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DUE ON 04.05.2015

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## Homework - 6

1. (a) In homework 2, problem 1, you have shown that the current (critical) density of our universe corresponds to 6 Hydrogen atoms per  $1m^3$ , which is essentially the same as six protons (baryons) per  $1m^3$ . However, only 5% of the energy density of our current universe is in the form of baryons. From the ratio

$$\frac{n_b}{n_\gamma} = .73 \times 10^{-9}, \quad (1)$$

determine the number of photons per  $1cm^3$  in our current universe. Note that the answer should be in *centimeter*<sup>3</sup>.

- (b) From the formula for the number density for photons, as given in equation (11) in the lecture 6 notes, determine the number of CMB photons per *centimeter*<sup>3</sup> today.
- (c) Using equation (14) in the lecture notes 6, calculate the contribution of these huge number of photons to the normalized energy density today  $\Omega_{CMB,0}$ .
2. (a) Calculate explicitly the contribution of the standard model particles to the number of relativistic degrees of freedoms  $g_\star(T \gtrsim 150MeV) = 61.75$  right before the QCD phase transition.
- (b) After the QCD phase transition the only relativistic particles are the electron  $e$ , the  $\mu$ , the three neutrinos, the photon  $\gamma$  and three pions  $\pi^0, \pi^+, \pi^-$ . This leads to  $g_\star(T \lesssim 150MeV) = 17.25$ . All three pions contribute the same number of relativistic degrees of freedom. What is  $g$  for one of the pions?
3. As we will discuss next time, the neutrinos and photons decouple in the early universe so that today the neutrinos have a temperature that is different from the temperature of the photons, i.e. the cosmic microwave background. All three neutrinos have however the same temperature. From equation (24)-(26) in the lecture notes 6 and  $g_\star(T_{CMB,0}) = 3.36$ , calculate the temperature of the neutrinos today (recall that  $T_{CMB,0} = 2.725K$  and only photons and the three neutrinos contribute).