Lecture 39: The Fate of the Universe

Key Ideas

Matter-dominated Universe:
- High-$\Omega$: expansion stops & collapses (Big Crunch)
- Low-$\Omega$ 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

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

Low Density or Flat ($\Omega_0 < 1$):
- Keeps expanding forever
- Cools off, ending in a “Big Chill”

DENSITY IS DESTINY!

What is the matter density $\Omega_m$?

Baryonic Matter (stars & gas)
- Best estimate $\Omega_b$~0.04 +/- 0.01
- Contribution from stars $\Omega_\ast$ ~0.004

Radiation (photons):
- Cosmic Background $\Omega_{\text{rad}}$~0.00005

Dark Matter:
- Galaxy Cluster dynamics gives $\Omega_{\text{dm}}$ ~ 0.26

TOTAL: $\Omega_m$ =0.2-0.4

Expansion Forever?
If the Universe is *matter dominated*,
  Total Density: $\Omega_0 = \Omega_m = 0.2-0.4$
This means $\Omega_0 < 1$
  Too little matter to stop the expansion
  The universe has a hyperbolic geometry

**Future:**
Universe will expand forever at a steadily decreasing rate

**What About $\Lambda$?**

If there is a Cosmological Constant ($\Lambda$), the Density Parameter becomes

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

$\Omega_m$ = Density of Matter and Energy (photons)
$\Omega_\Lambda$ = Density of the Vacuum Energy

**DENSITY IS NO LONGER DESTINY!**

What does $\Omega_\Lambda$ do?
If $\Omega_\Lambda = 0$, matter *slows* the expansion:
  Expansion rate is *faster* in the past
  Distant galaxies (distant past) will have *larger* recession velocities
  than “steady” expansion
If $\Omega_\Lambda$ 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:

$$\Omega_m \approx 0.3 \pm 0.1$$
$$\Omega_A \approx 0.7 \pm 0.1$$

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, the 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...*