Cosmology

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Big Bang

The universe started with the big bang

Big bang timeline:

- T=0 Big Bang, inflation begins
- T=10^-32s, inflation ends
- T = 100s, formation of simplest elements
- T=1 month CMB fixed
- T=10,000 years, Radiation = Matter Energy
- T=380,000 years, CMB last scattering

4 main pieces of evidence for big bang

- Expansion of universe
  - We can see that the universe is expanding (see Hubble's law)
  - If universe is expanding it must have started from a small point
  - Using Hubble's law we estimate the age of the universe is roughly 14billion years
- Evolution of universe

- Cosmic microwave background radiation (CMBR)
  - If the universe started from the big bang, we should be able to see radiation from this time
  - This was detected in 1960
  - Shows the universe is a blackbody with temperature of 2.73K
  - Radiation comes from "last scattering" time of universe
  - When temperature after big bang dropped below 3000K, electrons bound with protons
    - This meant photons could travel through space
    - Before this the universe was opaque

- Abundances of lightest chemical elements
  - 20 minutes after big bang, temperature is too low for new elements to be formed
    - Not enough high energy photons to destroy existing elements
  - This is why universe is largely H and He
  - Our calculations match the true abundances in the universe very well
    - Major strong point for Big Bang model
  - To make the values match we get important clues about dark matter

The Cosmological Principle

On the largest scales of the universe, we make some assumptions:

- Homogeneity
  - On large scales, the universe has the same physical properties
    - Same mass density, same expansion rate, same ratio of visible to dark matter
- Isotropy
  - Same large scale structure in any direction
- Universality
  - Laws of physics are the same everywhere in the universe

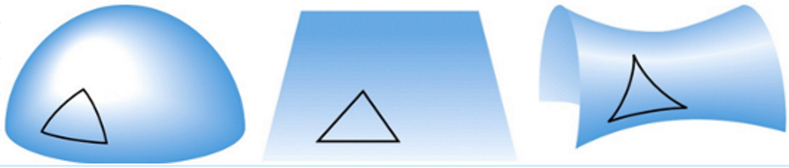
Dynamics of the Universe

Shape of the universe

- Friedmann equation describes state of universe:

$$\dot{R}^2(t) = \frac{8\pi G\rho R^2(t)}{3} - kc^2 + \frac{\Lambda}{3}R^2(t)$$

  - R is 'scale factor'
  - Λ Is the 'cosmological constant'
  - K is curvature, describes shape of universe



K=-1, spherical space: parallel light beams converge
K=0, Flat space, parallel light beams remain parallel
K=1, Hyperbolic space, Parallel light beams diverge
K is thought to be 0

Deceleration of the Universe:

Expansion of universe should slow down due to gravity
Fate of universe depends on matter density
We can define critical density, the density at which expansion stops at infinity.
Critical mass can be found by:

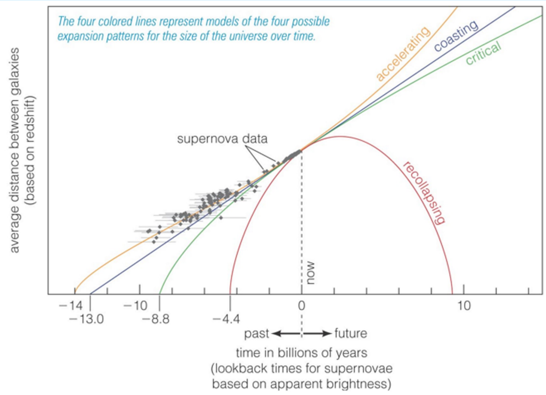
$$\rho_{\text{crit}} = \frac{3H_0^{\ 2}}{8\pi G}$$

When looking at our universe, we define:

$$\Omega = {}^{\rho}\!/_{\rho_{\text{crit}}}$$

If density > critical density, matter will slow expansion after a finite time
Universe collapse on itself
Big Crunch
If density < critical density, universe will never stop expanding
'Open universe'
If density = critical density $\Omega = 1$, Critical universe
Universe will stop expanding at t=infinity

By looking at type Ia supernova, we can measure distances and recession speeds, and so find rate of expansion
We expected to find the expansion of the universe decelerating
Instead we found it's accelerating



What is driving this acceleration?

The cosmological constant:

Vacuum of universe is not perfectly empty
Quantum physics predicts vacuum full of particles that pop into existence and then annihilate
Therefore universe has a constant energy density
We can explain acceleration using Cosmological constant
Cosmological constant is the Λ In Friedman equation from earlier
Used to believe it was 0

Energy corresponding to it can account for the mass (E=mc^2) needed to produce a flat space-time
- This energy is what we call dark energy

From knowing geometry of universe, we can tell that the universe is the sum of visible, dark matter, and dark energy
- Visible ~ 4%
- Dark matter ~ 22%
- Dark energy ~ 74%

Cosmic Microwave Background

The CMB is quite smooth, but has some fluctuations
- Galaxy formation is highly dependant on these fluctuations
- Looking at CMB also tells use universe has flat geometry
- This likely comes from inflation
  - Period of rapid expansion in moments after big bang
    - Occurred when strong and electroweak forces became separate
  - Rapid expansion during start of universe may have smoothed out ripples in space time
  - Results in smooth CMB and flat geometry