بسم الله الرحمن الرحیم

Cosmology, 2nd Homework Assignment, Spring 1401

1. Would matter be decoupled from radiation if recombination had never occurred, and would CMB ever exist? If yes, at what redshift?

2. Find a relation for the entropy density using the first law of thermodynamics, in an FLRW universe, and when the chemical potential is nonzero.

3. Try to explain quantitatively how a) the difference in mass between proton and neutron, and b) the half-life of neutrons, can affect BBN.

4. Derive the equations 3.32 and 3.33 in Baumann's book.

5. After the neutrino's decoupling at the temperature of about $T \approx 10^{10} K$, the temperature of both photons and neutrinos continue decreasing similarly as $T \propto 1/a$. However, when the temperature becomes less than the electron's mass ($T < m_e$), electron and positron annihilate and this leads to an exclusive jump in the temperature of photons. The temperature of these relic neutrinos is now $T \approx 1.96 K$.
   (a) Derive the approximate redshift at which neutrinos decouple.
   (b) Find the effective number of degrees of freedom before and after $e^- e^+$ annihilation and then evaluate the increase in the temperature of photons.
   (c) Estimate the current temperature of the relic photons.

Good Luck
H. Shojaie