# The Next 2-3 Weeks

[27.1] The Extragalactic Distance Scale.
[27.2] The Expansion of the Universe.
[29.1] Newtonian Cosmology
[29.2] The Cosmic Microwave Background
[17] General Relativity & Black Holes
[29.3] Relativistic Cosmology

Starting ~ Wed. or Fri. next week

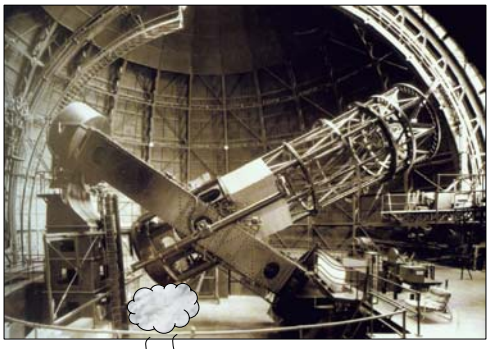
Important to read through Chapter 17 (Relativity) before I start lecturing on it.

Pay particular attention to 17.2 "Intervals & Geodesics"
- What is a metric?
- The Schwarzschild metric (= non-rotating black hole)
- "The orbit of a satellite" (somewhat flakey example)

I will present additional material assuming that you have read at least 17.2.

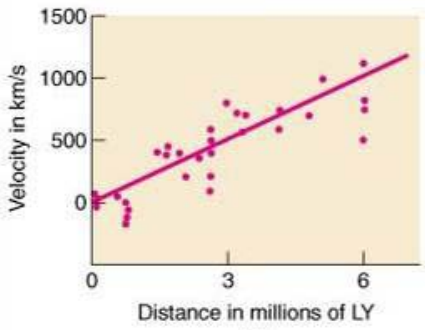
# Astronomy in 1929

100 inch telescope
Completed 1918



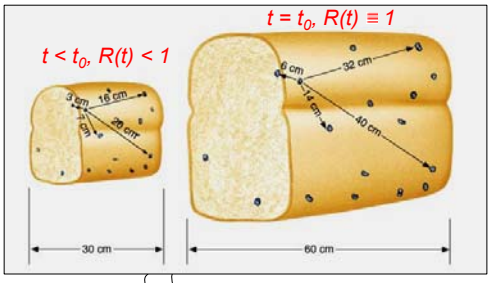
Edwin Hubble

- 1923: Hubble measured distance to M31
  - Pulsating variables
- 1926: Hubble's E, S, I galaxy classification scheme.
- 1929 Expanding Universe



# Astronomy in 1929

A loaf of raisin bread in a 1929 oven




Edwin Hubble

**The Scale Factor *R(t)***

Sometimes called *a(t)*

Ratio of size of U. at time *t* to its current size.

Current time designated $t = t_0$

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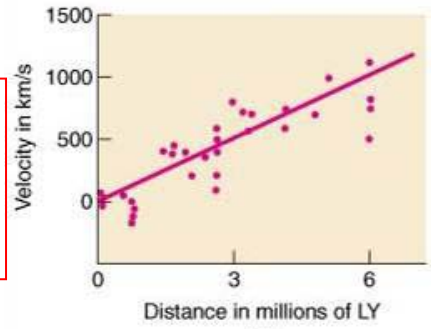
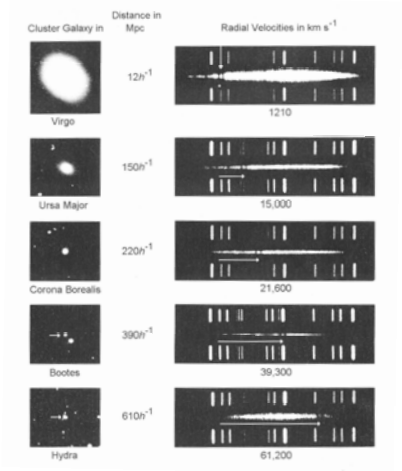
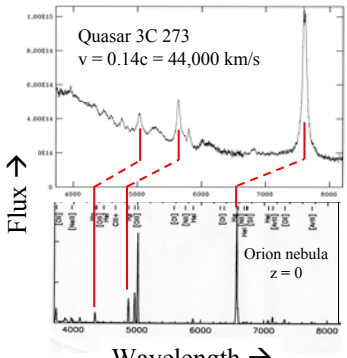
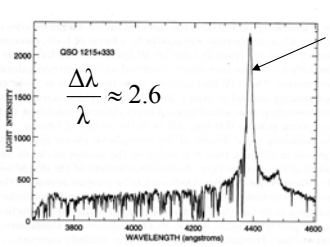



# Velocity from Redshifts




$$\text{Redshift} = z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

$$\frac{v}{c} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1}$$

Special relativistic result [CO eqn. 4.38]

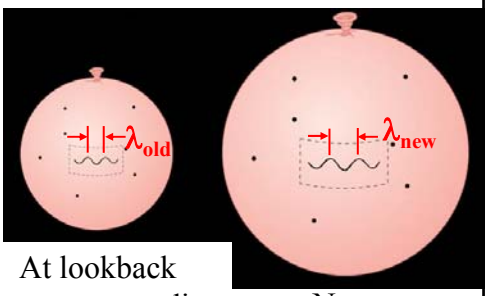
# The Expanding Universe

- Individual galaxies do not get stretched.
- Light waves *do* get stretched ➔ redshift.

Redshift

$$z = \frac{\lambda_{new} - \lambda_{old}}{\lambda_{old}} = \frac{\lambda_{new}}{\lambda_{old}} - 1$$

$$R(t) = \frac{\lambda_{old}}{\lambda_{new}} = \frac{1}{1+z}$$




At lookback time corresponding to redshift z

Now

doppler demo applet

Redshift ➔ scale factor R(t) at time light was emitted.

# Hubble's Distance Measurements

From *The Astrophysical Journal*, 1929:

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

By Edwin Hubble

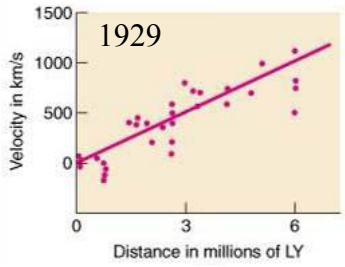
Mount Wilson Observatory, Carnegie Institution of Washington

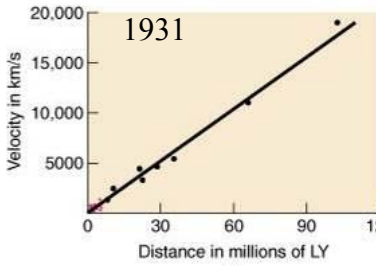
Communicated January 17, 1929

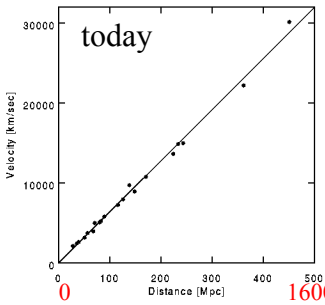
Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a $K$ term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results 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

# Hubble's Law



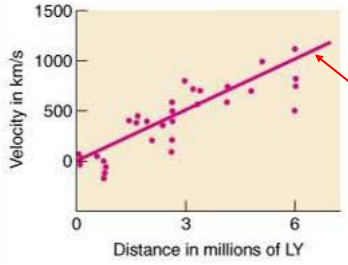




0 1600

millions of LY

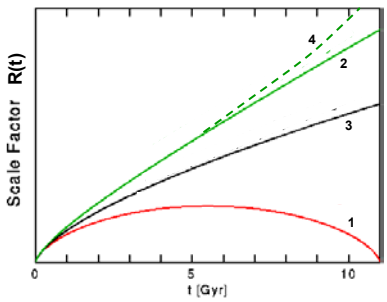
# Velocity vs. Distance

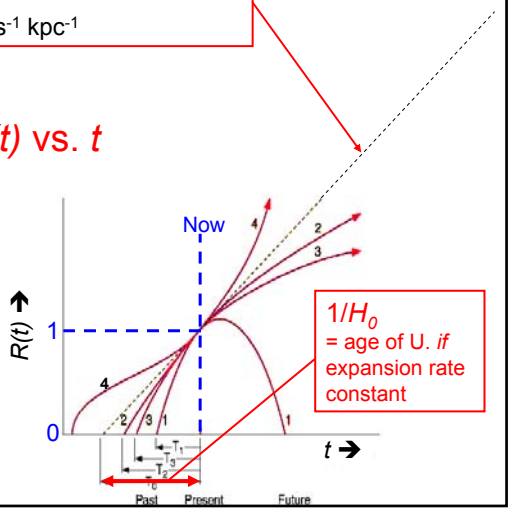



Slope = $H_0$
(Hubble constant at time $t_0$)

Km $s^{-1}$ $kpc^{-1}$

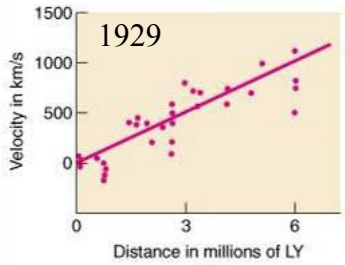
## *R(t)* vs. *t*

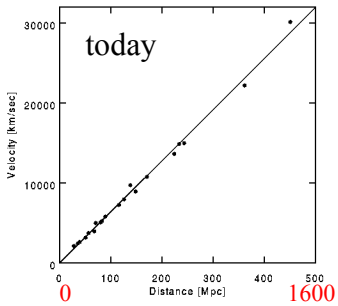



$1/H_0$
= age of U. *if* expansion rate constant

# Large Distances Needed



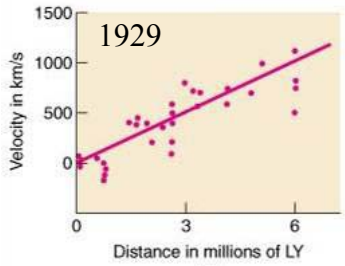




0 1600

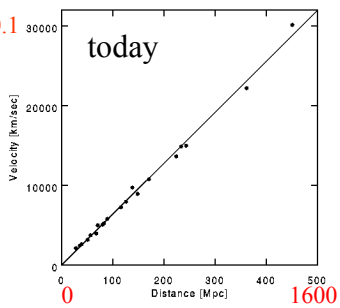
millions of LY

- Hubble flow: $v = Ho\ d$
  - Peculiar velocities are superimposed on this.


# Large Distances Needed



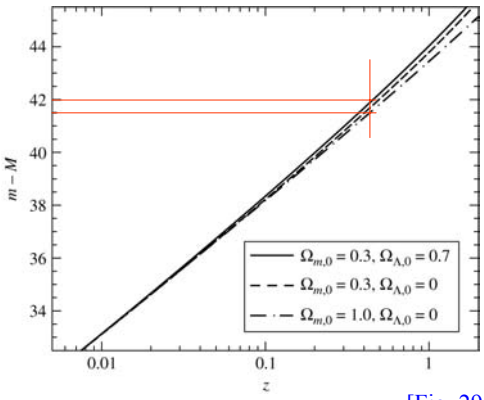

z=0.1



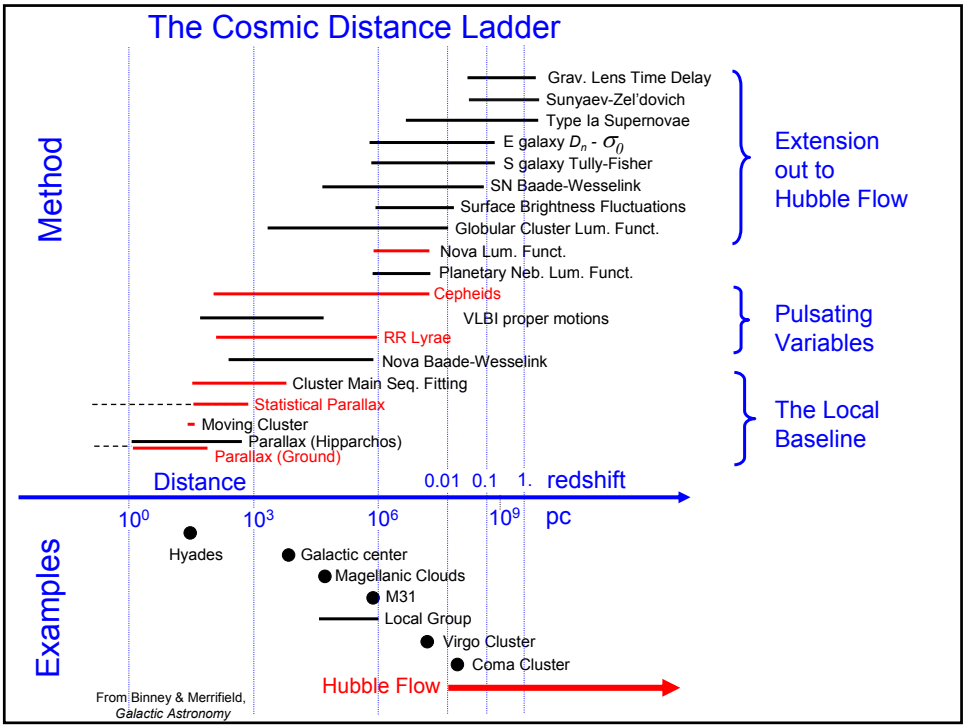

0 1600

millions of LY

- To distinguish between cosmological models
  - In the example, 0.5 mag accuracy ~ 50% accuracy.



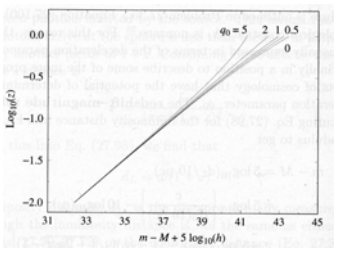

[Fig. 29.26]

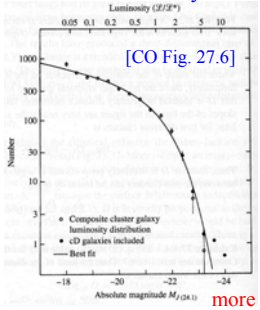



# Former approach for reaching large distances: Calibrate Brightest Cluster Galaxies

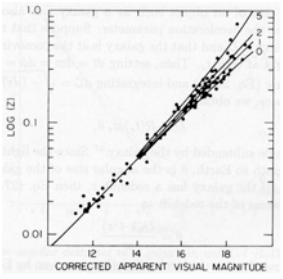
- To get out to large distances ➔ want most luminous possible objects.

Schecter Luminosity Function



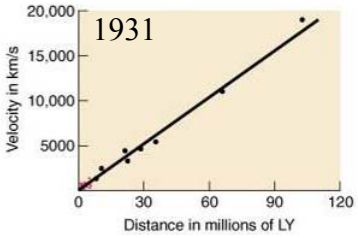

more luminous

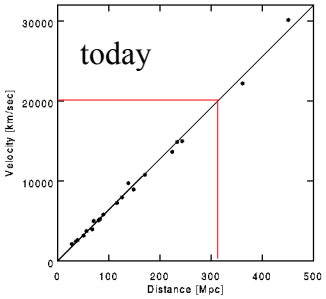



But large distances ➔ large lookback time ➔ evolution effects.

*Disaster!*

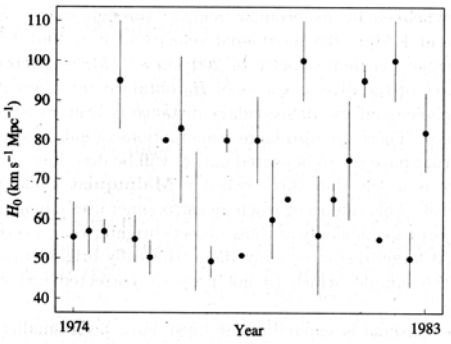
# Hubble's Law




0 990 1600

millions of LY




## Little *h*

- The Hubble Un-constant (blush)

  $H_o = 100h$ km s$^{-1}$ Mpc$^{-1}$

- Hubble time

  $t_H = 1/H_o = 9.78 \times 10^9\ h^{-1}$ yr.