SAIFR - ICTP Summer School 2018 Early Universe Laura Covi

Exercise Sheet 3: Thermal Universe & Big Bang Nucleosynthesis

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Exercise 1

The neutrinos contribute substantially to the energy density of relativistic species and change the expansion rate during BBN. Let us compute their effect.

a) Compute the relative contribution of one massless neutrino to g_* after the annihilation of $e^\pm$ into photons.
Note: the $e^\pm$ annihilation transfers the lepton entropy into the photons, consider therefore the new temperature of the photons after the neutrinos already decoupled due to $e^\pm$ annihilation !

b) How many additional neutrinos are allowed during BBN, if the neutron density at decoupling is given by

$$X_{n,*} = \frac{n_n}{n_n + n_p}(T_*) = 0.158 + 0.0028\Delta g_*$$

and the measurement of the present Helium density gives

$$Y_p = \frac{2X_n}{1 + X_n} = 0.249 \pm 0.009(1\sigma) \ .$$

Assume first that the neutrons are stable, and discuss then the effect of neutron decay.

c) Neutrinos are not massless. Assume that their masses are $0.05, 0.009$ and 0 eV and compute at which values of z they become non-relativistic (if any) and their contribution to the present energy density of the Universe.

Exercise 2

You can also explore the effect of changing other parameters, e.g. the baryon density of the Universe or the chemical potential of the neutrinos by exploiting the numerical code PArthENoPE.