Weekly Report

Summary

- **Period:** Jan 1 to Jan 10, 2021.
- **Task Finished:** Reading textbooks and documents to learn the basic physics of BBN. Details are shown below.
- **Questions still need to clarify:**
    - How does WIMP change the standard BBN process, provide a different Y_p and change the CMB power spectrum signal.
- **Plans for next weeks**:
    - Read arXiv: 1312.5725. Clear the standard BBN physics, and the impact on Y_p and CMB after adding WIMP.
    - Finish the first attempt of CMB and BBN joint analysis (similar with 1312.5725).
    - Summarize current results (theory, coding and other) to a short note as a very initial draft for the paper in the future.

Progress in Details

In this part, I will summarize what I've learned in past 10 days about the physics of cosmic thermal history and others.

The thermal history

- At $0.001\,\mathrm{s}$ after Big Bang, $T = 10^{11}\,\mathrm{K}$, we have the constituents of the universe as (1) γ with 2 spin states, (2) three species of ν with one spin state for each, (3) three species of $\bar{\nu}$ with one spin state for each, (4) electrons with 2 spin states, (5)positrons with 2 spin states. All are in **thermal equilibrium** and can be treated as **highly relativistic ideal gas**.
- At $10^{10}\,\mathrm{K}$ and lower, neutrino just go out the equilibrium and begin a free expansion. γ, e^- and e^+ are in equilibrium. Neutrinos are still in Fermi-Dirac statistic, so $T_\nu \propto 1/a$. We need to have distinct T_ν and T_γ to describe two parts. We would have T_γ/T_ν and $T_\gamma/T_\nu \to (11/4)^{1/3}$ when $T_\gamma \to 0$.
- After electron-positron annihilation, e^- and e^+ become γ. γ, ν and $\bar{\nu}$ are still relativistic. For the universe which is dominant by highly relativistic ideal gas, we have

$$s(T) = \frac{2\mathcal{N} a_{\mathcal{B}} T^3}{3}, \rho(T) = \frac{\mathcal{N} a_{\mathcal{B}} T^4}{2}$$

  where $\mathcal{N}$ is the number of particle type. **For fermions**, an extra $7/8$ factor should be added to the energy density.
- When lower than $10^6\,\mathrm{K}$ need to consider non-relativistic matter.
- Note that WIMP particle (if exists) also decoupled.

Boltzmann equation of WIMP

The Boltzmann equation for WIMP can be written by

$$\frac{\mathrm{d}(n_\chi a^3)}{\mathrm{d}t} = -\left(n^2 - n_{\mathrm{eq}}^2\right) a^3 \langle \sigma v \rangle$$

where $\langle \sigma v \rangle$ is the thermal average, σ is annihilation cross-section, n_χ is density of χ in thermal equilibrium. **WIMP will change the density then the expansion rate (more details required)**.

Reference

- S. Weinberg, *Cosmology*, 149-159 (2008).
- S. Dodelson, *Modern Cosmology*, 62-63 (2003).
- A. Arbey, J. Auffinger, K. P. Hickerson, E. S. Jenssen, *AlterBBN v2: A public code for calculating Big-Bang nucleosynthesis constraints in alternative cosmologies*, arXiv:1806.11095.