Astr 102: Introduction to Astronomy

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Lecture 14:

Expansion of the Universe

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)

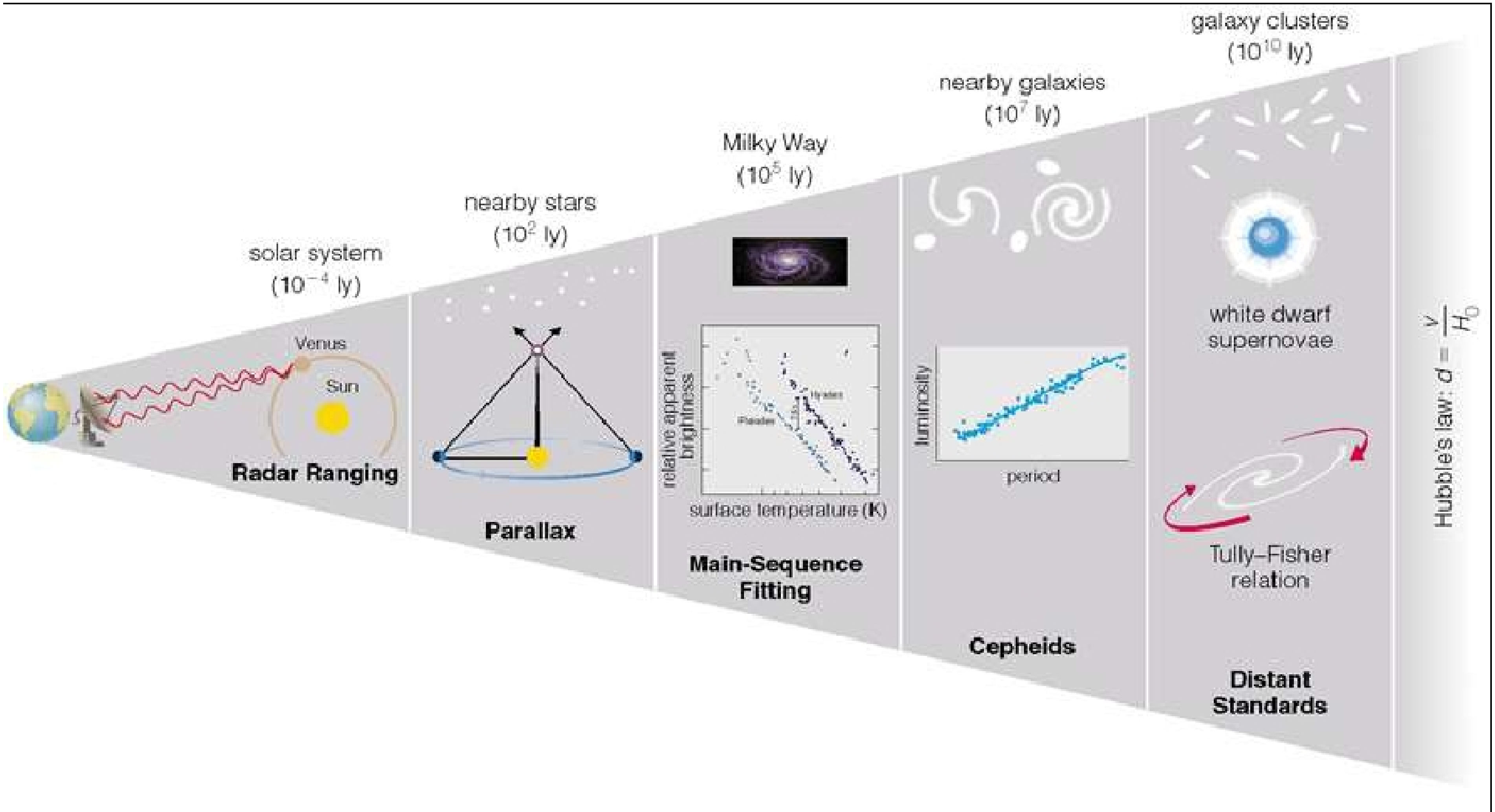
- If you believe you know luminosity L, measure flux F and get distance D from $D^2 = L/4\pi F$

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

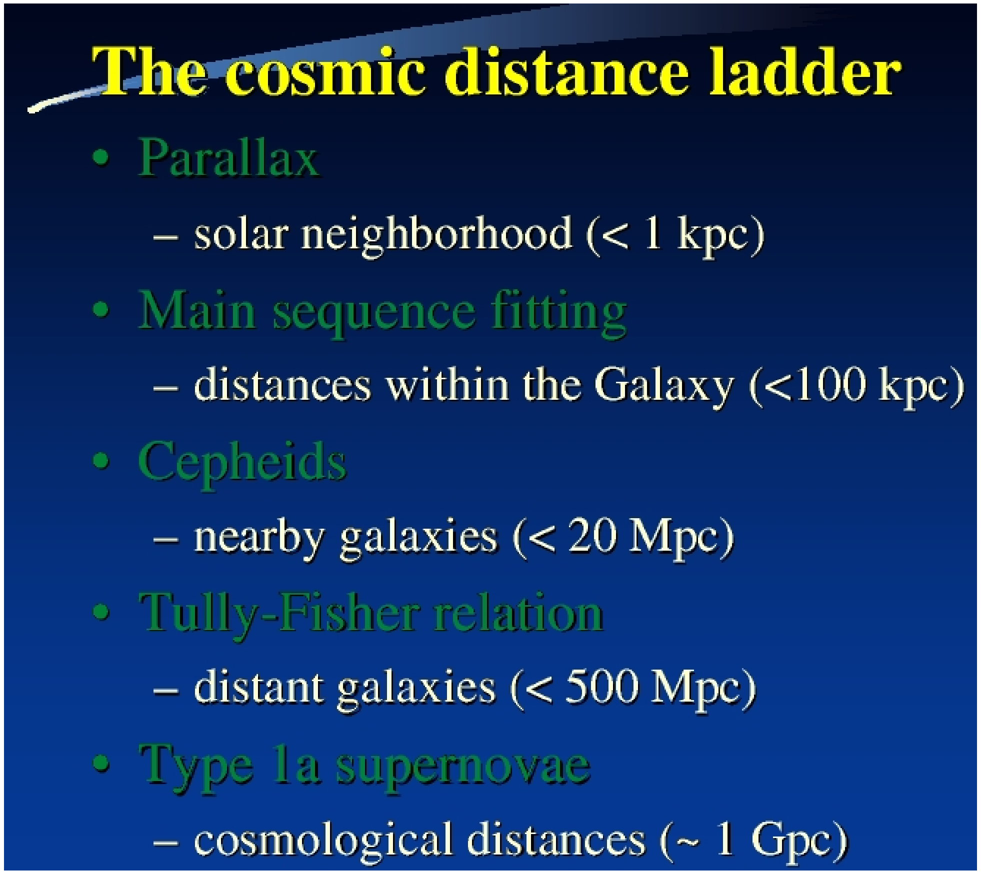
- The accuracy of the resulting D depends on 1) how good are your assumptions about L and S, and how accurate are your measurements (a side issue: are those expressions correct?)

- 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
Hyades
Pleiades
surface temperature (K)
Main-Sequence Fitting
luminosity
period
Cepheids
white dwarf supernovae
Tully–Fisher relation
Distant Standards
Hubble's law: $d = \frac{v}{H_0}$

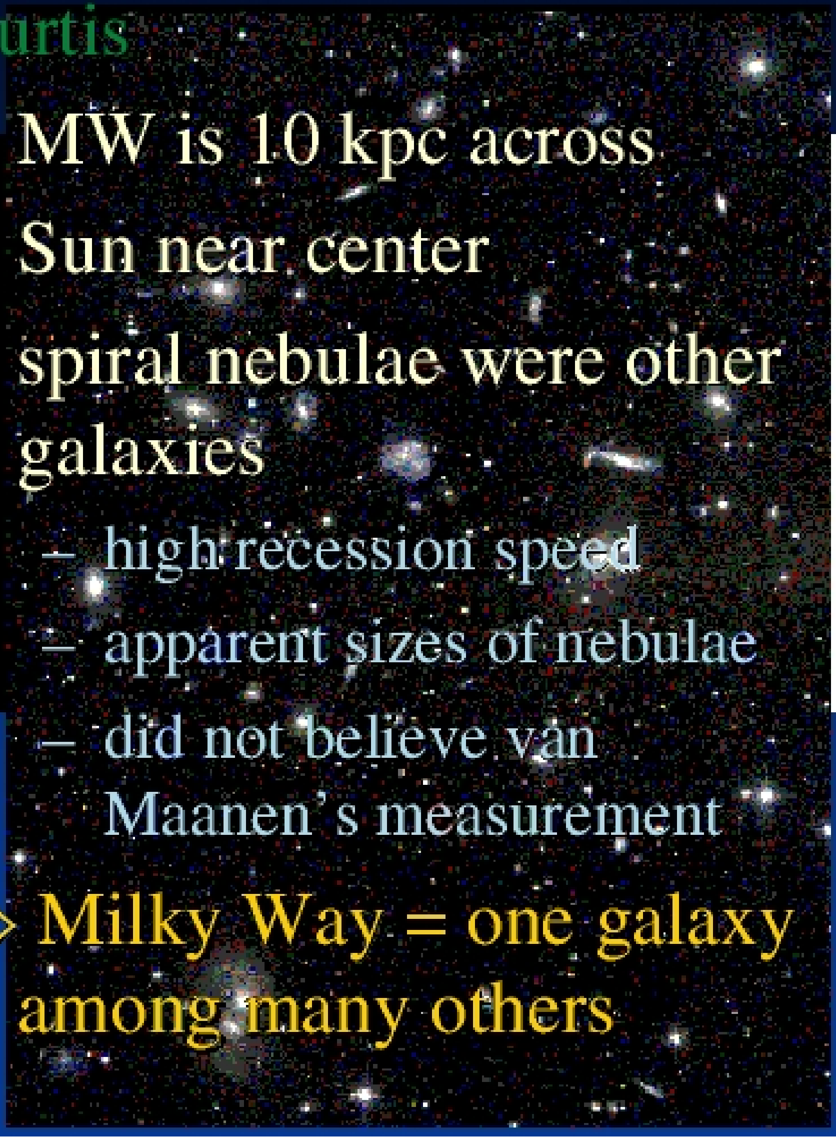
The Cosmic Distance Ladder



Tully-Fisher relation: the luminosity of spiral galaxies is correlated with their rotation speed (which can be measured from spectra):
L is proportional to v_{rot}^4

- 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, later...)
- 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

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

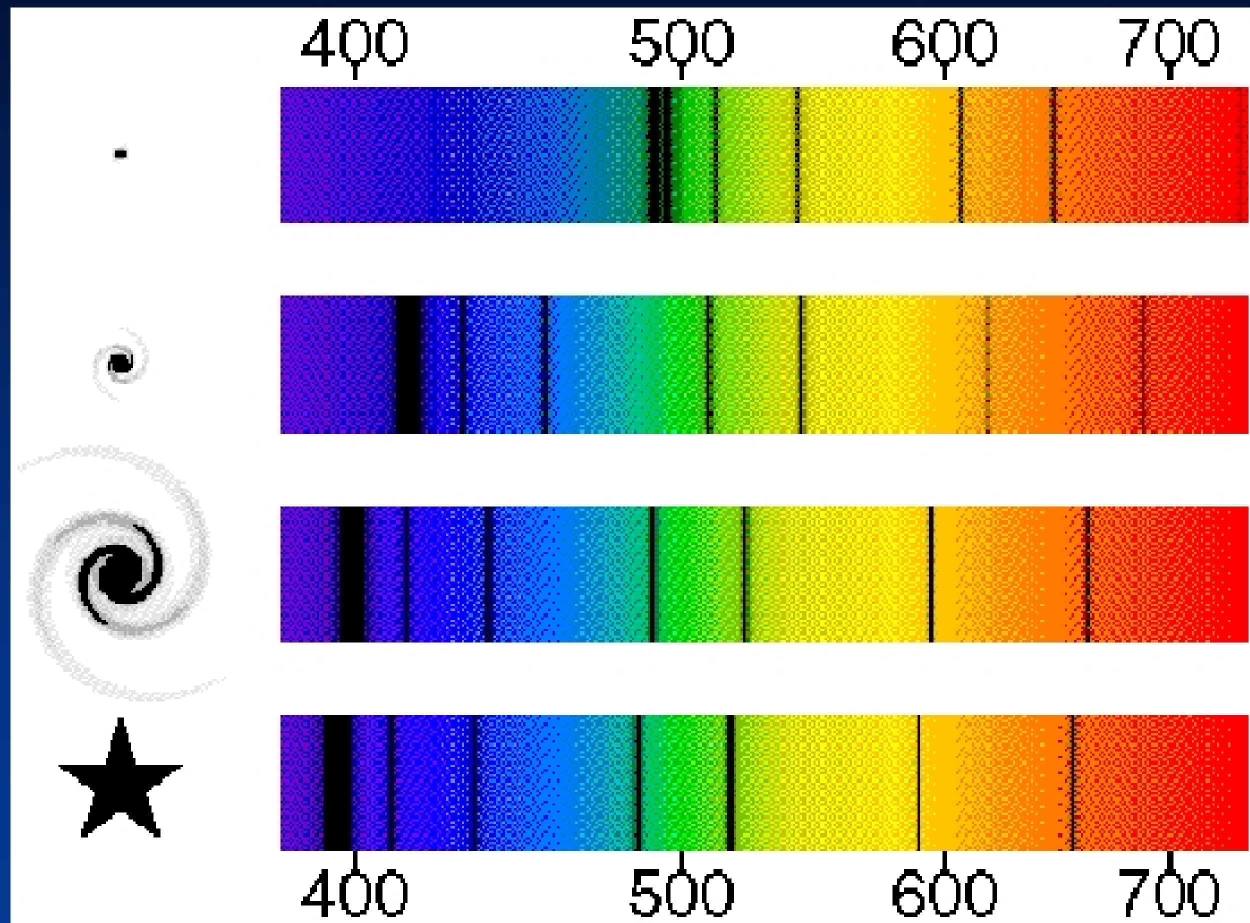
redshift:

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

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

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

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

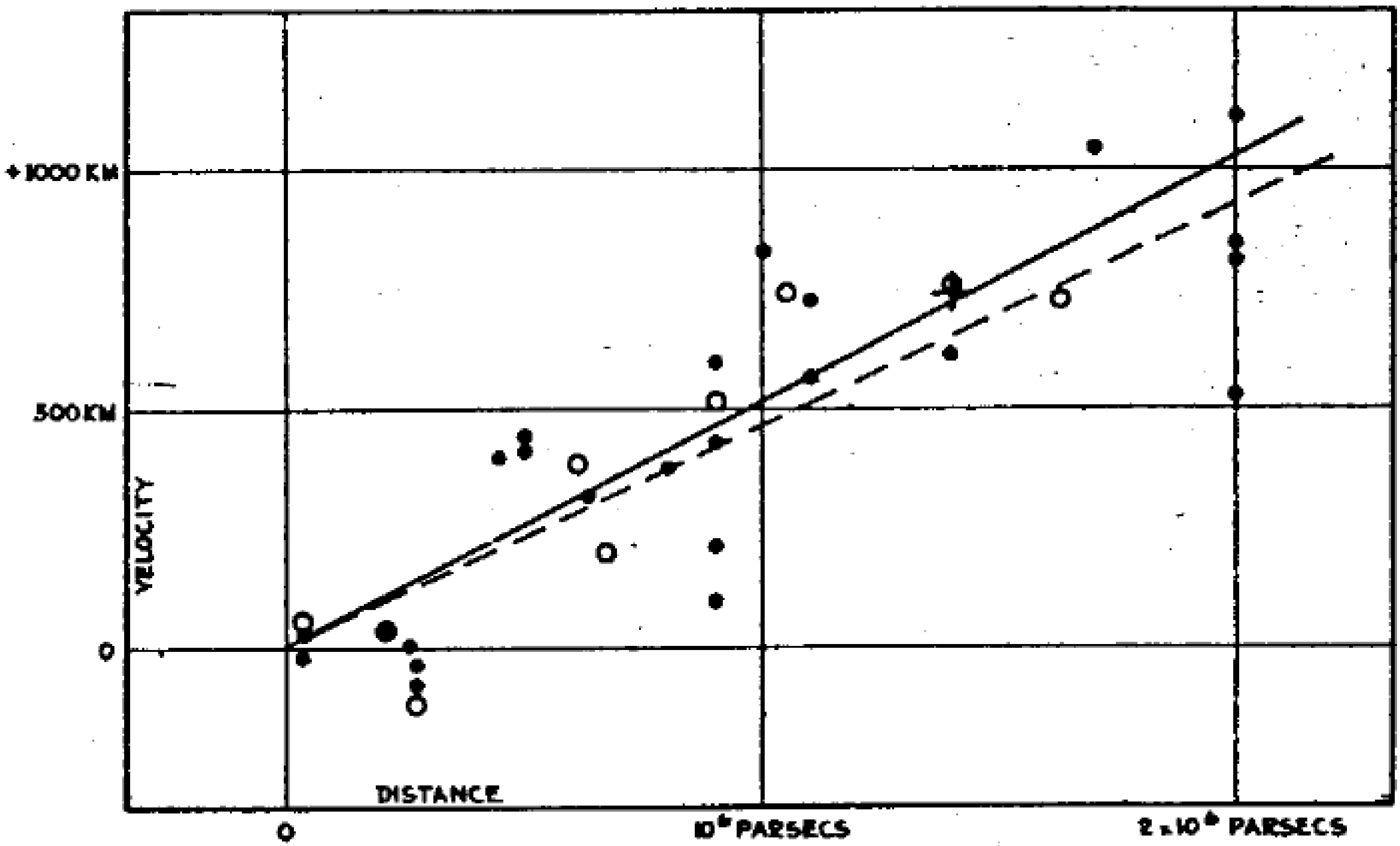


FIGURE 1

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

Hubble's discovery in mathematical form:

$$v = H_o D$$

That is, the recession speed of galaxies, v (km/s), is proportional to their distance, D (Mpc). The constant of proportionality, H_o, is called the Hubble constant, and its value is about 70 km/s/Mpc (km/s per Mpc).

Hubble's discovery has had a fundamental impact on our understanding of the Universe!

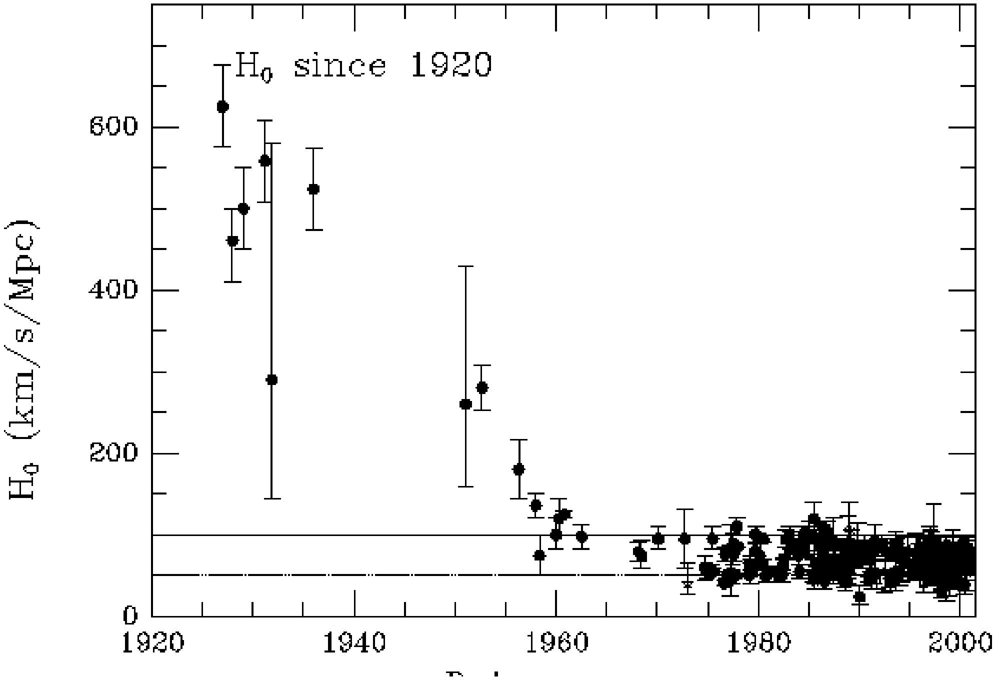
The Universe is Expanding!

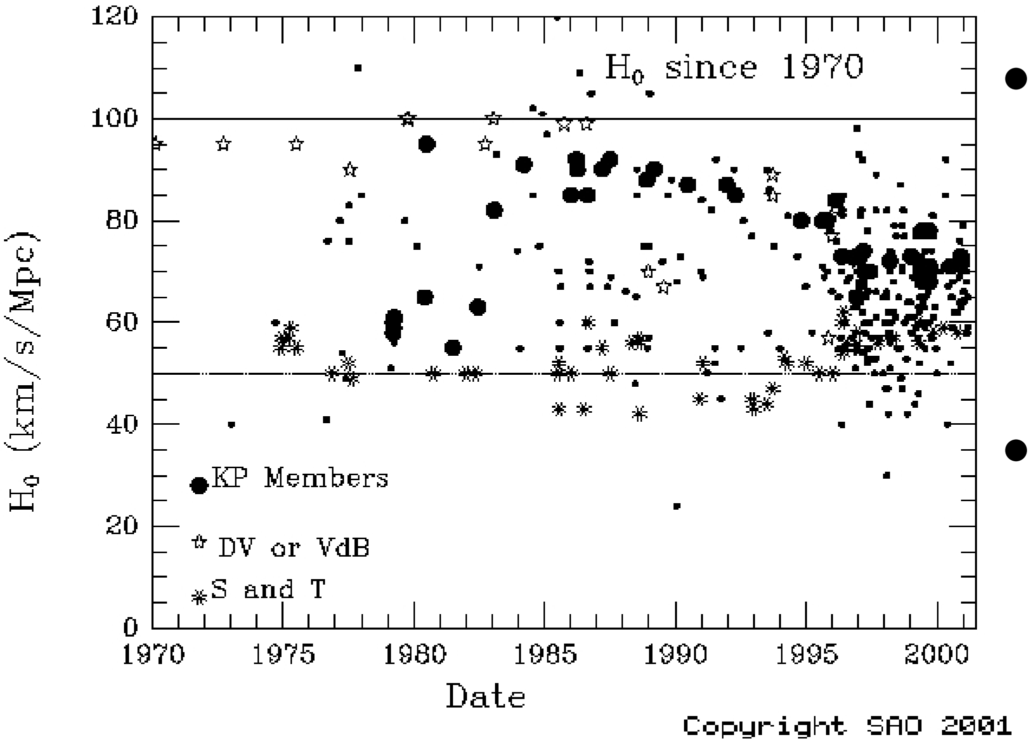
Hubble's 1929 discovery made Einstein abolish the cosmological constant, which he introduced in 1917 to produce a static Universe (the idea that the universe was expanding was thought to be absurd in 1917)

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

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

More about that later...

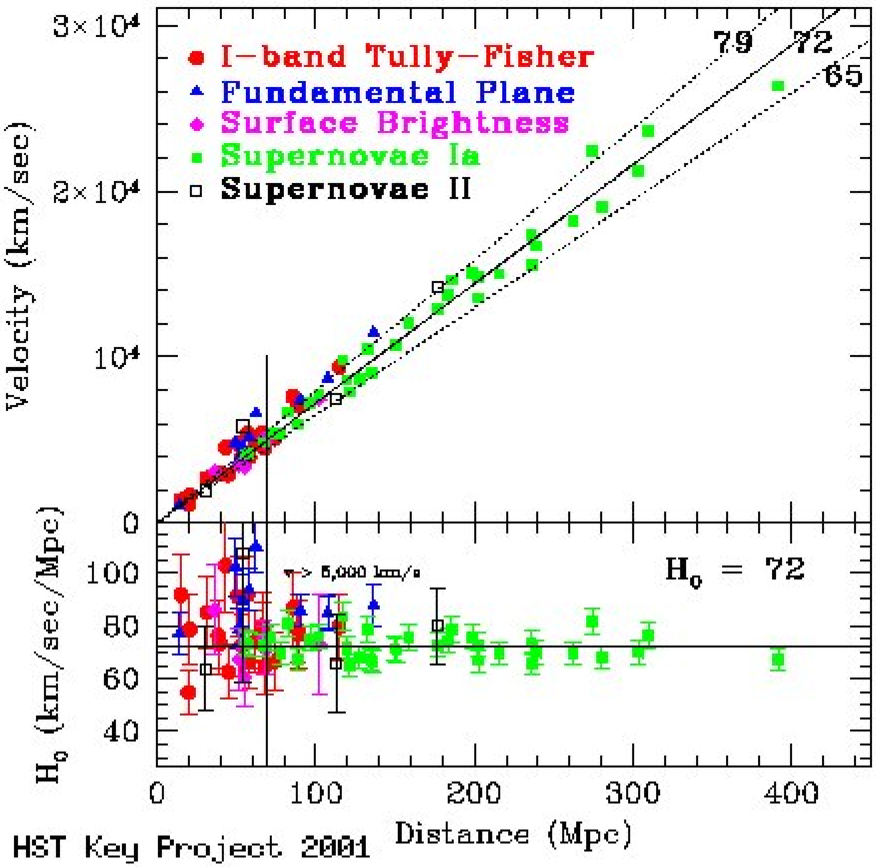




H_o as a function of time

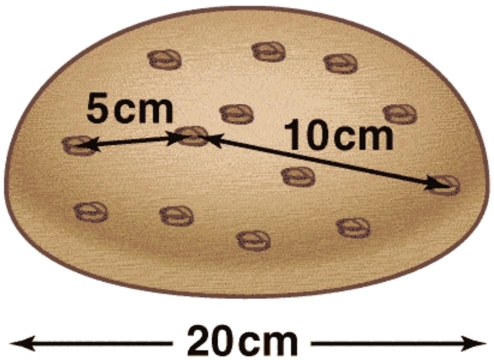
- the first three points: Lemaitre (1927), Robertson (1928), Hubble (1929), all based on Hubble's data
- the early low value (290 km/s/Mpc): Jan Oort
- the first major revision: discovery of Population II stars by Baade
- the very recent convergence to values near 65±10 km/sec/Mpc
- the best Cepheid-based 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.
- Science doesn't happen overnight!

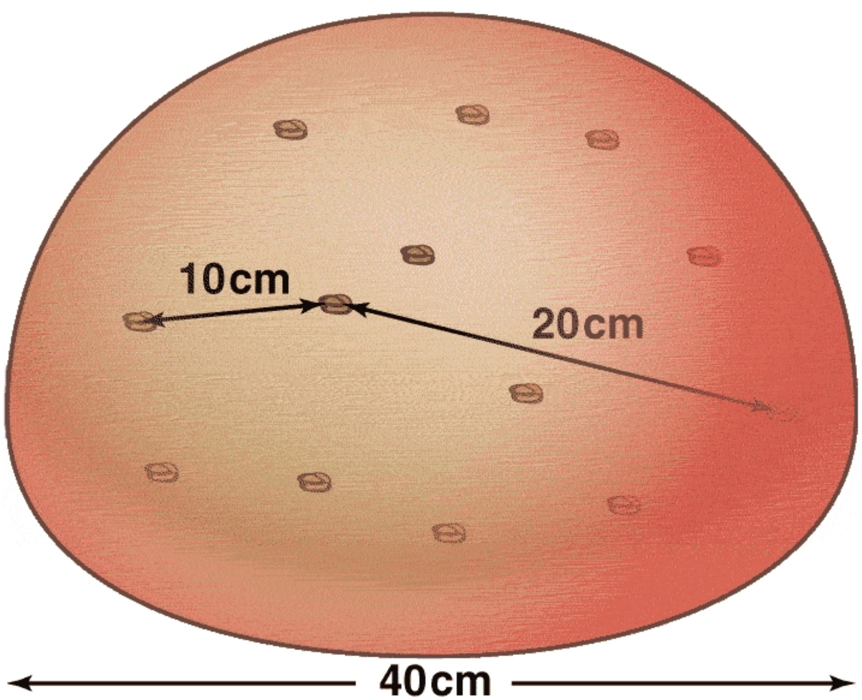
How important are the remaining uncertainties?



Note: the x axis extends to 450 Mpc. Hubble's sample extended to ∼1 Mpc!

- 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
- Despite the remaining uncertainties, the fact that the Universe is expanding is irrefutable!





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!