation period at solar radius is ~200kyr). There would be **many** "windings-up" during just a 2Gyr period, and many more over the ~10^{10} yr lifetime of the galaxy.

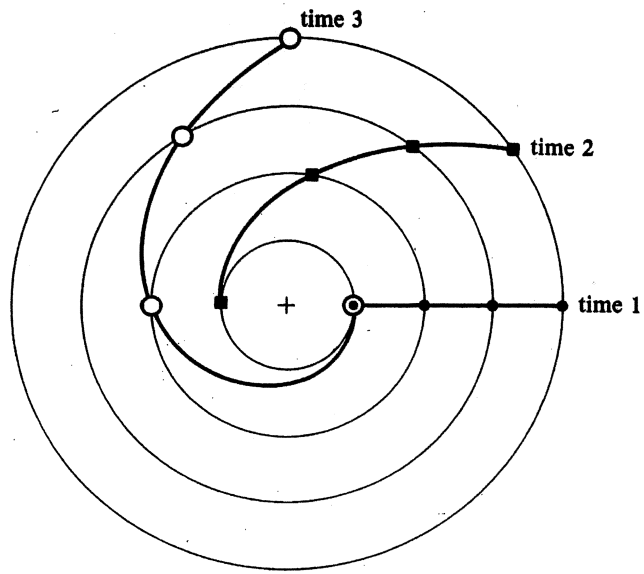


Figure 12.24. The winding dilemma associated with thinking of spiral arms as material alignments in a field of differential rotation. By the time ($\sim 10^8$ yr) the innermost gas cloud has completed one circle of rotation, an originally straight arm would have added almost a complete turn. Since spiral galaxies are likely to be 10^{10} years old, this picture cannot account for the observed spiral structures.

Shu, Chapter 12

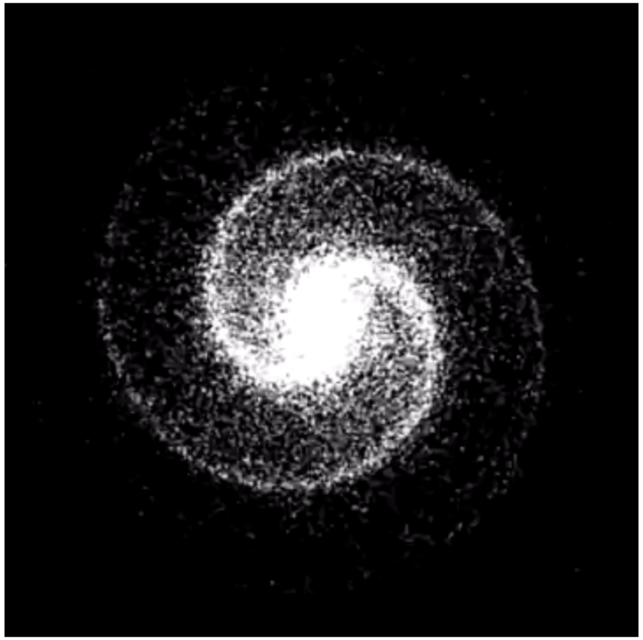
Spiral arms cannot be structures that contain the same material over a galactic lifetime. The spiral arms must propagate through the disk, like waves.

Galaxy rotation

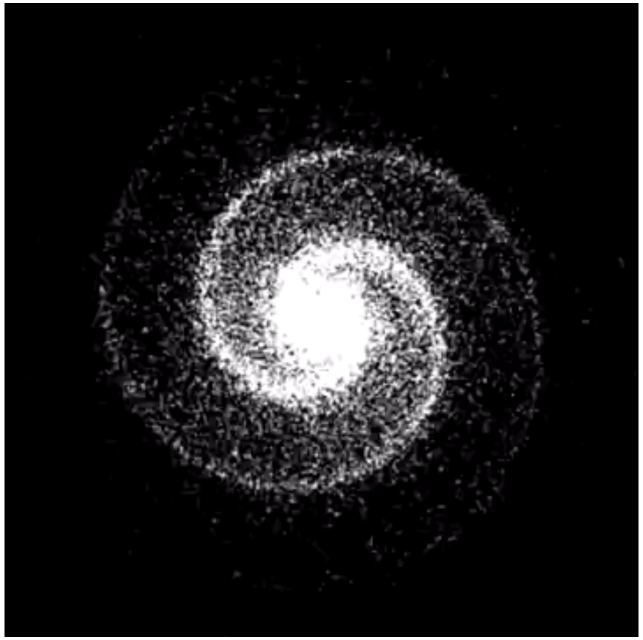
- Movies on winding and density waves …
  - http://commons.wikimedia.org/wiki/File:Galaxy_rotation_rigid.ogv
  - http://commons.wikimedia.org/wiki/File:Galaxy_rotation_wind.ogv
  - http://commons.wikimedia.org/wiki/File:Galaxy_rotation_wave.ogv

    Sourced from Wikimedia Commons

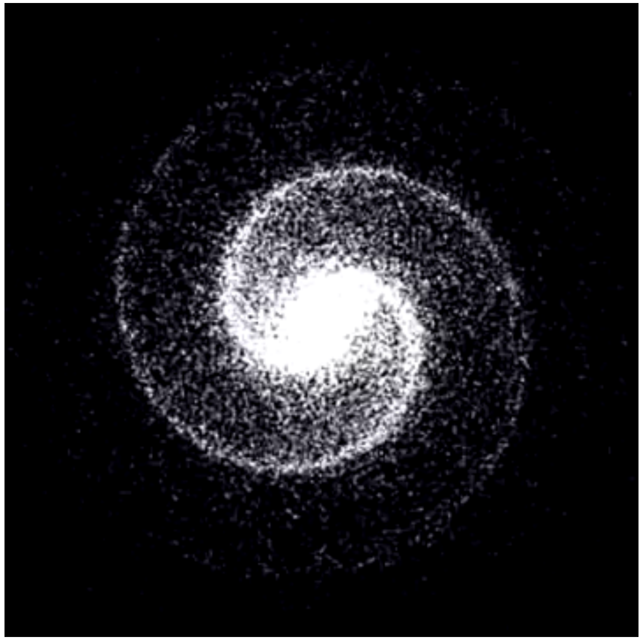
Solid-Body Rotation



Arms Locked to Stars



Density Wave



PHYS2160 – Lecture 6 – Galaxy Types – Spirals

Density Waves and Spiral Structure

How else do we know that spiral structures are a wave?

1. Massive young main sequence stars are mainly found in spiral galaxies in the spiral arms, suggesting that the spiral arms are where recent star formation is taking place (because massive stars have short main-sequence lifetimes). We also know that both massive and low-mass stars tend to get formed in the same way and in the same regions.
2. The fact we find massive main sequence stars largely confined to spiral arms (or just behind the arms), but lower mass stars spread more evenly throughout the disk, suggests that the spiral arms are "triggering" star formation.

Frank Shu and C.C. Lin proposed in 1963 that spiral arms are a "density wave" in the gas of a galactic disk.

(A traffic jam on a freeway may be a helpful analogy – the cars that approach it slow down, then speed up after leaving the jam, such that the 'jam' propagates even while cars flow through it).

The speed of such a density wave can be very different from the material speed (i.e. the speed of the jam is very different from the speed of the cars).

PHYS2160 – Lecture 6 – Galaxy Types – Spirals

Density Waves and Spiral Structure

This wave can be parameterised … imagine the disk is composed of gas that is not perfectly axisymmetric. This will result in a gravitational potential that is also not perfectly axisymmetric.

A particle rotating in the disk will feel a *periodic* perturbing force (F_1 in the figure to the right), and this periodicity will distort the circular orbits into ovals. If we model perturbation as periodic (using with a cosine as a function of azimuthal angle φ and a mode number m) we can write the force as

$$F_1 = A(r) \cos (m\varphi)$$

At any one radius we get a flattened oval (b), and if the amplitude A(r)=constant, we get a series of aligned flattened ovals (c). However if the force changes with radial direction then the phase of the disruptive force will change with radius, and you get a series of tilted ovals (d). These cause materials to "pile up" in a spiral pattern. Once this perturbing potential has been created it can then persist.

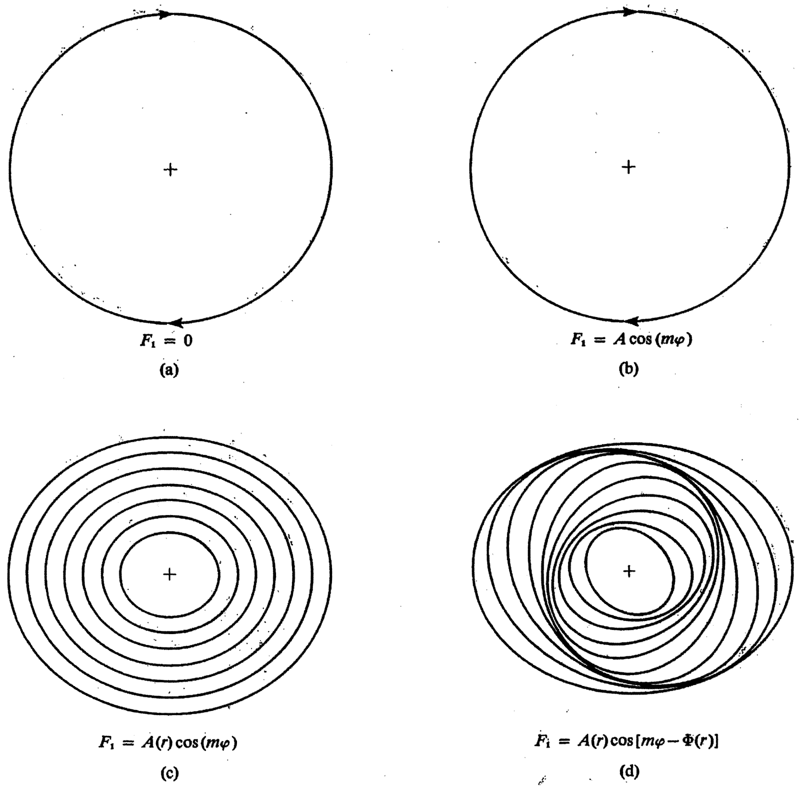


Figure 12.25. The response of the mean motions of stars or gas clouds to the presence of a nonaxisymmetric gravitational force field F_1. The perturbational force F_1 is assumed periodic in time and angle, with radian frequency ω and angular mode number m, in an inertial frame of reference. Viewed in a frame which rotates at angular speed $\Omega_p = \omega/m$, the same force field is m-times periodic in the angle $\varphi = \theta - \Omega_p t$. Each time a star goes once around in this frame, it is pulled outward m times, causing its orbit to have m bumps. Here, $m = 2$.

PHYS2160 – Lecture 6 – Galaxy Types – Spirals

Density Waves and Spiral Structure

The Density Wave model for spiral structure explains a number of other observations that have been made about spiral galaxies.

As clouds of gas and dust enter into a density wave and are compressed, the rate of star formation increases as some clouds meet the criteria for gravitational instability, and collapse to form new stars.

Since star formation does not happen immediately, the stars are observed to form slightly behind the density waves. The hot OB stars that are created ionize the gas of the interstellar medium, and form HII regions.

These stars have relatively short lifetimes, however, and expire before fully leaving the density wave.

The smaller, redder stars do leave the wave, and become distributed throughout the galactic disk.

PHYS2160 – Lecture 6 – Galaxy Types – Spirals

- References
  - Hubble Ultra Deep Field – images available at many locations on web. Image used in class came from an ESA site - http://www.spacetelescope.org/images/heic0611b/
  - The Sloan Digital Sky Survey site has an excellent discussion of the characteristics and classification of galaxies, with many lovely images from their large survey of the Northern sky (http://skyserver.sdss.org/dr1/en/proj/advanced/galaxies/tuningfork.asp)
  - Movies used in class are from http://en.wikipedia.org/wiki/Density_wave_theory)
- Bibliography
  - Chapter 12 of Shu (he did invent the density wave theory after all!)

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	$=$	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	$=$	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	$=$	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	$=$	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	$=$	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	$=$	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	$=$	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	$=$	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	$=$	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	$=$	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	$=$	1.496	$\times$	10^{11}	m
Parsec	pc	$=$	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	$=$	$5\log d - 5 \quad (d \text{ in pc})$
Apparent magnitude	$m_2 - m_1$	$=$	$2.5\log\frac{f_1}{f_2}$
For small recession velocities	v/c	$=$	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$

PHYS2160 – Lecture 7 – Spirals and Dark Matter

Last time

- Galaxy Types
- The Hubble Galaxy Classification “Tuning Fork”
- Spiral Galaxies
- Density Waves

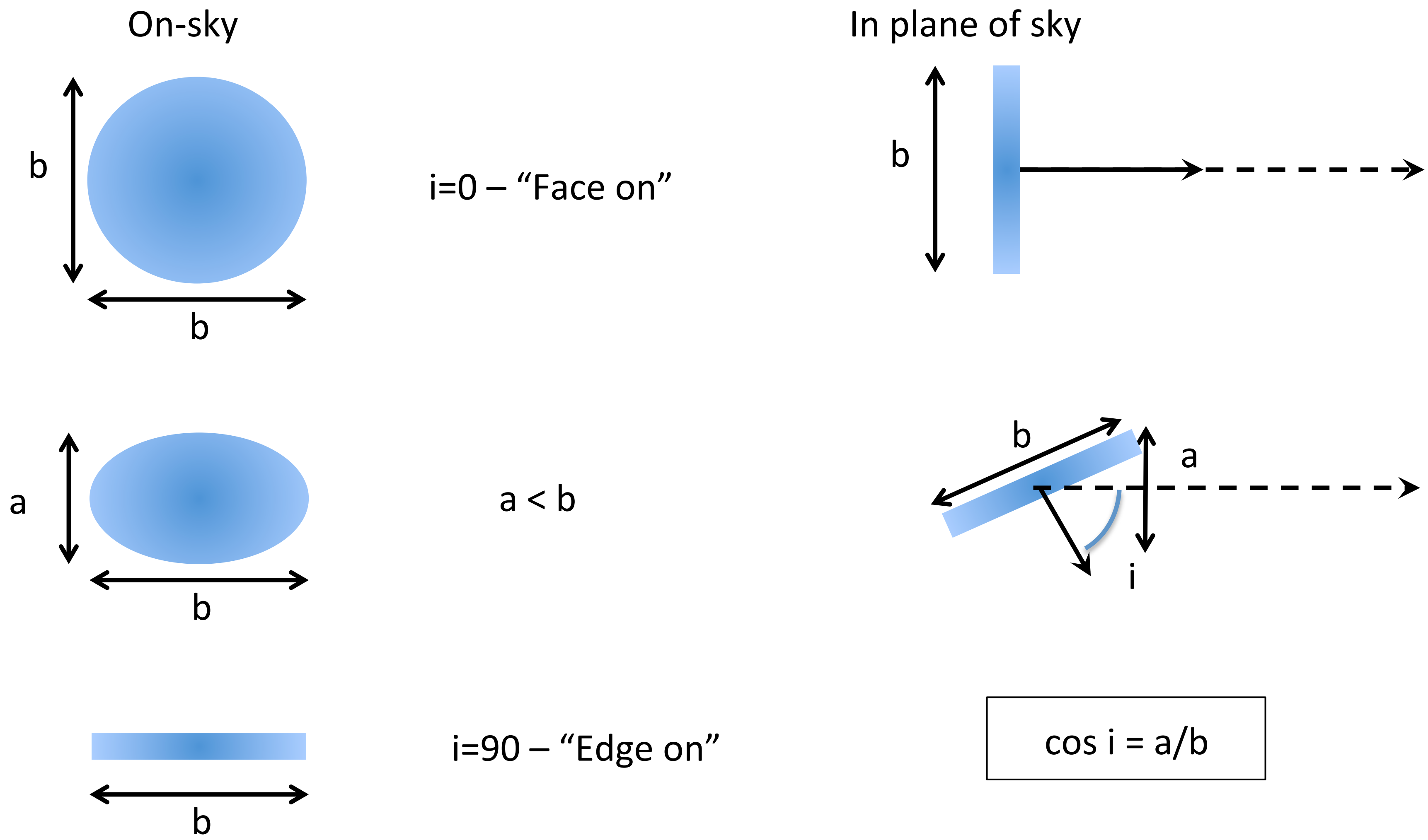
This Time

- Interpreting Spiral Galaxy Rotation curves – Inclination, Velocities, Masses
- Other evidence for dark matter in the Universe
- What is dark matter?

PHYS2160 – Lecture 7 – Spirals and Dark Matter

Spiral Galaxy Inclination Angles

For a rotationally supported disk, assuming the disk is circular is a good approximation



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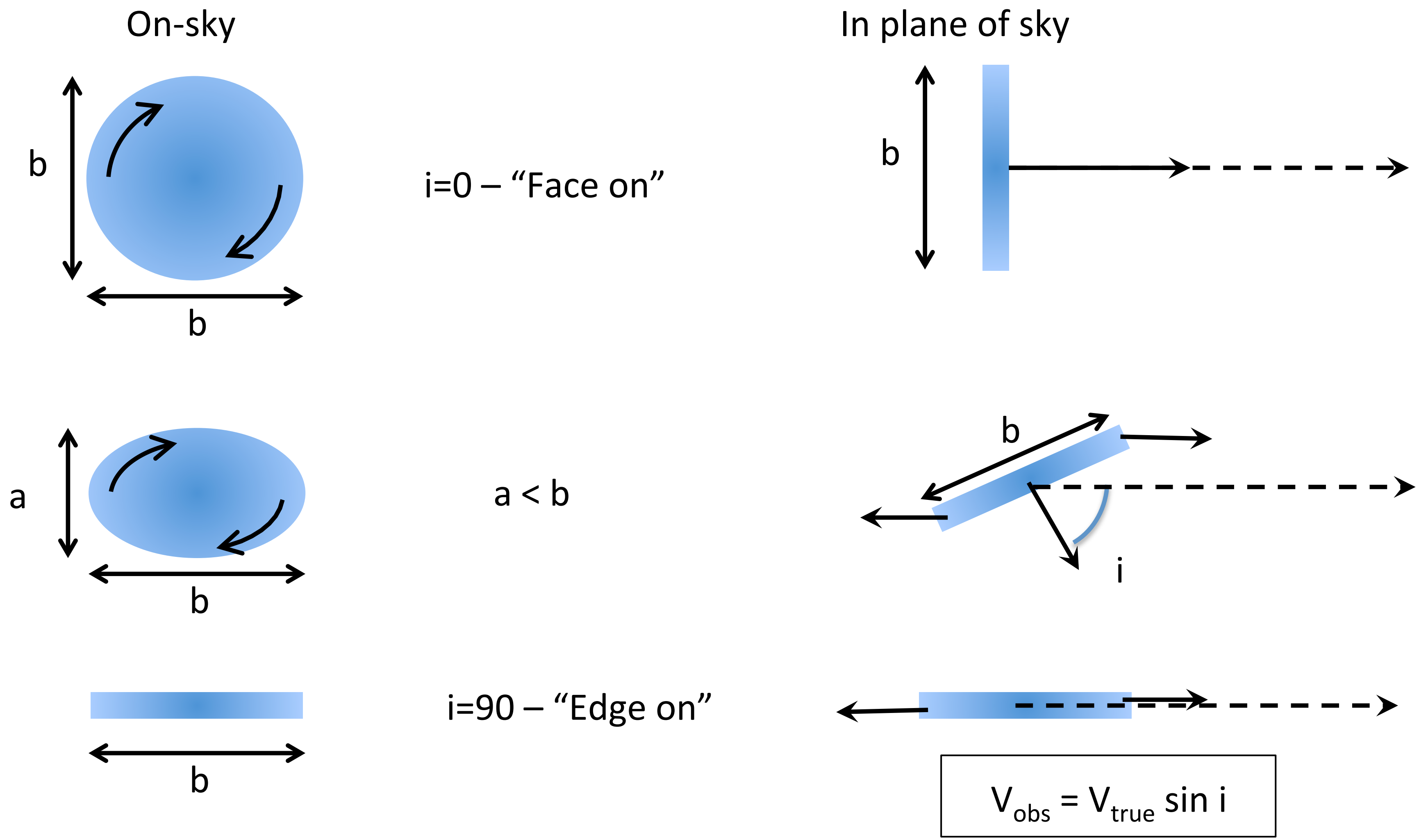
Spiral Galaxy Inclination Angles & Velocities

The observed velocities of a tilted galaxy will depend on the true velocities and the angle of inclination



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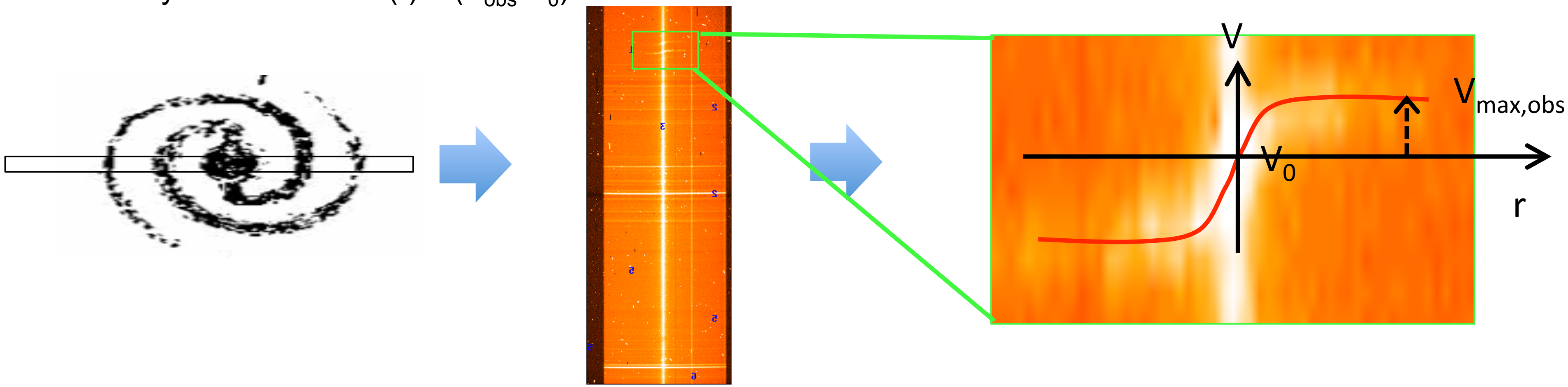
Interpreting Rotation Curves & Measuring Masses

Every galaxy will have a ‘central velocity’ associated with the galaxy (V_0) as a whole, which is then modified (as a function of position in the galaxy) to give the rotation curve V_{obs}. The galaxy’s true rotation velocity curve is then $V(r) = (V_{obs} - V_0) / \sin i$



Moreover, if we know the velocity at a given radius (e.g. the “maximum” velocity where the velocity curve flattens out [at that relevant radius in that galaxy]) we can estimate the mass contained within that radius for the galaxy (as discussed in Lecture 6) from the balance of the centripetal force seen by a particle with mass *m* on a circular orbit with radius *r*, with the gravitational force exerted by mass contained within that orbit

$$mV^2/r = GM_r m/r^2 \quad \text{or} \quad M_r = V^2 r/G$$

PHYS2160 – Lecture 7 – Spirals and Dark Matter

Evidence for Dark Matter

1. **Spiral Galaxy Rotation Curves** – as already noted most spiral galaxies (including our own) display flat rotation curves implying the existence of significant amounts of dark matter (e.g. Rubin & Ford, ApJ, 1980)

480 RUBIN, FORD, AND THONNARD Vol. 238

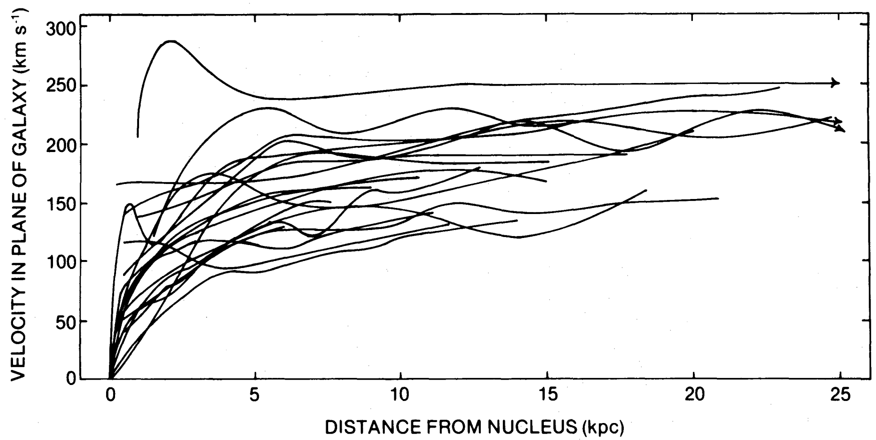


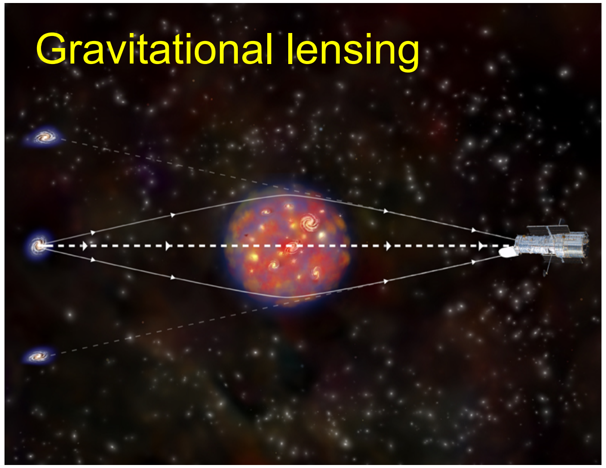
FIG. 6.—Superposition of all 21 Sc rotation curves. General form of rotation curves for small galaxies is similar to initial part of rotation curve for large galaxies, except that small galaxies often have shallower nuclear velocity gradient and tend to cover the low velocity range within the scatter at any *R*.

2. **Velocity Dispersions of Elliptical Galaxies** – measurement of the widths of spectral lines through elliptical galaxies indicate they must have significantly more mass than can be accounted for by their visible stars – around 5-10 times larger M/L_B (mass to luminosity in the B band) than the Sun (e.g. Faber & Jackson, ApJ, 1976)

PHYS2160 – Lecture 7 – Spirals and Dark Matter

Evidence for Dark Matter

3. **Galaxy Cluster Velocity Dispersions** – Galaxies are themselves often found clustered in massive units. Observations of velocity dispersions (but this time done for the individual galaxies in a cluster) show the dispersion of these galaxy velocities about the central velocity of the cluster imply the cluster must be at least 10 times larger than the visible matter.

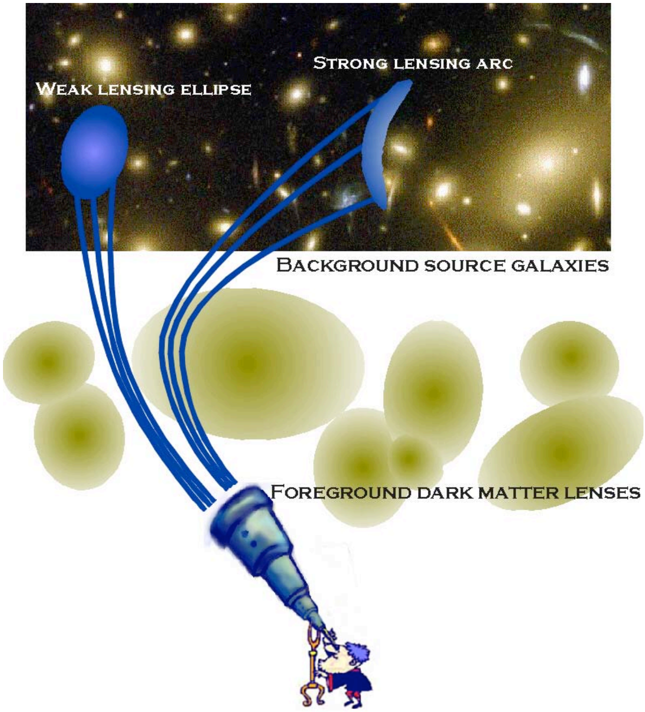


4. **Strong Gravitational Lensing by Clusters** - General relativity tells us that large masses can lens the light of background galaxies (as is seen in Abell 363 above). The geometry of the distortion of background galaxies by this “strong lensing” provides a mass estimate independent of the lensing cluster’s dynamics. In the dozens of cases where this has been done, the mass-to-light ratios obtained correspond to the dynamical dark matter measurements of clusters.

PHYS2160 – Lecture 7 – Spirals and Dark Matter

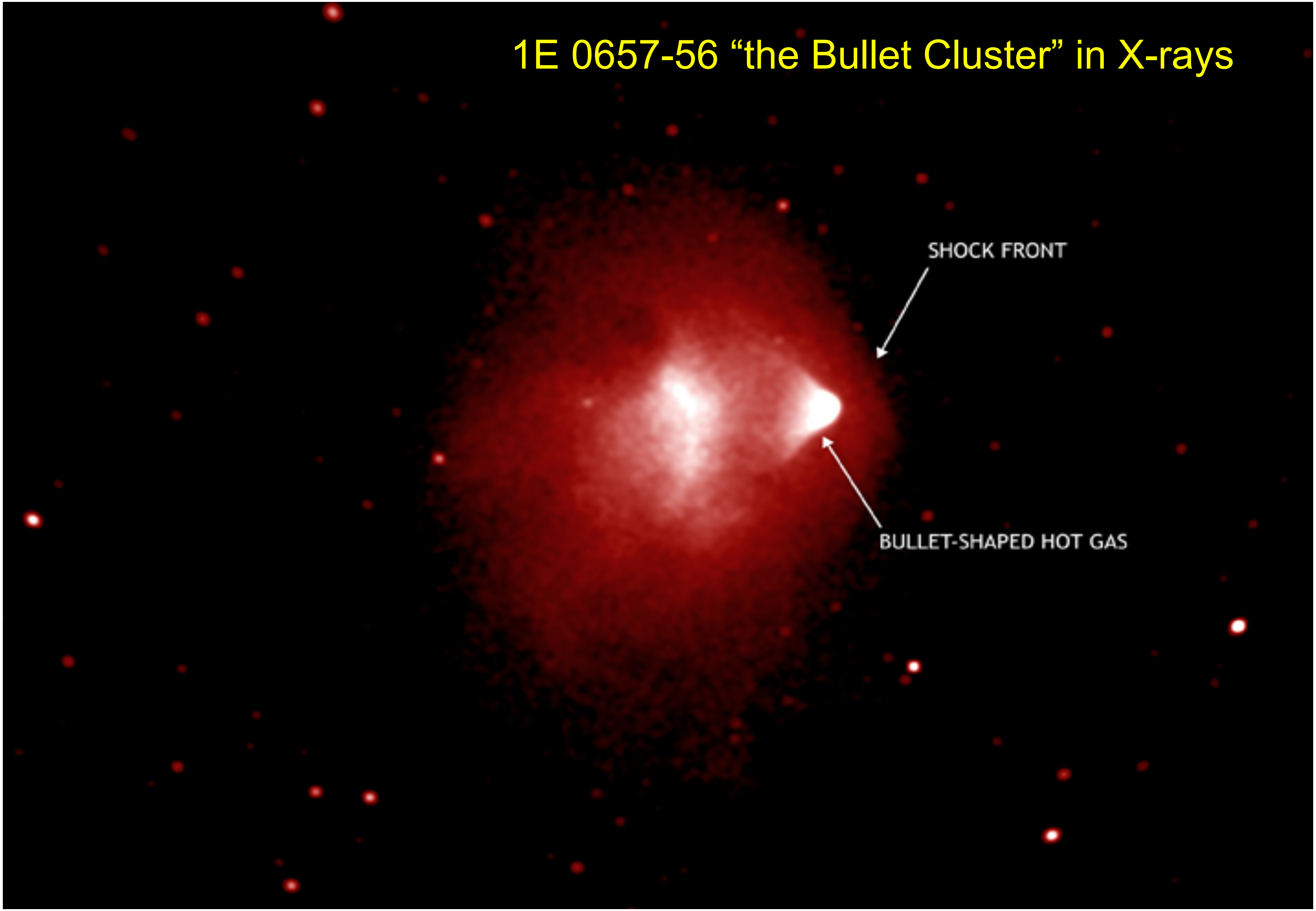
Evidence for Dark Matter

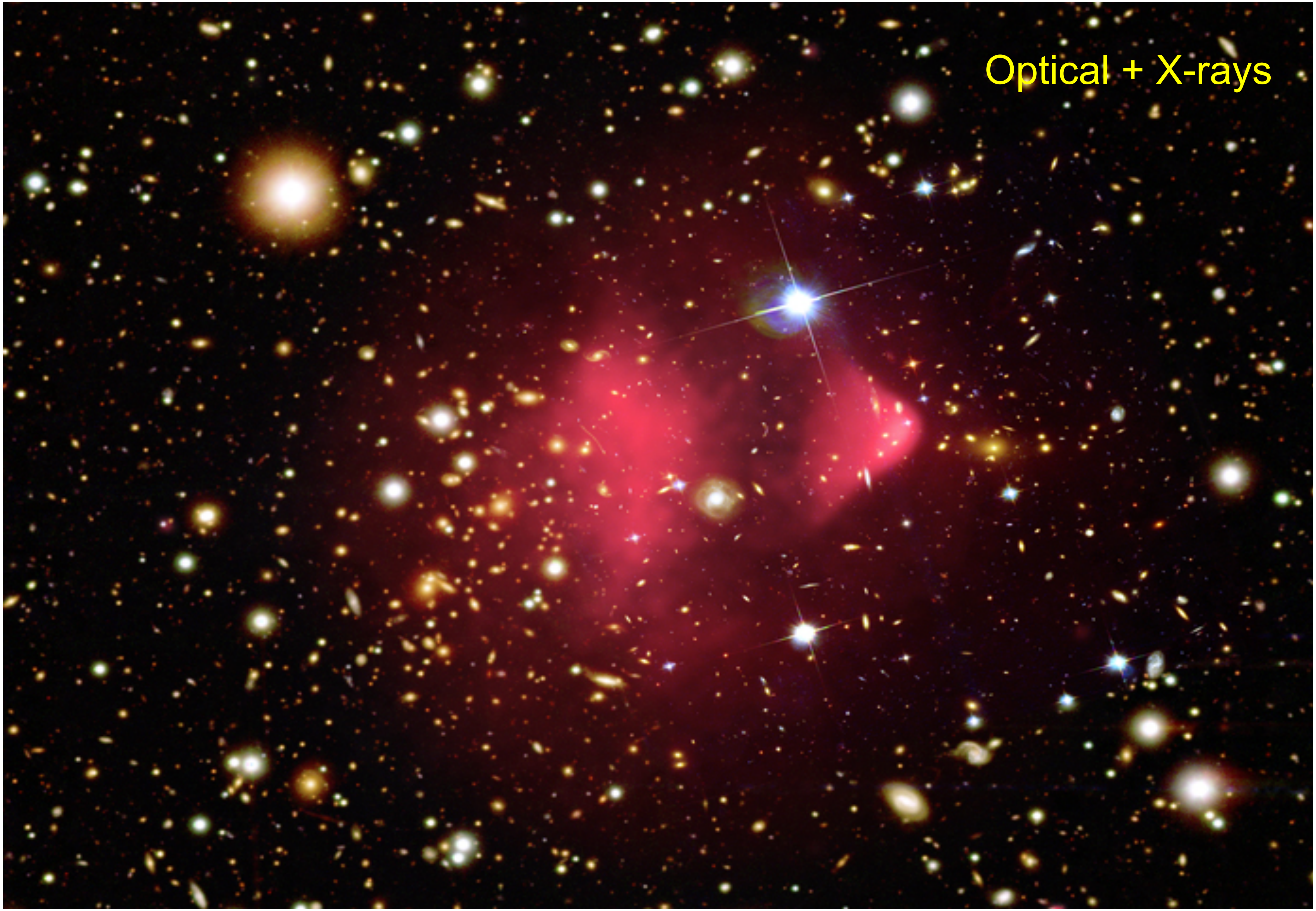
5. **X-ray Gas around Elliptical Galaxies and in clusters** – many elliptical galaxies have significant quantities of hot gas around them (seen in X-rays). Temperatures can be as high as kT_X=3keV, or T_X = 35000K . Hydrostatic equilibrium requires that significant mass must be required in the otherwise the gas would escape.
6. **Weak Gravitational Lensing by Clusters** – in addition to lensing so strong as to produces highly distorted arcs, the mass along a line of sight can also be inferred from small distortions to galaxy shapes known as weak lensing. Assuming the background galaxies will (in general) have randomly distributed elongations, and then looking at the actual distribution of elongations, measurements can be made of the "shear" produced by weak lensing.



Both techniques spectacularly combined
in the cluster 1E 0657-56 "the Bullet Cluster"


Optical – HST + Magellan


1E 0657-56 “the Bullet Cluster” in X-rays
SHOCK FRONT
BULLET-SHAPED HOT GAS


Optical + X-rays


Optical – HST + Magellan


Optical + “dynamical mass” from lensing

1E 0657-56 – The Bullet Cluster

- Pink clumps: hot gas (seen in X-rays) – shows most of the "normal", or baryonic matter in the cluster. The "bullet-shaped clump" shows where one cluster has passed through the hot gas from the other larger cluster during a collision.

- An optical image (Magellan and the HST) shows the galaxies in orange and white. The blue overlay in this image shows the gravitating mass in the clusters (estimated from the gravitational lensing). This is most of the mass.

- The hot gas in each cluster was slowed by a drag force (similar to air resistance) during the collision. In contrast, the dark matter was not slowed by the impact because it does not interact directly with itself or the gas except through gravity.

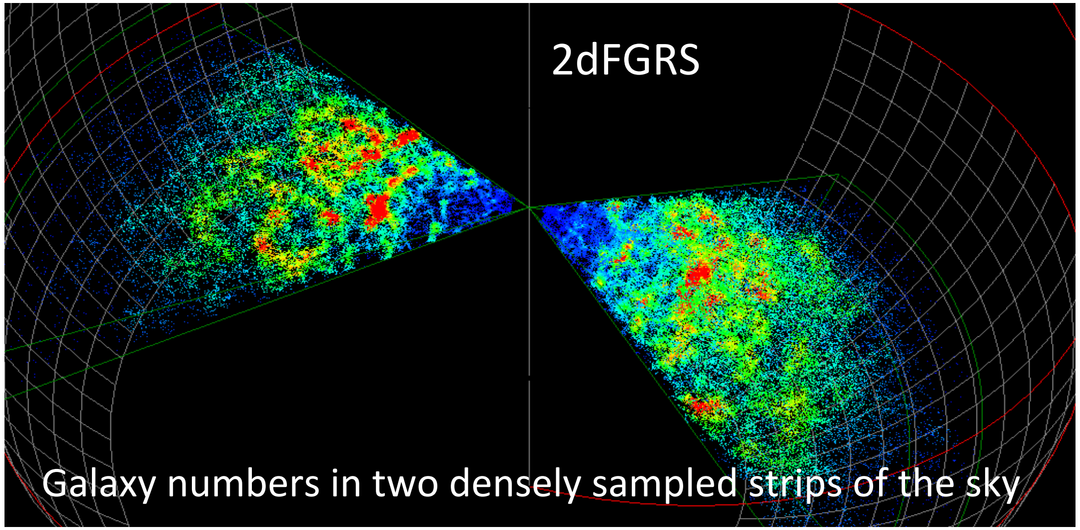
- As a result most of the gravitating matter in the clusters (blue) is clearly separate from the baryonic matter (pink) - fairly direct evidence that nearly all of the matter in the clusters is dark.


Optical + X-rays + “dynamical mass”

PHYS2160 – Lecture 7 – Spirals and Dark Matter

Evidence for Dark Matter

7. **Large scale structure** – large surveys of the galaxies in the nearby Universe (e.g. 2dF Galaxy Redshift Survey and the Sloan Digital Sky Survey see substantial structure on extremely large scales. Current models predict that this structure formation in the Universe proceeds hierarchically, with the smallest structures collapsing first and followed by galaxies and then clusters of galaxies. As the structures collapse in the evolving universe, they begin to "light up" as the baryonic matter heats up through gravitational contraction and the object approaches hydrostatic pressure balance. Ordinary baryonic matter had too high a temperature, and too much pressure left over from the Big Bang to collapse and form smaller structures, like stars, via the Jeans instability. Dark matter acts as a “compactor” of structure.

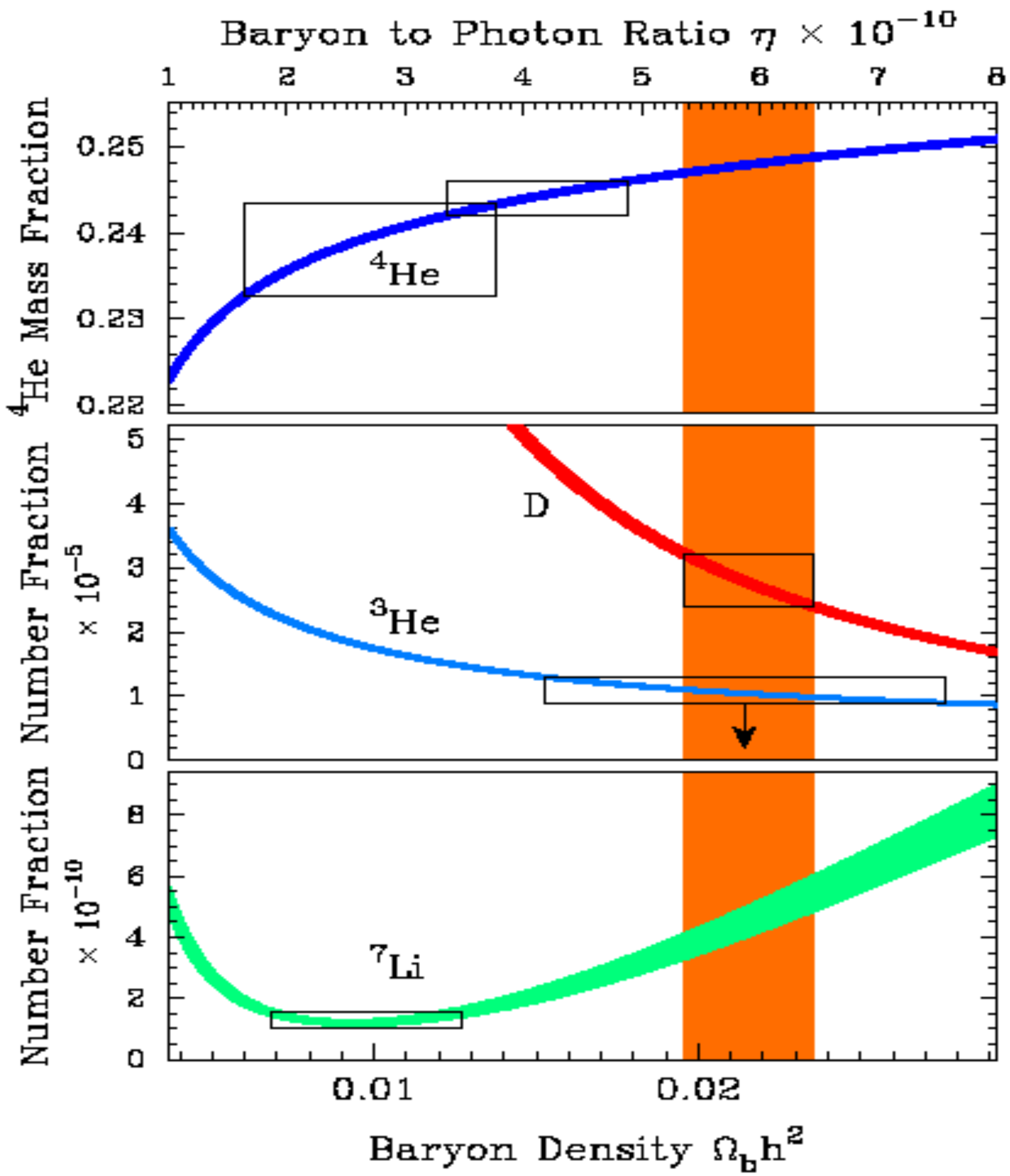
   

   This *bottom up* model of structure formation requires something like cold dark matter to succeed. Large computer simulations of billions of dark matter particles have been used to confirm that the cold dark matter model of structure formation is consistent observations.

8. **Big Bang Nucleosynthesis** – models for the generation of the elements by the recombination of sub-atomic particles as the early universe cooled. These models provide good estimates of the mean baryonic density of the Universe, and these results are in reasonable agreement with the “visible” baryonic matter we see. This (together with the evidence for dynamical masses from – for example – gravitational lensing) suggests that dark matter must be non-baryonic

Big bang nucleosynthesis & light element abundances

- H, ^{4}He, ^{3}He, ^{7}Li and D (^{2}H) were all produced during Big Bang Nucleosynthesis.
- The amount of each element produced is dependent on the baryon density, Ω_b (measured relative to the total mass density of the universe Ω, where Ω=1 produces a flat universe).
- While the Ω_b values predicted by He, D and Li observations do not agree, they all place the fraction of the universe made up by baryons at just a few percent of the total mass of the universe.



PHYS2160 – Lecture 7 – Spirals and Dark Matter

What **is** this Dark Matter? Things its not likely to be …

1. *Baryonic – Rocks?* If the dark matter was composed of small masses of ~1kg, then there would be so many required to attain the requires density (i.e. 10^{28} pc^{-3}, or a spacing of around 60,000km) that we would see them cluttering up the Solar System and impacting on the Earth. Moreover, to make small solid compact objects, you need heavy elements (Si,C,Mg,Ca etc) and these would have to have been created by Big Bang Nucleosynthesis, so our current models for that would have to be all wrong. **Unlikely**.
2. *Baryonic – Gas giant planets and/or brown dwarfs?* Jupiter is around 1/1000th of a solar mass. Old objects of this size dating from the formation of the Universe would be very cold (~100k) and would radiate most of their flux in the 5-20um wavelength range. The required density would be about $10pc^{-3}$, so the nearest would be ~0.4pc away and so we should have detected several in nearby sky surveys like the IRAS and WISE satellites. **Unlikely**.
3. *Baryonic – Tiny Black holes?* Imagine tiny black holes (~10^{12}kg, r~10^{-13} cm) were created under the enormous pressures of the Big Bang. As we will see later in the course when we look at black holes more closely, these would evaporate via Hawking radiation on a timescale of about 10Gyr with most of their energy released as gamma rays. These could in principle exist, as long as they somehow predated the BB, so the baryons from which they formed didn't participate in BBN and so could not influence the light element yields. **Unlikely**
4. *Baryonic – Mid-sized black holes?* If there was a population of black holes with mass ~$3M_{\odot}$ the space density would have to be about 10^{-2} pc^{-3}. Such black holes could be formed from stars of >$10M_{\odot}$. However, they would have to have formed very early in the Universe, would have been extremely luminous, and would have rapidly produced significant metal enrichment in the earliest galaxies. **Unlikely**

PHYS2160 – Lecture 7 – Spirals and Dark Matter

What **is** this Dark Matter? Things its not likely to be …

7. *Baryonic – Massive-sized black holes?* Pop III stars of 10^3 to $10^6 M_\odot$ (required to make much more massive black holes) would have been highly luminous and very easy to spot, unless they formed only for a brief period very early in the Universe. They have the same problem as less massive stars in making too many heavy elements too early in the Universe. It would take some 10^6 black holes of 10^3-$10^6 M_\odot$ to make up the Galactic halo with a velocity dispersion of some 300km/s, so one would cross the disk every ~100 years. The impact of this on the disk would be seen and it isn't. **Unlikely**

Non-baryonic forms …

1. Neutrinos – are abundant (there are about as many v in the universe as there are γ). In the standard particle physics model neutrinos are massless. However, if v are allowed a mass of just a few eV they can provide the critical density. If v oscillate between different types, then at least one type of neutrino must have *some* mass. Experiments do suggest they oscillate. At the moment it appears some flavours of neutrino may have some mass, but it is not clear this is enough to explain galactic dynamics.
2. Exotic new particles – axions, neutralino, gravitino, photino, … Most of these models are at present essentially untestable.
3. WIMPs (Weakly Interacting Massive Particles) the main characteristics of a WIMP are: Interactions only through the weak nuclear force and gravity and large mass compared to standard particles. Again, essentially unobservable and untestable.

PHYS2160 – Lecture 7 – Spirals and Dark Matter

Looking for Dark Matter

1. MACHOs – Massive Compact Halo Objects. In 1986 Polish astrophysicist Bohdan Paczyński first used the term “microlensing” to describe lensing on a small scale of a dark intermediate object against a background field of stars. He suggested this would be a potential technique for detecting compact, dark objects in the Halo of our galaxy.

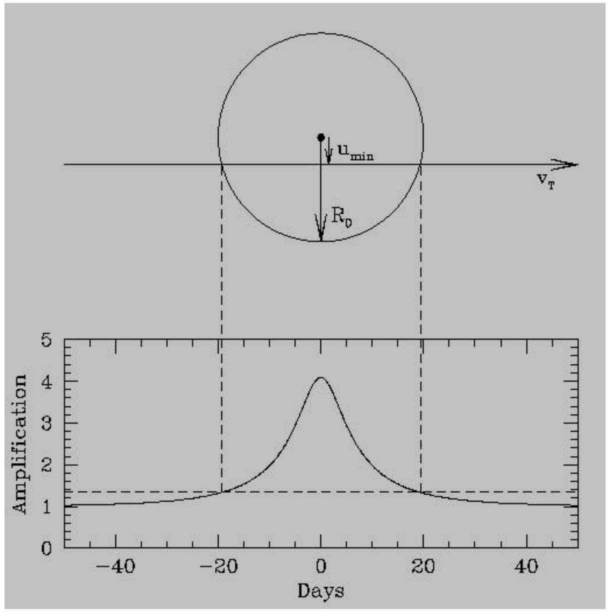
   When a star and lens are perfectly aligned with an observer, they produce an “Einstein ring”. This defines the characteristic scale (the Einstein radius) below which microlensing will occur. That is if a background star and lens align to less than the Einstein radius, then some level of lensing will happen.

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_S - d_L}{d_S d_L}}$$

   For example, for $M=1M_{\odot}$, d_L = 4000 parsecs, and d_S = 8000 parsecs (typical for a Bulge microlensing event), the Einstein radius is 0.001 arcseconds (1 milliarcsecond).

   A lens “moving” relative to a background source can be thought of as tracking across the “Einstein radius” for that background star.

   The result is a characteristic light curve shape due to lensing, that depends on the minimum impact parameter, the mass of the lens, the relative speed of the two objects (and the distances).



PHYS2160 – Lecture 7 – Spirals and Dark Matter

Looking for Dark Matter – MACHO searches

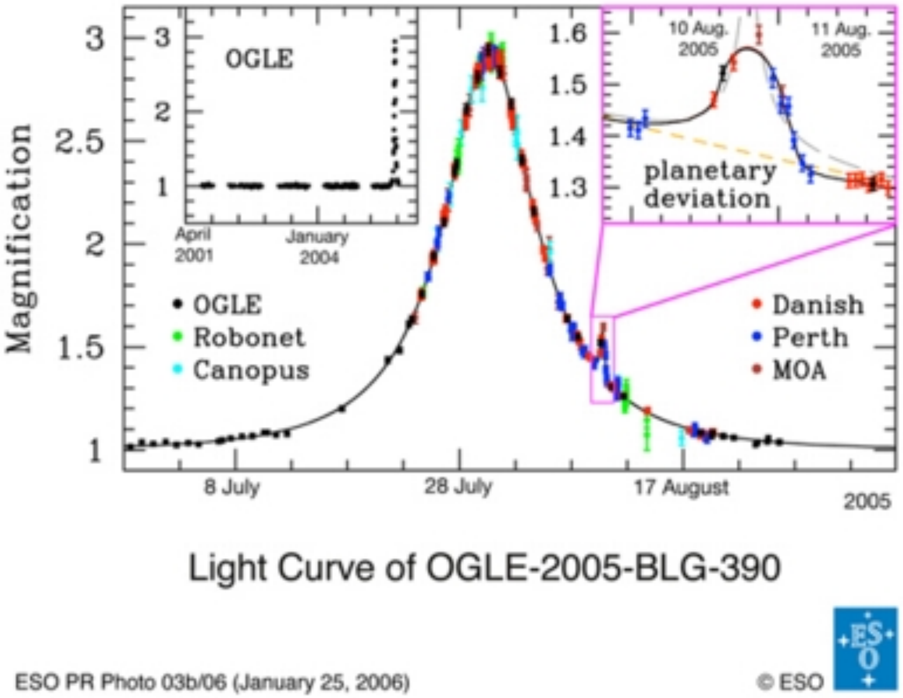
What is clear is that the alignment must be very precise. One therefore needs to look at a dense screen of background stars to have a high probability of the chance alignment of an intervening object to the level of precision required.

Extensive searches have therefore targetted the Magellanic Clouds, and windows towards the Galactic bulge for use as background screens.

You have to monitor these fields almost continuously for long observing campaigns and measure the brightness as a function of time (the "light curve") for millions of stars.

And amazingly it does work.

And the result – 5.7 years of monitoring of the LMC by the MACHO experiment (at MSO) of 11.9 million stars revealed 13-17 events. Most likely masses between 0.13-0.9$M_\odot$ and analysis of these showed that at most 20% of the dark Halo can be made up of MACHOs.



PHYS2160 – Lecture 7 – Spirals and Dark Matter

Dark Matter – Conclusion

1. Dark matter in our Galaxy's halo is not in the form of compact objects (i.e. brown dwarfs or giant planets)
2. In fact, its almost certainly got to be non-baryonic.
3. We still basically have no idea.

Tutorial Problems

Which problems did people have trouble with?

PHYS2160 – Lecture 7 – Spirals and Dark Matter

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	$=$	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	$=$	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	$=$	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	$=$	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	$=$	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	$=$	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	$=$	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	$=$	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	$=$	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	$=$	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	$=$	1.496	$\times$	10^{11}	m
Parsec	pc	$=$	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	$=$	$5 \log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	$=$	$2.5 \log \frac{f_1}{f_2}$
For small recession velocities	v/c	$=$	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$

PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

Last time

- Interpreting Spiral Galaxy Rotation curves – Inclination, Velocities, Masses
- Other evidence for dark matter in the Universe
- What is dark matter? Answer (sad) – we still don't know.

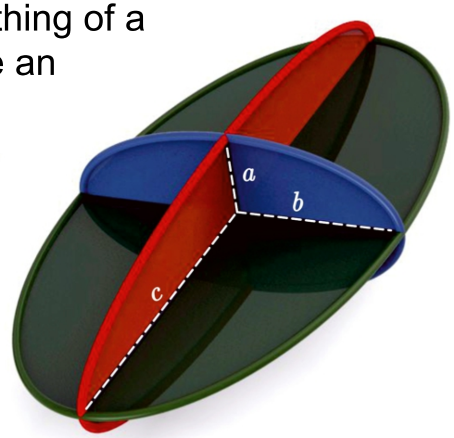
This Time

- Elliptical galaxies
- Active Galaxies – Active Galactic Nucleii (AGN)
- Radio structures – Jets & Lobes – Superluminal Motion
- Quasars
- AGN Spectral Features and what they imply
- AGN/Quasar structure model

PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

Elliptical Galaxies

Elliptical Galaxies (while in principle quite simple in structure) turn out to be something of a disappointment. 'Unscrambling' their orientation effects is very complicated, since an ellipsoid (even a triaxial one) always projects to an ellipsoid on the sky.



Though as noted earlier isophotal twisting can help you make some headway at disentangling triaxiality.

cD Galaxies

Are a special kind of elliptical found in the centres of rich clusters, which manifest as a giant elliptical surrounded by a large halo.

They are believed to grow via the mergers of galaxies in the cluster, reflected in their location t the dynamical centre of the cluster. The often have two or more nucleii reflecting giant galaxies in the process of merging.

Left: The supergiant elliptical NGC 3311 – the centrally dominant cD galaxy in the Hydra I cluster. The normal giant elliptical, NGC 3309 at the bottom of the picture, is also in the cluster.

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Active Galaxies

Unusual galaxies characterised by one or more of the following features

- Greater amounts of radio radiation than a normal galaxy
- Greater amounts of X-ray radiation than a normal galaxy
- Strong optical emission lines coming from an unusually bright nucleus

… all things that “normal” galaxies don’t have.

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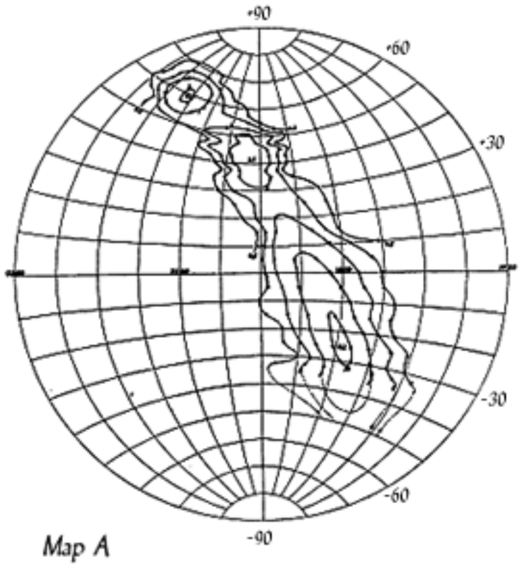
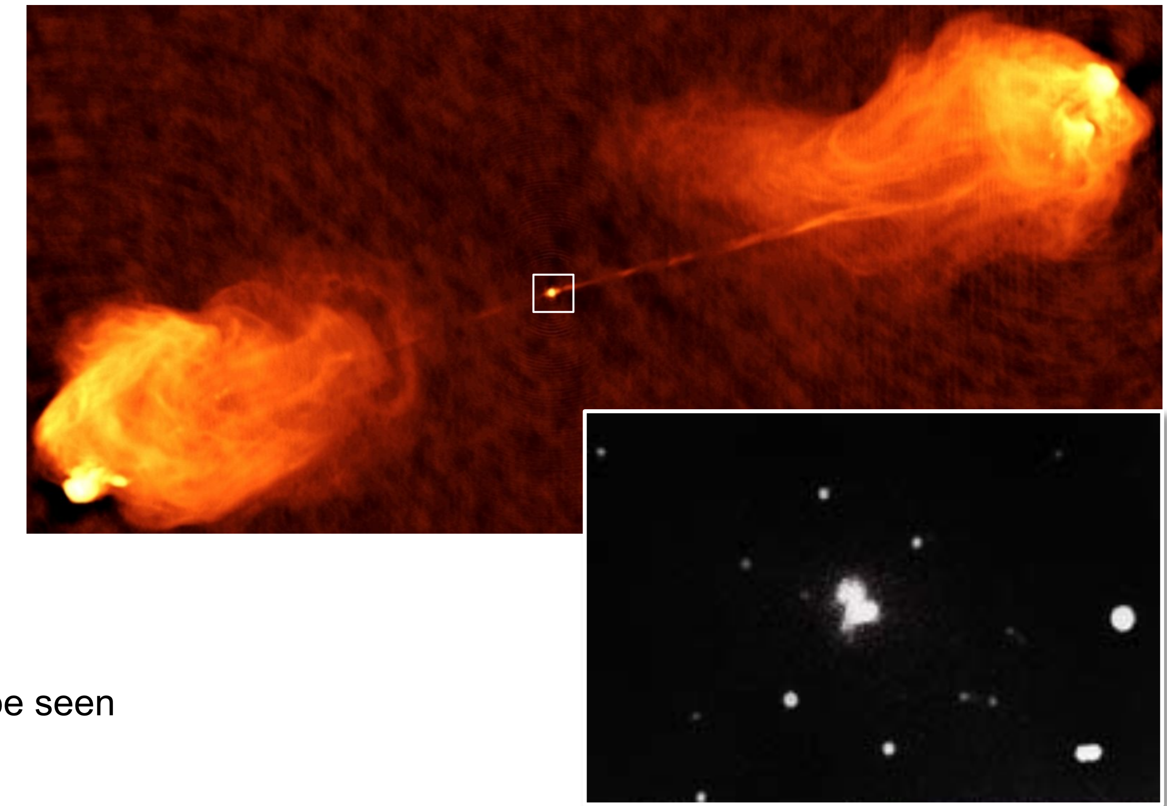
Extragalactic Radio Sources

First extragalactic radio sources discovered in the sky surveys of Grote Reber (made from 1939-1944), including the object Cygnus A, which could be positionally associated with a strange, optically faint galaxy, but which was enormously bright and huge in the radio.





These jets and lobes would come to be seen as common features in radio galaxies

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Extragalactic Radio Sources

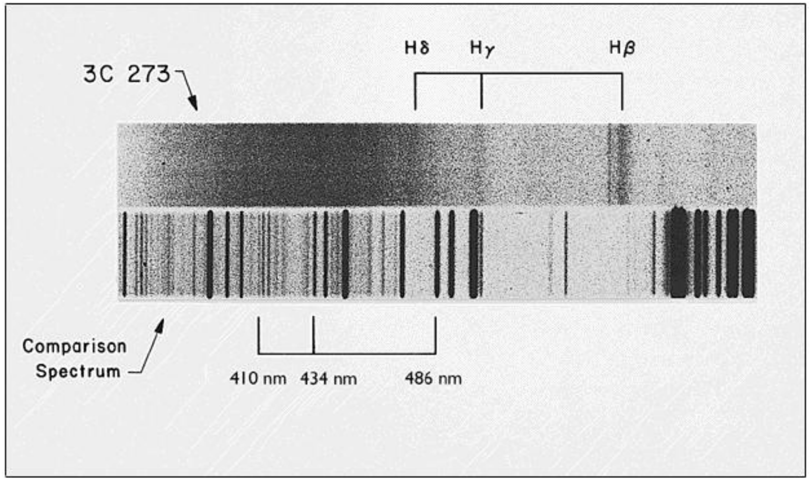
In the 1950s astronomers carried out the third radio survey at Cambridge (the 3C survey) uncovering hundreds more radio galaxies. **Plus** a number that were identified with stars – 3C48 and 3C273

But the spectra of these objects were truly weird – no-one could work out what the crazy emission lines seen in these “stars” were.

In 1963 Caltech astronomers Maarten Schmidt and Bev Oke realised the spectrum was actually one that had been enormously redshifted, making its lines (H_β 486nm, H_γ 434nm, H_δ 410nm) actually well-known ones, moved to unheard of wavelengths. So the first QSOs/Quasars were discovered.

These redshifts implied these quasars must lie at **huge** distances, while the radio fluxes at these distances made them the brightest known objects in the Universe.

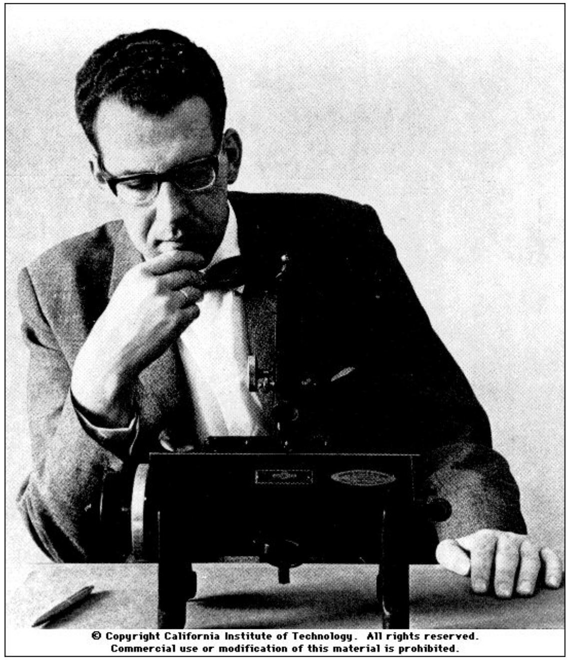
We now know that they are part of the much larger class of active galaxies introduced earlier, and that most of this luminosity is coming from a nuclear source in the galaxy.



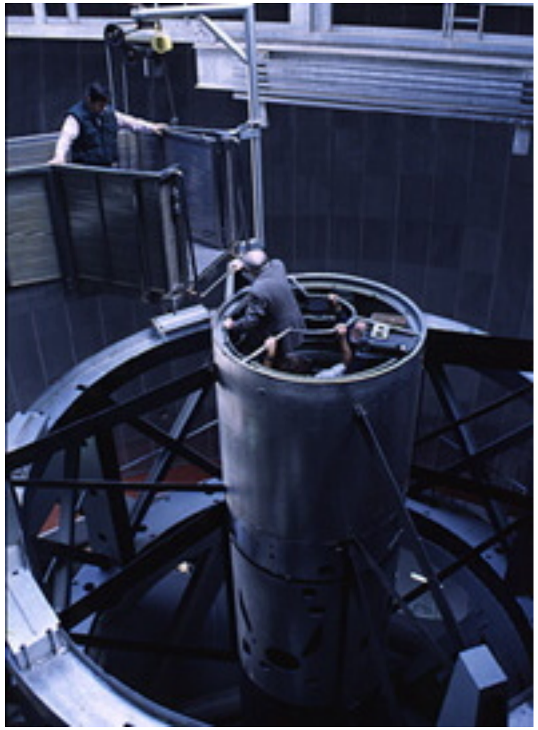
Maarten Schmidt’s 3c273 spectrum

PHYS2160 – Lecture 8 – Historical Diversion

Jesse Greenstein – was the stellar guru at the time, and was *just about* to publish a paper on 3C273's spectrum explained as a white dwarf with lines of crazy heavy elements like U …



… when Maarten Schmidt walked into his office with the simpler explanation.



Jesse in 1995 climbing into the PF cage of Palomar 200" one last time (at age 85).

PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

Extragalactic Radio Sources

Radio Galaxies - In addition to these quasars, many radio sources were identified with galaxies, though many don't have an identifiable optical counterpart.

The radio spectra of these objects are continuous and smooth without any spectral lines (so no redshifts are measurable).

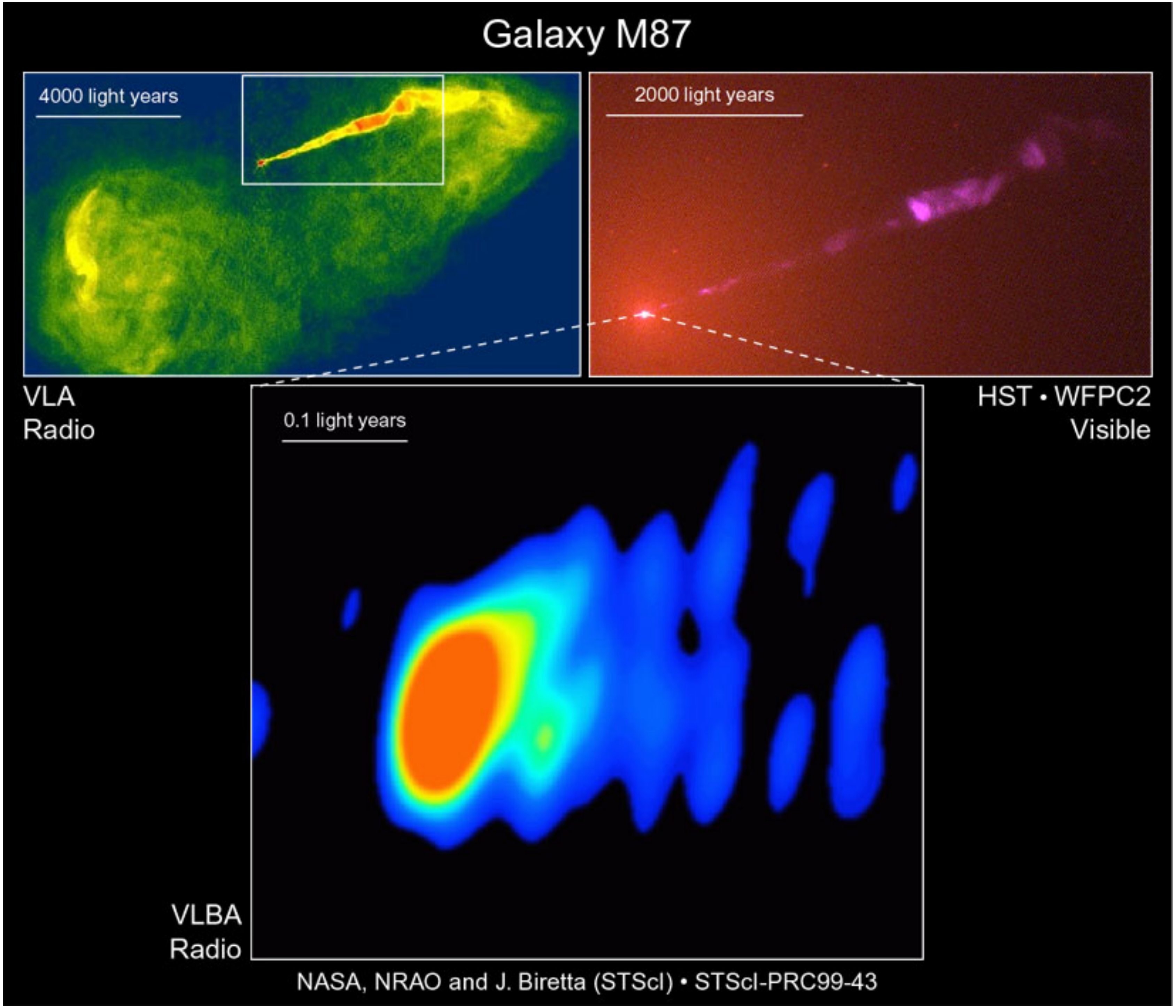
Radio Source structure: two basic structures were identified in these surveys

– *Extended* : sources with two lobes on opposite sides of the nucleus of a galaxy or quasar. The radio source structure dwarfs the optical extent, with radio lobes hundreds of kpc apart and kpcs across. (cf. Cyg A VLA image earlier). Optical jets are sometimes seen aligning with the radio jet
– *Compact* : point-like source coincident with the nucleus. At very high resolution it often breaks up into multiple components that are separating at enormous speeds – in some cases relativistic velocities.

The radio power of the strongest radio galaxies and QSOs is 10^{39}-10^{40} W, which compares with the radio power of a normal galaxy like our own of ~10^{30}W.

The strong radio variability of these compact sources on timescales of days-weeks also allows us to place limits on the size of the emitting region as being ~ light-days to light-weeks – which is ≤ 0.015pc. This is truly tiny for a region emitting a billion times more radio flux than a whole galaxy!

What is the engine powering this activity in the cores of radio galaxies?

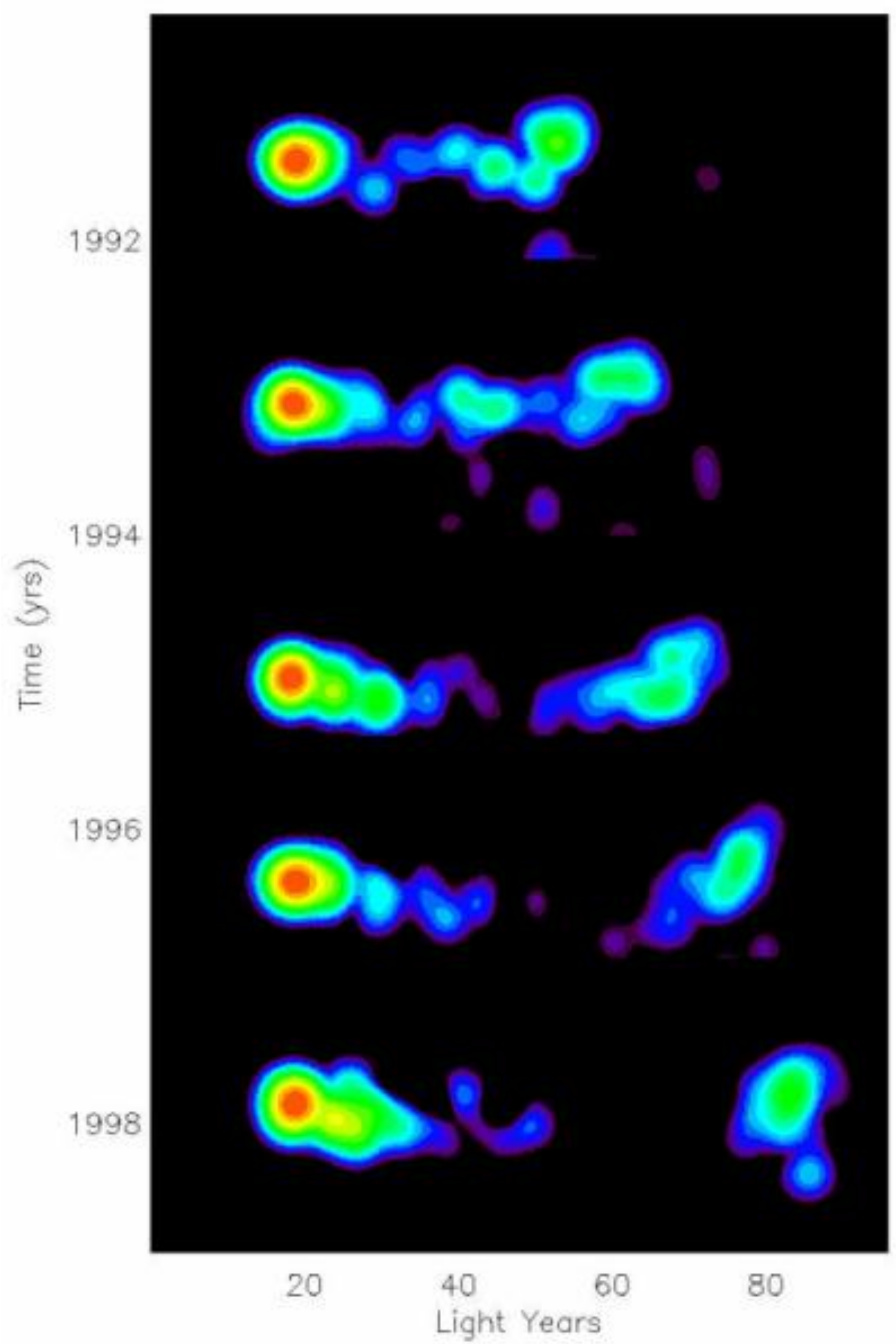

Galaxy M87
4000 light years
2000 light years
VLA
Radio
HST • WFPC2
Visible
0.1 light years
VLBA
Radio
NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

3C279's relativistic core.

VLA radio images - courtesy of NRAO

These blobs are separating at apparently "superluminal" velocities, which tells us the jet in this quasar is pointed almost *directly* at us.

Quasar "superluminal" motion (the blobs shown to the right appear to have separated by 27 light years over an 8 year period!) is a relativistic effect. The blobs are moving at velocities near the speed of light (0.997c) along a jet pointed within 2 degrees of the line of sight.



“Superluminal” motion

Consider view from observer looking at a radio core “C” that emits a blob “B” with speed 0.99c.

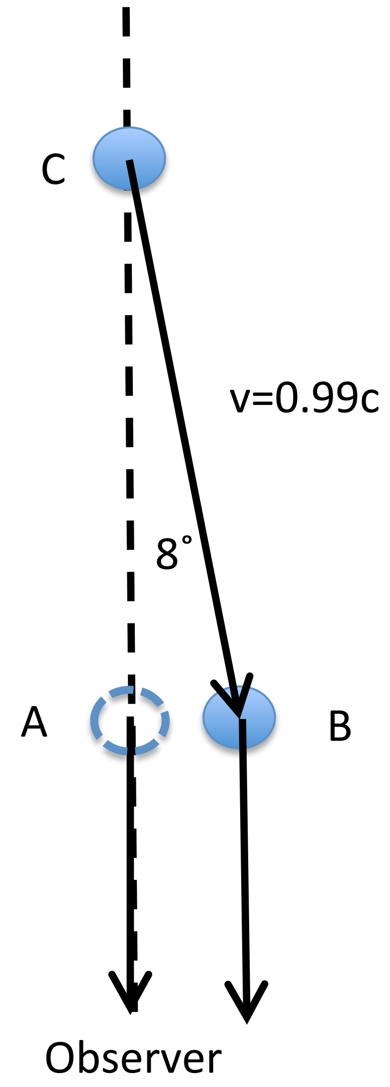
After 100 years the light from the core (travelling at speed c) will have reached position A along line of sight to the system.

The blob will have reached the same apparent distance from the core after 101 years (position B) and the apparent separation is then 101 lyr × sin(8°) = 14 lyr.

So to the observer the blob at position B appears to have arrived just 101-100 = 1yr behind that from A.

Which means it seems to have moved 14ly (as projected onto the sky) in just 1yr. So it “looks” superluminal. But this is just a projection effect – no actual matter is travelling faster than c.

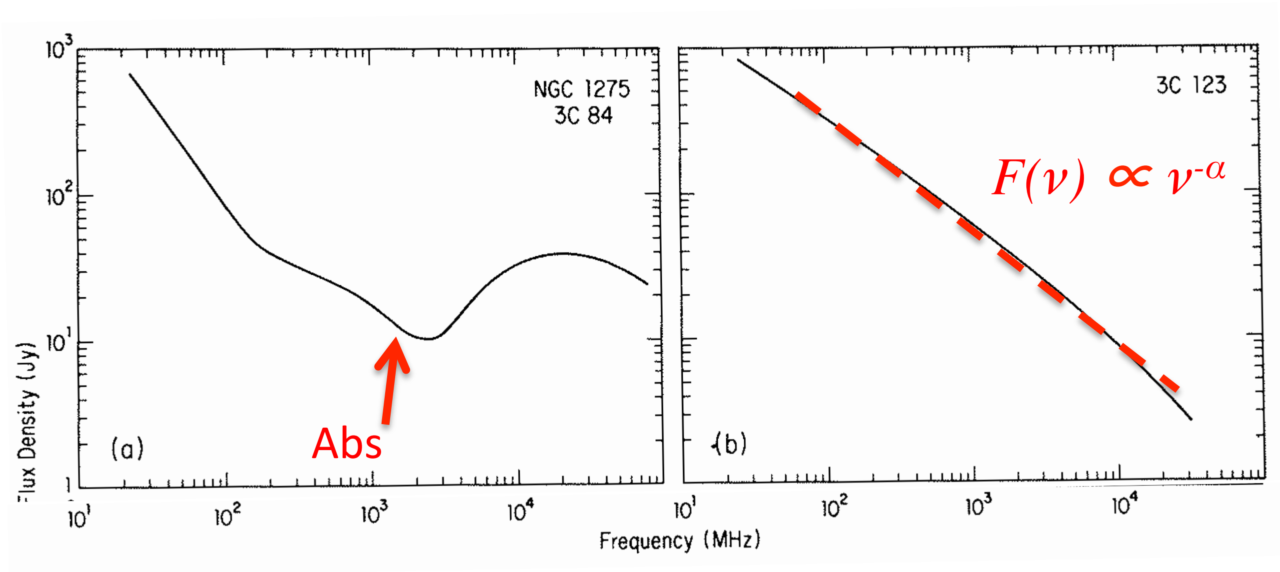
But it DOES mean the jet is closely aligned to the line of sight.



PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

Extragalactic Radio Sources – Spectrum and Emission Mechanisms

Extended and **Compact** radio sources are seen to generally have different radio spectra. Extended sources (e.g. b below) have a power law spectrum with α ~ 0.6 – 1.2. Compact sources (e.g. a below) have a more complex spectrum characterised by apparent absorptions.



Polarisation – radio emission is also seen to be generally polarised in much the same direction over the full extent of the extended sources, suggesting the presence of magnetic fields.

X-Ray emission is also detected from the nucleii of many active galaxies and quasars, and also with a generally power-law spectrum. However, this light is **not** polarised as the radio emission is, so it must come from a different emission mechanism.

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Extragalactic Radio Sources – Spectrum and Emission Mechanisms

Together these suggest the emission mechanism (for the extended sources at least) is synchrotron emission in the radio, produced by magnetic fields with $B \sim 10^{-8}$ to 10^{-10} T, and electrons with energies of ~ 1 GeV. Compact sources seem to have an overlying absorption due to high density, but cooler, material in their outer regions.

The X-ray emission is due to the **inverse compton scattering** of low energy radio photons off high energy electrons, which increases their energy into X-ray regimes resulting in a power-law spectrum with no polarisiation. The electron energies required to do this are ~ GeV.

Both types of emission (radio and X-ray) require a powerful source of relativistic electrons.

PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

Optically ID'ed active galaxies - are generally seen to be galaxies with bright nucleii

Spectra can have 2 components: continuum (c), emission lines (e)

1. Seyfert Galaxies (generally spirals) – have bright nucleii and strong, broad emission lines [c+e]
2. N galaxies – more extreme Seyferts with a very compact, very bright nucleus (generally galaxy type is hard to see) [c+e]
3. Quasars (Quasi-Stellar Radio Sources) = QSOs
   - More extreme version of the above with a nucleus so bright that the galaxy cannot be seen (hence "star-like")
   - Also have broad emission line spectra [c+e]
4. BL Lac objects – like 1,2,3, but don't show emission lines – nuclear light is featureless. They are highly variable. If radio loud they are called "blazars". [c only]

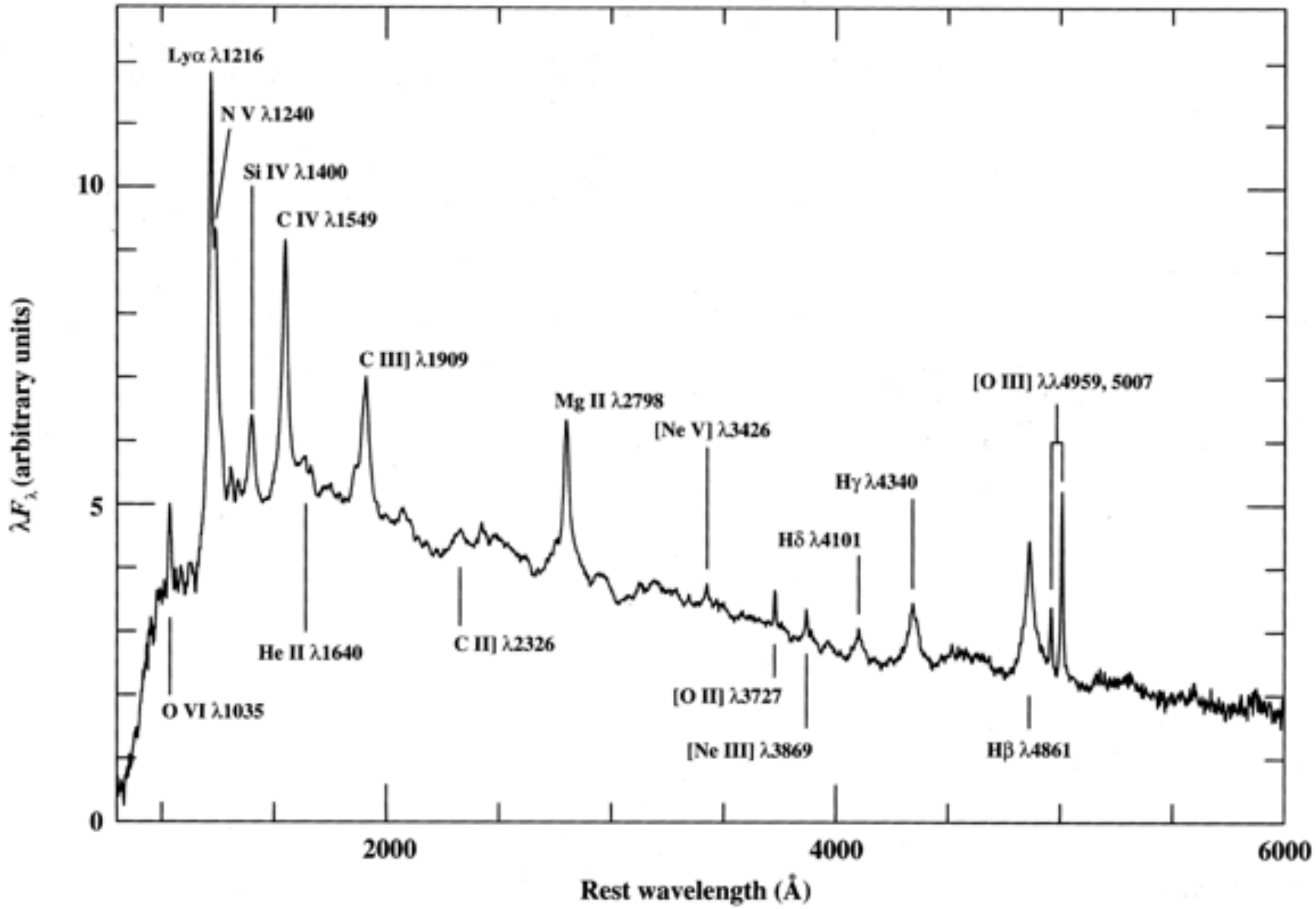
The continuum is a smooth and featureless underlying component to the spectrum, which can be isolated as coming from the nucleus.

PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

Active Galaxy Spectra

The **continuum** is a smooth, featureless and blue underlying component to the spectrum, which can be isolated as coming from the nucleus.

Emission lines are high broad peaks in the spectrum and come from the region surrounding the nucleus



PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

Seyfert Galaxies

First identified in 1943 by Carl Seyfert, who noticed a class of galaxies with broad emission lines and unusually bright nucleii.

- At least 90-95% of these were spirals (though classification became more difficult for the more distant galaxies)
- Around 1% of all galaxies are Seyferts.
- Subsequently classified into two types
  - Type 1 (both broad and narrow emission lines)
  - Type 2 (only narrow lines).

Seyfert galaxy NGC1097

Many Seyfert galaxies are close enough to spatially resolve on sky, and therefore we (generally) can study them in more detail than we can the more distant quasars.

Quasars do, however, show many of the same spectral features and in particular show both broad and narrow emission lines.

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Seyfert Galaxies

Broad Lines are *permitted* transitions – i.e. downward transitions from energy levels with very short lifetimes (~10^{-8} s). They are typically seen with line widths of 5000-10,000 km/s.

Narrow lines are seen to arise from *forbidden* transitions. These are transitions downwards from energy levels that are *metastable*, because they are strongly prohibited by the quantum mechanical rules for atomic transitions. As a result their lifetimes in the relevant upper level last from seconds to days. In the laboratory (and in astrophysical plasmas where the density is high) these transitions are never seen, because long before the transition can take place, they are de-excited by collisions.

However when the gas density is low, collisions can be infrequent enough that these de-excitations can take place radiatively and forbidden lines are seen. (Notation – these transitions are highlighted with square brackets – e.g. [OIII] 4959).

Typical line widths for these narrow line transitions in Seyferts are 200-400km/s.

Seyfert 2s have only “narrow lines” (compared to the broad permitted lines of Seyfert 2s) – in Seyfert 2s there is no distinction between permitted and forbidden line width.

PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

Seyfert Galaxies and Quasars

Broad Line Region (BLR) – the broad line emisison from quasars and Seyfert galaxies can vary on short timescales of days to weeks.

1. This emission line variability constrains the size of this coherently varying region to be ≤ 10^{14}m (or ~700 au or 10^7 times smaller than a typical galaxy diameter)
2. However, the density must also be high (10^{13}-10^{15} particles/m^3) because no forbidden lines are seen from the broad line region.

Knowing a size scale and a typical density, means a typical mass can be estimated ➔ total gas mass of 30-50 $M_{\odot}$. Moreover, the line widths seen imply the gas is moving at turbulent velocities of up to 10,000km/s.

Narrow Line Region – the regions from which forbidden lines originate have lower density than the BLR. Little or no emission line variability is seen in the narrow line region, so sizes are uncertain but likely to be at least 1000 times larger than in the BRL.

However, different ions that produce the different forbidden lines do have different critical densities (i.e. densities that allow forbidden lines to occur), and so spectroscopic measurements ppoint to particle density falling as one moves radially outward.

PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

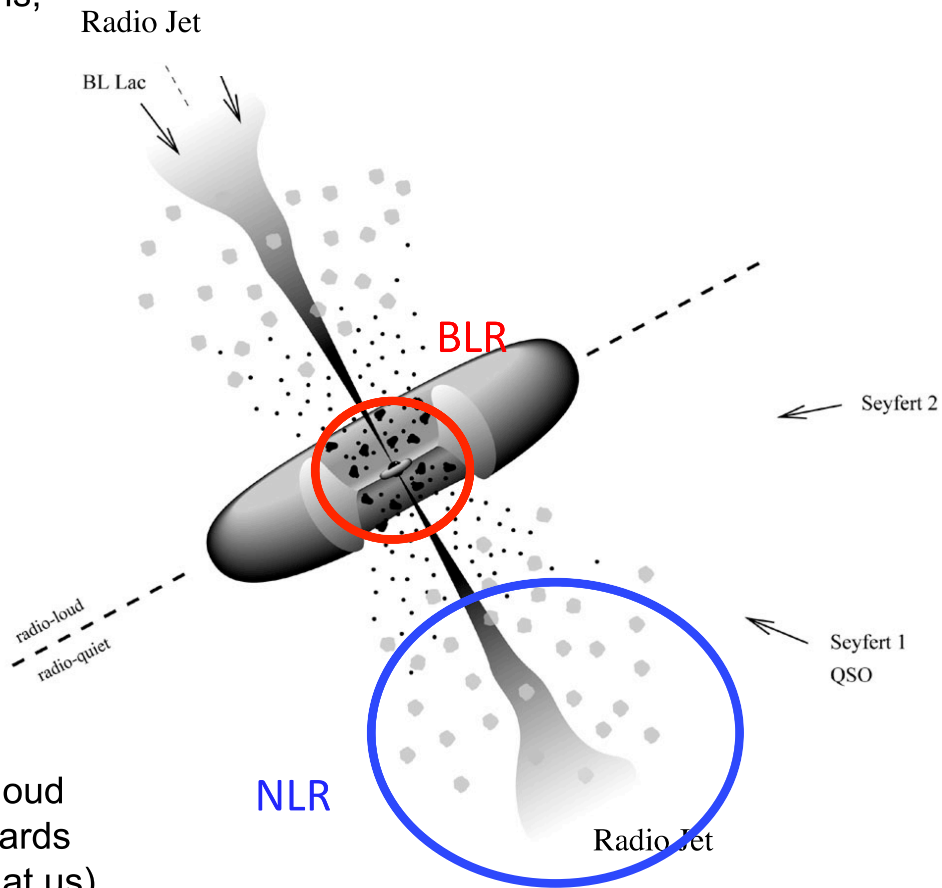
Wrapping it all up – the AGN "Unified" Model

These observations suggest a model for Seyfert galaxies, quasars and many other types of AGN.

A compact core (containing a black hole and an accretion disk) generates an axisymmetric geometry, magnetic fields and a powerful jet of relativistic electrons, as well as being a powerful source of ionising photons.

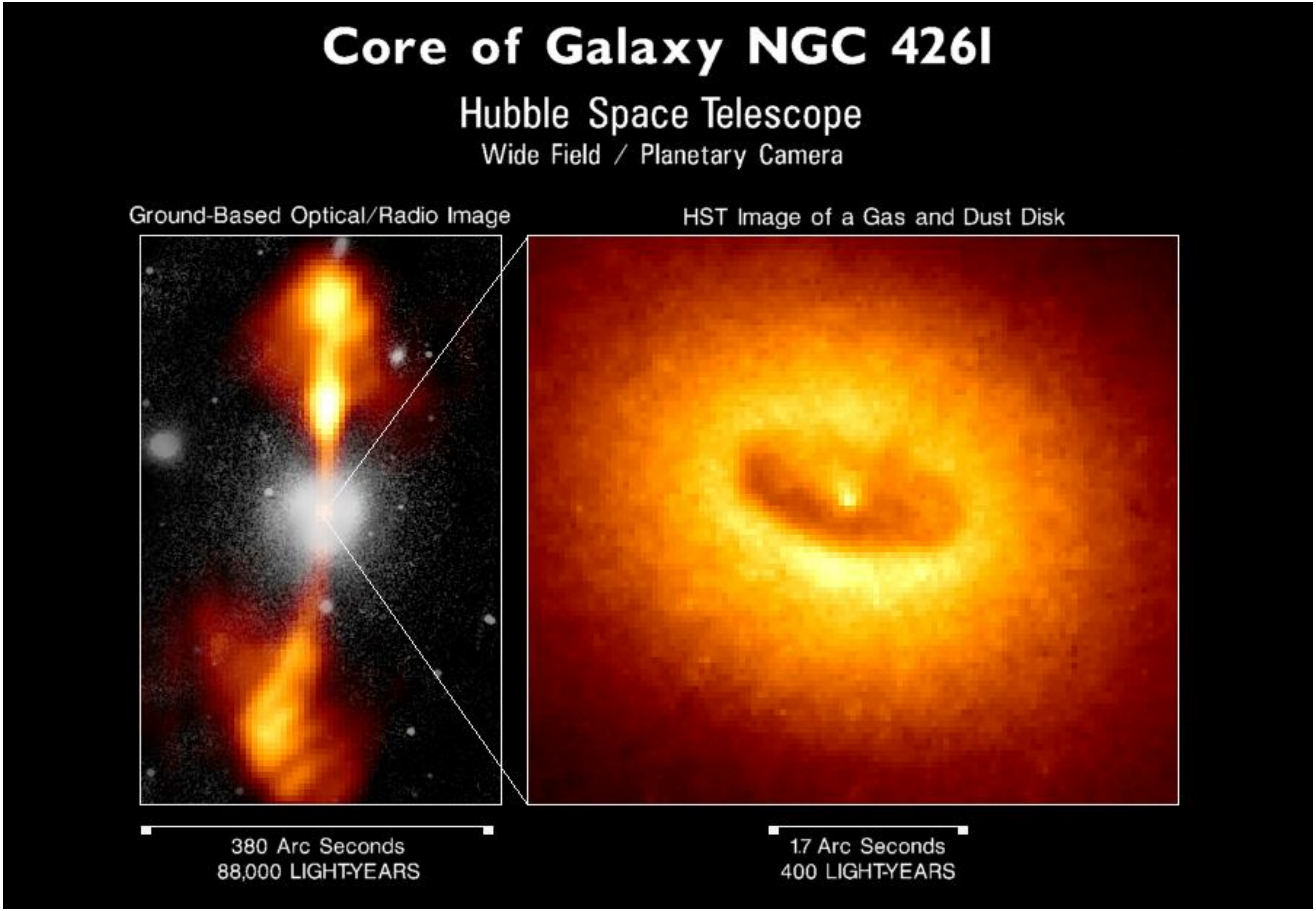
This bright core illuminates a spatially segregated and physically distinct set of gaseous cloud regions. More distant clouds orbit the core less rapidly and have lower turbulence. The BLR clouds lie close to the core, while the narrow-line clouds lie further out.

This accretion disk is surrounded by an extended dusty torus of material feeding the disk, which (depending on viewing angle) can obscure the core.



Which type of object we see depends on (1) the viewing angle, and how (2) powerful the core is (Seyfert is low power relative to rest of galaxy, QSO is high power).

If the jet is one-sided, then whether the object is radio loud of radio quiet will depend on whether the jet points towards you or away from you (recall 3C279 is pointed *straight* at us).


Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS

PHYS2160 – Lecture 8 – Ellipticals & Active Galaxies

- References
- Bibliography
  - –

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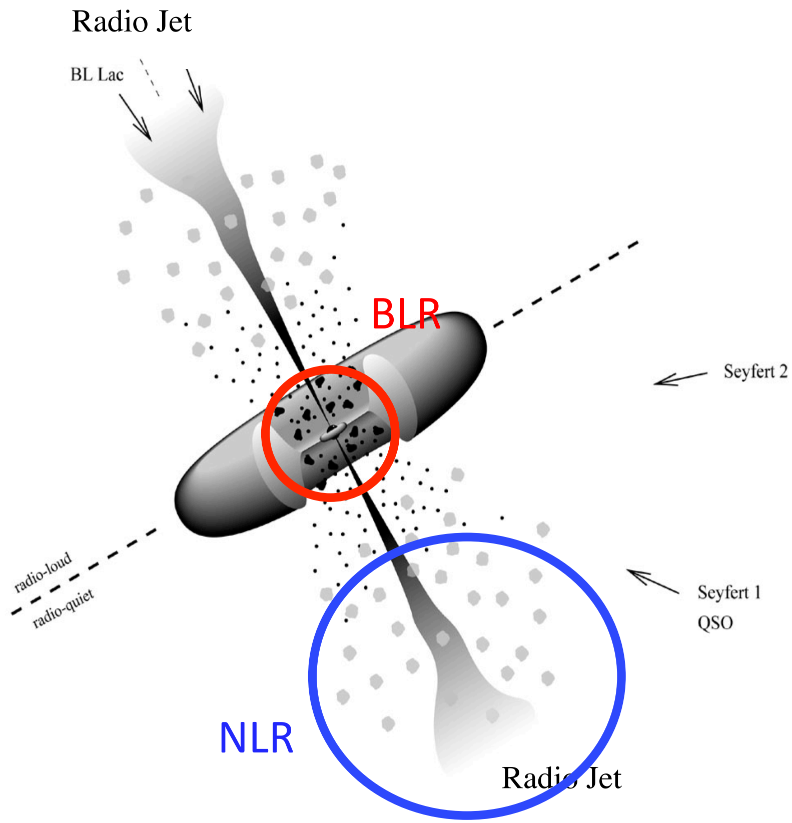
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$

PHYS2160 – Lecture 9 – Quasars as probes of the Universe

Last time

- Active Galaxies – Radio structures: Jets & Lobes – Superluminal Motion – Emission
- Seyfert galaxies and Quasars and their optical spectra
- Narrow-line Regions/Forbidden lines
- Broad-line Regions/Permitted Lines
- AGN/Quasar structure model …
  what we see depends on size/power of the nucleus (relative to galaxy) and orientation the line of sight.



This Time

- Quasars as "lamposts" for studying Universe
- Numbers
- Optical spectra – emission lines, absorption lines
- The Distance Ladder I

PHYS2160 – Lecture 9 – Quasars as probes of the Universe

Quasars/QSOs

We looked last lecture at the discovery of AGN (quasars, Seyferts etc) and what they tell us about how active galaxies work.

Recall Redshift ….

$$z = \Delta\lambda/\lambda = (\lambda - \lambda_0)/\lambda = \lambda/\lambda_0 - 1$$

and since

$$\Delta\lambda/\lambda = v/c \qquad \Rightarrow \qquad v = zc$$

Hubble law then gives $v = H_0 d$ (with modern values for H_0=72±2 km/s/Mpc)

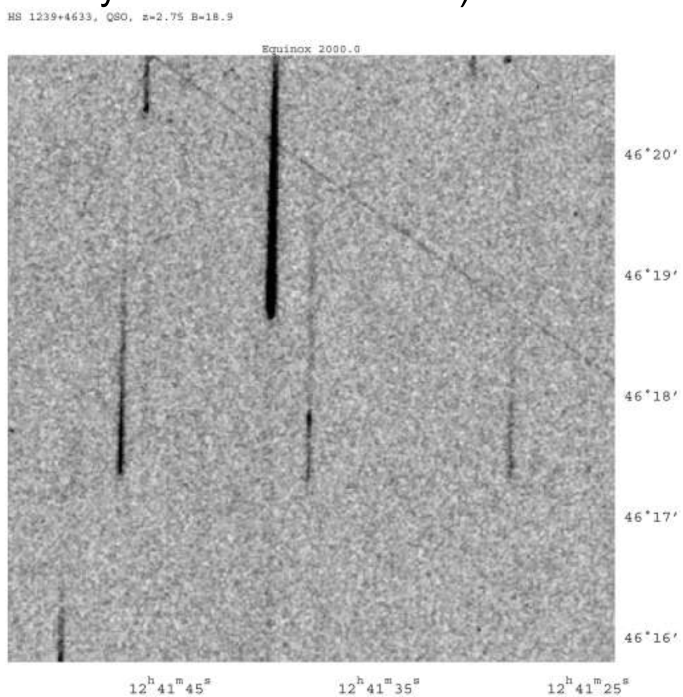
When the first quasar (3C273) was finally understood as being at z=0.15 (v=cz=45,000 km/s or d ~ 600 Mpc), it became clear that quasars are incredibly luminous and can be easily found at enormous distances.

Indeed for most of the 1980's and 1990's the 'distance record' for the highest redshift object known was *always* a quasar …

PHYS2160 – Lecture 9 – Quasars as probes of the Universe

Finding Quasars

- Radio surveys looking for compact sources with either flat or steep spectra.
- Colour-colour diagrams from optical surveys (e.g. SDSS-UKIDDS data to right)
- Objective prism surveys – placing a prism in your telescope turns every image into a tiny low-resolution spectrum (e.g. Hamburg survey – data shown below)



www.hs.uni-hamburg.de/EN/For/Exg/Sur/hes/qso_**surveys**.html

Wu & Jia (2010)

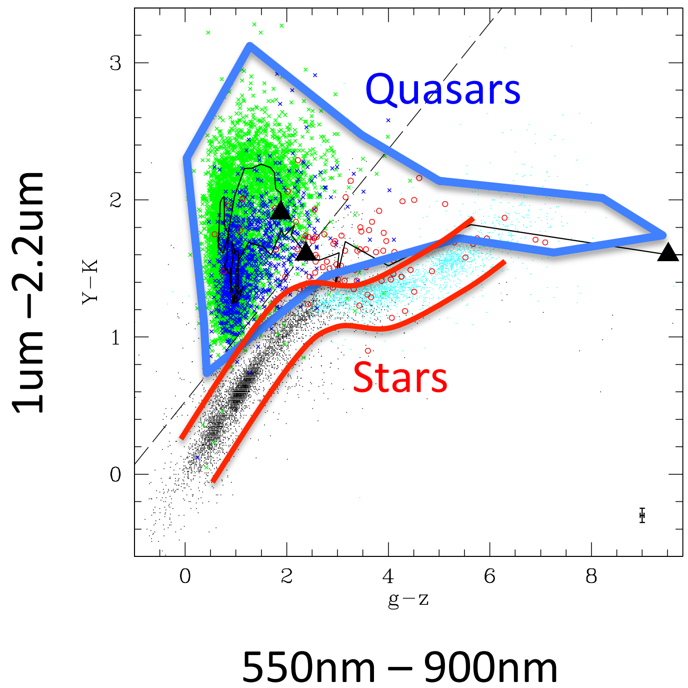


Figure 5. The $Y-K$ vs. $g-z$ colour-colour diagram of the SDSS-UKIDSS quasar and star samples. Green crosses, blue crosses and red circles denote quasars with $z \leqslant 2.2$, $2.2 < z \leqslant 4$ and $z > 4$, respectively. Black dots and cyan dots denote stars classified as 'STAR' and 'STAR_LATE' by SDSS spectroscopy. Dashed line indicates the separation criterion $Y-k > 0.46*(g-z)+0.53$. Solid curve is derived from the median colour-z relation (see section 3) of quasars. The solid triangles, from left to right, mark the colours of quasars with z=0.02, 4, and 5 respectively, derived from the colour-z relation. Typical error bars are shown in the lower-right corner.

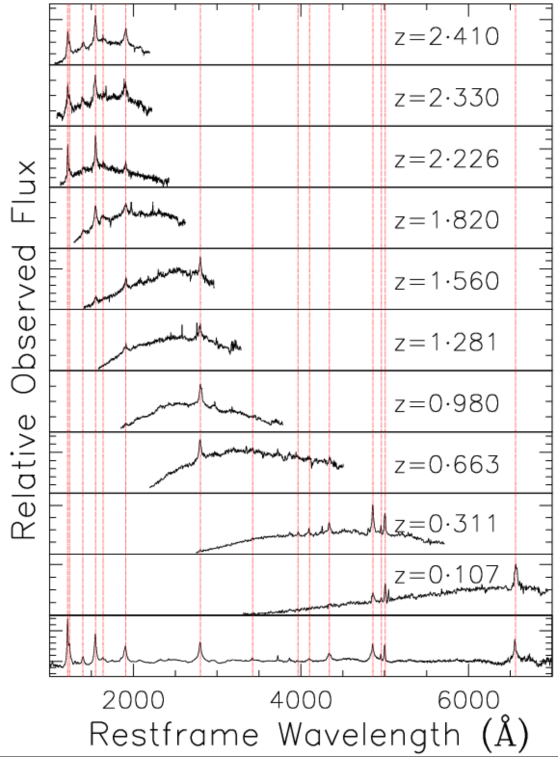
PHYS2160 – Lecture 9 – Quasars as probes of the Universe

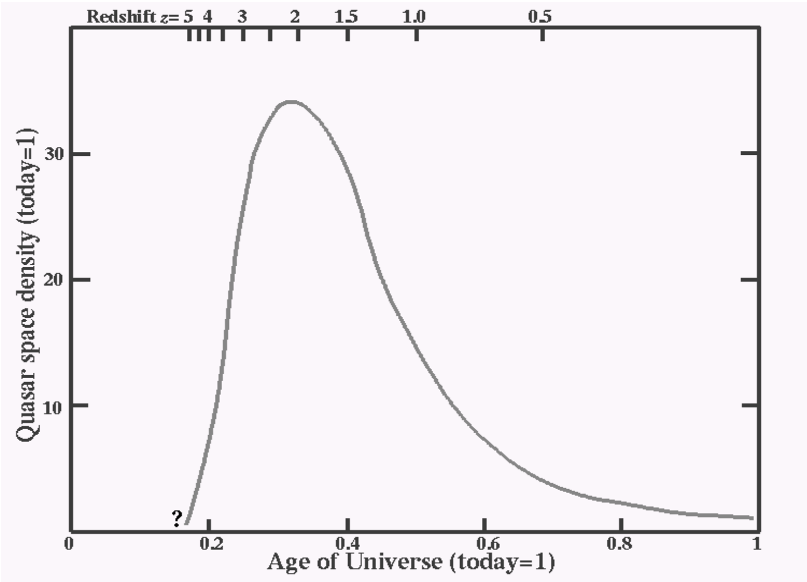
Quasar numbers

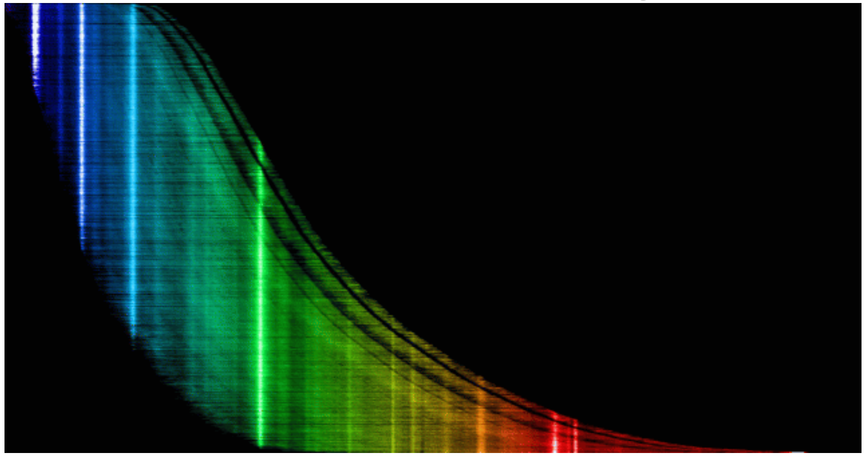
Large surveys over the last decade (2QZ, SDSS) have enabled us to further explore the evolution of the number density of quasars over the lifetime of the Universe.

In the diagram below (due to Shaver et al. 1996, Nature 384, 449) quasar numbers are shown as a function of *co-moving coordinates* to remove cosmological effects.

Few at z>5, almost none in local Universe today, and lots in between.







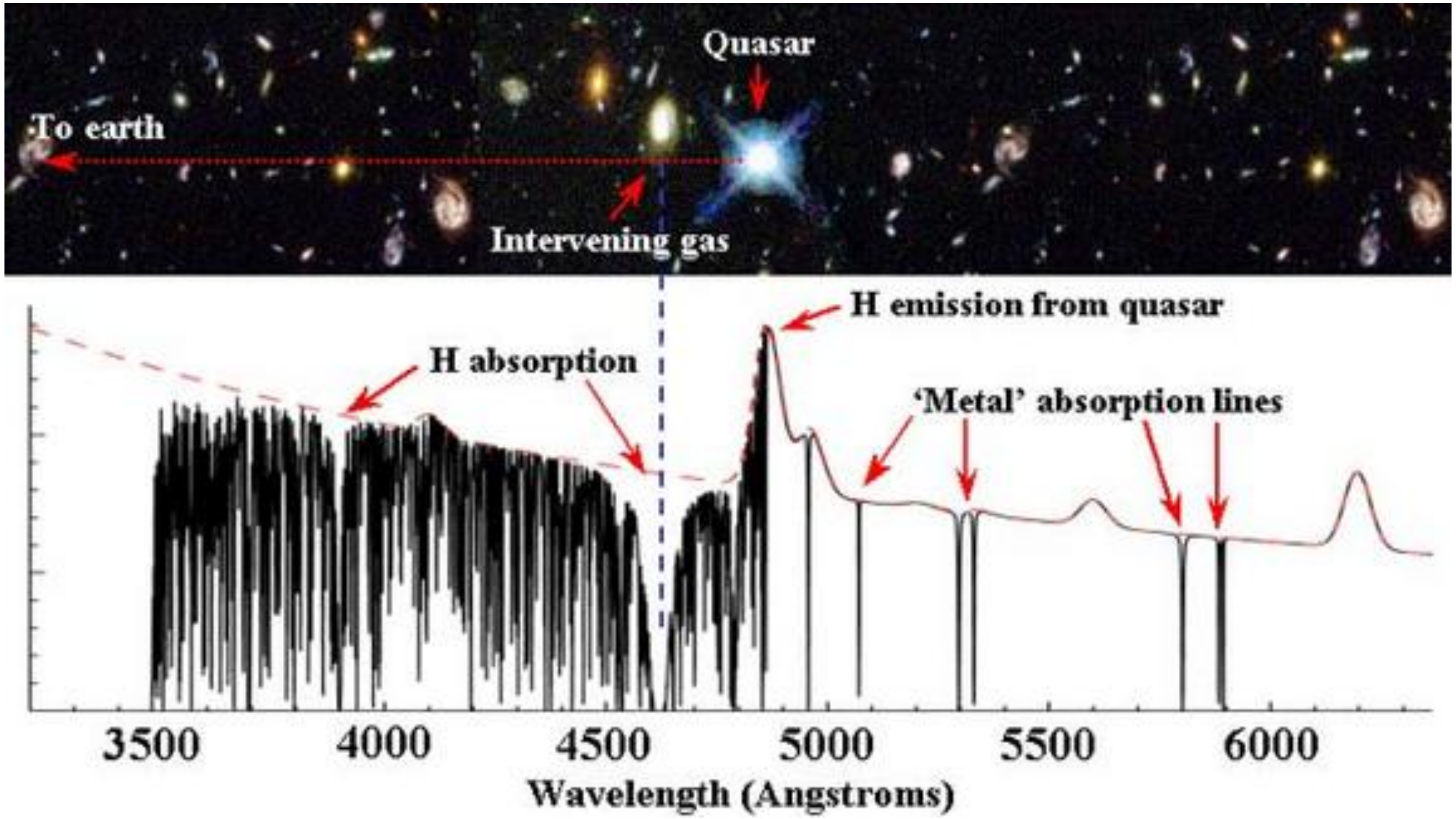
PHYS2160 – Lecture 9 – Quasars as probes of the Universe

An Exmaple Quasar Spectrum … the emission Spectrum

The emission redshift of this quasar is $z = \lambda/\lambda_0 - 1 = 4862.68 / 1215.67 - 1 = 3.0$

The continuum emission is synchrotron, and so is reasonably well modelled by by a power law.

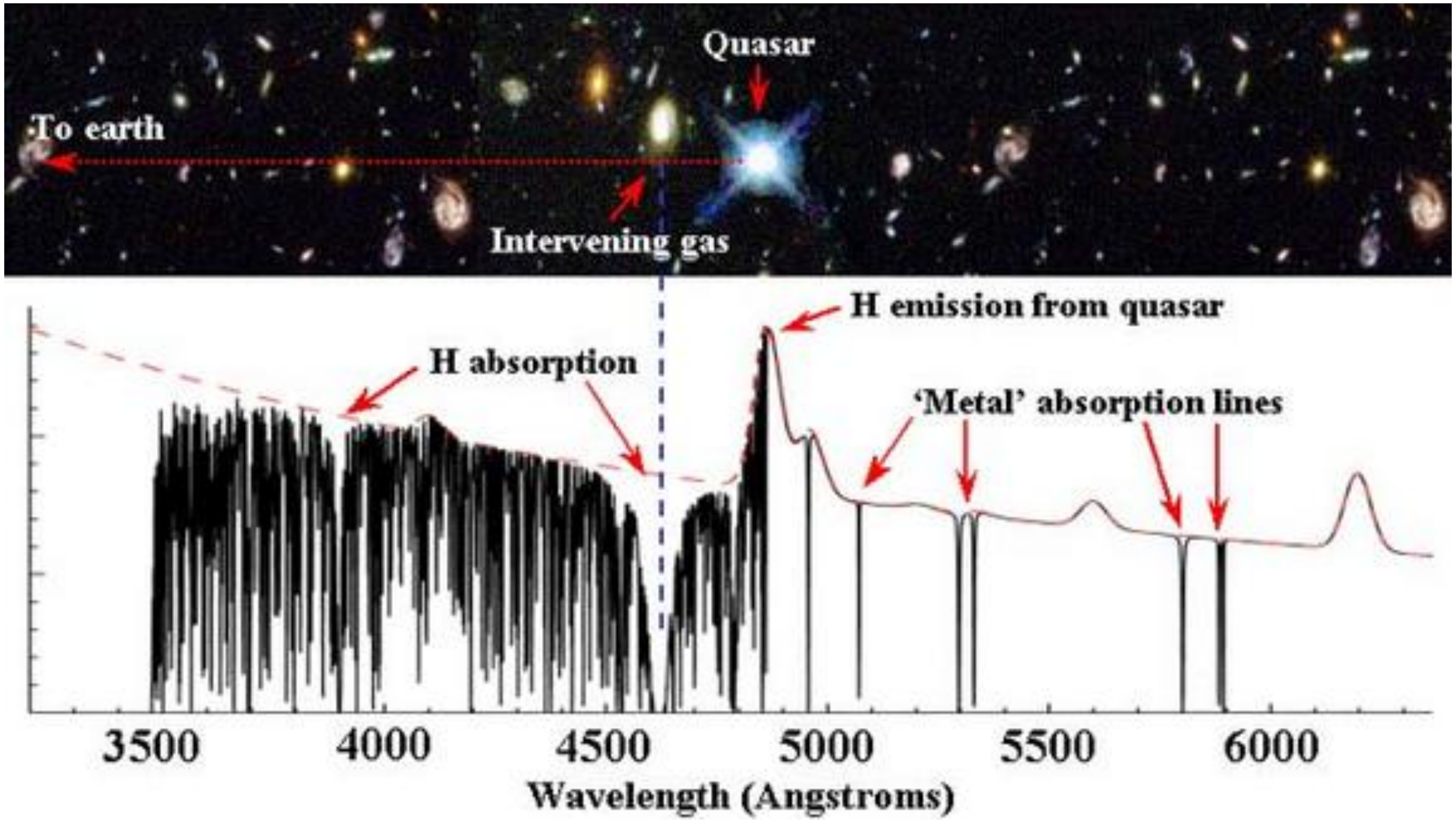
Emission lines are broad (as noted last lecture) – few thousands of km/s. Emission lines in this example include Lyman alpha (the transition from hydrogen's first excited state back to its rest state at 1215.67), quadruply-ionised nitrogen (NV), singly ionised silicon (SiII) and triply-ionised carbon (CIV).



PHYS2160 – Lecture 9 – Quasars as probes of the Universe

An Example Quasar Spectrum … in a bit more detail

- Underlying unabsorbed quasar continuum
- Quasar emission lines
- A “damped” Lyman alpha absorption system (DLA) at 4620A
- A “Lyman limit” break at 3466A (wavelengths shorter than this can always ionise H).
- Multiple heavy element absorption lines + a Lyman alpha forest



PHYS2160 – Lecture 9 – Quasars as probes of the Universe

Quasar Spectra … the absorption spectrum

The absorption spectrum enables the quasar to be used as a probe of the intervening Universe between us and the quasar.

Clouds of hydrogen along the line of sight will readily absorb in their Lyman alpha line at their individual redshifts. The sensitivity of these absorption signatures is several orders of magnitude greater than for the detection of objects by their Lyman alpha emission (since emission is isotropically emitted, while absorption only happens along the lines of sight).

The result is a detailed probe of the physics and chemistry of the early Universe.

We can characterise the density of the clouds responsible for the absorption by their *column density*, *N*, measured as the number of atoms/cm^3.

The systems seen get classified into a variety of types.

- Lyman-limit systems (LLSs) : $17.2 < \log N(HI) < 20.2$
- Damped Lyman alpha clouds (DLAs): $\log N(HI) > 20.2$
- Broad Absorption Line (BAL) systems: are strong absorptions seen at close to the QSO redshift, and are considered to arise from gas being emitted by the QSO itself.

PHYS2160 – Lecture 9 – Quasars as probes of the Universe

Quasar Summary

- Quasars/QSOs are some of the most luminous objects in the Universe.
- *The light from quasars travels through the intervening Universe, and absorption lines in quasar spectra therefore tell us about conditions between us and them.*
- Survey techniques to identify them are now quite sophisticated – known numbers of quasars now exceed 100,000. While they are uncommon at very high redshifts (z>4), they *can* be found (e.g. the distant quasar, ULAS J1120+0641 at z=7.1 around 750 million years after the big bang) and are amongst the best available probes of the very young universe.

- Damped Lyman alpha systems – deep absorptions thought to be the gas disks of young galaxies in which both Lyman alpha (i.e. H) and some heavier elements can be observed, telling us about element enrichment in the early Universe.
- Lyman alpha forest – weaker absorptions along the line of sight.
- Observations and modelling of the absorptions on the blue and red sides of Lyman alpha can probe the extent of the Inter-Galactic Medium's ionisation, and so the amount of hydrogen 'left over' and residing between galaxies *and* the source of ionising photons.

Much more on quasars as cosmological probes in Part II of the course …

PHYS2160 – Lecture 9 – The Distance Ladder - I

Galaxy Redshifts

By 1916 Vesto Slipher had obtained spectra for some 50-odd galaxies – the results confounded both him and the other astronomers of the day because almost every galaxy was *redshifted!*

In the 1920's Edwin Hubble began observing these galaxies with the (then) world's most powerful telescope – the 100 inch reflector at Mt Wilson, near Los Angeles.

Hubble had already used a class of variable stars called "Cepheids" (discovered to be useful as standard candles in 1908 by Henrietta Leavitt) to determine that the Andromeda galaxy could not be part of the Milky Way. **And** then classified different types of galaxies using his "tuning fork" system.

In the 1920s he began using Cepheid distances to estimate the maximum brightness that stars had in nearby galaxies. And then used the observed apparent magnitude of the brightest stars to estimate distances to more distant galaxies and compare them with Slipher's velocities.

PHYS2160 – Lecture 9 – The Distance Ladder - I

The "Hubble Diagram"

Hubble's results (Proceedings of the National Academy of Sciences, 15, 1929 – replotted below) were remarkable – *the distances were correlated with the redshifted velocities*! If we parameterise the velocity shift with redshift, z

$$z = \Delta\lambda/\lambda = \lambda/\lambda_0 - 1$$

then

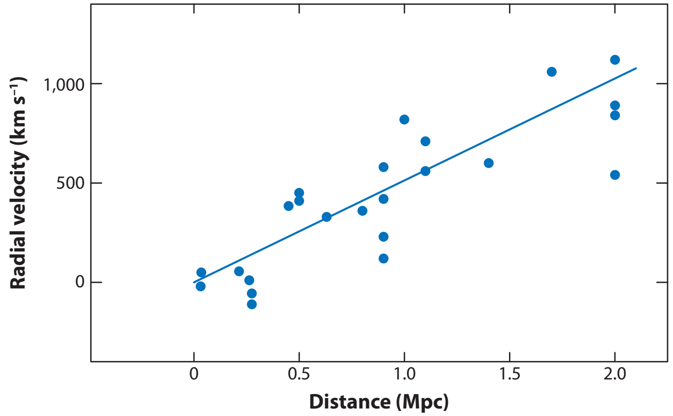
$$\Delta\lambda/\lambda = v/c$$

or

$$v = zc$$

The correlation observed can then be paramaterised with a constant H_0 to give the Hubble law

$$v = H_0 d$$



Freedman & Madore (2010)

Figure 1

Radial velocities, corrected for solar motion, plotted versus distances estimated from stars and mean luminosities of galaxies in clusters. The solid dots and line represent the solution for solar motion using individual galaxies. Hubble wrote, "The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space." (Adapted from Hubble 1929a.)

Most commonly H_0 is given in units of km/s / Mpc. The "0" subscript is used to refer to the fact that this is the present-day value of the Hubble constant. This relation was actually predicted earlier as an outcome of General Relativity by Georges Lemaître for an expanding universe, in 1927. (A rare case of an observer who confirmed a law getting it named after him, rather than the theorist who predicted it!)

PHYS2160 – Lecture 9 – The Distance Ladder - I

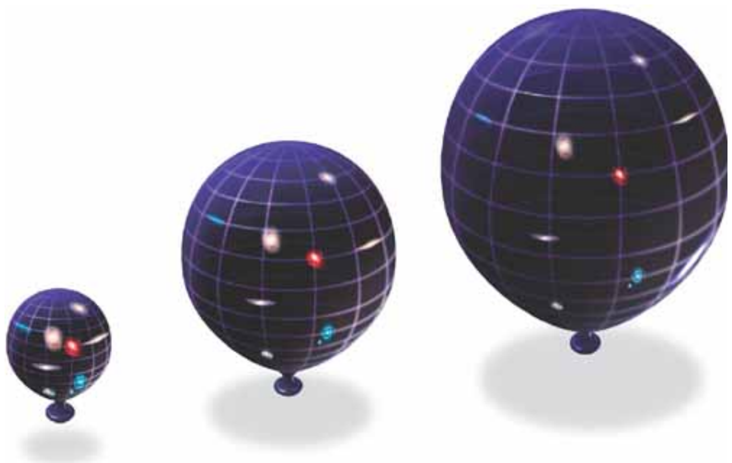
The “Hubble Diagram”

It turns out Hubble’s value for the Hubble constant (500 km/s/Mpc) was ***hugely*** wrong – in the most distant galaxies the objects he thought were the “brightest” stars were actually globular clusters. Nonetheless while the value for H_0 was wrong, the general principle (that distance and redshift were correlated) was correct.

The meaning of this discovery is remarkable – wherever you look in the sky, galaxies are receding away from you, and the further they are away, the faster they are receding.

At first glance this violates the “Copernican principle” that we, as observers, should not lie in a special place within the Universe!

The modern interpretation of this discovery is that our location is **not** special. Rather, **all** of space is expanding, as as a result no matter **where** you are, all directions will appear to expand away from you.



Moreover, because expansion effects light as well, the radiation is “stretched” or redshifted the further it travels.

PHYS2160 – Lecture 9 – The Distance Ladder - I

The Hubble's Constant and the Age of the Universe

Hubble's constant provides a "first order" constraint on the age of the Universe. Assume the Universe has been expanding at a constant rate since its birth. One can then imagine running it "backwards" to an initial time.

Since $v = H_0 d$ and a velocity can be written as a distance divided by a time, then

$H_0 d = v = d / t$ … or equivalently … $t = 1 / H_0$

So if H always had value H_0, then t would correspond to the age of the Universe. Hubble's 500km/s/Mpc implied an age of about 1.8Gyr, which was a problem even in 1930, because there was substantial geological evidence that the Earth was older than this.

Modern values of H_0 are closer to 70 ± 1 km/s/Mpc (though still with some scatter between the various methods that is larger than their individual uncertainties – e.g. Planck and WMAP cosmic microwave background experiments, HST Cepheid Key Project). In which case the above calculation gives a rough age of 14Gyr.

Note that this is only a first-order approximation since H will actually have varied over time since the birth of the Universe.

PHYS2160 – Lecture 9 – The Distance Ladder - I

Measuring Distances

To measure Hubble's constant, one needs observations of two things –

galaxy velocities/redshifts (**easy**) and

galaxy distances (**hard**). [There are no tape measures in astronomy.]

To do the latter we invoke the idea of a "standard candle". If you know the intrinsic luminosity of something – or even just that the intrinsic luminosity doesn't change – you can measure distances via the $1/r^2$ law … i.e. flux $\propto L/d^2$

This is the same physical law that drives our old friend the relationship between apparent and absolute magnitude expressed as the distance modulus (DM):

$m - M = DM = 5 \log d - 5$ (where d is in pc, and so DM=0 at 10pc).

PHYS2160 – Lecture 9 – Quasars as probes of the Universe

- References
  - http://www.2dfquasar.org and http://www.2slaq.info
  - Freedman, W. L., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47 (http://arxiv.org/abs/astroph/0012376); Freedman & Madore (2010), ARAA, 48, 673 (see Materials page)
- Bibliography
  - Wendy Freedman (2013) “The cosmic distance scale and H0: Past, present, and future” http://dx.doi.org/10.1017/S1743921312021047

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	$=$	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	$=$	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	$=$	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	$=$	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	$=$	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	$=$	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	$=$	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	$=$	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	$=$	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	$=$	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	$=$	1.496	$\times$	10^{11}	m
Parsec	pc	$=$	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	$=$	$5 \log d - 5 \quad (d \text{ in pc})$
Apparent magnitude	$m_2 - m_1$	$=$	$2.5 \log \frac{f_1}{f_2}$
For small recession velocities	v/c	$=$	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$

PHYS2160 – Lecture 10 – The Distance Ladder - II

Last time
- Quasars as “lamp posts” for studying Universe
- Numbers
- Optical spectra – emission lines, absorption lines
- The first part of the distance ladder – the Hubble Law & the expanding Universe.
- Discovery of the Universe’s expansion

This Time
- Measuring Distances & Standard Candles
- The Distance Ladder: Parallaxes ➔ Cepheids ➔ Tully-Fisher ➔ Dn-Sigma

Mid-term Exam will take place in OMB151 next Wed, Sep 2 at 1 pm.

- It will start at 1:05pm.
- It will be closed book and last 50 minutes.
- You will leave your bags (including mobile phones & other computing devices) at the front of the room and spread about the room to the maximum extent allowed.
- Exam booklets will be provided.
- You may use a scientific calculator.

PHYS2160 – Lecture 9 – The Distance Ladder - I

The "Hubble Diagram"

It turns out Hubble's value for the Hubble constant was ***hugely*** wrong (500 km/s/Mpc) – in the most distant galaxies the objects he thought were the "brightest" stars were actually globular clusters. Nonetheless while the value for H_0 was wrong, the general principle (that distance and redshift were correlated) was correct.

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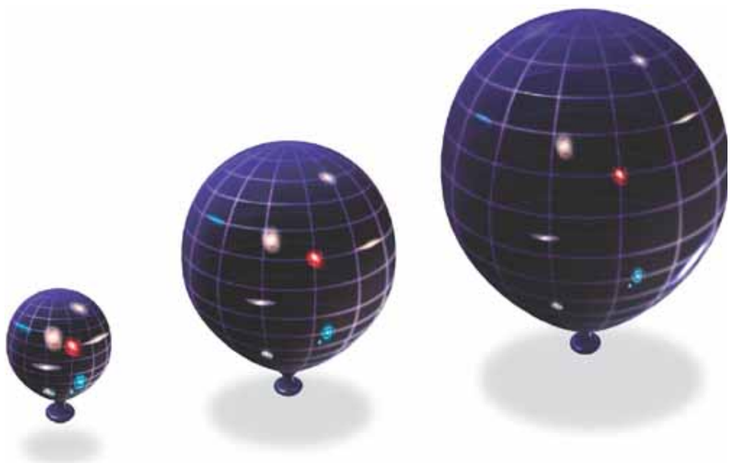


Moreover, because expansion effects light as well, the radiation is "stretched" or redshifted the further it travels.

PHYS2160 – Lecture 10 – The Distance Ladder - II

Standard Candles

The ideal standard candle would be something we can observe so close to the Sun we can get a geometric distance from a trigonometric parallax, **and** so bright we can observe it in the most distant galaxies. Sadly these types of objects don't exist.

Also the dynamic range we can access from observations is limited. If the brightest nearby stars have visual magnitude of about 0, and the most faintest things we can observe with current technologies are around 25th magnitude, then our *dynamic range* is only 25 magnitudes. This represents a range of fluxes of 10 orders of magnitude. Or a range in distance of 5 orders of magnitude. So any one "standard candle" can only get me 5 orders of magnitude in distance.

As a result we have to "bootstrap" distance measures from classes of standard candles we **can** observe nearby, to more luminous classes of object we can see at larger distances.

As long as each successive class works in a distance range that overlaps, we can build a distance scale to more and more distant objects.

Hence the term "distance ladder" is a bit of a misnomer … its not so much a single ladder, as …

A bunch of ladders strapped together …

PHYS2160 – Lecture 10 – The Distance Ladder - II

Peculiar Velocities

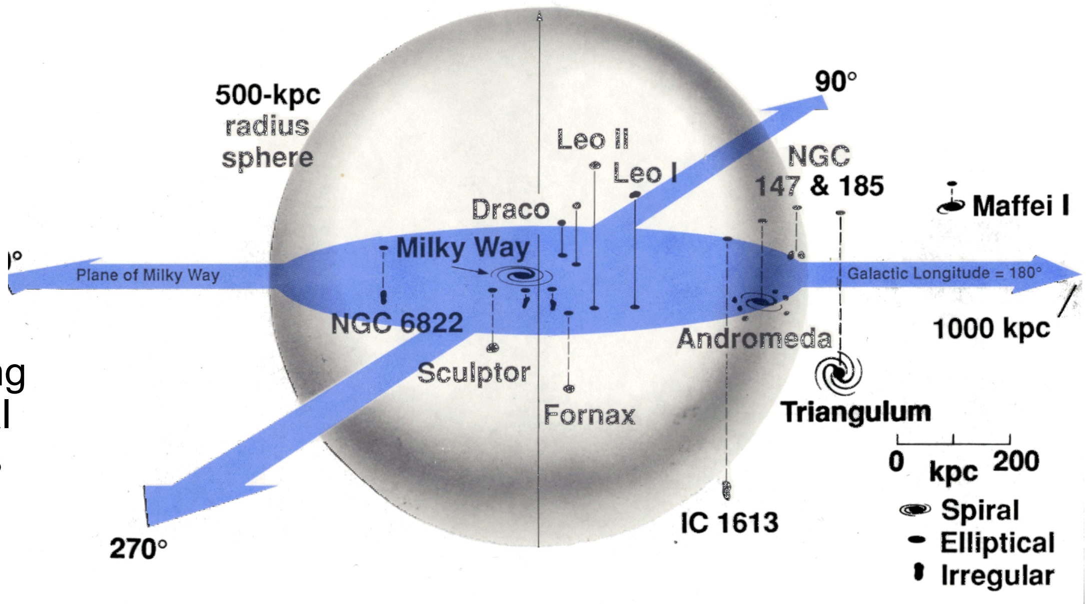
There is a complication. Just as in our Galaxy's disk, stars have their own small, random velocities which are imprinted on top of an underlying rotation, so the galaxies in the universe have "peculiar velocities" relative to the underlying Hubble expansion.

For example, the nearest spiral galaxy of similar size to the Milky Way is Andromeda (or M31). It lies at a distance of 778kpc from the MW, but has a blueshifted radial velocity – i.e. it is moving **towards** the MW not away from it.

Which means that if you want to probe the Hubble flow to measure H_0 you have to have distance measures that work **well beyond** 10Mpc to avoid this source of "noise" (which has values up to the ±1000km/s level).

(Though the noise is **also** interesting since these motions reflect the local gravitational potential and so tell us about matter densities in the local area).

The "Local Group" of galaxies near the MW



PHYS2160 – Lecture 10 – The Distance Ladder - II

Standard Candles – Cepheids

Cepheids (named after their brightest proto-type δ Cepheii) are a class of supergiant undergoing radial pulsation. This pulsation is driven by a He ionization envelope – this layer traps energy resulting in an increase in internal pressure, which causes expansion, which causes cooling, which causes opacity to drop, so the star's expansion stops and it recollapses, driving the He opacity back up, and re-starting the process.

The period of this cycle is proportional to the luminosity of the star, meaning that if you can find Cepheids, and measure their periods, you can derive their luminosities.

That is – you have a standard candle.

This period-luminosity relation was discovered by Henrietta Leavitt in 1908 and is now known as the "Leavitt Law".

The figure to the right shows examples of these relations for stars in both our Galaxy and the Large Magellanic Cloud (from Freedman & Madore 2010).

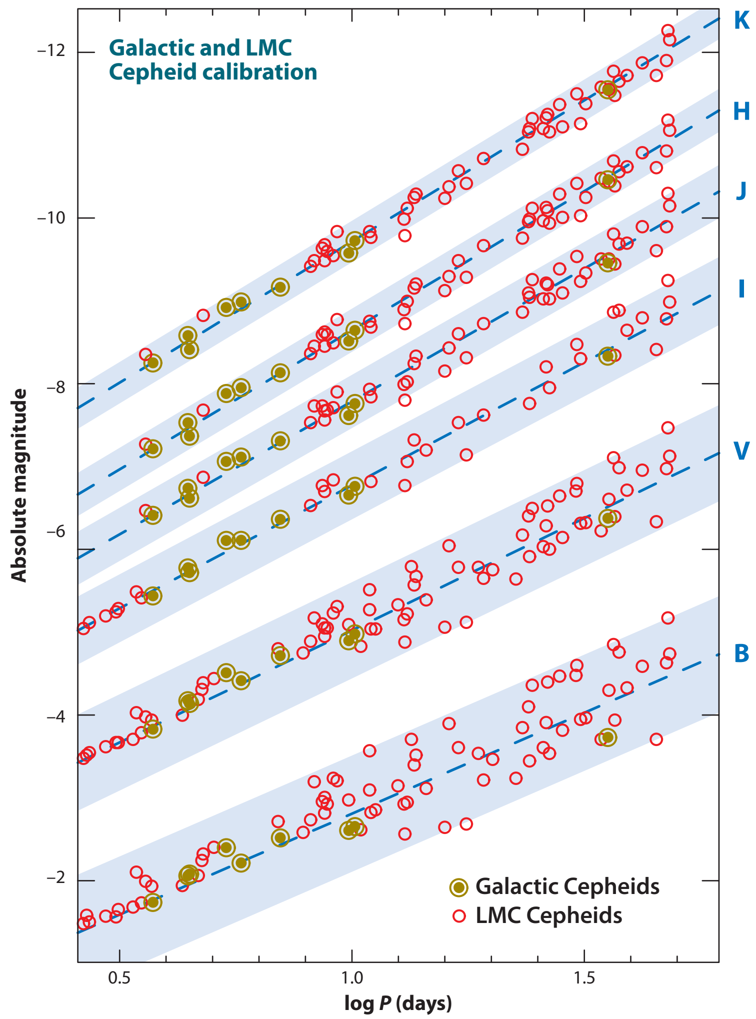


Figure 3

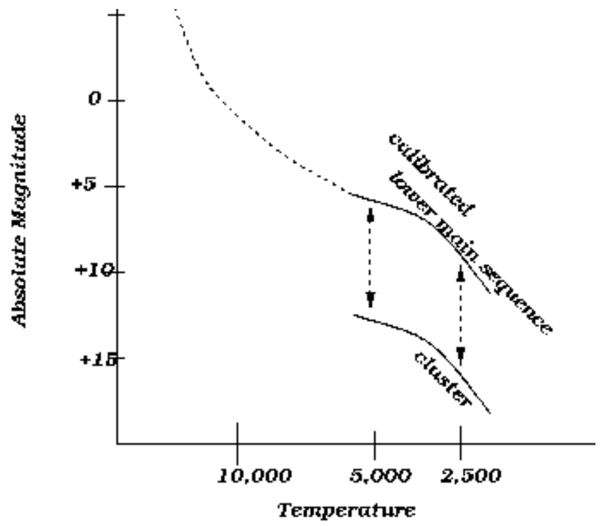
Composite multiwavelength period-luminosity (PL) relations (Leavitt Laws) for Galactic (*circled filled dark yellow dots*) and Large Magellanic Cloud (LMC) (*open red circles*) Cepheids from the optical (BVI) through the near-IR (JHK). There is a monotonic increase in the slope, coupled with a dramatic decrease in total dispersion of the PL relations as one goes to longer and longer wavelengths.

PHYS2160 – Lecture 10 – The Distance Ladder - II

Standard Candles – Zero-pointing the Cepheids

The calibration of this relation, however, still requires an absolute distance measurement for at least some Cepheids, and the only way to get that is from trigonometric parallaxes. Unfortunately, the closest Cepheids are 250pc away which can only be done from space.

Traditionally this calibration required an extra “ladder” – main sequence fitting for star clusters near enough to measure parallaxes (e.g. the Pleiades), and more distant clusters with Cepheids. This is problematic and complex.



Fortunately the Hubble Space Telescope’s Fine Guidance Sensors are able to do these sorts of precisions for ~10 of the nearest Cepheids giving us (in recent years) a zero-point calibration good to ±3%.

Even better in 2013, the European Space Agency launched its *GAIA* satellite, which will measure distances for hundreds of thousands of stars out to several kpc, revolutionising our fundamental calibration of Cepheids.

PHYS2160 – Lecture 10 – The Distance Ladder - II

Standard Candles – Calibrating the Cepheids

In addition to getting the zero-point on the Leavitt laws (in various observational passbands) right, it is also important to get the slopes of these laws measured precisely.

The Large Magellanic Cloud has played a key role here, as the nearest galaxy to our own Milky Way. Thousands of Cepheids have been observed in this one system (at a single distance), so one can densely populate the Leavitt Law plots to more precisely (both statistically and systematically) determine the relevant slopes (e.g. the plots 2 pages back).

As a result the slopes of the Leavitt Laws used all come from LMC data, while the zero-points come Galactic Cepheids.

This also gives us a precise distance to the LMC of DM=18.39±0.03 mag (see Freedman & Madore 2010), or 47.6±1.4kpc.

PHYS2160 – Lecture 10 – The Distance Ladder - II

Standard Candles – Cepheids – The Second Rung

The most distant Cepheids provide us with distances out to around 25Mpc. The resulting Hubble diagram (from the HST H_0 Key Project, Freedman et al. 2001) is shown below.

The formal H_0 solution for this data is 75±10km/s/Mpc.

This is certainly more precise than Hubble's result, but there is still substantial scatter due to peculiar velocities in the "local universe"

Cepheids alone don't have the dynamic range to probe H_0 by them selves. We need to strap on another ladder

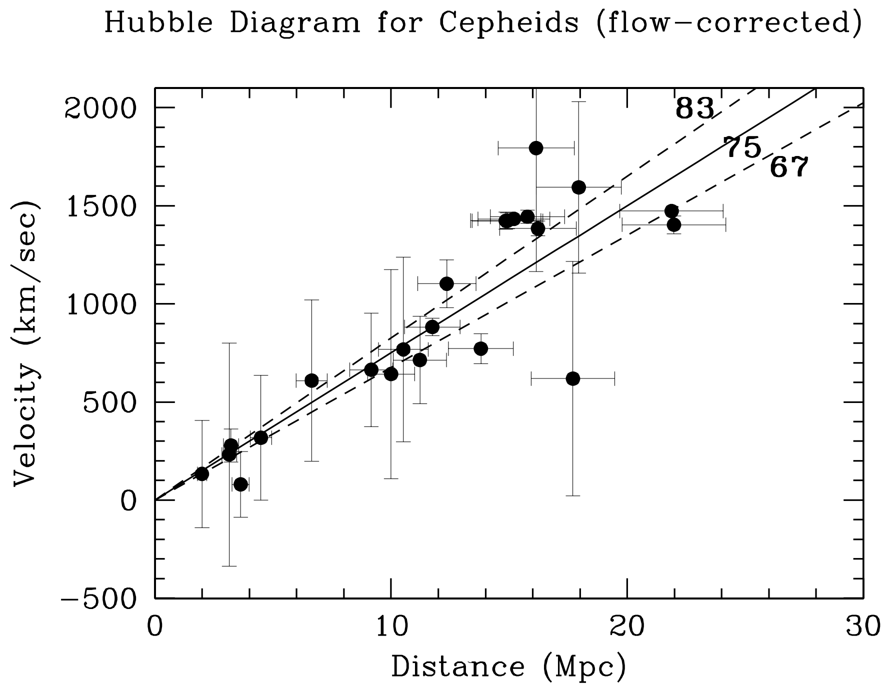


Fig. 1.— Velocity versus distance for galaxies with Cepheid distances. Velocities in this plot have been corrected using the flow model described in Mould et al. (2000). The Cepheid distances have been corrected for metallicity. A formal fit to these data yields a slope of $H_0 = 75 \pm 10_r$ km/sec/Mpc, in good agreement, to within the uncertainties, of the value of H_0 obtained for methods which extend to much greater distances.

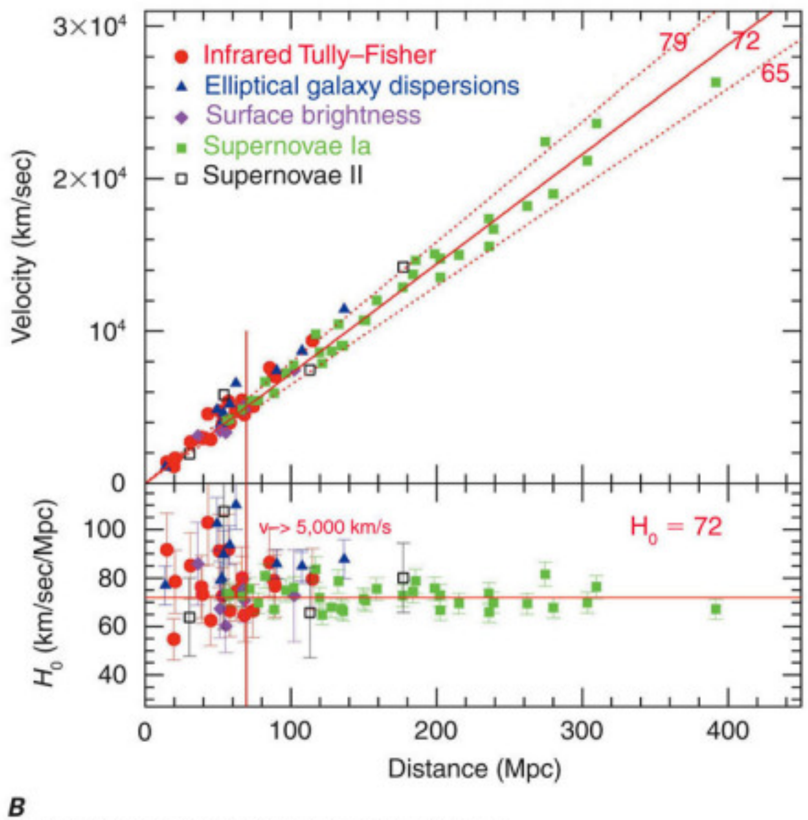
PHYS2160 – Lecture 10 – The Distance Ladder - II

Adding More Ladders – More Standard Candles

A range of relative distance indicators have been used to extend precise distance measurement beyond the <30Mpc accessible to Cepheids.

These include

- the Tully-Fisher relation,
- Elliptical galaxy surface-brightness fluctuations
- Type II supernovae, and
- Type Ia supernovae.

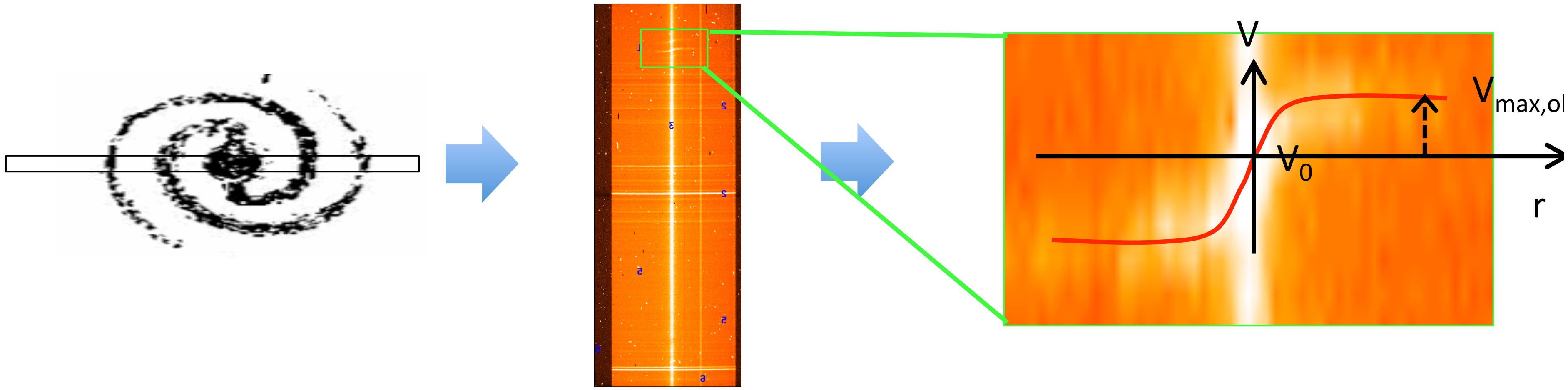


(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

PHYS2160 – Lecture 10 – The Distance Ladder - II

More Ladders – Tully-Fisher

Tully-Fisher utilises a relation between a galaxy's mass (and luminosity) and its maximum observed rotation velocity. You will recall from Lectures 7/8, that we examined how an optical spectrum of a spiral galaxy could be used to measure a rotation curve, and that the maximum velocities observed would tell you to total mass enclosed at that radius in the galaxy.



$M_{gal} = V_{max}^2 r/G$

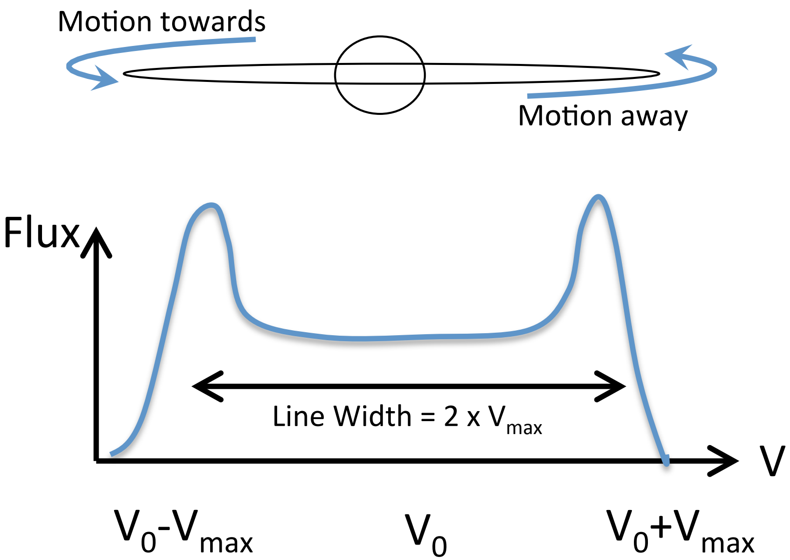
If we assume that L $\propto M_{gal}$, we can derive that $V_{max} \propto \sqrt{L}$

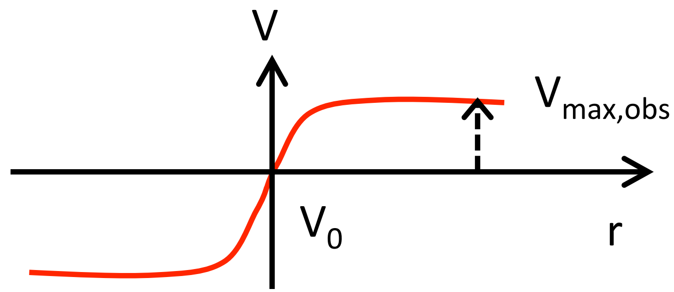
PHYS2160 – Lecture 10 – The Distance Ladder - II

More Ladders – Tully-Fisher

This $V_{max} \propto \sqrt{L}$ relationship can then be calibrated using nearby galaxies (for which Cepheids can be used to get distances to obtain L), and used to extend distance measures to larger distances.

V_{max} for this technique is usually measured using *HI radio observations* of the galaxy's gas disk. Rather than a velocity profile as a function of position on the disk, this technique produces an integrated velocity along the line of sight, and Vmax comes from the observed line width





Leading to the ability to derive relations of the form

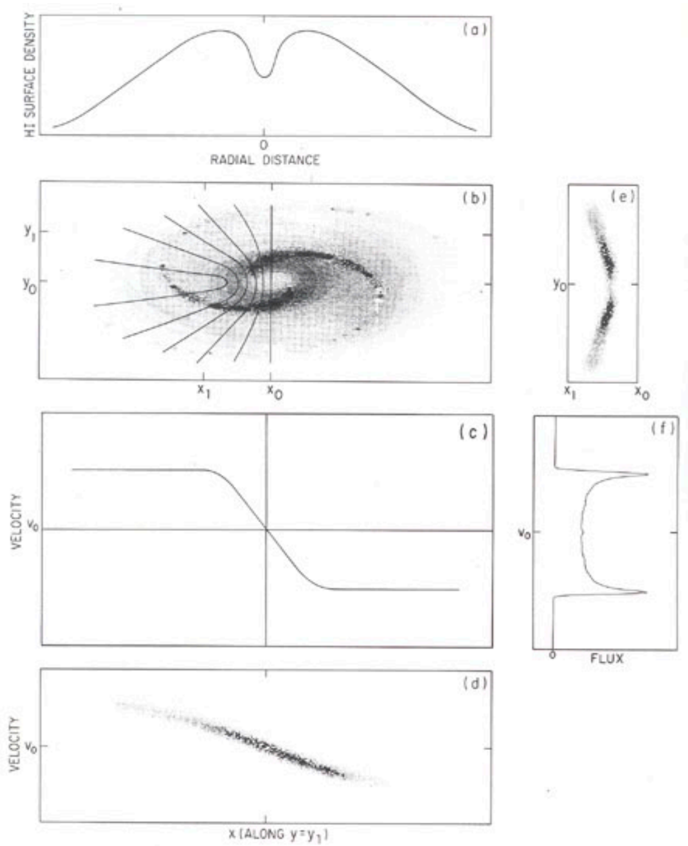
$$\text{Abs.Mag} = A \log(V_{max}) + B$$

where V_{max} is a maximum rotation velocity (corrected for inclination), A, B are consts.

PHYS2160 – Lecture 10 – The Distance Ladder - II

For those interested … some more on HI Velocity Profiles (from http://ned.ipac.caltech.edu/level5/Sept04/Giovanelli/Giovanelli1_3.html)

The HI data for a galaxy can be thought of as a three-dimensional array of intensities, expressed in terms of two angular coordinates in the plane of the sky and radial velocity, which may be referred to as a "data cube." The array values are set by the six-dimensional position-velocity distribution of the galaxy's HI. Assume that the HI is confined to a thin disk and that axial symmetry holds for both its distribution and velocity field. In panels (a) and (c) of the figure, both the radial dependence of the HI surface density and the rotation curve are idealized averages of those observed in intermediate-type spirals. Integration of the data cube along the radial velocity axis will yield a map of the column density distribution in the sky; in panel (b), the disk is simulated at a viewing inclination of 60°. The degree of shading represents the column density map. Each member of the superimposed family of lines identifies the locus of points characterized by a constant radial velocity. If instead of integrating over radial velocity, we slice the data cube at a constant value of one of the sky coordinates, for example, slightly off and parallel to the major axis of the tilted disk, we obtain a position-velocity map (d) which mimics the rotation curve (b), blurred by the limitations of spatial and spectral resolution. A slice of the cube at constant velocity will yield a "channel map," as in panel (e): the angular distribution of all HI whose velocity falls within a narrow velocity range, for example, the span of a single receiver channel, now mimicking one of the loci of panel (b). Finally, observation of the galaxy with a single dish that does not resolve the HI disk will yield an integrated profile of the type shown in panel (f).



Of course, real data will be cursed (or blessed ...) with asymmetries, spiral features, small-scale irregularities, flared or disrupted disks, etc.

PHYS2160 – Lecture 10 – The Distance Ladder - II

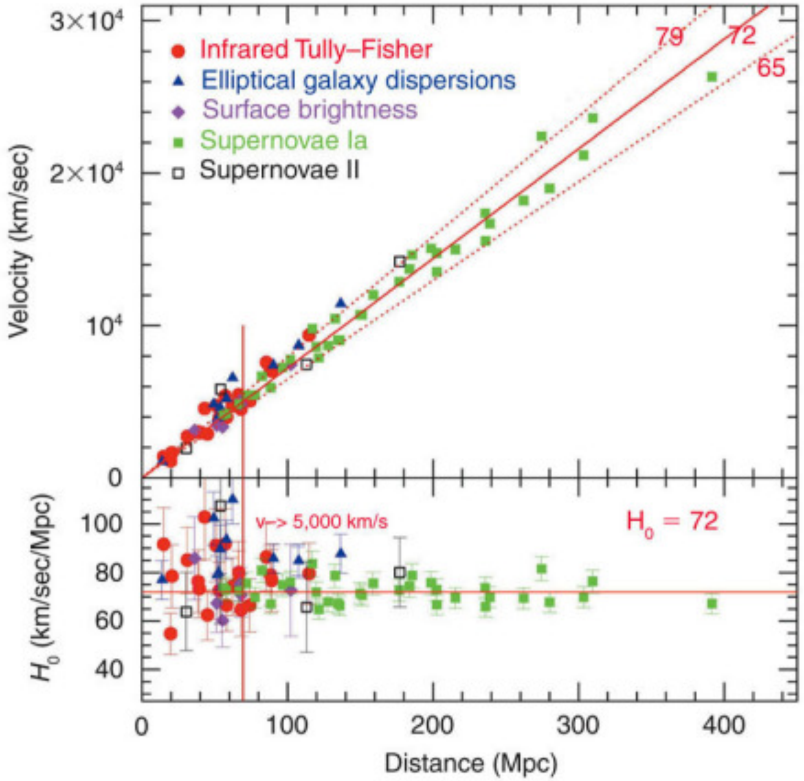
More Ladders – Tully-Fisher

And as we see from the Figure from Freedman et al. 2001 (below), this then allows us to bootstrap out to distances of ~100Mpc.

Of course there are issues …

… specifically the technique relies on the assumption that luminosity is correlated with mass in the same way for all galaxies.

This is not strictly true, and so it is a more 'secondary' technique than Cepheids.



B

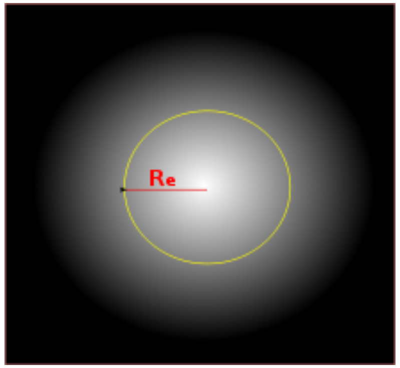
(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

PHYS2160 – Lecture 10 – The Distance Ladder - II

More Ladders - Elliptical galaxies – D_n-σ or "Fundamental Plane"

The "fundamental Plane" is a set of *empirical* relationships for elliptical galaxies …

– Larger galaxies have fainter effective surface brightness. (Surface brightness is the brightnes of a galaxy per unit area on sky, and are usually measured I magnitude per square arcsecond). For example it has been observed that (Djorgovski & Davis 1987),



$$R_e \propto \langle I_e \rangle^{-0.83\pm0.08}$$

where R_e is the effective radius of the galaxy (the radius containing half the galaxy's luminosity) and $\langle I_e \rangle$ is the mean surface brightness interior to R_e.

*That is larger galaxies are **less** centrally condensed.*

– Since the effective luminosity (L_e) is just $\pi\langle I_e \rangle R_e^2$, one can also substitute … *more luminous galaxies have lower surface brightness*.

– More luminous galaxies also have larger central velocity dispersions (this is the Faber-Jackson relation – an elliptical galaxy equivaent to the Tully-Fisher relation).

If central velocity dispersion is correlated to luminosity, and luminosity is correlated with effective radius, then it follows that *the central velocity dispersion is positively correlated to the effective radius*.

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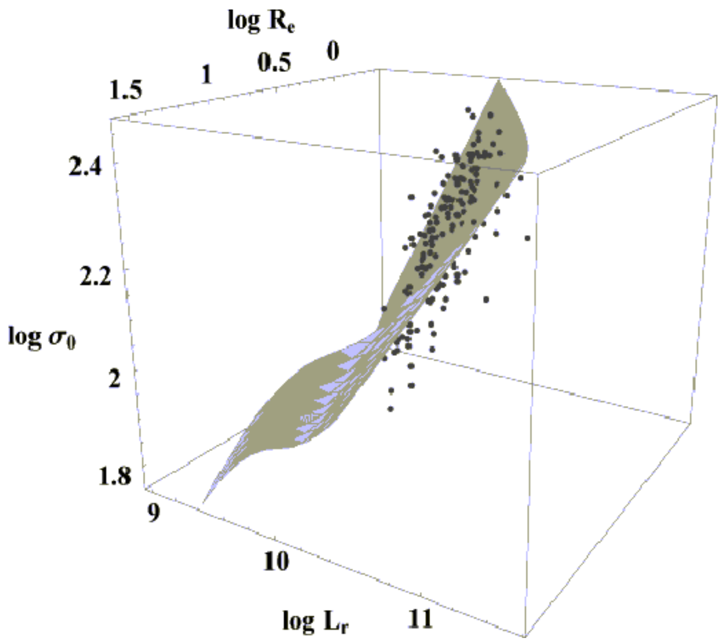
Elliptical galaxies – D_n-σ or "Fundamental Plane"

It is this last correlation that constitutes the D_n-σ relation as used from the 1980s onwards to estimate distances to elliptical galaxies. For example, Dressler et al. (1987) found that iif D_n is the diameter where surface brightness falls below 20.75 mag/sq.arcsec, and σ is the stellar velocity dispersion, then

$$\frac{D_n}{\mathrm{kpc}} = 2.05 \left(\frac{\sigma}{100\,\mathrm{km/s}}\right)^{1.33}$$

Given one then knows the physical radius, and can observe actual radius on sky, the comparison can tell you the distances. This gave distances with a scatter of about 15%.

However, this correlation is just a projection onto two terms of a correlation that actually lies in a three dimensional parameter space. This *fundamental plane* in the three space of ($\log R_e$, $<I_e>$, $\log \sigma$) can be used to determine a physical radius from surface brightness and velocity dispersion.



Example fundamental plane in a three-space of log Re, log σ, log L. (L can always be created if you know log R_e and $<I_e>$)
http://www.astro.rug.nl/~etolstoy/ACTUEELONDERZOEK/JAAR2005/pieter/distance.html

PHYS2160 – Lecture 10 – The Distance Ladder - II

- References
  - Freedman, W. L., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47 (http://arxiv.org/abs/astroph/0012376)
  - Freedman & Madore (2010), ARAA, 48, 673 (see Materials page)
- Bibliography
  - Wendy Freedman (2013) "The cosmic distance scale and H0: Past, present, and future" http://dx.doi.org/10.1017/S1743921312021047

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	$=$	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	$=$	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	$=$	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	$=$	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	$=$	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	$=$	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	$=$	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	$=$	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	$=$	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	$=$	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	$=$	1.496	$\times$	10^{11}	m
Parsec	pc	$=$	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	$=$	$5 \log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	$=$	$2.5 \log \frac{f_1}{f_2}$
For small recession velocities	v/c	$=$	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$

PHYS2160 – Lecture 11 – The Distance Ladder - III

Last time

- Discovery of the Universe's expansion
- Measuring Distances & Standard Candles
- The Distance Ladder: Parallaxes ➔ Cepheids ➔ Tully Fisher (for spiral galaxies)

This Time

- Other Distance Indicators
  - Elliptical galaxies – surface-brightness fluctuations
  - Elliptical galaxies – Dn-σ or "Fundamental Plane"
- Supernovae
  - Type Ia supernovae and their use in cosmology.

Mid-term Exam will take place in **that room** (OMB230) next Wed, Sep 3 at 3pm.

- It will start at 3:05pm.
- It will be closed book and last 50 minutes.
- You will leave your bags (including mobile phones & other computing devices) at the front of the room and spread about the room to the maximum extent allowed.
- Exam booklets will be provided.
- You may use a scientific calculator.

PHYS2160 – Lecture 11 – The Distance Ladder - III

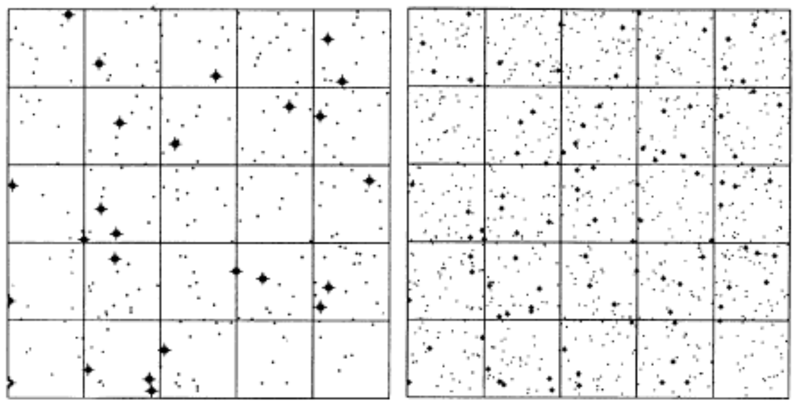
More Ladders – Elliptical galaxies – Surface-Brightness fluctuations

The technique (first proposed by John Tonry in the late 1980s) makes use of the fact that galaxy images will contain a finite number of stars per pixel, and that this number will vary from pixel-to-pixel, creating a noise-like fluctuation in the surface brightness distribution.

- The flux received from an elliptical galaxy is proportional to the distance as $1/r^2$.
- But the number of stars per pixel is proportional to the distance as r^2.
- Thus the surface brightness (the total flux received per pixel, or in this case flux per star times the number of stars) is independent of distance.
- But there is a difference between the nearby and faraway case – the more distant elliptical will look twice as smooth (i.e. the fluctuations between pixels will be smaller).

Thus by comparing the "smoothness" of two elliptical galaxies (one with known distance), using normalized fluxes (so they have both the same flux per pixel), one can obtain the distance of the other galaxy.

"Smoothness" will scale as $\sqrt{N}/N = 1/\sqrt{N} \equiv 1/\sqrt{d}$



Two example galaxy fields with the same surface brightness, but sampled at distances different by a factor of 2. Jacoby et al. 1992, PASP, 104, 599

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Another Ladder – Supernovae

Supernovae are observationally classified into multiple classes, which (in the main) are considered to arise from different physical causes.

- SN Type II - the SN spectrum contains lines of hydrogen
- SN Type I - the SN spectrum contains no lines of hydrogen
  - SN Ia – spectrum has an Si II absorption line at 615nm near maximum
  - SN Ib – weak or no SiII, and shows a He I line at 587.6nm
  - SN Ic – weak or no SiII, and shows weak or no He

These types are *taxonomic* – i.e. they arise form observable differences. *But what do they mean?*

- All SNe except Ia are thought to arise from "core collapse" – when nuclear fusion suddenly become unable to sustain a star's core against its own gravity.
- Stars more massive than about $10M_\odot$ will develop an iron core larger than the Chandrasekhar limit (i.e. a gravitationally unstable mass large enough ($\gtrsim 1.4M_\odot$) that electron degeneracy pressure is unable to stop the core from collapsing into a neutron star or black hole).
- When a core is unable to gravitationally support itself it will collapse at speeds reaching up to >0.2c.
- For progenitor masses below about $25M_\odot$ the core's collapse will rapidly halt as it forms a neutron star (i.e. neutron degeneracy pressure eventually supports the core). The resulting "bounce" coverts up to 10% of the star's mass into neutrinos, as well as a blastwave that propagates out through the remaining stellar envelope.

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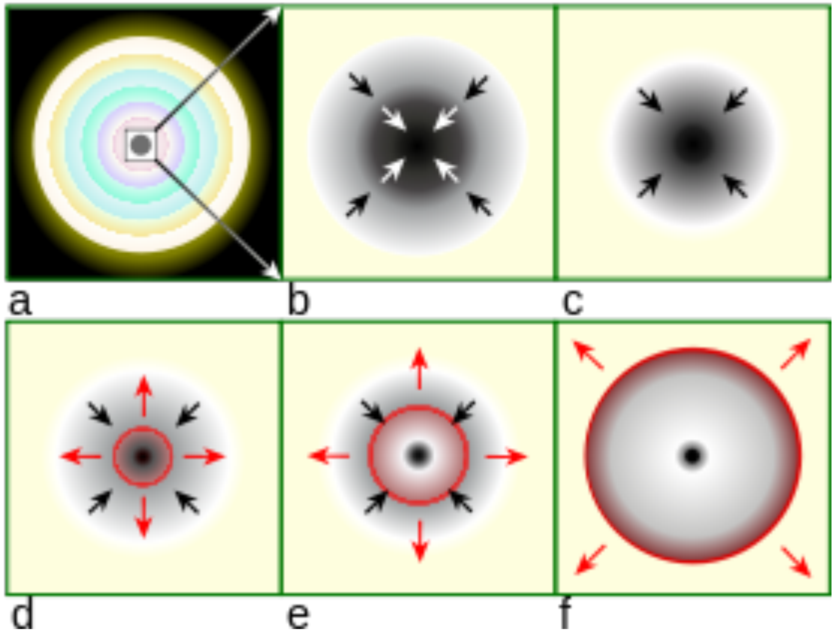
Supernovae

It is this blast that produces the vastly energetic explosion that we classify as SNe. (Current models predict a variety of variations on this theme of core collapse for masses above $25M_{\odot}$).



SN Type II - Within a massive, evolved star (a) the layered shells of elements undergo fusion, forming an iron core (b) that reaches the Chandrasekhar mass and starts to collapse. The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is re-invigorated by a process that may include neutrino interaction. The surrounding material is blasted away (f), leaving only a degenerate remnant.

(Note: The Chandrasekhar mass is the maximum core mass which can be supported against gravitational collapse by electron degeneracy pressure – two fermions cannot occupy the same quantum state, so in a dense sea of fermions (e.g. electrons) a repulsive force manifests as a pressure against the compression of matter into smaller volumes. Above the Chandrasekhar mass protons and electrons combine (via electron capture) to make neutrons. The corresponding neutron degeneracy liming mass is much larger, and poorly understood. Above this limit, the core will collapse into a black hole).

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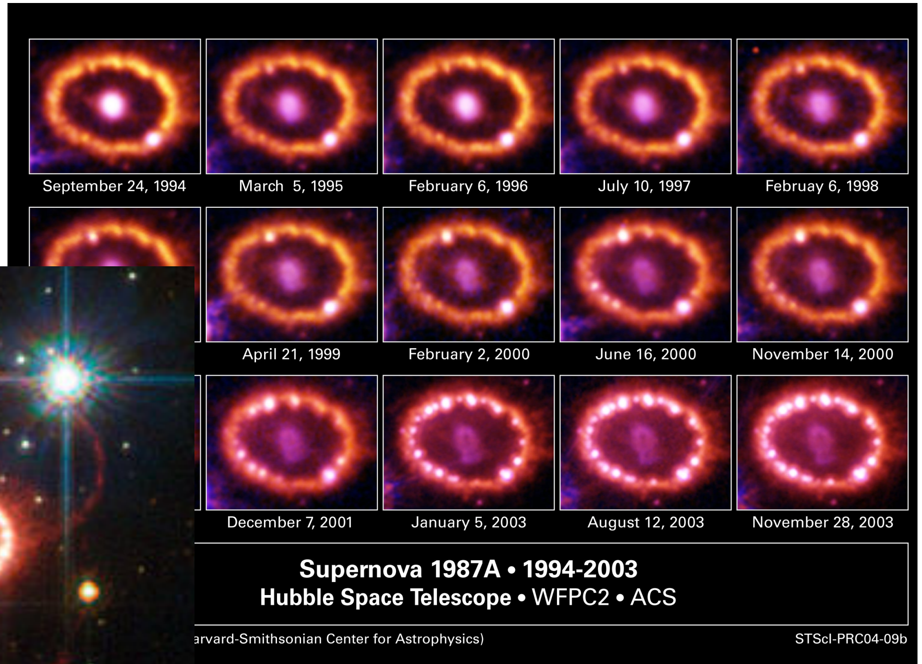
Supernovae – Type II

SN1987a exploded in the LMC on Feb 23-24 1987. Progenitor is though to have been an $18M_{\odot}$ B star. This very nearby SN is the only one for which the neutrino burst has been detected.



Because the neutrino burst *precedes* the emergence of optical radiation it was detected by looking *back* through neutrino detector data after the SN was discovered visually.

The “rings” are previously ejected material form the star being “lit up” over time by the blast wave from the SN.

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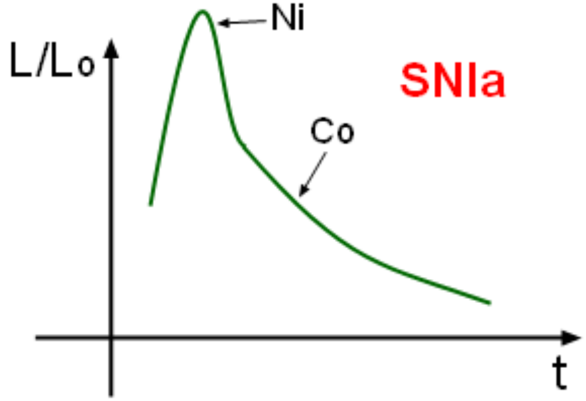
Supernovae – Type Ia

Except for SNe Ia – these SNe are thought to form via a variety of processes, all of which lead to matter being accreted onto a C-O (carbon-oxygen) white dwarf, such that nett mass exceeds ~1.4$M_\odot$. This much mass cannot sustain itself via electron degeneracy pressure and so the white dwarf will begin to collapse.

However, since this is a C-O white dwarf, this collapse generates the pressures and temperatures required to initiate C burning, and within a few seconds a substantial fraction of the matter in the white dwarf will undergo fusion, releasing sufficient energy to unbind the star. An expanding shock wave is generated, expelling material at up to 0.03c.

Type Ia SNe display a characteristic light curve after their explosion. This luminosity is generated by the radioactive decay of ^{56}Ni through ^{56}Co to ^{56}Fe. (The Ni is generated from Si burning in explosion; Si➔S➔Ar➔Ca➔Ti➔Cr➔Fe➔Ni; which itself follows O burning, which follows Ne burning, which follows C burning).



Amazingly, the peak luminosity of the light curve is extremely consistent across normal Type Ia SNe, having a maximum absolute magnitude ~ −19.3. This allows them to be used as a secondary standard candle to measure the distance to their host galaxies.

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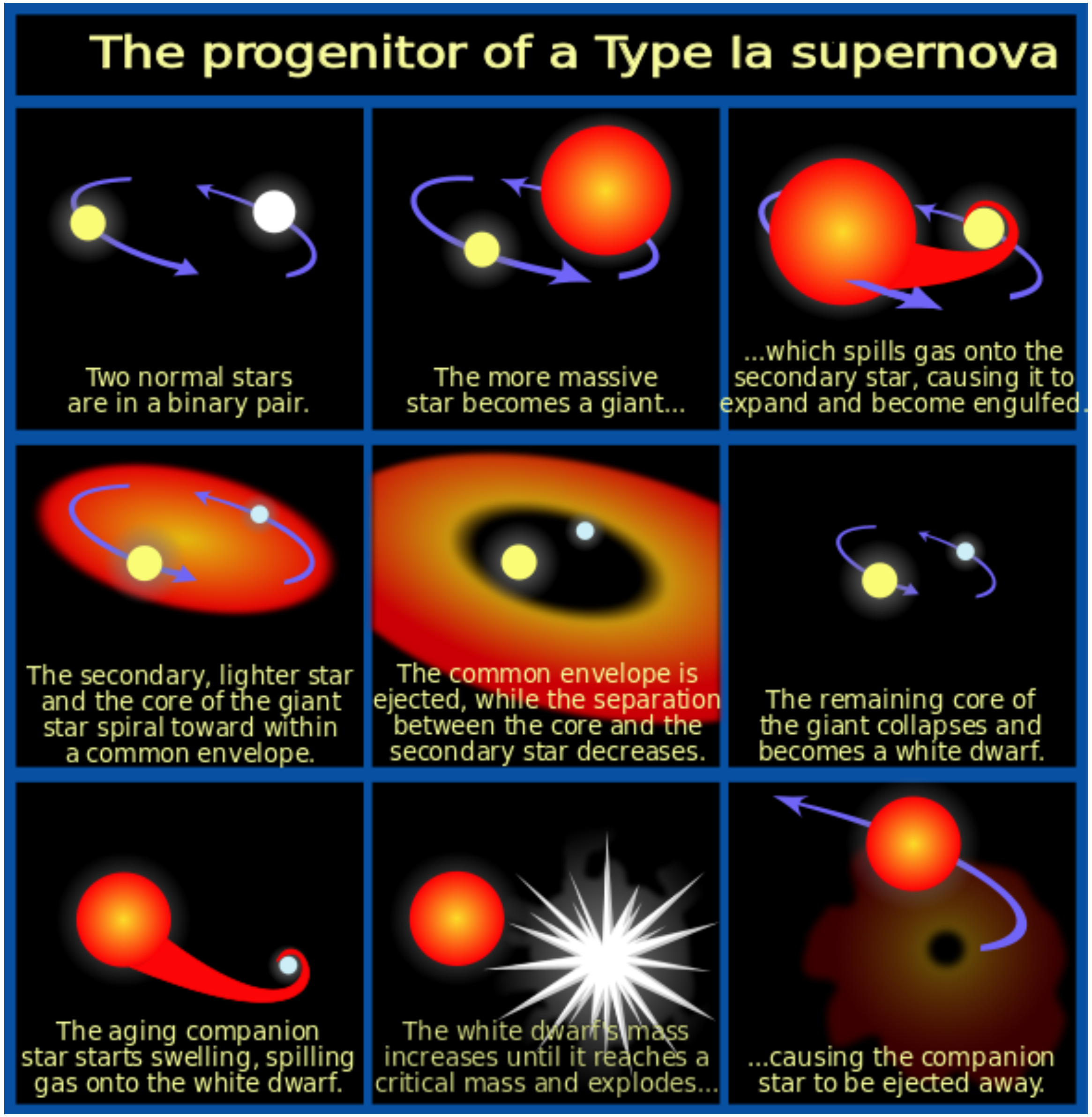

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Supernovae – Type Ia as Distance Indicators

Actually using SN Ia as a distance indicators, however, is just a little more complicated than this simple picture. The galaxy in which the SN resides may host dust which lies between us and the SN, which will (a) redden the light curve and (b) produce a fainter maximum luminosity.

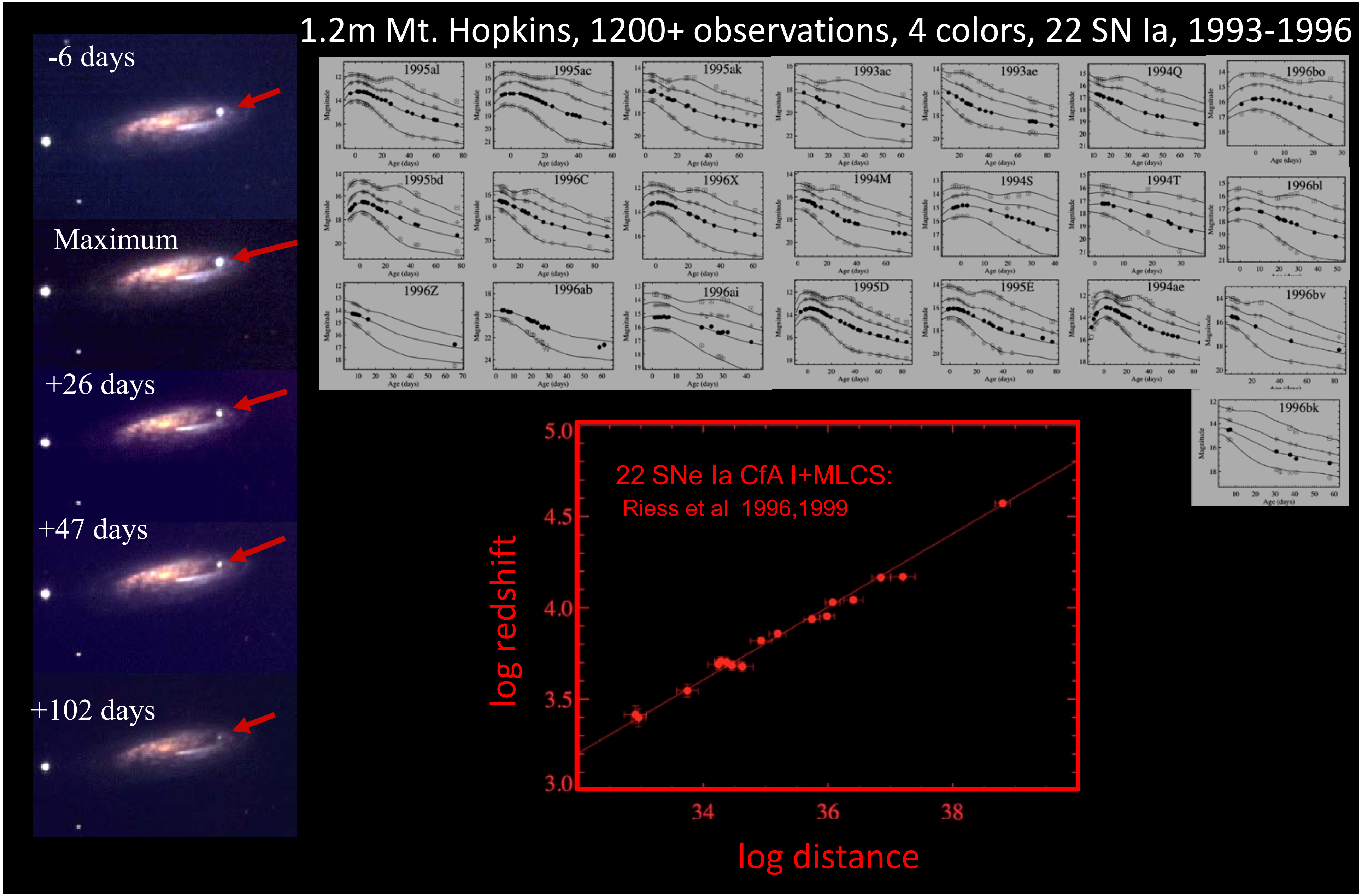
In the 1990s two teams were working hard at the problem of how to calibrate Ia Sne (a team led by Saul Perlmutter at Berkeley, and the High-Z team led by Brian Schmidt and Adam Riess).

As their analysis techniques developed, it turned out that Ia SNe really were remarkable distance indicators. And because a SN is a **very** bright event, it makes distance measurement at much larger distances feasible. Indeed all the way out to z=1 and beyond (equivalent to v=300,000km/s which is ~4300Mpc if we think H_0 is 70km/s/Mpc).

This is a sufficiently large distance that it becomes feasible to look for **changes** in the Hubble constant with time/distance, and so to probe the cosmology of our Universe.

Multi-Colour Light Curve Shapes (MCLS)

(Slide from Adam Reiss' Nobel Lecture 2011)

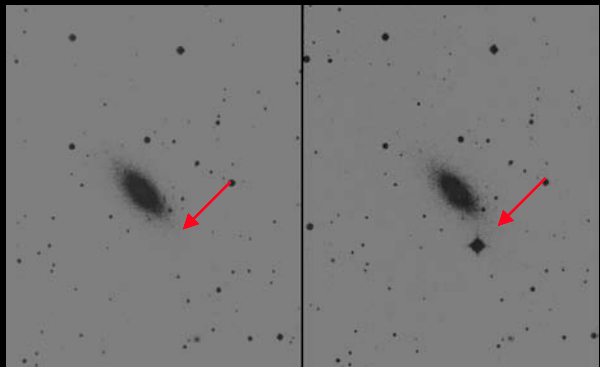


Multi-Colour Light Curve Shapes (MCLS)

(Slide from Adam Reiss' Nobel Lecture 2011)

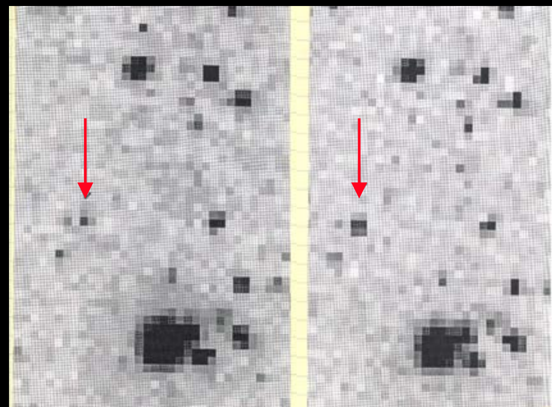
Though at large distances, these observations become very challenging!

SN Ia 1972E at 10 million light years



Before After

SN Ia 1996E at 6.6 billion light years



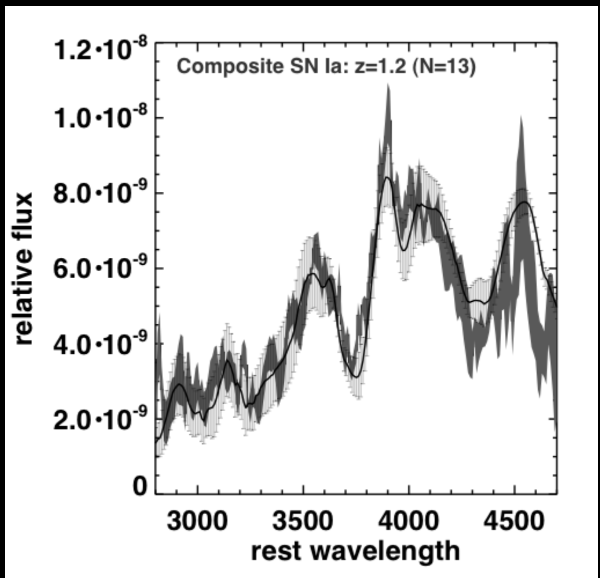
Before After

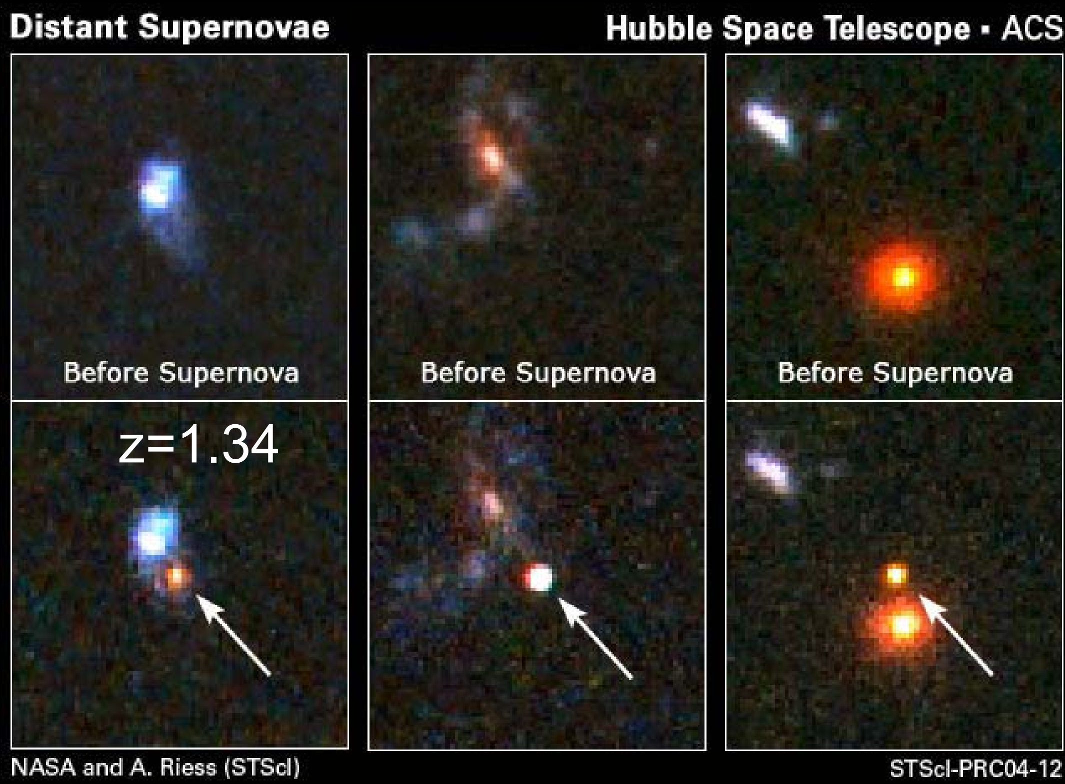
(Recall ly ~ 3.3pc, so 6.6 Gly is ~2000Mpc)

High-Z Type Ia

(Slide from Adam Reiss' Nobel Lecture 2011)

- In 2002 Astronauts install ACS
- From 2002-2007 the *Higher*-z Team measured 23 new SNe Ia at z>1

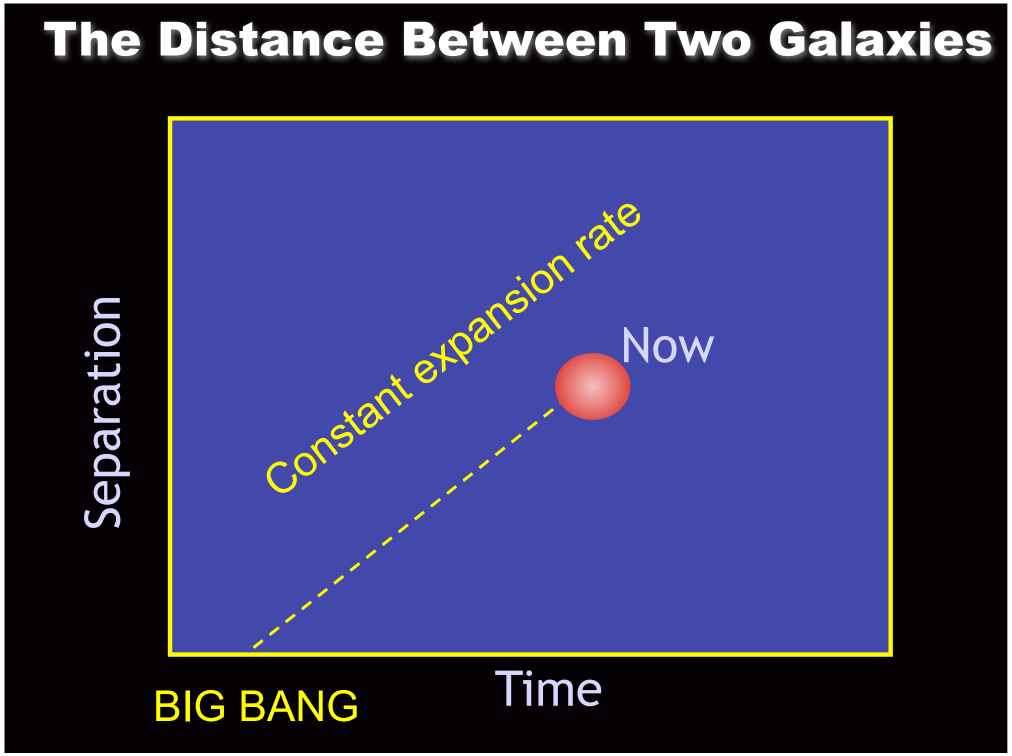




PHYS2160 – Lecture 11 – The Distance Ladder - III

Interpreting Type Ia SNe Distances

Imagine we probe the evolution of the Universe by measuring the distance between two galaxies today. If the Universe has been expanding at a constant rate, then we can extrapolate back to when that scale was zero to determine when the Big Bang was (as we did earlier).



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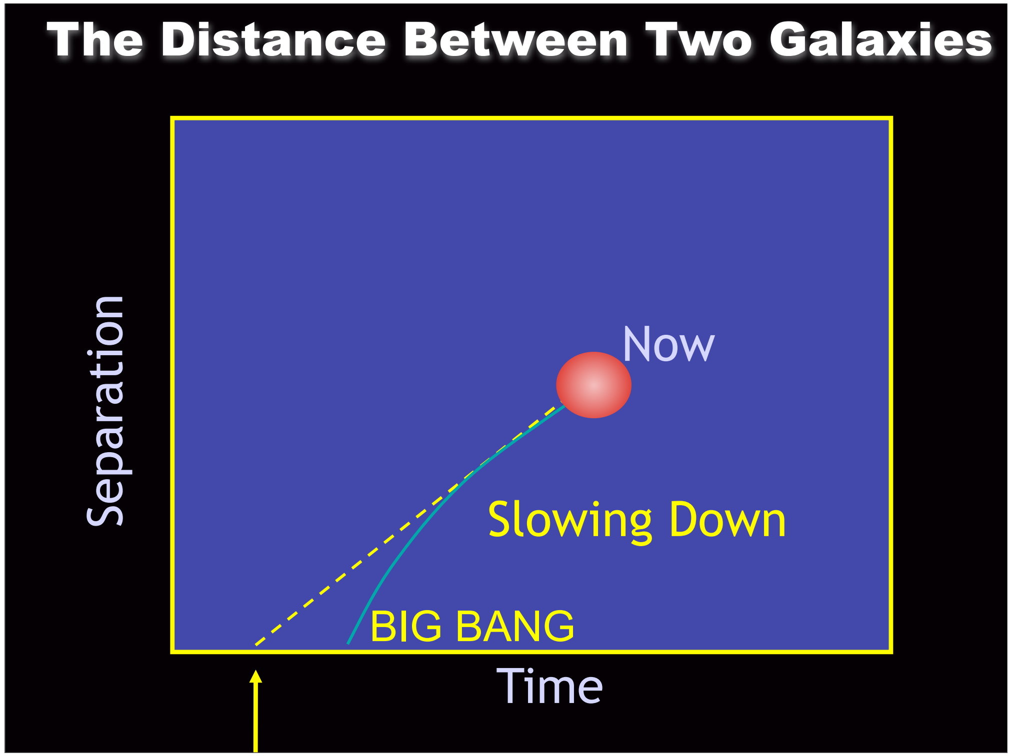
Interpreting Type Ia SNe Distances

But if the expansion is not constant (e.g. if it is slowing down – which is what we believe is happening because the presence of baryons and dark matter in the Universe will tend to slow the expansion), then the Big Bang will have happened more recently than the simple linear extrapolation of H_0 predicts.



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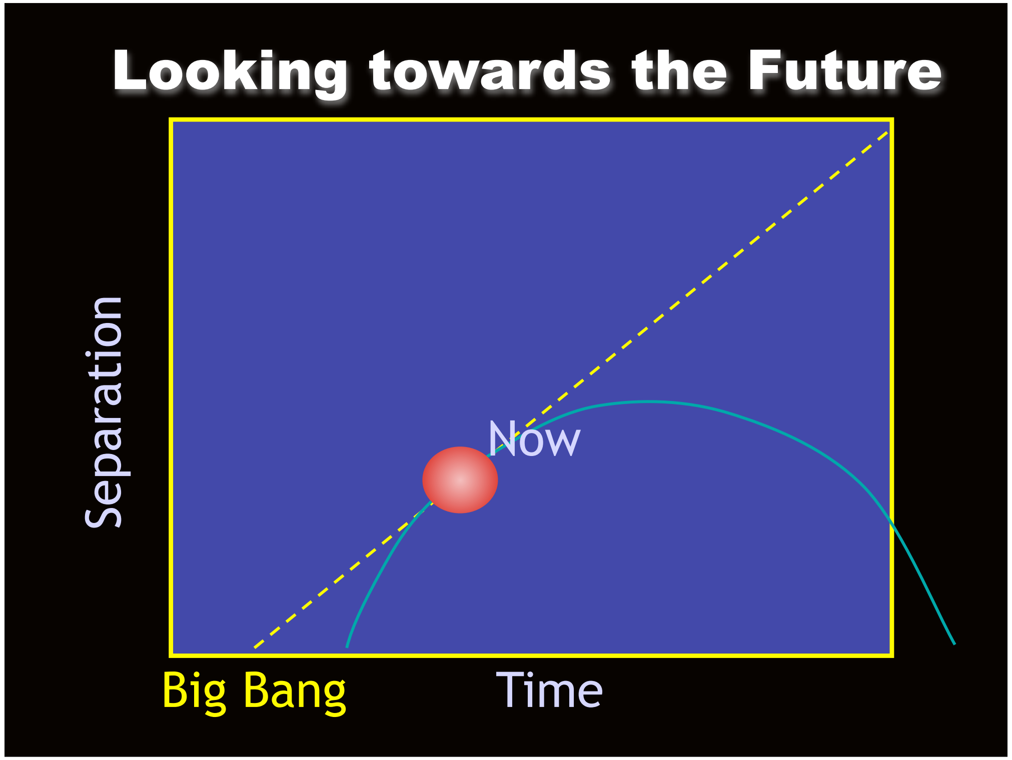
Interpreting Type Ia SNe Distances

We can also try to imagine what will happen in the future. If there is enough matter in the universe, the expansion will reverse and the Universe will collapse. Distance measurements allow us to probe the expansion of the Universe and determine into which regime it falls. If we measure the change in the Hubble constant with time and find we are below the blue line, then gravity wins and the Universe will recollapse.

If it lies between the blue line and the yellow dotted line, then the Universe will continue to expand indefinitiely.

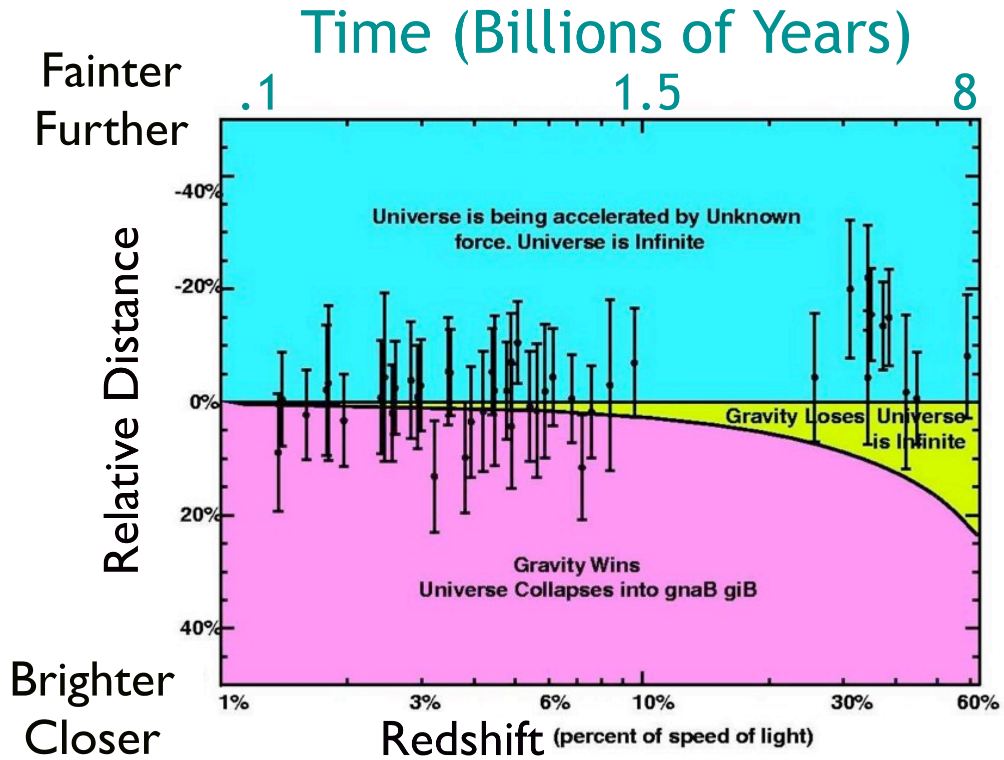
If it lies above the yellow dotted line, then something is making the Universe accelerate!



PHYS2160 – Lecture 11 – The Distance Ladder - III

And the Nobel Prize goes to …

SN Type Ia distances have shown that the last case is what is happening … if we plot change in the Hubble constant (here denoted "Relative Distance") vs Redshift (equivalent to time looking back into the Universe), we find that the trend is that the Universe is accelerating. Something is causing its expansion to increase, rather than contract. The cause of this acceleration has been christened "Dark Energy"



(Plot from Brian Schmidt's Nobel Lecture, 2011)

PHYS2160 – Lecture 11 – The Distance Ladder - II

- References
  - Adam Ríess (http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/riess-lecture.html) and Brian Schmidt (http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/schmidt-lecture.html) Nobel Prize lectures (text and slides available at these pages). Between them these give a good introduction to both SN as distance indicators, and their use for cosmology.
- Bibliography

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
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Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	$=$	$5\log d - 5$ (d in pc)
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