RELATIVITY AND COSMOLOGY II

Problem Set 9 15th April 2025

1. Freeze-out of $p^+e^- \to n\nu_e$

Let's consider the Universe at the moment of decoupling of the reaction $p^+e^- \to n\nu_e$.

1. First, assume that the lepton asymmetry is of the same order as the baryon asymmetry, i.e.,
$$\frac{n_\nu - n_{\bar{\nu}}}{T^3} \sim \eta \sim 10^{-9}. \tag{1}$$
Show that this implies $\mu_n \approx \mu_p$.

2. Suppose now that there was a sizable asymmetry, $(n_\nu - n_{\bar{\nu}})/T^3 \lesssim 1$. Given that an uncertainty in determination of the ^{4}He abundance during nucleosynthesis does not exceed 5%, find a constraint on μ_{ν_e}.

2. Variation of ^{4}He abundance

Our goal is to determine how the abundance of ^{4}He depends on various parameters.

1. Find the change in the abundance of ^{4}He if we alter the number of relativistic degrees of freedom at nucleosynthesis. Can we say something about the presence of additional neutrinos?

2. Estimate the change in the abundance of ^{4}He that would be caused by increasing $m_n - m_p$ by 10 %.

3. Similarly, determine the effect of decreasing the neutron lifetime τ_n by 10%.

3.* Post-freezing antiprotons density

Assuming that at temperatures $T \gg m_p$ the Universe had an excess of protons of the order of
$$\frac{n_p - n_{\bar{p}}}{n_p + n_{\bar{p}}} = 10^{-10} \ ,$$
find the relic abundance of antiprotons now ($T \ll m_p$). The annihilation cross section is given by
$$\langle \sigma_{ann} v \rangle \approx 25\,\mathrm{GeV}^{-2}.$$
Hint: Consider that baryon number is conserved when $T \ll 100\,GeV$.
$$\frac{n_B}{n_\gamma} = 6 \times 10^{-10} \tag{2}$$