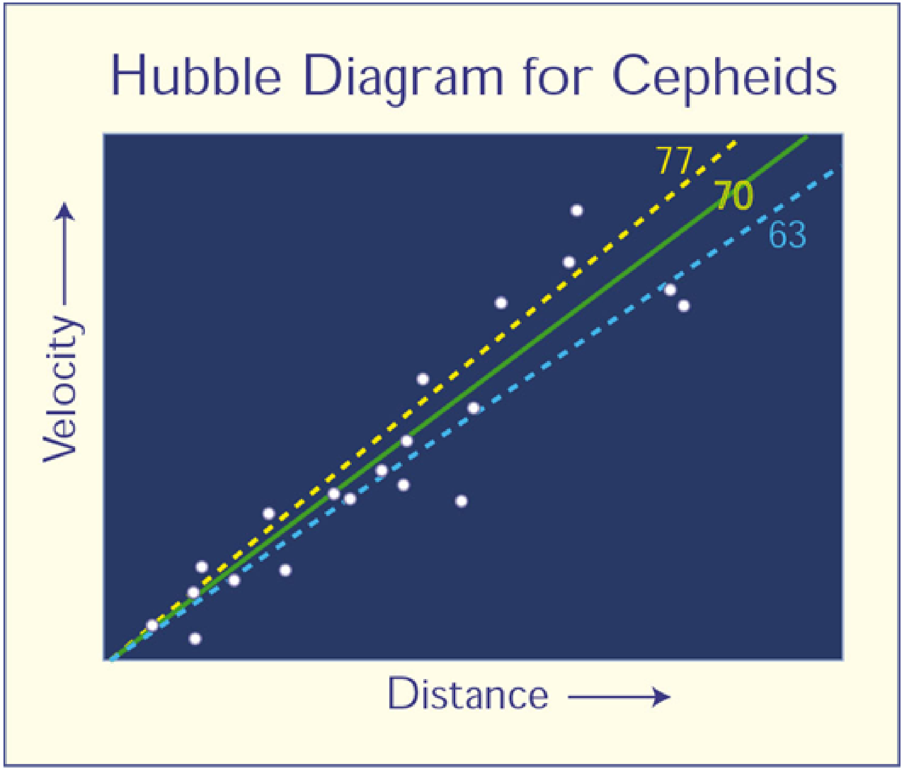
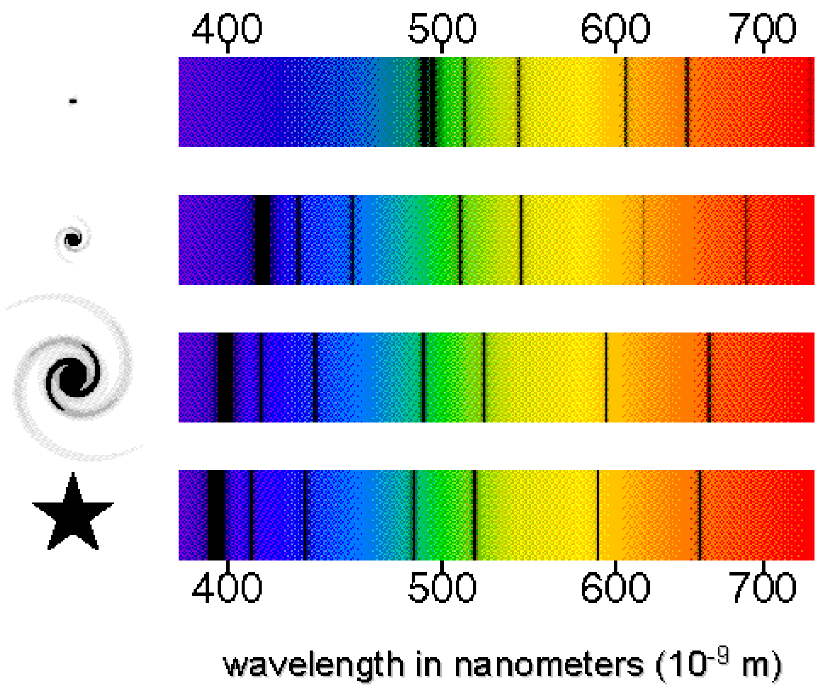
Discovery of the Expanding Universe

Reading: "State of the Universe", Chapter 5



"The history of astronomy is a history of receding horizons" – Edwin Hubble.

Redshift and blueshift



$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}},$$

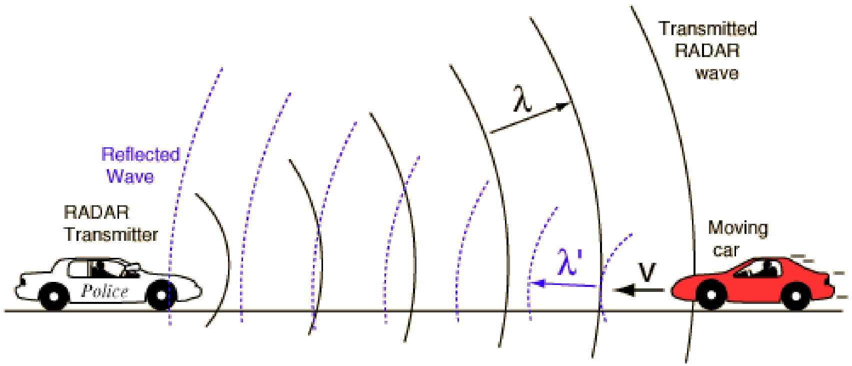
$$1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{f_{\text{emitted}}}{f_{\text{observed}}}.$$

z can be measured from an observed spectrum if we know what the lines are and which wavelength they should correspond to *at rest*

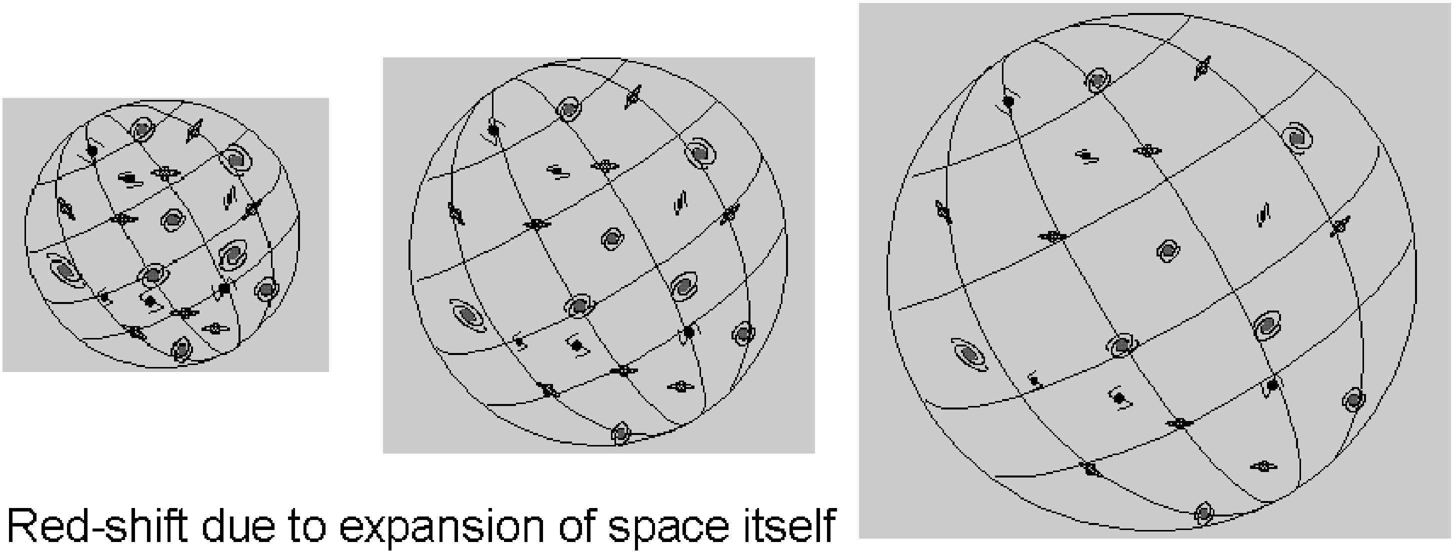
Motion away from us will shift lines to longer wavelengths (redward) and result in ***redshift***
Motion towards us will shift lines to shorter wavelength (blueward) and result in ***blueshift***

Some nearby galaxies (for example, Andromeda) have blueshifted spectra (moving towards us), but a vast majority of galaxies have redshifted spectra.

Two sources of spectral line shifts



Usual spectral red- or blue-shift due to physical motion of objects away or towards observer



Red-shift due to expansion of space itself

Cosmological redshift due to expansion of space

$1+z = Rnow/Rthen = 1/Rthen$

Where *z* corresponds to a Doppler-like shift of wavelength and frequency of light as the Universe expands from the epoch when scale factor is *Rthen* to the current epoch corresponding to *Rnow*.

For example, $z=1$ corresponds to the epoch when the Universe was twice “smaller” than now.

Discovery of spectral shifts in spectra of galaxies

Vesto Slipher
(1875-1969)

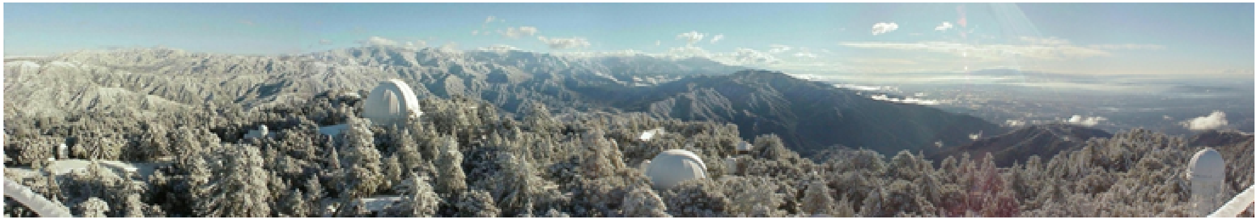
1912. New and important data is introduced by *Vesto Slipher* of the Lowell Observatory in Flagstaff, Arizona, who measured shifts of spectral lines for some galaxies, and found that some of them move much faster than the stars. He also found that most of them showed positive shifts indicating that they are moving away from us.

Andromeda galaxy (M31)

Andromeda nebula, however, was one of the few galaxies that showed negative shift of spectral lines, Indicating that it approaches us (the shift measured by Slipher indicating that it approaches us with celocity of 300 km/s or 186 mph).

So the trend later discovered by Hubble was not apparent at the time due to small number of galaxies for which the shift was measured.

Mount Wilson Observatory
San Gabriel Mnts, near LA



George E. Hale

George Ellery Hale, native of Hyde Park, led development of the Mount Wilson Observatory and construction of its first two great 60- and 100-inch telescopes in 1905-1917

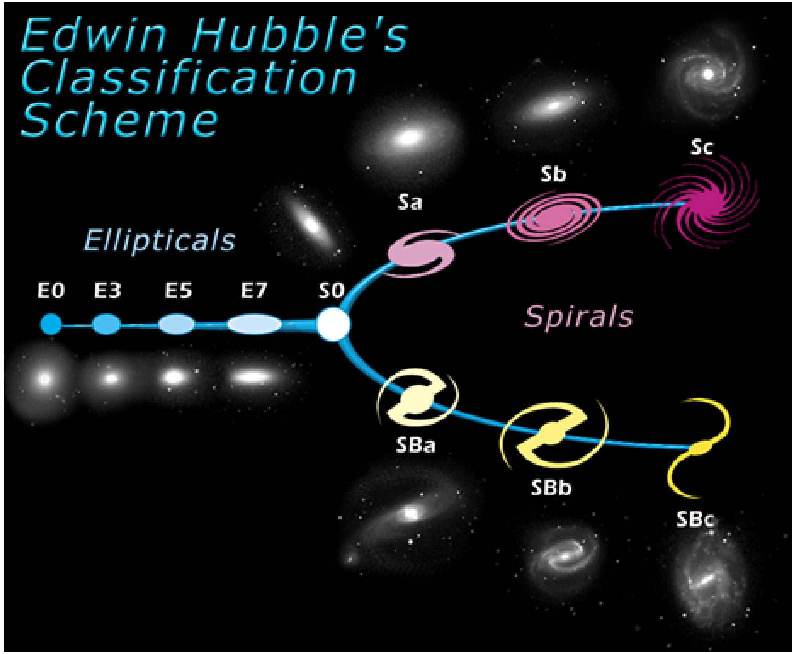
100 inch telescope
used by Edwin to prove that
galaxies were outside the Milky Way
and discover expansion of
the Universe

Edwin Hubble
1889-1953
A U.Chicago alum!
(PhD in Astronomy, 1917)

1924. Hubble discovered a variable star of the type called the Cepheids in the Andromeda spiral nebula.

Cepheids are one example of astronomical objects called 'standard candles' – the objects for which intrinsic brightness (or luminosity) can be calculated through some observable property. For the Cepheids the intrinsic brightness can be measured by observing over which time (period) it varies its apparent brightness.

Using the period-luminosity relation for Cepheids, discovered by Henrietta Leavitt in 1912, Hubble measured distance to the Andromeda, showing once and for all that it was far outside the Milky Way (it is slightly more than 2 million light years away from us), even for the large MW size advocated by Shapley



Using the new 100-inch reflecting telescope at the Mount Wilson observatory in Pasadena, CA, Hubble proceeded to construct galaxy classification scheme (the tuning fork diagram) and (with Milton Humason) to systematically measure spectra of galaxies.

Hubble's greatest discovery in cosmology came in 1929, when he showed convincingly that most galaxies are receding from us with recession velocity proportional to their distance.

Edwin Hubble observing at the 100-inch telescope at Mount Wilson

1924-1929. Hubble and Milton Humason, measured spectra for dozens of galaxies. They also measured distances – using the Cepheids when possible or the bright stars called supergiants and brightness of the brightest globular clusters for more distant galaxies (not as accurate as Cepheid distances).

appearance the spectrum is very much like spectra of the Milky Way clouds in Sagittarius and Cygnus, and is also similar to spectra of binary stars of the W Ursae Majoris type, where the widening and depth of the lines are affected by the rapid rotation of the stars involved.

The wide shallow absorption lines observed in the spectrum of N. G. C. 7619 have been noticed in the spectra of other extra-galactic nebulae, and may be due to a dispersion in velocity and a blending of the spectral types of the many stars which presumably exist in the central parts of these nebulae. The lack of depth in the absorption lines seems to be more pronounced among the smaller and fainter nebulae, and in N. G. C. 7619 the absorption is very weak.

It is hoped that velocities of more of these interesting objects will soon be available.

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a K term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

Distances of extra-galactic nebulae depend ultimately upon the application of absolute-luminosity criteria to involved stars whose types can be recognized. These include, among others, Cepheid variables, novae, and blue stars involved in emission nebulosity. Numerical values depend upon the zero point of the period-luminosity relation among Cepheids, the other criteria merely check the order of the distances. This method is restricted to the few nebulae which are well resolved by existing instruments. A study of these nebulae, together with those in which any stars at all can be recognized, indicates the probability of an approximately uniform upper limit to the absolute luminosity of stars, in the late-type spirals and irregular nebulae at least, of the order of M (photographic) = -6.3.[1] The apparent luminosities of the brightest stars in such nebulae are thus criteria which, although rough and to be applied with caution,

The paper that revolutionized cosmology

1929. Hubble published his first paper showing correlation between recession velocity and distance to the galaxy

“A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae”

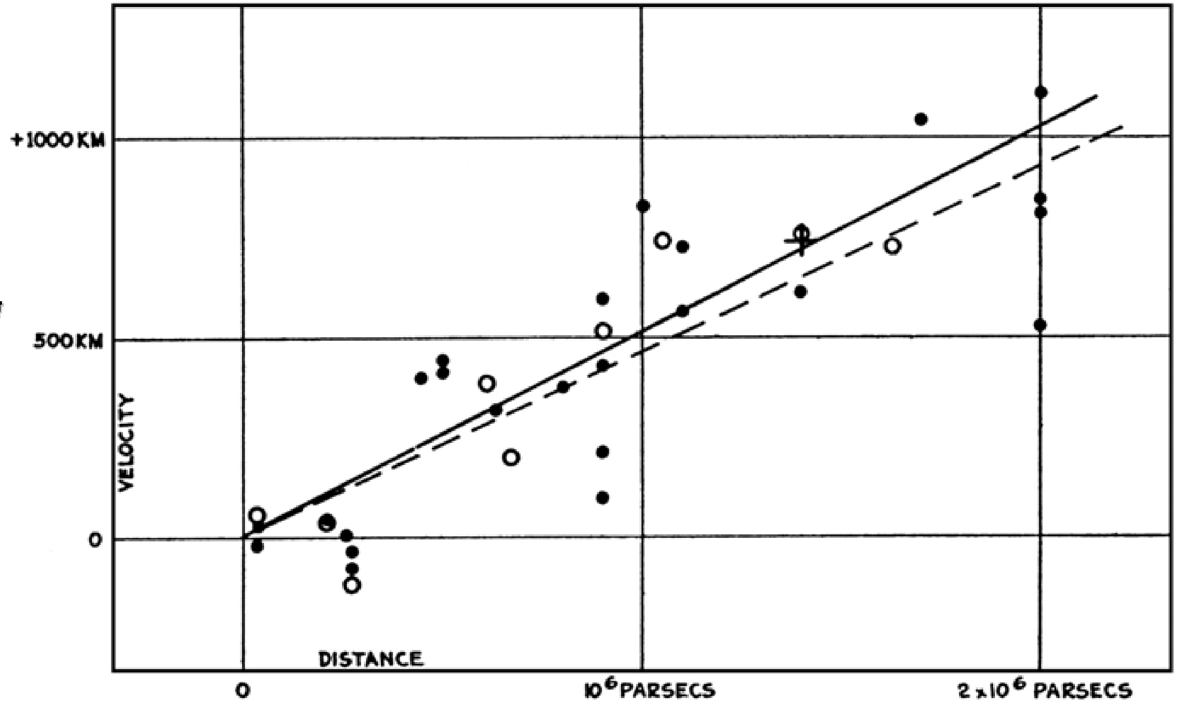
6 pages, 1 table, 1 figure

A figure from the paper – what's now called the *"Hubble diagram"* showing relation between recession velocity and distance to the galaxy

Hubble law: *velocity* = *H*d* (*i.e.*, *H* times *distance*)
where *H* is a constant now called the *Hubble constant*

Hubble estimated *H* to be ~500 km/s/Mpc –
about 7 times larger than current measurements indicate

Velocity inferred from galaxy spectrum in km/s



Distance in parsecs (1 parsec = 3.26 light years, 1 million parsecs = Megaparsec or Mpc)

The last paragraph of the Hubble's 1929 paper

The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space. In the de Sitter cosmology, displacements of the spectra arise from two sources, an apparent slowing down of atomic vibrations and a general tendency of material particles to scatter. The latter involves an acceleration and hence introduces the element of time. The relative importance of these two effects should determine the form of the relation between distances and observed velocities; and in this connection it may be emphasized that the linear relation found in the present discussion is a first approximation representing a restricted range in distance.

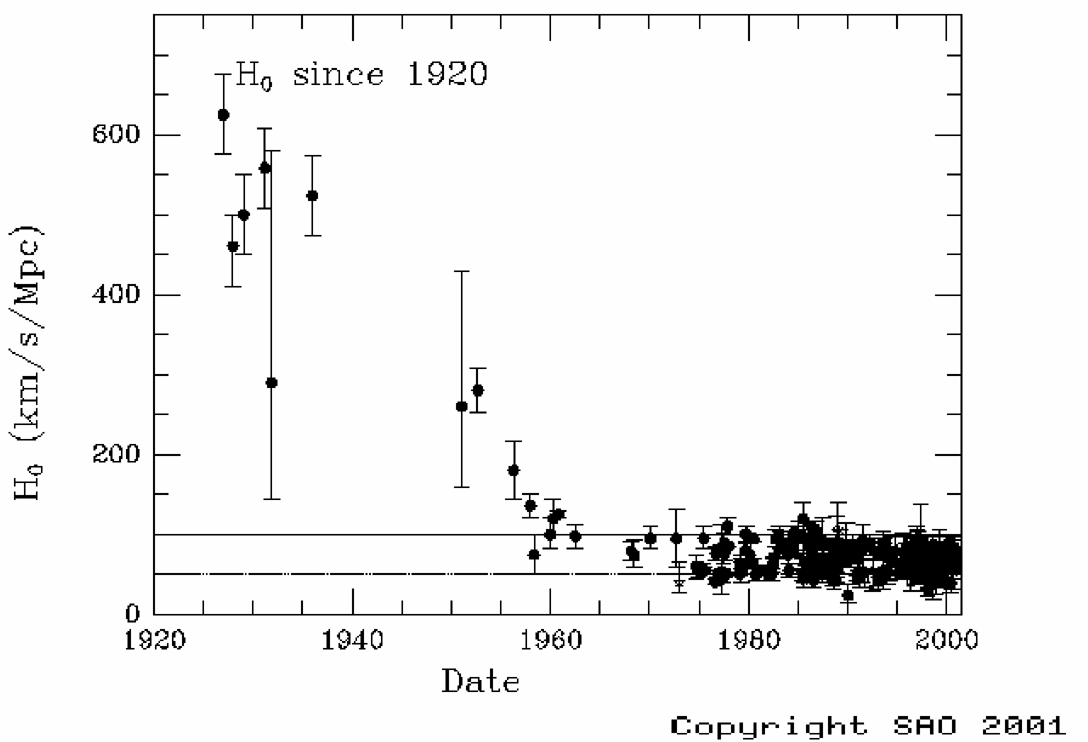
[1] *Mt. Wilson Contr.*, No. 324; *Astroph. J., Chicago, Ill.*, **64**, 1926 (321).

[2] *Harvard Coll. Obs. Circ.*, 294, 1926.

[3] *Mon. Not. R. Astr. Soc.*, **85**, 1925 (865–894).

[4] These Proceedings, **15**, 1929 (167).

History of the Hubble constant measurements since 1920s

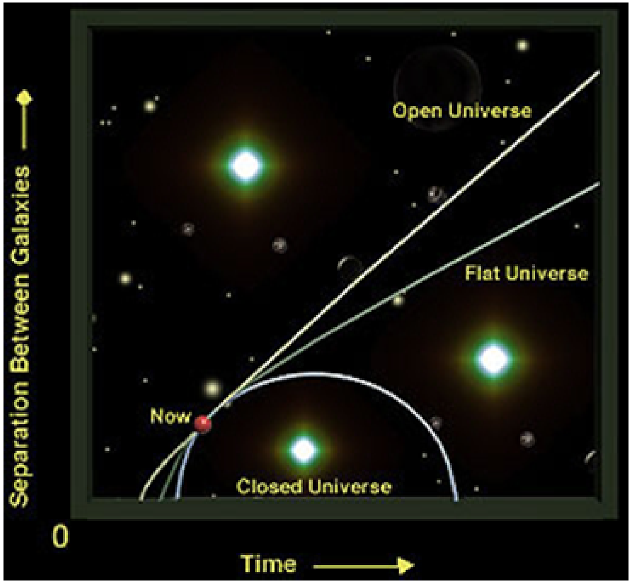


http://cfa-www.harvard.edu/~huchra/hubble/

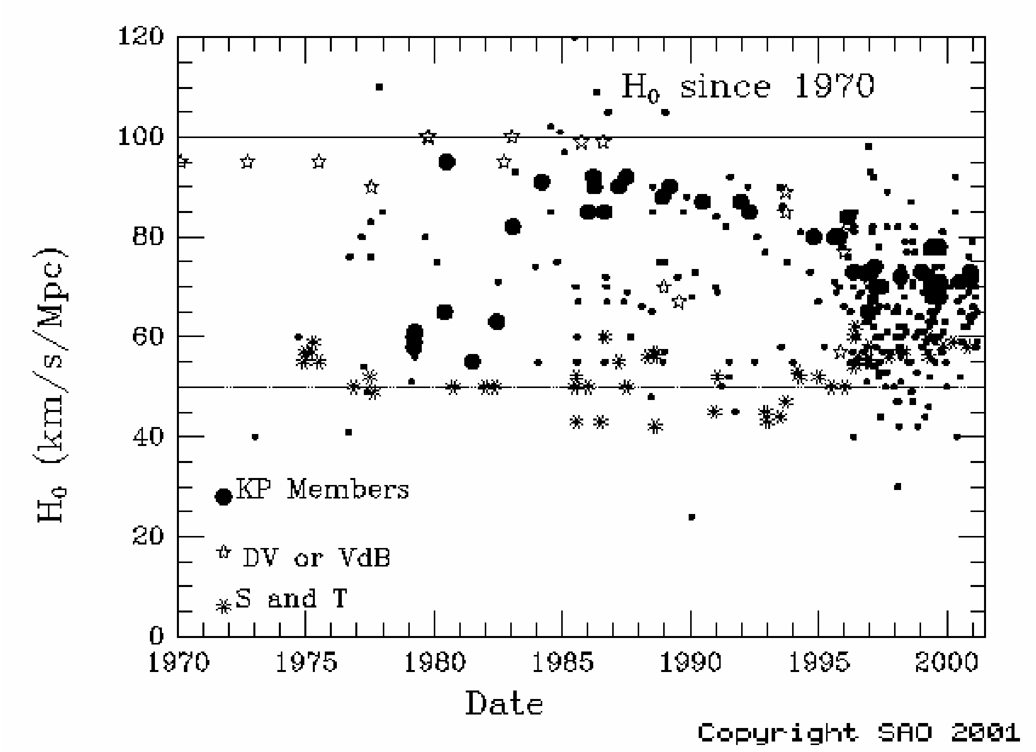
Importance of the Hubble constant: the age of the Universe

Inverse of the Hubble constant has units of time and corresponds to the *age of the Universe*

If we use *H* to be ~500 km/s/Mpc, as estimated by Hubble, the age will be ~2 billion years.

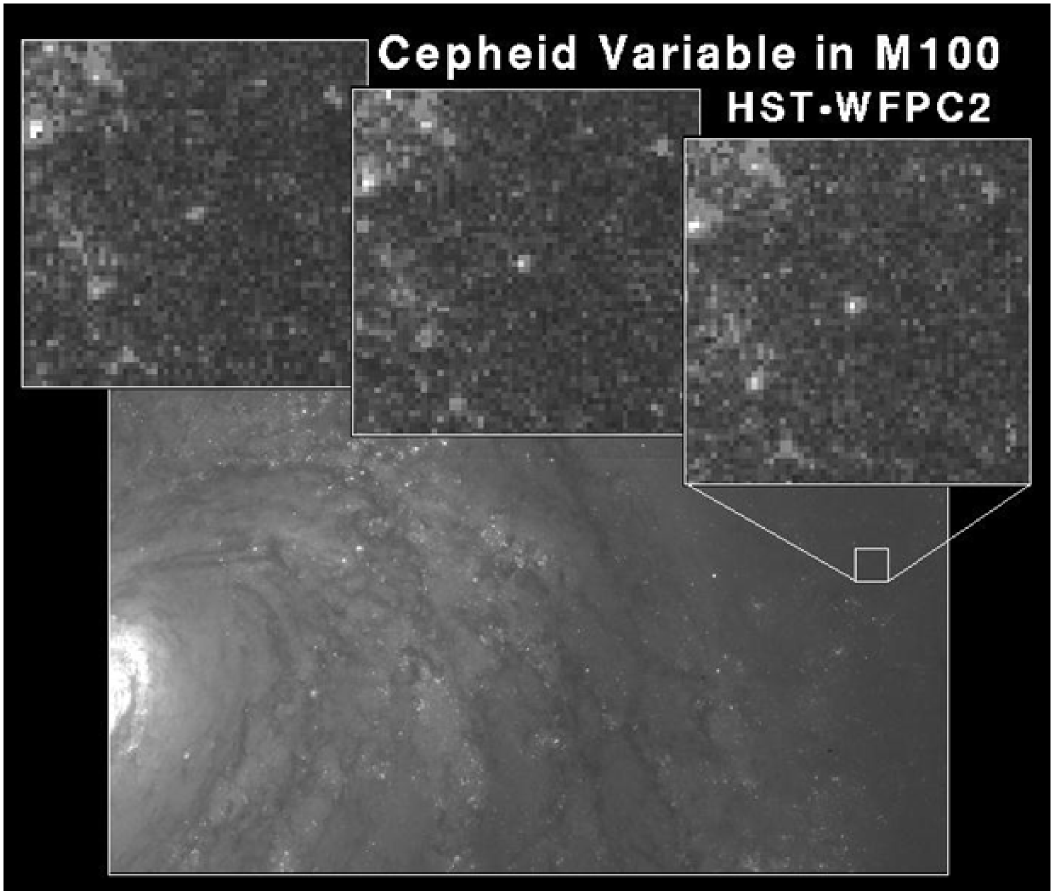


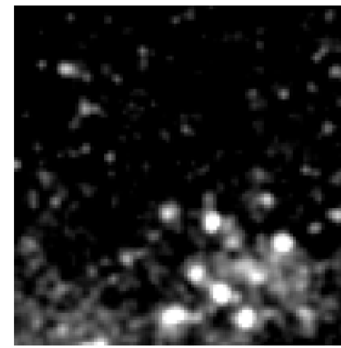
History of the Hubble constant measurements since 1970



http://cfa-www.harvard.edu/~huchra/hubble/

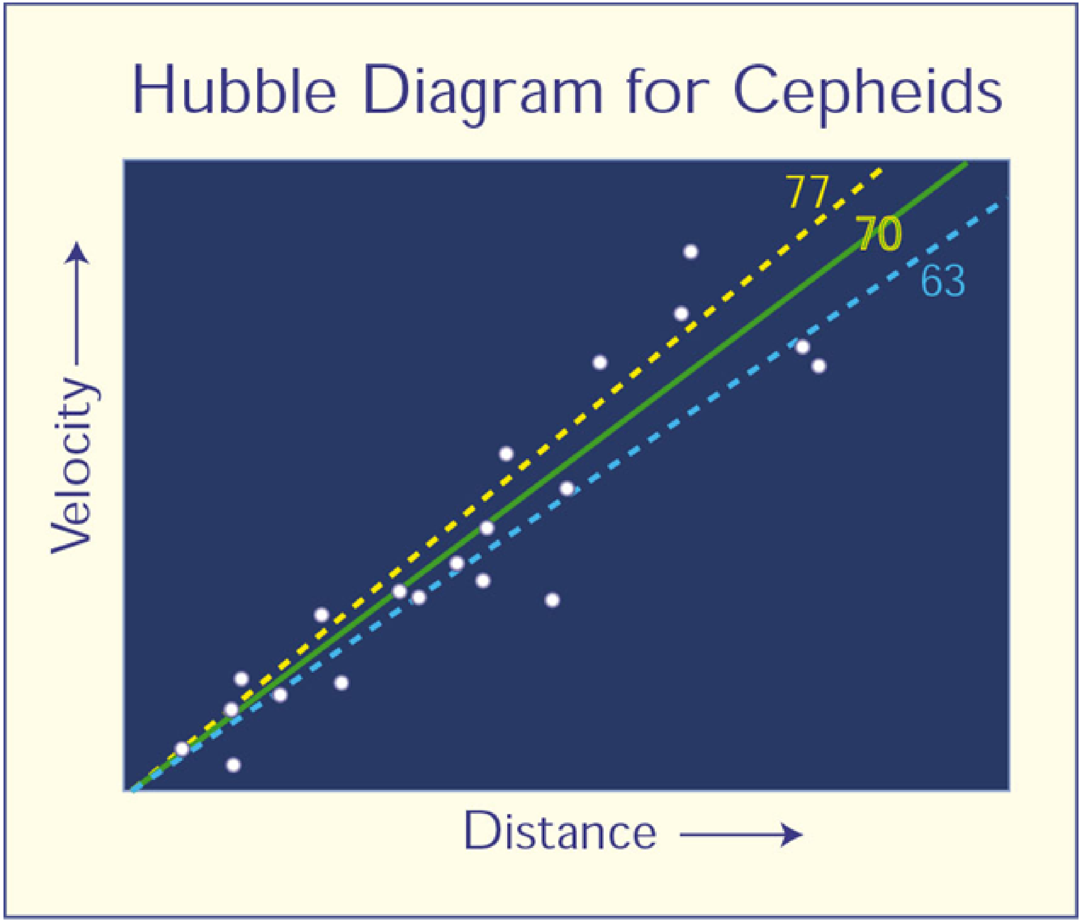
Hubble Space Telescope observations of Cepheids in M100





can you find a Cepheid?

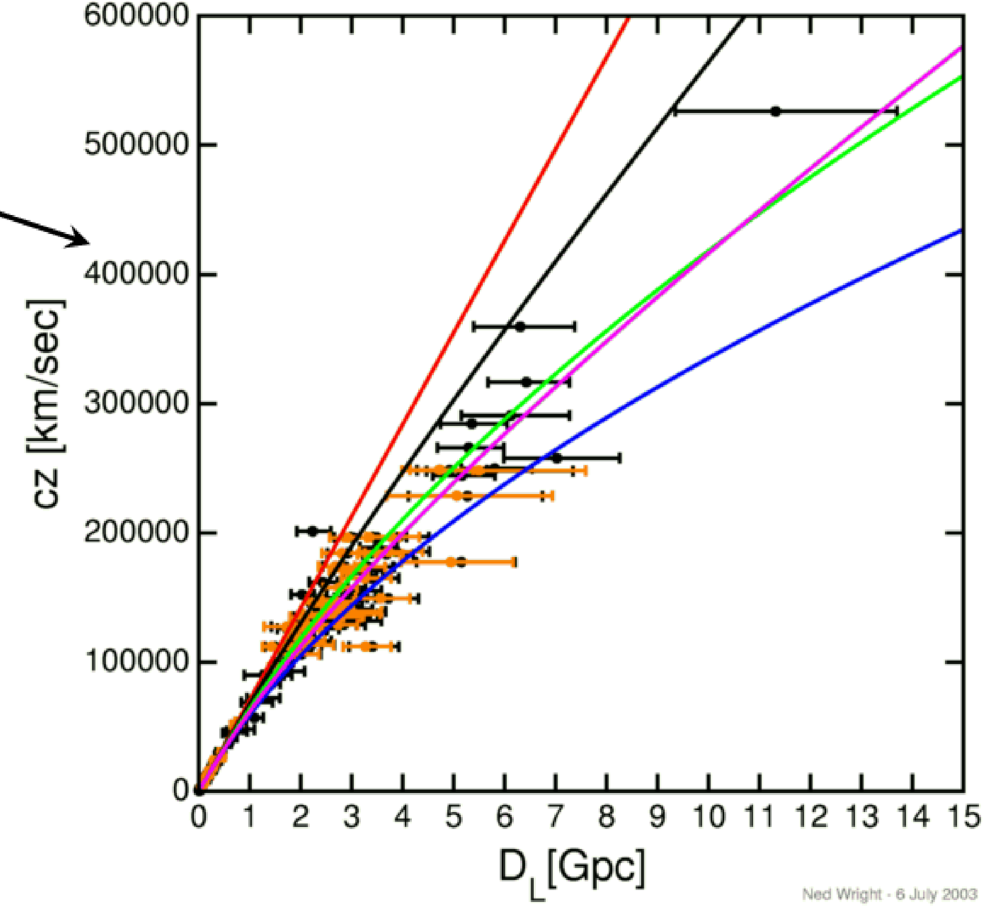
Modern measurements of the Hubble constant using the HST = 70+-5 km/s/Mpc



HST Hubble Key Project web site: http://www.ipac.caltech.edu/H0kp/

Modern Hubble diagram using supernovae type Ia

Faster than the speed of light?



Note that relation is curved (or non-linear)

Distance in billions of parsecs (1 parsec = 3.26 light years)