Last time: Cosmology I - The Age of the Universe & 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 - Testing the Big Bang
• Testing the Big Bang - synthesis of the elements (helium in particular)
• 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

Remnant radiation from primeval fireball
• prior to \(10^6\) years:
  • \(T > 3,000\)K, all Hydrogen ionized
  • Universe was opaque
• at \(10^6\) years: recombination
  • Hydrogen recombines
  • Universe becomes transparent
• Most distant visible* “thing”
  • is the “fog” of the recombination epoch:
    when the Universe was a 3000 K black body
  * but Red Shifted by a factor of 1000;

The 3 degree background radiation
• 1965: 3 K Background radiation discovered by Penzias and Wilson (Nobel Prize, 1978)
• 1990: Cosmic Background Explorer: “COBE”
  • Precisely a black body (to 1 part in 100,000)
  • Very uniform distribution in space
Is there an “edge” to the Universe?

- **Olbers’ Paradox**
  - assume: infinite Universe
  - assume: uniform distribution of matter (on large scales)
  - consequence: all lines of sight end on a star
  - consequence: whole sky should be as bright as the Sun
  - Dark night sky → Universe has an “edge”

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

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**Testing the Big Bang Idea**

- **Big Bang Nucleosynthesis**
  - production of light and heavy 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

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**Structure and the Uniformity Problem**

- 2.7 Kelvin in all directions
  - smoothed by rapid expansion
  - smooth Universe today
  - but opposite points in sky can’t communicate ($d > c t$)

- **Superclusters**: organized and old
  - how did they form from a smooth medium
  - how did they form in such large sizes

- for Big Bang to “work”:
  - at early times, all must have been in causal contact
  - followed by later rapid expansion - INFLATION
  - provide some early structure to seed galaxies

- Dramatically confirmed by COBE in 1992 (NOBEL - 2006)
**Inflation - a solution to the uniformity problem**

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

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**COBE maps of the Microwave background**

- COBE–DMR Map of CMB Anisotropy
  - North Galactic Hemisphere
  - $-100 \mu K$ to $+100 \mu K$
  - South Galactic Hemisphere

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**from COBE to WMAP**

- (1992) to (2010)

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scale of ‘bumps’ is not uniform...
Testing the Big Bang Idea

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Will the Universe expand forever... or will it eventually collapse?

- is there enough mass for gravity to stop expansion?
- critical density:
  \[ \rho_{\text{crit}} = \frac{3H^2}{8\pi G} \approx 9.1 \times 10^{-30} \text{ g/cc} \times (H/70)^2 \]
- measured density: \( \rho \)
  - recast as \( \Omega_0 = \rho / \rho_{\text{crit}} \)
    - 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

- Flat: $\Omega = 1$
- Closed: $\Omega > 1$
- Open: $\Omega < 1$

Inflation - a solution to the uniformity problem

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inflation requires $\Omega_0 = 1$

if true:
  - we live in 1 part of an inflated Universe
  - our Universe is FLAT ($\Omega_0 = 1.000000000...$)

note: from B.B. nucleosynthesis:
  - $\Omega_0 < 0.1$ for “normal” matter
  - so any $\Omega > 0.1$ is in a new, unknown form
Testing Inflation #1: Add up all mass in the Universe

- **count up all mass in galaxies**
  - include massive dark galaxy halos
  - $M_{\text{detected}} \rightarrow \Omega_0 \sim 0.03$

- **include more “dark matter”**
  - galaxy clusters need dark matter to stay together
  - 90% of cluster mass must be dark matter
  - $M_{\text{detected}} \rightarrow \Omega_0 \sim 0.3$

Testing Inflation #2: Hubble law at large distances

- **Expansion was faster at earlier times**
  - closed (higher density) Universe - much faster
  - open (lower density) Universe - not as fast
  - empty (zero density) Universe - same speed always

- **Curvature of Hubble law at large distance**
  - distant = younger = faster than now

$\Omega_0$