Announcements

• Help sessions will restart today at 5:30pm.

• Quiz#5 after 50min lecture.

• Homework#5 will be handed out at the end of lecture; please pick it up when you finish quiz.

Station#7, “Cosmic History”

Lecture 20: An Overview
Lecture 21: The Big Bang
Lecture 22: The Fate of the Universe
Lecture 23: Inflation – before the Big Bang

Conditions in the Early Universe

• The most distant galaxies we observe come from a time when the Universe was a few billion years old.
• The cosmic microwave background prevents us viewing light from before the Universe was 380,000 years old.
• So how do we know what conditions were like at the beginning of time?
• We know the the conditions & expansion rate of the Universe today.
• By running the expansion backwards
  • we can predict the temperature & density of the Universe at anytime in its history using basic physics
  • we study how matter behaves at high temperatures & densities in laboratory experiments
  • current experimental evidence provides info on conditions as early as \(10^{-10}\) sec after the Big Bang

Lecture 20
Cosmic History - An Overview

Reading: Chapter 23
A Scientific History of the Universe

- What was the Universe made of during its earliest moments?
- Briefly describe the various eras of the universe since the Big Bang.

The Creation of Matter
- The early Universe was filled with radiation & subatomic particles.
- We’ve seen matter converted to energy…
  - but Einstein’s famous equation is a two-way street!
  \[ E = m c^2 \]
- If \( T > 10^{12} \text{ K} \)
  \[ \gamma \rightarrow p^+ \ n \ e^- \]
  \[ \gamma \rightarrow p^- \ \bar{n} \ e^+ \]
- matter
- antimatter

The Destruction of Matter
- When two identical particles of matter & antimatter collide
  - they annihilate each other and form gamma photons
- During the very first few moments of the Universe…
  - matter and radiation (energy) were continually converting into each other
  - the total amount of mass-energy remained constant
  \[ E = m c^2 \]
**Planck Era** (t < 10<sup>-43</sup> sec)
- This era, the “first instant”, lasted for 10<sup>-43</sup> sec.
- Because we are as yet unable to link...
  - quantum mechanics (our successful theory of the very small)
  - general relativity (our successful theory of the very large)
- **We are powerless to describe what happened in this era.**
- 10<sup>-43</sup> sec after the birth is as far back as our current science will allow us to go.
- We suppose that all four natural forces were unified during this era.

**GUT Era** (10<sup>-43</sup> < t < 10<sup>-38</sup> sec)
- The Universe contained two natural forces:
  - gravity
  - Grand Unified Theory (GUT) force
    - electromagnetic + strong (nuclear) + weak forces unified
- This lasted until the Universe was 10<sup>-38</sup> sec old.
  - at this time, the Universe had cooled to 10<sup>29</sup> K
  - the strong force “froze out” of the GUT force
- At around this epoch, the universe undergoes a sudden and dramatic **inflation** of its size.
- When inflation ends, the energy driving inflation is converted into heat -- **BANG!**

**Electroweak Era** (10<sup>-38</sup> < t < 10<sup>-10</sup> sec)
- The Universe contained three natural forces:
  - gravity, strong, & electroweak
- This lasted until the Universe was 10<sup>-10</sup> sec old.
  - at this time, the Universe had cooled to 10<sup>15</sup> K
  - the electromagnetic & weak forces separated
- Unification of weak and EM forces was predicted by Steven Weinberg and others.
- This was experimentally verified in 1983:
  - discovery of W & Z bosons
  - electroweak particles predicted to exist above 10<sup>15</sup> K

**Particle Era** (10<sup>-10</sup> < t < 10<sup>-3</sup> sec)
- The four natural forces were now distinct.
- Particles were as numerous as photons.
- When the Universe was 10<sup>-4</sup> sec old...
  - quarks combined to form protons, neutrons, & their antiparticles
- At 10<sup>-3</sup> sec old, the Universe cooled to 10<sup>12</sup> K.
  - protons, antiprotons, neutrons, & antineutrons could no longer be created from two photons (radiation) because they are too heavy.
  - the remaining particles & antiparticles annihilated each other into radiation
  - slight imbalance in number of protons & neutrons allowed matter to remain
- Electrons & positrons are still being created from photons. (They are 2000 times lighter than p and n.)
Era of Nucleosynthesis ($10^{-3}$ sec $< t < 3$ min)

- During this era, protons & neutrons started fusing…
  - but new nuclei were also torn apart by the high temperatures
- When the Universe was 3 min old, it had cooled to $10^9$ K.
  - at this point, the fusion stopped
- Afterwards, the baryonic matter leftover in the Universe was:
  - 75% Hydrogen nuclei (i.e. individual protons)
  - 25% Helium nuclei
  - trace amounts of Deuterium (H isotope) & Lithium nuclei

Era of Nuclei ($3$ min $< t < 3.8 \times 10^5$ yr)

- The Universe was a hot plasma of H & He nuclei and electrons.
  - photons bounced from electron to electron, not traveling very far
  - the Universe was opaque

- When the Universe was 380,000 yrs old…
  - it had cooled to a temperature of 3,000 K
  - electrons combined with nuclei to form stable atoms of H & He
  - the photons were free to stream across the Universe
  - the Universe became transparent
  - Called “decoupling”

Era of Atoms ($3.8 \times 10^5 < t < 10^9$ yr)

- The Universe was filled with atomic gas.
  - sometimes referred to as the “Cosmic Dark Ages”
- Density enhancements in the gas and gravitational attraction by dark matter…
  - eventually form protogalactic clouds
  - the first star formation lights up the Universe
  - which provokes the formation of galaxies

Era of Galaxies ($t > 10^9$ yr)

- The first galaxies came into existence about 1 billion years after the Big Bang.
- This is the current era of the Universe.
Announcements

- Help sessions will restart today at 5:30pm.

- Quiz#5
  - Mark the answers to multiple questions on the scantron sheet.
  - Write the answers to short answer questions in the blank below each quiz.

- Pick up Homework#5

- Next Lecture: The Big Bang (Reading: Chapter23)