Physics 371: Problem Set 3

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Due Thursday 6 May, 1:30 p.m.

1. Consider the dependence of the weak intereactions freeze-out temperature on the number of relativistic species at temperatures of about 1 MeV. The central value of the fraction of baryon number density in ^{4}He, in the Standard Model, with three light neutrinos, is $Y_P = 0.235$ ($Y_P = 4n_{He}/n_B$). Assuming an experimental bound on $Y_P < 0.25$, find the upper bound on the number of light neutrino species coming from Big-Bang Nucleosynthesis.

2. Consider a massive particle X (equal in number to $\bar{X}$), which has a non-relativistic annihilation cross-section
$$\sigma_A = \left(\frac{m_N}{m_X}\right)^2 \sigma_{N\bar{N}} \ ,$$
where $\sigma_{N\bar{N}} = (90 \text{ GeV}^{-2})/v$ is a typical nucleon annihilation cross-section. For what mass m_X will $\Omega_{X0} = 1$?

3. Assume that there are three right-handed neutrino, that due to the existence of new interactions is in equilibrium at high temperatures and decouple while being relativistic at a temperature T_D, larger than 1 MeV, when the number of degrees of freedom was larger than 10.75. Assume that the Nucleosynthesis bound on the number of "extra neutrinos" is equal to 1. Taking into account that the temperature of the decoupled right-handed neutrinos is determined by entropy consideration, and counting only the Standard Model degrees of freedom (plus the extra neutrino ones),

   a) Derive an upper bound on the decoupling temperature T_D.

   b) If the three left-handed and right-handed neutrino masses is about 0.25 eV, what is their relic density contribution today $\Omega_{\nu,0}$?