Lecture 39: The Fate of the Universe

Key Ideas

Matter-dominated Universe:
- High-Ω: expansion stops & collapses (Big Crunch)
- Low-Ω or Flat: expands forever (Big Chill)

Cosmological Constant
- Evidence from Supernova distances
- Flat, accelerating, Infinite Universe

Fate of an Accelerating Universe:
- Expands forever at an ever-increasing rate
- Ends in a cold, dark, disordered state

Matter-Dominated Universes

Future depends on the *density of matter*

<u>High Density</u> ($\Omega_0 > 1$):
- Enough matter to slow and stop expansion
- Universe collapses in a "Big Crunch"

<u>Low Density or Flat</u> (Ω_0 < or = 1):
- Keeps expanding forever
- Cools off, ending in a "Big Chill"

DENSITY IS DESTINY!

What is the matter density Ω_m?

<u>Baryonic Matter</u> (stars & gas)
- Best estimate Ω_b~0.04 +/- 0.01
- Contribution from stars Ω_* ~0.004

<u>Radiation</u> (photons):
- Cosmic Background Ω_{rad} ~0.00005

<u>Dark Matter:</u>
- Galaxy Cluster dynamics gives Ω_{dm} ~ 0.26

TOTAL: Ω_m =0.2-0.4

Expansion Forever?

If the Universe is *matter dominated,*

Total Density: $\Omega_0 = \Omega_m = 0.2\text{-}0.4$

This means $\Omega_0 < 1$

Too little matter to stop the expansion

The universe has a hyperbolic geometry

<u>Future:</u>

Universe will expand forever at a steadily decreasing rate

What About Λ?

If there is a Cosmological Constant (Λ), the Density Parameter becomes

$$\Omega_0 = \Omega_m + \Omega_\Lambda$$

Ω_m =Density of Matter and Energy (photons)

Ω_Λ= Density of the Vacuum Energy

DENSITY IS NO LONGER DESTINY!

What does Ω_Λ do?

If Ω_Λ=0, matter *slows* the expansion:

Expansion rate is *faster* in the past

Distant galaxies (distant past) will have *larger* recession velocities than "steady" expansion

If Ω_Λ is large, the expansion *accelerates*

Expansion rate is slower in the past

Distant galaxies have *smaller* recession speeds

Test:

Make a Hubble diagram for deep space

See Figure 28-17b

Distant Type Ia Supernova

Type Ia SNe are excellent standard candles

Exploding white dwarfs in binary stars

Very Luminous (can see them very far away)
Have a characteristic spectrum

Distant Supernovae show that the Universe is accelerating
See Figure 28-18

The Accelerating Universe
The SNIa results combined with constraints from the cosmic background radiation and galaxy clusters give:

$$\Omega_m \approx 0.3 \pm 0.1$$

$$\Omega_\Lambda \approx 0.7 \pm 0.1$$

Taken together: $\Omega_0 \sim 1$

We live in a spatially flat, accelerating, infinite Universe

The Once & Future Universe
As the Universe expands:
- Expansion continues forever at a faster rate
- Space between galaxy clusters widens
- Universe cools down at a faster rate

Details of the future Universe depend upon:
- Stellar Evolution
- Gravity
- Quantum Mechanics

Epoch of Star Formation
The Present Day (t=14 Gyr):
- Most stars are metal-rich, and make more metals ejected in supernova explosions.
- Next generation starts with a little less H and a few more metals.

Some fraction of the star's matter gets locked away in stellar remnants:
- White dwarfs, neutron stars & black holes

End of Star Formation

After t~10^{12} years
Successively more matter is locked up in stellar remnants, depleting the free gas reserves
Cycle of star birth and death is broken:

- Nuclear fuel is exhausted, not enough gas to make more stars
- Red dwarfs burn out as low-mass white dwarfs
- Remaining matter is locked up in black dwarfs, cold neutron stars, and black holes

The last stars fade into a long night….

Solar System "Evaporation"

After t=10^{17} years:
Gravitational encounters between stars are rare, but disrupt orbiting systems:

- Planetary systems get disrupted by stellar encounters and their planets scattered
- Wide binary systems are broken apart
- Close binary stars coalesce into single remnants

Dissolution of Galaxies

After t=10^{27} years

- Stellar remnants within galaxies interact over many, many orbits
- Some stars gain energy from the interaction and ~90% get ejected from the galaxy.
- Others lose energy and sink towards the center

The last 10% coalesce into Supermassive Black Holes

Dissolution of Matter?

After 10^{32} years:

- Some particle models predict that protons are unstable
- Protons decay into electrons, positrons and neutrinos
- All matter not in Black Holes comes apart

Current experimental limits suggest that the proton decay time may > 10^{32} years

Evaporation of Black Holes

After t=10^{67} years:

Remaining stellar-mass black holes evaporate by emitting particles and photons via Hawking radiation

After $t=10^{100}$ years

Supermassive Black Holes evaporate one-by-one in a last final weak flash of gamma rays

End of the epoch of organized matter

The Big Chill

After black holes have all evaporated

Universe continues to cool off towards a Radiation Temperature of absolute zero

Only matter is a thin, formless gas of electrons, positrons and neutrinos

Only radiation is a few increasingly redshifted photons

The end is cold, dark, and disordered…