Astr 102: Introduction to Astronomy

Fall Quarter 2009, University of Washington, Željko Ivezić

Lecture 5:

Measuring Distances in Astronomy

The Astronomical Distance Measurements

Measuring distance to astronomical objects is a very hard problem because we can't drive there and back, and read the odometer!

- There are two type of methods: direct and indirect

- Direct methods: radar ranging (for nearby Solar System objects) and geometric parallax ($<$1 kpc, limited by astrometric accuracy)

- Indirect methods: standard candles and rulers – their apparent magnitude and apparent angular size depend only on their distance (an extension: it's OK even if L or size intrinsically vary - if they can be estimated by other means)

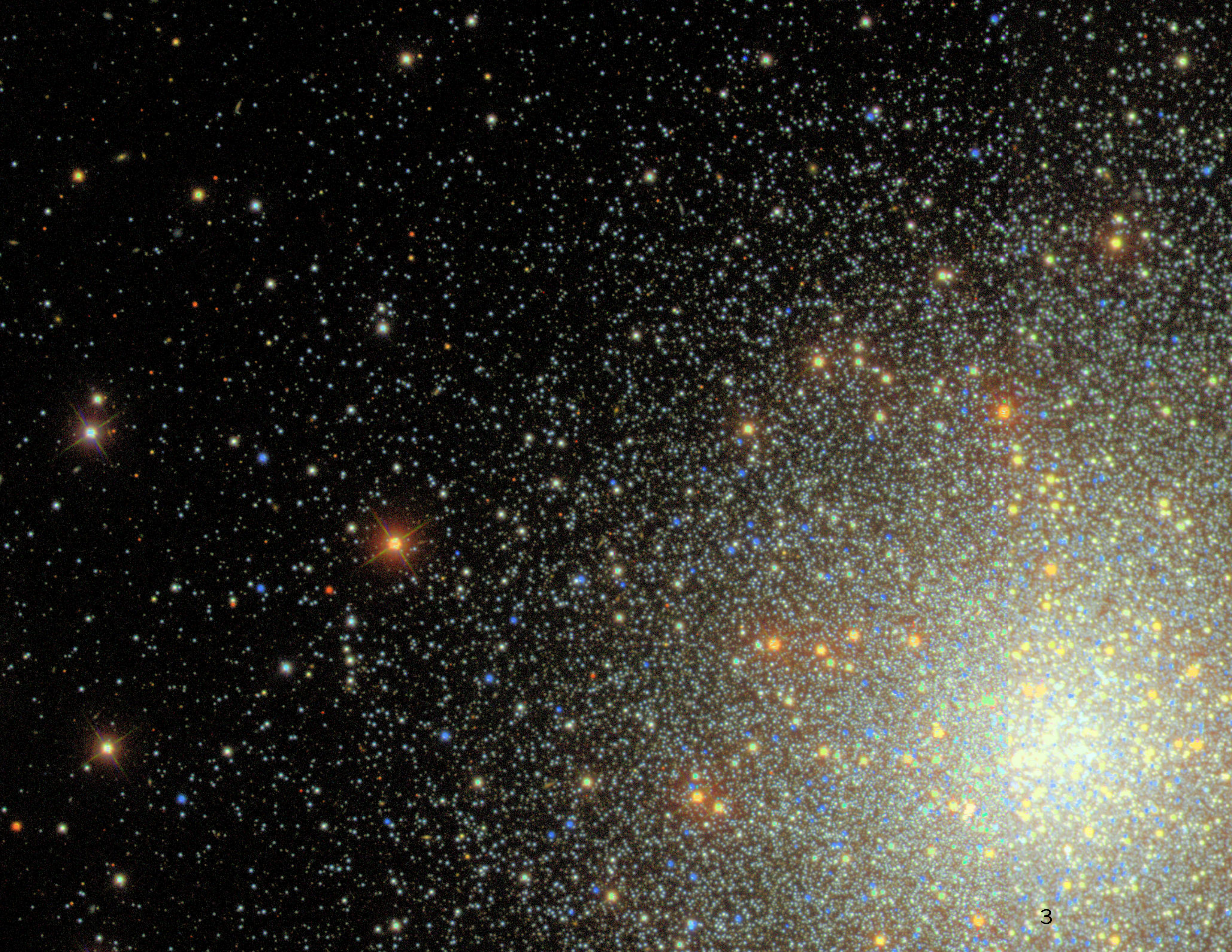
- *If you believe you know luminosity*, L, measure flux F and get distance D from $D^2 = L/4\pi F$

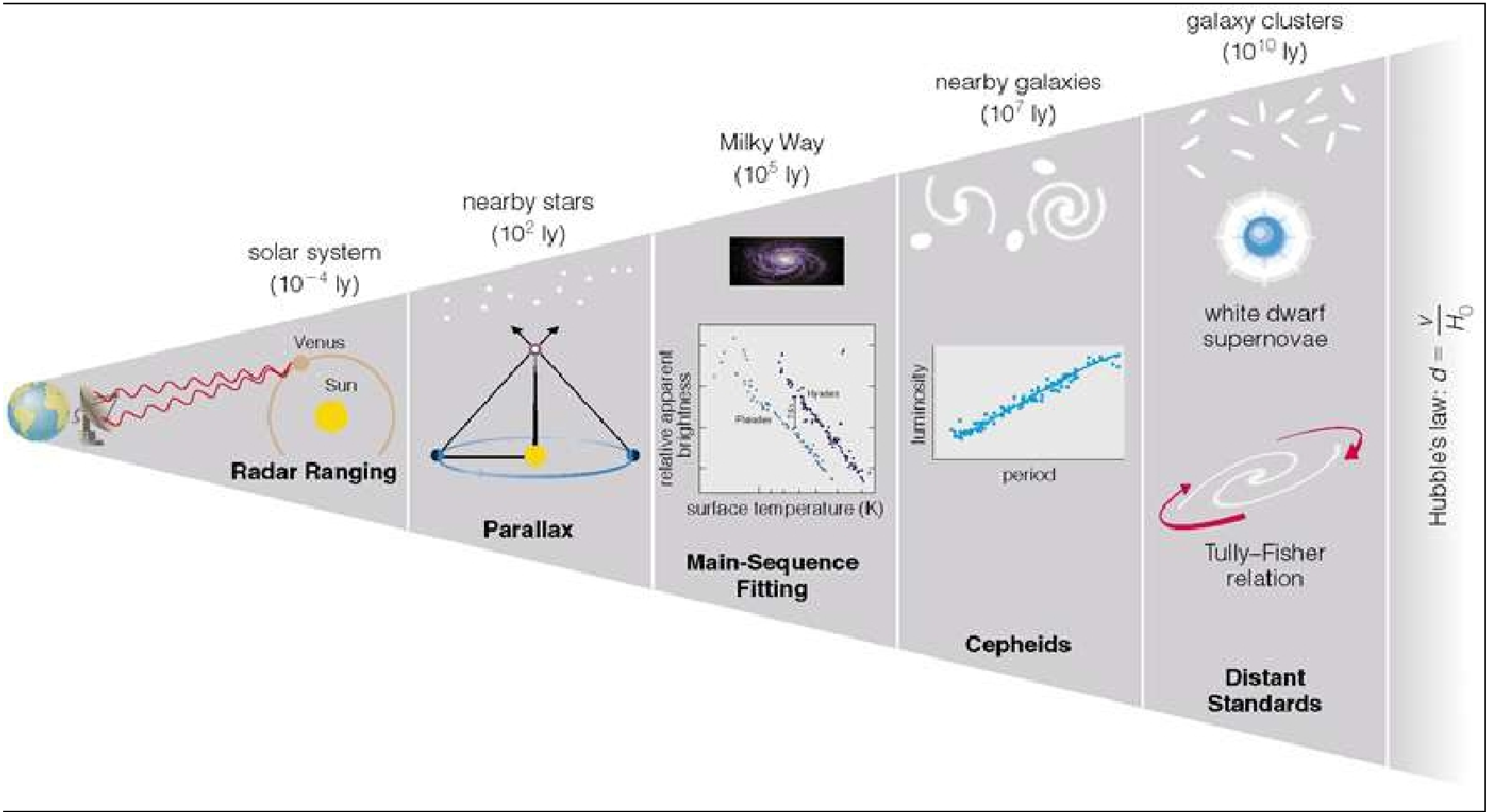
- *If you believe you know the true metric size*, S, measure the angular size θ and get distance D from $D = S/\theta$

- The accuracy of the resulting D depends on 1) how good are your assumptions about L and S, and how accurate are your measurements (a side issue: are those expressions correct?)

- redshift: for objects at cosmological distances (once the Hubble constant and other cosmological parameters are known)

- **A crucial concept is that applicable distance range of different methods overlap, and thus indirect methods can be calibrated using direct methods, leading to cosmic distance ladder**

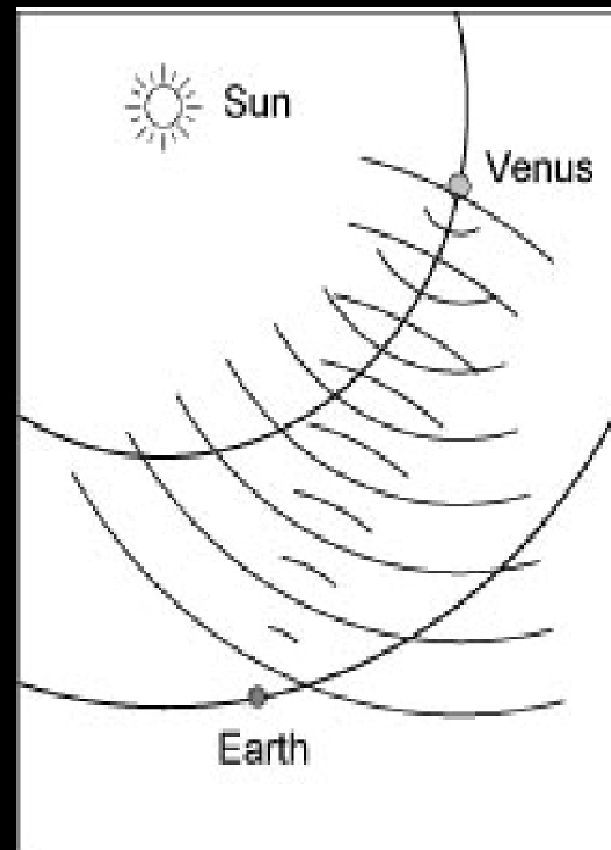



galaxy clusters
(10^10 ly)
nearby galaxies
(10^7 ly)
Milky Way
(10^5 ly)
nearby stars
(10^2 ly)
solar system
(10^−4 ly)
Venus
Sun
Radar Ranging
Parallax
relative apparent brightness
surface temperature (K)
Main-Sequence Fitting
luminosity
period
Cepheids
white dwarf supernovae
Tully–Fisher relation
Distant Standards
Hubble's law: d = v/H0

If one step in the ladder is revised, the whole universe will be bigger or smaller than previously thought!

53

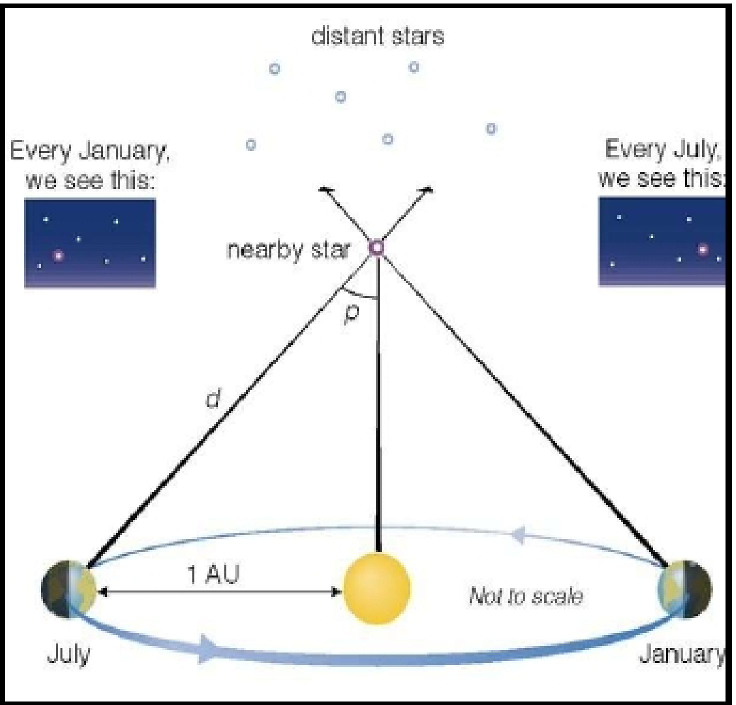
Distances *within the solar system* can be measured by radar ranging



Send out pulses of radio frequency radiation
Measure how long it takes for pulse to go and come back
Distance = c x (t/2)

A traditional unit of distance, the **PARSEC**, is defined in terms of parallax angle p

$$d\,(parsecs) = \frac{1}{p\,(arcseconds)}$$

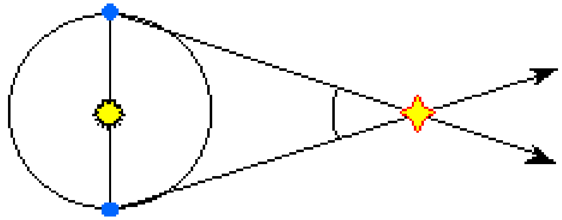


The distance to an object with a parallax angle of 1 arcsecond is 1 parsec

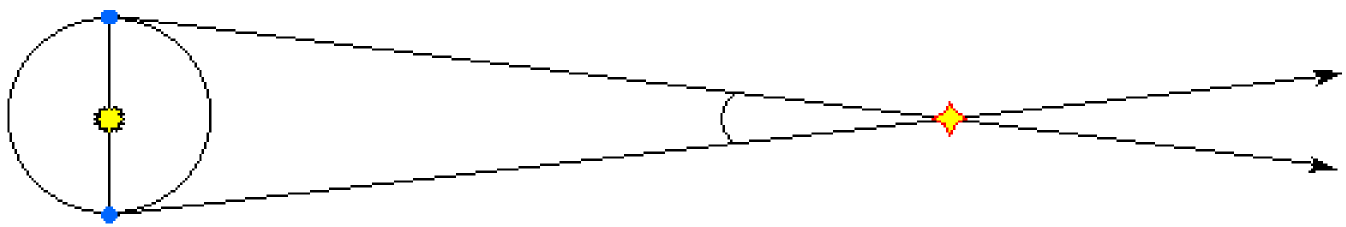
1 parsec = 3.26 light-years

We can measure parallax only for stars within a few hundred light years...but there is a good sampling of stars within this range

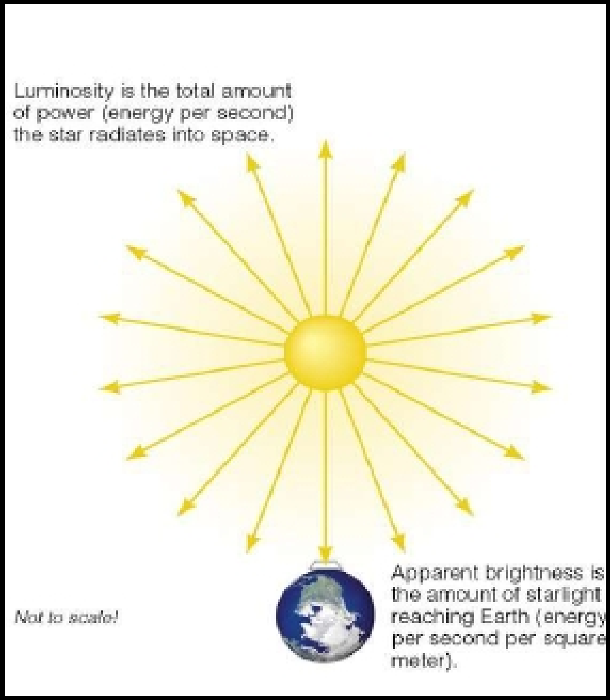
Closer stars have *larger* parallaxes:

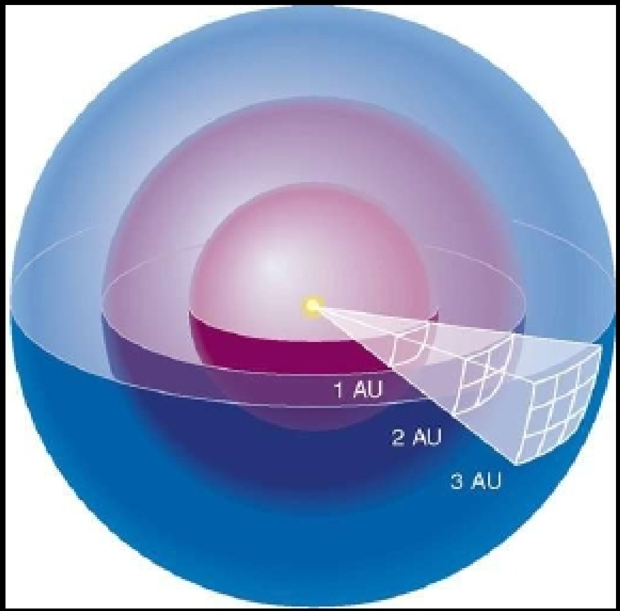


Distant stars have *smaller* parallaxes:



To measure distances of objects that are farther away, make use of **STANDARD CANDLES:** objects of *known* luminosity





Luminosity-Distance relation

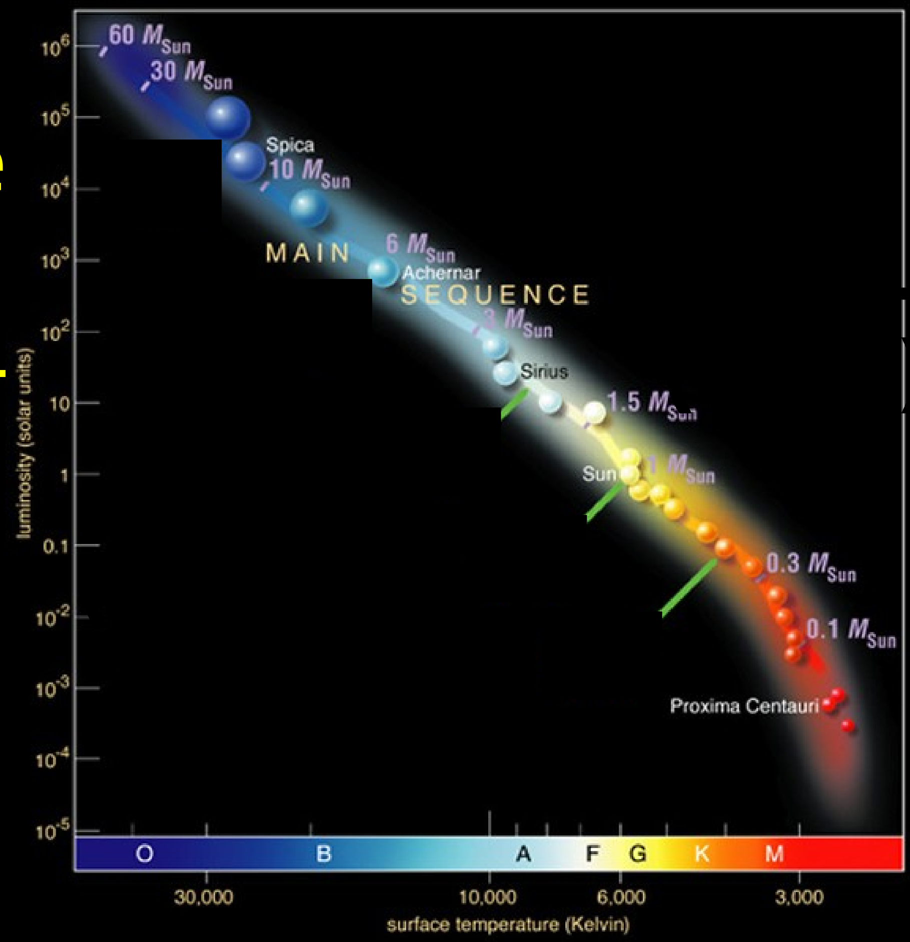
$$Apparent\ \ brightness = \frac{L}{4\pi d^2}$$

If you *measure* B, and you *know* L, you can solve for d

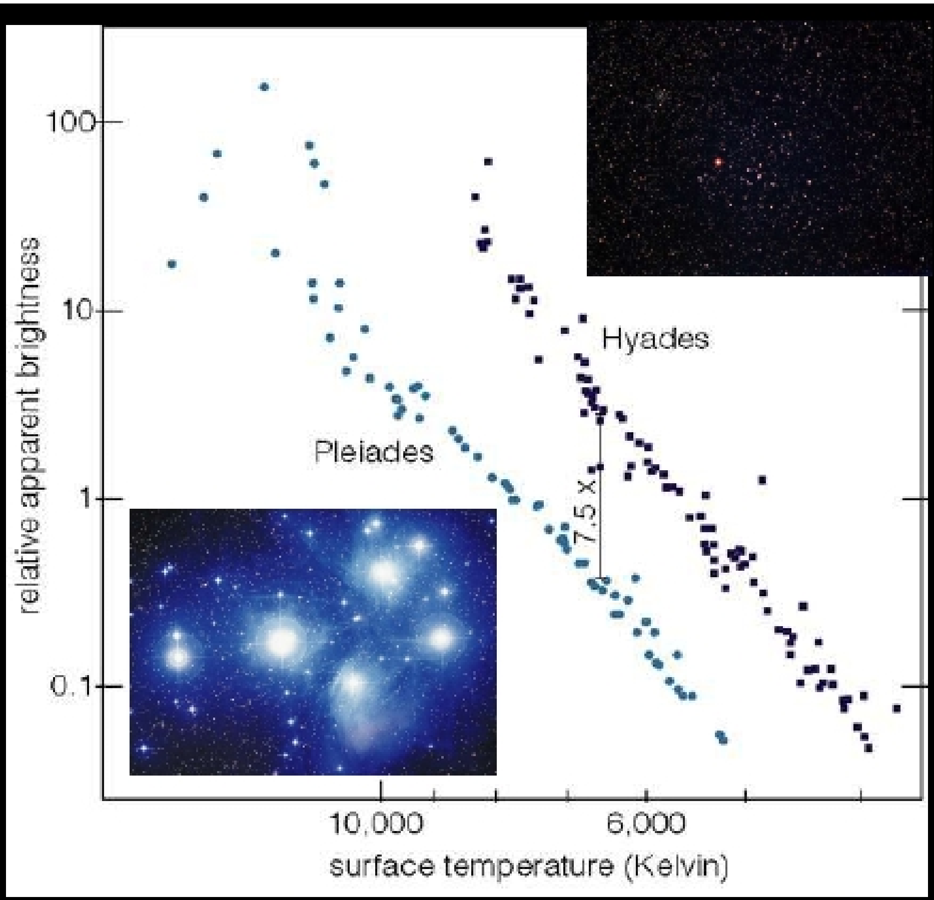
It's hard to know L perfectly, but it's often possible to do a decent job for some kinds of objects

Main Sequence Fitting

- The main sequence always lies on the *same place* in an H-R diagram



Same color = Same luminosity!



Main-Sequence Fitting

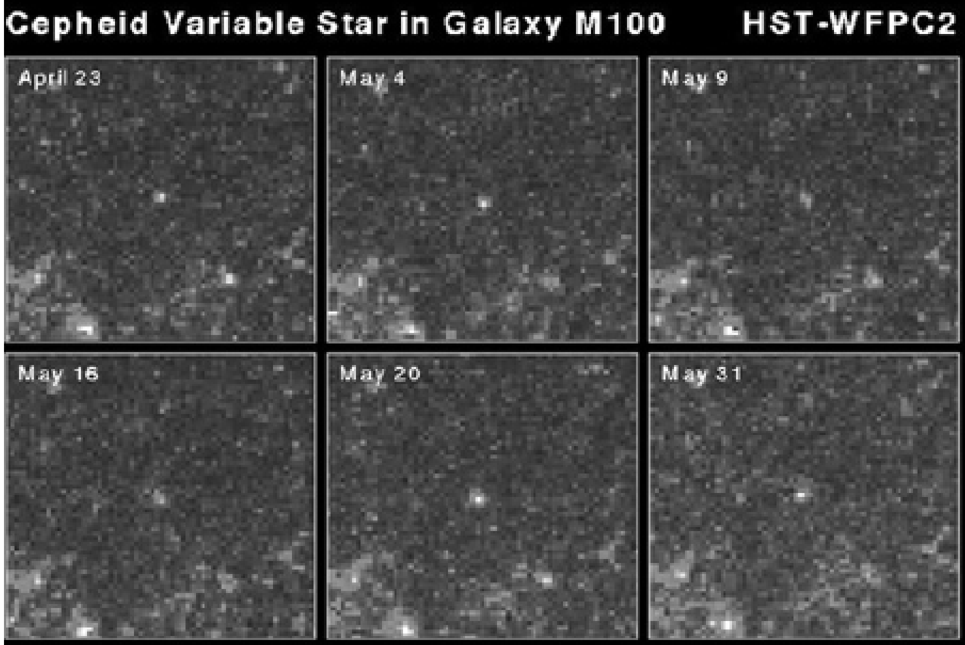
Works within the Galaxy

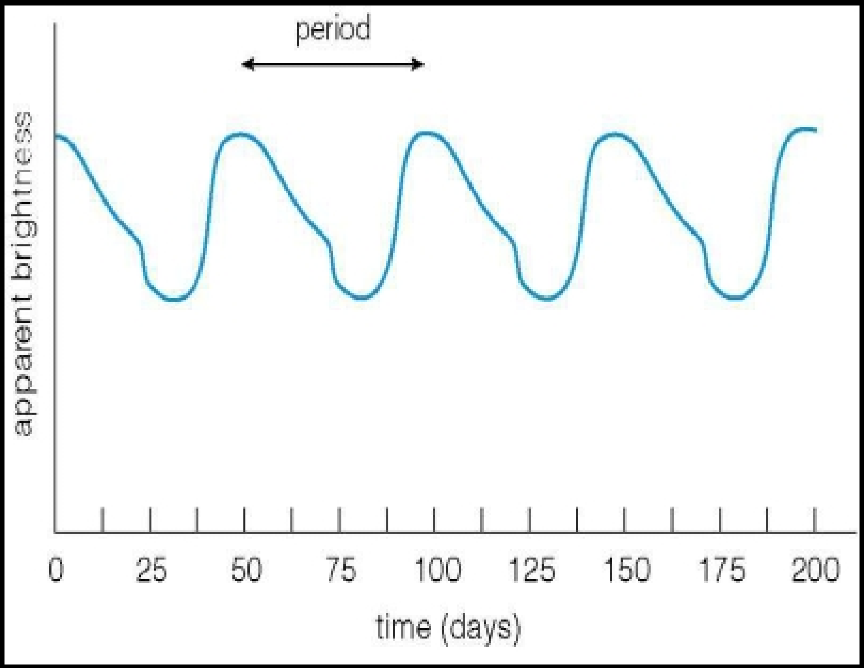
1. First, find one close enough to determine distance by parallax, e.g. Hyades, in Taurus (46 pc away)

2. Next, compare apparent brightnesses of distant and nearby cluster, and calculate distance to farther cluster

Another kind of standard candle:
CEPHEID VARIABLES

Giant, whitish stars that *pulsate:*
they expand and contract with a period of a few to a few hundred days

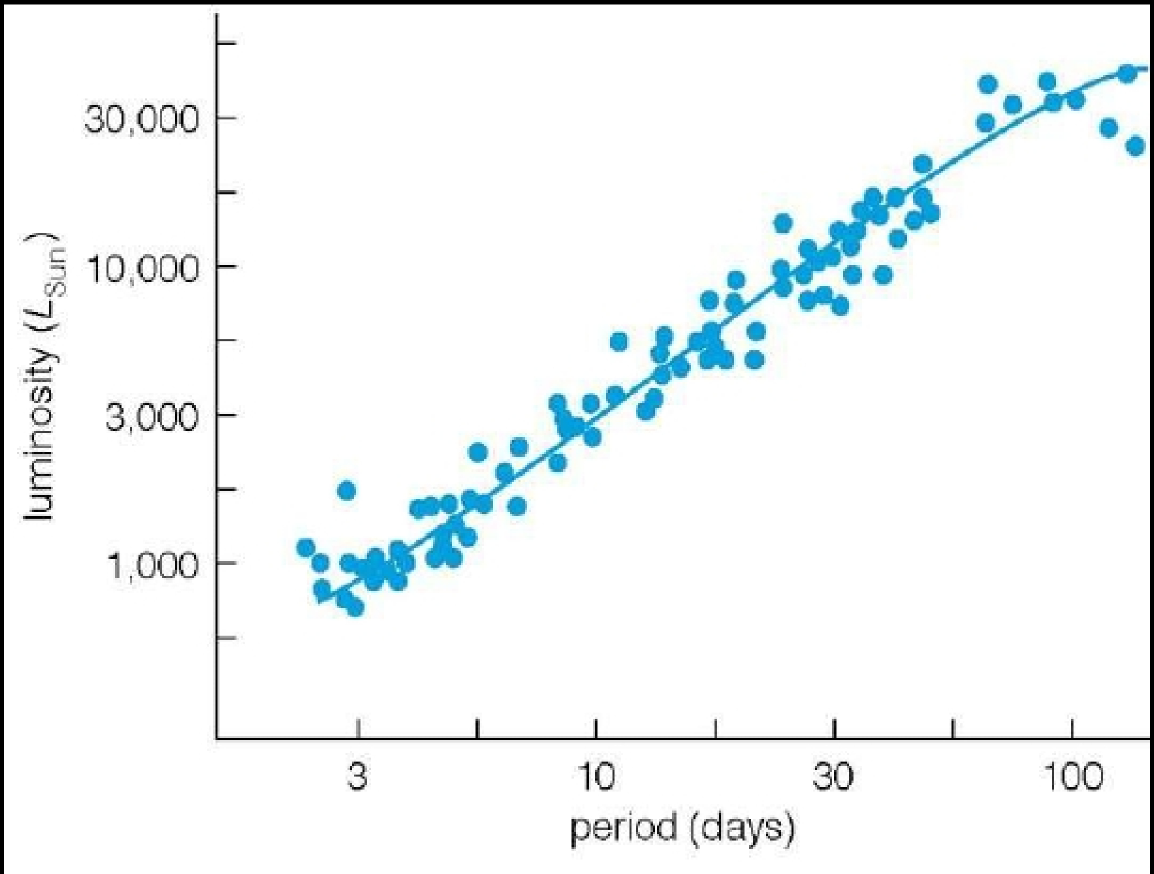




Luminosity varies cyclically with time

The (mean) luminosity depends on the period!

If you determine this relation for nearby stars (for which distance, and hence luminosity, are known)...



.. then you can determine the distance to another galaxy by observing the periods of its Cepheids!

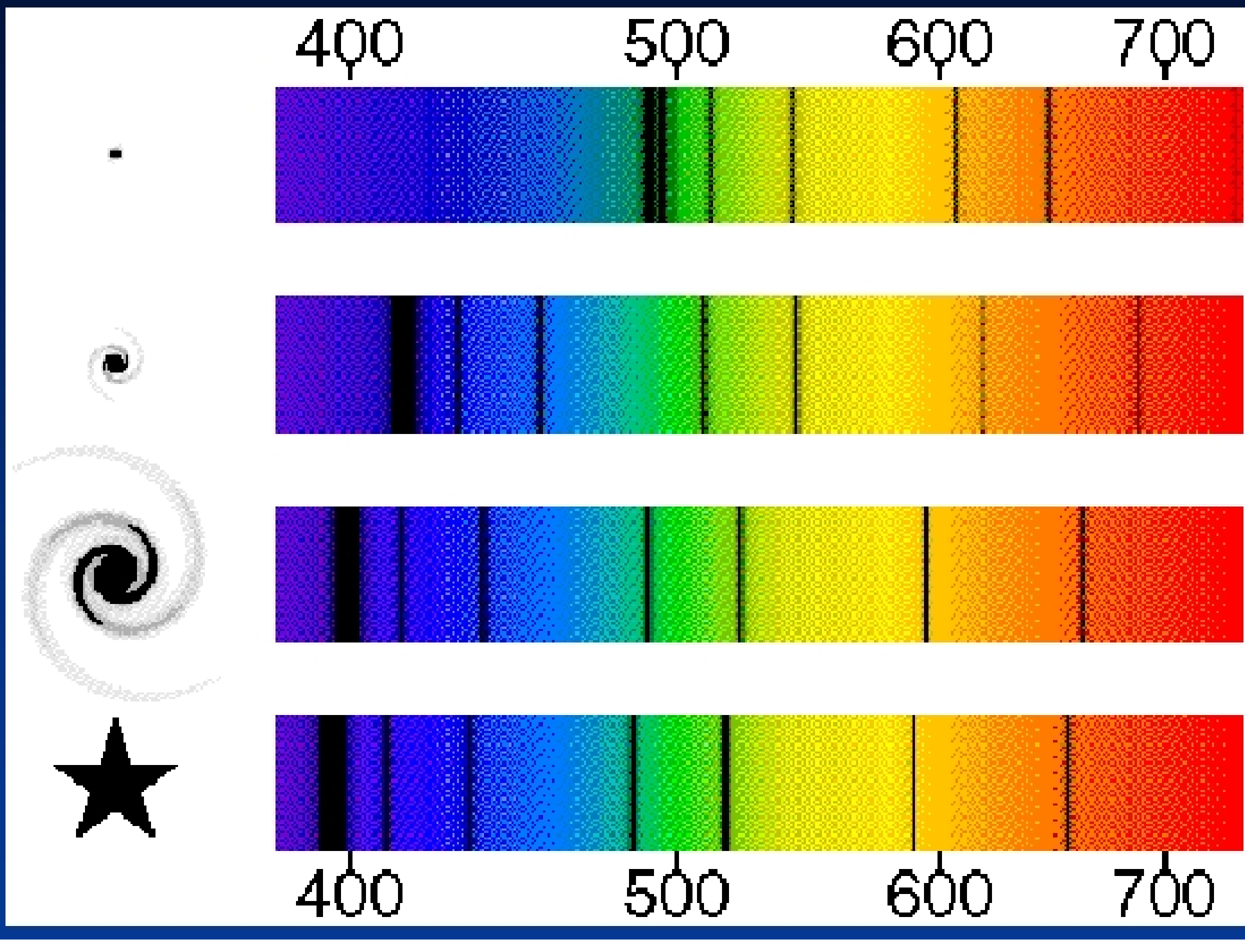
This works well for up to 10's of millions of lt-yr distances redshift:

$$1+z=\sqrt{\frac{1+v/c}{1-v/c}}$$

z=0: not moving

z=2: v=0.8c

z=∞: v=c



Redshift, z, Distance D, and Relative Radial Velocity v

Redshift is **defined** by the shift of the spectral features, relative to their laboratory position (in wavelength space)

$$z = \frac{\Delta\lambda}{\lambda} \tag{1}$$

(n.b. for negative $\Delta\lambda$ this is effectively *blueshift*).

When interpreted as due to the Doppler effect,

$$z = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1 \tag{2}$$

where v is the *relative* velocity between the source and observer, and c is the speed of light. This is the correct relativistic expression! For nearby universe, $v << c$, and

$$\frac{1}{1 - v/c} \approx 1 + v/c, \sqrt{1 + v/c} \approx 1 + v/2c, \text{ and thus } z \approx \frac{v}{c} \tag{3}$$

E.g. at $z = 0.1$ the error in implied v is 5% (and 17% for $z = 0.3$)

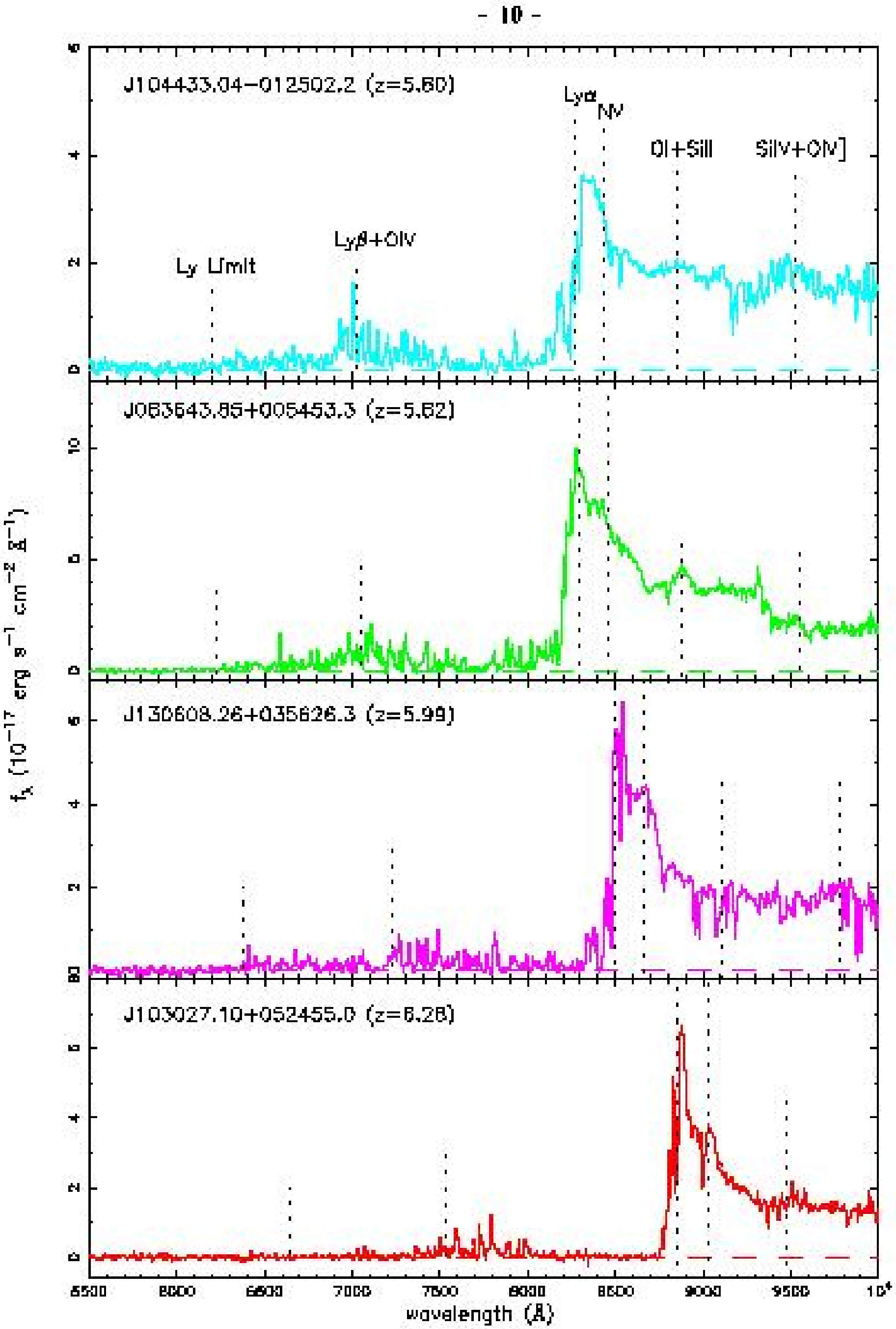


Figure 1. Optical spectrum of $z \gtrsim 5.8$ quasars observed with Keck/ESI, in the observed frame.

Most Distant Quasars

- The panels show quasar spectra: how much flux, i.e. photons, is detected at each wavelength (or frequency)
- The four spectra are similar, but are shifted in wavelength towards longer (red) wavelengths: **redshift**
- For very distant objects, their distance can be estimated from the measured redshift
- The relationship between redshift and distance was first found by Edwin Hubble (1929) (for galaxies)

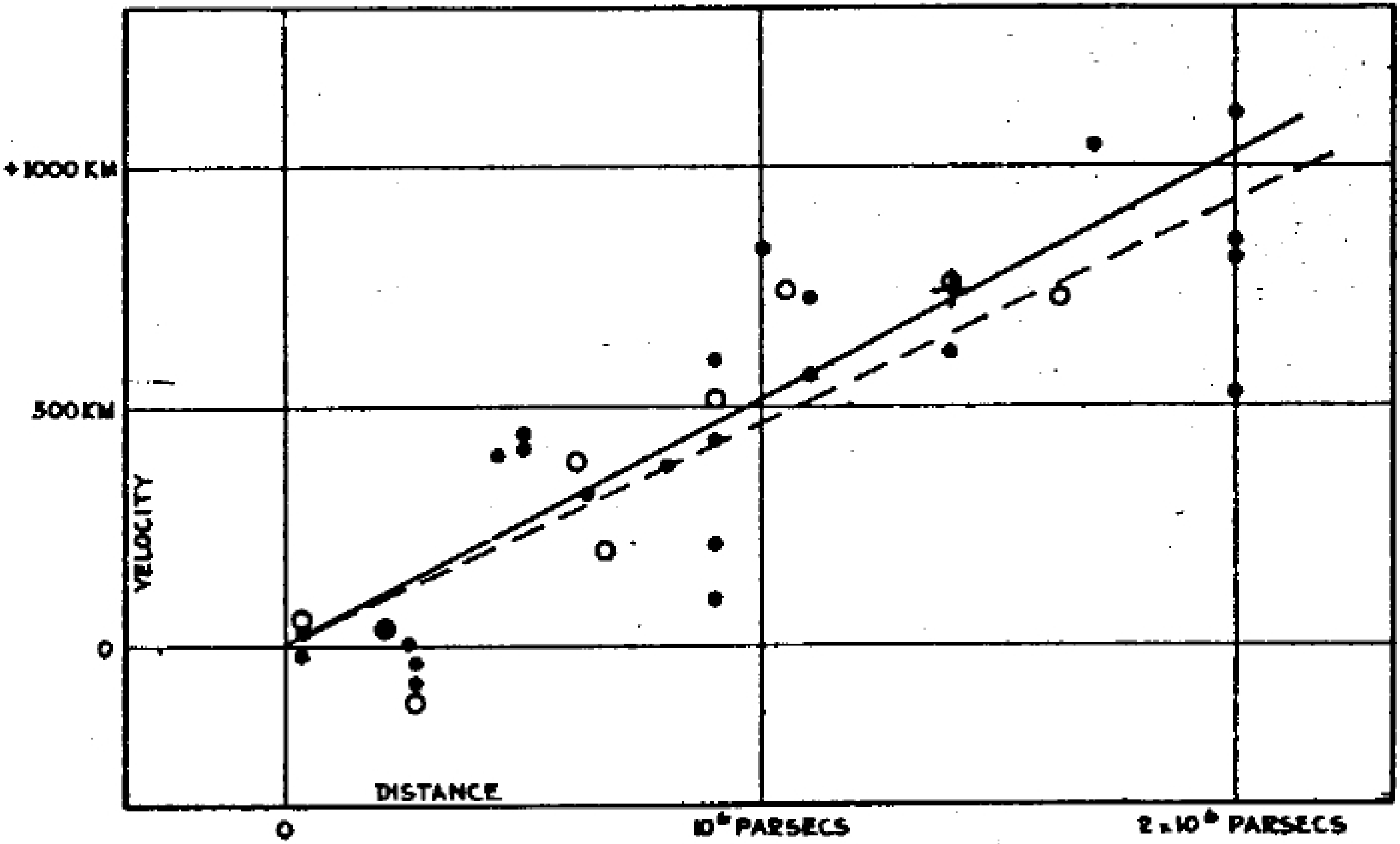
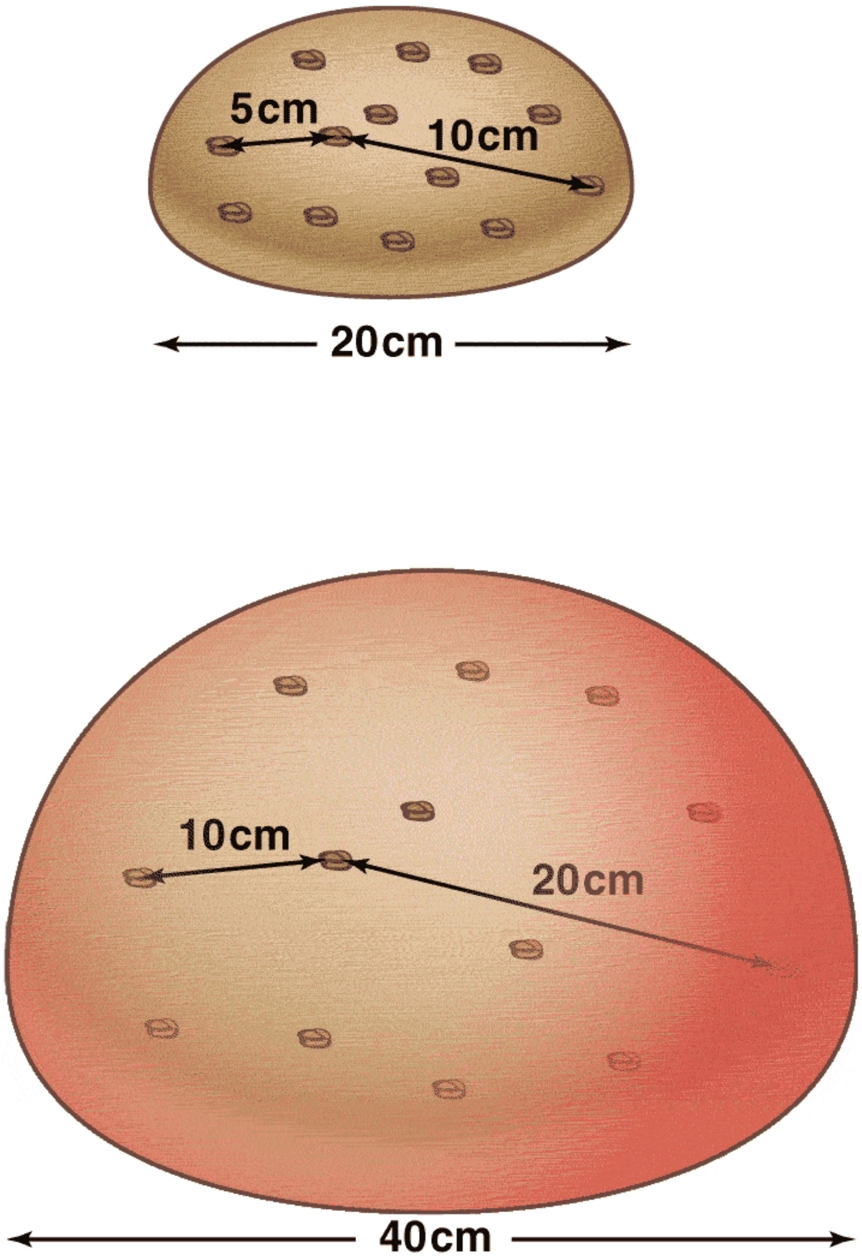


FIGURE 1

Hubble's redshift*c vs. distance diagram (1929)



Are we special?

- Does the expansion of the Universe imply that we are special?
- No, think of the raisin bread analogy.
- If every portion of the bread expands by the same amount in a given interval of time, then the raisins would recede from each other with exactly a Hubble type expansion law – and the same behavior would be seen from any raisin in the loaf.
- No raisin, or galaxy, occupies a special place in this universe
- We can run the expansion of the Universe backwards in time (at least in our thoughts) and conclude that all galaxies should converge to a single point: the Big Bang!