PHYS 4170, Homework 6

Due date: April 16

1. **Ryden Problem 9.3** Begins "Imagine that at the time of recombination....".

2. **Neutrino Decoupling**: In the early Universe, electrons and neutrinos are strongly coupled through scattering ($\nu\ e \leftrightarrow \nu\ e$) and annihilation ($\nu\ \bar{\nu} \leftrightarrow e\ \bar{e}$). The interaction cross section is given by $\sigma \simeq G_F^2 E^2$ where $G_F = 1.16 \times 10^{-5}\ (\hbar c)^3 \mathrm{GeV}^{-2}$ and E is the average energy of the neutrinos. In thermal equilibrium, $E \sim k_B T$.

   (a) Find the redshift and temperature of neutrino decoupling. Assume that the current temperature of the neutrino background is $T_0 = 2K$, $n_{e,0} = .22\mathrm{m}^{-3}$, $\Omega_{r,0} = 10^{-5}$, and $H_0 = 68\mathrm{km/s/Mpc}$.

   (b) After neutrino decoupling, the Universe is filled with a cosmic neutrino background. Assuming that all 3 species of neutrinos have a mass of $m_\nu = 1$ eV, and that neutrinos follow a Maxwell Boltzmann distribution since they are currently non-relativistic, how many relic neutrinos are in a cubic meter?

3. **Ryden Problem 11.3** Begins "It has been speculated that the..."