

Name:

DUE ON 13.05.2019

Matrikelnummer:

## 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*<sup>3</sup> 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?