Previously: **Cosmology I - The Age of the Universe and the Big Bang**

- Cosmology - answering questions about the origin of the Universe and answering them using observations
- Independent measurements all yield an age of the Universe of about 13.5 billion years
- Time began with a hot Big Bang - expansion and cooling until today
- The Big Bang makes several predictions that can be tested

Today: **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
The earliest moments of the Big Bang

![Diagram showing the cooling of the universe after the Big Bang, with different eras labeled such as 'Earliest era: rules unknown', 'Forces are unified', 'Radiation dominates', 'Protons and anti-protons form', 'Electrons and positrons form', 'Atoms form', 'Galaxies form', 'Stars form', and 'Today'.]
The earliest moments of the Big Bang

- Particle creation
  - photon
  - electron

- Particle annihilation
  - photon
  - antielectron

Energy (radiation) and mass were in equilibrium
Testing the Big Bang Idea

• Big Bang Nucleosynthesis
  • production of light elements in the early Universe

• Remnant radiation from primeval fireball
  • universal background radiation

• Origin of Cosmic Structures
  • formation of galaxies and huge superclusters in an expanding Universe
Big Bang Nucleosynthesis

(a) 10^{-2} seconds

(b) 3 minutes

(c) 300,000 to 700,000 years
Big Bang Nucleosynthesis

- **Earliest minutes**
  - H, deuterium
  - He$^3$, He$^4$

- **Expansion and cooling**
  - halts further fusion

- **net Big Bang production**
  - ~ 75% Hydrogen
  - ~ 25% Helium
  - < 0.1% lithium, beryllium, etc.

- Matches composition of the oldest stars!
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Discovery of the Big Bang

- Found strange radio radiation
- Pointed telescope in many directions and found same thing (cosmological principle)
- Thought it was pigeon poo
- Radiation was consistent with a blackbody at $T \sim 3$ K
Discovery of the Big Bang

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Won Nobel Prize in 1987!
The Universe was opaque until about 380,000 years.
The Universe was opaque until about 380,000 years

- Universe cooled down
- Hydrogen recombined
- Universe was transparent
- Exterior to star — light moves freely

- Universe was hot
- Hydrogen was ionized
- Universe was opaque
- Kind of like the interior of a star
At 380,000 years, Universe was a blackbody of $T = 3000\,\text{K}$
**Cosmic Background Explorer (COBE)**

- **Launched in 1990 to observe CMB from space**
- **Found that the CMB is a blackbody to 1 part in 100,000**
- **$T = 2.728$ K**
CMB observed by COBE is at a much lower temperature.
A quiz question!

• *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)?*
Can again address the “edge” of the Universe

- **The Edge (or Horizon)**
  - back in space = back in time
  - beyond ~14 billion light years → no stars, but CMB
  - is this a physical edge? No
  - viewed from anywhere, $R_{\text{univ}} = 14$ billion ly
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The CMB is remarkably uniform!

Map of sky from COBE

$T = 2.728 \text{ K}$

Confirms the cosmological principle that the Universe is homogenous and isotropic
But, if we look closer at the COBE data...

- Differences at the 0.3 mK level
- Not quite a blackbody! (but still very close)
From COBE to WMAP

WMAP - Wilkinson Microwave Anisotropy Probe
From COBE to WMAP

WMAP - Wilkinson Microwave Anisotropy Probe
The “scale” of ‘bumps’ is not uniform...
From WMAP to Planck
From WMAP to Planck
Further refinement!

Temperature differences are greatest between patches separated by 1°.
Further refinement!
Further refinement!
What are these fluctuations?

- On VERY small scales, quantum mechanics dominates.
- Quantum mechanics states that energy can fluctuate randomly on these small scales.
- In the CMB, these fluctuations are manifested as temperature and density variations.
Small scale fluctuations get amplified by **Inflation**

- $t \sim 10^{-37}$ sec
  - gravity repulsive
  - brief accelerated expansion
- **before inflation**: all points in space could communicate
- **after inflation**: too distant for further contact
Small scale fluctuations get amplified by \textit{Inflation}
Small scale fluctuations get amplified by *Inflation*
Small scale fluctuations get amplified by *Inflation*

Not to scale....
Small scale fluctuations get amplified by Inflation

- \( t \sim 10^{-37} \text{sec} \)
  - gravity repulsive
  - brief accelerated expansion

- **before inflation**: all points in space could communicate
- **after inflation**: too distant for further contact
Regions of higher density begin to collapse
These fluctuations become the seeds of superclusters
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  • formation of galaxies and huge superclusters in an expanding Universe
  • (requires an epoch of “Cosmic Inflation” at very early times)
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What exactly this “inflation” is is still somewhat mysterious!
Summary so far
(in one picture)

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

Next time