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:

\[
\Delta x = \frac{2a}{\Delta t} = H_0 d
\]

- 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 $d_A$ and $d_B$

• Recession velocities according to the observer

$$v_A = H_0 d_A, \quad v_B = H_0 d_B$$

• According to galaxy $B$, the recession velocity of galaxy $A$ is

$$v_B - v_A = H_0 d_B - H_0 d_A = H_0 d_{AB}$$

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

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

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

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

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

and for $v \ll c$, $z = \frac{v}{c}$
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 $H_0 \sim 500\text{km/s/Mpc}$ due to a miscalibration of the Cepheid distance scale

- $H_0$ now measured as $74.2 \pm 3.6\text{km/s/Mpc}$ 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 \( = \text{distance} \times \text{angular proper motion} \)
  \[
  v_t = d_A \left( \frac{d\alpha}{dt} \right)
  \]
- Method 2: centripetal acceleration and radial velocity from line infer physical size
  \[
  a = \frac{v^2}{R}, \quad R = d_A \theta
  \]
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 ~ 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...