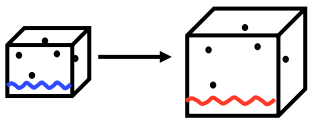
Q1: What changes to the particle content of the expanding Universe occur at the epochs of:

- Annihilation:
  - pair soup -> quark soup (10^9 photons/quark)
- Baryogenesis:
  - quarks bound (by strong force) into baryons.
  - UUD = proton DDU = neutron
- Nucleosynthesis:
  - Atomic nuclei: 75% H, 25% He, traces of Li, Be
- Recombination:
  - Neutral atoms form as free electrons recombine
  - photons fly free

Q2: Given present-day density parameters $\Omega_M = 0.3$ for matter and $\Omega_R = 5\text{x}10^{-5}$ for radiation, at what redshift z were the energy densities equal ?

volume R^3 N particles of mass m

photon wavelengths stretch:



$$\lambda \propto R \propto \frac{1}{1+z}$$

$$\varepsilon_M = \rho_M c^2 = \Omega_M \left(\rho_{crit} c^2\right)(1+z)^3 \qquad \rho_M = \frac{N_b m}{R^3} \propto (1+z)^3$$

$$\varepsilon_R = \Omega_R \left(\rho_{crit} c^2\right)(1+z)^4 \qquad \varepsilon_R = \frac{N_\gamma h\nu}{R^3} \propto R^{-4} \propto (1+z)^4$$

$$1 = \frac{\varepsilon_M}{\varepsilon_R} = \frac{\Omega_M}{\Omega_R}\frac{1}{1+z} \quad \Rightarrow \quad 1+z = \frac{\Omega_M}{\Omega_R} = \frac{0.3}{5\times10^{-5}} = 6000$$

Q3 a) Evaluate the neutron/proton ratio in thermodynamic equilibrium at high and low T.

$$m_n = m_p + \Delta m = 1.0014\, m_p \qquad \frac{N_n}{N_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left(-\frac{\Delta m c^2}{kT}\right)$$

$$T \to \infty \quad \frac{N_n}{N_p} \to \left(\frac{m_n}{m_p}\right)^{3/2} \exp(0) = (1.0014)^{3/2} \approx 1$$

$$T \to 0 \quad \frac{N_n}{N_p} \to \left(\frac{m_n}{m_p}\right)^{3/2} \exp(-\infty) = 0$$

b) Evaluate the n/p ratio and Y_p if $m_n = m_p$.

$$m_n = m_p \quad \Rightarrow \quad \Delta m = 0 \quad \frac{m_n}{m_p} = 1 \qquad \frac{N_n}{N_p} \to (1)^{3/2} \exp(0) = 1$$

$$N_n = N_p \quad \Rightarrow \quad 100\%\ \text{He} \quad Y_p = 1$$

Q4 Alien's CMB-meter reads 5.1K and 4.9K in the fore and aft directions. Evaluate the velocity.

$$\frac{V}{c} = \frac{\Delta T}{T} = \frac{0.1K}{5K} \quad \Rightarrow V = \frac{c}{50} = 6000\ \text{km/s}$$

Are humans present on Earth at this time?

$T = 5K \quad T_0 = 2.7K \quad \lambda \propto R \quad \Rightarrow \quad T \propto \frac{1}{R}$

mater dominated expansion: $R \propto t^{2/3}$

time : $\frac{t}{t_0} = \left(\frac{R}{R_0}\right)^{3/2} = \left(\frac{T_0}{T}\right)^{3/2} = \left(\frac{2.7K}{5K}\right)^{3/2} = 0.40$

now: $t_0 \sim \frac{1}{H_0} \sim 13 \times 10^9\,\text{yr}$ Age of Sun: $\sim 5 \times 10^9\, yr$

look-back time: $t_0 - t = 0.6\, t_0 \sim 8 \times 10^9\,\text{yr}$ (Before Sun was born!)