Lecture 36: The First Three Minutes

Readings: Sections 29-1, 29-2, and 29-4 (29-3)

Key Ideas

Physics of the Early Universe
- Informed by experimental & theoretical physics
- Later stages confirmed by observations

The Cosmic Timeline:
- Unification of forces until just after the Big Bang
- Separation of forces as the Universe cools
- Inflation explains smoothness & flatness
- Emergence of matter starting at $t=10^{-6}$ sec
- Recombination & emergence of visible Universe

The Big Bang's Hot Past

<u>The Universe Today:</u>
- Low density, dark and very cold (2.7K)
- Continues to expand

<u>14 Gyr Ago:</u>
- Universe was smaller, denser and hotter
- Opaque and filled with photons

How far back can we go in cosmic history?

Binding & Loosing

<u>Binding Energy:</u>
- Energy needed to unbind (break up) matter.

<u>Binding Temperature:</u>
- *Temperature* equivalent to the binding energy
- Matter at this temperature "melts" (unbinds)

Example:
- In massive stars, nuclei melt at T~10 Billion K.

Typical Sizes & Binding Energies

	Size	Binding Energy
Atoms	10^{-10} m	10^{3} K
Nuclei	10^{-14} m	10^{10} K
p&n	10^{-15} m	10^{11} K
Quarks	10^{-18} m	10^{13} K

Equilibrium

When there is sufficient energy, matter and anti-matter particles can annihilate and produce energetic photons and *vice versa.* If equilibrium exists, then for every reaction one way, there's a reaction the other way.

$$e^- + e^+ \leftrightarrow \gamma + \gamma$$

When photons do not have enough energy (=2x the rest mass energy of the electron) to make electron-positron pairs, then we fall out of equilibrium and the reaction proceeds only one way. Leads to *freeze-out.*

Similar idea applies to electrons no longer having enough energy to combine with protons to make neutrons, etc.

Coupling and Decoupling

Matter coupled when it can switch from one form to another (such as
 protons to neutrons and back)
Photons coupled when absorbed/scattered by matter
 Electrons good at this

Particles can be coupled but not in equilibrium.

Fundamental Forces of Nature

<u>Gravitation:</u>
 Long-Range Force, weakest in Nature
<u>Electromagnetic Force:</u>
 Long-Range, 10^{39} x stronger than gravity
<u>Weak Nuclear Force:</u>
 Range < 10^{-17} meters, 10^{28} x stronger than gravity
<u>Strong Nuclear Forces:</u>
 Range < 10^{-15} meters, 10^{41} x stronger than gravity

Electromagnetism & Weak Force

At "low" energies

- Electromagnetism governs reactions between charged particles, carried by massless photons
- Weak force changes neutrons into protons, carried by massive W and Z bosons.

At "high" energies

- Electromagnetic interactions become indistinguishable from weak interactions
- W&Z Bosons lose their mass and the weak force becomes long-range as well.

Theories suggest that at high energies, the strong force has the same strength as the electromagnetic and weak as well.

Unification of the Forces

See Figure 29-4

The Cosmic Timeline

Physics gives us a framework within which to describe the Big Bang from the earliest phases to the present:

- Particle accelerators probe matter at states similar to some of these early phases
- Theoretical physics formulating descriptions of the interplay of forces and particles
- Astronomers look for evidence in the present Universe (e.g. Cosmic Background, amounts of primordial deuterium & helium)

The Planck Epoch

Before $t=10^{-43}$ sec

- All 4 forces unified into a single Superforce
- 1 force rules all of physics

Few details, as we do not yet have a quantum theory of gravity to guide us.

The Grand Unification Epoch

At $t=10^{-43}$ sec, $T=10^{32}$K (?)

Gravity separates from the Superforce

Strong & Electroweak Forces still unified

The Universe is a hot, dense soup of quark, anti-quarks & photons in equlibrium.

The Inflationary Epoch

At $t=10^{-35}$ sec, $T=10^{27}$ K:

Strong force separates from GUTs force

EM & Weak forces still unified

The rapid separation of the forces triggers a rapid "inflation" of the Universe

The Inflationary Universe

Universe grows exponentially by $\sim 10^{43}$ between 10^{-36} & 10^{-34} sec:

Expansion slows down to normal afterwards

Explains smoothness & flatness on large scales

Cosmic Background is smooth to 1 part in 10^5

Observations suggest that $\Omega_0 \sim 1$ (flat)

See Figure 29-3

Four Forces at Last!

At $t=10^{-12}$ sec, $T=10^{15}$ K:

Electroweak separates into EM & Weak forces

All forces are now separate

Conditions becoming right for free matter to exist separately from photons

Quark Freeze-out

At $t=10^{-6}$ sec, $T=10^{13}$ K:

  Free quark combine into hadrons (primarily protons & neutrons)
  Particle-antiparticle pairs & photons in equilibrium

Matter as we understand it begins to emerge.

Nucleon Freeze-out

At $t=0.01$ sec, $T=10^{11}$ K

  Protons & neutrons decouple from photons
  Electrons & positrons in equilibrium with photons
  Neutrinos & nucleons are in equilibrium

Free neutrons are stable during this epoch

Neutrino Decoupling

At $t=1$ sec, $T=10^{10}$ K

  Neutrinos decouple from matter and stream out into space
  Forms a Cosmic Neutrino Background
  (predicted but not yet observed)

Free neutrons are no longer stable

  Decay into protons, electrons & neutrinos
  Left with 1 neutron for every 5 protons

The Epoch of Nucleosynthesis

At $t=3$ minutes, $T=10^{9}$ K
Fusion of protons & remaining free neutrons

  Formation of ^{2}H (Deuterium) & ^{4}He
  End up with ~75% H, 25% He
  Traces of D, Li, Be, B

We cannot observe this epoch directly, but we can measure the products of primordial nucleosynthesis.

The Epoch of Recombination

At t=300,000 years, T=3000 K

Electrons & nuclei combine into neutral atoms
Universe becomes transparent, photons stream out into space
Origin of the *Cosmic Background Radiation*

The earliest epoch we can observe directly

Recombination to Today
See Figure 29-11

What about the very Beginning?

Our physics can not yet probe earlier than the end of the Planck Epoch ($t=10^{-43}$ seconds)

The current frontier is before the Electroweak Epoch ($t=10^{-12}$ seconds), during the period of rapid inflation. There is much active research in this area.

This will be the astrophysics of the 21st Century (or maybe the 22nd….)