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

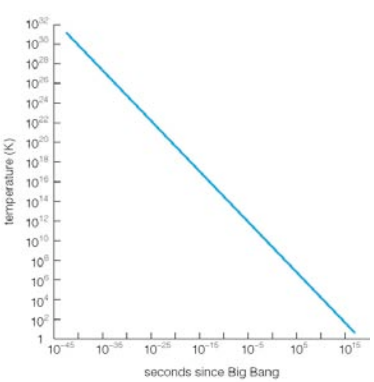
Lecture 20
Cosmic History - An Overview

Reading: Chapter 23

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



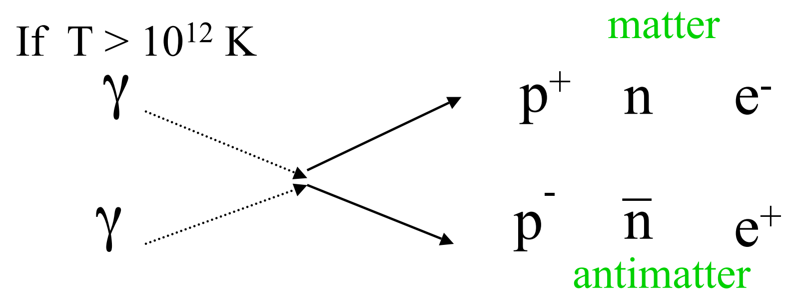
A Scientific History of the Universe

- 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!

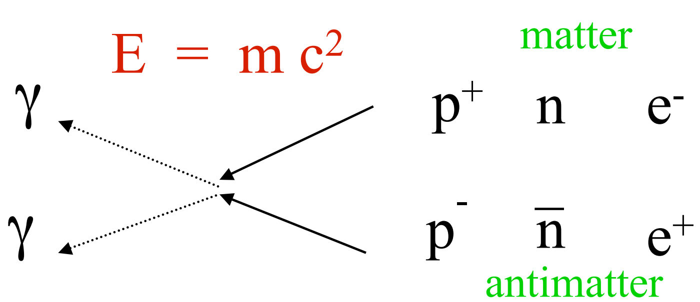
$$E = m c^2$$



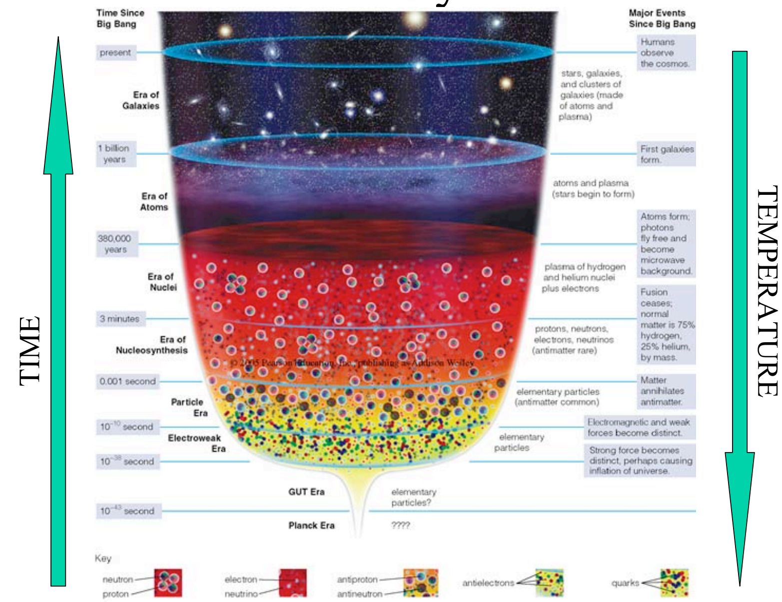
The Destruction of Matter

- 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

$$E = m c^2$$



The Scientific History of the Universe



Universe Born!

Planck Era ($t < 10^{-43}$ sec)

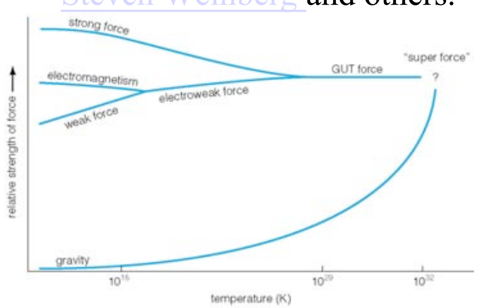
- This era, the "first instant", lasted for 10^{-43} sec.
- Because we are as yet unable to link…
  - quantum mechanics (our successful theory of the very small)
  - general relativity (our successful theory of the very large)
- **We are powerless to describe what happened in this era.**
- 10^{-43} sec 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 ($10^{-43} < t < 10^{-38}$ 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^{-38} sec old.
  - at this time, the Universe had cooled to 10^{29} 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 ($10^{-38} < t < 10^{-10}$ sec)

- The Universe contained three natural forces:
  - gravity, strong, & electroweak
- This lasted until the Universe was 10^{-10} sec old.
  - at this time, the Universe had cooled to 10^{15} 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^{15} K

Particle Era ($10^{-10} < t < 10^{-3}$ sec)

- The four natural forces were now distinct.
- Particles were as numerous as photons.
- When the Universe was 10^{-4} sec old…
  - quarks combined to form protons, neutrons, & their anti-particles
- At 10^{-3} sec old, the Universe cooled to 10^{12} 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 x 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"

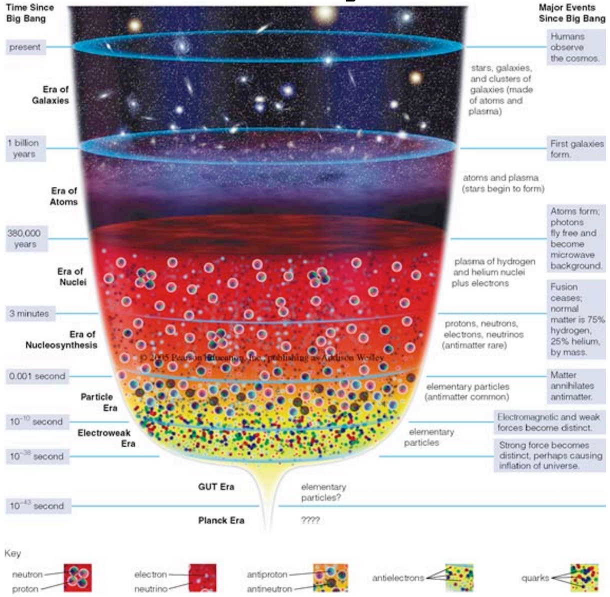
Era of Atoms (3.8 x 10^5 < t < 10^9 yr)

- 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.

The Scientific History 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)