Constraints on neutrino mass in the scenario of vacuum energy interacting with cold dark matter after Planck 2018

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Received 15 July 2020
Accepted for publication 4 August 2020
Published 12 November 2020

Abstract

In this work, we investigate the constraints on the total neutrino mass in the scenario of vacuum energy interacting with cold dark matter (abbreviated as ΛCDM) by using the latest cosmological observations. We consider four typical interaction forms, i.e. \( Q = \beta H \rho_c \), \( Q = \beta H_0 \rho_c \), and \( Q = \beta H_0 \rho_c \), in the ΛCDM scenario. To avoid the large-scale instability problem in interacting dark energy models, we employ the extended parameterized post-Friedmann method for interacting dark energy to calculate the perturbation evolution of dark energy in these models. The observational data used in this work include the cosmic microwave background (CMB) measurements from the Planck 2018 data release, the baryon acoustic oscillation (BAO) data, the type Ia supernovae (SN) observation (Pantheon compilation), and the 2019 local distance ladder measurement of the Hubble constant \( H_0 \) from the Hubble Space Telescope. We find that, compared with those in the ΛCDM+\( \sum m_\nu \) model, the constrains on \( \sum m_\nu \) are looser in the four ΛCDM+\( \sum m_\nu \) models. When considering the three mass hierarchies of neutrinos, the constraints on \( \sum m_\nu \) are tightest in the degenerate hierarchy case and loosest in the inverted hierarchy case. In addition, in the four ΛCDM+\( \sum m_\nu \) models, the values of coupling parameter \( \beta \) are larger using the CMB+BAO+SN+\( H_0 \) data combination than that using the CMB+BAO+SN data combination, and \( \beta > 0 \) is favored at more than 1σ level when using CMB+BAO+SN+\( H_0 \) data combination. The issue of the \( H_0 \) tension is also discussed in this paper. We find that, compared with the ΛCDM+\( \sum m_\nu \) model, the \( H_0 \) tension can be alleviated in the ΛCDM+\( \sum m_\nu \) model to some extent.

Keywords: total neutrino mass, neutrino mass hierarchies, interacting dark energy, Hubble tension, cosmological observations

(Some figures may appear in colour only in the online journal)

1. Introduction

The phenomenon of neutrino oscillation indicates that neutrinos have nonzero masses and there are mass splittings between different neutrino species [1, 2]. The neutrino oscillation experiments can provide the information about the squared mass differences between the neutrino mass eigenstates. Specifically, the solar and reactor experiments give the result of \( \Delta m_{21}^2 \approx 7.5 \times 10^{-5} \) eV², and the atmospheric and accelerator beam experiments give the result of \( |\Delta m_{31}^2| \approx 2.5 \times 10^{-3} \) eV² [2, 3]. Therefore, we can get two possible mass hierarchies of the neutrino mass spectrum, i.e. the normal hierarchy (NH) with \( m_1 < m_2 \ll m_3 \) and the inverted hierarchy (IH) with \( m_3 \ll m_1 < m_2 \), where \( m_1, m_2, m_3 \),
and $m_1$ denote the masses of neutrinos for the three mass eigenstates. However, the absolute masses of neutrinos are still unknown.

In principle, laboratory experiments of particle physics can directly measure the absolute masses of neutrinos, but these experiments have always been facing great challenges [4–12]. Compared with these particle physics experiments, cosmological observations are more prone to be capable of measuring the absolute masses of neutrinos [13–15], since massive neutrinos can leave rich signatures on the cosmic microwave background (CMB) anisotropies and the large-scale structure (LSS) formation at different epochs of the cosmic evolution [16]. Thus, we can extract useful information on neutrinos from these available cosmological observations.

Recently, the issue of cosmological constraints on the total neutrino mass with the consideration of mass hierarchy using the latest observational data has been discussed in [17]. In [17], the authors discussed the constraints on neutrino mass in several typical dark energy (DE) models, e.g. the Λ cold dark matter ($\Lambda$CDM), wCDM, Chevallier–Polarski–Linder (CPL), and holographic dark HDE (HDE) models. It was found that, compared to the $\Lambda$CDM+$\sum m_i$ model, larger neutrino masses are favored in the $w$CDM+$\sum m_i$ and CPL+$\sum m_i$ models, and the most stringent upper limits are obtained in the HDE+$\sum m_i$ model. Moreover, in [17], it was also confirmed that the NH case is more favored by current cosmological observations than the IH case. For more recent studies on constraining the total neutrino mass by using cosmological observations, see e.g. [18–69].

Furthermore, the impacts of interaction between DE and cold dark matter (CDM) on constraining neutrino mass have also been considered. For example, in the scenario of vacuum energy interacting with cold dark matter, which is abbreviated as the I$\Lambda$CDM scenario in this work, the constraint on $\sum m_i$ becomes $\sum m_i < 0.10$ eV $(2\sigma)$ for $Q = \beta H_\rho c$, $\sum m_i < 0.20$ eV $(2\sigma)$ for $Q = \beta H_\rho$ [70], and $\sum m_i < 0.214$ eV $(2\sigma)$ for $Q = \beta H_\rho$ [71]. When the mass hierarchies of neutrinos are considered in the I$\Lambda$CDM model [72, 73], the results showed that the degenerate hierarchy (DH) case gives the smallest upper limit of the neutrino mass and the NH case is more favored over the IH case.

In the present work, we will revisit the constraints on the total neutrino mass in the I$\Lambda$CDM scenario after the Planck 2018 data release. We will consider more forms of interaction term $Q$, and also adopt the mass hierarchies of neutrinos in this work.

In the so-called ‘interacting dark energy’ (IDE) scenario, some direct, nongravitational coupling between DE and dark matter is assumed and its cosmological consequences have been widely studied [74–114]. Theoretically speaking, the consideration of such an interaction is helpful in solving the cosmic coincidence problem [76–87, 89], but actually what is more important is to detect such an interaction using the cosmological observations. The impacts of interactions between DE and dark matter on the CMB [89, 106] and LSS [75, 83, 87, 90, 101, 106] have been studied in-depth.

In this paper, we only consider the simplest class of models in the IDE scenario, i.e. the I$\Lambda$CDM models, in which the vacuum energy with $w = −1$ serves as DE. In this scenario, the energy conservation equations of the vacuum energy and the cold dark matter satisfy

$$\rho_{de} = Q, \quad (1)$$
$$\dot{\rho}_c = -3H\rho_c - Q, \quad (2)$$

where $\rho_{de}$ and $\rho_c$ represent the densities of DE (namely, vacuum energy) and cold dark matter, respectively, $H$ is the Hubble parameter, the dot represents the derivative with respect to the cosmic time $t$, and $Q$ is the energy transfer rate. Usually, the form of $Q$ is assumed to be proportional to the density of DE or dark matter, i.e. $Q = \beta H\rho_{de}$ or $Q = \beta H\rho_c$, where the appearance of $H$ is only for mathematical convenience. In the research area of IDE, another perspective is to consider $Q = \beta H_0\rho_{de}$ or $Q = \beta H_0\rho_c$ [86], where the appearance of $H_0$ is only for a dimensional consideration. From equations (1) and (2), it is known that $\beta > 0$ means cold dark matter decaying into DE, $\beta < 0$ means DE decaying into cold dark matter, and $\beta = 0$ indicates no interaction between vacuum energy and cold dark matter.

Different phenomenological models of I$\Lambda$CDM can be built by assuming different forms of $Q$. In this work, we will collect the popular forms of $Q$ in the current literature and then focus on the impacts of different forms of $Q$ on constraining the total neutrino mass after the Planck 2018 data release. We will consider the four typical forms of $Q$: $Q = \beta H_0\rho_{de}$, $Q = \beta H_0\rho_c$, $Q = \beta H_0\rho_{de}$ and $Q = \beta H_0\rho_c$. The mass hierarchies of neutrinos are also considered in this work.

In addition, we also wish to see whether some hint of the existence of nonzero interaction can be found in these I$\Lambda$CDM models by using the latest observational data.

This paper is organized as follows. In section 2, we introduce the cosmological observations used in this work and briefly describe the analysis method. In section 3, we report the constraint results and then make some relevant discussions. The issue of $H_0$ tension will also be discussed in this section. Conclusion is given in section 4.

2. Method and data

In the I$\Lambda$CDM model, there are seven basic cosmological parameters $(\omega_b, \omega_c, 100\theta_{MC}, \tau, n_s, \ln(10^9\Omega_\Lambda), \beta)$, where $\omega_b$ is the present density of baryons, $\omega_c$ is the present density of cold dark matter, $\theta_{MC}$ is the ratio between the sound horizon and the angular diameter distance at the decoupling epoch, $\tau$ is the Thomson scattering optical depth to reionization, $n_s$ is the scalar spectral index, $A_s$ is the amplitude of primordial scalar perturbation power spectrum, and $\beta$ is the dimensionless coupling constant describing the coupling strength between vacuum energy and dark matter.

For the I$\Lambda$CDM model there is a problem of early-time perturbation instability, because in the IDE models, the cosmological perturbations of DE will be divergent in a part of the parameter space, which ruins the IDE cosmology in the perturbation level. The origin of the difficulty is that we know little about the nature of DE, so we do not know how to treat the spread of sounds in DE fluid which has a negative equation of state. To overcome the problem of perturbation
instability, in 2014, Yun-He Li, Jing-Fei Zhang, and Xin
Zhang established an effective theoretical framework for IDE
cosmology based on the extended version of the parameterized
post-Friedmann (PPF) approach, which can safely calculate the cosmological perturbations in the whole para-
meter space of an IDE model. About the extended PPF
method, see [115–119], and the original PPF method is introduced in [120, 121]. In this work, we will employ
the extended PPF method [115–119] to calculate the cosmological perturbations in the ΛCDM model.

We use the modified version of the publicly available
Markov-chain Monte Carlo package CosmoMC [122] to constrain the neutrino mass and other cosmological parameters. We monitor the convergence of the generated MCMC chains by using the Gelman-Rubin parameter R [123], requiring R < 1 < 0.1 for our MCMC chains to be consid-
ered as converged. When considering the neutrino mass splitting, we should note the following rules. For the NH case, the neutrino mass spectrum is

\[
(m_1, m_2, m_3) = (m_1, \sqrt{m_1^2 + \Delta m_{12}^2}, \sqrt{m_1^2 + |\Delta m_{13}^2|}),
\]

where \(m_1\) is a free parameter; for the IH case, the neutrino mass spectrum is

\[
(m_1, m_2, m_3) = (\sqrt{m_1^2 + \Delta m_{12}^2}, \sqrt{m_1^2 + \Delta m_{13}^2} + \Delta m_{21}^2, m_3),
\]

where \(m_1\) is a free parameter; for comparison, the DH case is also considered, in which the neutrino mass spectrum is

\[
m_1 = m_2 = m_3 = m,
\]

where \(m\) is a free parameter. Since we have two values of squared mass differences, \(\Delta m_{12}^2 = 7.5 \times 10^{-5} \text{ eV}^2\) and \(\Delta m_{13}^2 = 2.5 \times 10^{-3} \text{ eV}^2\) [2, 3], the lower limits of NH and

IH can be derived by setting the smallest mass be zero. Thus, the input lower bounds of \(\sum m_\nu\) are 0.06 eV for the NH case, 0.10 eV for the IH case, and 0 eV for the DH case, respectively.

The current observational data sets we used in this paper include CMB, BAO, SN and \(H_0\). For the CMB data, we use the Planck TT, TE, EE spectra at \(\ell > 30\), the low-\(\ell\) temperature Commander likelihood, and the low-\(\ell\) SimAll EE likelihood, from the Planck 2018 data release [124]. For the BAO data, we consider the measurements from 6dFGS (\(\Delta eff = 0.106\)) [125], SDSS-MGS (\(\Delta eff = 0.15\)) [126], and BOSS DR12 (\(\Delta eff = 0.38, 0.51\), and 0.61) [127]. For the SN data, we employ the latest Pantheon sample, which is comprised of 1048 data points from the Pantheon compilation [128]. For the \(H_0\) data, we use the 2019 local distance ladder measurement of the Hubble constant \(H_0 = 74.03 \pm 1.42 \text{ km s}^{-1} \text{ Mpc}^{-1}\) from the Hubble Space Telescope [129]. In our analysis, we will use two data com-
binations, i.e. CMB+BAO+SN and CMB+BAO+SN+\(H_0\) to
cr

| Data               | CMB+BAO+SN               | CMB+BAO+SN+\(H_0\)               |
|--------------------|--------------------------|----------------------------------|
| Model              | \(\Lambda \text{CDM} + \sum m_\nu\) | \(\Lambda \text{CDM} + \sum m_\nu\) |
| \(\Omega_m\)       | 0.3126 \pm 0.0063         | 0.3105 \pm 0.0060               |
| \(H_0\)            | 67.48 \pm 0.47            | 67.26 \pm 0.45                  |
| \(\sigma_8\)       | 0.801^{+0.011}_{-0.008}   | 0.793^{+0.010}_{-0.008}         |
| \(\sum m_\nu\)     | <0.156                   | <0.185                          |
| \(\Delta CDM + \sum m_\nu\) | 0.3097 \pm 0.0063         | 0.3097 \pm 0.0063               |
| \(\Lambda \text{CDM} + \sum m_\nu\) | 0.3044 \pm 0.0056         | 0.3069 \pm 0.0056               |
| \(\Lambda \text{CDM} + \sum m_\nu\) | 0.3044 \pm 0.0056         | 0.3069 \pm 0.0056               |
| \(\Lambda \text{CDM} + \sum m_\nu\) | 0.3044 \pm 0.0056         | 0.3069 \pm 0.0056               |
| \(\Lambda \text{CDM} + \sum m_\nu\) | 0.3044 \pm 0.0056         | 0.3069 \pm 0.0056               |
| \(\Lambda \text{CDM} + \sum m_\nu\) | 0.3044 \pm 0.0056         | 0.3069 \pm 0.0056               |
| \(\Lambda \text{CDM} + \sum m_\nu\) | 0.3044 \pm 0.0056         | 0.3069 \pm 0.0056               |
| \(\Lambda \text{CDM} + \sum m_\nu\) | 0.3044 \pm 0.0056         | 0.3069 \pm 0.0056               |
| \(\Lambda \text{CDM} + \sum m_\nu\) | 0.3044 \pm 0.0056         | 0.3069 \pm 0.0056               |

3. Results and discussion

In this section, we report the constraint results of cosmological parameters for these \(\Lambda \text{CDM} + \sum m_\nu\) models. The fitting results are listed in table 1 for the \(\Lambda \text{CDM} + \sum m_\nu\) model and tables 2–5 and figures 1–4 for the four \(\Lambda \text{CDM} + \sum m_\nu\) models. For convenience, the \(\Lambda \text{CDM}\) models with the interaction terms \(Q = \beta H_0 \rho_c\), \(Q = \beta H_0\), and \(Q = \beta H_0\) are denoted as ’\(\Lambda \text{CDM1}\)’, ’\(\Lambda \text{CDM2}\)’, ’\(\Lambda \text{CDM3}\)’, and ’\(\Lambda \text{CDM4}\)’, respectively. In these tables, we show the best fit values with \(\pm 1\sigma\) errors of the cosmological parameters, but for the total neutrino mass \(\sum m_\nu\), which cannot be well constrained, the 2\(\sigma\) upper limits are given.
Table 3. Fitting results for the ΛCDM+$\sum m_\nu$ ($Q = \beta H_0$) model by using the CMB+BAO+SN and CMB+BAO+SN+$H_0$ data combinations, respectively. Here, $H_0$ and $\sum m_\nu$ are in units of km s$^{-1}$ Mpc$^{-1}$ and eV, respectively.

| Data | CMB+BAO+SN | CMB+BAO+SN+$H_0$ |
|------|------------|------------------|
| Model | $\Omega_m$ | $H_0$ | $\beta$ | $\sigma_8$ | $\sum m_\nu$ | $\Omega_m$ | $H_0$ | $\beta$ | $\sigma_8$ | $\sum m_\nu$ |
| $\Lambda$CDM+$\sum m_\nu$ | 0.3085 ± 0.0080 | 67.83 ± 0.64 | 0.0014 ± 0.0012 | 0.800 ± 0.012 | <0.190 | 0.2953 ± 0.0071 | 68.92 ± 0.60 | 0.0024 ± 0.0012 | 0.815 ± 0.013 | <0.170 |
| $\Omega$CDM+$\sum m_\nu$ | 0.3092 ± 0.0081 | 67.74 ± 0.65 | 0.0014 ± 0.0012 | 0.800 ± 0.012 | <0.223 | 0.2960 ± 0.0071 | 68.83 ± 0.60 | 0.0028 ± 0.0012 | 0.809 ± 0.013 | <0.202 |
| $\Omega$CDM+$\sum m_\nu$ | 0.3077 ± 0.0081 | 67.92 ± 0.65 | 0.0005 ± 0.0013 | 0.814 ± 0.014 | <0.149 | 0.2960 ± 0.0071 | 69.01 ± 0.60 | 0.0019 ± 0.0012 | 0.824 ± 0.014 | <0.126 |

Table 4. Fitting results for the ΛCDM3+$\sum m_\nu$ ($Q = \beta H_0$) model by using the CMB+BAO+SN and CMB+BAO+SN+$H_0$ data combinations, respectively. Here, $H_0$ and $\sum m_\nu$ are in units of km s$^{-1}$ Mpc$^{-1}$ and eV, respectively.

| Data | CMB+BAO+SN | CMB+BAO+SN+$H_0$ |
|------|------------|------------------|
| Model | $\Omega_m$ | $H_0$ | $\beta$ | $\sigma_8$ | $\sum m_\nu$ | $\Omega_m$ | $H_0$ | $\beta$ | $\sigma_8$ | $\sum m_\nu$ |
| $\Lambda$CDM+$\sum m_\nu$ | 0.287 ± 0.036 | 68.03 ± 0.81 | 0.14 ± 0.16 | 0.886 ± 0.099 | <0.179 | 0.223 ± 0.032 | 69.57 ± 0.72 | 0.37 ± 0.13 | 1.072 ± 0.095 | <0.166 |
| $\Omega$CDM+$\sum m_\nu$ | 0.276 ± 0.035 | 67.96 ± 0.80 | 0.18 ± 0.16 | 0.899 ± 0.072 | <0.208 | 0.217 ± 0.033 | 69.50 ± 0.74 | 0.40 ± 0.14 | 1.071 ± 0.10 | <0.198 |
| $\Omega$CDM+$\sum m_\nu$ | 0.291 ± 0.036 | 68.10 ± 0.83 | 0.06 ± 0.17 | 0.868 ± 0.068 | <0.140 | 0.233 ± 0.032 | 69.60 ± 0.74 | 0.31 ± 0.14 | 1.036 ± 0.091 | <0.128 |

Table 5. Fitting results for the ΛCDM4+$\sum m_\nu$ ($Q = \beta H_0$) model by using the CMB+BAO+SN and CMB+BAO+SN+$H_0$ data combinations, respectively. Here, $H_0$ and $\sum m_\nu$ are in units of km s$^{-1}$ Mpc$^{-1}$ and eV, respectively.

| Data | CMB+BAO+SN | CMB+BAO+SN+$H_0$ |
|------|------------|------------------|
| Model | $\Omega_m$ | $H_0$ | $\beta$ | $\sigma_8$ | $\sum m_\nu$ | $\Omega_m$ | $H_0$ | $\beta$ | $\sigma_8$ | $\sum m_\nu$ |
| $\Lambda$CDM+$\sum m_\nu$ | 0.299 ± 0.016 | 68.05 ± 0.80 | 0.043 ± 0.047 | 0.814 ± 0.019 | <0.202 | 0.272 ± 0.013 | 69.58 ± 0.72 | 0.111 ± 0.043 | 0.840 ± 0.019 | <0.202 |
| $\Omega$CDM+$\sum m_\nu$ | 0.297 ± 0.016 | 68.07 ± 0.82 | 0.058 ± 0.048 | 0.812 ± 0.019 | <0.235 | 0.269 ± 0.013 | 69.58 ± 0.73 | 0.128 ± 0.043 | 0.837 ± 0.019 | <0.239 |
| $\Omega$CDM+$\sum m_\nu$ | 0.303 ± 0.016 | 68.07 ± 0.81 | 0.024 ± 0.047 | 0.820 ± 0.020 | <0.156 | 0.275 ± 0.013 | 69.58 ± 0.72 | 0.092 ± 0.044 | 0.845 ± 0.019 | <0.162 |

Figure 1. Observational constraints (68.3% and 95.4% confidence level) on the ΛCDM1+$\sum m_\nu$ ($Q = \beta H_0$) model by using the CMB+BAO+SN (left) and CMB+BAO+SN+$H_0$ (right) data combinations, respectively.
3.1. Neutrino mass

Firstly, we use the CMB + BAO data combination to constrain these models. In the $\Lambda$CDM + $\sum m_\nu$ model, we obtain $\sum m_\nu < 0.156$ eV for the NH case, $\sum m_\nu < 0.185$ eV for the IH case, and $\sum m_\nu < 0.123$ eV for the DH case, as shown table 1. In the $\Lambda$CDM1 + $\sum m_\nu$ model, the constraint results are $\sum m_\nu < 0.187$ eV for the NH case, $\sum m_\nu < 0.218$ eV for the IH case, and $\sum m_\nu < 0.151$ eV for the DH case (see table 2); in the $\Lambda$CDM2 + $\sum m_\nu$ model, the results are $\sum m_\nu < 0.190$ eV for the NH case, $\sum m_\nu < 0.223$ eV for the IH case, and $\sum m_\nu < 0.149$ eV for the DH case (see table 3); in the $\Lambda$CDM3 + $\sum m_\nu$ model, we get $\sum m_\nu < 0.179$ eV for the NH case, $\sum m_\nu < 0.208$ eV for the
IH case, and $\sum m_\nu < 0.140 \text{ eV}$ for the DH case (see table 4); in the $\Lambda$CDM+$\sum m_\nu$ model, the constraint results become $\sum m_\nu < 0.202 \text{ eV}$ for the NH case, $\sum m_\nu < 0.235 \text{ eV}$ for the IH case, and $\sum m_\nu < 0.156 \text{ eV}$ for the DH case (see table 5). We find that, the constraint results of $\sum m_\nu$ are looser in the four $\Lambda$CDM+$\sum m_\nu$ models than those in the $\Lambda$CDM+$\sum m_\nu$ model. When considering the three mass hierarchies, we find that the constraint results of $\sum m_\nu$ are tighter in the DH case and looser in the IH case (see the left panels in figures 1–4); actually this is mainly because in the NH and IH cases there are lower limits for the total neutrino mass.

Then, we consider the data combination involving the latest local measurement of the Hubble constant $H_0$ to constrain these models. By using the CMB+BAO+SN+H$_0$ data combination, we find that the constraint results of $\sum m_\nu$ are looser in the four $\Lambda$CDM+$\sum m_\nu$ models than those in the $\Lambda$CDM+$\sum m_\nu$ model, and when considering the three mass hierarchies, the constraint results of $\sum m_\nu$ are tightest in the DH case and looser in the IH case. These conclusions are consistent with the case using the CMB+BAO+SN data combination. Additionally, we also find that the constraints on $\sum m_\nu$ become slightly tighter for using CMB+BAO+SN+H$_0$ than CMB+BAO+SN.

### 3.2. Coupling parameter

In this subsection, we discuss the fitting results of the coupling parameter $\beta$ in these four $\Lambda$CDM+$\sum m_\nu$ models by using the CMB+BAO+SN and CMB+BAO+SN+H$_0$ data combinations, respectively.

First, we constrain the $\Lambda$CDM1+$\sum m_\nu$ model (see table 2) using the CMB+BAO+SN data combination, and we obtain $\beta = 0.10^{+0.10}_{-0.11}$ for the NH case, $\beta = 0.13 \pm 0.11$ for the IH case, and $\beta = 0.07^{+0.10}_{-0.11}$ for the DH case. It is shown that a positive value of $\beta$ is favored and $\beta > 0$ is at the $0.91\sigma$, $1.18\sigma$, and $0.64\sigma$ levels for the three mass hierarchy cases, respectively. Furthermore, we constrain this model by using the CMB+BAO+SN+H$_0$ data combination, and we obtain $\beta = 0.257^{+0.089}_{-0.097}$ for the NH case, $\beta = 0.286 \pm 0.098$ for the IH case, and $\beta = 0.215 \pm 0.099$ for the DH case. Now, $\beta > 0$ is obtained at the $2.65\sigma$, $2.92\sigma$, and $2.17\sigma$ levels, respectively. This indicates that cold dark matter decaying into DE is favored when using the CMB+BAO+SN+H$_0$ data combination.

For the $\Lambda$CDM2+$\sum m_\nu$ model (see table 3), we obtain $\beta = 0.0011^{+0.0011}_{-0.0013}$ for the NH case, $\beta = 0.0014^{+0.0013}_{-0.0011}$ for the IH case, and $\beta = 0.0005 \pm 0.0013$ for the DH case, by using the CMB+BAO+SN data combination. Thus, $\beta > 0$ is favored at the $0.92\sigma$, $1.08\sigma$, and $0.38\sigma$ levels, respectively. When using the CMB+BAO+SN+H$_0$ data combination, we obtain $\beta = 0.0024 \pm 0.0012$ for the NH case, $\beta = 0.0028 \pm 0.0012$ for the IH case, and $\beta = 0.0019 \pm 0.0012$ for the DH case, which indicates that a positive value of $\beta$ can be detected at the $2.00\sigma$, $2.33\sigma$, and $1.58\sigma$ levels, respectively.

As for the $\Lambda$CDM3+$\sum m_\nu$ model (see table 4), we obtain $\beta = 0.14 \pm 0.16$ for the NH case, $\beta = 0.18 \pm 0.16$ for the IH case, and $\beta = 0.08^{+0.17}_{-0.15}$ for the DH case, by using the CMB+BAO+SN data combination. Therefore, the positive values of $\beta$ are favored and $\beta > 0$ is preferred at the $0.88\sigma$, $1.13\sigma$, and $0.50\sigma$ levels, respectively. When using the CMB+BAO+SN+H$_0$ data combination, we obtain $\beta = 0.37^{+0.11}_{-0.14}$ for the NH case, $\beta = 0.40 \pm 0.14$ for the IH case, and $\beta = 0.31 \pm 0.14$ for the DH case, respectively. And $\beta > 0$ is detected at the $2.64\sigma$, $2.90\sigma$, and $2.21\sigma$ levels, respectively, which indicates cold dark matter decaying into DE.

Finally, we show the constraint results of $\Lambda$CDM4+$\sum m_\nu$ model (see table 5). We obtain $\beta = 0.043 \pm 0.047$ for the NH case, $\beta = 0.058^{+0.047}_{-0.048}$ for the IH case, and $\beta = 0.024^{+0.047}_{-0.048}$ for the DH case, by using the CMB+BAO+SN+H$_0$ data combination. So, a positive value of $\beta$ is favored and $\beta > 0$ is at the $0.91\sigma$, $1.21\sigma$, and $0.50\sigma$ levels, respectively. When using the CMB+BAO+SN+H$_0$ data combination, we obtain $\beta = 0.111 \pm 0.043$ for the NH case, $\beta = 0.128 \pm 0.043$ for the IH case, and $\beta = 0.092 \pm 0.044$ for the DH case. Now, $\beta > 0$ is preferred at the $2.58\sigma$, $2.98\sigma$, and $2.09\sigma$ levels, respectively. The conclusion is the same as the above three cases, i.e. cold dark matter decaying into DE is supported by the CMB+BAO+SN+H$_0$ data combination.

In summary, for all the $\Lambda$CDM+$\sum m_\nu$ models considered in this paper, the values of $\beta$ are greater by using the CMB+BAO+SN+H$_0$ data combination than using CMB+BAO+SN data combination. We can also intuitively obtain this conclusion by comparing the left and right panels of figures 1–4. Additionally, when using CMB+BAO+SN+H$_0$ data combination, $\beta > 0$ is favored at more than $1\sigma$ level in all the $\Lambda$CDM+$\sum m_\nu$ models, which indicates that cold dark matter decaying into DE is supported in these models.

### 3.3. The $H_0$ tension

In this subsection, we discuss the issue of $H_0$ tension between the Planck observation of the CMB power spectra and the local measurement based on the method of distance ladder. In the $\Lambda$CDM scenario, $\beta > 0$ (in the convention defined in this work) leads to the vacuum energy behaving as an effective phantom, and thus a larger cosmic expansion rate compared with $\Lambda$CDM can be obtained. We therefore can use this scenario to discuss the issue of relaxing the Hubble tension. The detailed fitting results are given in tables 1–5 and figures 5–7.

In table 1, we show the constraint results of the $\Lambda$CDM+$\sum m_\nu$ model by using the CMB+BAO+SN data combination. We obtain $H_0 = 67.48 \pm 0.47 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the NH case, $H_0 = 67.26 \pm 0.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the IH case, and $H_0 = 67.75 \pm 0.49 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the DH case, which are $4.38\sigma$, $4.54\sigma$, and $4.18\sigma$ lower than the direct measurement of the Hubble constant ($H_0 = 74.03 \pm 1.42 \text{ km s}^{-1} \text{ Mpc}^{-1}$). So, we investigate whether the $H_0$ tension can be solved or relieved in the IDE scenario. In tables 2–5, we show the constraint results of the $\Lambda$CDM1+$\sum m_\nu$, $\Lambda$CDM2+$\sum m_\nu$, $\Lambda$CDM3+$\sum m_\nu$, and $\Lambda$CDM4+$\sum m_\nu$ models from the CMB+BAO+SN data combination. In the $\Lambda$CDM1+$\sum m_\nu$ model, we obtain $H_0 = 68.08 \pm 0.81 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the NH case, $H_0 = 68.08^{+0.83}_{-0.82} \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the IH case, and $H_0 = 68.14 \pm 0.83 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the DH case; in the $\Lambda$CDM2+$\sum m_\nu$ model, we obtain $H_0 = 67.83 \pm 0.64 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for
For the IH case, and $H_{0} = 67.96\pm0.80\,\text{km s}^{-1}\,\text{Mpc}^{-1}$ for the DH case; in the $\Lambda$CDM$\,\Lambda$ model, we obtain $H_{0} = 68.03\pm0.81\,\text{km s}^{-1}\,\text{Mpc}^{-1}$ for the NH case, $H_{0} = 67.96\pm0.79\,\text{km s}^{-1}\,\text{Mpc}^{-1}$ for the IH case, and $H_{0} = 68.10\pm0.83\,\text{km s}^{-1}\,\text{Mpc}^{-1}$ for the DH case. For these cases, the tensions with the Hubble constant direct measurement are at the 3.64$\sigma$ level, 3.62$\sigma$ level, 3.58$\sigma$ level, 3.98$\sigma$ level, 4.03$\sigma$ level, 3.91$\sigma$ level, 3.67$\sigma$ level, 3.74$\sigma$ level, 3.61$\sigma$ level, 3.67$\sigma$ level, 3.62$\sigma$ level, and 3.65$\sigma$ level, respectively.

Then, we show the constraint results of these models by using the CMB + BAO + SN data combination (see tables 1–5). In the $\Lambda$CDM$\,\Lambda$ model, we obtain $H_{0} = 68.11\pm0.43\,\text{km s}^{-1}\,\text{Mpc}^{-1}$ for the NH case, $H_{0} = 67.88\pm0.43\,\text{km s}^{-1}\,\text{Mpc}^{-1}$ for the IH case, and $H_{0} = 68.40\pm0.44\,\text{km s}^{-1}\,\text{Mpc}^{-1}$ for the DH case, which indicates that the tensions with the Hubble constant direct measurement are at the 3.99$\sigma$ level 4.14$\sigma$ level and 3.79$\sigma$ level, respectively. In the I$\Lambda$CDM$\,\Lambda$ model, we obtain $H_{0} = 69.64\pm0.72\,\text{km s}^{-1}$.
Mpc$^{-1}$ for the NH case, $H_0 = 69.62^{+0.73}_{-0.72}$ km s$^{-1}$ Mpc$^{-1}$ for the IH case, and $H_0 = 69.67^{+0.74}_{-0.73}$ km s$^{-1}$ Mpc$^{-1}$ for the DH case; in the $\Lambda$CDM+$\sum m_\nu$ model, we obtain $H_0 = 68.92 \pm 0.60$ km s$^{-1}$ Mpc$^{-1}$ for the NH case, $H_0 = 68.83^{+0.61}_{-0.60}$ km s$^{-1}$ Mpc$^{-1}$ for the IH case, and $H_0 = 69.01^{+0.66}_{-0.63}$ km s$^{-1}$ Mpc$^{-1}$ for the DH case; in the $\Lambda$CDM+$\sum m_\nu$ model, we obtain $H_0 = 69.57 \pm 0.72$ km s$^{-1}$ Mpc$^{-1}$ for the NH case, $H_0 = 69.50 \pm 0.74$ km s$^{-1}$ Mpc$^{-1}$ for the IH case, and $H_0 = 69.63^{+0.73}_{-0.72}$ km s$^{-1}$ Mpc$^{-1}$ for the DH case; in the $\Lambda$CDM+$\sum m_\nu$ model, we obtain $H_0 = 69.58 \pm 0.72$ km s$^{-1}$ Mpc$^{-1}$ for the NH case, $H_0 = 69.58 \pm 0.73$ km s$^{-1}$ Mpc$^{-1}$ for the IH case, and $H_0 = 69.58^{+0.73}_{-0.72}$ km s$^{-1}$ Mpc$^{-1}$ for the DH case. The tensions with the Hubble constant direct measurement are at the 2.75σ level, 2.75σ level, 2.72σ level, 3.31σ level, 3.36σ level, 3.25σ level, 2.80σ level, 2.83σ level, 2.76σ level, 2.80σ level, 2.79σ level, and 2.80σ level, respectively.

From the above constraint results, we find that compared with the $\Lambda$CDM+$\sum m_\nu$ model, the $H_0$ tension can indeed be relieved in the $\Lambda$CDM+$\sum m_\nu$ model. From figures 5, 6 we can clearly see that for whichever neutrino mass hierarchy case, the fitting values of $H_0$ in the $\Lambda$CDM+$\sum m_\nu$ models (here, we take $\Lambda$CDM+$\sum m_\nu$ with $Q = \beta H_0 \rho_c$ as an example) are always much larger than those in the $\Lambda$CDM+$\sum m_\nu$ model. We also find that, the CMB+BAO+SN+$H_0$ data combination (about 2.7−3.4σ level) is slightly more effective in relieving the $H_0$ tension than the CMB+BAO+SN data combination (about 3.6−4.0σ level), due to the employment of the $H_0$ prior in the data combination. To visually display the result, we also take the $\Lambda$CDM1+$\sum m_\nu$ model as an example to give this result in figure 7. From these figures, we can clearly see that for whichever hierarchy of the neutrino mass spectrum, the values of $H_0$ are always much larger when adding the $H_0$ data in a cosmological fit. Certainly, the $H_0$ tension problem only can be alleviated to some extent in these cases, but cannot be truly solved. For the issue of $H_0$ tension, further exploration is needed.

4. Conclusion

In this work, we have investigated the constraints on the total neutrino mass in the scenario of vacuum energy interacting with cold dark matter by using the latest cosmological observations. We consider four typical models, i.e., $\Lambda$CDM1+$\sum m_\nu$ ($Q = \beta H_0 \rho_c$) model, $\Lambda$CDM2+$\sum m_\nu$ ($Q = \beta H_0 \rho_c$) model, $\Lambda$CDM3+$\sum m_\nu$ ($Q = \beta H_0 \rho_c$) model, and $\Lambda$CDM4+$\sum m_\nu$ ($Q = \beta H_0 \rho_c$) model. For the three-generation neutrinos, we consider the NH, IH, and DH cases. We employ the extended version of the PPF approach to calculate the perturbation of DE in the IDE cosmology. We use the Planck 2018 CMB data, the BAO measurements, the SN data of Pantheon compilation, and the local measurement of the Hubble constant $H_0$ from the Hubble Space Telescope to constrain these models.

We find that, compared with the $\Lambda$CDM+$\sum m_\nu$ model, these four $\Lambda$CDM+$\sum m_\nu$ models can provide a much looser constraint on the total neutrino mass $\sum m_\nu$. When considering the three mass hierarchies, the upper limits on $\sum m_\nu$ are smallest in the DH case and largest in the IH case. We also find that, the constraints on $\sum m_\nu$ are slightly tighter by using CMB+BAO+SN+$H_0$ than using CMB+BAO+SN. In addition, in all the $\Lambda$CDM+$\sum m_\nu$ models considered in this paper, the fit values of $\beta$ are greater using the CMB+BAO+SN+$H_0$ data combination than using the CMB+BAO+SN data combination, and $\beta > 0$ is favored at more than 1σ level in all the $\Lambda$CDM+$\sum m_\nu$ models when using the CMB+BAO+SN+$H_0$ data combination, implying the preference of cold dark matter decaying into DE. In addition, we also find that, compared with the $\Lambda$CDM+$\sum m_\nu$ model, the $H_0$ tension can be alleviated to some extent in the $\Lambda$CDM+$\sum m_\nu$ models.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11975072, 11875102, 11835009, and 11690021), the Liaoning Revitalization Talents Program (Grant No. XLYC1905011), the Fundamental Research Funds for the Central Universities (Grant No. N2005030), and the Top-Notch Young Talents Program of China (W02070050).

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