Astr 323: Extragalactic Astronomy and Cosmology

Spring Quarter 2014, University of Washington, Željko Ivezić

Lecture 4:

The Extragalactic Distance Scale

The Extragalactic Distance Scale

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, e.g. Tully-Fisher and Faber-Jackson relations)

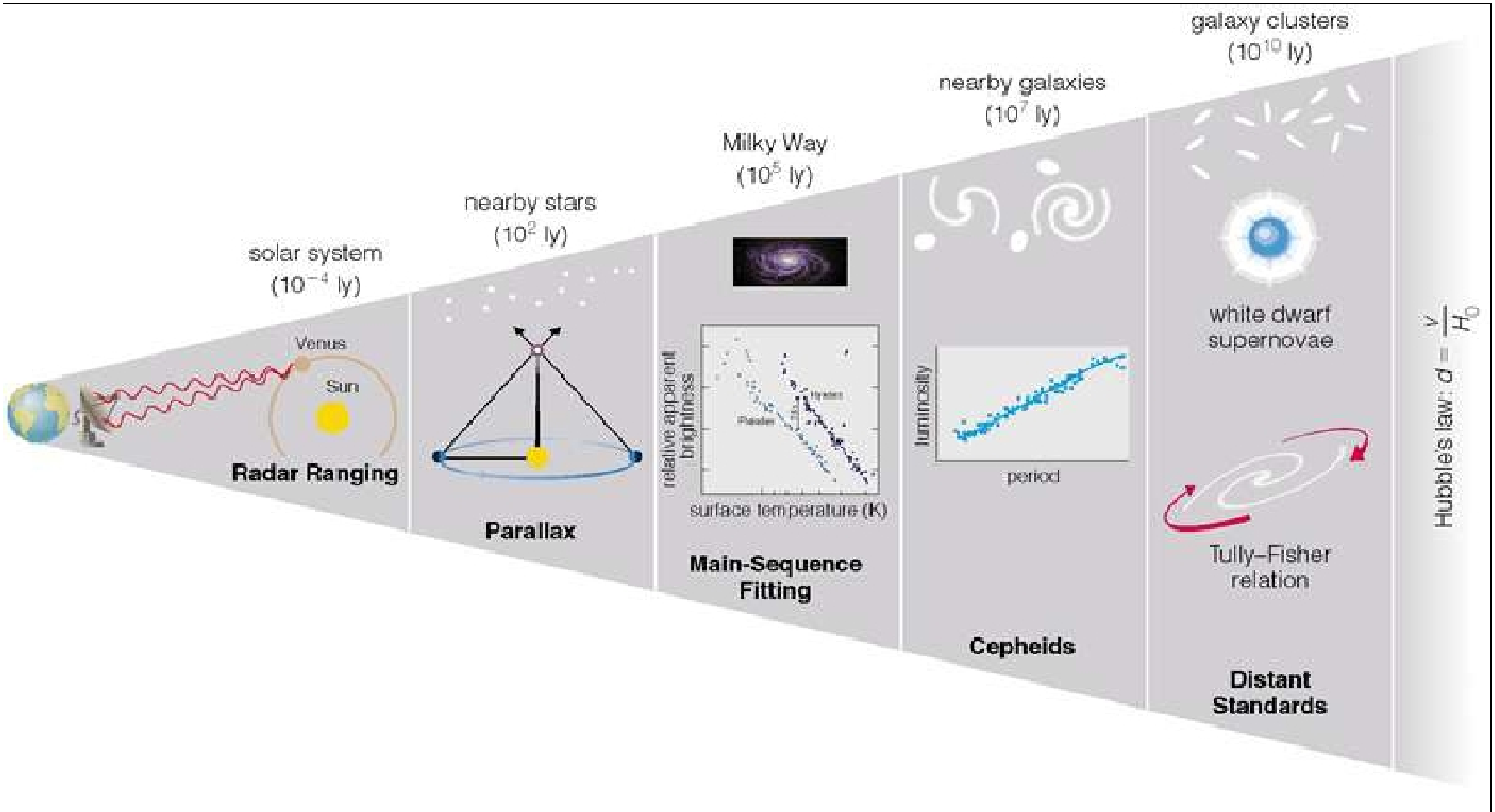
- If you believe you know luminosity L, measure flux F and get distance D from $D^2 = L/4\pi F$

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

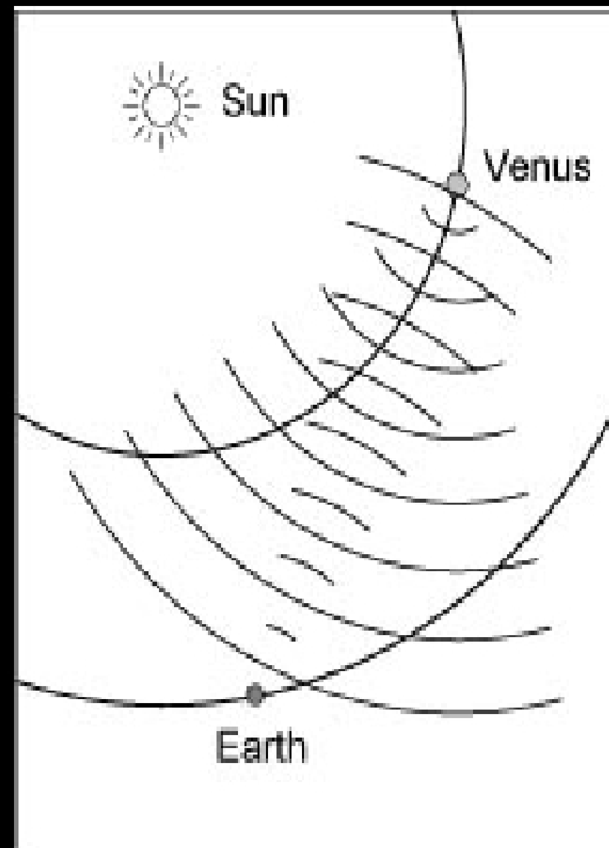
- The accuracy of the resulting D depends on 1) how good are your assumptions about L and S, and 2) how accurate are your measurements (a side issue: are those expressions correct?)

- 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**

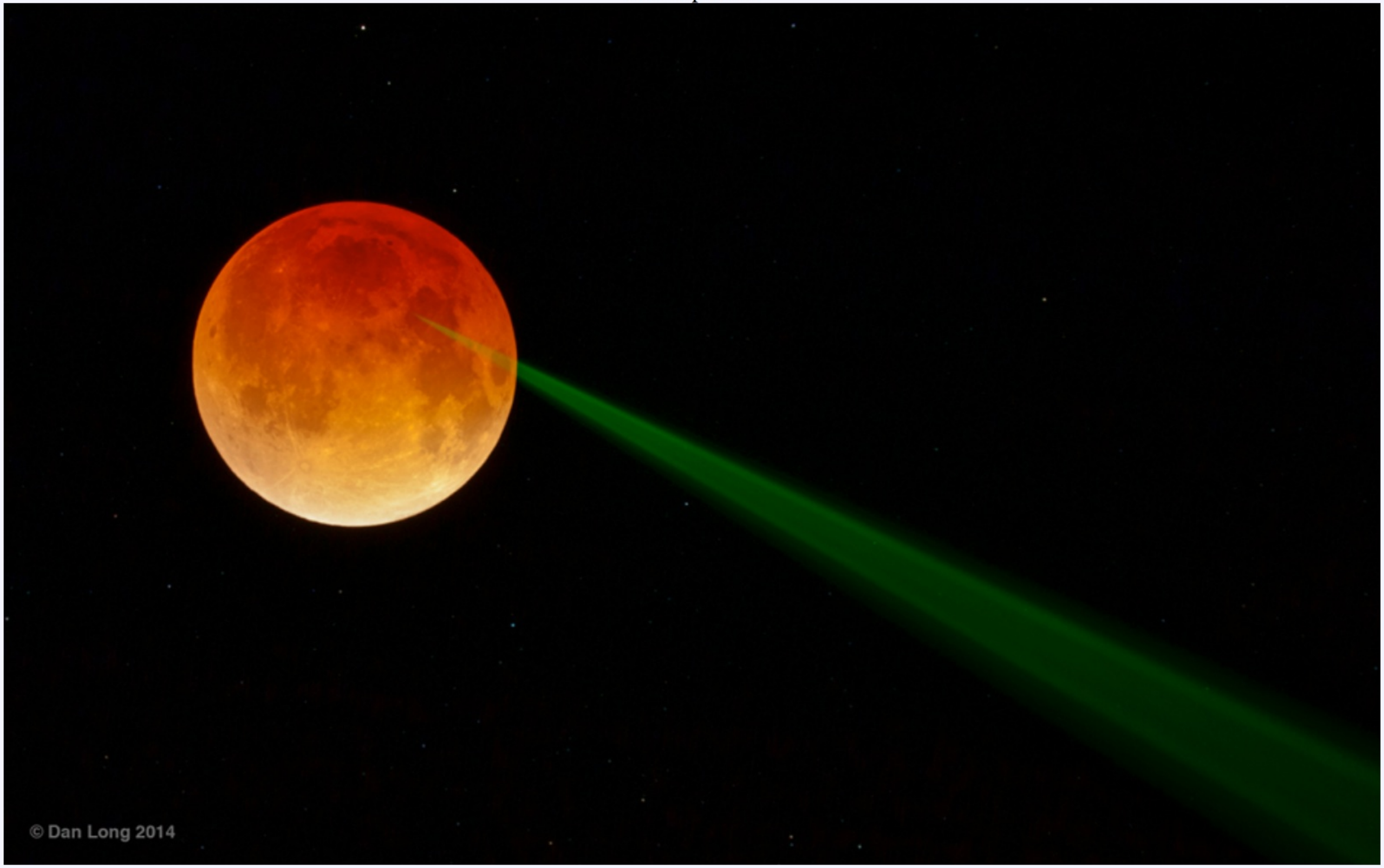

galaxy clusters
(10^{10} ly)
nearby galaxies
(10^{7} ly)
Milky Way
(10^{5} ly)
nearby stars
(10^{2} ly)
solar system
(10^{-4} ly)
Venus
Sun
Radar Ranging
Parallax
relative apparent brightness
surface temperature (K)
Main-Sequence Fitting
luminosity
period
Cepheids
white dwarf supernovae
Tully–Fisher relation
Distant Standards
Hubble's law: $d = \frac{v}{H_0}$

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)

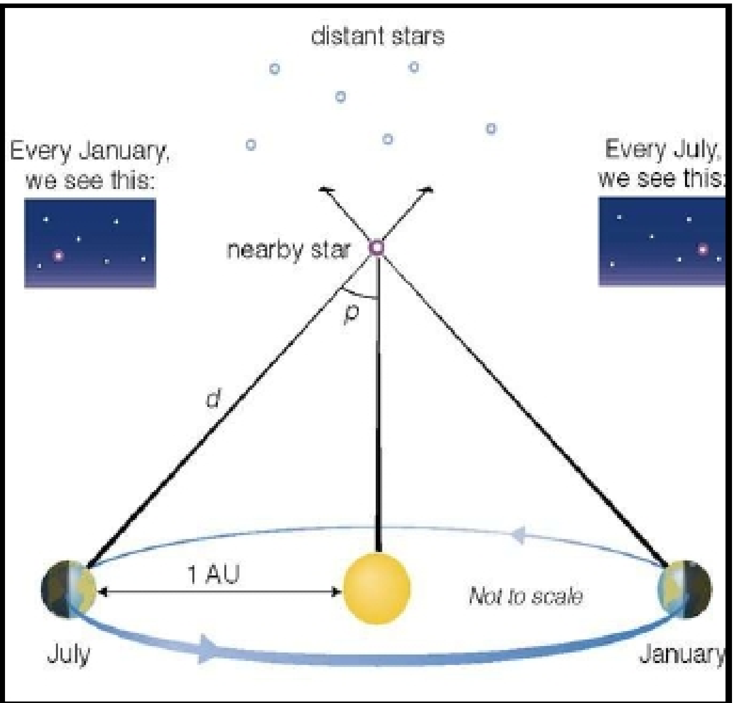
2014 April 18



Red Moon, Green Beam
Image Credit & Copyright: Dan Long (Apache Point Observatory) - *Courtesy:* Tom Murphy (UC San Diego)

Explanation: This is not a scene from a sci-fi special effects movie. The green beam of light and red lunar disk are real enough, captured in the early morning hours of April 15. Of course, the reddened lunar disk is easy to explain as the image was taken during this week's total lunar eclipse. Immersed in shadow, the eclipsed Moon reflects the dimmed reddened light of all the sunsets and sunrises filtering around the edges of planet Earth, seen in silhouette from a lunar perspective. But the green beam of light really is a laser. Shot from the 3.5-meter telescope at Apache Point Observatory in southern New Mexico, the beam's path is revealed as Earth's atmosphere scatters some of the intense laser light. The laser's target is the Apollo 15 retroreflector, left on the Moon by the astronauts in 1971. By determining the light travel time delay of the returning laser pulse, the experimental team from UC San Diego is able to measure the Earth-Moon distance to millimeter precision and provide a test of General Relativity, Einstein's theory of gravity. Conducting the lunar laser ranging experiment during a total eclipse uses the Earth like a cosmic light switch. With direct sunlight blocked, the reflector's performance is improved over performance when illuminated by sunlight during a normal Full Moon, an effect known as the real Full Moon Curse.

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



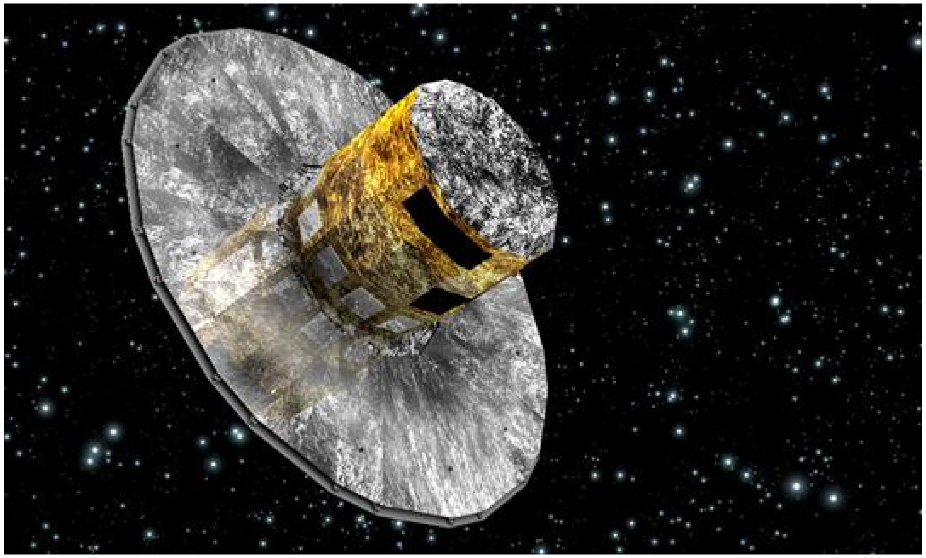
$$d(parsecs) = \frac{1}{p(arcseconds)}$$

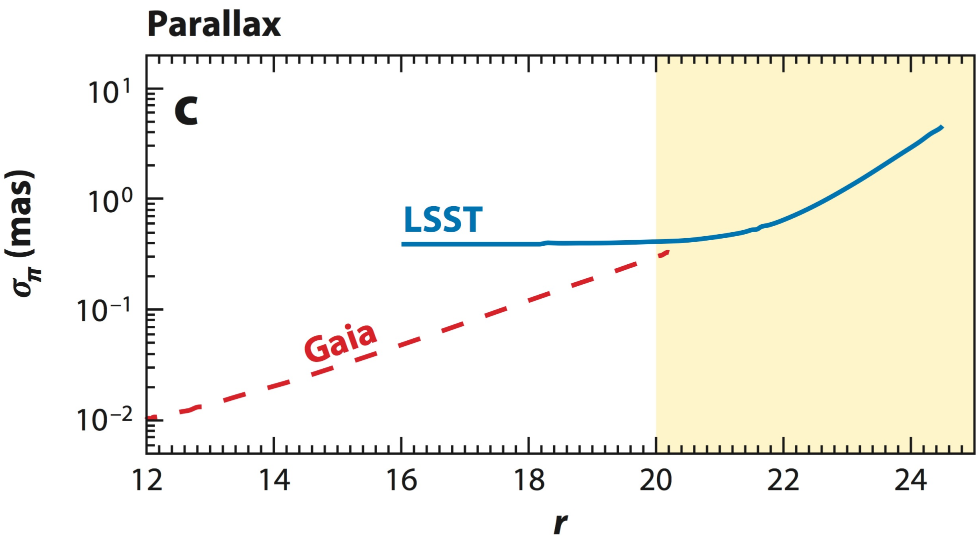
The distance to an object with a parallax angle of 1 arcsecond is 1 parsec

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

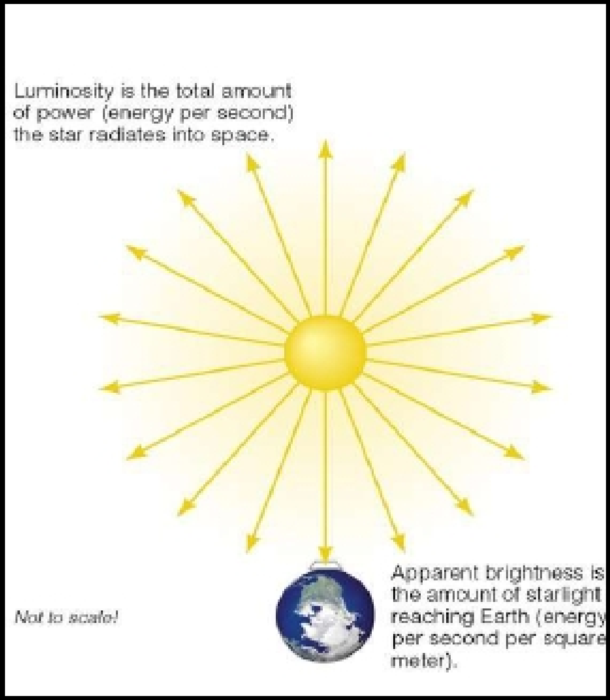
Astrometric space missions

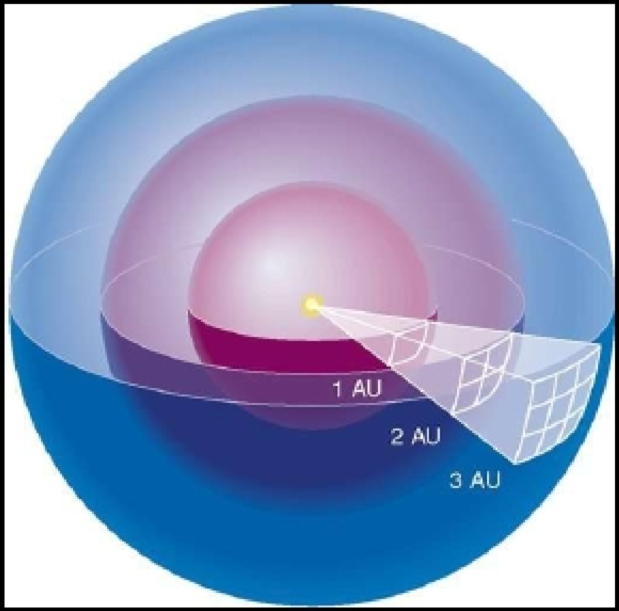




- German astronomer Bessel made the first (in 1838) successful parallax measurement, for the star 61 Cygni. Today, the best measurements come from space missions.
- ESA's Hipparcos mission (1989-1993): parallax-based distances for ~100,000 brightest stars
- ESA's Gaia mission (2013-now): astrometric measurements for a billion stars ($r < 20$! Parallax-based distances for a significant fraction of the total sample (errors from 0.01 mas at $r = 12$ to ~1 mas at $r = 20$): distance errors of 10% or smaller to about 1 kpc distance (for more details see Ivezić et al. 2012, ARA&A 50, 251).

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



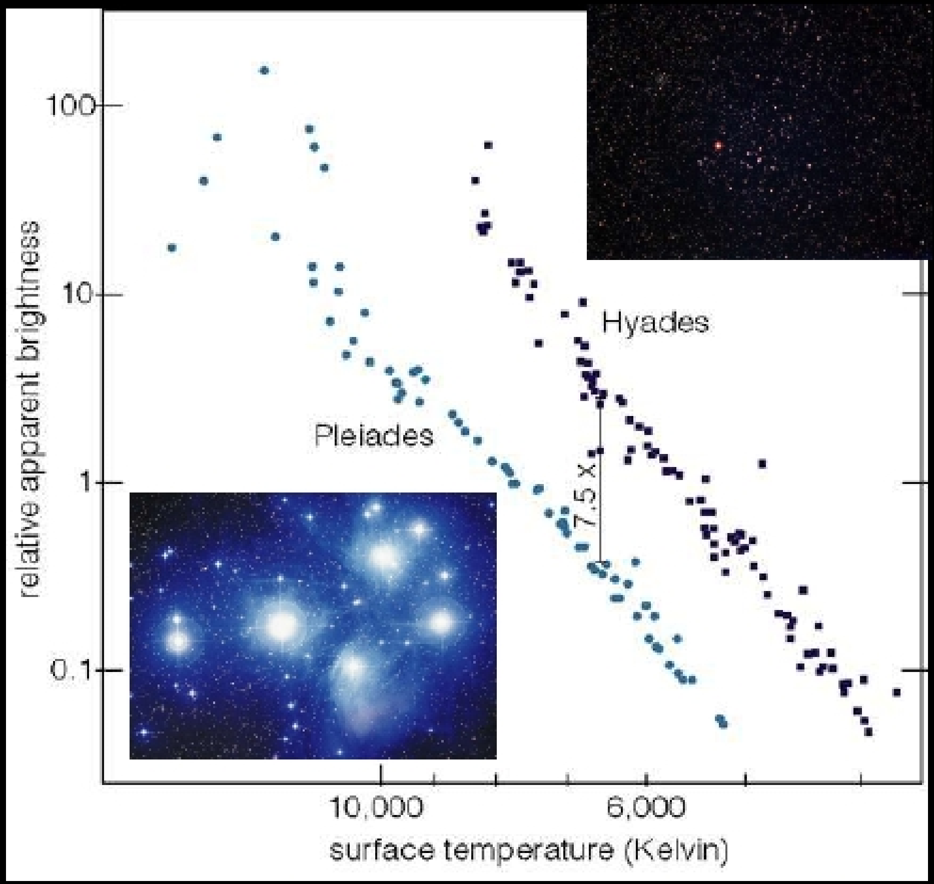


Luminosity-Distance relation

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

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

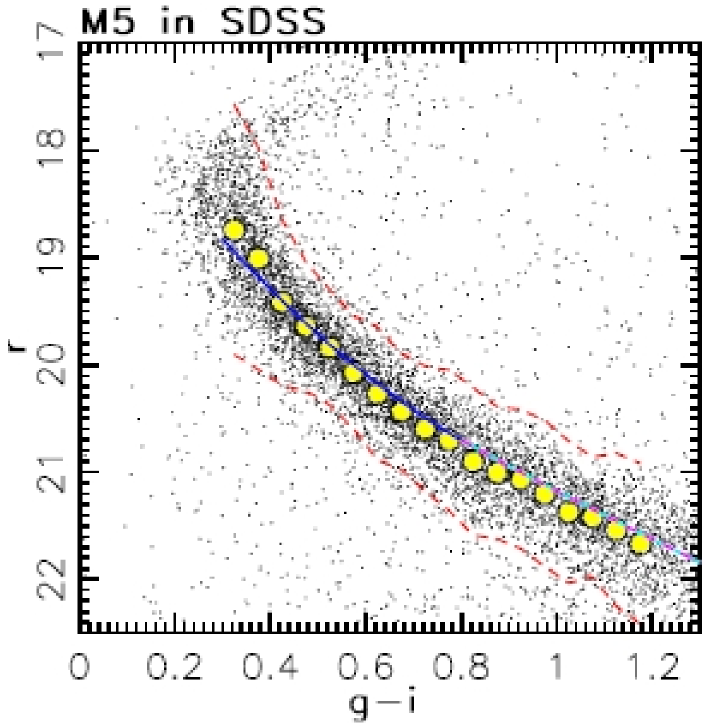
It's hard to know L perfectly, but it's often possible to do a decent job for some kinds of objects

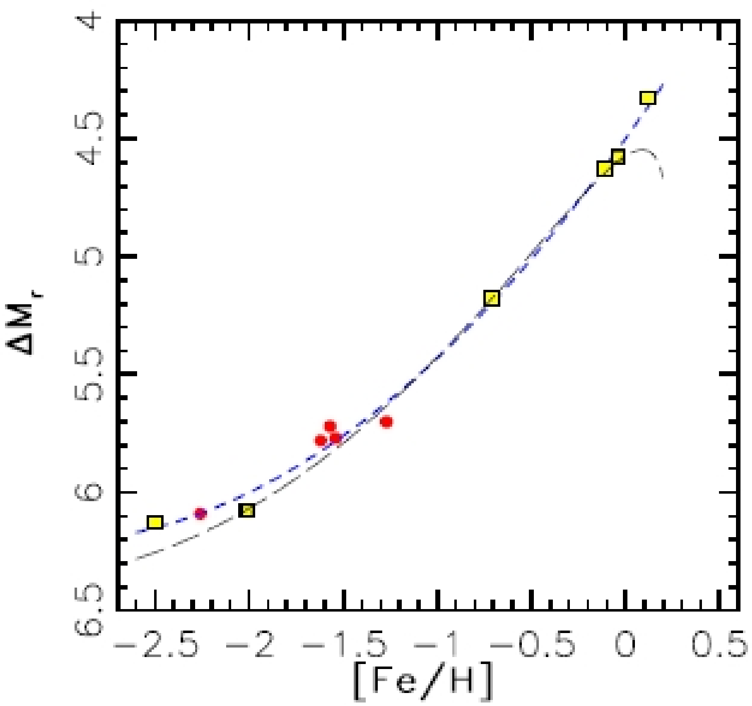


Main-Sequence Fitting

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



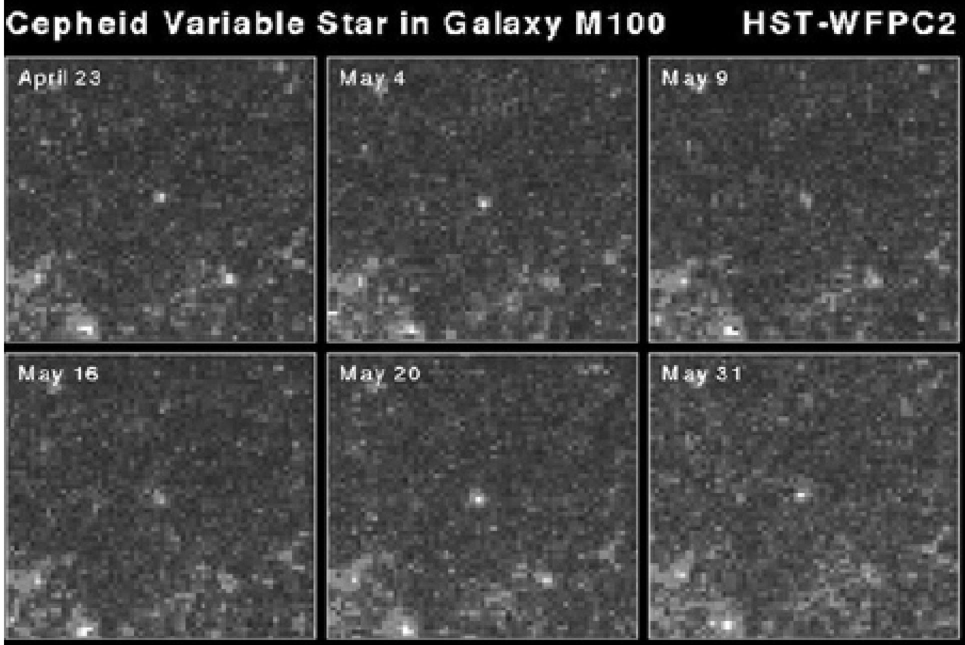


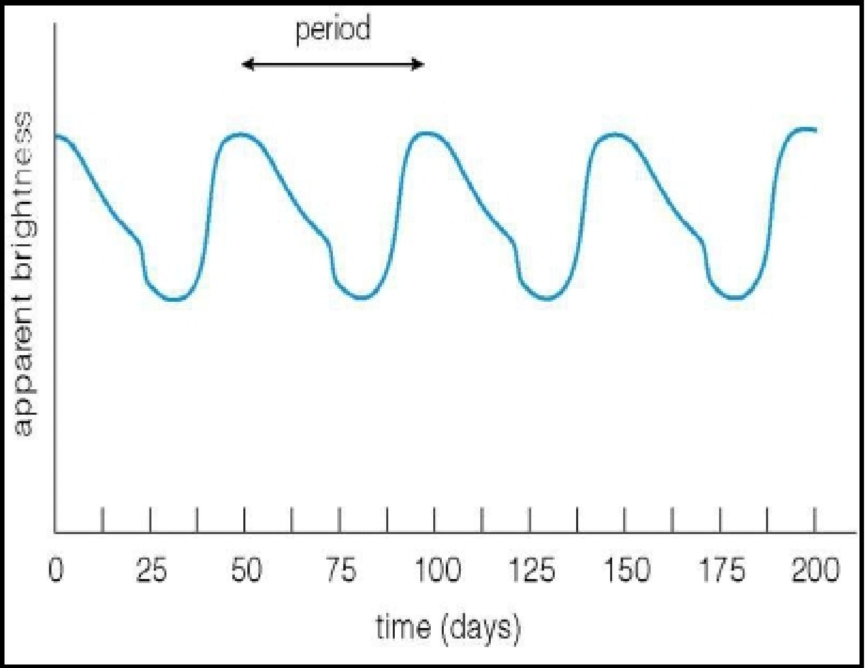
Photometric Distance and Photometric [Fe/H]

- Determined absolute magnitude vs. color vs. metallicity relation using globular clusters observed by SDSS (blue end), and nearby stars with trigonometric parallaxes (red end)
- The $g - i$ color of a main-sequence star constrains its absolute magnitude to within 0.1-0.2 mag (0.3 mag for unresolved binaries), assuming [Fe/H] is known
- This method was known half a century ago, but only recently applied to tens of millions of stars because large-scale surveys did not have the required photometric accuracy (Ivezić et al. 2008, ApJ 684. 287)

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

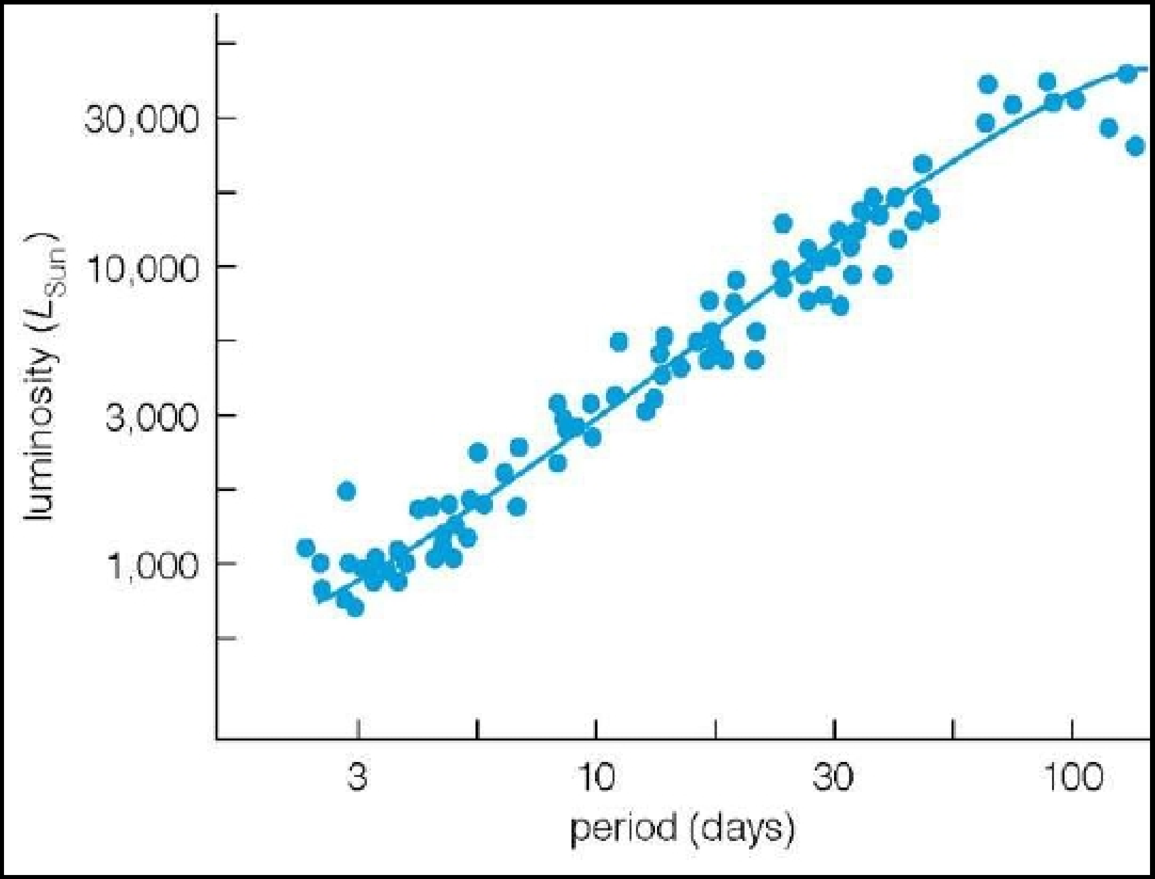




Luminosity varies cyclically with time

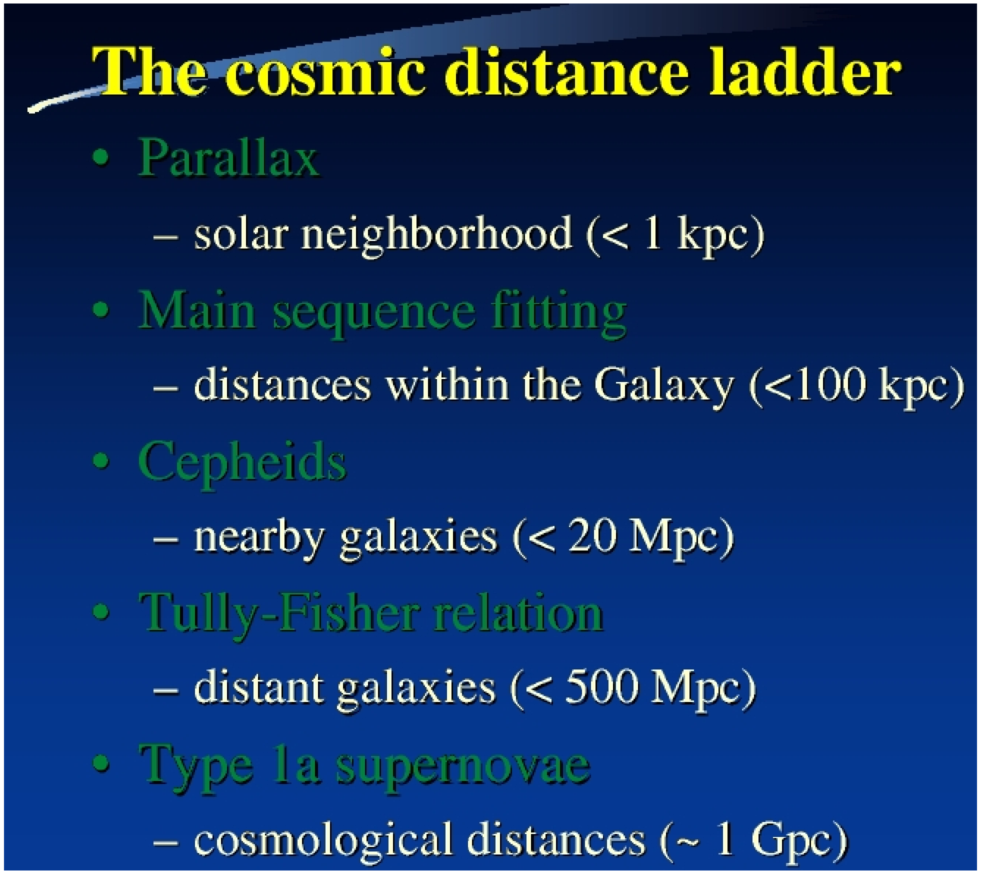
The (mean) luminosity depends on the period!

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



The Cosmic Distance Ladder

- Direct (parallax) and indirect (standard candles and rulers) methods
- Tied to cepheid distances; still uncertain at the 10% level
- Cosmological distances estimated from redshift, uncertain at the 10% level
- Distance scale tied to Hubble's constant, H_o, which can be determined **independently!** (e.g. from CMB data)
- An important example of the early use of extragalactic distance scale: the nature of nebulae (or, the Great Debate of 1920)

Nature of spiral nebulae ?

Curtis

- MW is 10 kpc across
- Sun near center
- spiral nebulae were other galaxies
  - high recession speed
  - apparent sizes of nebulae
  - did not believe van Maanen's measurement

⇒ Milky Way = one galaxy among many others

Shapley

- MW is 100 kpc across
- Sun off center
- spiral nebulae part of the Galaxy
  - apparent brightness of nova in the Andromeda galaxy
  - measured rotation of spirals (via proper motion) by van Maanen

⇒ Milky Way = Universe

Photo by David Malin

Edwin Hubble (1889-1953)

Four major accomplishments in extragalactic astronomy

- The establishment of the Hubble classification scheme of galaxies
- The convincing proof that galaxies are island "universes"
- The distribution of galaxies in space
- The discovery that the universe is expanding

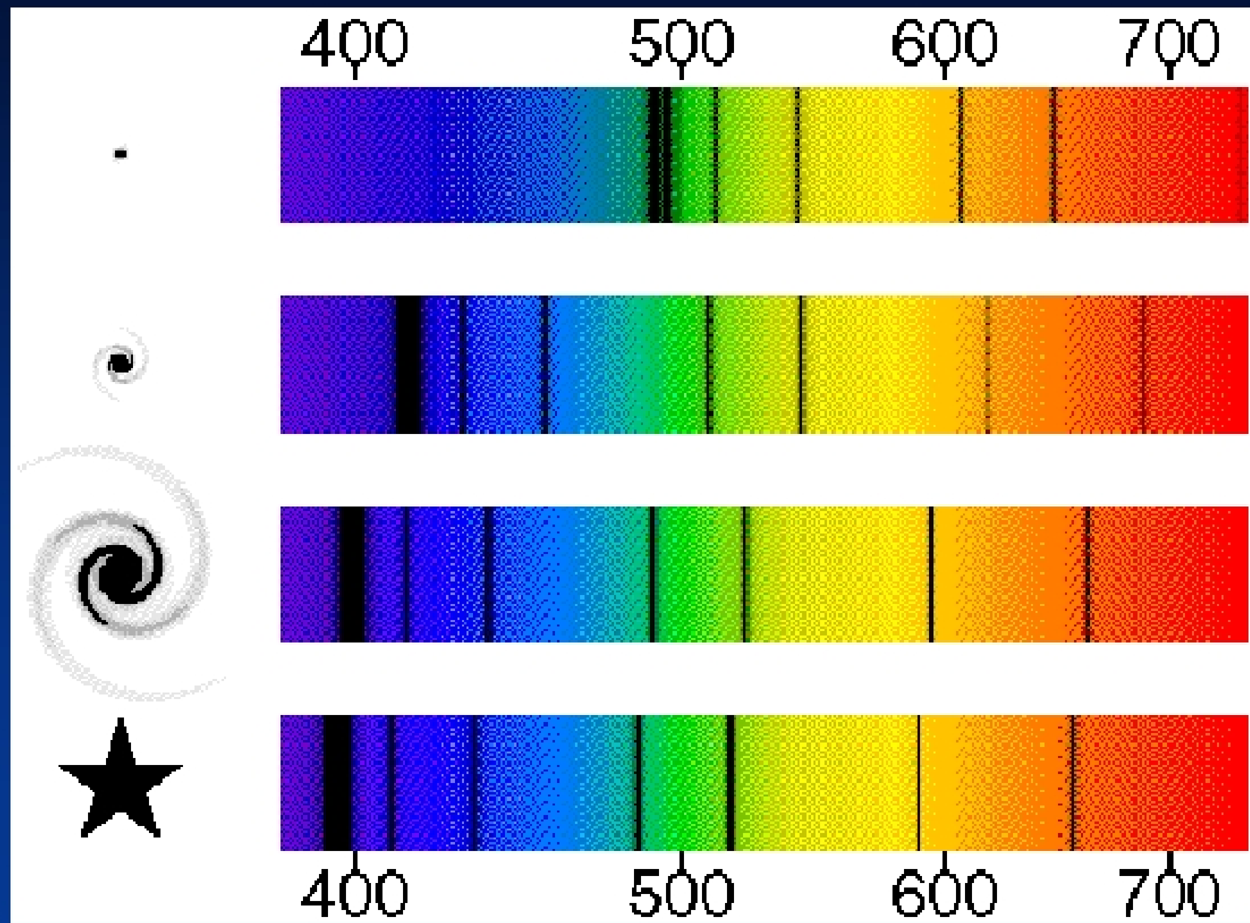
redshift:

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

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

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

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

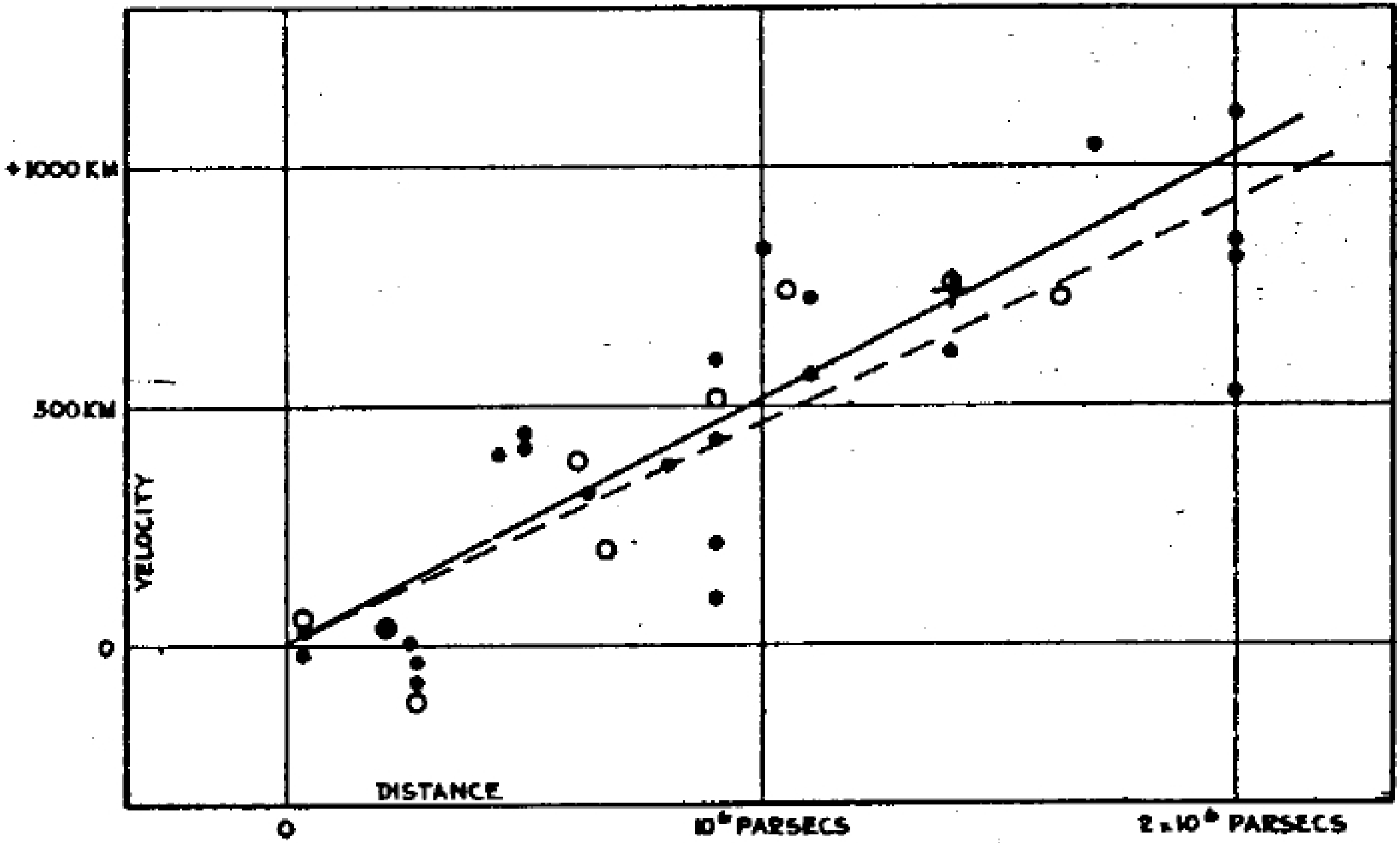


FIGURE 1

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

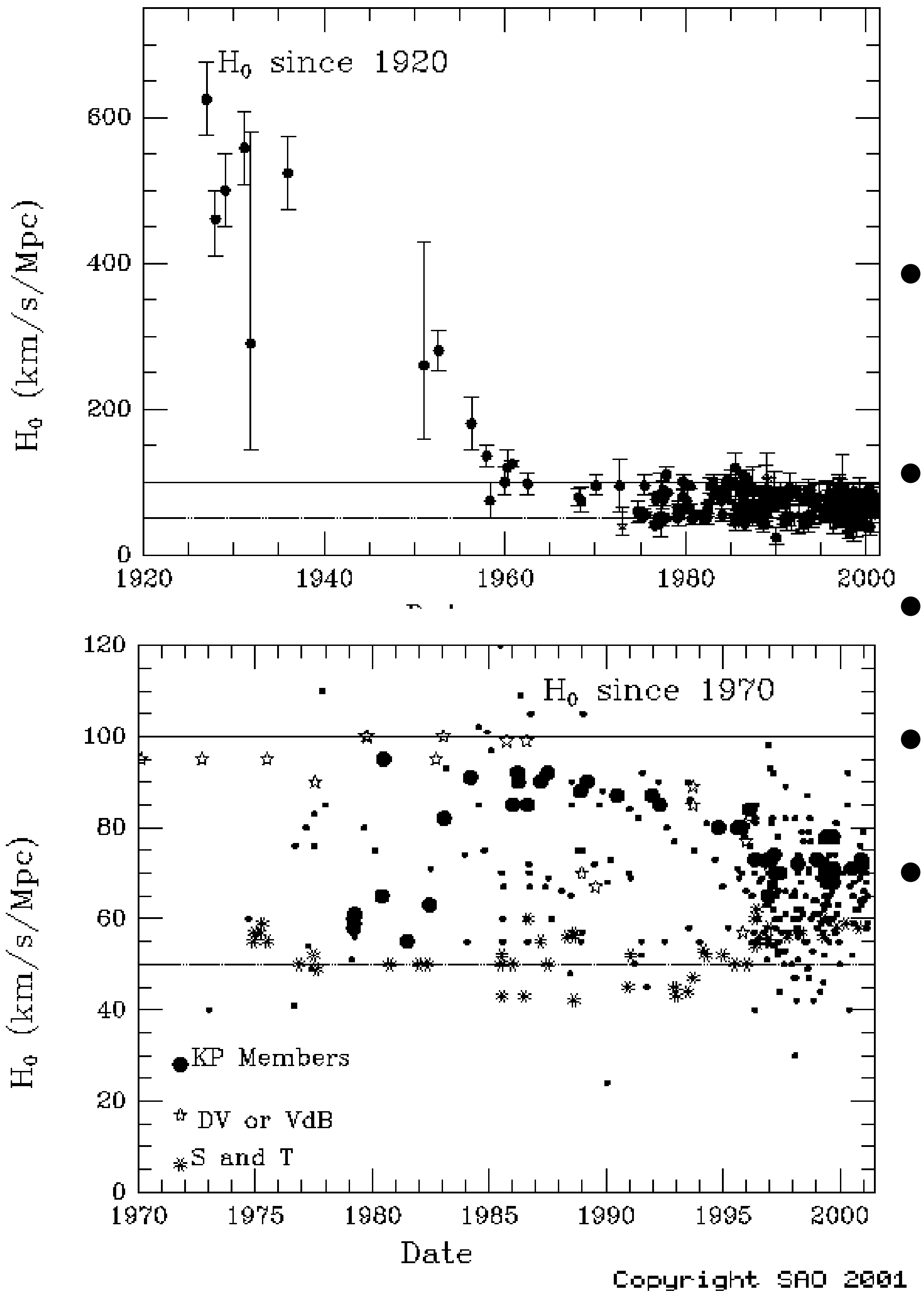
The Universe is Expanding!

Hubble's 1929 discovery made Einstein abolish the cosmological constant, which he introduced in 1917 to produce a static Universe (at that time the idea that the universe was expanding was thought to be absurd; today, some still think so...)

1 Mpc distance corresponds to $z = 0.0002$! With SDSS we can go 1000 times ($\sim$Gpc) further away! At z=0.2 the expansion velocity is $\sim$60,000 km/s: the scatter around Hubble's law is **dominated by errors in estimating distances and peculiar velocities**.

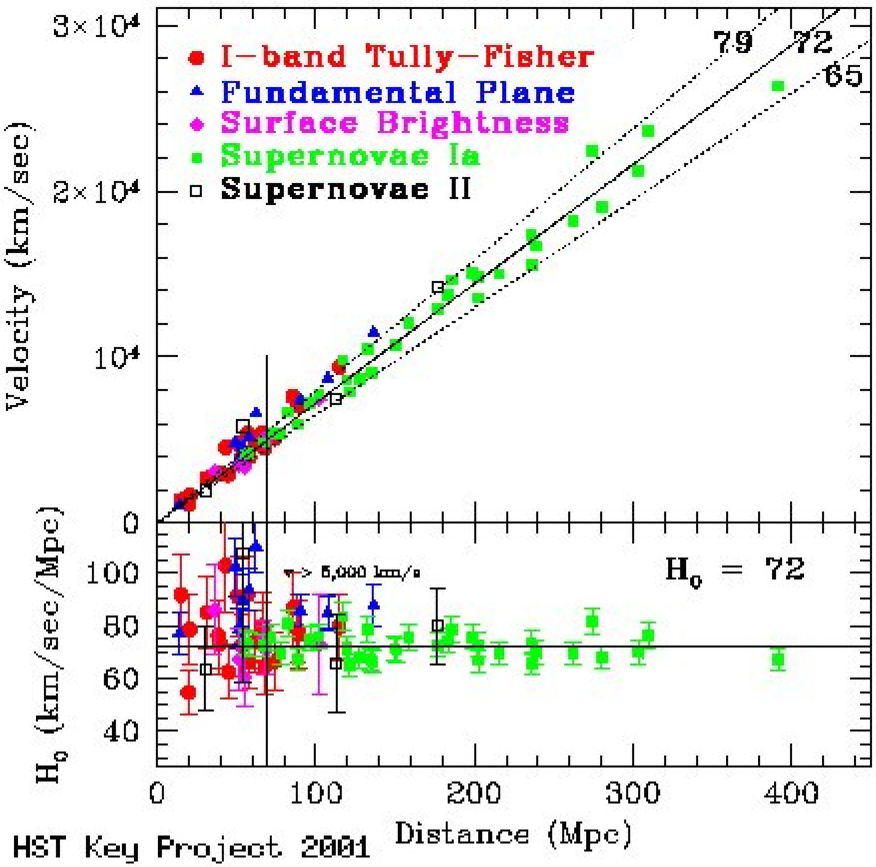
Such distance vs. redshift measurement was recently extended to significantly larger distances using supernovae Ia: Hubble's law is not a linear relationship anymore; the measurements imply the existence of the cosmological constant!

More about that later...



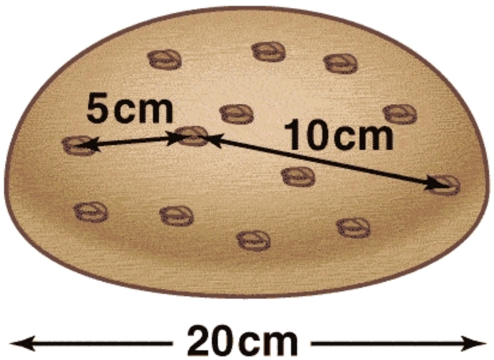
H_o as "a function of time"

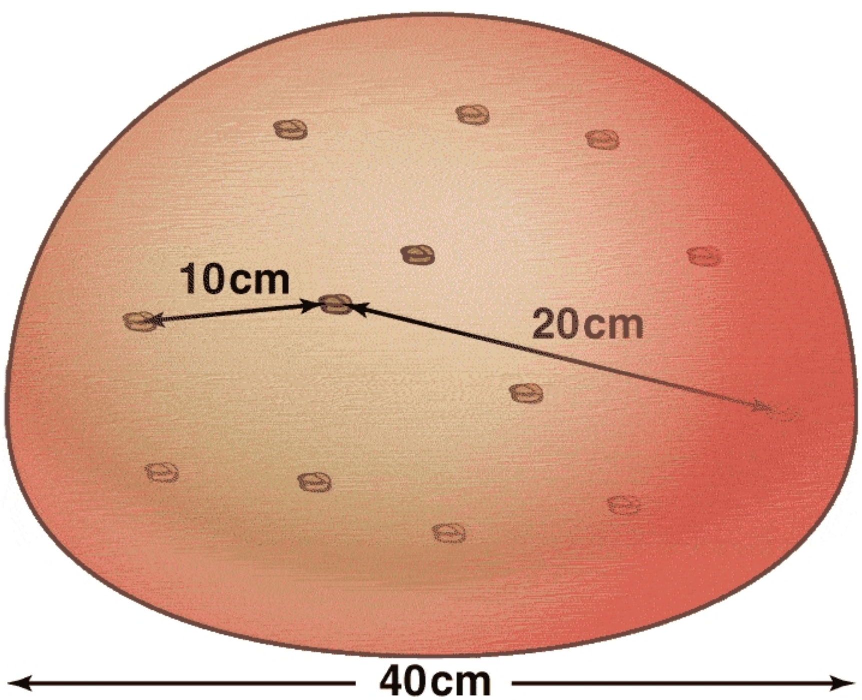
- the first three points: Lemaitre (1927), Robertson (1928), Hubble (1929), all based on Hubble's data
- the early low value (290 km/s/Mpc): Jan Oort
- the first major revision: discovery of Population II stars by Baade
- the very recent convergence to values near 65±10 km/sec/Mpc
- the best Cepheid-based value for the local H_o determination is 71±7 km/s/Mpc, the WMAP value based on cosmic microwave background measurements: 72±5 km/s/Mpc.



How important are the remaining uncertainties?

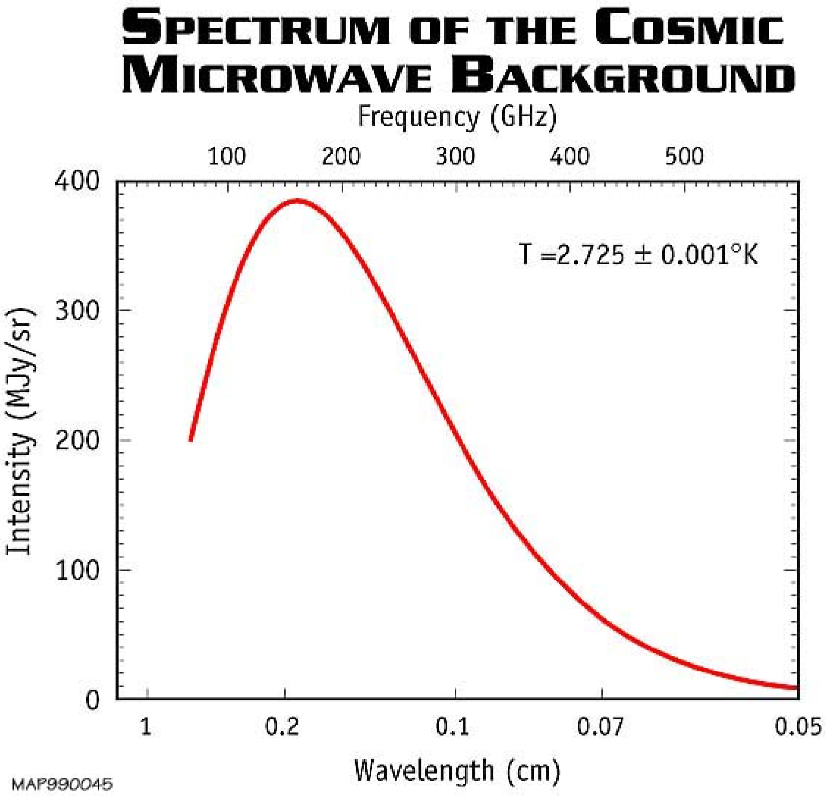
- The fact that measurement errors propagate and accumulate through different rungs in the cosmic distance ladder results in potentially large errors
- Cepheid distances are still uncertain at the 10% level
- The effects of intergalactic absorption may be important
- The cosmic evolution of objects used as standard candles and rulers may be important

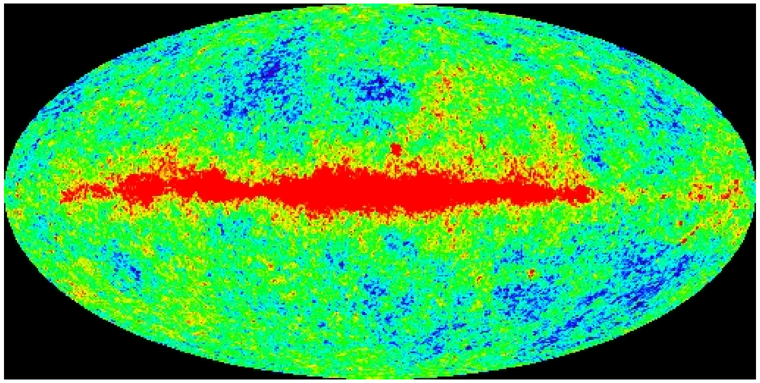




Are we special?

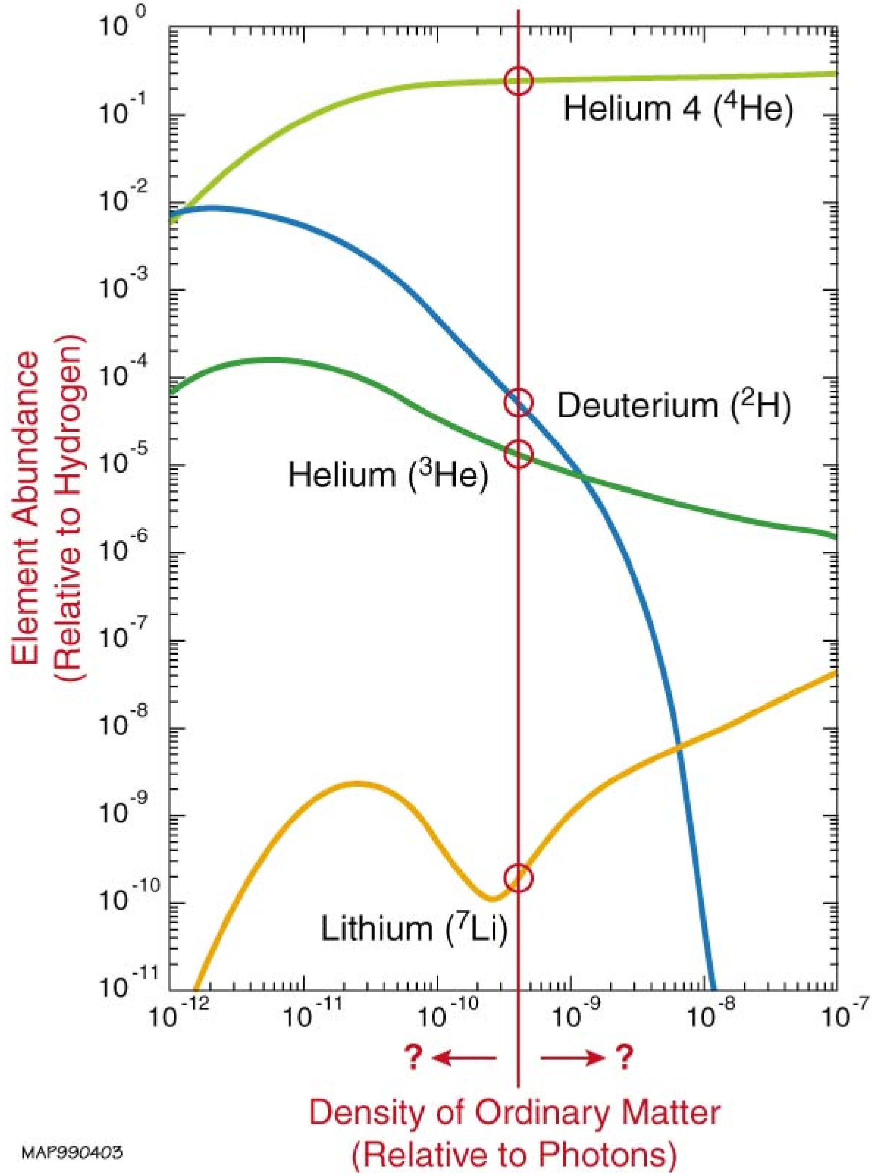
- Does the expansion of the Universe imply that we are special?
- No, think of the raisin bread analogy.
- If every portion of the bread expands by the same amount in a given interval of time, then the raisins would recede from each other with exactly a Hubble type expansion law – and the same behavior 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!





The Big Bang

- Implied by the expansion of the Universe, and also supported by independent evidence: the cosmic microwave background radiation and nucleosynthesis
- The spectrum (a perfect blackbody with $T = 2.725$ K) and the behavior of fluctuations in the cosmic microwave background radiation are both in agreement with expectations
- There is no other theory that is fully consistent with these observations!



The Big Bang model and Nucleosynthesis

- The Big Bang model "predicts" that the Universe was much hotter in the past than today.
- As the universe cooled, the neutrons either d ecayed into protons and electrons or combined with protons to make deuterium (an isotope of hydrogen). During the first three minutes of the universe, most of the deuterium combined to make helium. Trace amounts of lithium were also produced at this time.
- The Big Bang predictions for the abundance of various elements are in good agreement with the data!