Previously: **Cosmology II - The Big Bang and its aftermath**

- Remnant radiation produces a cosmic microwave background
- Small density fluctuations needed to make galaxy clusters were present in the very early universe
- A very “Inflation” epoch is needed to make the post-Big Bang expanding universe look like what we see today

Today: **Cosmology III - The content of the Universe and its evolution**

- We live in a very flat Universe (as suggested by inflation and the CMB)
- Dark Matter (~30%) + Dark Energy (~70%) + ordinary matter (~ 5%)
- Expansion is now “accelerating” - dark matter joined by dark energy
- Possible alternative future Universes include Big Rip, Big Crunch, but most likely slowly expanding and cooling forever
(Review) At 380,000 years, Universe was a blackbody of $T = 3000K$
(Review) CMB observed by COBE is at a much lower temperature
A quiz question! (Answer)

- *If the Universe was 3000 K (and emitted at infrared wavelengths) at 380,000 years of age, why is it now observed to be 2.73 K (microwave)?
A quiz question! (Answer)

- **If the Universe was 3000 K (and emitted at infrared wavelengths) at 380,000 years of age, why is it now observed to be 2.73 K (microwave)?**

- Redshift increases with distance
- CMB is VERY far away (14 billion light years!)
- Its redshift will be sufficiently large to shift infrared light to microwave
(Review) Summary so far

- Afterglow light pattern 375,000 years
- Quantum fluctuations
- First stars about 400 million years
- Development of galaxies, planets, etc.
- Dark energy accelerated expansion

Big bang expansion 13.77 billion years
Will the Universe expand forever or will it eventually collapse?
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Whether the Universe reverses its expansion or continues to expand depends on the “density”
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- is there enough mass for gravity to stop expansion?
- critical density: 
  \[ \rho_{\text{crit}} \sim 9.1 \times 10^{-30} \text{ g/cm}^3 \]
- measured density: \( \rho \)
  recast as \( \Omega = \rho / \rho_{\text{crit}} \)
    - if \( \Omega < 1 \): expansion continues forever: universe is “open”
    - if \( \Omega > 1 \): expansion reverses: universe is “closed”

- Open (infinite) Universe: 
  • infinite volume  no true edge

- Closed (finite) Universe: 
  • finite volume  no true edge

- Flat Universe: density = critical density  \( \Omega = 1 \)
Three possible geometries for the Universe

- **Closed**
  \[ \Omega > 1 \]

- **Flat**
  \[ \Omega = 1 \]

- **Open**
  \[ \Omega < 1 \]

\[ \Omega \equiv \rho/\rho_{\text{crit}} \]
How these different universes evolve

\[ \Omega \equiv \frac{\rho}{\rho_{\text{crit}}} \]
Size of CMB fluctuations can tell us what type of Universe we live in

- The size of the cold and hot spots depends on the geometry of the Universe

- A size of $\sim 1^\circ$ means the Universe is flat!

- $\Omega = 1$

$\Omega \equiv \rho / \rho_{\text{crit}}$
\[ \Omega \equiv \frac{\rho}{\rho_{\text{crit}}} \]
Quick review of inflation

- Time:
  - Now
  - 380,000 yr

- Distance:
  - $10^{-36}$ s
  - $10^{-38}$ s

- Period of inflation

- Examples of ripple sizes:
  - Size of ripple before inflation = size of atomic nucleus
  - Size of ripple after inflation = size of solar system
Inflation provides an explanation for this flatness
Flat Universe

- Universe goes on forever — there is no physical edge (but still CMB represents an "observational edge")
- $\Omega = 1$ implies that all matter and energy in the Universe must add up to equal a number VERY close to the critical density

$$\Omega \equiv \frac{\rho}{\rho_{\text{crit}}}$$
\[ \Omega \equiv \frac{\rho}{\rho_{\text{crit}}} \]

\[ \Omega = \Omega_{\text{matter}} + \Omega_{\text{energy}} \]

Remember that \( E = mc^2 \)
From Big Bang Nucleosynthesis, we know how much matter there should be

\[ \Omega_{\text{matter}} < 0.1 \]

• But if we add up all the luminous matter in stars and galaxies, we get

\[ \Omega_{\text{luminous matter}} < 0.01 \]

\[ \Omega \equiv \frac{\rho}{\rho_{\text{crit}}} \]
There is a LOT of mass in intergalactic (and interstellar) gas

- While the density of this gas is very low, the amount of space that it takes up is tremendous
- $\Omega_{\text{gas matter}} = 0.04$
- $\Omega_{\text{baryonic matter}} \approx 0.05$

All baryonic matter only makes up 5% of the total Universe!!!
Adding in dark matter...

- There is a lot of matter that we can’t see (dark matter)

\[ \Omega_{\text{baryonic matter}} = 0.05 \]
\[ \Omega_{\text{dark matter}} = 0.27 \]

All matter is only \(~32\%\) of the critical density of the Universe, but \(\Omega = 1\)

\[ \Omega \equiv \frac{\rho}{\rho_{\text{crit}}} \]
For a long time, the fate of the Universe was unknown

• Would there be a Big Crunch?

• Would the Universe just continue to expand forever?
In the late 1990s, a team set out to measure the Hubble constant.
Type 1a Supernovae

- Expansion in past was **slower** than any prediction
- Universe has accelerated compared with expectations
- Conclusion: $\Omega$ has a **non-gravity** part
- "Dark energy" helping push the expansion (?)
Universe’s expansion is **accelerating**!

Saul Perlmutter  Brian Schmidt  Adam Riess

*2011 Nobel Prize in Physics*
The rest of the mass/energy in the Universe is due to some anti-gravity type “stuff” called dark energy.
Everything that we can see only makes up 5% of the Universe!!!!

**Composition of the Universe**

- Dark matter: 27%
- Dark energy: 68%
- Ordinary matter: 5%
- Ordinary matter: 4% H and He
  - <1% Stars
  - <1% Other
So, what is this dark energy?

We don’t yet know, but some possibilities…

• Empty space itself has its own form of energy: the cosmological constant!
• Quantum energy (particles continually forming and annihilating)
• Some new kind of energy fluid or field (yes, the vagueness of this statement reflects our lack of understanding!)
• Maybe our understanding of gravity (GR) isn’t yet complete

“I think you should be more explicit here in step two.”
Models for evolution of the Universe

Appears to be the currently favored model
SN data only shows so much — maybe the Universe will surprise us yet again…
Alternate Universe possibilities

The “Oscillating” Universe

The Universe could oscillate between Big Bangs and Big Crunches
The Big Rip

- If $w < -1$, then as the Universe expands, the amount of dark energy per volume increases!

- Eventually, galaxies, stars, planets, and even atoms would be ripped apart!

- But current data suggests $w = -1$ (i.e., no Big Rip)
The most likely extrapolation (though still an extrapolation!)

- Clusters of galaxies will spread further apart over time
- All stars will eventually die (even the low mass ones that live for trillions of years)
- White dwarfs will cool into black dwarfs
- Pulsars will stop spinning and slowly cool down as well
- Black holes will consume the remainder of their gas and “shut off”
- Overall, things will slowly fade into darkness and cold (yikes!)
- But remember — this is still speculation! Science is always a progress report!
Final summary of Cosmology

- Afterglow light pattern 375,000 years
- Quantum fluctuations
- First stars about 400 million years
- Development of galaxies, planets, etc.
- Dark energy accelerated expansion
- Big bang expansion 13.77 billion years