Weekly Report

Summary

- **Period:** Dec 3 to Dec 7, 2020
- **Task Finished:** Reading two papers (1312.5725 and 1908.00007) carefully, learn the formulism in this paper and try to understand how light WIMP particle with mass in $0.1 - 10^2\ \mathrm{MeV}$ affects the BBN progress.
- **Questions Meet:** What is the physics details during BBN: what does "WIMP couples with photon and $e^{\pm}$" means, what is the freeze-out and what is the decouple (especially "neutrino decouple"). What is the four type of light WIMP? Is the temperature T for different component is the Also, not clearly know what should do next.
- **Plans for next 7 days:**
  - Reading *Modern Cosmology* and other textbooks or review paper *Big Bang Nucleosynthesis: Present status*, understand the basic physics of BBN
  - Reading 3 theoretical papers discussing 3 ways WIMP affects the BBN
  - Summarize reading result and do a presentation on Thursday's group meeting (need to finish two steps above)
  - Try to learn Kawano BBN code and do the Figure 1 in 1312.5725

Progress in details

In this part, I will write a bit more about the progress for the past 5 days (Dec 3 to Dec 7). I have done literature reading these days so I will write a short reading report below.

Reading Report

This week I read two papers concerning the study of light WIMP particles with BBN. In this paper they consider the case with (1) photon, (2) $e^{\pm}$, (3) standard model neutrino, (4) equivalent neutrino and (5) light WIMP. The basic physics I learn from the paper 1312.5725 is listed below

- There are four kinds of light WIMP we are interested in: (1) real scalar, (2) complex scalar, (3) Majorana fermion, (4) Dirac WIMP
- WIMP particles can annihilate into $\gamma, e^{\pm}$ and SM ν. They can also couple with these three particles
- The exist of equivalent neutrino and light WIMP particle can affect the N_{eff}. We have from the textbook that

$$\rho_\nu = 3 \times \frac{7}{8} \times \left(\frac{T_\nu}{T_\gamma}\right)^4 \rho_\gamma \tag{1}$$

where $(T_\nu/T_\gamma)^3 = 4/11$ in standard BBN. If we define $\rho_R = \rho_\gamma + \rho_\nu + \rho_\xi$ where ξ denotes equivalent neutrino (e.g., sterile neutrino), we have

$$\left(\frac{\rho_R}{\rho_\gamma}\right)_0 = 1 + \frac{7}{8}\left[3\left(\frac{T_\nu}{T_\gamma}\right)_0^4 + N_\xi\left(\frac{T_\xi}{T_\gamma}\right)_0^4\right] = 1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}} \tag{2}$$

so we have

$$N_{\text{eff}} = \left[\frac{11}{4}\left(\frac{T_\nu}{T_\gamma}\right)_0^3\right]^{4/3}\left[3 + N_\xi\left(\frac{T_\xi}{T_\nu}\right)^4\right] = 3\left[\frac{11}{4}\left(\frac{T_\nu}{T_\gamma}\right)_0^3\right]^{4/3}\left[1 + \frac{\Delta N_\nu^*}{3}\right] = N_{\text{eff},0}\left[1 + \frac{\Delta N_\nu^*}{3}\right] \tag{3}$$

where $\Delta N_\nu^* = N_\xi (T_\xi/T_\nu)^4$.

- N_{eff} depends on (1) WIMP properties, (2) coupling and (3) mass of particle
- The combination of different couple scenario (couple with $\gamma/e^\pm$ or SM ν) and the presence of ξ will bring different effect on $N_{\text{eff},0}$. CMB can measure $N_{\text{eff},0}$ directly, but it can hard to solve the degenercy of different scenarios as well as constrain the mass of particle (Figure 1 in 1312.5725).
- There are three ways light WIMP affect the BBN:
    - WIMP contributes to ρ_{tot} and modify the expansion rate, and it tends to cause late freeze-out
    - Colder neutrinos suppress the rate of $n \rightleftharpoons p$, and it suppress $p \to n$ more, which will cause early freeze-out
    - When $m_\chi \le m_e$, the baryon-to-photon ratio η changes also when WIMP annihilates. η will be improved more significantly when WIMP annihilates after $e^\pm$ annihilation
- We need to add the density

$$\rho_\chi = \frac{g_\chi}{\pi^2}\int_{m_\chi}^{\infty} \frac{(E^2 - m_\chi^2)^{1/2}}{\exp(E/T) \pm 1} E^2 \mathrm{d}E \tag{4}$$

and the change of η by entropy of light WIMP particle

$$\eta = \eta_0 \left(1 + \frac{S_e + S_\chi}{S_\gamma}\right) \tag{5}$$

to Kawano code.