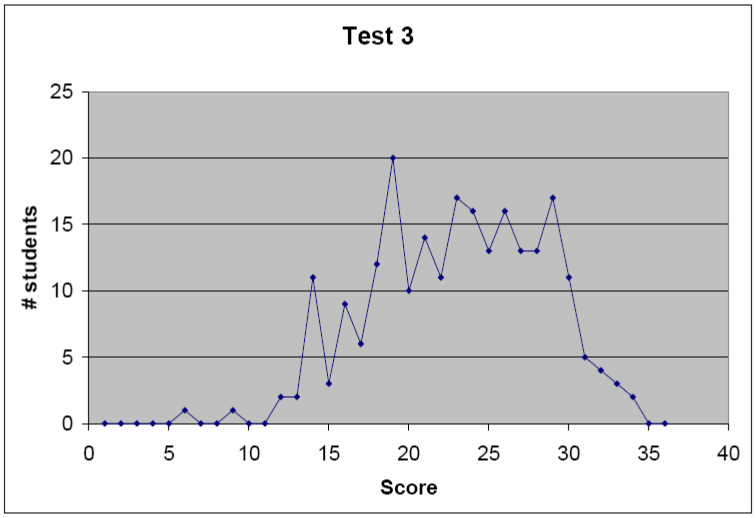


2. A giant hand took one of the planets discovered around other stars and put it in the solar system at the same distance from the sun as from its star. The mass of the planet is approximately that of Jupiter and the orbit is approximately that of Earth.

These are the “hot Jupiters”, as big as Jupiter but much closer to their star than Jupiter is to the Sun.

13. Has the sun ever been or will it be a star like Barnard’s star, a K main sequence star?

- No, the Sun is a G type main sequence star, more massive than a K-type star
- So no for Barnard’s star (and also no for the Crab pulsar)

36. Potassium 40 (K40) decays into argon 40 (Ar40) with a half-life of 1.25 billion years. An asteroid is found with 3 parts of K40 for every 1 part of Ar40. Assume there was no Ar40 when the asteroid formed. The asteroid formed

  Age 0: 0 Ar40

  Age 1.25 billion years: half of the K40 is now Ar40, so 1 part of K40 and 1 part of Ar40

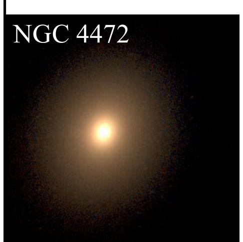
  Age of 2.5 billion years: one quarter K40 and three quarters Ar40; so 1 part K40 to 3 parts of Ar 40

So the answer must be an age smaller than 1.25 billion years

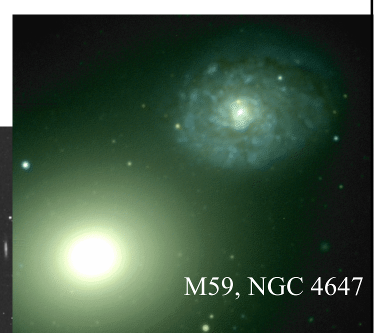
Three Main Types of Galaxies

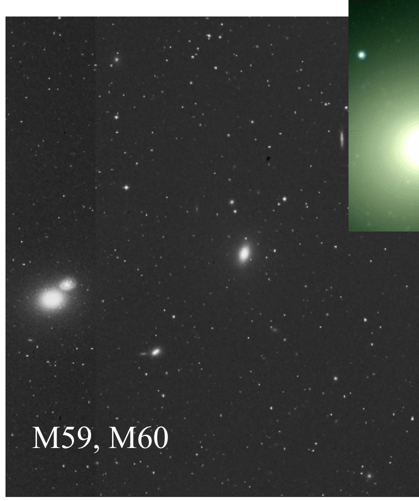
1. Spiral Galaxies
2. Elliptical Galaxies
3. Irregular Galaxies

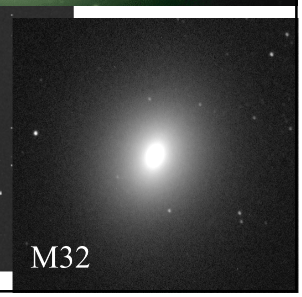
Elliptical Galaxies



No gas.
No dust.
No young stars.







NGC 4414: Spiral Galaxy

- Gas
- Young stars
- Dust
- Halo
- Globular clusters
- Dark matter

Clicker Question

Where in this galaxy would we find
Very young, massive, stars?

A. Spiral arms

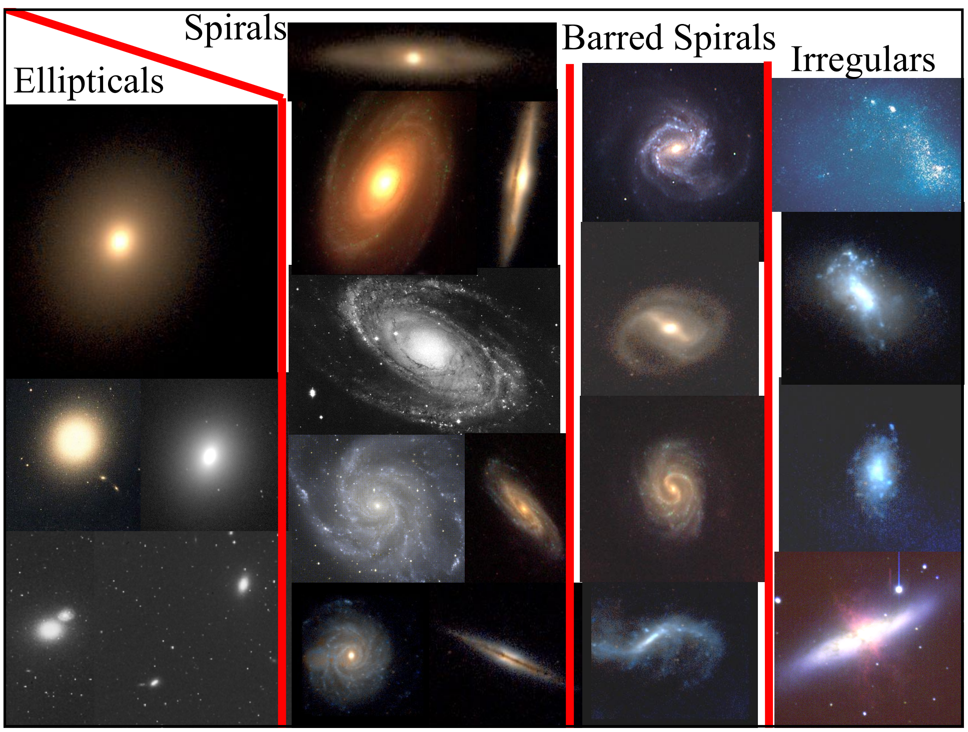
B. Central bulge

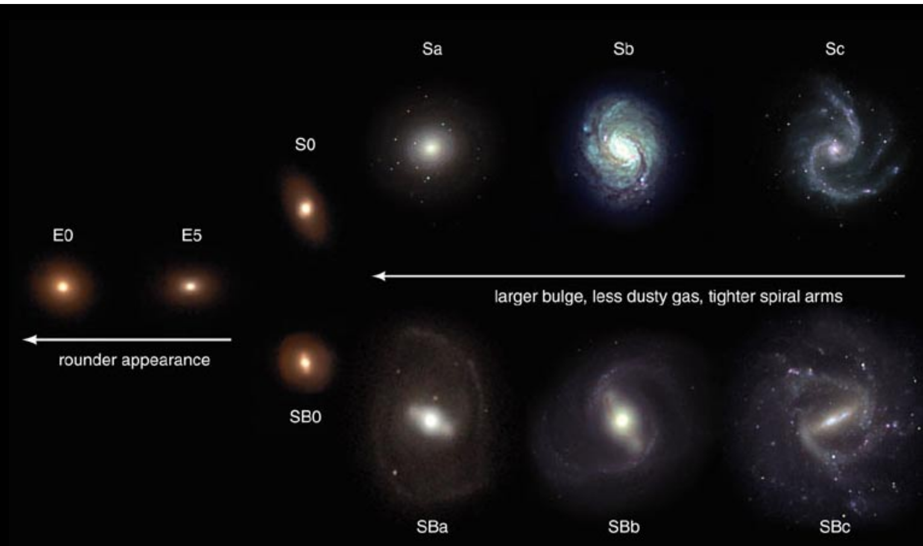
C. Globular clusters

D. Halo

Large Magellanic Cloud: Irregular Galaxy

- Gas
- Young stars
- Dust
- Globular clusters
- Dark matter



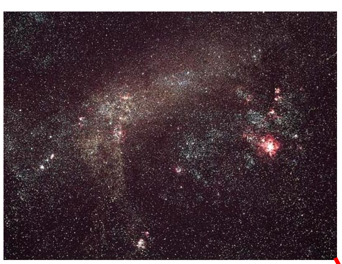


Spheroid Dominates

Hubble's galaxy classes

Disk Dominates

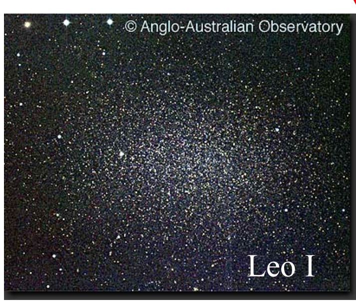
Satellite Galaxies



Large Magellanic Cloud

Small Magellanic Cloud

Milky Way



M31, M32,
NGC 205

Life in the fastlane…

Colliding galaxies

Meanwhile, in a galaxy close, close to home…

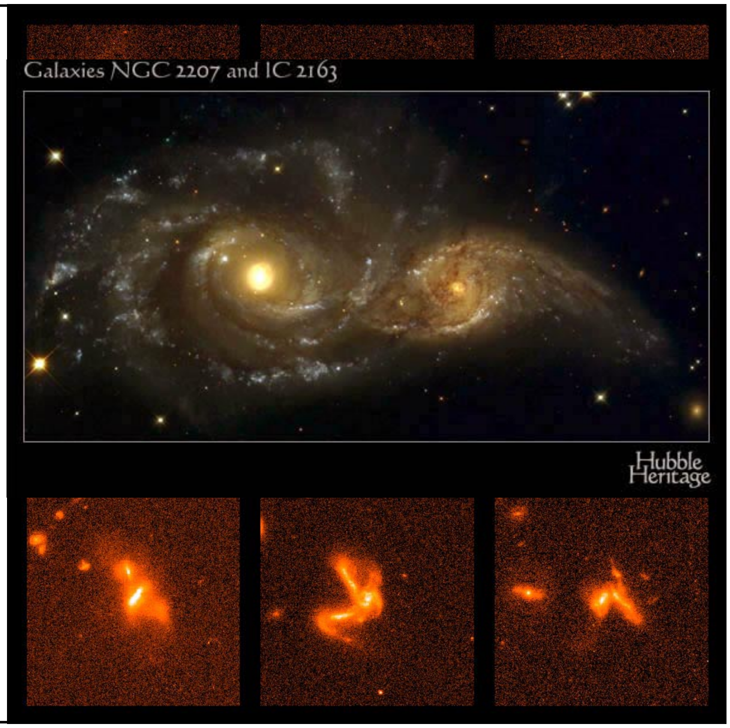
The Milky Way Meets Andromeda

2.5 million ly away

Approaching at 500,000 km/hr

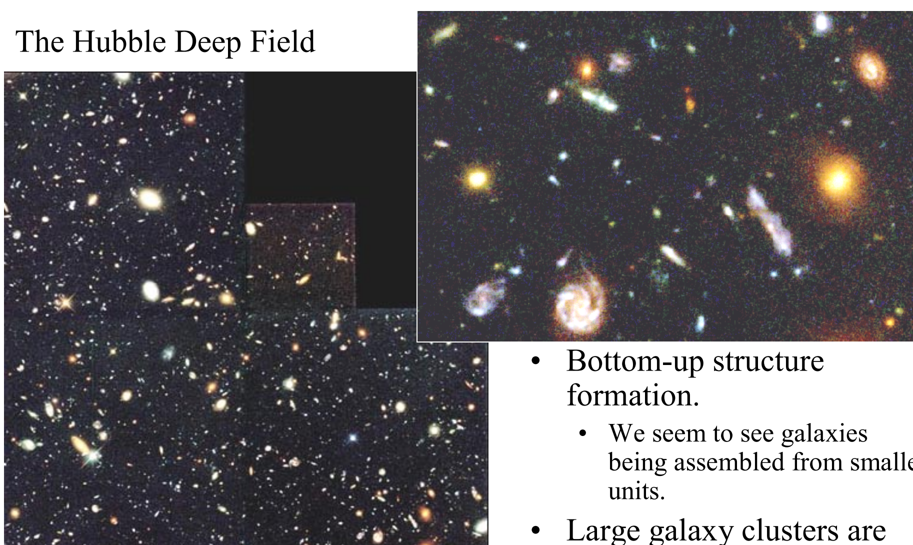
➔ Collision in several billion yrs

play



Looking back to the time of galaxy formation

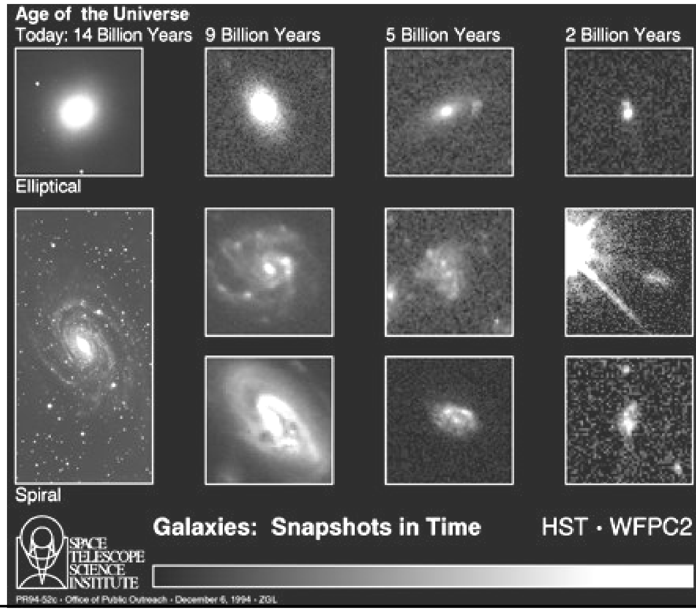
The Hubble Deep Field



- Bottom-up structure formation.
  - We seem to see galaxies being assembled from smaller units.
- Large galaxy clusters are still forming.

Bottom-Up Galaxy Formation

← time



How are galaxies grouped together?

Spiral galaxies are often found in ***groups*** of galaxies

(up to a few dozen galaxies)

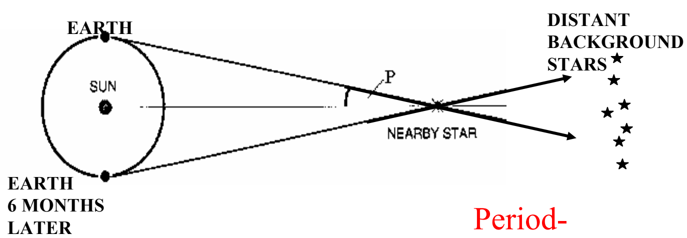
Elliptical galaxies are much more common in huge ***clusters*** of galaxies

(hundreds to thousands of galaxies)

How do we measure the distances to galaxies?

Measuring distances inside the Galaxy

- Parallax: to 300 pc = 1000 LY

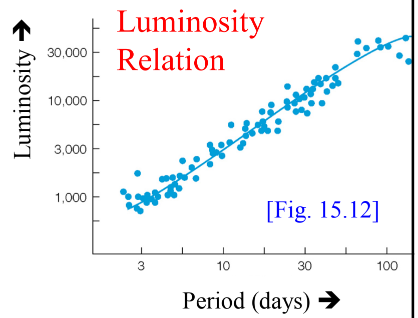


- Then… Pulsating variables (Cepheids, RR Lyraes)

$$F = L/(4\pi r^2)$$

$$r = \sqrt{L/(4\pi F)}$$

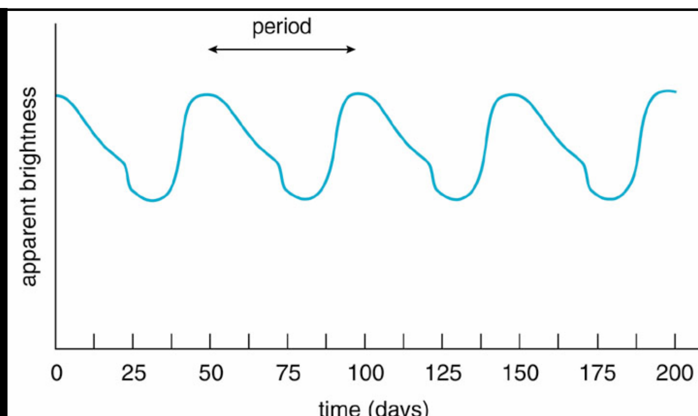
Period-Luminosity Relation



[Fig. 15.12]

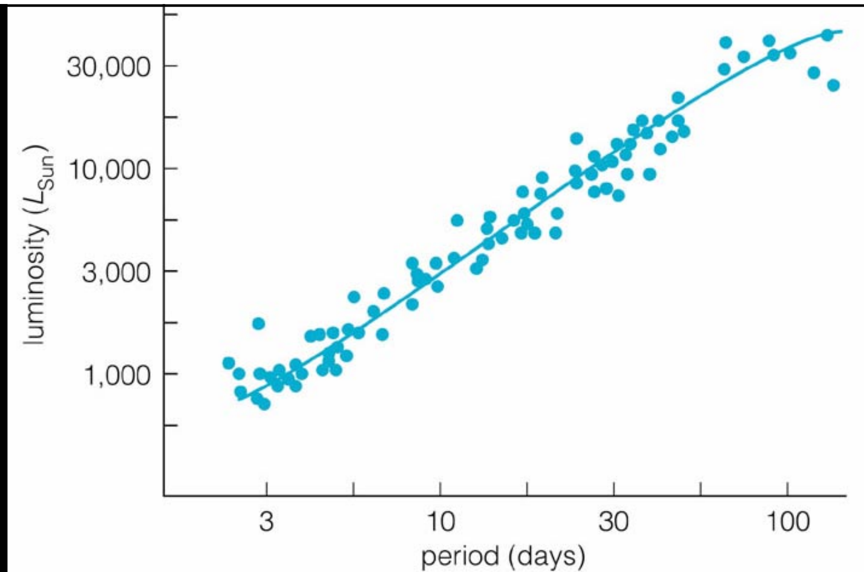
Cepheid Variable Stars

- These are pulsating giant stars
- They change brightness as they pulsate
- The brighter they are, the longer they take to pulsate



- BRIGHT: 1,000-30,000 solar luminosities
- Regular variations in brightness

Cepheid Variables



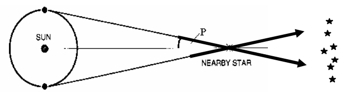
Period-Luminosity Relation

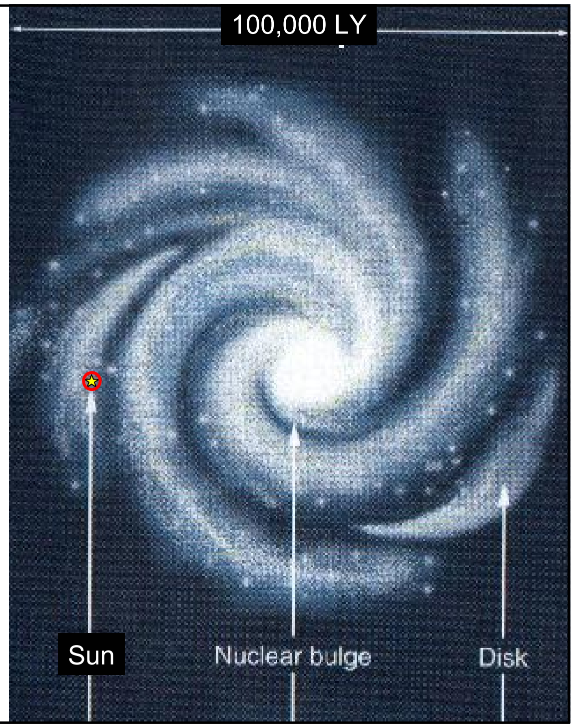
Clicker question. You see two Cepheid stars that have the same period, but one has an apparent brightness 10,000 times fainter than the other one. The fainter Cepheid is how many times farther away than the brighter one?

A. 10,000 times farther
B. 100 times farther
C. 10 times farther

The Cosmic Distance Ladder

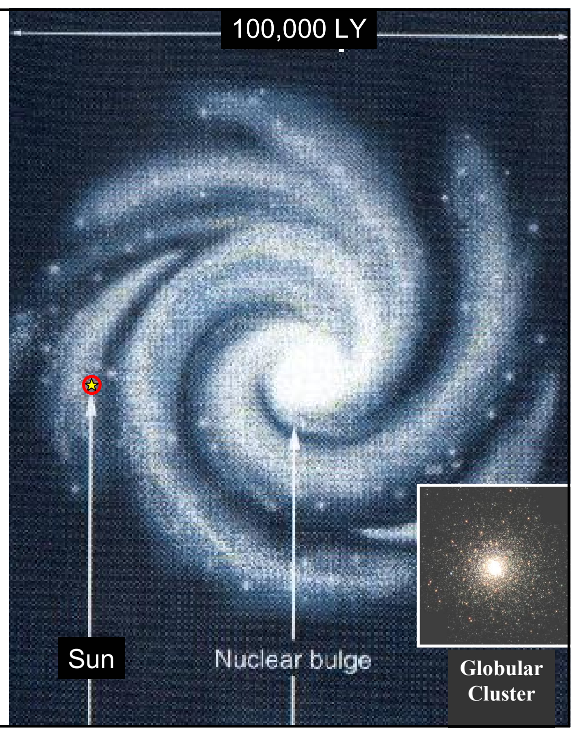
- Parallax
  - 300 pc = 1000 LY



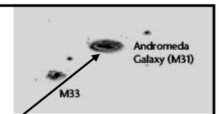


The Cosmic Distance Ladder

- Parallax
  - 300 pc = 1000 LY
  - Calibrate main sequence fitting.
  - Calibrate luminosities of Pulsating Variables
- Map rest of Milky Way



The Cosmic Distance Ladder



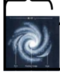
M31, M33

- Parallax
  - 300 pc = 1000 LY
  - Calibrate main sequence fitting.
  - Calibrate luminosities of Pulsating Variables
- Map rest of Milky Way and out to M31

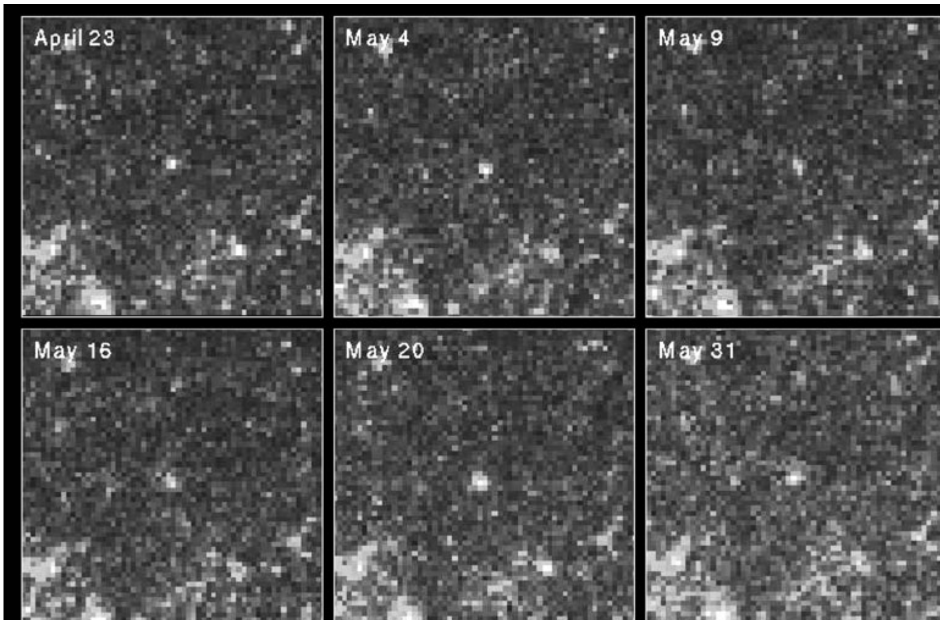
2,500,000 LY

Measure luminosities of
- Brightest stars 10,000 $L_\odot$
- Brightest globular clusters 100,000 $L_\odot$
- Brightest H II regions 100,000 $L_\odot$
- Etc.
- ➔ can now measure distances to more distant galaxies

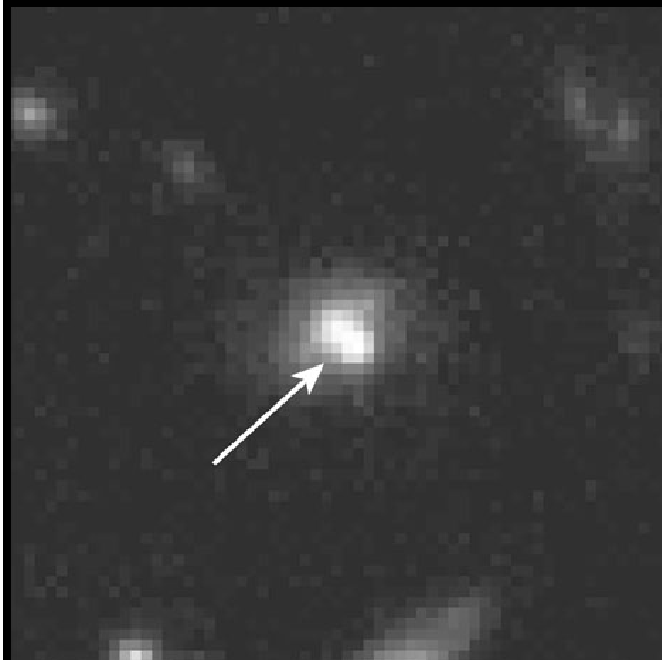
100,000 LY



Milky Way



Cepheid variable star in M100 with period of about a month



Apparent brightness of white-dwarf supernova tells us the distance to its galaxy

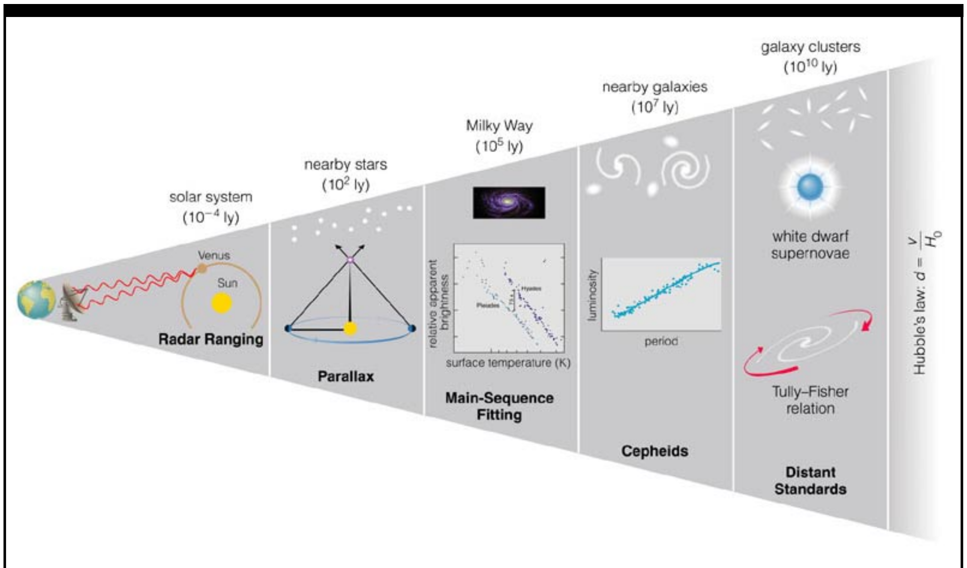
(up to 10 billion light-years)

Modern methods of determining distances

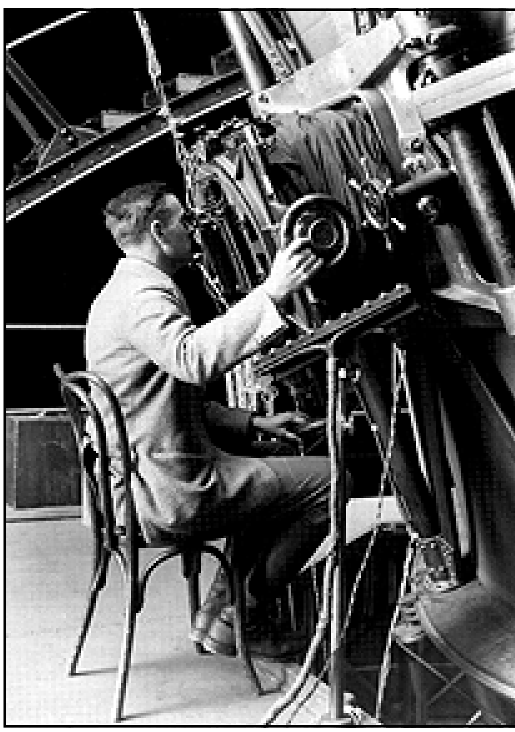
Method	Distance Range (millions of LY)
Pulsating variable stars (Cepheids)	0-65
Brightest star in galaxy	0-150
Planetary Nebulae	0-70
Globular clusters	0-100
Rotation velocities	0-300
Supernovae	0-8000
~~Brightest galaxy in cluster~~	~~70-13,000~~

But these are still calibrated with parallaxes!

Calibrated with pulsating variables



Galaxy distances come from a chain of techniques



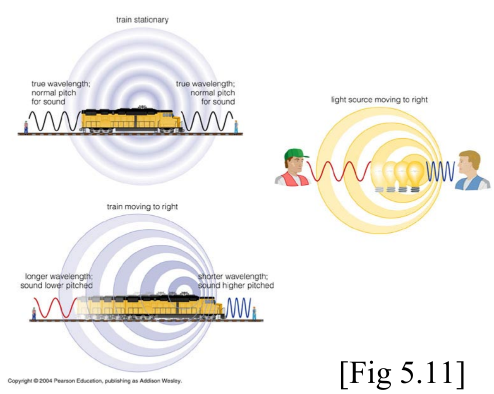
Edwin Hubble was the first to measure the distances to other galaxies

Measuring Radial Velocity: The Doppler effect

- If wave's source is moving,
  - stationary observer measures different frequency
  - = different wavelength.
- True for water waves, sound waves, and light waves.
  - Shift in wavelength is
    $\Delta\lambda = \lambda_{observed} - \lambda_{rest}$
  - For v = velocity of emitter,
    c = velocity of light

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

  - This *Doppler shift* only measures velocity along line of sight.
  - v/c is called redshift source is moving away, if $\Delta\lambda>0$
  - v/c is called blueshift source is moving towards us, if $\Delta\lambda<0$



[Fig 5.11]

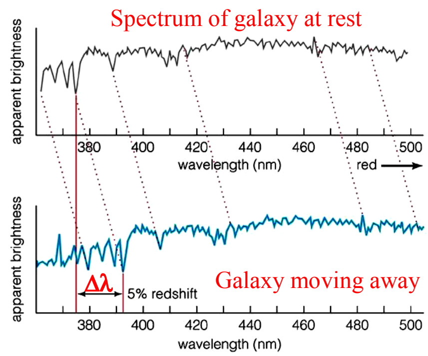
Measuring Radial Velocity: The Doppler effect

- Vesto Slipher in Flagstaff
  - Observed spectra of nearby galaxies
  - Some observations took several nights

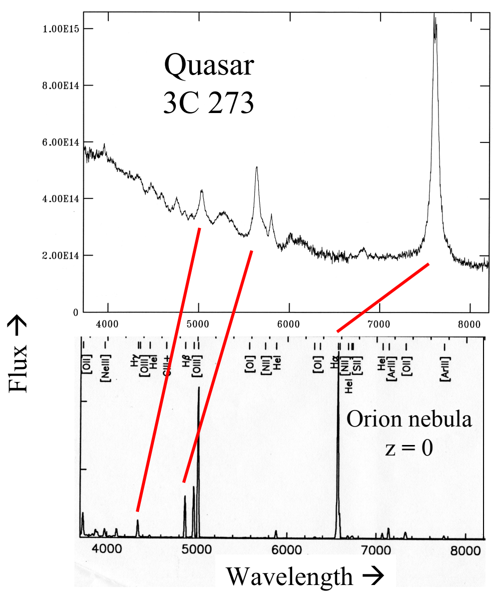
Vesto Slipher

- Shift in wavelength is
  $\Delta\lambda = \lambda_{observed} - \lambda_{rest}$
- For v = velocity of emitter,
  c = velocity of wave
  $$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$
- This *Doppler shift* only measures velocity along line of sight.

[Fig. 15.14]



Large redshifts



- Measure Doppler shift from emission or absorption lines:

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

Hubble's Law

- Hubble's Law: v = H D
  - Hubble 1929, Proc. Nat. Acad. Sci. 15, 168