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A search for sterile neutrinos with the latest cosmological observations

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Abstract We report the result of a search for sterile neutrinos with the latest cosmological observations. Both cases of massless and massive sterile neutrinos are considered in the ΛCDM cosmology. The cosmological observations used in this work include the Planck 2015 temperature and polarization data, the baryon acoustic oscillation data, the Hubble constant direct measurement data, the Planck Sunyaev–Zeldovich cluster counts data, the Planck lensing data, and the cosmic shear data. We find that the current observational data give a hint of the existence of massless sterile neutrino (as dark radiation) at the 1.44σ level, and the consideration of an extra massless sterile neutrino can indeed relieve the tension between observations and improve the cosmological fit. For the case of massive sterile neutrino, the observations give a rather tight upper limit on the mass, which implies that actually a massless sterile neutrino is more favored. Our result is consistent with the recent result of neutrino oscillation experiment done by the Daya Bay and MINOS collaborations, as well as the recent result of cosmic ray experiment done by the IceCube collaboration.

1 Introduction

Since the discovery of the acceleration of expansion of the universe, dark energy has been proposed to explain the cause of the acceleration phenomenon [1–7]. The cosmological constant Λ [8] is the preferred candidate for dark energy. In practice, the Λ cold dark matter (ΛCDM) model has been achieving successes in fitting various observational data (it is still the best model so far in fitting data; see, e.g., Refs. [9,10]). However, it has been found that several important astrophysical observations are inconsistent with the Planck observation (based on the ΛCDM cosmology), to some extent. For example, the fit results of the six-parameter base ΛCDM model based on the Planck+WP+highL data [11] are in tension with the direct measurement of the Hubble constant [12], the Planck Sunyaev–Zeldovich clusters counts [13], and the cosmic shear measurement of CFHTLenS survey [14].

In our previous work [15], we have shown that involving a light (sub-eV) sterile neutrino species in the ΛCDM model can help to reconcile the tensions between Planck and above-mentioned astrophysical observations (see also Refs. [16–19]). It was shown that [15], under the CMB+BAO constraint, when taking the sterile neutrino into account, the inconsistencies with Planck are improved from 2.4σ to 1.0σ for H_0 observation, from 4.3σ to 2.0σ for SZ cluster counts observation, and from 2.3σ to 1.7σ for cosmic shear observation. For other relevant studies of sterile neutrinos, see, e.g., Refs. [20–30]. Thus, to relieve the tensions in cosmological observations, a natural choice is to consider the model with light sterile neutrinos.

The possibility of the existence of light sterile neutrinos has been motivated to explain the anomalies of short-baseline neutrino experiments [31–40]. It seems that the fully thermalized ($\Delta N_{\rm eff} \approx 1$) sterile neutrinos with eV-scale mass are needed to explain these results [41–43]. The cosmological observations play an important role in constraining the total mass of the active neutrinos (see, e.g., Refs. [44–66]). In fact, since the sterile neutrinos have some effects on the evolution of the universe, the cosmological observations can also provide independent evidence in searching for sterile neutrinos [15].

Recently, some important updated observational data were released. For example, Riess et al. [67] reported the new result of local measurement of the Hubble constant, $H_0 = 73.00\pm1.75$ km s^{-1} Mpc^{-1}, which is 3.3σ higher than the result of 66.93 ± 0.62 km s^{-1} Mpc^{-1} derived by the Planck mission based on the ΛCDM model with $\sum m_\nu = 0.06$ eV using the latest Planck CMB data. Moreover, the BAO measurements were also updated for the CMASS and LOWZ

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galaxy samples, done by the Data Release 12 (DR12) [68] of SDSS-III BOSS (Baryon Oscillation Spectroscopic Survey).

The aim of this work is to search for the sterile neutrinos by using the latest cosmological observations. We shall investigate how the sterile neutrinos can relieve the tensions in the current observations and whether the current cosmological data can provide evidence for the existence of sterile neutrino.

This paper is organized as follows. In Sect. 2, we introduce the analysis method and the observational data we use in this paper. The results are given and discussed in Sect. 3. Conclusion is given in Sect. 4.

2 Analysis method and observational data

In this section, we introduce the analysis method and the observational data that will be used in this paper.

2.1 Analysis method

We will consider the two cases of massless and massive sterile neutrinos in the framework of ΛCDM cosmology. The massless sterile neutrino serves as the dark radiation, and thus when this case is considered, an additional parameter $N_{\rm eff}$ needs to be added in the model; this case is called ΛCDM+$N_{\rm eff}$ model in this paper. When the sterile neutrino is considered to be massive, then one needs to add another extra parameter, $m_{\nu,\rm sterile}^{\rm eff}$, in the model; this case is thus called ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model in this paper.

In the case of massive sterile neutrino, the true mass of a thermally distributed sterile neutrino reads $m_{\rm sterile}^{\rm thermal} = (N_{\rm eff} - 3.046)^{-3/4} m_{\nu,\rm sterile}^{\rm eff}$. In order to avoid a negative $m_{\rm sterile}^{\rm thermal}$, $N_{\rm eff}$ must be larger than 3.046 in a universe with sterile neutrinos. In this work, the active neutrino mass is kept at 0.06 eV (i.e., the minimal-mass normal hierarchy is assumed).

We place constraints on the ΛCDM cosmology with sterile neutrinos by using the current observational data. The conventions used in this paper are consistent with those adopted by the Planck collaboration [69], i.e., those used in the camb Boltzmann code [70]. There are six independent cosmological parameters in the base ΛCDM model,

$$\mathbf{P} = \{\omega_b,\ \omega_c,\ 100\theta_{\rm MC},\ \tau,\ \ln(10^{10}A_s),\ n_s\},$$

where $\omega_b \equiv \Omega_b h^2$ and $\omega_c \equiv \Omega_c h^2$ are the present-day baryon and cold dark matter densities, respectively, $\theta_{\rm MC}$ is the ratio between the sound horizon and the angular diameter distance at the decoupling epoch, τ is the Thomson scattering optical depth due to reionization, A_s is the amplitude of initial curvature perturbation power spectrum at $k = 0.05$ Mpc^{-1}, and n_s is its spectral index. In addition, there are two additional free parameters, $N_{\rm eff}$ and $m_{\nu,\rm sterile}^{\rm eff}$, for describing the sterile neutrino. Thus, there are seven independent parameters in total for the ΛCDM+$N_{\rm eff}$ model, and there are eight independent parameters in total for the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model. Other parameters, such as $\Omega_{\rm m}$, σ_8, H_0, and so on, are the derived parameters.

We use the CosmoMC package [71] to infer the posterior probability distributions of parameters. Flat priors for the base parameters are used. The prior ranges for the base parameters are chosen to be much wider than the posterior ranges in order not to affect the results of parameter estimation.

2.2 Observational data

In this paper, the data sets we use include the cosmic microwave background (CMB), the baryon acoustic oscillations (BAO), the Hubble constant (H_0), the Planck Sunyaev–Zeldovich (SZ), the Planck lensing, and the weak lensing (WL) observations.

The CMB data: We use the Planck 2015 CMB temperature and polarization data [72] in our calculations. We consider the combination of the likelihood at $30 \le \ell \le 2500$ in the temperature (TT), the cross-correlation of temperature and polarization (TE), and the polarization (EE) power spectra and the Planck low-ℓ likelihood in the range of $2 \le \ell \le 29$, which is denoted "Planck TT,TE,EE+lowP", following the nomenclature of the Planck collaboration [69].

The BAO data: In order to break the geometric degeneracy, it is necessary to consider the BAO data. We use the LOWZ ($z_{\rm eff} = 0.32$) and CMASS ($z_{\rm eff} = 0.57$) samples of BOSS DR12 [68], as well as the 6dFGS (six-degree-field galaxy survey) ($z_{\rm eff} = 0.106$) sample [73] and the SDSS MGS (main galaxy sample) ($z_{\rm eff} = 0.15$) sample [74].

The H_0 measurement: We use the recently measured new local value of the Hubble constant, $H_0 = 73.00 \pm 1.75$ km s^{-1} Mpc^{-1}, reported in Ref. [67].

The SZ data: The counts of rich clusters of galaxies are from the sample of Planck thermal Sunyaev–Zeldovich (SZ) cluster observation [75].

The Lensing data: We use the Planck lensing data [76], which provide additional information at low redshift.

The WL data: We use the cosmic shear data of weak lensing (WL) from the CFHTLenS survey [77].

In what follows, we will use these observational data to place constraints on the ΛCDM cosmology with sterile neutrinos. We will compare the ΛCDM, ΛCDM+$N_{\rm eff}$, and ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ models under the uniform data sets. The basic data combination adopted in this paper is the Planck TT,TE,EE+lowP+BAO combination. In order to show the impacts from the other astrophysical observations on measuring the properties of the sterile neutrino, we also further combine the H_0+SZ+Lensing+WL data in the analysis. Thus, in our analysis, we use the two data combinations: (i) Planck TT,TE,EE+lowP+BAO, and (ii) Planck TT,TE,EE+lowP+BAO+H_0+SZ+Lensing+WL. For convenience, we occasionally use the abbreviations "CMB+BAO" and "CMB+BAO+other" for them in the paper. In the next section, we will report and discuss the fitting results of the cosmological models in the light of these data sets.

3 Results and discussion

In this section, we report the fitting results of the cosmological models (the ΛCDM model, the ΛCDM+$N_{\rm eff}$ model, and the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model) and discuss the implications of these results in the search for sterile neutrinos. We will discuss the cases of massless and massive sterile neutrinos, respectively, in the two subsections.

Detailed fit values for the three models for cosmological parameters are given in Table 1. In the table, we quote the $\pm 1\sigma$ errors, but for the parameters that cannot be well constrained, we quote the 95.4% CL upper limits.

When we make comparison for the three models from the statistical point of view, we must be aware of the fact that they have different numbers of parameters. In general, a model with more parameters tends to give a better fit to the same data, i.e., it tends to have a smaller $\chi^2_{\rm min}$. Thus, when the comparison is made for models with different parameter numbers, the simple comparison of $\chi^2_{\rm min}$ is not appropriate because it is unfair. A punishment mechanism must be considered for those models with more parameters. The simplest way, for our purpose in this work, is to consider the Akaike information criterion (AIC) [78], with the definition AIC $= \chi^2_{\rm min} + 2k$, where k is the number of parameters of a model. A model with a lower AIC is more favored by data. So, when we make model selection for two models, we will calculate the difference of AIC for them, i.e., $\Delta{\rm AIC} = \Delta\chi^2_{\rm min} + 2\Delta k$. In the case of this paper, we take the ΛCDM model as a reference model, and thus the ΛCDM+$N_{\rm eff}$ model has $\Delta k = 1$ and the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model has $\Delta k = 2$. They are considered to be more favored over the ΛCDM model provided that the ΛCDM+$N_{\rm eff}$ model has $\Delta\chi^2 < -2$ and the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model has $\Delta\chi^2 < -4$.

3.1 The case of massless sterile neutrino

The massless sterile neutrinos serve as the dark radiation, and thus in this case the effective number of relativistic species $N_{\rm eff}$ is treated as a free parameter. The total energy density of radiation in the universe is given by

$$\rho_r = \left[1 + N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\right]\rho_\gamma,$$

Table 1 Fitting results for the ΛCDM model, the ΛCDM+$N_{\rm eff}$ model, and the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model. We quote $\pm 1\sigma$ errors, but for the parameters that cannot be well constrained, we quote the 95.4% CL upper limits

Data	Planck TT,TE,EE+lowP+BAO			Planck TT,TE,EE+lowP+BAO+H_0+SZ+lensing+WL		
Model	ΛCDM	ΛCDM+$N_{\rm eff}$	ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$	ΛCDM	ΛCDM+$N_{\rm eff}$	ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$
$\Omega_b h^2$	0.0223 ± 0.0001	0.0225 ± 0.0002	0.0224 ± 0.0002	0.0224 ± 0.0001	0.0226 ± 0.0002	0.0226 ± 0.0002
$\Omega_c h^2$	0.1186 ± 0.0010	$0.1212^{+0.0017}_{-0.0027}$	$0.1187^{+0.0044}_{-0.0027}$	0.1175 ± 0.0010	$0.1214^{+0.0021}_{-0.0028}$	$0.1210^{+0.0026}_{-0.0031}$
$100\theta_{\rm MC}$	1.0409 ± 0.0003	1.0406 ± 0.0004	$1.0407^{+0.0004}_{-0.0003}$	1.0411 ± 0.0003	1.0406 ± 0.0004	1.0407 ± 0.0004
τ	$0.085^{+0.017}_{-0.016}$	$0.088^{+0.018}_{-0.017}$	0.090 ± 0.017	0.072 ± 0.012	0.071 ± 0.012	0.079 ± 0.014
$\ln(10^{10}A_s)$	$3.103^{+0.033}_{-0.032}$	$3.114^{+0.036}_{-0.033}$	$3.116^{+0.034}_{-0.035}$	3.072 ± 0.022	3.081 ± 0.023	3.096 ± 0.028
n_s	$0.9676^{+0.0039}_{-0.0040}$	$0.9732^{+0.0055}_{-0.0064}$	$0.9719^{+0.0050}_{-0.0078}$	$0.9699^{+0.0040}_{-0.0039}$	$0.9774^{+0.0056}_{-0.0058}$	$0.9789^{+0.0064}_{-0.0073}$
$m_{\nu,\rm sterile}^{\rm eff}$	…	…	<0.7279	…	…	<0.2417
$N_{\rm eff}$	…	<3.4384	<3.4273	…	$3.29^{+0.11}_{-0.17}$	$3.30^{+0.12}_{-0.20}$
Ω_m	$0.3080^{+0.0061}_{-0.0062}$	0.3048 ± 0.0067	$0.3085^{+0.0067}_{-0.0068}$	$0.3011^{+0.0057}_{-0.0058}$	$0.2975^{+0.0059}_{-0.0064}$	$0.3010^{+0.0065}_{-0.0070}$
σ_8	0.832 ± 0.013	0.841 ± 0.015	$0.817^{+0.030}_{-0.021}$	$0.8154^{+0.0085}_{-0.0084}$	$0.826^{+0.010}_{-0.011}$	$0.814^{+0.018}_{-0.013}$
H_0	$67.81^{+0.47}_{-0.46}$	$68.81^{+0.71}_{-1.02}$	$68.30^{+0.53}_{-1.00}$	68.33 ± 0.45	$69.71^{+0.84}_{-1.01}$	$69.44^{+0.84}_{-1.14}$
$\chi^2_{\rm min}$	12952.922	12952.976	12953.554	13140.214	13138.042	13141.042

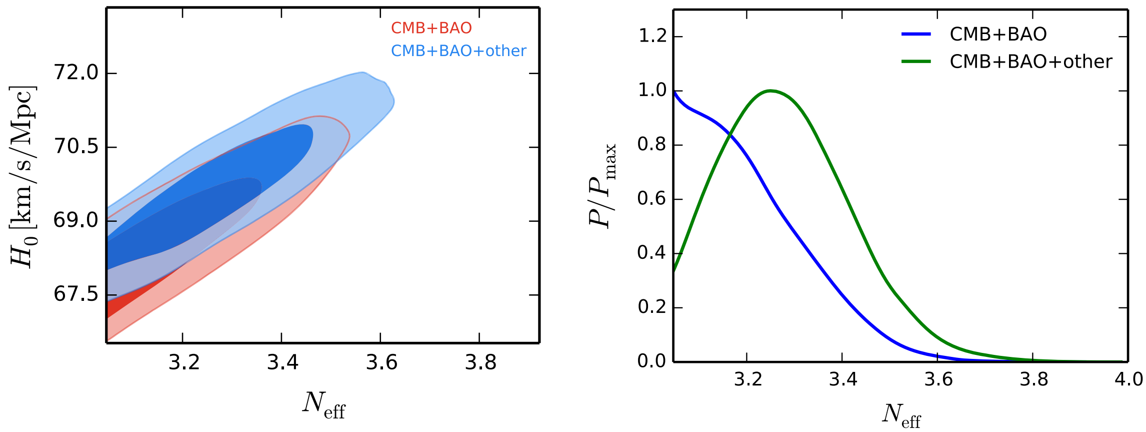

Fig. 1 Constraint results for the ΛCDM+$N_{\rm eff}$ model from the CMB+BAO data combination and the CMB+BAO+other data combination. *Left panel* Two-dimensional marginalized posterior contours (68.3 and 95.4% CL) in the $N_{\rm eff}$–H_0 plane. *Right panel* One-dimensional marginalized posterior distributions for $N_{\rm eff}$

where ρ_γ is the energy density of photons. The standard case of three-generation neutrinos leads to $N_{\rm eff} = 3.046$ [79,80]. The detection of $\Delta N_{\rm eff} = N_{\rm eff} - 3.046 > 0$ indicates the presence of extra relativistic particle species in the universe, and in this paper we take the fitting result of $\Delta N_{\rm eff} > 0$ as evidence of the existence of massless sterile neutrinos.

In this subsection, we constrain the ΛCDM+$N_{\rm eff}$ model by using two combinations of data sets, namely, the CMB+BAO and CMB+BAO+other combinations. As mentioned above, hereafter, we shall use "CMB" to denote Planck TT,TE,EE+ lowP and use "other" to denote H_0+SZ+lensing+WL. The free parameters include six base parameters and $N_{\rm eff}$, and we fix the active neutrino mass $\sum m_\nu = 0.06$ eV (two massless and one massive active neutrinos). The results of constraints on $N_{\rm eff}$ can be found in Table 1, and in this table the constraint results of other free parameters are also listed.

To directly show how the effective number of relativistic species $N_{\rm eff}$ affects the constraints on H_0, we plot the two-dimensional posterior distribution contours (68.3% and 95.4% CL) in the $N_{\rm eff}$–H_0 plane for the ΛCDM+$N_{\rm eff}$ model, under the constraints from the two data combinations in the left panel of Fig. 1. We find that, in the ΛCDM+$N_{\rm eff}$ model, H_0 is positively correlated with $N_{\rm eff}$, for the two data combinations. Moreover, under the constrains of CMB+BAO+other data, the ΛCDM model gives $H_0 = 68.33\pm0.45$ km s^{-1} Mpc^{-1}, and the ΛCDM+$N_{\rm eff}$ model gives $H_0 = 69.71^{+0.84}_{-1.01}$ km s^{-1} Mpc^{-1}, indicating that the tension with the direct measurement of Hubble constant, $H_0 = 73.00\pm1.75$ km s^{-1} Mpc^{-1}, is relieved to be at 2.58σ level and 1.69σ level, respectively. Therefore, the addition of the parameter $N_{\rm eff}$ can indeed relieve the tension between Planck data and H_0 direct measurement.

In the right panel of Fig. 1, we show the one-dimensional marginalized posterior distributions of $N_{\rm eff}$ for the ΛCDM+ $N_{\rm eff}$ model using the two data combinations. We find that the CMB+BAO data can only give an upper limit, $N_{\rm eff} < 3.44$ (95.4% CL), but the CMB+BAO+other data can well constrain $N_{\rm eff}$, giving the result of $N_{\rm eff} = 3.29^{+0.11}_{-0.17}$, which indicates a detection of $\Delta N_{\rm eff} > 0$ at the 1.44σ level.

Fitting to the CMB+BAO data, the ΛCDM and ΛCDM+ $N_{\rm eff}$ models yield a similar $\chi^2_{\rm min}$, implying that with this data combination adding the parameter $N_{\rm eff}$ cannot improve the fit. But, when fitting to the CMB+BAO+other data, the ΛCDM+$N_{\rm eff}$ model leads to an increase of $\Delta\chi^2 = -2.172$, compared to the ΛCDM model, indicating that in this case the addition of the parameter $N_{\rm eff}$ can evidently improve the fit. Actually, when we use the information criterion to make a model selection, we have ΔAIC $= -0.172$ for the ΛCDM+$N_{\rm eff}$ model in this case, which shows that the ΛCDM+$N_{\rm eff}$ model is only slightly better than the ΛCDM model from the statistical point of view.

Therefore, we find that the current CMB+BAO+other data can give a hint of the existence of massless sterile neutrino (as dark radiation) at the 1.44σ level, and the consideration of an extra massless sterile neutrino can indeed relieve the tension between observations and improve the cosmological fit.

3.2 The case of massive sterile neutrino

In this subsection, we further consider the case of massive sterile neutrino, i.e., we consider two extra parameters, $N_{\rm eff}$ and $m_{\nu,\rm sterile}^{\rm eff}$, compared to the ΛCDM model.

We make a comparison for the ΛCDM model and ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model using the two data combinations. In Fig. 2, we show the posterior distribution contours in the $\Omega_{\rm m}$–H_0 plane, for the two models. In the left panel, we show the case of fitting to the CMB+BAO data,

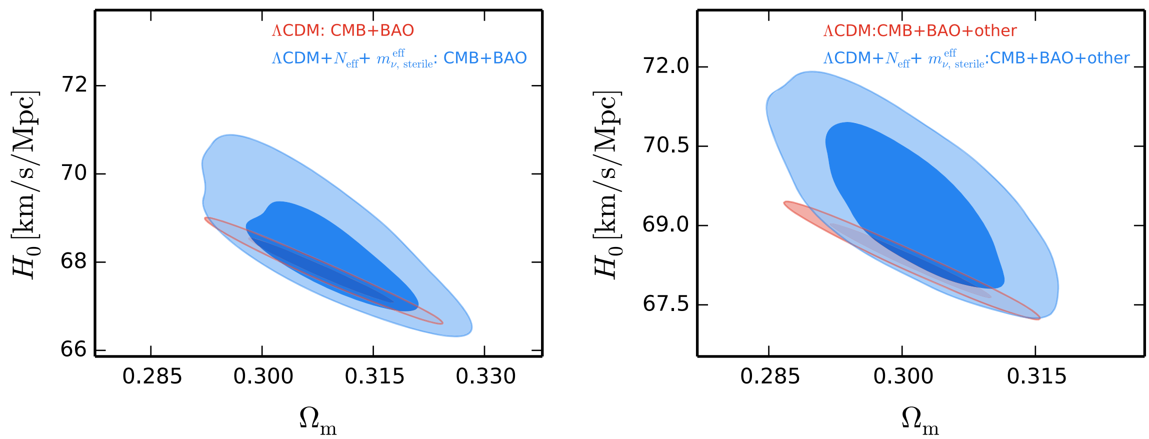

Fig. 2 The two-dimensional marginalized contours (68.3 and 95.4% CL) in the Ω_m–H_0 plane, for the ΛCDM and ΛCDM+$N_{\rm eff}$+$m^{\rm eff}_{\nu,\rm sterile}$ models, from the constraints of CMB+BAO (*left*) and CMB+BAO+other (*right*)

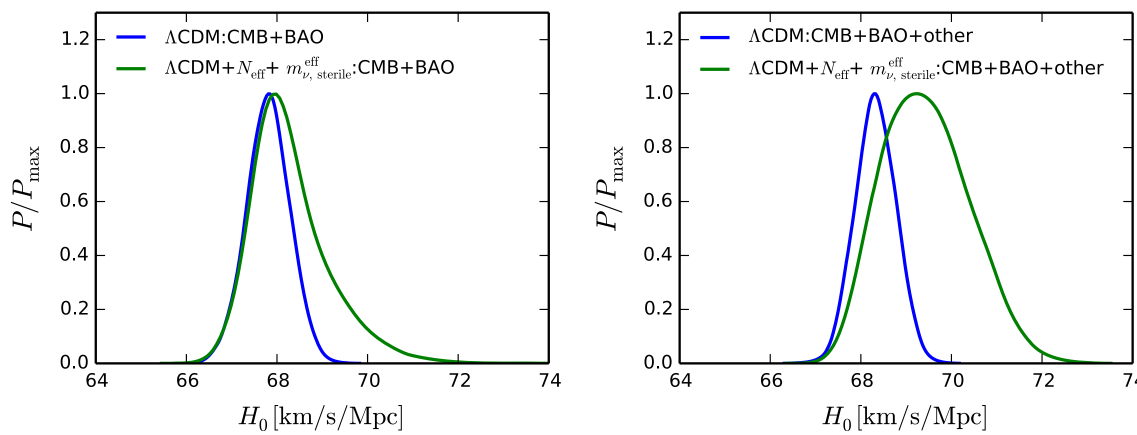

Fig. 3 The one-dimensional posterior distributions of H_0 in the ΛCDM and ΛCDM+$N_{\rm eff}$+$m^{\rm eff}_{\nu,\rm sterile}$ models, from the constraints of CMB+BAO (*left*) and CMB+BAO+other (*right*)

and in the right panel, we show the case of fitting to the CMB+BAO+other data. We find that H_0 is anti-correlated with $\Omega_{\rm m}$ in the two models, and the consideration of massive sterile neutrino amplifies the parameter space, in particular, in the direction of H_0. Actually, the involvement of massive sterile neutrino can indeed give a much higher value of H_0.

We show the one-dimensional posterior distributions of H_0 for the two models in Fig. 3 (left panel for CMB+BAO and right panel for CMB+BAO+other). From this figure, we can clearly see that once the massive sterile neutrino is considered in cosmology, then under the constraint of CMB+BAO+other data the fit value of H_0 can become much larger. Under the constraints of CMB+BAO data, we obtain $H_0 = 67.81^{+0.47}_{-0.46}$ km s^{-1} Mpc^{-1} for the ΛCDM model and $H_0 = 68.30^{+0.53}_{-1.00}$ km s^{-1} Mpc^{-1} for the ΛCDM+$N_{\rm eff}$+$m^{\rm eff}_{\nu,\rm sterile}$ model, which indicates that the consideration of massive sterile neutrino improves the tension with the Hubble constant direct measurement ($H_0 = 73.00 \pm 1.75$ km s^{-1} Mpc^{-1}) from 2.86σ to 2.57σ. So, in this case, the tension can only be slightly relieved. Under the constraints of CMB+BAO+other data, we obtain $H_0 = 68.33 \pm 0.45$ km s^{-1} Mpc^{-1} for the ΛCDM model and $H_0 = 69.44^{+0.84}_{-1.14}$ km s^{-1} Mpc^{-1} for the ΛCDM+$N_{\rm eff}$+$m^{\rm eff}_{\nu,\rm sterile}$ model, which indicates that the involvement of massive sterile neutrino improves the tension from 2.58σ to 1.83σ. Thus, in this case, the tension can be largely relieved. But we must admit that the improvement for the tension (from 2.58σ to 1.83σ) is mainly owing to the fact that the introduction of two extra parameters leads to the posterior distribution of H_0 becoming much broader (see the right panel of Fig. 3).

Then we show the constraint results for the parameters $N_{\rm eff}$ and $m^{\rm eff}_{\nu,\rm sterile}$ in the ΛCDM+$N_{\rm eff}$+$m^{\rm eff}_{\nu,\rm sterile}$ model (see Table 1):

$$\left.\begin{array}{r}N_{\rm eff} < 3.4273\\ m^{\rm eff}_{\nu,\rm sterile} < 0.7279\ {\rm eV}\end{array}\right\}\quad \text{CMB+BAO},$$

$$\left.\begin{array}{r}N_{\rm eff} = 3.30^{+0.12}_{-0.20}\\ m^{\rm eff}_{\nu,\rm sterile} < 0.2417\ {\rm eV}\end{array}\right\}\quad \text{CMB+BAO+other}.$$

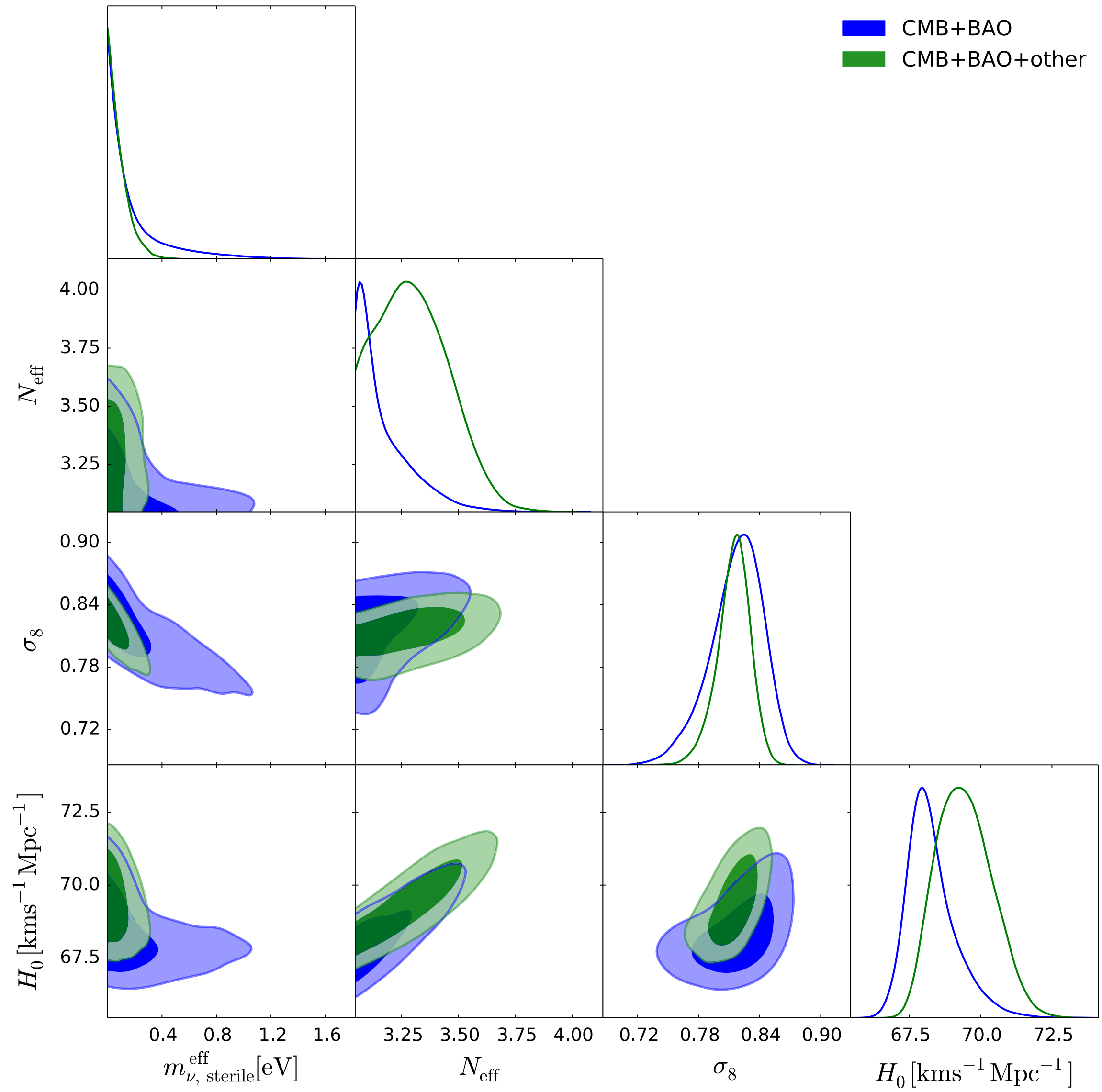

Fig. 4 The one-dimensional posterior distributions and two-dimensional marginalized contours (68.3 and 95.4% CL) for the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model, from the constraints of the CMB+BAO and CMB+BAO+other data combinations

We find that $N_{\rm eff}$ cannot be well constrained using only the CMB+BAO data, but the addition of H_0, SZ, Lensing, and WL data can significantly improve the constraint on $N_{\rm eff}$, favoring $\Delta N_{\rm eff} > 0$ at the 1.27σ statistical significance. For the mass of sterile neutrino, the CMB+BAO data give $m_{\nu,\rm sterile}^{\rm eff} < 0.7279$ eV (95.4% CL), and further including the H_0+SZ+Lensing+WL data leads to the result of $m_{\nu,\rm sterile}^{\rm eff} < 0.2417$ eV (95.4% CL). Evidently, adding low-redshift data tightens the constraint on $m_{\nu,\rm sterile}^{\rm eff}$ significantly. This indicates that the SZ cluster data (as well as the H_0, Lensing, and WL data) play an important role in constraining the mass of sterile neutrino. In Fig. 4, we show the one- and two-dimensional marginalized posterior distributions of the parameters $N_{\rm eff}$, $m_{\nu,\rm sterile}^{\rm eff}$, σ_8, and H_0, for the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model. We find that, in the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model, σ_8 is anti-correlated with $m_{\nu,\rm sterile}^{\rm eff}$, and H_0 is positively correlated with $N_{\rm eff}$, which leads to the fact that considering massive sterile neutrinos in cosmology can effectively relieve the tensions among the current observations.

Compared to the ΛCDM model, the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model does not provide an improved fit to the current observational data. Considering the massive sterile neutrino in cosmology leads to an increase of $\Delta\chi^2 = 0.632$ under the CMB+BAO constraint and an increase of $\Delta\chi^2 = 0.828$ under the CMB+BAO+other constraint. That is to say, the ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$ model has ΔAIC = 4.632 and 4.828 for the two data-combination cases, which shows that the massive sterile neutrino is not favored by the current cosmological observations.

Therefore, we find that the current CMB+BAO+other data give a rather tight upper limit on $m^{\rm eff}_{\nu,\rm sterile}$ and favor $\Delta N_{\rm eff} > 0$ at the 1.27σ level. Together with the constraint results for the massless sterile neutrino, we can conclude that the current observations do not seem to favor a massive sterile neutrino, but favor a massless sterile neutrino in some sense (only at the more than 1σ statistical significance). Our result is consistent with the recent result of neutrino oscillation experiment by the Daya Bay and MINOS collaborations [81], as well as the recent result of cosmic ray experiment by the IceCube collaboration [82].

4 Conclusion

The aim of this work is to search for sterile neutrinos using the latest cosmological observations. We consider the two cases of massless and massive sterile neutrinos, corresponding to the ΛCDM+$N_{\rm eff}$ model and the ΛCDM+$N_{\rm eff}$+$m^{\rm eff}_{\nu,\rm sterile}$ model, respectively. The observational data used in this paper include the Planck TT,TE,EE+lowP data, the BAO data, the H_0 direct measurement, the Planck SZ cluster counts data, the Planck CMB lensing data, and the cosmic shear data.

For the ΛCDM+$N_{\rm eff}$ model, the CMB+BAO+other data give $N_{\rm eff} = 3.29^{+0.11}_{-0.17}$ (68.3% CL), favoring $\Delta N_{\rm eff} = N_{\rm eff} - 3.046 > 0$ at the 1.44σ level. Therefore, there is a hint of the existence of massless sterile neutrinos, from the current cosmological observations. We also find that the addition of the parameter $N_{\rm eff}$ can indeed relieve the tension between the Planck observation and the recent H_0 direct measurement (the tension is reduced to be at the 1.69σ level).

For the ΛCDM+$N_{\rm eff}$+$m^{\rm eff}_{\nu,\rm sterile}$ model, using the CMB+BAO data, we obtain $m^{\rm eff}_{\nu,\rm sterile} < 0.7279$ eV (95.4% CL) and $N_{\rm eff} < 3.4273$ (95.4% CL). Thus, in this case, only upper limits on $N_{\rm eff}$ and $m^{\rm eff}_{\nu,\rm sterile}$ (for the massive sterile neutrino) can be derived. Further including the other (H_0+SZ+Lensing+WL) data significantly improves the constraints, and in this case we obtain $m^{\rm eff}_{\nu,\rm sterile} < 0.2417$ eV (95.4% CL) and $N_{\rm eff} = 3.30^{+0.12}_{-0.20}$ (68.3% CL). Thus, the current observations give a rather tight upper limit on $m^{\rm eff}_{\nu,\rm sterile}$ and favor $\Delta N_{\rm eff} > 0$ at the 1.27σ level. This result seems to favor a massless sterile neutrino, in tension with the previous short-baseline neutrino oscillation experiments that prefer the mass of sterile neutrino at around 1 eV. But our result is consistent with the recent result of neutrino oscillation experiment done by the Daya Bay and MINOS collaborations [81], as well as the recent result of cosmic ray experiment done by the IceCube collaboration [82].

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References

1. V. Sahni, A.A. Starobinsky, The case for a positive cosmological lambda-term. Int. J. Mod. Phys. D **9**, 373 (2000). arXiv:astro-ph/9904398
2. P.J.E. Peebles, B. Ratra, The cosmological constant and dark energy. Rev. Mod. Phys. **75**, 559 (2003). arXiv:astro-ph/0207347
3. T. Padmanabhan, Cosmological constant: the weight of the vacuum. Phys. Rep. **380**, 235 (2003). arXiv:hep-th/0212290
4. J. Frieman, M. Turner, D. Huterer, Dark energy and the accelerating universe. Ann. Rev. Astron. Astrophys. **46**, 385 (2008). arXiv:0803.0982 [astro-ph]
5. D.H. Weinberg, M.J. Mortonson, D.J. Eisenstein, C. Hirata, A.G. Riess, E. Rozo, Observational probes of cosmic acceleration. Phys. Rep. **530**, 87 (2013). arXiv:1201.2434 [astro-ph.CO]
6. M.J. Mortonson, D.H. Weinberg, M. White, Dark energy: a short review. arXiv:1401.0046 [astro-ph.CO]
7. S. Wang, Y. Wang, M. Li, Holographic dark energy. arXiv:1612.00345 [astro-ph.CO]
8. A. Einstein, Cosmological considerations in the general theory of relativity. Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.) **1917**, 142 (1917)
9. M. Li, X. Li, X. Zhang, Comparison of dark energy models: a perspective from the latest observational data. Sci. China Phys. Mech. Astron. **53**, 1631 (2010). arXiv:0912.3988 [astro-ph.CO]
10. Y.Y. Xu, X. Zhang, Comparison of dark energy models after Planck 2015. Eur. Phys. J. C **76**(11), 588 (2016). arXiv:1607.06262 [astro-ph.CO]
11. P.A.R. Ade et al. (Planck Collaboration), Planck 2013 results. XVI. Cosmological parameters. Astron. Astrophys. **571**, A16 (2014). arXiv:1303.5076 [astro-ph.CO]
12. A.G. Riess et al., A 3% solution: determination of the hubble constant with the hubble space telescope and wide field camera 3. Astrophys. J. **730**, 119 (2011). arXiv:1103.2976 [astro-ph.CO] [Erratum: Astrophys. J. **732**, 129 (2011)]
13. P.A.R. Ade et al. (Planck Collaboration), Planck 2013 results. XX. Cosmology from Sunyaev–Zeldovich cluster counts. Astron. Astrophys. **571**, A20 (2014). arXiv:1303.5080 [astro-ph.CO]
14. J. Benjamin et al., CFHTLenS tomographic weak lensing: quantifying accurate redshift distributions. Mon. Not. R. Astron. Soc. **431**, 1547 (2013). arXiv:1212.3327 [astro-ph.CO]
15. J.F. Zhang, X. Zhang, Sterile neutrinos help reconcile the observational results of primordial gravitational waves from Planck and BICEP2. Phys. Lett. B **740**, 359 (2015). arXiv:1403.7028 [astro-ph.CO]
16. C. Dvorkin, M. Wyman, D.H. Rudd, W. Hu, Neutrinos help reconcile Planck measurements with both the early and local Universe. Phys. Rev. D **90**(8), 083503 (2014). arXiv:1403.8049 [astro-ph.CO]
17. J. Hamann, J. Hasenkamp, A new life for sterile neutrinos: resolving inconsistencies using hot dark matter. JCAP **1310**, 044 (2013). arXiv:1308.3255 [astro-ph.CO]

18. M. Wyman, D.H. Rudd, R.A. Vanderveld, W. Hu, Neutrinos help reconcile Planck measurements with the local Universe. Phys. Rev. Lett. **112**(5), 051302 (2014). arXiv:1307.7715 [astro-ph.CO]
19. R.A. Battye, A. Moss, Evidence for massive neutrinos from cosmic microwave background and lensing observations. Phys. Rev. Lett. **112**(5), 051303 (2014). arXiv:1308.5870 [astro-ph.CO]
20. A. Palazzo, Phenomenology of light sterile neutrinos: a brief review. Mod. Phys. Lett. A **28**, 1330004 (2013). arXiv:1302.1102 [hep-ph]
21. P. Ko, Y. Tang, $\nu\Lambda$MDM: a model for sterile neutrino and dark matter reconciles cosmological and neutrino oscillation data after BICEP2. Phys. Lett. B **739**, 62 (2014). arXiv:1404.0236 [hep-ph]
22. M. Archidiacono, N. Fornengo, S. Gariazzo, C. Giunti, S. Hannestad, M. Laveder, Light sterile neutrinos after BICEP-2. JCAP **1406**, 031 (2014). arXiv:1404.1794 [astro-ph.CO]
23. J.F. Zhang, Y.H. Li, X. Zhang, Cosmological constraints on neutrinos after BICEP2. Eur. Phys. J. C **74**, 2954 (2014). arXiv:1404.3598 [astro-ph.CO]
24. M. Archidiacono, S. Hannestad, R.S. Hansen, T. Tram, Cosmology with self-interacting sterile neutrinos and dark matter—a pseudoscalar model. Phys. Rev. D **91**(6), 065021 (2015). arXiv:1404.5915 [astro-ph.CO]
25. Y.H. Li, J.F. Zhang, X. Zhang, Tilt of primordial gravitational wave spectrum in a universe with sterile neutrinos. Sci. China Phys. Mech. Astron. **57**, 1455 (2014). arXiv:1405.0570 [astro-ph.CO]
26. F.P. An et al. (Daya Bay Collaboration), Search for a light sterile neutrino at Daya Bay. Phys. Rev. Lett. **113**, 141802 (2014). arXiv:1407.7259 [hep-ex]
27. J.F. Zhang, J.J. Geng, X. Zhang, Neutrinos and dark energy after Planck and BICEP2: data consistency tests and cosmological parameter constraints. JCAP **1410**(10), 044 (2014). arXiv:1408.0481 [astro-ph.CO]
28. J.F. Zhang, Y.H. Li, X. Zhang, Measuring growth index in a universe with sterile neutrinos. Phys. Lett. B **739**, 102 (2014). arXiv:1408.4603 [astro-ph.CO]
29. Y.H. Li, J.F. Zhang, X. Zhang, Probing $f(R)$ cosmology with sterile neutrinos via measurements of scale-dependent growth rate of structure. Phys. Lett. B **744**, 213 (2015). arXiv:1502.01136 [astro-ph.CO]
30. P.C. de Holanda, A.Y. Smirnov, Solar neutrino spectrum, sterile neutrinos and additional radiation in the Universe. Phys. Rev. D **83**, 113011 (2011). arXiv:1012.5627 [hep-ph]
31. S. Gariazzo, C. Giunti, M. Laveder, Light sterile neutrinos in cosmology and short-baseline oscillation experiments. JHEP **1311**, 211 (2013). arXiv:1309.3192 [hep-ph]
32. C. Giunti, M. Laveder, Y.F. Li, H.W. Long, Pragmatic view of short-baseline neutrino oscillations. Phys. Rev. D **88**, 073008 (2013). arXiv:1308.5288 [hep-ph]
33. J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, Sterile neutrino oscillations: the global picture. JHEP **1305**, 050 (2013). arXiv:1303.3011 [hep-ph]
34. C. Giunti, M. Laveder, Y.F. Li, H.W. Long, Short-baseline electron neutrino oscillation length after Troitsk. Phys. Rev. D **87**(1), 013004 (2013). arXiv:1212.3805 [hep-ph]
35. C. Giunti, M. Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, Update of short-baseline electron neutrino and antineutrino disappearance. Phys. Rev. D **86**, 113014 (2012). arXiv:1210.5715 [hep-ph]
36. A.A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), A combined $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation analysis of the MiniBooNE excesses. arXiv:1207.4809 [hep-ex]
37. J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, J. Spitz, Sterile neutrino fits to short baseline neutrino oscillation measurements. Adv. High Energy Phys. **2013**, 163897 (2013). arXiv:1207.4765 [hep-ex]
38. G. Mention, M. Fechner, T. Lasserre, T.A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau, The reactor antineutrino anomaly. Phys. Rev. D **83**, 073006 (2011). arXiv:1101.2755 [hep-ex]
39. C. Giunti, M. Laveder, Statistical significance of the gallium anomaly. Phys. Rev. C **83**, 065504 (2011). arXiv:1006.3244 [hep-ph]
40. A. Aguilar-Arevalo et al. (LSND Collaboration), Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam, Phys. Rev. D **64**, 112007 (2001). arXiv:hep-ex/0104049
41. K.N. Abazajian et al., Light sterile neutrinos: a white paper. arXiv:1204.5379 [hep-ph]
42. S. Hannestad, I. Tamborra, T. Tram, Thermalisation of light sterile neutrinos in the early universe. JCAP **1207**, 025 (2012). arXiv:1204.5861 [astro-ph.CO]
43. J.M. Conrad, W.C. Louis, M.H. Shaevitz, The LSND and MiniBooNE oscillation searches at high Δm^2. Ann. Rev. Nucl. Part. Sci. **63**, 45 (2013). arXiv:1306.6494 [hep-ex]
44. M.M. Zhao, Y.H. Li, J.F. Zhang, X. Zhang, Constraining neutrino mass and extra relativistic degrees of freedom in dynamical dark energy models using Planck 2015 data in combination with low-redshift cosmological probes: basic extensions to ΛCDM cosmology. Mon. Not. Roy. Astron. Soc. **469**, 1713 (2017). arXiv:1608.01219 [astro-ph.CO]
45. S. Wang, Y.F. Wang, D.M. Xia, X. Zhang, Impacts of dark energy on weighing neutrinos: mass hierarchies considered. Phys. Rev. D **94**(8), 083519 (2016). arXiv:1608.00672 [astro-ph.CO]
46. Q.G. Huang, K. Wang, S. Wang, Constraints on the neutrino mass and mass hierarchy from cosmological observations. Eur. Phys. J. C **76**(9), 489 (2016). arXiv:1512.05899 [astro-ph.CO]
47. X. Zhang, Impacts of dark energy on weighing neutrinos after Planck 2015. Phys. Rev. D **93**(8), 083011 (2016). arXiv:1511.02651 [astro-ph.CO]
48. J.F. Zhang, M.M. Zhao, Y.H. Li, X. Zhang, Neutrinos in the holographic dark energy model: constraints from latest measurements of expansion history and growth of structure. JCAP **1504**, 038 (2015). arXiv:1502.04028 [astro-ph.CO]
49. Y.H. Li, S. Wang, X.D. Li, X. Zhang, Holographic dark energy in a Universe with spatial curvature and massive neutrinos: a full Markov Chain Monte Carlo exploration. JCAP **1302**, 033 (2013). arXiv:1207.6679 [astro-ph.CO]
50. J. Lesgourgues, S. Pastor, Massive neutrinos and cosmology. Phys. Rep. **429**, 307 (2006). arXiv:astro-ph/0603494
51. M. Drewes, The phenomenology of right handed neutrinos. Int. J. Mod. Phys. E **22**, 1330019 (2013). arXiv:1303.6912 [hep-ph]
52. M.C. Gonzalez-Garcia, M. Maltoni, Phenomenology with massive neutrinos. Phys. Rep. **460**, 1 (2008). arXiv:0704.1800 [hep-ph]
53. X. Zhang, Weighing neutrinos in dynamical dark energy models. Sci. China Phys. Mech. Astron. **60**(6), 060431 (2017). arXiv:1703.00651 [astro-ph.CO]
54. R.Y. Guo, Y.H. Li, J.F. Zhang, X. Zhang, Weighing neutrinos in the scenario of vacuum energy interacting with cold dark matter: application of the parameterized post-Friedmann approach. JCAP **1705**, 040 (2017). arXiv:1702.04189 [astro-ph.CO]
55. F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri, A. Palazzo, Global constraints on absolute neutrino masses and their ordering. Phys. Rev. D **95**, 096014 (2017). arXiv:1703.04471 [hep-ph]
56. E.K. Li, H. Zhang, M. Du, Z.H. Zhou, L. Xu, Probing the neutrino mass hierarchy with dynamical dark energy model. arXiv:1703.01554 [astro-ph.CO]
57. S. Vagnozzi, E. Giusarma, O. Mena, K. Freese, M. Gerbino, S. Ho, M. Lattanzi, Unveiling ν secrets with cosmological data: neutrino masses and mass hierarchy. arXiv:1701.08172 [astro-ph.CO]

58. J. Lu, M. Liu, Y. Wu, Y. Wang, W. Yang, Cosmic constraint on massive neutrinos in viable $f(R)$ gravity with producing ΛCDM background expansion. Eur. Phys. J. C **76**(12), 679 (2016). arXiv:1606.02987 [astro-ph.CO]
59. F. Capozzi, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, Neutrino masses and mixings: status of known and unknown 3ν parameters. Nucl. Phys. B **908**, 218 (2016). arXiv:1601.07777 [hep-ph]
60. S. Dell'Oro, S. Marcocci, M. Viel, F. Vissani, The contribution of light Majorana neutrinos to neutrinoless double beta decay and cosmology. JCAP **1512**(12), 023 (2015). arXiv:1505.02722 [hep-ph]
61. E. Giusarma, M. Gerbino, O. Mena, S. Vagnozzi, S. Ho, K. Freese, Improvement of cosmological neutrino mass bounds. Phys. Rev. D **94**(8), 083522 (2016). arXiv:1605.04320 [astro-ph.CO]
62. E. Di Valentino, A. Melchiorri, J. Silk, Beyond six parameters: extending ΛCDM. Phys. Rev. D **92**(12), 121302 (2015). arXiv:1507.06646 [astro-ph.CO]
63. E. Di Valentino, A. Melchiorri, J. Silk, Reconciling Planck with the local value of H_0 in extended parameter space. Phys. Lett. B **761**, 242 (2016). arXiv:1606.00634 [astro-ph.CO]
64. W. Yang, R.C. Nunes, S. Pan, D.F. Mota, Effects of neutrino mass hierarchies on dynamical dark energy models. Phys. Rev. D **95**, 103522 (2017). arXiv:1703.02556 [astro-ph.CO]
65. W.M. Dai, Z.K. Guo, R.G. Cai, Y.Z. Zhang, Lorentz invariance violation in the neutrino sector: a joint analysis from big bang nucleosynthesis and the cosmic microwave background. Eur. Phys. J. C **77**, 386 (2017). arXiv:1701.02553 [astro-ph.CO]
66. H.M. Zhu, U.L. Pen, X. Chen, D. Inman, Probing neutrino hierarchy and chirality via wakes. Phys. Rev. Lett. **116**(14), 141301 (2016). doi:10.1103/PhysRevLett.116.141301. arXiv:1412.1660 [astro-ph.CO]
67. A.G. Riess et al., A 2.4% determination of the local value of the hubble constant. Astrophys. J. **826**(1), 56 (2016). arXiv:1604.01424 [astro-ph.CO]
68. A.J. Cuesta et al., The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: baryon acoustic oscillations in the correlation function of LOWZ and CMASS galaxies in Data Release 12. Mon. Not. R. Astron. Soc. **457**(2), 1770 (2016). arXiv:1509.06371 [astro-ph.CO]
69. P.A.R. Ade et al. (Planck Collaboration), Planck 2015 results. XIII. Cosmological parameters. Astron. Astrophys. **594**, A13 (2016). arXiv:1502.01589 [astro-ph.CO]
70. A. Lewis, A. Challinor, A. Lasenby, Efficient computation of CMB anisotropies in closed FRW models. Astrophys. J. **538**, 473 (2000). arXiv:astro-ph/9911177
71. A. Lewis, S. Bridle, Cosmological parameters from CMB and other data: a Monte Carlo approach. Phys. Rev. D **66**, 103511 (2002). arXiv:astro-ph/0205436
72. N. Aghanim et al. (Planck Collaboration), Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters. Astron. Astrophys. **594**, A11 (2016). arXiv:1507.02704 [astro-ph.CO]
73. F. Beutler et al., The 6dF Galaxy Survey: baryon acoustic oscillations and the local hubble constant. Mon. Not. R. Astron. Soc. **416**, 3017 (2011). arXiv:1106.3366 [astro-ph.CO]
74. A.J. Ross, L. Samushia, C. Howlett, W.J. Percival, A. Burden, M. Manera, The clustering of the SDSS DR7 main Galaxy sample C I. A 4 per cent distance measure at $z = 0.15$. Mon. Not. R. Astron. Soc. **449**(1), 835 (2015). arXiv:1409.3242 [astro-ph.CO]
75. P.A.R. Ade et al. (Planck Collaboration), Planck 2015 results. XXIV. Cosmology from Sunyaev–Zeldovich cluster counts. Astron. Astrophys. **594**, A24 (2016). arXiv:1502.01597 [astro-ph.CO]
76. P.A.R. Ade et al. (Planck Collaboration), Planck 2015 results. XV. Gravitational lensing. Astron. Astrophys. **594**, A15 (2016). arXiv:1502.01591 [astro-ph.CO]
77. C. Heymans et al., CFHTLenS tomographic weak lensing cosmological parameter constraints: mitigating the impact of intrinsic galaxy alignments. Mon. Not. R. Astron. Soc. **432**, 2433 (2013). arXiv:1303.1808 [astro-ph.CO]
78. H. Akaike, A new look at the statistical model identification. IEEE Trans. Autom. Control **19**, 716–723 (1974)
79. G. Mangano, G. Miele, S. Pastor, M. Peloso, A precision calculation of the effective number of cosmological neutrinos. Phys. Lett. B **534**, 8 (2002). arXiv:astro-ph/0111408
80. G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, P.D. Serpico, Relic neutrino decoupling including flavor oscillations. Nucl. Phys. B **729**, 221 (2005). arXiv:hep-ph/0506164
81. P. Adamson et al. (Daya Bay and MINOS Collaborations), Limits on active to sterile neutrino oscillations from disappearance searches in the MINOS, Daya Bay, and Bugey-3 experiments. Phys. Rev. Lett. **117**(15), 151801 (2016). arXiv:1607.01177 [hep-ex] [Addendum: Phys. Rev. Lett. **117**(20), 209901 (2016)]
82. M.G. Aartsen et al. (IceCube Collaboration), Searches for sterile neutrinos with the IceCube detector. Phys. Rev. Lett. **117**(7), 071801 (2016). arXiv:1605.01990 [hep-ex]