Set 5:

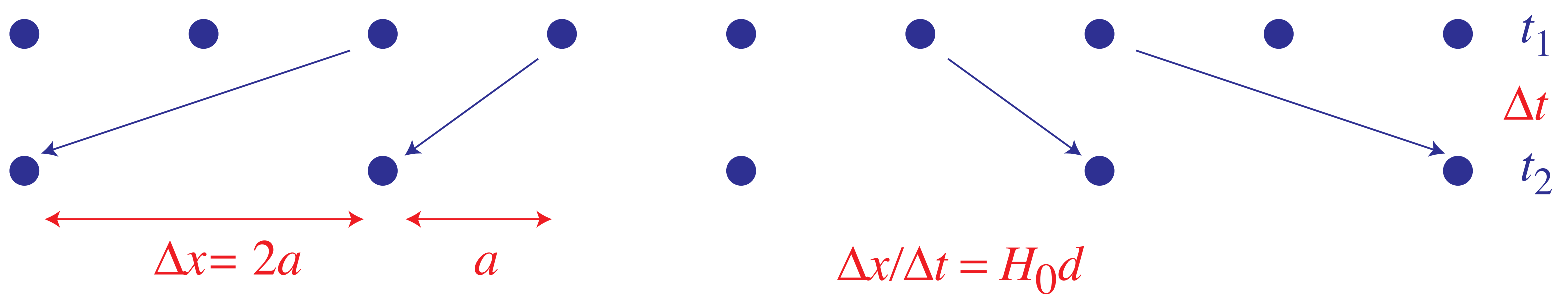
Expansion of the Universe

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 $v = v_r$

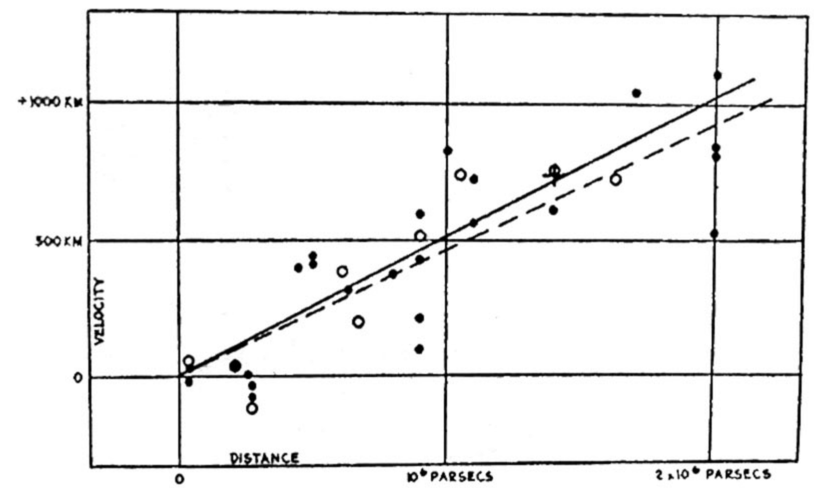
$$\frac{\nu_{\rm obs}}{\nu_{\rm rest}} = \frac{\sqrt{1 - v^2/c^2}}{1 + v/c}$$

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

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 74.2 ± 3.6km/s/Mpc by SHOES calibrating off AGN water maser

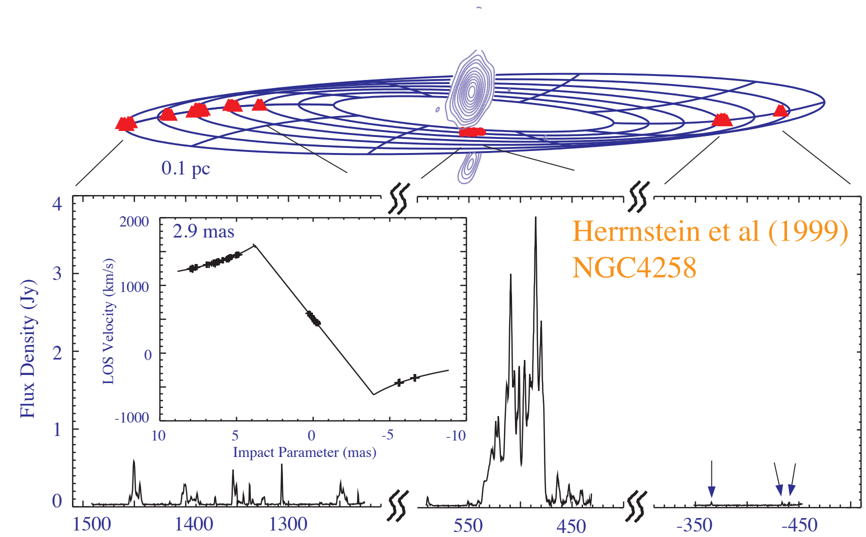
Hubble Constant History

- 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
- Primary distance indicators cepheids, novae planetary nebula or globular cluster luminosity function, AGN water maser
- Use more luminous secondary distance indications to go out in distance to Hubble flow

  Tully-Fisher, fundamental plane, surface brightness fluctuations, Type 1A supernova

Maser-Cepheid-SN Distance Ladder

- Water maser around AGN, gas in Keplerian orbit
- Measure proper motion, radial velocity, acceleration of orbit



- Method 1: radial velocity plus orbit infer tangential velocity = distance × angular proper motion

$$v_t = d_A(d\alpha/dt)$$

- Method 2: centripetal acceleration and radial velocity from line infer physical size

$$a = v^2/R, \qquad R = d_A\theta$$

Maser-Cepheid-SN Distance Ladder

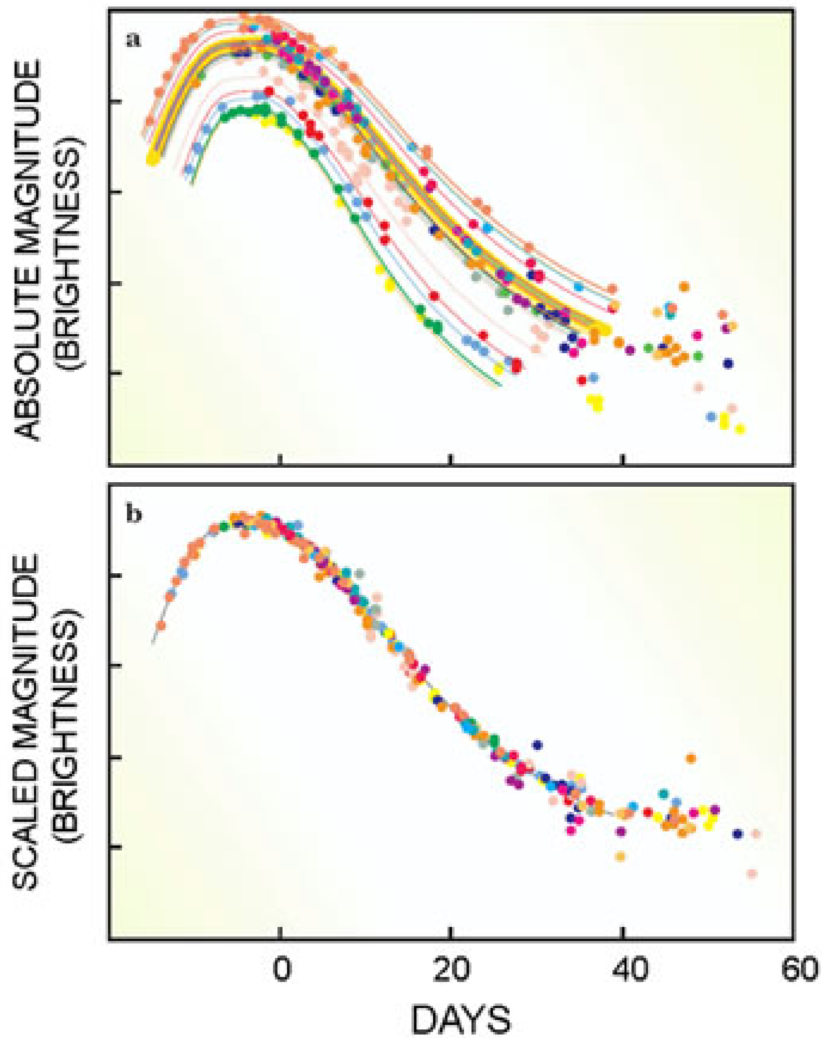
- Calibrate Cepheid period-luminosity relation in same galaxy
- SHOES project then calibrates SN distance in galaxies with Cepheids

  Also: consistent with recent HST parallax determinations of 10 galactic Cepheids (8% distance each) with $\sim 20\%$ larger H_0 error bars - normal metalicity as opposed to LMC Cepheids.

- Measure SN at even larger distances out into the Hubble flow
- Riess et al $H_0 = 74.2 \pm 3.6$km/s/Mpc more precise (5%) than the HST Key Project calibration (11%).
- Ongoing VLBI surveys are trying to find Keplerian water maser systems directly out in the Hubble flow (100 Mpc) to eliminate rungs in the distance ladder

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 "Phillips relation"



- Higher ^{56}N, brighter SN, higher opacity, longer light curve duration

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 $z \sim 1$
- Two groups in 1999 found that SN more distant at a given redshift than expected
- Cosmic acceleration discovery won the 2011 Nobel Prize in Physics
- Requires more on FRW dynamics or Newtonian cosmology to understand...