

ASTR 425/525 Cosmology

Worksheet #12
Monday 10/6/2025

Question 1.

- (a) We saw that the number density of non-relativistic particles with zero chemical potential in *thermal equilibrium* is

$$n_{\text{NR}} = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}. \quad (1)$$

For $T \ll m$, this tells us that the abundance of such particle is exponentially suppressed. What is the actual physical process that is responsible for exponentially suppressing the abundance?

- (b) Assuming that the process you found in part (a) is efficient, abundances will indeed get exponentially suppressed. However, the presence of a chemical potential can change that. Show that the difference in abundances between a particle (number density n) and its antiparticle (number density $\bar{n}$) is

$$n - \bar{n} = 2g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T} \sinh \left(\frac{\mu}{T} \right), \quad (2)$$

where μ can be a function of temperature.

- (c) Near the epoch of recombination ($T \sim 1$ eV) just before neutral atoms formed, the Universe was full of non-relativistic electrons ($m_e \sim 0.5$ MeV), apparently contradicting Eq. (1) above. How is this possible? Which eventual value of the chemical potential do you need to make this possible?

