Cosmology

**Problem C6.1** Estimate the redshift corresponding to matter-radiation equality ( $\rho_m = \rho_{rad}$ ) for  $\Omega_{m0} = 0.27$ , assuming that photons are the only form of radiation. What is the corresponding temperature of the photons in eV? Today, we have that  $\Omega_{rad}h^2 = 4.18 \times 10^{-5}$ , is the radiation content today only made of photons?

**Problem C6.2** Give the age of the universe as a function of temperature during radiation domination. Primordial nucleosynthesis started at  $T \sim 1$  MeV and ended around  $T \sim 10$  keV, how old was the universe during that time? Using your estimation of the temperature of the photon at matter-radiation equality from above, how old was the universe then?

**Problem H6.1** In the lecture the particle number densities were computed neglecting chemical potentials and masses assuming. Now expand the phase space densities for first order in  $\mu_i$  and compute Show that for  $T \gg m_i, \mu_i$  the difference of the number densities of particles and their antiparticles is

$$\Delta n_i = \frac{\mu T^2}{3} \text{ for bosons}$$
$$\Delta n_i = \frac{\mu T^2}{6} \text{ for fermions}$$
$$\int_0^\infty dz \frac{z}{e^z \pm 1} = \begin{cases} \frac{\pi^2}{6} \\ \frac{\pi^2}{12} \end{cases}$$

Hint:

**Problem H6.2** Compute the entropy of a thermal bath of non-relativistic particles.