Cosmological bound on neutrino masses in the light of H_0 tension

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Although cosmic microwave background (CMB) is a critical component of cosmological probes of neutrino masses, it has trouble with local direct measurements of H_0, and this is called the H_0 tension. Since neutrino masses are correlated with H_0 in CMB, one can expect the cosmological bound on neutrino masses would be much affected by the H_0 tension. We investigate what impact this tension brings to the cosmological bound on neutrino masses by assuming a model with early recombination in the framework allowing a nonflat Universe which has been shown to resolve the tension. We argue that constraints on neutrino masses become significantly weaker in models where the H_0 tension can be resolved.

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I. INTRODUCTION

The evidence of neutrino masses has been established by neutrino oscillation experiments which precisely measure the mass differences as $\Delta m_{21}^2 = (7.53 \times 0.18) \times 10^{-5}$ eV^2, $\Delta m_{32}^2 = (2.453 \pm 0.034) \times 10^{-3}$ eV^2 for normal hierarchy, and $\Delta m_{32}^2 = (-2.546^{+0.034}_{-0.040}) \times 10^{-3}$ eV^2 for inverted hierarchy [1], where $\Delta m_{ij}^2 = m_i^2 - m_j^2$ with m_i being the mass of the i-th neutrino mass eigenstate. Since oscillation experiments cannot obtain their absolute values, other methods should be pursued to probe them. Although terrestrial experiments such as tritium beta decay and neutrinoless double beta decay are such an example (see [2,3] for recent results), indeed cosmology has been regarded as a strong tool to probe their absolute values. Among cosmological observations, cosmic microwave background (CMB) is currently the most powerful probe of neutrino masses.

Recent data from Planck satellite provided the upper bound on the sum of neutrino masses, in combinations with other observations such as baryon acoustic oscillation (BAO), as $\sum m_\nu < 0.13$ eV(95%C.L.) [4] in the framework of ΛCDM model with neutrino masses and assuming degenerate mass. Bounds on neutrino mass have also been investigated by incorporating other recent observations of large scale structures, such as weak lensing [5,6], galaxy power spectrum [7–9], and so on (see also [10] for a review).

When one investigates the bound on neutrino masses from CMB, one can easily notice that the neutrino masses have a degeneracy with other cosmological parameters, especially the Hubble constant H_0, which can also be well measured by CMB as $H_0 = (67.4 \pm 0.5)$ km/sec/Mpc [4]. However, the values of H_0 obtained by local direct measurements are significantly higher than this [11–13], for instance, $H_0 = (73.8 \pm 1.0)$ km/sec/Mpc [14], which is inconsistent with the value obtained by CMB with more than 5σ deviation. This inconsistency is now called the Hubble (H_0) tension. As mentioned above, the neutrino masses have a degeneracy with H_0 in CMB and hence the value of H_0 would significantly affect the determination of neutrino masses from cosmology (see, e.g., [15,16]). Therefore the H_0 tension is expected to give a strong impact on the cosmological bound on neutrino masses.

The origin of the H_0 tension has been a target of intense research recently. It might be due to some unknown systematic errors, however it is now widely considered that the tension could indicate an extension/modification of the standard model of cosmology (for lists of such works, see e.g., [17,18]). Since cosmological bounds on neutrino masses have been usually investigated in the framework of the standard ΛCDM model,[1] if the tension is resolved by extending/modifying the cosmological model, the neutrino masses should be reinvestigated in such a new framework since the bound might be significantly affected, which is the issue we would like to argue in this paper.[2]

Although there is no consensus on the plausible model to solve the H_0 tension, the present authors have recently proposed a model which can significantly resolve the tension, based on a model with early recombination in the framework allowing a nonflat Universe [33]. Since this

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[1] For works in which bounds on neutrino masses have been investigated in extended models, see, e.g., [19–32].

[2] We in this paper consistently assume that neutrinos are the standard active ones and the sum of the masses is the only relevant parameter associated with them.

model satisfies the necessary conditions that a plausible scenario should share to solve the H_0 tension [33], a model with early recombination can be regarded as a representative one as a solution for the tension. Models with early recombination can also be motivated by some high energy theories where the fundamental constants such as the electron mass can be varied in the course of the cosmological evolution (e.g., for a recent review, see [34]) which can realize early recombination. Therefore we adopt this model and investigate a constraint on neutrino masses in the model by using cosmological observations such as CMB and BAO and compare its constraint obtained in the framework of ΛCDM, which would highlight the impact of the H_0 tension to the cosmological bound on neutrino masses.

The structure of this paper is as follows. In the next section, we discuss the setup of our analysis where we briefly review a model with early recombination proposed in [33] and explain our method of the analysis to investigate a cosmological bound on neutrino masses. Then in Sec. III, we show our results on constraints on neutrino masses in the framework of early recombination and flat and nonflat ΛCDM, and then make a comparison between those constraints. As mentioned above, the model with early recombination would have properties which a successful model for the H_0 tension should share and hence the bound obtained in the framework would show general tendencies for models where the H_0 tension is solved. The final section is devoted to conclusion of this paper.

II. SETUP OF THE ANALYSIS

In this section, we discuss the setup of our analysis. First we briefly review a model with early recombination which can significantly relax the H_0 tension and be regarded as a representative model to solve the tension. Then we summarize the method of our analysis to constrain neutrino masses from cosmological observations such as CMB, BAO, and type Ia supernovae (SNeIa). We also make an analysis including the Planck lensing data and the local H_0 measurements.

A. Model with early recombination

Here we briefly describe a model with early recombination we adopt in our analysis as a representative model to solve the H_0 tension. In the following, we eventually adopt varying m_e as a successful model to solve the H_0 tension. More explicitly, we assume the following form of the time-variation of m_e:

$$m_e(t)/m_{e,0} = \begin{cases} m_e/m_{e,0} & (\text{for } z \geq z_t) \\ 1 & (\text{for } z < z_t) \end{cases}, \tag{1}$$

where $m_{e,0}$ is the current value of m_e and z_t is a transition redshift when the value of m_e changes. If the transition takes place well after recombination but well before today [e.g., $z_t = O(10)$], which we are assuming, the precise value of z_t is irrelevant as far as CMB and late-time distance measurements are concerned. Therefore, the relevant parameter associated with varying m_e is only $m_e/m_{e,0}$.

As we have shown in Ref. [33], effects of varying m_e on CMB can be encoded by the recombination epoch a_* alone with good accuracy, which evokes the analytical argument we are to present in this section. Meanwhile, readers should be reminded that effects of varying m_e are thoroughly incorporated in our numerical calculation. For the details of the model, we refer the readers to Ref. [33].

As mentioned in the introduction, this model satisfies the necessary conditions which a successful solution would meet.[3] Among the conditions, the most nontrivial one is to reduce the sound horizon at recombination $r_s(z_*)$[4] with z_* being the redshift at recombination epoch, by ∼10% compared to the value obtained by fitting to Planck data in the ΛCDM model, keeping the fit to the CMB (Planck data) remains unchanged. A model with the early recombination realizes this condition in a nontrivial way. As a possible realization of an early recombination scenario, we adopt a model with time-varying electron mass m_e. Although we can explicitly show that $r_s(z_*)$ can be reduced by $\sim\mathcal{O}(10)\%$ without spoiling the fit to CMB by directly calculating the CMB power spectrum numerically, we can also argue analytically to some extent by using some key quantities which characterize the CMB power spectrum.

We can approximately well describe the effect of early recombination by the shift of the scale factor at recombination epoch a_*. The change of the recombination epoch affects the CMB power spectrum, which is characterized by the changes of the position and height of acoustic peaks and the diffusion damping. Regarding the height of the acoustic peaks, the following two quantities well describe it:

$$R(x) = \frac{3\omega_b}{4\omega_\gamma} = \frac{3\omega_b a_*}{4\omega_\gamma} x, \tag{2}$$

$$A(x) = a^2 H = \frac{H_0}{h}\sqrt{\omega_m a_* x + \omega_r}, \tag{3}$$

where we have introduced a quantity $x \equiv a/a_*$ with the scale factor being normalized by the one at recombination. $\omega_b(= \Omega_b h^2)$, $\omega_m(= \Omega_m h^2)$, $\omega_\gamma(= \Omega_\gamma h^2)$, and $\omega_r(= \Omega_r h^2)$ represent energy densities of baryon, total matter, photons, and radiation (assuming neutrinos are sufficiently relativistic by the time of recombination) with Ω_i being the normalized energy density for a component i and h being the reduced Hubble constant in units of 100 km/s/Mpc

[3]These necessary conditions are listed in [33].

[4]Precisely speaking, this should be the sound horizon at the drag epoch; however, given $r_s(z_*)$, the one at the drag epoch can also be determined. Therefore we use $r_s(z_*)$ in the following.

(i.e., $H_0 = 100h$ km/s/Mpc). The former quantity $R(x)$, the ratio between baryon and photon densities, gives the relative height of even and odd peaks. The latter $A(x)$ characterizes the integrated Sachs-Wolfe (ISW) effect which determines the heights of the first few acoustic peaks. From the above formulas, the shift of a_* can leave R and A unchanged by changing ω_m and ω_b as

$$\Delta_{\omega_b} = \Delta_{\omega_m} = -\Delta_{a_*}, \tag{4}$$

where Δ_i denotes a fractional change of a quantity f from its reference value $\Delta = (f - f_{\text{reference}})/f_{\text{reference}}$.

The sound horizon at recombination is given by

$$r_s(a_*) = \frac{a_*}{\sqrt{3}} \int_0^1 \frac{1}{\sqrt{1+R(x)}} \frac{dx}{A(x)}, \tag{5}$$

from which one can see that $r_s(a_*)$ also changes by the shift of a_* as

$$r_s(a_*) \propto a_* \tag{6}$$

when Eq. (4) is satisfied. On the other hand, the diffusion damping (Silk damping) scale $1/k_D$ is given by

$$\frac{1}{k_D(z_*)^2} = \frac{a_*^2}{6} \int_0^1 \frac{R^2 + \frac{16}{15}(1+R)}{(1+R)^2} \frac{1}{a_*^2 n_e \sigma_T} \frac{dx/x}{A}, \tag{7}$$

where σ_T and n_e are the Thomson scattering cross section and the electron number density. To keep the CMB power spectrum intact, the ratio between $1/k_D$ and the sound horizon at recombination epoch $r_s(a_*)$ should be kept unchanged. In other words,

$$1/k_D \propto a_* \tag{8}$$

should be satisfied. This is satisfied in an early recombination model if

$$a_*^2 n_e \sigma_T = x_e \frac{1-Y_p}{m_H} \frac{\rho_{\text{crit}}}{h^2} (\omega_b a_*) \left(\frac{\sigma_T}{a_*^2}\right) \frac{1}{x^3} \tag{9}$$

is kept unchanged as a function of x.

Finally, we also need to keep the viewing angle of the sound horizon untouched, which is represented by the quantity $\theta_s(a_*) \equiv r_s(a_*)/D_M(a_*)$ with $D_M(a)$ being the angular diameter distance to $a(=1/(1+z))$:

$$D_M(z) = \begin{cases} \frac{\sin[\sqrt{-\Omega_k} H_0 \chi(z)]}{\sqrt{-\Omega_k} H_0} & \text{for } \Omega_k < 0 \,(\text{closed}) \\ \chi(z) & \text{for } \Omega_k = 0 \,(\text{flat}) \\ \frac{\sinh[\sqrt{\Omega_k} H_0 \chi(z)]}{\sqrt{\Omega_k} H_0} & \text{for } \Omega_k > 0 \,(\text{open}) \end{cases}, \tag{10}$$

where χ is the comoving distance to z which is given by

$$\chi(z) = \int_0^z \frac{dz}{H(z)}. \tag{11}$$

Around the mean cosmological parameters of the ΛCDM model from the Planck 2018 result [4], the change of $\theta_s(a_*)$ can be canceled by shifting the Hubble parameter, in the ΛCDM background, as

$$\Delta_h \simeq -3.23 \Delta_{a_*}. \tag{12}$$

Even when we consider a different background, the relation $\Delta_h \propto -\Delta_{a_*}$ holds, which introduces a strong degeneracy between H_0 and a_*.

From the above argument, one can see that the reduction of the sound horizon is realized by the change of a_* whose effects on CMB power spectrum can be canceled by changing other cosmological parameters as given in Eqs. (4) and (12) once Eq. (9) is satisfied. Importantly, H_0 can be shifted to a higher value by taking the recombination epoch earlier, which can solve the H_0 tension.

As mentioned above, the early recombination can be realized by assuming a time-varying electron mass m_e. The effects of varying m_e can be understood by noting that: (i) m_e changes the energy level of hydrogen as $E \propto m_e$, (ii) Thomson scattering cross section is affected as $\sigma_T \propto m_e^{-2}$. These effects amount to the shift of the recombination epoch as

$$\Delta_{m_e} = -\Delta_{a_*}, \tag{13}$$

with Eq. (9) being kept unchanged automatically. Therefore a model with early recombination can be realized by assuming a time-varying m_e and can solve the H_0 tension as far as CMB power spectrum is concerned[5] since the fit to the CMB is automatically kept unchanged.

Figure 1 demonstrates how the scaling relations Eqs. (4) and (12) can keep the CMB temperature power spectrum almost unchanged. Taking $\Delta_{\omega_m} = \Delta_{m_e}$ can adjust the early ISW effect (see top-right panel), while taking $\Delta_{\omega_b} = \Delta_{\omega_m} = \Delta_{m_e}$ can adjust the relative heights of acoustic peaks simultaneously (bottom-left panel). Varying h in conjunction with $m_e/m_{e,0}$ according to Eq. (12) can adjust the angular locations of the acoustic peaks (bottom-right). As we have discussed, since relative scale of the sound horizon to the Silk length is automatically conserved in varying m_e model, CMB power spectra can be kept unchanged except for late ISW effect at very low ℓ, where cosmic variance fundamentally limits observation sensitivities.

The above demonstration indicates that by varying m_e, H_0 can be shifted to a higher value which can significantly

[5]For the effects of time-varying electron mass on CMB, see also [35,36].

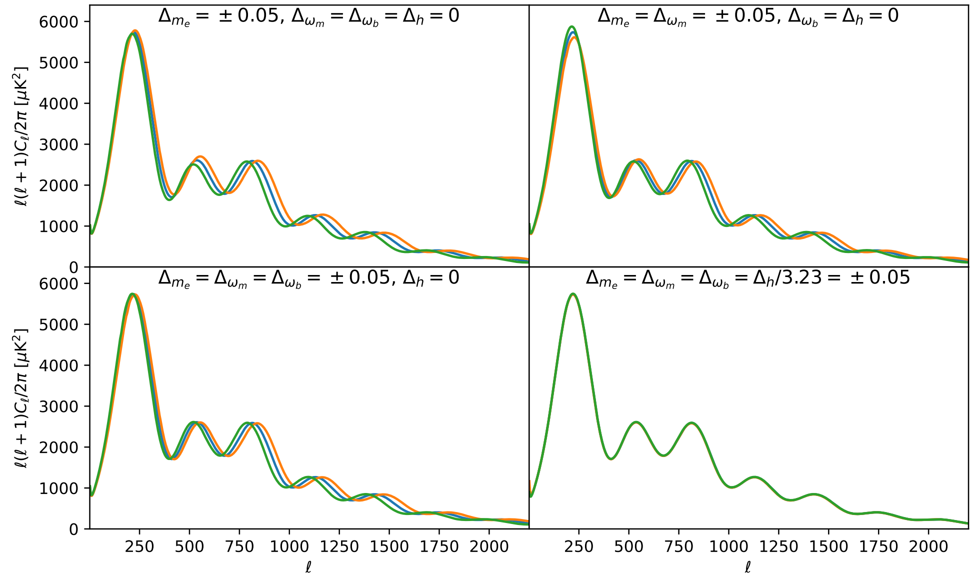

FIG. 1. How effects of varying m_e in CMB temperature power spectrum are canceled by varying the degenerate parameters ω_b, ω_m, and h in the ΛCDM model. Blue line is the baseline model ($\Delta_{m_e} = 0$) with Planck 2018 best ΛCDM parameters. Orange and green lines correspond to varying m_e models with $\Delta_{m_e} = +0.05$ and -0.05, respectively. In top left panel, only $m_e/m_{e,0}$ is varied and ω_m, ω_b, and h are fixed. In top right panel, $m_e/m_{e,0}$ and ω_m are varied according to Eq. (4) but ω_b and h are fixed. In bottom left panel, $m_e/m_{e,0}$, ω_m, and ω_b are varied according to Eq. (4) but h is fixed. All the parameters are varied according to Eqs. (4) and (12) in bottom right panel. The last panel clearly demonstrates that CMB temperature power spectrum can be kept almost unchanged in varying m_e models by varying standard cosmological parameters appropriately in conjunction with $m_e/m_{e,0}$.

relax the tension without spoiling the fit to CMB. However, when we combine the data from BAO and SNeIa, the distance measures cannot be well-fitted in the framework above and we need to modify the background evolution after recombination. This might be done in several ways, but here we consider a simple extension, a nonflat Universe to realize this since we just introduce one additional free parameter in this case: the curvature of the Universe Ω_k. Therefore, in the following we investigate bounds on neutrino masses in a model with varying m_e in a nonflat Universe. We refer to this model as $m_e\Omega_k\Lambda$CDM for brevity in the following.

B. Analysis

We investigate the cosmological bound on neutrino masses from the data from Planck (TT, TE, EE + LowE) [37], BAO [38–40], and SNeIa [41] by performing Markov Chain Monte Carlo (MCMC) analysis. In addition, we optionally also include CMB lensing data from Planck [42] and the direct measurements of Hubble constant, $H_0[\mathrm{km/sec/Mpc}] = 74.1 \pm 1.3$ from [14],[6] which we denote as H0 in the following. In parameter estimation, we use a modified version of CosmoMC [43] which accommodates the time-varying electron mass supported by the recombination code HyRec [44,45]. We note that, although we discussed the effects of modified recombination or time-varying electron mass just focusing on the change of the recombination epoch in the previous section, HyRec code adopted in the analysis incorporates its full effects. We refer the readers to Ref. [45] for detail.

We assume the degenerate mass hierarchy for neutrinos and investigate cosmological constraints on $\sum m_\nu$ in a canonical flat ΛCDM background and an early recombination model with varying m_e and nonzero spatial curvature ($m_e\Omega_k\Lambda$CDM). For reference, we also consider a nonflat ΛCDM model ($\Omega_k\Lambda$CDM). The primary parameters in our analysis for the ΛCDM model are: cold dark matter density ω_c, baryon density ω_b, the acoustic angular scale θ_{MC}, the reionization optical depth τ, the amplitude of primordial power spectrum A_s, the spectral index n_s, and the sum of neutrino masses $\sum m_\nu$. In the analysis in the framework of the $\Omega_k\Lambda$CDM model, the curvature density $\omega_k(=\Omega_k h^2)$ is also varied in addition to the above parameters. For the case of the $m_e\Omega_k\Lambda$CDM model, the electron mass m_e is also included as a free parameter. When the electron mass is varied, we assume that m_e becomes the standard value some time after recombination so that it does not affect late time Universe. Flat priors are assumed for all primary parameters in the analysis.

III. RESULTS

Now we present our results. First we show 1D posterior distribution for neutrino masses in the framework of flat

[6]We adopt the results without SNeIa in order to minimize systematic errors associated with SNeIa data.

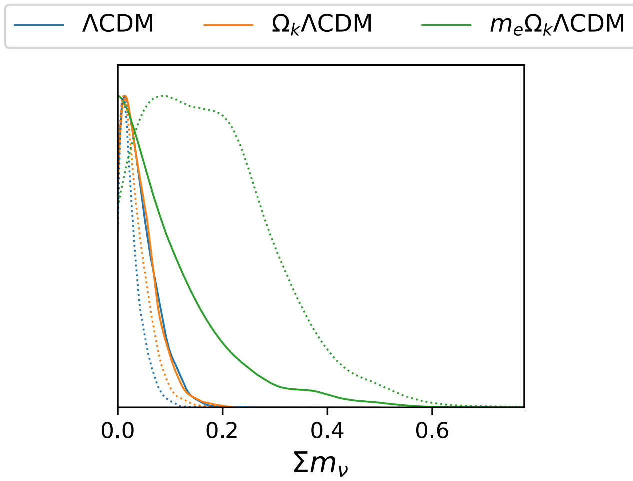

FIG. 2. 1D posterior distributions neutrino masses from CMB + BAO + SNeIa + lensing (solid line) and CMB + BAO + SNeIa + lensing + H0 (dotted line), where the cosmological backgrounds are assumed to be ΛCDM (blue), $\Omega_k\Lambda$CDM (orange), and $m_e\Omega_k\Lambda$CDM (green).

and nonflat ΛCDM (i.e., ΛCDM and $\Omega_k\Lambda$CDM) models and the modified recombination in nonflat Universe (i.e., $m_e\Omega_k\Lambda$CDM model) in Fig. 2. 95% C.L. upper bounds on $\sum m_\nu$ are summarized in Table I. Constraints in the $\sum m_\nu$-H_0 plane for some combinations of datasets and the scatter plot of the angular diameter distance to last scattering surface $D_M(z_*)$ for the analysis of CMB+BAO +SNe are shown in Fig. 3. Full triangle plots for flat ΛCDM, nonflat ΛCDM, and $m_e\Omega_k\Lambda$CDM models are, respectively, depicted in Figs. 4–6, in which 1D posterior distribution and 2D allowed regions for the analysis of CMB + BAO + SNeIa + lensing, CMB + BAO + SNeIa+ H0, and CMB + BAO + SNeIa + lensing + H0 are shown for the primary parameters, except for the acoustic angular scale $\theta_{\rm MC}$ being replaced by H_0. In 2D panels, scatter plots for the angular diameter distance to last scattering surface $D_M(z_*)$ are depicted for the analysis of CMB + BAO + SNeIa to discuss the degeneracies among the parameters.

When a flat ΛCDM is assumed, CMB + BAO + SNeIa + lensing gives $\sum m_\nu < 0.11$ eV (95% C.L.), which is consistent with Planck 2018 results [4]. As long as the Planck lensing data is included, flat and nonflat ΛCDM background gives similar constraints as read off from Fig. 2 and Table I. However, in models with modified recombination (i.e., varying m_e) in a nonflat framework, the upper bound is significantly weakened, which suggests that in a scenario where the H_0 tension can be solved, cosmological constraint on neutrino masses gets less severe. We will take a closer look at each model below.

A. Case of ΛCDM model

In the case of ΛCDM model, when we incorporate the local H_0 measurements, the upper bounds on $\sum m_\nu$ are superficially tightened. This is because the neutrino mass and H_0 are negatively correlated in the CMB data in the ΛCDM model [16], and hence the local measurement of H_0, which prefers a large H_0, inevitably leads to a lower $\sum m_\nu$ as seen from the left panel of Fig. 3. The scatter plot of $D_M(z_*)$ in Fig. 3 also shows that the degeneracy between $\sum m_\nu$ and H_0 corresponds to the direction of constant $D_M(z_*)$. When $\sum m_\nu \lesssim 0.1$ eV, neutrinos become nonrelativistic well after the recombination, and, hence, for this magnitude of $\sum m_\nu$, neutrino masses only marginally change perturbation evolution by the time of recombination. Primary effects of neutrino masses on CMB anisotropy therefore should arise from the modification

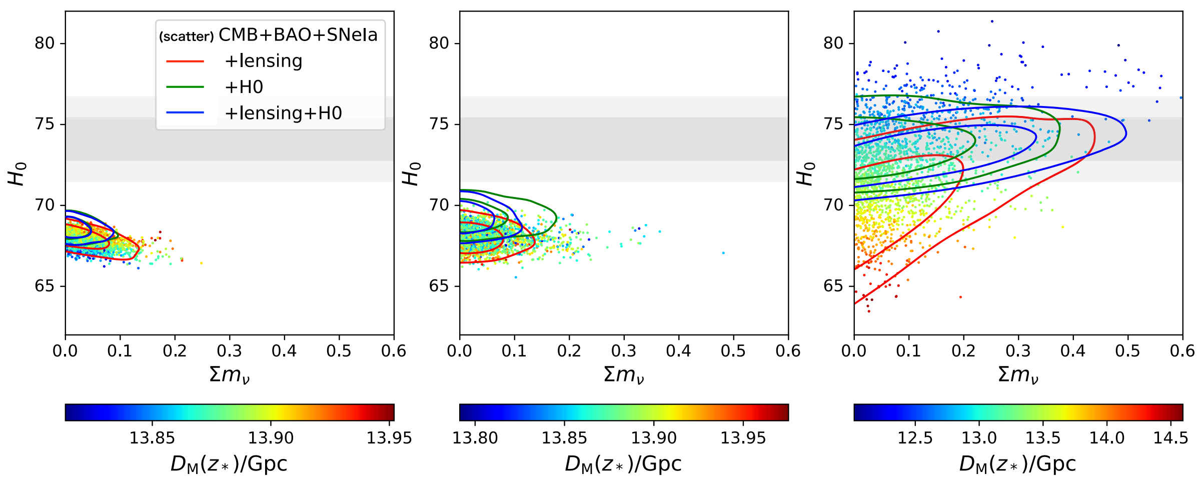

FIG. 3. Constraints in the plane of neutrino masses and H_0 in the framework of ΛCDM (left), $\Omega_k\Lambda$CDM (middle) and $m_e\Omega_k\Lambda$CDM (right) models. 1σ and 2σ allowed regions are shown for the analysis of CMB + BAO + SNeIa + lensing, CMB + BAO + SNeIa + H0, and CMB + BAO + SNeIa + lensing + H0 are depicted. Scatter plots of $D_M(z_*)$ for the analysis of CMB + BAO + SNeIa are also shown. Grey horizontal shaded band indicates the values obtained from the local H_0 measurement.

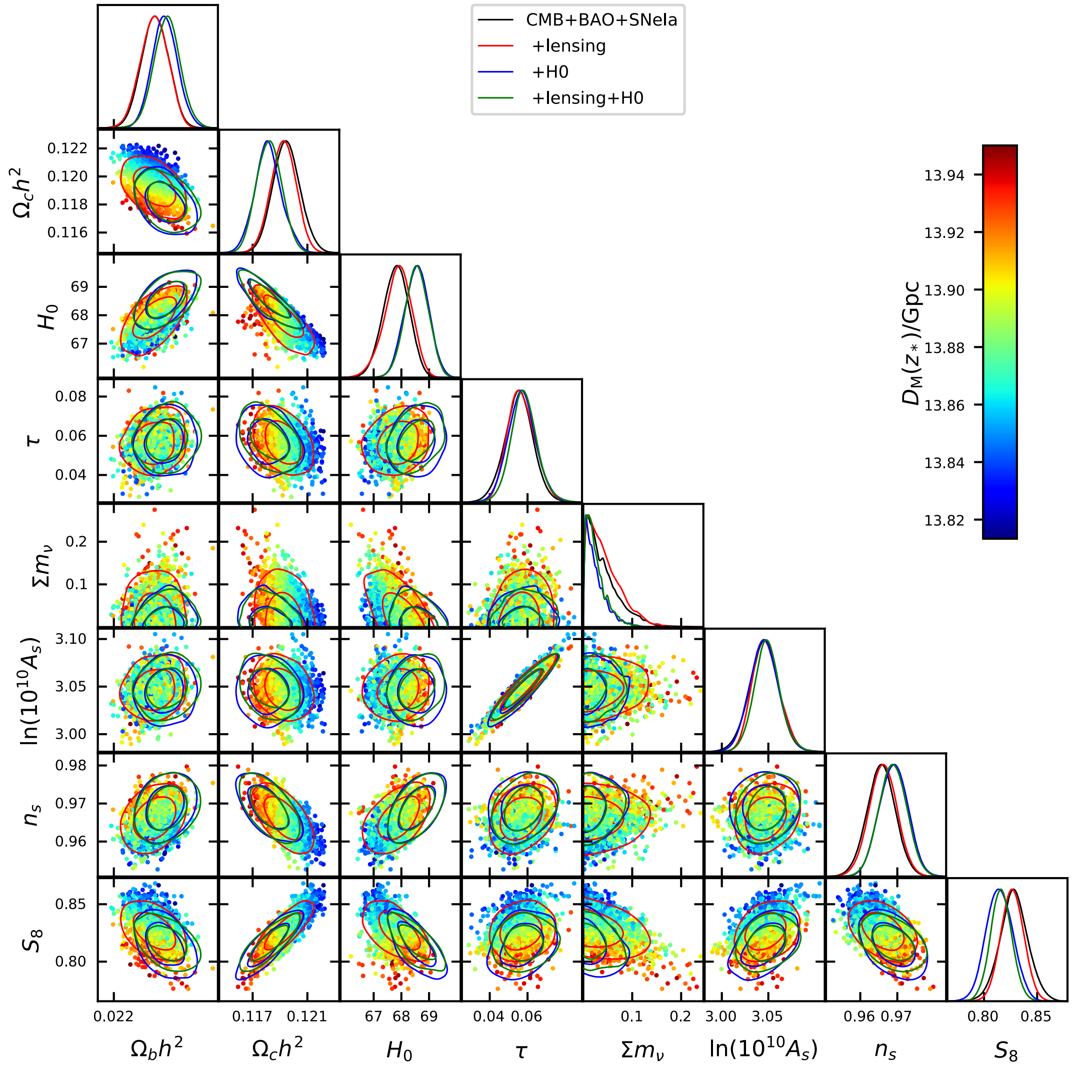

FIG. 4. Triangle plot of cosmological parameters in the ΛCDM model.

to late-time expansion, namely the distance to last scattering surface $D_M(z_*)$ [15]. Given the fact that $\Omega_b h^2$ and $\Omega_c h^2$ are tightly constrained by spectral shape of the CMB power spectrum, H_0 (or $\Omega_\Lambda h^2$) is the only cosmological parameter which can cancel the effects of neutrino masses to $D_M(z_*)$ in a flat ΛCDM model, as far as only CMB power spectrum is concerned. The heavier the neutrino masses get, the earlier neutrinos become nonrelativistic, which makes the angular diameter distance to z_* smaller. To keep $D_M(z_*)$ unchanged, H_0 should be taken to be smaller, which explains the negative correlation between $\sum m_\nu$ and H_0. The allowed region in the $\sum m_\nu - H_0$ plane in this model reflects this fact and is in significant tension with the local H_0 measurement. In other words, nonzero neutrino masses exacerbate the Hubble tension. Even late-time distance measurements, i.e., BAO and SNeIa, lift the degeneracy only slightly.

B. Case of $\Omega_k\Lambda$CDM model

In a nonflat ΛCDM model (i.e., $\Omega_k\Lambda$CDM), the curvature of the Universe can also affect the angular diameter distance to last scattering surface $D_M(z_*)$. As mentioned above, $D_M(z_*)$ can be modified by changing neutrino masses; however, Ω_k is more powerful in changing $D_M(z_*)$ than neutrino masses, and H_0 is mainly degenerate with Ω_k, which can be read off from the panel showing the constraint in the H_0–Ω_k plane in Fig. 5. As seen from the figure, H_0 and Ω_k degenerate along a constant $D_M(z_*)$. On the other hand, due to the existence of Ω_k, the degeneracy between $\sum m_\nu$ and H_0 gets significantly weakened and almost disappears in the $\Omega_k\Lambda$CDM model as seen from the middle panel of Fig. 3. Scatter plot of $D_M(z_*)$ in the panel also suggests that $D_M(z_*)$ is almost irrelevant to set a constraint in the $H_0 - \sum m_\nu$ plane, which is quite different from the case of a flat ΛCDM model.

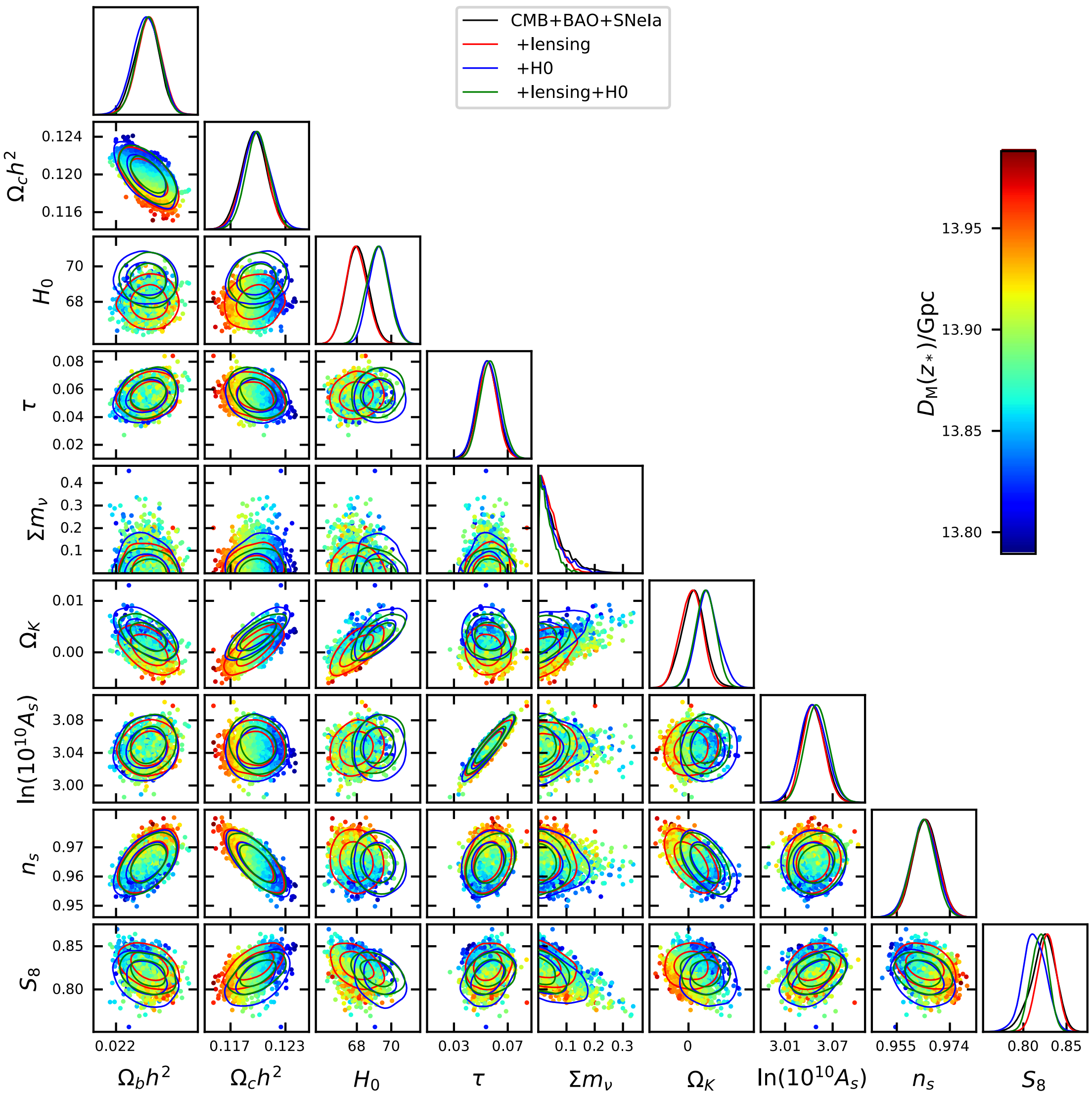

FIG. 5. Triangle plot of cosmological parameters in the $\Omega_k\Lambda$CDM model.

It should be noted here that, although the degeneracy between H_0 and $\sum m_\nu$ disappears in the $\Omega_k\Lambda$CDM model, Ω_k and $\sum m_\nu$ are degenerate along the direction of a constant $D_M(z_*)$, which makes an upper bound on neutrino masses weaker. When the local H_0 measurement is included, the degeneracy between H_0 and Ω_k is broken, which in turn makes an upper bound on neutrino masses more stringent. However, it should be noted that, due to the indirect effect of the degeneracy between H_0 and Ω_k, constraints on neutrino masses get weaker compared to the one in the ΛCDM model. In any case, the inclusion of neutrino masses does not improve the H_0 tension in the $\Omega_k\Lambda$CDM model as well.

C. Case of $m_e\Omega_k\Lambda$CDM model

Finally, we discuss the case of the $m_e\Omega_k\Lambda$CDM model which has been suggested as a solution to the H_0 tension [33]. As seen from Fig. 2 and Table I, when we assume the $m_e\Omega_k\Lambda$CDM model, the constraint on $\sum m_\nu$ is relaxed significantly from the ones for flat and nonflat ΛCDM models. In models with varying m_e, the recombination epoch can be altered, which substantially changes $r_s(z_*)$ as we have discussed in Sec. II A. These effects mainly introduce strong degeneracies among several parameters, while the fits to CMB, BAO, and SNeIa can be kept well due to the existence of the curvature [33].

When m_e is increased, the recombination epoch becomes earlier, which makes $r_s(z_*)$ smaller [35]. To keep a good fit to CMB angular power spectra, we need to tune the acoustic scale $\theta_s(z_*) = r_s(z_*)/D_M(z_*)$ and hence H_0 can be increased to cancel the effect due to the change of m_e, which introduces a strong degeneracy among m_e, $\Omega_b h^2$, $\Omega_c h^2$, H_0, and Ω_k as seen in Fig. 6.

Interestingly, due to this severe degeneracy among several parameters in the $m_e\Omega_k\Lambda$CDM model, $\sum m_\nu$ and H_0 are now positively correlated and the direction of

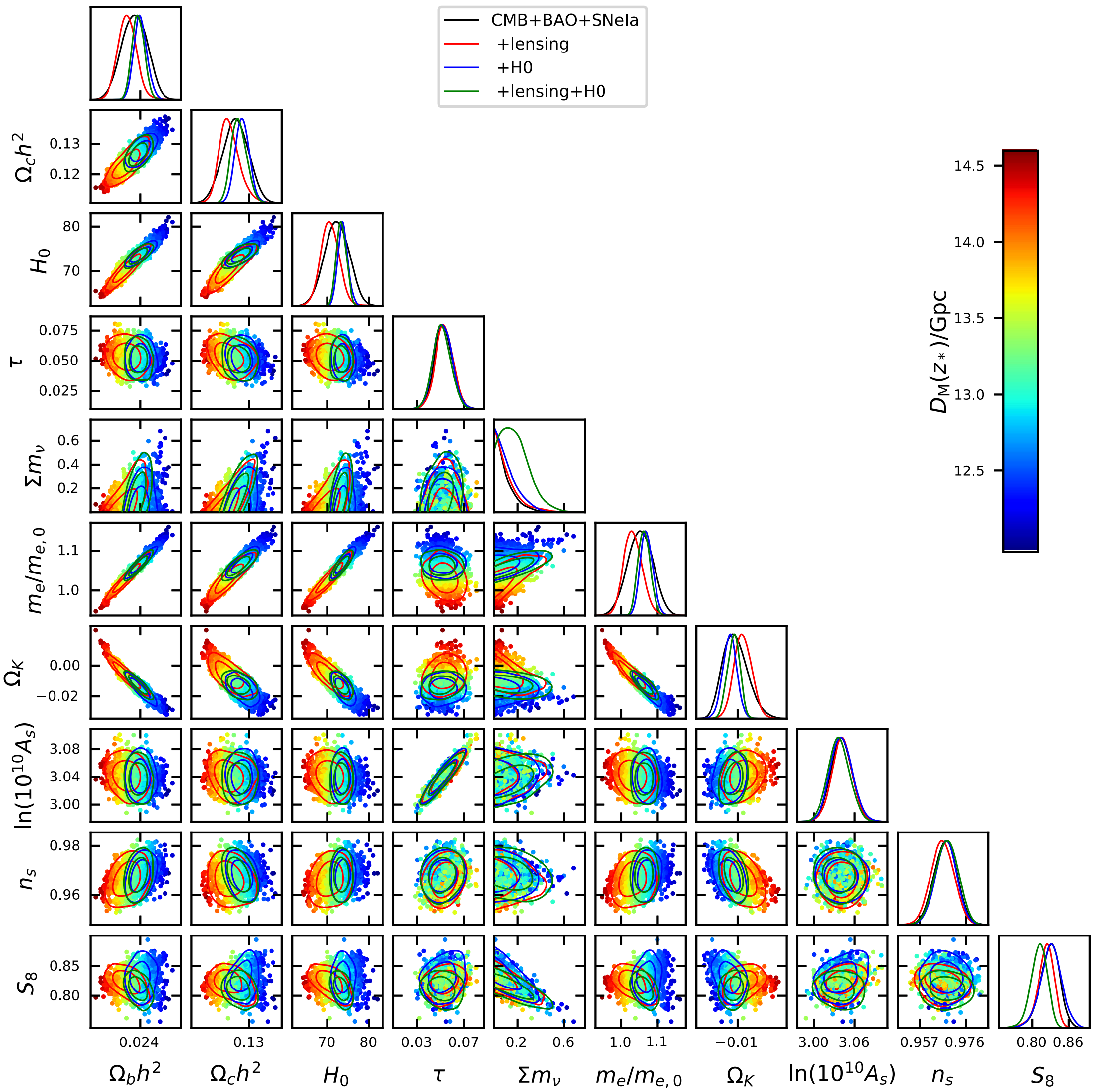

FIG. 6. Triangle plot of cosmological parameters in the $m_e\Omega_k\Lambda$CDM model.

correlation follows a constant $D_M(z_*)$ line as can be observed in Fig. 3. Because of this positive correlation, the bound on neutrino masses is pushed upward when the local H_0 measurement is included in the analysis. As shown in Table I, the 95% upper bound on $\sum m_\nu$ is 0.28 eV for the analysis of CMB + BAO + SNeIa; however, it becomes 0.31 eV for CMB + BAO + SNeIa + H0.

It should also be mentioned that the inclusion of the Planck lensing data tends to prefer nonzero neutrino masses [42], which can also make the upper bound on $\sum m_\nu$ weaker. When one includes the lensing and local H_0 measurement data in addition to CMB + BAO + SNeIa, the upper bound on neutrino masses $\sum m_\nu$ is 0.4 eV, which is fairly weak compared to the counterpart in the ΛCDM framework.

As we have already emphasized, the $m_e\Omega_k\Lambda$CDM model holds the properties which should be satisfied by a successful model resolving the H_0 tension and hence this model can be regarded as a representative model to solve the tension. Therefore constraints on neutrino masses obtained in the framework of the $m_e\Omega_k\Lambda$CDM model would share a general tendency for the neutrino mass constraint in models where the H_0 tension is solved.

TABLE I. 95% upper bounds on $\sum m_\nu$ [eV].

	ΛCDM+ m_ν	$\Omega_k\Lambda$CDM+ m_ν	$m_e\Omega_k\Lambda$CDM+ m_ν
CMB + BAO + SNeIa	0.11	0.16	0.28
+lensing	0.11	0.11	0.34
+H0	0.072	0.14	0.31
+lensing + H0	0.069	0.089	0.40

D. Effects on the amplitude of matter fluctuations

Finally, let us comment on the amplitude of matter fluctuations. It has been argued that cosmological models, which reduce $r_s(a_*)$ to solve the H_0 tension tend to indicate a high matter amplitude, or $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$, where σ_8 is the root-mean-square of matter fluctuations smoothed at $8h^{-1}$ Mpc [46,47]. This is in tension with the estimation of S_8 obtained from large scale structure data such as weak lensing (WL) and cluster counts (see e.g., Fig. 5 in [48]).

In our analysis, from CMB + BAO + SNeIa, we have obtained $S_8 = 0.828^{+0.013}_{-0.013}$, $S_8 = 0.823^{+0.016}_{-0.012}$, and $S_8 = 0.829^{+0.014}_{-0.017}$ from ΛCDM, $\Omega_k\Lambda$CDM, and $m_e\Omega_k\Lambda$CDM, respectively. Compared to recent estimation of S_8, e.g., $S_8 = 0.783^{+0.021}_{-0.025}$ from [5], the significance of tension does not exceed 2σ. While our early recombination tends to prefer earlier matter-radiation equality and, hence, larger S_8, the presence of nonzero neutrino mass can easily relax the increase in S_8. Due to the enhancement of uncertainty in S_8, the tension rather weakens in our early recombination model compared to the baseline ΛCDM.

IV. CONCLUSION

In this paper, we have investigated cosmological constraint on neutrino masses in the light of the H_0 tension. Since H_0 and neutrino masses $\sum m_\nu$ are correlated, particularly in CMB data, the H_0 tension would give significant implications for cosmological bounds on neutrino masses.

In the ΛCDM model, H_0 and neutrino masses are negatively correlated, which indicates that the upper bound on $\sum m_\nu$ becomes superficially tighter when the local H_0 measurement is included in the analysis as shown in Fig. 2 and Table I. However as seen from Fig. 3, the value of H_0 indicated by CMB + BAO + SNeIa, even including other datasets, is in large tension with the one obtained from the local H_0 measurement. Therefore the cosmological bound on neutrino masses in the framework of ΛCDM cannot be taken at face value if we take a position that the H_0 tension suggests the modification of the cosmological model.

In the light of this consideration, it would be indispensable to study the cosmological bound on neutrino masses in the framework where the H_0 tension is resolved. Although many models have been proposed for a solution to the H_0 tension, there is no consensus on what framework can solve the tension so far. However, a model with early recombination in a nonflat Universe proposed in [33] satisfies the necessary conditions which a successful model should share to solve the H_0 tension. Therefore the analysis of a cosmological constraint on neutrino masses in this framework (i.e., $m_e\Omega_k\Lambda$CDM model) should give a general tendency with regard to the cosmological bound on neutrino masses in the framework where the H_0 tension can be solved, which was the main issue of this paper. To check how the assumption of a nonflat Universe affects a constraint on $\sum m_\nu$, we also made an analysis in the $\Omega_k\Lambda$CDM model as well.

From the analysis using the data of CMB + BAO+ SNeIa, an upper bound on the neutrino masses in the ΛCDM, $\Omega_k\Lambda$CDM, and $m_e\Omega_k\Lambda$CDM models are $\sum m_\nu < 0.11$ eV, 0.16 eV, and 0.28 eV (95% C.L.), respectively. In the $\Omega_k\Lambda$CDM model, the curvature of the Universe Ω_k can change the angular diameter distance to last scattering surface, which generates a degeneracy between Ω_k and $\sum m_\nu$ and an upper bound on $\sum m_\nu$ gets weaker compared to the ΛCDM case. When the varying m_e is introduced (i.e., in the $m_e\Omega_k\Lambda$CDM model), the bound on $\sum m_\nu$ gets significantly weaker since the varying m_e degenerates with several parameters [36]. Furthermore, in the framework of $m_e\Omega_k\Lambda$CDM model, the correlation between H_0 and $\sum m_\nu$ is positive, differently from the case of ΛCDM model, and hence including the local H_0 measurement, the bound on $\sum m_\nu$ gets significantly looser.

As argued in this paper, the H_0 tension can also affect other aspects of cosmology such as neutrino masses. We have investigated this issue and demonstrated that a cosmological bound on neutrino masses is actually affected in the light of the H_0 tension. Since the H_0 tension is now more than 5σ, we need to investigate further the implications of the H_0 tension to other aspects of cosmology.

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