Class 18 : The hadron and lepton eras

- This class
  - Study a particularly important period of the Universe… $t=10^{-5}$–10s after big bang
  - Formation of the neutrino background
  - Ratio of p to n (important for H/He ratio!!)

I : Adiabatic behavior of matter in an expanding Universe

- Recall two important facts about matter…
  - For non-relativistic matter ($E_{kin}<<mc^2$), we have

    $$T_{\rm mat} \propto a^{-2}$$ *(proven last class)*

  - For relativistic matter ($E_{kin}>>mc^2$), we have

    $$T \propto 1/a$$ *(proof on board)*

  - i.e., relativistic matter behaves very much like radiation (or, viewed another way, photons are the ultimate in relativistic matter!)

II : Physics in the hadron era

- At $t \sim 10^{-6}$s ($T > 10^{13}$K; just after Q-H phase transition)
  - Universe consists of soup of elementary particles, most noteworthy are:
    - Photons ← BOSONS
    - Protons + anti-protons
    - Neutrons + anti-neutrons
    - Electrons + positrons
    - Neutrinos (all flavors)

    (Protons through neutrinos: FERMIONS)
  - All of these species are relativistic.
  - All of these species are in thermal equilibrium
    - Energy density in a given (relativistic) fermionic species = (7/8) x energy density in a given (relativistic) bosonic species (Not obvious!)
    - Need to include spin-states in this assessment

- This can't go on forever…
  - Define **threshold temperature of a species** as the point where the average particle energy equals the rest-mass energy of the species

$$\frac{3}{2}kT_{thres} = mc^2 \quad \Rightarrow T_{thres} = \frac{2mc^2}{3k}$$

  - For protons, $T_{thres} = 7 \times 10^{12}$K
    - Once T falls below this temperature ($t \sim 10^{-5}$s), p/n and anti-p/n cease to be relativistic, and it becomes difficult to make them (need higher energy than average photons to interact)
    - At $t \sim 10^{-4}$s, we have $T \sim 10^{12}$K and there's no more p/n or anti-p/n productions.
    - Vast majority of protons/anti-protons and neutrons/anti-neutrons annihilate… but there is a slight excess of matter over anti-matter and so 1 in every 10^9 survive!

III : Physics in the lepton era

- Zoom forward to $t \sim 10^{-2}$s ($T \sim 10^{11}$K)
  - Universe consists of soup of….
    - Photons
    - Electrons and positrons
    - Neutrinos (all species)
    - Small number of p and n
  - Other important physical considerations…
    - p and n are non-relativistic; all other species relativistic
    - **Energy density completely dominated by relativistic species**
    - **All of these ingredients are in thermal equilibrium**
    - Again… energy density in a given fermionic species = (7/8) x energy density in a given bosonic species (i.e. photons)
  - At $t \sim 10^{-2}$s ($T \sim 10^{11}$K), average photon energy much greater than mass-energy difference between p and n… equal numbers of p and n

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- As Universe cools and becomes less dense, the typical time between interactions increases…
- At $t \sim 10^{-1}$s ($T \sim 3 \times 10^{10}$K), the typical time between neutrino interactions exceeds expansion timescale… **neutrinos decouple** and **free stream**
  - So we now have a **decoupled neutrino background**
  - Neutrinos continue to cool as the Universe expands, preserving their thermal spectrum ($T \sim 1/a$)
  - Since radiation is also cooling in same way, neutrinos and radiation maintain same temperature even though they are no longer interacting
  - ALSO, the average photon energy now becoming comparable to the p-n mass difference… **reactions start to prefer protons** over neutrons (putting $T=3\times10^{10}$K gives $n_n:n_p=0.38:0.62$).

- At t~1s ($T \sim 10^{10}$K), time between weak-force reactions involving p and n exceeds expansion time… protons and neutrons fall out of thermal equilibrium
  - Known as **proton-neutron freeze-out**
  - At this time, $n_n:n_p \approx 1:5$… we will see that this had a profound effect on the H:He ratio in the Universe!!
  - Photons, electrons, positrons still in thermal equilibrium

$$\gamma + \gamma \rightleftharpoons e^- + e^+$$

  - Electrons and positrons still relativistic (just)
  - But the Universe is still cooling…

- Finally, t~10s ($T \sim 3 \times 10^9$K) : Temperature falls below threshold temperature for the electrons.
  - All positrons annihilate with an electron to form photons
  - Thus, huge amount of energy dumped into photon field… temperature of the radiation *increases*!
  - In fact, the annihilation occurs at constant entropy which, for relativistic species, is $S=gT^3$
  - These considerations allow us to calculate that the temperature of the radiation increases by a factor $(11/4)^{1/3}$ (see board)
- The neutrino background
  - Up to this point, neutrino & radiation background are in lock-step
  - Suddenly, radiation temperature increases by factor $(11/4)^{1/3}$
  - From that point on (until today!), the radiation background evolves passively (no wholesale destruction or creation of photons)
  - Can use this fact to calculate the neutrino background today. Answer is

$$\rho_\nu = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$