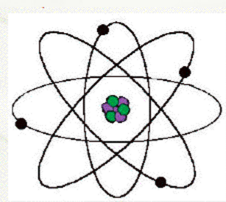
Lecture 17 : *Where does matter come from?*

- 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

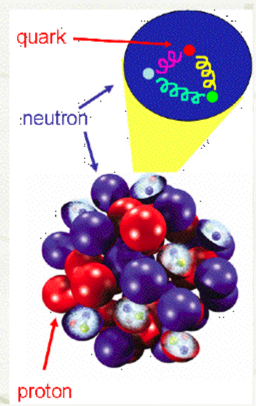
- Atom is made up of…
  - Nucleus (very tiny but contains most off mass)
  - Electrons (orbit around the nucleus)



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

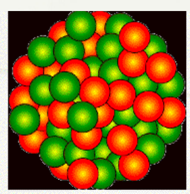
Atomic nuclei

- 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

Standard model of particle physics

- [Discussion on board]

II : Threshold temperature

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

$$T \propto \frac{1}{R}$$

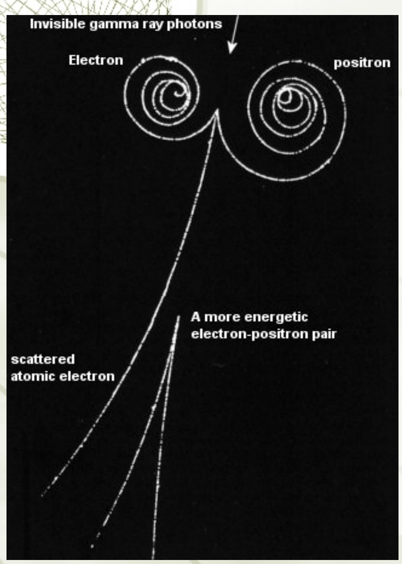
- The evolving radiation temperature controls what goes on in the early Universe...
  - At early times, the radiation completely dominates over the matter (in terms of energy).
  - The matter and radiation are tightly coupled; so they share the same temperature

- 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 $k_B = 1.38\times10^{-23}$ 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

Particle production

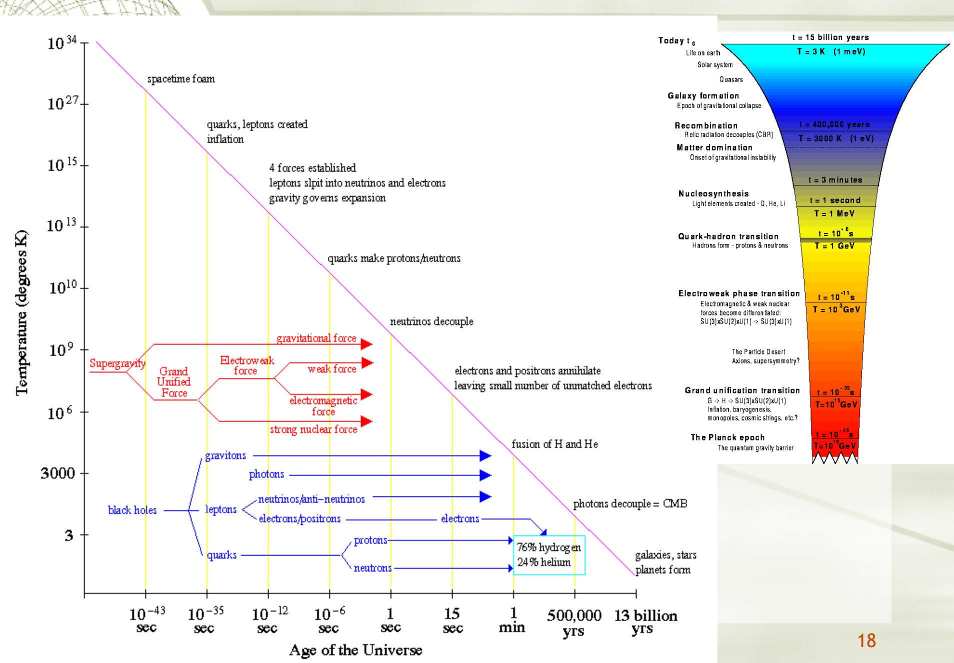


- Suppose two very early Universe photons collide
- If they have sufficient combined energy, a particle/anti-particle pair can be formed.
- So, we define ***Threshold Temperature***: the temperature above which particle and anti-particle pairs can be created.

$$T_{thres} = \frac{2mc^2}{3k_B}$$

- Different particles with different masses have different threshold temperatures
  - Protons : $T \approx 10^{13}$K
  - Electrons : $T \approx 5\times10^{9}$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}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} s)
- Universe consists of soup of
  - Quarks
  - Gluons
  - Electroweak forces particles
  - Photons
  - Other more exotic particles
- Electroweak force splits at about $t=10^{-11}$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.