Extra components consistency in the Hubble tension and BBN

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The standard ΛCDM cosmological model now seems to face some puzzles. One of the most serious problems is the so-called Hubble tension; the values of the Hubble constant H_0 obtained by local measurements look inconsistent with that inferred from Cosmic Microwave Background (CMB). Although introducing extra energy components such as the extra radiation or Early Dark Energy appears to be promising, such extra components could alter the abundance of light elements synthesized by Big Bang Nucleosynthesis (BBN). We perform a Monte Carlo simulation to evaluate the effect of those extra component scenarios to solve the Hubble tension on the BBN prediction.

Keywords: Cosmology; Big Bang Nucleosynthesis; Dark energy; Radiation; Hubble constant

1. Introduction

The ΛCDM model has been successful in explaining the evolution of our Universe. However, the tension of the Hubble constant is now apparent between the measurement of the local universe and the distant universe. Assuming ΛCDM model, Planck measurements of Cosmic Microwave Background (CMB) anisotropy infers the Hubble constant $H_0 = 67.4 \pm 0.5$ km/s/Mpc.[1] Other distant observations such as the Atacama Cosmology Telescope,[2] Baryon Acoustic Oscillation(BAO),[3] and the combined analysis of BAOand Big Bang Nucleosynthesis (BBN) (independent of CMB)[4] all infer $H_0 \sim 67$ km/s/Mpc. On the other hand, local measurements of H_0 by the SH0ES collaboration with Cepheids and type Ia supernovae (SNe Ia) in Ref.[5] and Ref.[6] and by the H0LiCOW collaboration with lensed quasars[7] have reported as $H_0 \sim 73$ km/s/Mpc. Another local measurement using the Tip of the Red Giant Branch (TRGB) as distance ladders has obtained a value between Planck and the SH0ES, $H_0 \sim 70$ km/s/Mpc.[8] It appears that the discrepancy is more than 3σ significance.

Several ideas have been proposed to extend ΛCDM model to resolve this tension. Among such ideas, we would like to consider the extra radiation and Early Dark Energy[9–18] solutions to the Hubble tension and the consistency with BBN. These extra components are promising solutions. However, the theoretical abundance of light elements synthesized by BBN should be different from the values of the standard scenario. Through the consideration, we confirm that extra radiation and Early Dark Energy are promising solutions. However, two scenarios are constrained by BBN measurements. Extra radiation is constrained by the helium abundance and Early Dark Energy is constrained by the deuterium abundance.[19]

2. H_0 from CMB

First, we explain how the Hubble constant is derived from the distant observation, especially the CMB anisotropy. The measured anisotropy includes the information of the angular size $\theta_* = r_*/D_{M*}$, where r_* is the comoving sound horizon at the recombination and D_{M*} is the comoving angular diameter distance. Planck team directly and strictly measured $\theta_* = 1.041 \times 10^{-2}$. A simple calculation according to the definition shows that $\theta_* \propto H_0/\sqrt{\rho_{\rm early}}$, where $\rho_{\rm early}$ is the energy density in the early universe. Therefore, in order for the Hubble constant from CMB to approach the local value, we need to increase ρ in the early universe. Then, we will consider two promising ways to increase ρ; Extra radiation and Early Dark Energy.

3. Modeling

3.1. *Extra radiation*

One simple "solution" to the Hubble tension is increasing the effective number of neutrinos $N_{\rm eff}$, which is expressed as

$$\Omega_r = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)\Omega_\gamma. \tag{1}$$

Here,

$$\Omega_i = \left.\frac{\rho_i}{3M_P^2 H^2}\right|_{t=t_0}, \tag{2}$$

with M_P being the reduced Planck mass, are the present values of density parameters for i spices. γ and r stand for CMB photon and total radiation, respectively.

3.2. *Early Dark Energy*

Another solution to the Hubble tension is introducing Early Dark Energy. In the Early Dark Energy scenario, the dark energy density in the early universe was much larger than today and after the critical point, the energy density decreases faster than the background energy densities do. In our analysis, we consider a model where

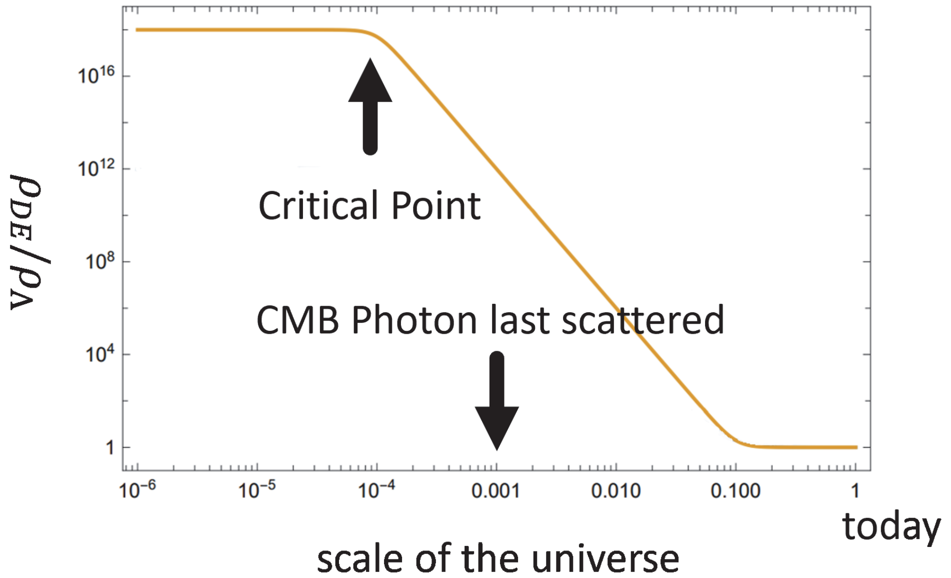

Fig. 1. Energy density evolution of Early Dark Energy

the energy density of Early Dark Energy ρ_{DE} decreases as the kination of scalar field after the critical point at $z = 3000$ around the matter-radiation equality. This setup is according to a preferred parameter set in Ref.[9]. The typical evolution of Dark Energy density $\rho_{DE}(a)$ normalized by ρ_Λ is shown in Fig. 1.

4. Data and Analysis

We perform a Markov-Chain Monte Carlo (MCMC) analysis on a $N_{\rm eff}$ model and the Early Dark Energy model described in the previous section. We use the public MCMC code `CosmoMC-planck2018`[20] with implementing the above Early Dark Energy scenarios by modifying its equation file in `camb`. For estimation of light elements, we have used `PArthENoPE_marcucci`.[21,22]

4.1. *Data sets*

We analyze models with referring to the following cosmological observation data sets. We include both temperature and polarization likelihoods for high l ($l = 30$ to 2508 in TT and $l = 30$ to 1997 in EE and TE) and low$l$ `Commander` and lowE `SimAll` ($l = 2$ to 29) of Planck (2018) measurement of the CMB temperature anisotropy.[1] We also include Planck lensing.[23] For constraints on low redshift cosmology, we include data of BAO from 6dF,[24] DR7[25] and DR12.[26] We also include Pantheon[27] of the local measurement of light curves and luminosity distance of supernovae as well as SH0ES (R19)[6] of the local measurement of the Hubble constant from the

Hubble Space Telescope observation of Supernovae and Cepheid variables. Finally, we include the data sets of helium mass fraction Y_P measurement[28] and deuterium abundance D/H measurement[29] to impose the constraints from BBN.

5. Result and Discussion

As is well known, an increase of $N_{\rm eff}$ affects the fit with the observation of light elements, because it contributes to the cosmic expansion at BBN epoch and alters the proton to neutron p/n ratio. This leads to increasing both the helium mass fraction Y_P and the deuterium abundance D/H. Thus, larger relativistic degrees are disfavored by the helium mass fraction measurement, while a little favored by deuterium measurement. This can be seen in Fig. 2.

On the other hand, in the Early Dark Energy scenarios, the Early Dark Energy increases the helium mass fraction little because the cosmic expansion rate in the BBN epoch increase little. Therefore, the Early Dark Energy scenario is consistent with the helium fraction measurement. However, increasing $\Omega_b h^2$ to adjust the CMB

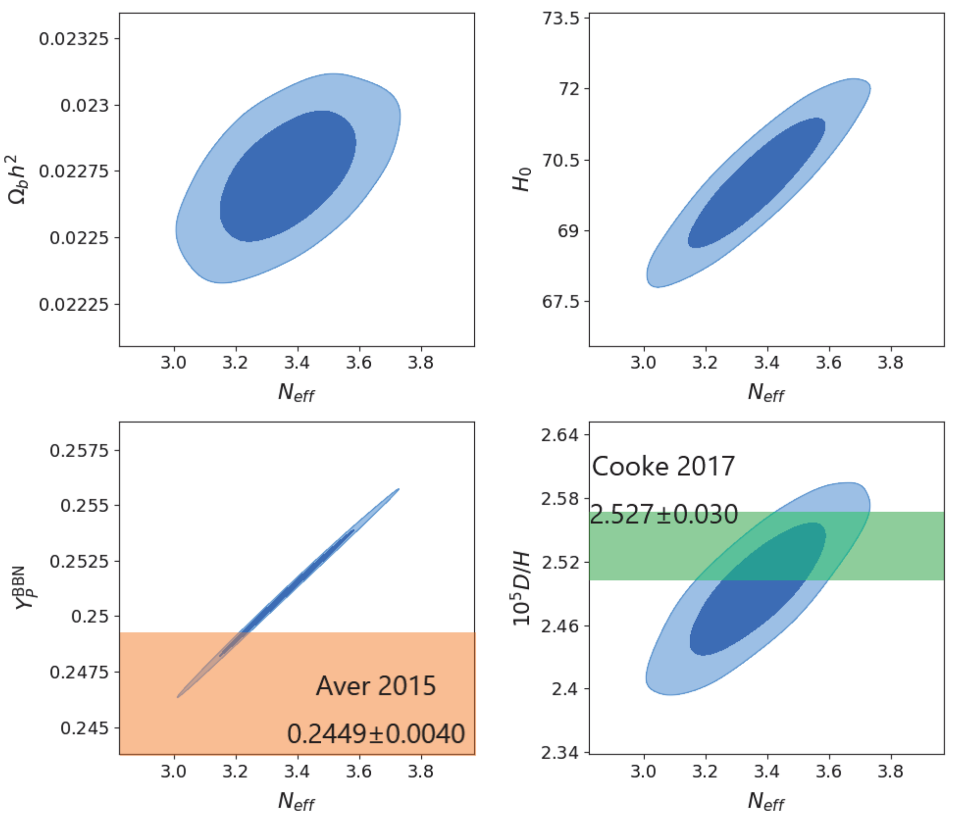

Fig. 2. The posterior and the constraints on the $N_{\rm eff}$ model

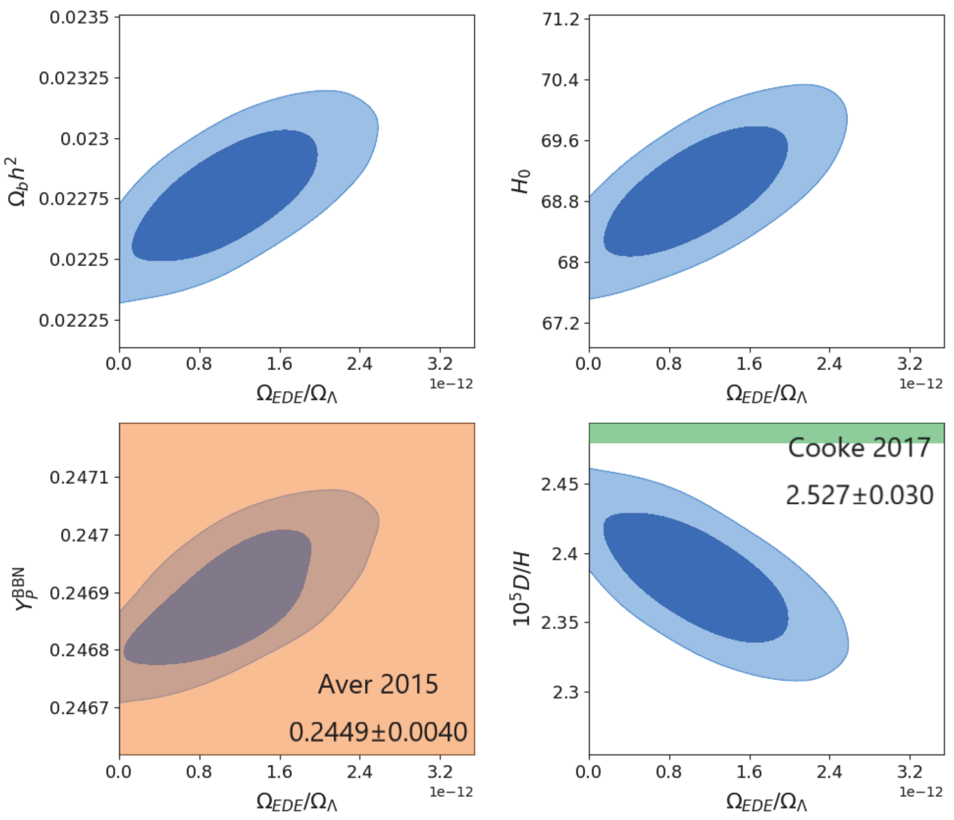

Fig. 3. The posterior and the constraints on the Early Dark Energy model

fit reduces the D/H abundance significantly. Thus, Early Dark Energy is disfavored from the deuterium measurement. This can be seen in Fig. 3.

6. Conclusion

The shorten sound horizon scale at the recombination epoch by introducing extra energy components such as the extra radiation or the Early Dark Energy is a promising solution to the Hubble tension. However, the compatibility with successful BBN would be another concern, because the extra radiation contribute the cosmic expansion or the inferred baryon asymmetry would differ from that in the ΛCDM.

We have performed analyses on the Early Dark Energy models and $N_{\rm eff}$ model with paying attention to the fit to BBN. Not only $N_{\rm eff}$ model but also the Early Dark Energy model is subject to the BBN constraints (as shown in Fig. 4.). Extra radiation is constrained by the helium abundance, while Early Dark Energy is constrained

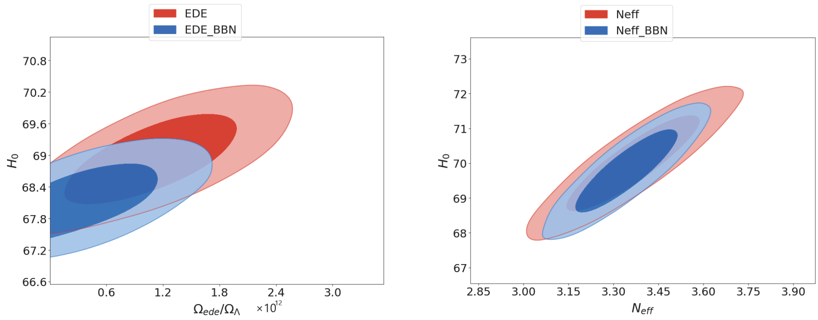

Fig. 4. Comparison of constraints based on data sets with and without BBN for the Early Dark Energy (left) model and the $N_{\rm eff}$ model (right)

by the deuterium abundance. Therefore, when we introduce extra components for the Hubble tension resolution, we should pay attention to the BBN as well.

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