

## Class 18 : The hadron and lepton eras

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- 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

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- Recall two important facts about matter...
  - For non-relativistic matter ( $E_{\text{kin}} \ll mc^2$ ), we have
$$T_{\text{mat}} \propto a^{-2} \quad (\textit{proven last class})$$
  - For relativistic matter ( $E_{\text{kin}} \gg mc^2$ ), we have
$$T \propto 1/a \quad (\textit{proof on board})$$
  - 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  $t \sim 10^{-6} \text{s}$  ( $T > 10^{13} \text{K}$ ; just after Q-H phase transition)
  - Universe consists of soup of elementary particles, most noteworthy are:
    - Photons
    - Protons + anti-protons
    - Neutrons + anti-neutrons
    - Electrons + positrons
    - Neutrinos (all flavors)

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BOSONS

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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

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

- For protons,  $T_{\text{thres}} = 7 \times 10^{12} \text{K}$ 
  - Once  $T$  falls below this temperature ( $t \sim 10^{-5} \text{s}$ ),  $p/n$  and anti- $p/n$  cease to be relativistic, and it becomes difficult to make them (need higher energy than average photons to interact)
  - At  $t \sim 10^{-4} \text{s}$ , we have  $T \sim 10^{12} \text{K}$  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

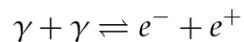
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- Zoom forward to  $t \sim 10^{-2} \text{s}$  ( $T \sim 10^{11} \text{K}$ )
  - Universe consists of soup of...
    - Photons
    - Electrons and positrons
    - Neutrinos (all species)
    - Small number of p and n
  - Other important physical considerations...
    - 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 =  $(7/8) \times$  energy density in a given bosonic species (i.e. photons)
  - At  $t \sim 10^{-2} \text{s}$  ( $T \sim 10^{11} \text{K}$ ), 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  $t \sim 10^{-1} \text{s}$  ( $T \sim 3 \times 10^{10} \text{K}$ ), 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  $T = 3 \times 10^{10} \text{K}$  gives  $n_n : n_p = 0.38 : 0.62$ ).

- At  $t \sim 1\text{s}$  ( $T \sim 10^{10}\text{K}$ ), 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



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

- Finally,  $t \sim 10\text{s}$  ( $T \sim 3 \times 10^9\text{K}$ ) : 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

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