Lecture 17: Where does matter come from?

- The Hot Big Bang model
- The structure of matter
  - Structure of atoms; the elements
  - The Standard Model for Particle Physics
- Timeline for the Hot Big Bang

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.
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
- $p$ is slightly less massive than $n$ (0.1% difference)
- Protons and neutrons bound together by the strong nuclear force (exchange of “gluons”)

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
II : Threshold temperature

- Universe started off very hot and cooled as it expanded; in fact the temperature characterizing the radiation goes as

\[ T \propto \frac{1}{R} \]

- The evolving radiation temperature controls what goes on in the early Universe...
  - At early times, the radiation completely dominates over the matter (in terms of energy).
  - The matter and radiation are tightly coupled; so they share the same temperature
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, 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 particle pairs could be created

\[ P \text{article production} \]

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.

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

Different particles with different masses have different threshold temperatures

- Protons: \( T = 10^{13} \text{K} \)
- Electrons: \( T = 5 \times 10^9 \text{K} \)
Above the threshold temperature...
- Continual creation/destruction of particles and anti-particles (equilibrium)

Below threshold temperature...
- Can no longer create pairs
- Particles and anti-particles annihilate
- Small residual of particles (matter) left over
III: TIMELINE FOR THE BIG BANG

- The Big Bang! (t=0)

- The “Planck” Epoch (t<10^{-43}s)
  - All fundamental forces are coupled
  - Very difficult to describe the universe at this time - something completely outside of our experience.
  - Full theory of Quantum Cosmology needed to describe this period of the Universe’s life
  - Such a theory doesn’t yet exist...

- End of the Planck Epoch (t=10^{-43}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 in present day)
The Unified Epoch \((t=10^{-43} - 10^{-35}\text{s})\)
- Universe is homogeneous “soup” of elementary particles
- Two forces operate
  - Gravity (described by GR)
  - All other forces (described by so-called Grand Unified Theories; GUT)
- Baryogenesis
  - Slight asymmetry between particle & antiparticle
  - Get more matter than antimatter by 1 part in \(10^9\)
  - Same as ratio of number of baryons to CMB photons today
  - This produces the matter dominance that we have today!
- At end of epoch, GUT force splits into Strong and Electroweak force.
- Inflation!!! [More later]

The quark epoch \((10^{-35} - 10^{-6}\text{ s})\)
- Universe consists of soup of
  - Quarks
  - Gluons
  - Electroweak forces particles
  - Photons
  - Other more exotic particles
- Electroweak force splits at about \(t=10^{-11}\text{s}\)
- Quark epoch ends with “quark-hadron phase transition”
  - Quarks pull themselves together into particles called hadrons (baryons are a subclass of this).
Hadron Epoch (t=10^{-6} - 10^{-4} s)
- Universe contains a 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 (t=10^{-4} - 15 s)
- Abundant production of electron/positron pairs
- Equilibrium between protons and neutrons
  \[ \bar{\nu} + p \rightarrow e^+ + n \]
  \[ \nu + n \rightarrow e^- + p \]
- Epoch ended when temperature falls below electron threshold temperature.
- Proton/Neutron ratio frozen in at this point.