Set 5:

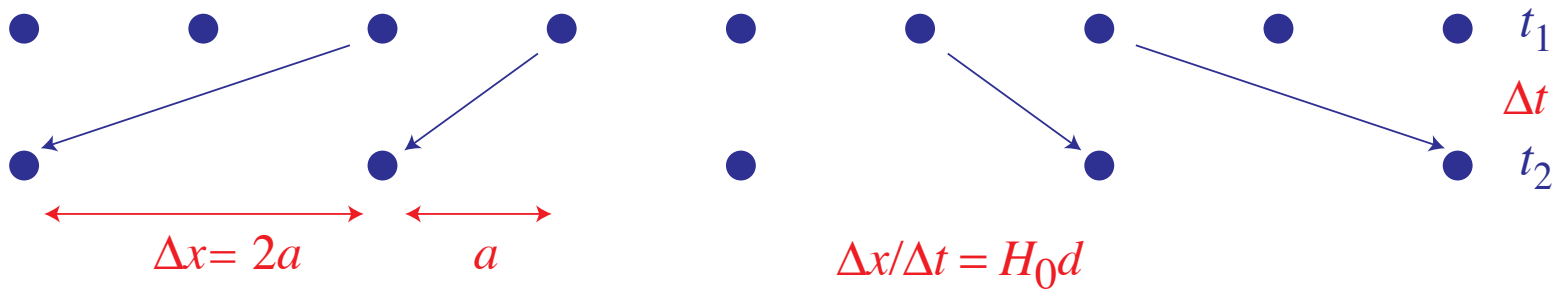
Expansion of the Universe

Cosmology

- Study of the origin, contents and evolution of the universe as a whole
- Expansion rate and history
- Space-time geometry
- Energy density composition
- Origin of structure
- Evolution of structure

Expansion of the Universe

- Measurements of the expansion rate of the universe depends on being able to measure distances accurately and compare them with "Doppler" redshift from recession velocity
- Consider a 1 dimensional expansion traced out by galaxies



- From the perspective of the central galaxy the others are receding with a velocity proportional to distance
- Proportionality constant is called the *Hubble Constant* H_0
- Each observer in the expansion will see the same relative recession of galaxies

Expansion of the Universe

- Generalizes to a three dimensional expansion. Consider the observer at the origin and two galaxies at position $\mathbf{d}_A$ and $\mathbf{d}_B$
- Recession velocities according to the observer

$$\mathbf{v}_A = H_0 \mathbf{d}_A \,, \quad \mathbf{v}_B = H_0 \mathbf{d}_B$$

- According to galaxy B, the recession velocity of galaxy A is

$$\mathbf{v}_B - \mathbf{v}_A = H_0 \mathbf{d}_B - H_0 \mathbf{d}_A = H_0 \mathbf{d}_{AB}$$

  so that B will see the same expansion rate as the observer at the origin given the linearity of Hubble's law
- Hubble's law is best thought of as an expansion of space itself, with galaxies carried along the "Hubble flow"

Cosmological Redshift

- Recession velocity likewise is best not thought of as a velocity through space and hence it is better to characterize it with the redshift z inferred from recession

$$1 + z \equiv \frac{\lambda_{\rm obs}}{\lambda_{\rm rest}}$$

- Compare with Doppler shift of recession where the velocity is purely radial $v = v_r$

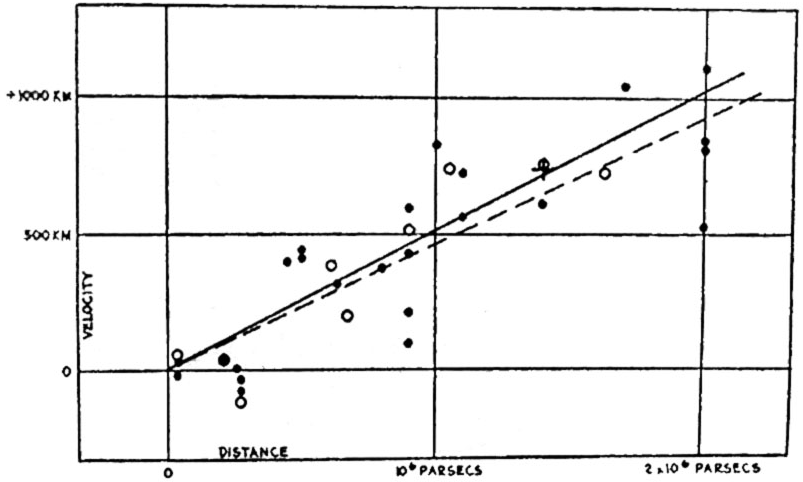
$$\frac{\nu_{\rm obs}}{\nu_{\rm rest}} = \frac{\sqrt{1 - v^2/c^2}}{1 + v/c}$$

$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm rest}} = \sqrt{\frac{1 + v/c}{1 - v/c}}$$

and for $v \ll c$, $z = v/c$

Hubble Constant

- Hubble
  in 1929 used the Cepheid
  period luminosity relation
  to infer distances to nearby
  galaxies thereby discovering
  the expansion of the universe



- Hubble actually inferred
  too large a Hubble constant of
  $H_0 \sim 500$km/s/Mpc due to a miscalibration of the Cepheid
  distance scale

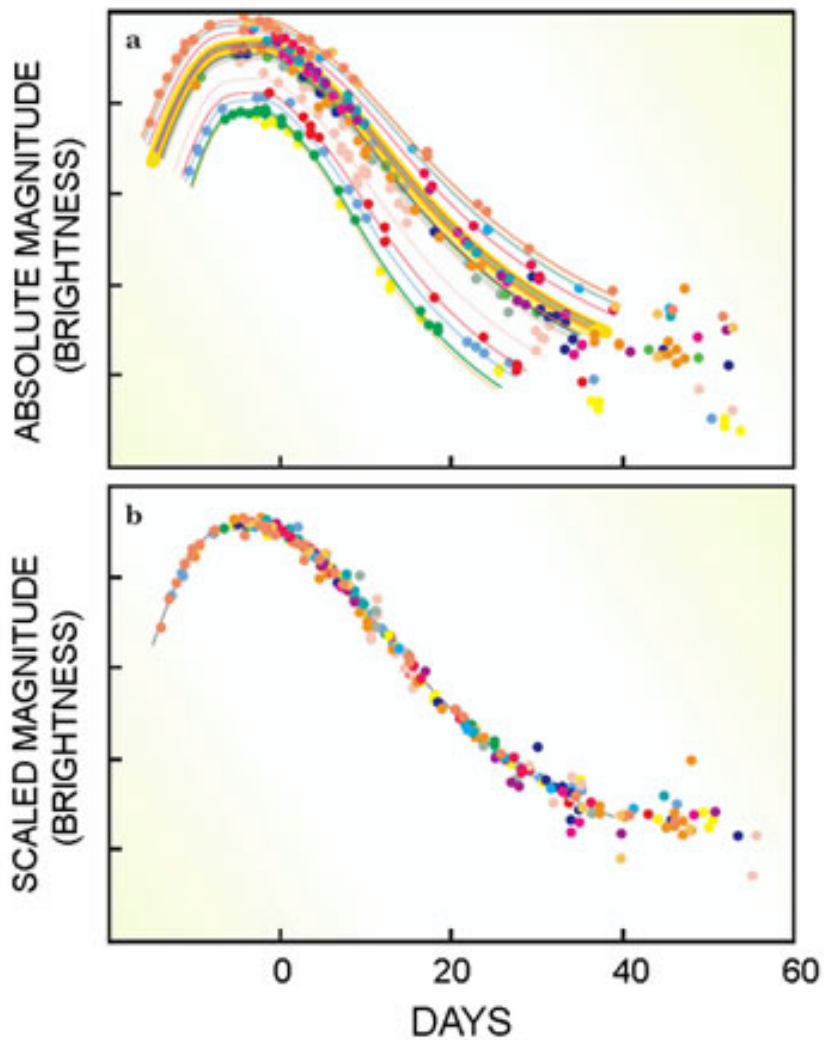
- H_0 now measured as 72 ± 9km/s/Mpc by HST Hubble Key project

Hubble Constant

- Took 70 years to settle on this value with a factor of 2 discrepancy persisting until late 1990's
- Difficult measurement since local galaxies where individual Cepheids can be measured have peculiar motions and so their velocity is not entirely due to the "Hubble flow"
- A "distance ladder" of cross calibrated measurements used to go out into the Hubble flow
- For example, calibrate the Tully-Fisher, fundamental plane, surface brightness fluctuations, Type 1A supernova relations with Cepheids, Novae, water maser, planetary nebula or globular cluster luminosity functions in nearby galaxies. Use secondary distance indications to go out in distance

Supernovae as Standard Candles

- Type 1A supernovae are white dwarfs that reach Chandrashekar mass where electron degeneracy pressure can no longer support the star, hence a very regular explosion
- Moreover, the scatter in absolute magnitude is correlated with the shape of the light curve - the rate of decline from peak light, empirical "Philips relation"



Beyond Hubble's Law

- Type 1A
  are therefore "standardizable" candles leading to a very low scatter $\delta m \sim 0.15$ and visible out to high redshift $z \sim 1$
- Deviation the linear Hubble's law indicate that the expansion of the universe is accelerating