Name: DUE ON 23.05.2016

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Homework - 7

Cosmological observations can constraint particle physics:

1. In class we have seen that the universe is filled with the cosmic neutrino background.

    (a) At the time of decoupling at T_{dec} the number density is given by equation (11) in the lecture 6 notes. Afterwards the temperature and the number density decay like a^{-3} so that the same formula for the number density applies today, if you replace T_{dec} with $T_{\nu,0}$. What is the number of neutrinos for *one* of the three species per *centimeter*^{3} today?

    (b) The neutrinos are massive and non-relativistic today. Let us focus on the heaviest neutrino only and assume its mass is given by $m_{\nu,h}$, with $h = heavy$. What is its contribution to the normalized energy density $\Omega_{\nu,h,0}$ today?

    (c) What is the upper bound on $m_{\nu,h}$ in a flat $(K = 0)$ universe that contains these neutrinos?

    (d) Current cosmological observations put a strong bound on the sum of the three neutrino masses: $\sum_{i=1}^{3} m_{\nu,i} < .23eV$. What does this mean for the contribution of the cosmic neutrino background to the normalized energy density, i.e. what is the corresponding bound on $\Omega_{\nu,0}$?

    (e) There is also a lower bound on the neutrino masses from neutrino oscillation experiments: $\sum_{i=1}^{3} m_{\nu,i} > .05eV$. In the last homework you calculated $\Omega_{CMB,0} \approx 5 \times 10^{-5}$. Calculate the lower bound on $\Omega_{\nu,0}/\Omega_{CMB,0}$.

2. Assume that there is a fourth neutrino that behaves exactly like the other three. Calculate $g_\star$ and $g_{\star S}$ after the neutrino and electron decoupling. The latest cosmological observations constraint $g_\star$ to be $g_\star = 3.43 \pm .11$. Is a fourth neutrino experimentally excluded?