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Cosmology

Pre-class reading 5

Project Proposal:
The proposed project focuses on modeling the primordial nucleosynthesis of helium-4 (4He) by solving the differential equations governing neutron-proton interconversion, incorporating neutron decay, and exploring the dependence of 4He abundance on the baryon-to-photon ratio (η) and cosmological parameters. This project is motivated by the pivotal role that Big Bang Nucleosynthesis (BBN) plays in cosmology, as it provides a critical test of the standard cosmological model and constraints on fundamental parameters such as η (baryon to photon ratio). Additionally, investigating how 4He abundance would differ in hypothetical universes with alternative expansion rates (characterized by different Hubble parameter evolutions H(t)) offers insights into the sensitivity of BBN to cosmological conditions.

Methods:
The method involves numerically solving the coupled differential equations for neutron-proton conversion rates from the MBW book on Python, which depend on weak interaction processes (e.g., beta decay and inverse beta decay). The freeze-out of these reactions occurs when the weak interaction rate falls below the Hubble expansion rate H(t), leaving a frozen neutron-to-proton ratio. Free neutron decay will be included to account for the lifetime of neutrons before they are captured during helium-4 synthesis. Using this ratio at the epoch of 4He formation, the mass fraction Y of helium-4 can be calculated as a function of η. The project will then extend this analysis to hypothetical universes with modified H(t), such as those with different matter or radiation densities, to explore how changes in cosmological dynamics affect BBN outcomes.

Expected Results:
The expected results include a numerical prediction of the primordial 4He abundance Y as a function of η, which can be compared with observational data on currently measured Y to validate the standard cosmological model. This would involve recreating Figure 3.7 in the MBW book with additional lines indicating Y as a function of η for different Universes. It is anticipated that variations in H(t) will shift the freeze-out time and thus alter the neutron-to-proton ratio at decoupling, leading to changes in 4He abundance. For example, a faster-expanding universe (higher H(t)) would lead to earlier freeze-out, preserving more neutrons and increasing Y. Conversely, slower expansion would allow more neutrons to

decay before fusion, reducing Y. By examining these trends, this project aims to address questions about how sensitive BBN is to fundamental cosmological parameters and whether alternative universes could produce similar or drastically different light element abundances.

Broader Implications and Learning Goals:

This study has broader implications for understanding the interplay between particle physics and cosmology. It connects microscopic processes (weak interactions and neutron decay) with macroscopic phenomena (cosmic expansion), providing a bridge between fundamental physics and observational cosmology. By exploring alternative universes, we will also be able to see degeneracies in inferred η from observed Y depending on which cosmological model is used, which may highlight the importance of other independent observational constraints in cosmology.