Lecture 33: Announcements

1) Pick up graded hwk 5. Good job: Jessica, Jessica, and Elizabeth for a 100% score on hwk 5 and the other 25% of the class with an A.

2) Article and homework 7 were posted on class website on Monday (Apr 18) . Due on Mon Apr 25.

3) Reading Assignment for Quiz Wed Apr 27   Ch 23, Cosmic Perspectives: The Beginning of Time

4) Exam moved to Wed May 4

Lecture 33: Galaxy Formation and Evolution

Several topics for galaxy evolution have already been covered in Lectures 2, 3, 4,14,15,16. you should refer to your in-class notes for these topics which include:

- Types of galaxies (barred spiral, unbarred spirals, ellipticals, irregulars)
- The Local Group of Galaxies, The Virgo and Coma Cluster of galaxies
- How images of distant galaxies allow us to look back in time
- The Hubble Ultra Deep Field (HUDF)
- The Doppler blueshift (Lectures 15-16)
- Tracing stars, dust, gas via observations at different wavelengths (Lecture15-16).

In next lectures, we will cover

- Galaxy Classification. The Hubble Sequence
- Mapping the Distance of Galaxies
- Mapping the Visible Constituents of Galaxies: Stars, Gas, Dust
- Understanding Galaxy Formation and Evolution
- Galaxy Interactions: Nearby Galaxies, the Milky Way, Distant Galaxies
- Mapping the Dark Matter in Galaxies and in the Universe
- The Big Bang
- Fates of our Universe and Dark Energy

Galaxy Classification

Galaxy: Collection of few times (10^8 to 10^{12}) stars orbiting a common center and bound by gravity. Made of gas, stars, dust, dark matter.

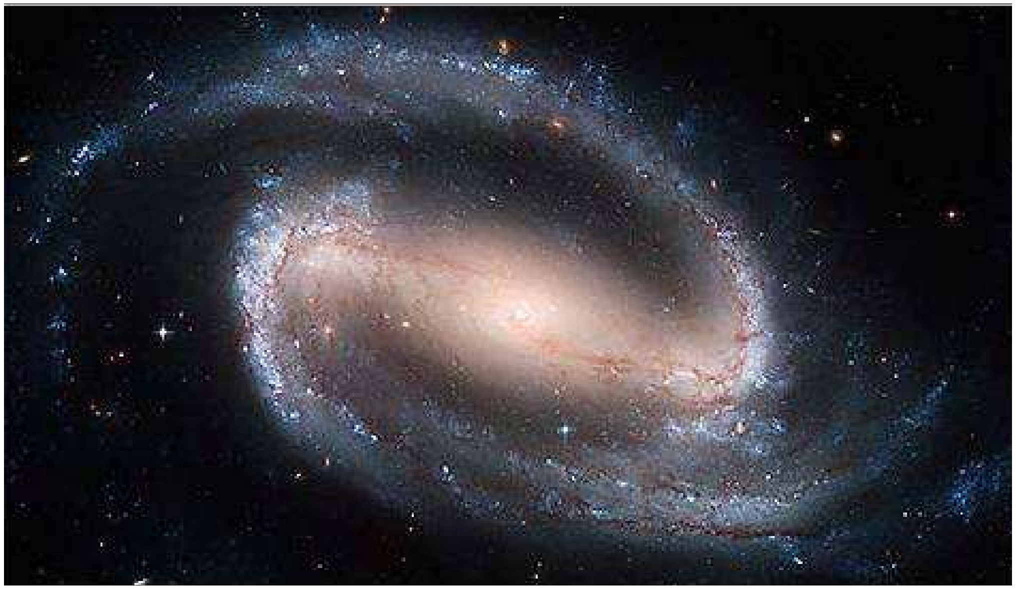
There are many types of galaxies and they can be classfiied according to different criteria. If we classify them according to their structure, sizes, total amounts of gas and star formation, we get the following types:

à Spiral galaxies, Elliptical galaxies,
à Irregular galaxies, Dwarf galaxies,
à Peculiar/Interacting galalxies

Spiral Galaxies

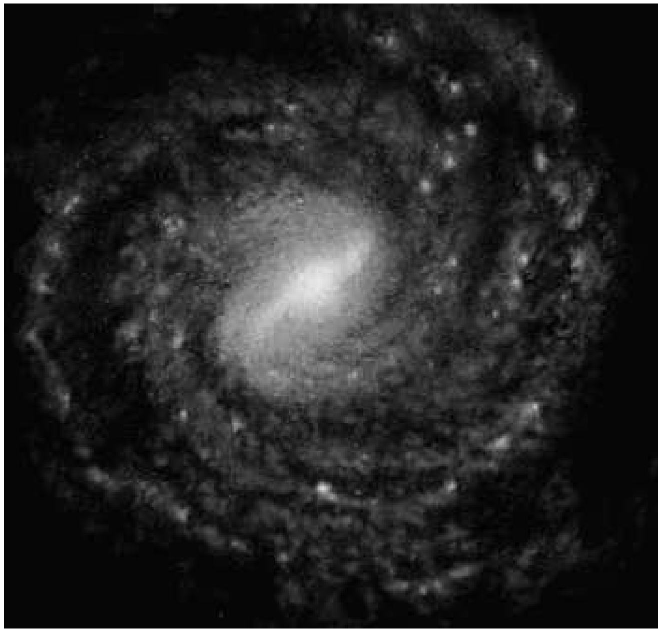
1) They have a disk component (shaped like a saucer). In the center of the disk, there is sometimes a spheroidal bulge (a melon-shaped component).
2) They contain up to 10^{12} stars and lots of gas, dust, ongoing star formation .
3) Most spiral galaxies are barred, meaning that their disk contains an elongated stellar feature called a bar. Bars carry gas from the disk to the center of a spiral galaxy, thus influencing its evolution. Our Milky Way is a barred spiral.

Unbarred spiral (SAab) NGC 4622



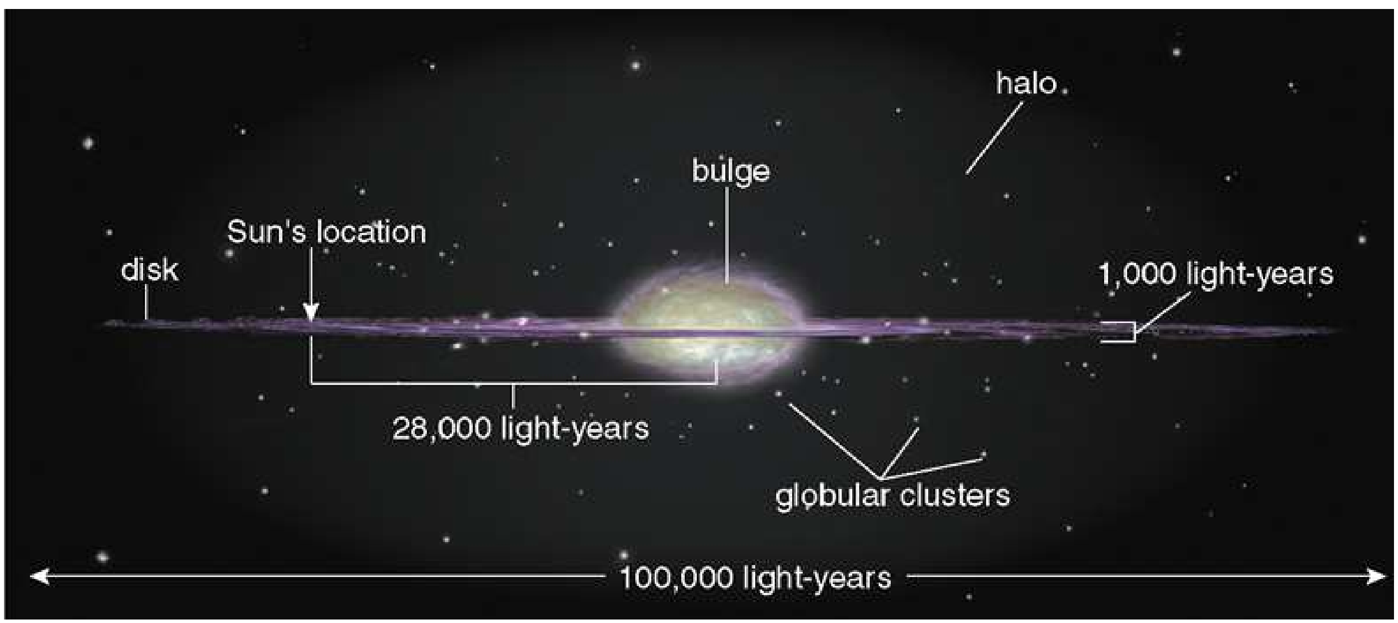
Strongly Barred spiral (SBbc) NGC 1300

Milky Way = a barred spiral galaxy, hosting our Sun and Solar system



Face-on view
(Artist's conception)

Edge-on view :
Actual infrared image
from COBE satellite



Edge-on view
(Artist's conception)

Spiral Galaxies

NGC 4594 or M104 (Sombrero) ; HST image
Spiral, with a large bulge and a dusty disk, seen edge-on

Weaky barred spiral (SABc) NGC 674

Elliptical Galaxies

1) They are spheroidal systems (shaped like a water melon) and do not have extended disk components. Contain up to up to 10^^{12} stars.
2) They have a smooth appearance as they are mostly made of old stars, and have little gas, dust, and recent star formation

Giant elliptical M87

Irregular Galaxies

1) They have irregular, peculiar morphologies in terms of gas, dust and star formation.
2) They are low mass gas-rich systems.Typically contain up to a few x 10^9 stars
3) Two of the three closest galaxy neighbors of the Milky Way, the LMC and SMC, are Irr galaxies

LMC; Irr; 30,000 ly across

SMC; Irr ;18,000 ly across

Dwarf Galaxies

1) They are much smaller than spirals or ellipticals, but may be comparable to Irr galaxies. Their optical radius is typically less than 15,000 lyr while that of spirals is greater than 50,000 lyr.
2) They typically contain up to a few x 10^^{8} stars (vs 10^^{12} in spirals)
3) They come in two types : dwarf ellipticals and dwarf irregulars

Leo I, dwarf elliptical

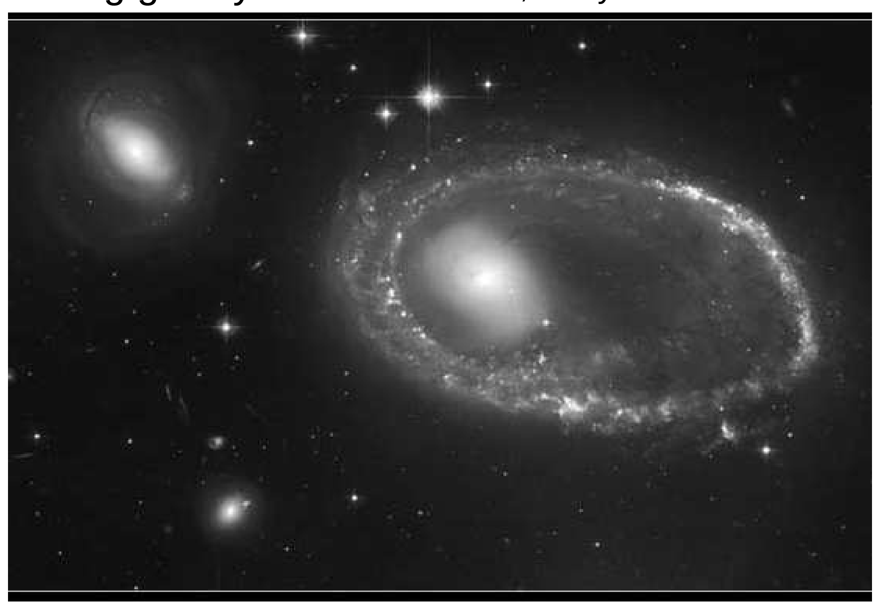
Peculiar/Interacting Galaxies

Galaxies which look peculiar and distorted. They do not fit on the Hubble sequence. These distortions are often caused by interactions with other galaxies.

Polar ring galaxyNGC 4650

Cartwheel galaxy
Head-on collision

Ring galaxy AM 0644-741 50,000 ly across



Peculiar/Interacting Galaxies

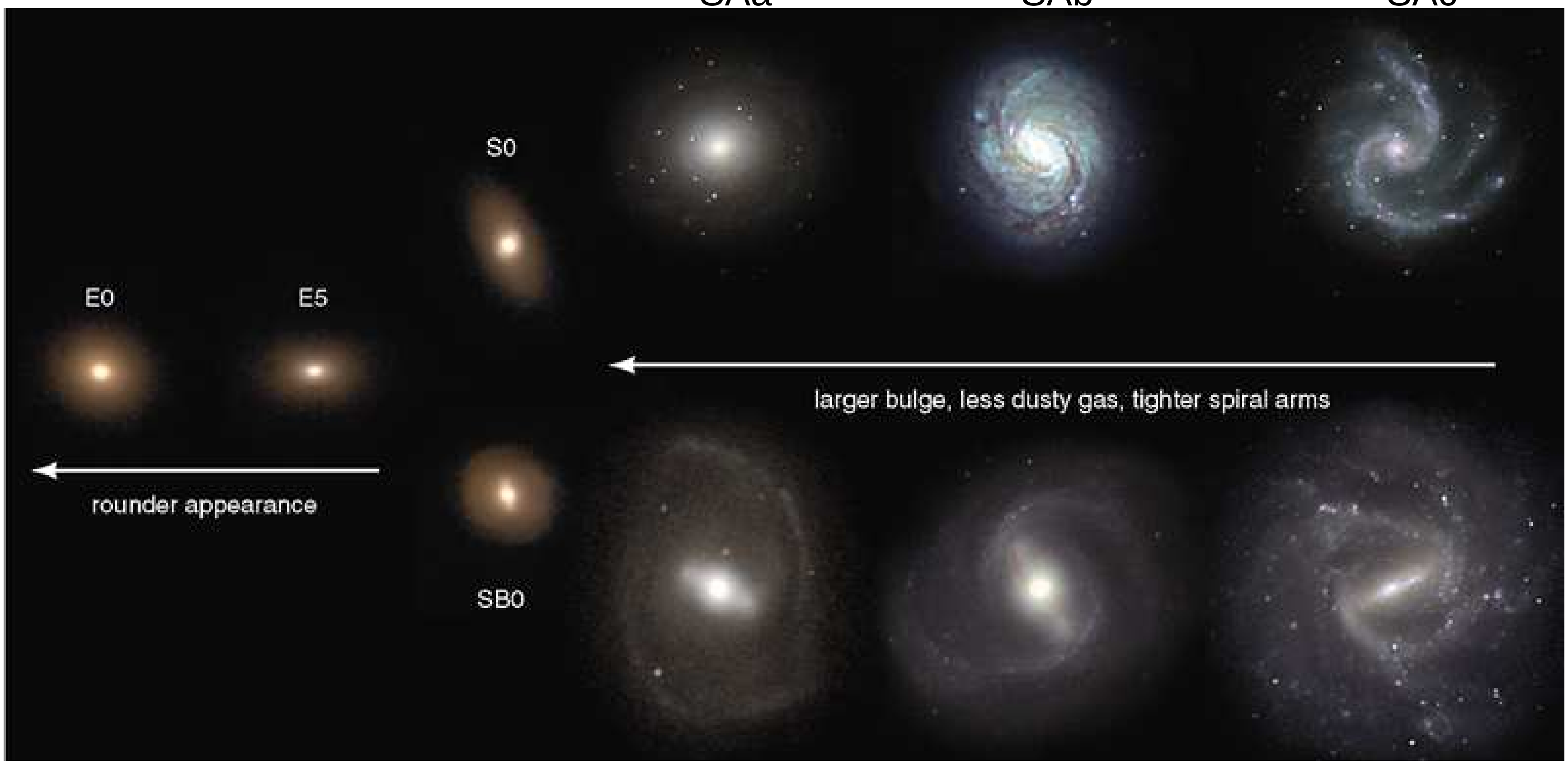
A dusty gas-rich warped disk inside an elliptical-like older system

The Hubble Scheme for Galaxy Classification
or
The Hubble Sequence

Hubble's Classification Scheme : The Hubble Sequence or Tuning Fork Diagram

- usually based on visual images of elliptical and spiral galaxies
- Elliptical galaxies become rounder along the sequence E5 E4 E3 E2 E1 E0
- Spirals are divided into two forks for barred spirals (SB) and unbarred spirals (SA).
- The spirals are further divided into sequences "c b a" (SBc, SBb, SBa or SAc, SAb SAa) along which the bulge luminosity, the bulge-to-disk ratio and the tightness of the spiral arms rises, while the relative amounts of gas and dust in the disk falls.

SAa SAb SAc



SBa SBb SBc

Hubble's classification scheme : What are its limitations?

In-class discussion

A galaxy looks different at infrared and optical wavelengths

Movie
(NASA/Spitzer)

The optical image of M81 shows intermediate age stars and patchy obscuration.
The infrared observations of M81 from the Spitzer satellite show old stars, but also penetrates the dust and reveal young stars enshrouded in dust

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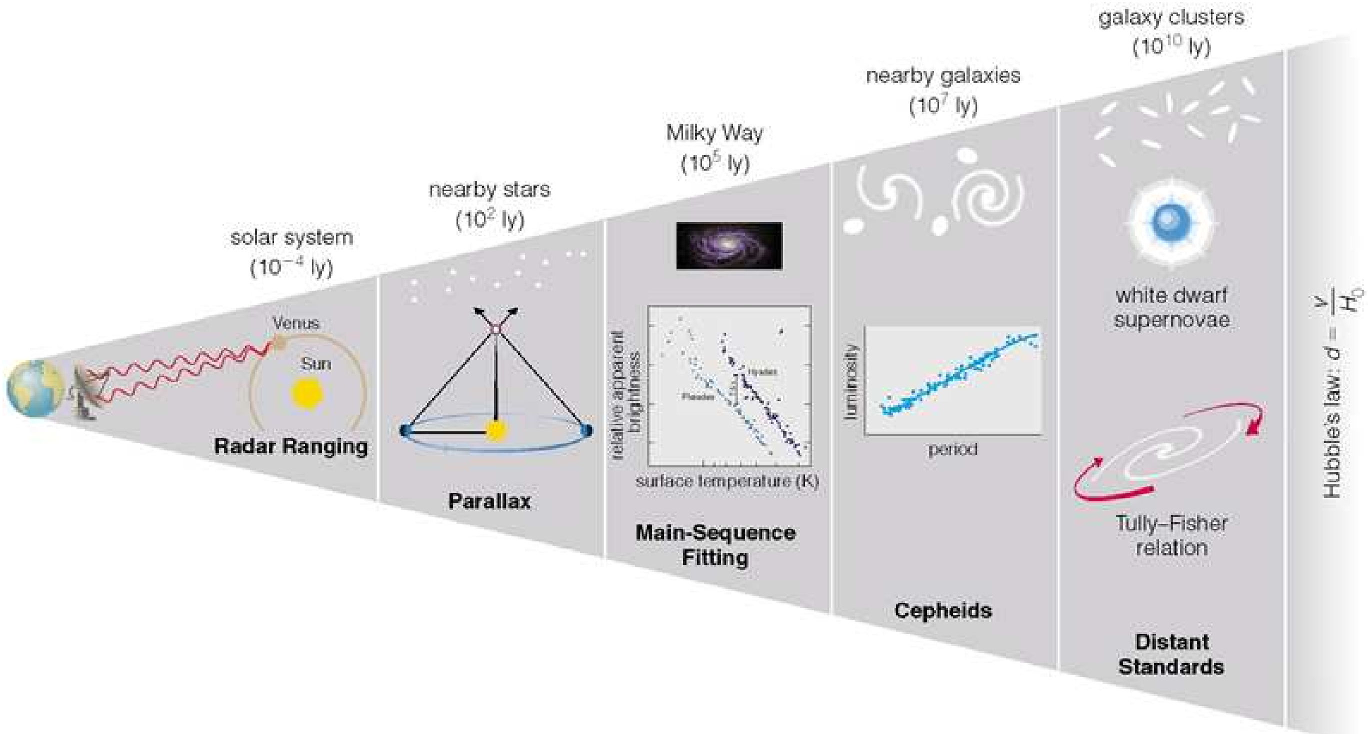
<u>Mapping the Distance of Stars and Galaxies</u>

The distance ladder for stars and galaxies

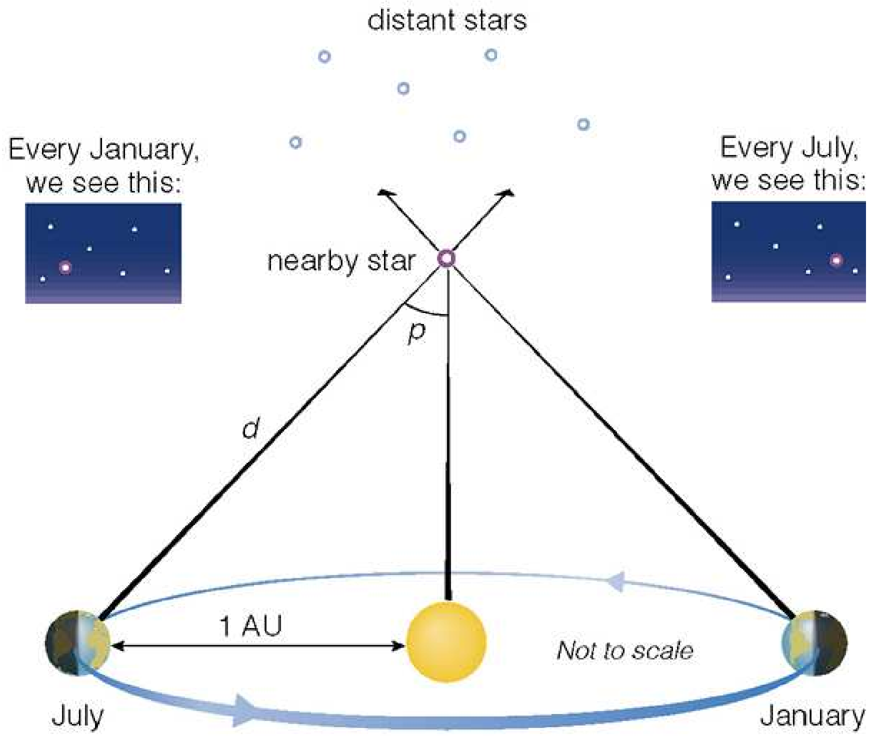


2) Standard candles are objects whose luminosities L is known or can be determined from some easily observable property. For instance a Cepheid's luminosity can be easily determined by observing its period. Standard candles are used determine distances D, by using the fact that once we know the luminosity L and we measure the flux F, we can trivially calculate D.

$$F = (L) / (4 \text{ pi } D^2)$$

3) As we move to larger distances we need brighter standard candles. For instance, we use the main sequence turn off of stellar clusters out to 10^5 lyr in our Milky Way, then brights Cepheids in external galaxies out to 10^7 lyr, then Type Ia supernovae etc

Stellar parallax to get distance out to 300 lyr



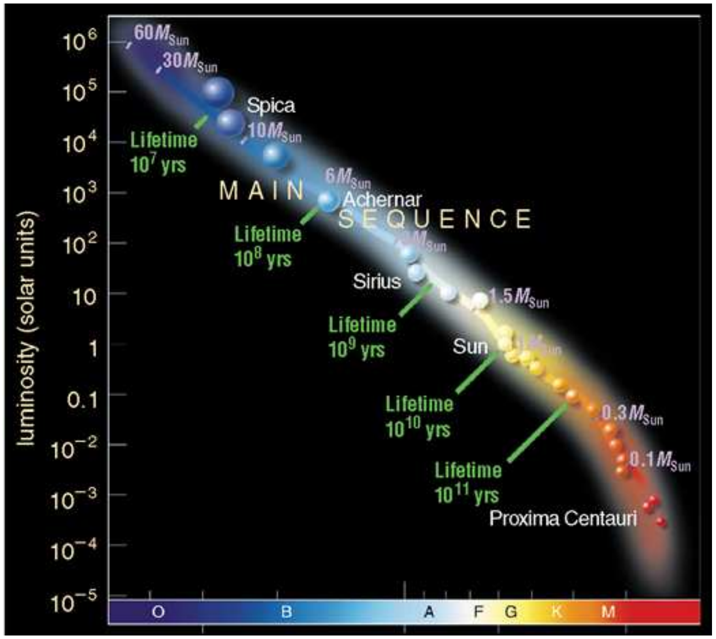
SIM in 2011

Stellar parallax angle p = (3/distance d of star in lyr) expressed in arcsecond

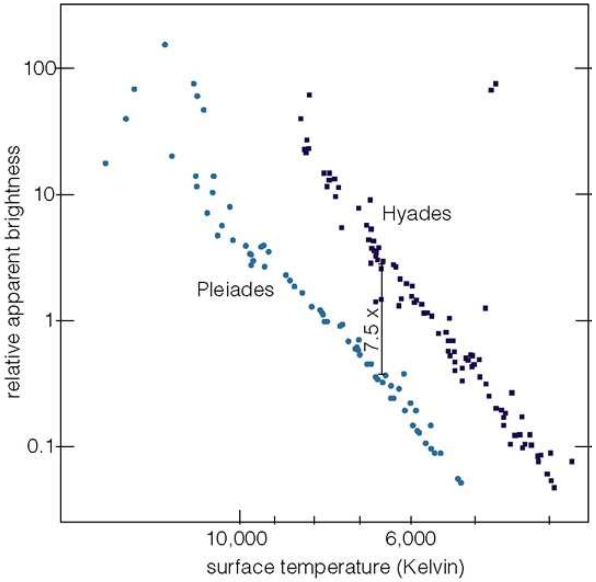
SIM= Space Interferometry Mission to be launched in 2011,will measure parallaxes of 10^{-5} arcseconds -- these are 1000 times smaller than present-day limit. This in turn will alllow distances of stars 75,000 lyr away to be measured, compared to present-day limit of 100 lyr.

Stellar Cluster Main Sequence Fits to get Distances out to 10^5 lyr

See in-class notes



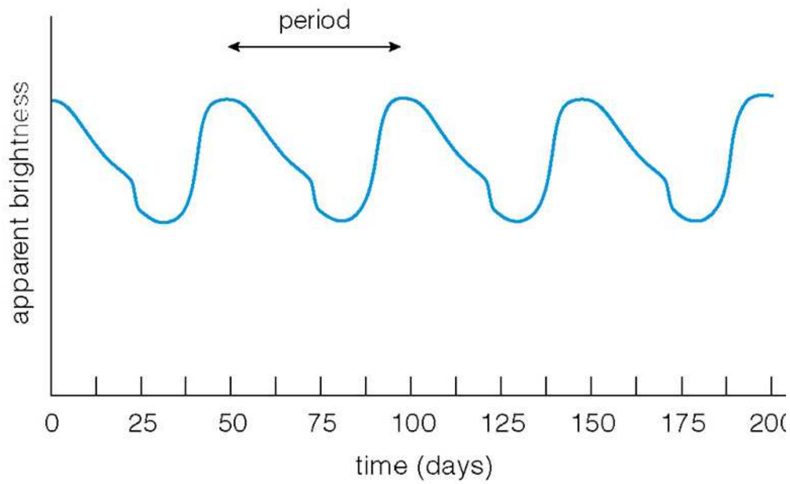
Step 1: Calibrate Color-Luminosity of main sequence stars using nearby clusters whose distance we know, and whose (color,flux) we measure.

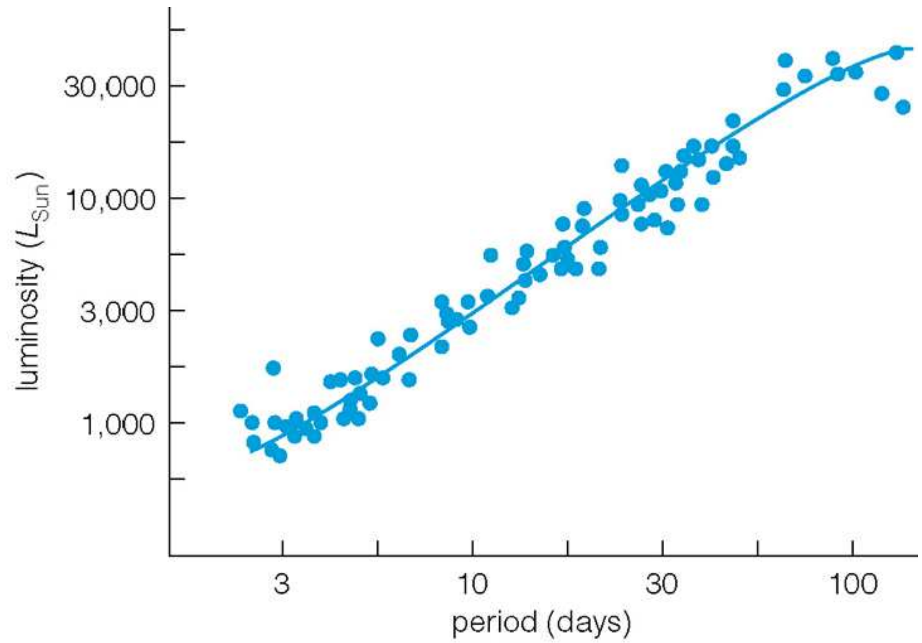


Step 2: In distant clusters where we measure (color, flux), apply calibrated Color-Luminosity relation to infer luminosity L. Then use L and flux to deduce distance

What are limitations of this method?

Using Cepheids to get Distances out to 10^7 lyr





1) Step 1: Calibrate Period-Luminosity using nearby Cepheids

Cepheids are pulsating variable stars. Their flux F fluctuates with a period P. For nearby Cepheids where we know the distance D, flux, and period P, we calculate the luminosity L from the flux. We then find that there is a P-L relation i.e, P is proportional to L.

2) Step 2: Apply calibrated Period-Luminosity relation to distant Cepheids

Cepheids are bright and can be observed in external galaxies. For distant Cepheids, where know only the flux and the period P we use the above calibrated period-luminosity relation to infer L from P. Once we know both L and the flux F, we can calculate D.

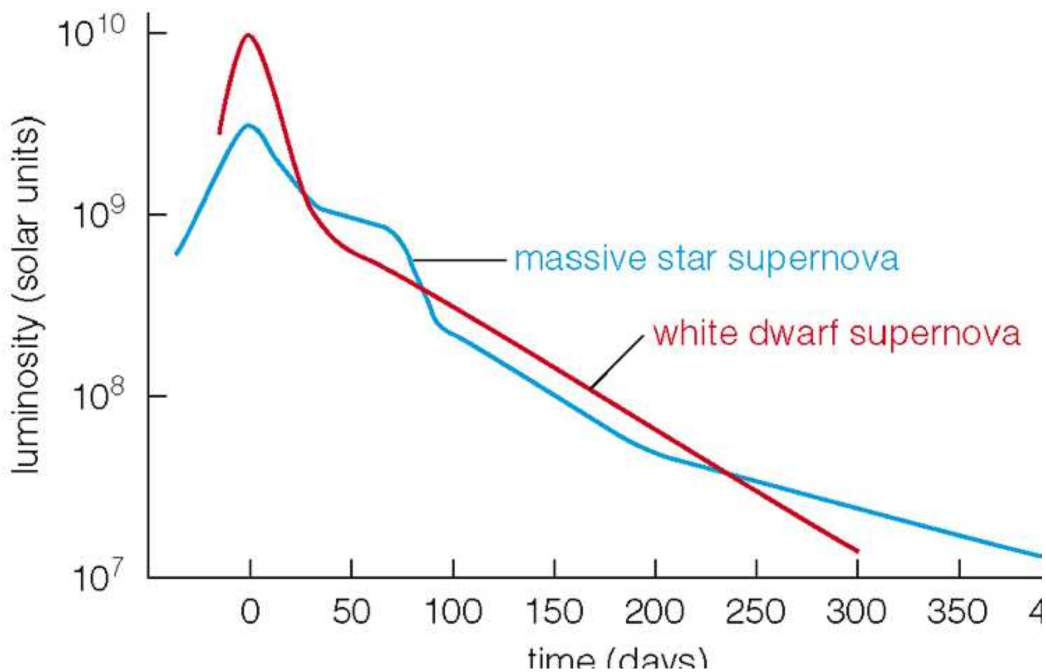
<u>Using White Dwarf Supernovae to get Distances out to 10^{10} lyr</u>

<u>White Dwarf supernovae</u> or Type I supernovae are derived from <u>low mass stars</u>. When such stars die they produce an inert C core called a white dwarf while their outer layers are ejected as a planetary nebula. This white dwarf has a mass which is always below 1.4 Msun.

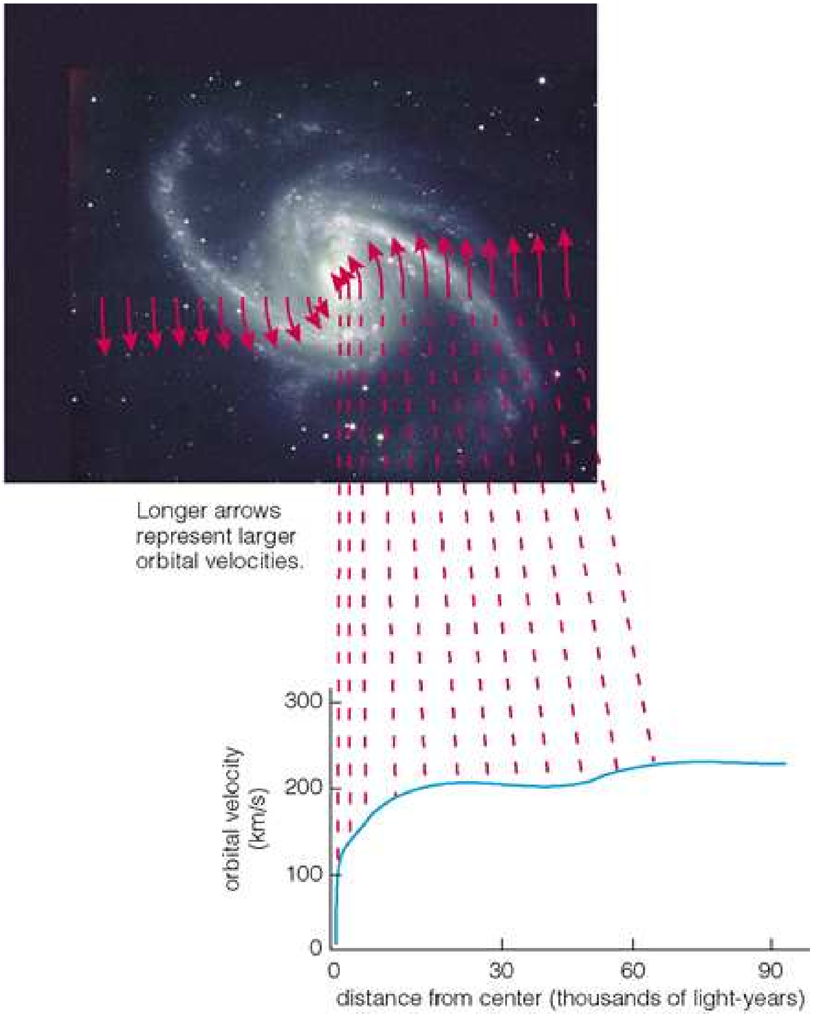
If the white dwarf later accretes mass from a companion star and its mass approches 1.4 Msun, it heats up, carbon fusion starts, <u>and the whole star detonates (no core left),</u> producing a white dwarf supernova. The peak luminosity is believed to be the same (10^10 Lsun) in all white dwarf supernovae

1) Step 1: Calibrate the peak Luminosity of the light curve using nearby White Dwarf SNe

2) Step 2: Assume this same peak luminosity to the light curves of distant White Dwarf SNe

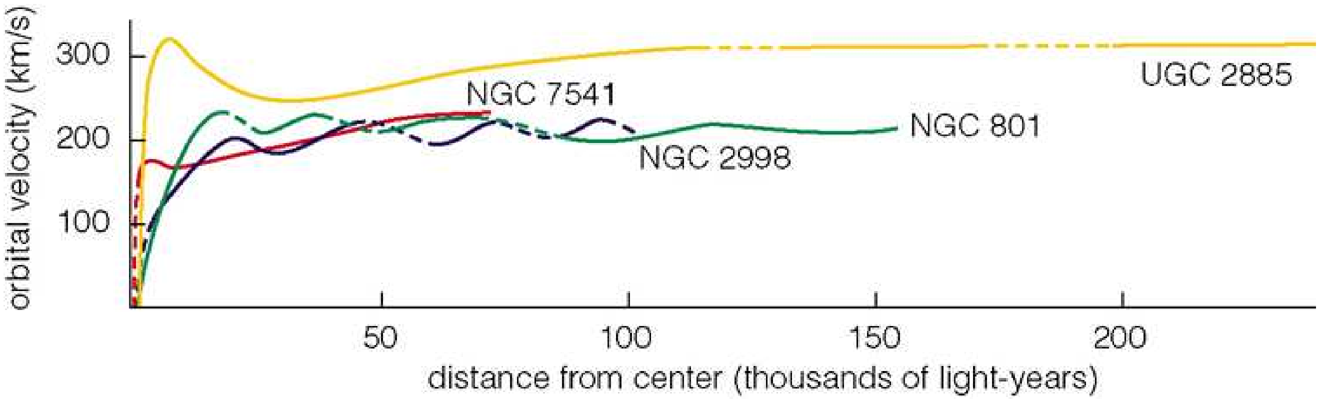


Using Rotation Curves of Spiral Galaxies to get Distances out to 10^{10} lyr



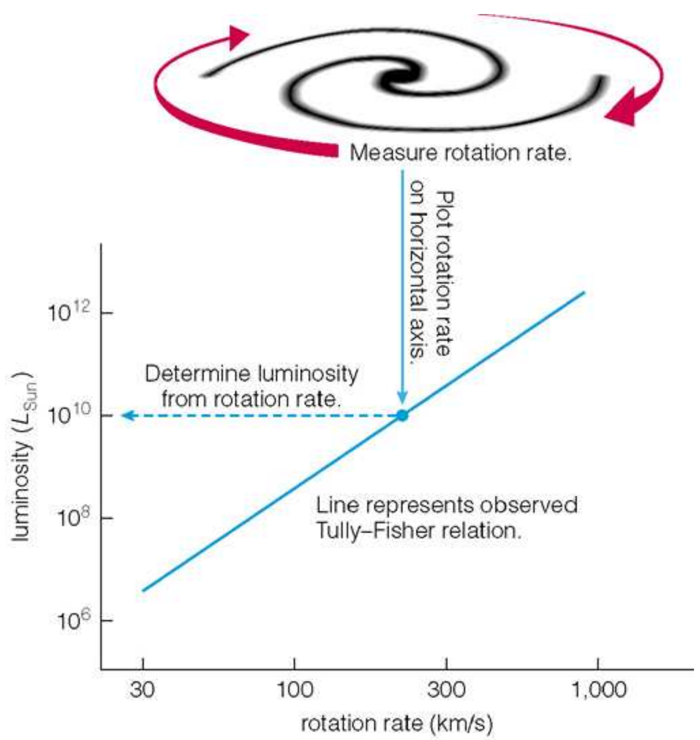
If we plot the velocity v of gas or stars in the disk of a spiral galaxy against the radius R of their orbits, we get a rotation curve.

Using Rotation Curves of Spiral Galaxies to get Distances out to 10^{10} lyr



When rotation curves of diffferent nearby galaxies are inspected, it is found that the maximun rotation speed Vmax of a galaxy is directly proportional to its luminosity. This is the Tully-Fisher relation.

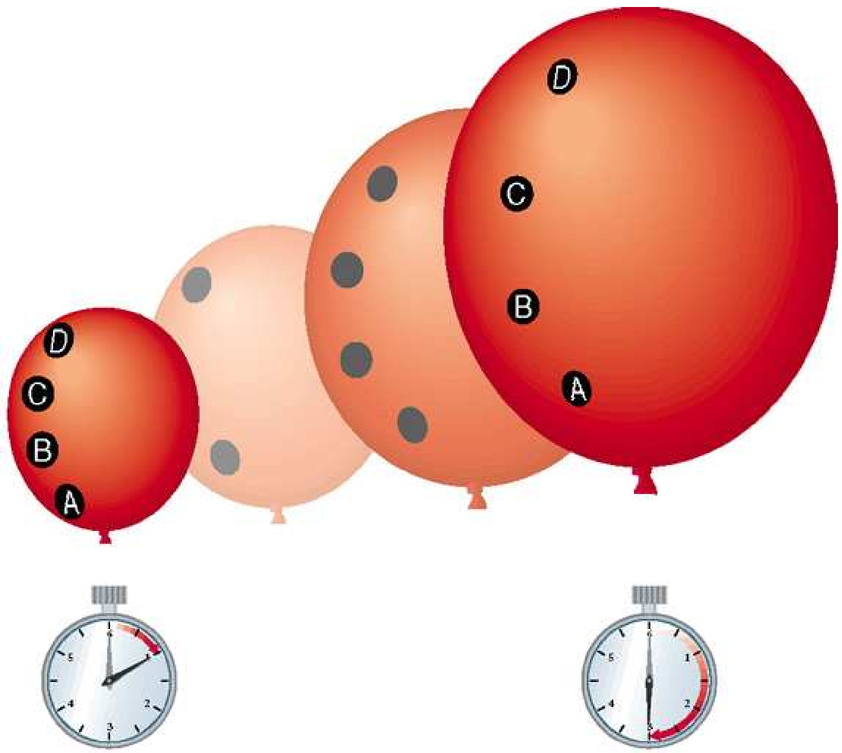
Step 1: Calibrate the Vmax-Luminosity relation using nearby galaxies.
Step 2: Measure rotation curve and flux in distant galaxies. Apply the above calibrated Vmax-Luminosity relation to this rotation curve and infer L. Then use L and flux to get distance d.



<u>Using Hubble's Law + Doppler Redshifts to get distances out to 10^{10} lyr</u>

à Hubble's law applies to distant galaxies, well outside the Local Group. It states that due to the expansion of the Universe, distant galaxies are moving away from us with a recession speed v that is directly proportional to the distance d of the galaxy from us

<u>v in km/s = (Hubble constant in km/s Mpc^{-1}) (d in Mpc)</u>



1 Mpc = 1 Mega parsec
= 3 Mega lyr

Hubble's constant
= 70 km/s Mpc^{-1}

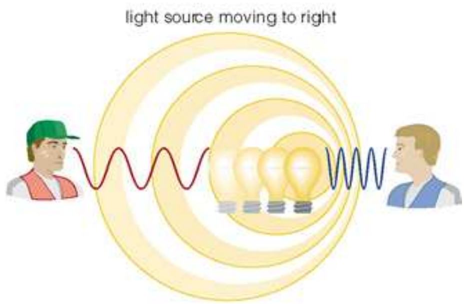
à If we can measure v, then we can infer distance d (since Hubble constant is known)
à This method does NOT depend on calibration of distance scale with other standard candles

Using Hubble's Law + Doppler Redshifts to get distances out to 10^{10} lyr

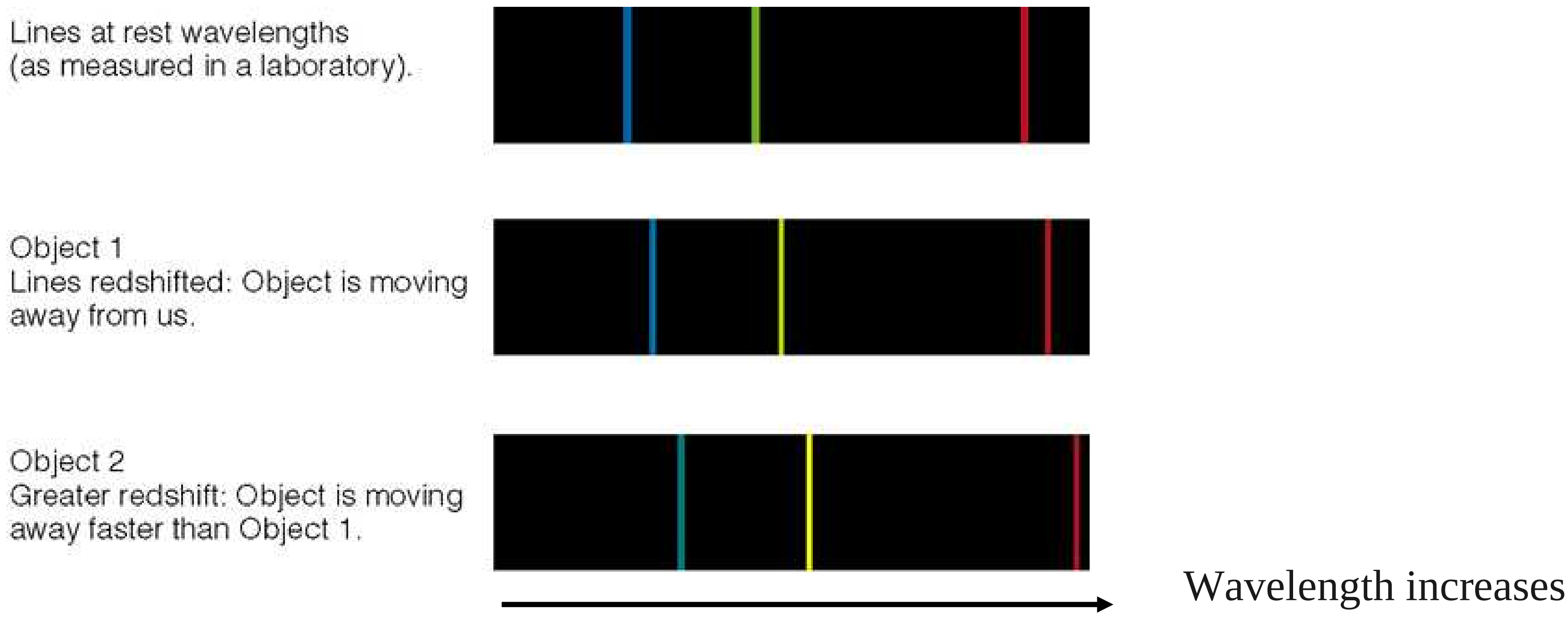
How to determine the recession velocity v?

1) Recall from lect. 14: The Doppler redshift of a line is the apparent increase in its wavelength produced when the emitter moves away from us at some speed v.

[Redshift = (Observed λ - Rest λ) / Rest λ]



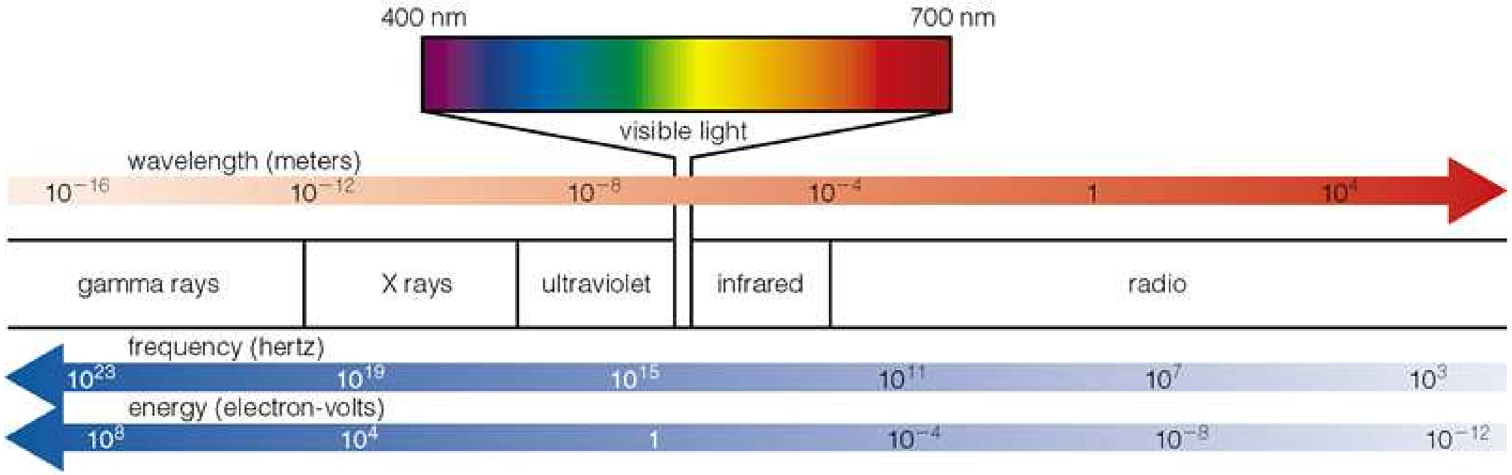
2) Thus, to get v, take spectra of galaxies and determine the Doppler redshift of well-known lines with specific sigatures , e.g., H, N, S lines.



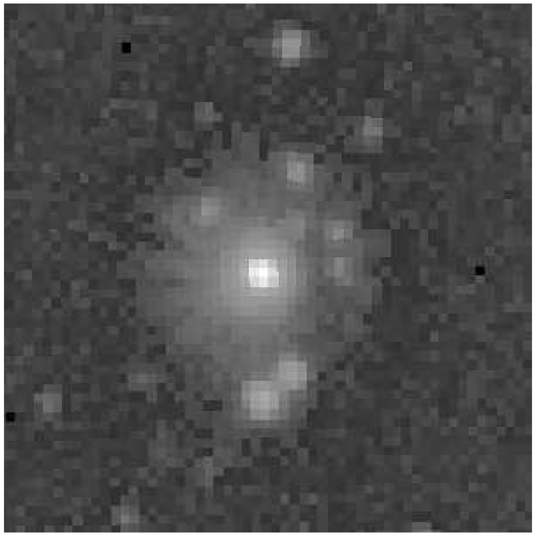
Mapping the Visible Components of Galaxies
(old and young stars, cold and hot gas)

Mapping the Components of Galaxies

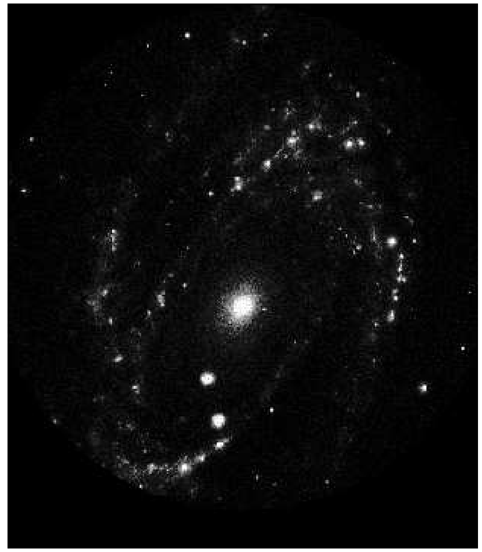
Need images of a galaxy at different wavelengths ,not just visible ones, to get a full representation of the different components of the galaxy, such as old and young stars, cold and hot gas, dark matter



Multi-Wavelength view of M81



X-ray/ROSAT

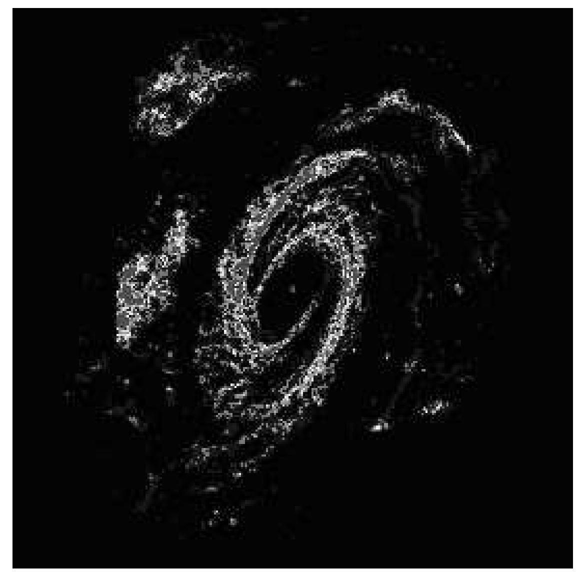


Ultraviolet/ASTR0-1

Visible light

Near infrared/Spitzer

Far-infrared/Spitzer

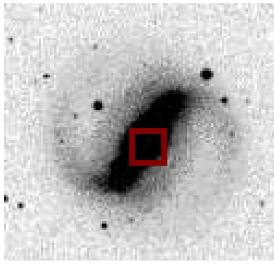


Radio 21cm/VLA

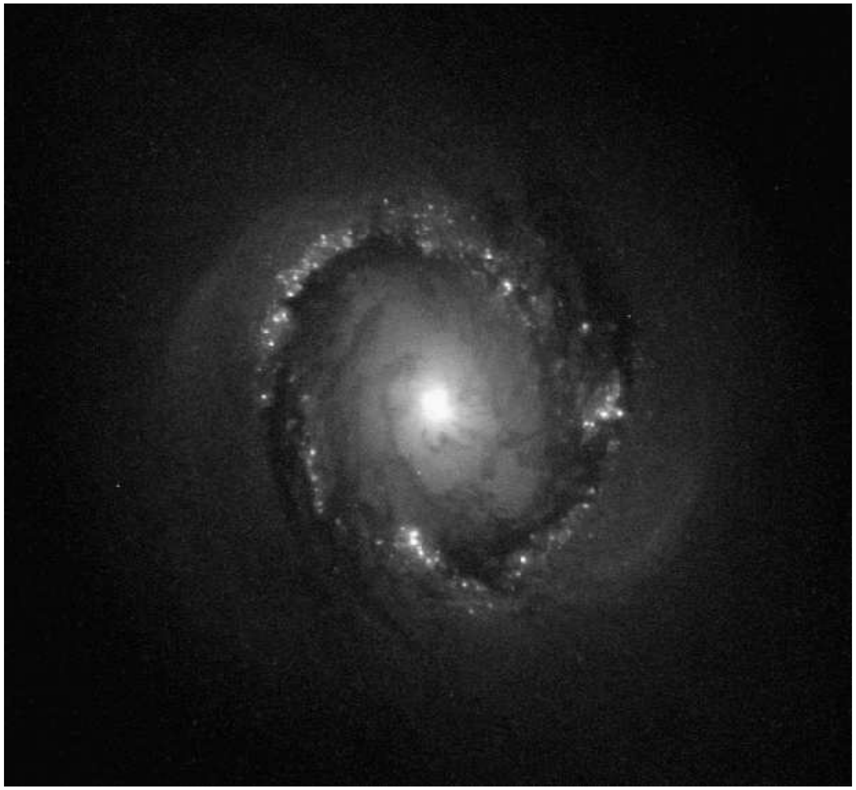
Tracing old stars and dust-enshrouded old+young stars

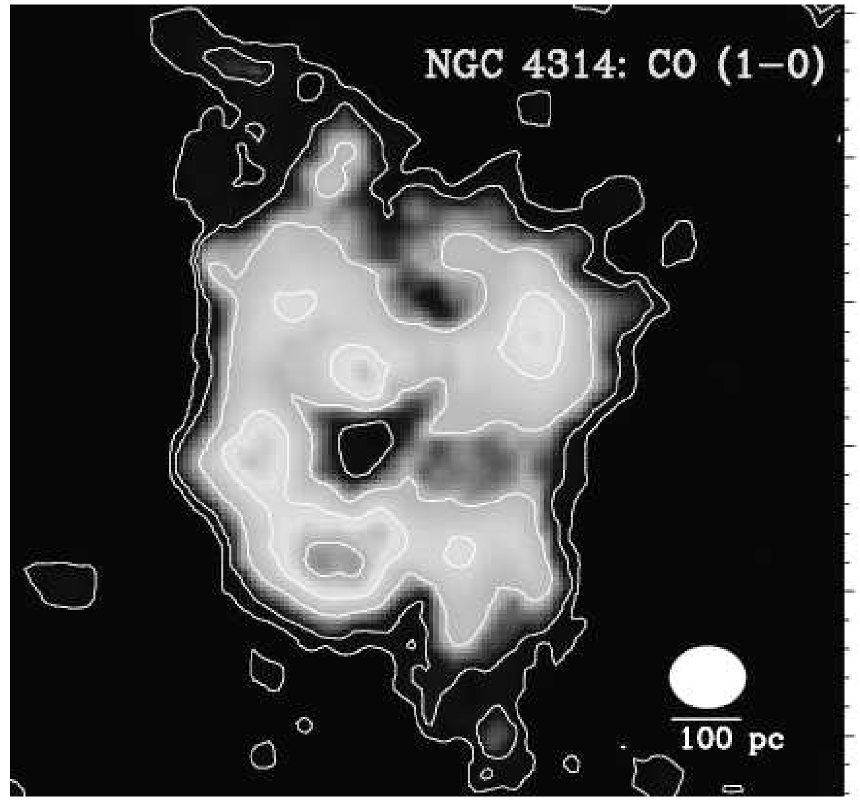
Movie
(NASA/Spitzer)

The optical image of M81 shows intermediate age stars and patchy obscuration.
The infrared observations of M81 from the Spitzer satellite show old stars, but also penetrates the dust and reveal young stars enshrouded in dust



Tracing cold molecular gas in galaxies

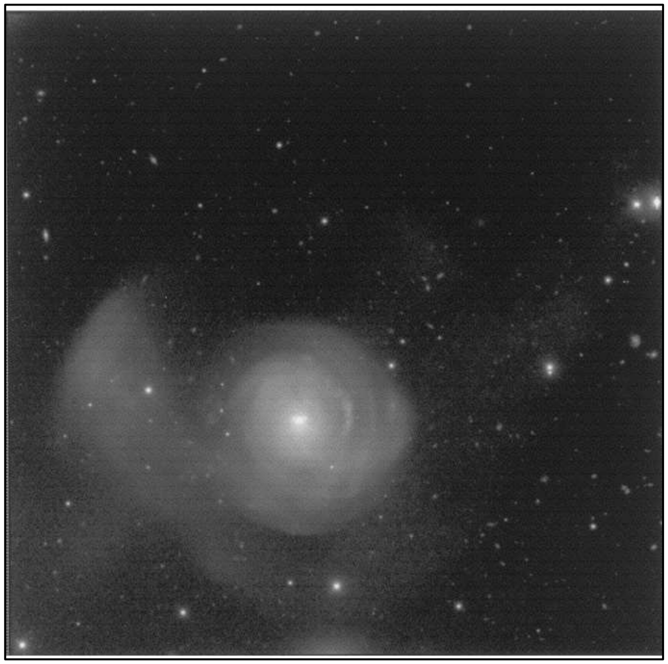




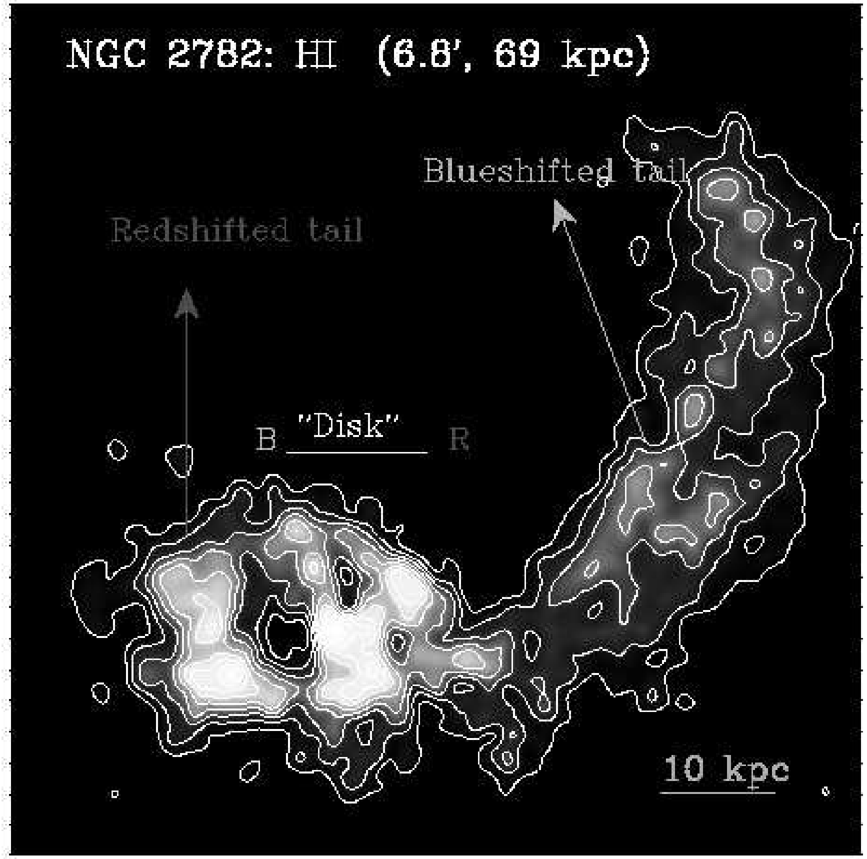
UV observations show young hot massive stars in clusters, only a few millon yrs old.
(Courtesy: Benedict/ NASA)

Radio observations at mm wavelengths trace the cold gas (molecular hydrogen) from which new stars are forming
(Jogee et al . 2004)

Tracing cold atomic gas in galaxies



Visible light image shows a rather undisturbed disk and no tail to the right

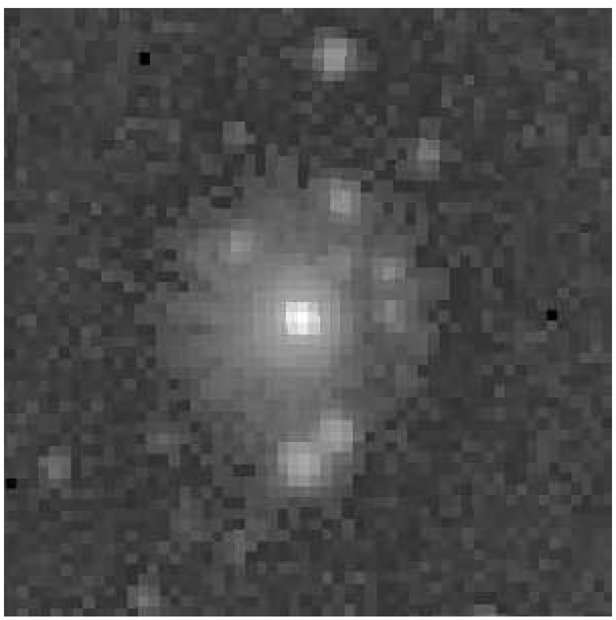


The 21 cm map shows a 50,000 pc tail of atomic H to the right

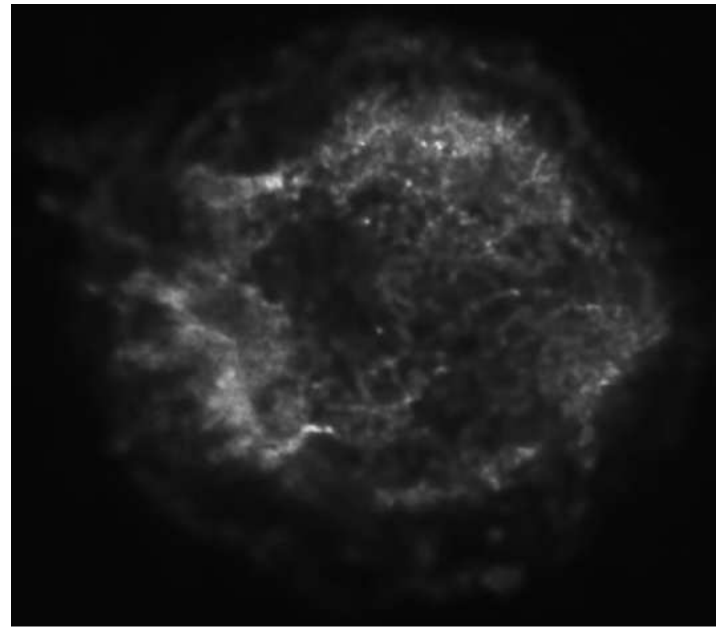
- Radio observations at 21 cm wavelengths trace cold atomic hydrogen from which molecular hydrogen and eventually new stars will form.
- Cold atomic hydrogen often extends out into the outer regions of spirals (e.g., in the outer parts of disks, in huge tidal tails), well beyond where stars are seen. Because of this, it can trace dark matter and give clues to the interaction history.

<u>Tracing hot gas in galaxies</u>

Visible
light image
of M81



X-ray/ROSAT
image of M81



X-ray image of supernova remnant
Cassiopeia A shows a hot bubble of
10^7 K gas that is heated by shocks