Class 18
The early universe and Nucleosynthesis and the structure of matter
+ ch 12 of book

A brief look at the stages of the Universe’s life...
+ We will discuss this diagram in detail in future classes...
+ Crude overview:
  + t=0: The Big Bang
  + For first 400,000 yrs, an expanding “soup” of tightly coupled radiation and matter
    + Earliest epochs were “extreme” physics
    + Then more “normal” physics: protons & neutrons form
    + Then came nucleosynthesis
  + After 400,000 yrs, atoms form (“recombination”) and radiation and matter “decouple”
  + Following decoupling, matter and radiation evolve independently
  + Galaxies, stars, planets, etc can then form and evolve
SOME TERMINOLOGY

- Our terminology...
  - Very Early Universe: from BB to $t=10^{-35}$ s
  - Early Universe: from $t=10^{-35}$ s to $t=3$ mins
- The study of the early universe:
  - No direct observations to constrain theories...
  - .. but, the basic physics governing the universe is well understood and tested in laboratories on Earth (particle accelerators).
- The study of the very early universe:
  - Still no observations to constrain theories...
  - ... and the basic physics gets less and less certain as one considers times closer and closer to the big bang.

THE TEMPERATURE OF THE UNIVERSE

- The universe started off very hot and cooled as it expanded.
- In fact, the radiation temperature is inversely proportional to the scale factor
  \[ T \propto \frac{1}{R} \]
- The evolving temperature is crucial in determining what goes on when in the early (and very early) universe
At a given temperature, each particle or photon has the same average energy:

\[ E = \frac{3}{2} k_B T \]

\( k_B \) is called “Boltzmann’s constant” (has the value of \( k_B = 1.38 \times 10^{-23} \text{ J/K} \))

In early Universe, the average energy per particle or photon increases enormously

- In early Universe, temperature was high enough that electrons had energies too high to remain bound in atoms
- In very early Universe, energies were too high for protons and neutrons to remain bound in nuclei
- In addition, photon energies were high enough that matter-anti matter particle pairs could be created

### Particle production

- Suppose two very early Universe photons collide
- If they have sufficient combined energy, a particle/anti-particle pair can be formed.
- So, we define **Threshold Temperature**: the temperature above which particle and anti-particle pairs can be created.

\[ T_{\text{thres}} = \frac{2mc^2}{3k_B} \]

- This comes from equating \( E=mc^2 \) to \( E=3/2k_B T \)
Particle production

+ Different particles with different masses have different threshold temperatures
  + Protons mass=1.6x10^{-27} kg : $T=10^{13}K$
  + Electrons : $T\approx4\times10^9 K$
  incredibly hot

lets calculate the proton temperature

$$T=\frac{(2/3)\times1.67\times10^{-27}\times(3\times10^8)^2}{1.38\times10^{-23}}$$

\[7\times10^{12} \text{ K}\]

+ so since $T-1/R$ and $T$ today is 2.7k the universe was $3.7\times10^{-13}$ its present size when it was this hot... the early universe.

Above the threshold temperature...
+ Continual creation/destruction of particles and anti-particles (equilibrium)

Below threshold temperature...
+ Can no longer create pairs
+ The particles and anti-particles that were created when the universe was hot annihilate
+ Small residual of particles (matter) left over ???
  - Since one needs an asymmetry between baryons and antibaryons in the very early universe, to produce the substantial amounts of matter that make up the universe today. this is a an unsolved problem called baryogenesis.
**Stages of the early Universe**

- In the high-temperature very, very early universe, these forces were all unified (in the same way that electricity and magnetism are unified today).
- As universe cooled down, they started to “decouple” from each other.

![Diagram of forces and their unification](Graphics: University of Oregon Astronomy Dept)

**Theories and unification of phenomena**

How are the forces of nature connected?
The 'standard model' of quantum mechanics connects 3 of the 4 forces (all except gravity)
In the early universe they were "unified"

We are still unable to connect gravity with the other 3 - do not have a Grand Unified Theory (GUT)

From [http://universe-review.ca](http://universe-review.ca)
The unification of forces occurs at high energies- the early universe was a very high energy place (very hot → very energetic)

[http://www.particleadventure.org/grand.html](http://www.particleadventure.org/grand.html)

What Else is There Besides Atoms, Neutrons Protons and Electrons

There are a ‘slew’ of other particles (we have already encountered the muon and the neutrino was in the news)

The early universe was a ‘equal opportunity’ place and if a particle could be created it was (lots more later)

I will not go into this in any detail

The two big families of particles which make up matter (fermions)

- hadrons made of 2-3 quarks- 2 families
  - baryons+ (proton, neutron)
  - mesons

- leptons\(^*\) (electrons, muons, neutrinos...)

+ From Greek word (barys) for "heavy"
+ From Greek (leptos), "fine, small, thin"

- The other type of particle (bosons) "carry forces" (e.g. photons)
The Standard Model that explains what the world is and what holds it together. It is a simple and comprehensive theory that explains all the hundreds of particles and complex interactions with only:

- 6 quarks- which make up most of the mass.
- 6 leptons. The best-known lepton is the electron.
- Force carrier particles, like the photon

http://www.particleadventure.org/standard_model.html

Many of the particles are very unstable and only exist for very short times after being created in particle accelerators.

The heavier leptons and hadrons, are not found in ordinary matter at all. This is because when they are produced they very quickly decay.

However they existed in the very early universe.

<table>
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<th>Particle</th>
<th>Symbol</th>
<th>Makeup</th>
<th>Rest mass MeV/c²</th>
<th>Spin</th>
<th>B</th>
<th>S</th>
<th>Lifetime (seconds)</th>
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The Big Bang!  \( (t=0) \)  

### Planck epoch

- The “Planck” Epoch \( (t<10^{-43}\text{s}) \)
  - Particle Horizon is \( c t<10^{-35}\text{m} \)
  - All fundamental forces are coupled, including gravity
  - Very difficult to describe the universe at this time - something completely outside of our experience.
  - Full theory of quantum gravity needed to describe this period of the Universe’s life
  - Such a theory doesn’t yet exist

http://www.guardian.co.uk/science/2008/apr/26/universe.physics

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After inflation, \( 10^{-6} \) seconds after the Big Bang, the universe continues to expand but not nearly so quickly.

As it expands, it becomes less dense and cool. The most basic forces in nature become distinct: first gravity, then the strong force, which holds nuclei of atoms together, followed by the weak and electromagnetic forces.

By the first second, the universe is made up of fundamental particles and energy: quarks, electrons, photons, neutrinos and less familiar types. These particles smash together to form protons and neutrons.

http://www.pbs.org/deepspace/timeline/
Stages of the early Universe

- In the high-temperature very, very early universe, these forces were all unified (in the same way that electricity and magnetism are unified today).
- As universe cooled down, they started to “decouple” from each other.
End of the Planck Epoch \((t=10^{-43}\text{ s})\)
- Gravity decouples from other forces
- Classical General Relativity starts to describe gravity very well
- Gravitons cease their interactions with other particles... start free streaming through space
- Produces a background of gravitational waves (almost completely redshifted away by the present day)

Unified epoch
- The Unified Epoch \((t=10^{-43} - 10^{-35}\text{ s})\)
  - Two forces operate
    - Gravity (described by GR)
    - All other forces (described by Grand Unified Theories; GUTs): Strong, Weak, Electromagnetic
  - Baryogenesis
    - Slight asymmetry developed between particles & antiparticles
    - Get more matter than antimatter by 1 part in \(1.6 \times 10^9\)
    - Same as ratio of number of baryons to CMB photons today
    - This produces the matter dominance that we have today!
  - During unified epoch \((-10^{-37}\text{ s})\), Universe is believed to have undergone a period of exponential expansion, called inflation
    - Size of universe expanded by factor \(10^{100}\) or \(10^{1000}\)
    - We’ll discuss evidence for this later on!
  - At end of epoch, GUT force splits into Strong and Electroweak force.
Quark epoch

- The quark epoch ($10^{-35} - 10^{-6}$ s)
- Universe consists of soup of
  - Quarks
  - Gluons
  - Electroweak force particles
  - Photons
  - Leptons
  - Other more exotic particles
- Electroweak force symmetry breaks at $t=10^{-11}$s
  - Electroweak force particles were transformed into
    - Weak carriers: W, Z bosons (massive; 1st detected in 1983 in CERN)
    - Electromagnetic carriers: photons (massless)
- Quark epoch ends with “quark-hadron phase transition”
  - Quarks pull themselves together into particles called hadrons (baryons are a subclass of this).

Hadron epoch

- Hadron Epoch ($t=10^{-6} - 10^{-4}$ s)
- Particle horizon $D=10^2 - 10^4$ m
- Soup of protons, neutrons, photons, W & Z particles
- exotics
- Matter/anti-matter asymmetry from GUT era gives baryon/anti-baryon asymmetry.
- End of epoch given when temperature falls below proton threshold temperature
Lepton epoch

+ Lepton Epoch (t=10^{-4} - 15 s)
  + Universe was “soup” of photons, neutrinos, electrons, positrons, plus much smaller number of protons & neutrons leftover from hadron epoch
  + Abundant ongoing production of electron/positron and pairs by interacting photons
  + Equilibrium between protons and neutrons

\[ \nu + p \leftrightarrow e^+ + n \]
\[ \nu + n \leftrightarrow e^- + p \]

+ Number of protons same as number of neutrons until t=0.1 s
  + Afterwards, protons favored since they have lower mass
+ After t=1 s, neutrinos ceased interacting with other particles
+ Lepton epoch ended when temperature falls below electron threshold temperature, 5\times10^9K, at t=14 s
+ Proton/Neutron ratio frozen in at this point:
  + 14% neutrons
  + 86% protons
+ Most of e+ and e- annihilated, leaving just enough e- to balance charge of protons

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I: THE STRUCTURE OF MATTER

♦ Atom is made up of...

♦ Nucleus (very tiny but contains most of mass)
♦ Electrons (orbit around the nucleus)

♦ Atom held together by (electromagnetic) attraction between positively-charged nucleus and negatively-charged electrons.

Elements & isotopes

♦ Number of protons determines the element:
  ♦ Hydrogen - 1 proton
  ♦ Helium - 2 protons
  ♦ Lithium - 3 protons
  ♦ Beryllium - 4 protons
  ♦ Boron - 5 protons
  ♦ Carbon - 6 proton
  ♦ ...

♦ Number of neutrons determines the isotope
  ♦ e.g., for hydrogen (1 proton), there are three isotopes
    ♦ Normal Hydrogen (H or p) - no neutrons
    ♦ Deuterium (d) - 1 neutron
    ♦ Tritium (t) - 2 neutrons
Atomic nuclei

+ The nucleus is itself made up of:
  + Protons, \( p \) (positively charged)
  + Neutrons, \( n \) (neutral; no charge)
  + Collectively, these particles are known as baryons (made up of 3 quarks)
  + \( p \) is slightly less massive than \( n \) (0.1% difference)
  + Protons and neutrons bound together by the strong nuclear force (exchange of “gluons”)

Inside the Atom

+ enormous range in scales
Enough was known about nuclear physics after 1945 (the atomic bomb project) that an attempt to understand the origin of the elements (nucleosynthesis) in the early universe was made.

The idea is that the very early on the hot universe could make protons, neutrons, electrons as it cooled nuclei could exist.

Some light elements were manufactured during the Big-Bang: the universe was only hot enough for this to happen for ~20 minutes. The physical laws and constants that govern the behavior of matter at these energies are very well understood, and hence BBN lacks some of the speculative uncertainties that characterize earlier periods in the life of the universe. The abundances of those elements tells us about the density of the Universe. Big Bang nucleosynthesis produced no elements heavier than beryllium, due to a bottleneck: the absence of a stable nucleus with 8 or 5 nucleons.
Next lecture...

- End of radiation-dominated era

Forces

- There are four fundamental forces in the Universe
  - Each has an associated particle (a boson) that mediates the force by constant “exchanges”
  - Electromagnetic force (mediated by photons)
    - Electric & Magnetic fields are familiar in everyday life!
  - Strong nuclear force (mediated by gluons)
    - Holds the nuclei of atoms together
    - Binds quarks together into hadrons
    - Does not affect leptons
  - Weak nuclear force (mediated by W and Z particles)
    - Responsible for neutron decay
  - Gravitational force (mediated by gravitons)
    - Gravitons have never been detected... still theoretical
Fundamental interactions

From http://universe-review.ca