Neutrino Mass Bounds from $0\nu\beta\beta$ Decays and Large Scale Structures

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Abstract. We investigate the way how the total mass sum of neutrinos can be constrained from the neutrinoless double beta decay and cosmological probes with cosmic microwave background (WMAP 3-year results), large scale structures including 2dFGRS and SDSS data sets. First we discuss, in brief, on the current status of neutrino mass bounds from neutrino beta decays and cosmic constrain within the flat $\Lambda\text{CMD}$ model. In addition, we explore the interacting neutrino dark-energy model, where the evolution of neutrino masses is determined by quintessence scalar filed, which is responsible for cosmic acceleration today. Assuming the flatness of the universe, the constraint we can derive from the current observation is $\sum m_\nu < 0.87 \text{eV}$ at the 95% confidence level, which is consistent with $\sum m_\nu < 0.68 \text{eV}$ in the flat $\Lambda\text{CDM}$ model. Finally we discuss the future prospect of the neutrino mass bound with weak-lensing effects.

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NEUTRINO MASS BOUNDS FROM THE $0\nu\beta\beta$ DECAYS AND COSMOLOGICAL PROBES WITH $\Lambda\text{CMD}$ MODEL

The existence of the tiny neutrino masses qualifies as the first evidence of new physics beyond the Standard Model. The answers to the hot questions on (1) whether neutrinos are Dirac or Majorana fermions $?$, (2) the mass hierarchy pattern (normal or inverted hierarchy type $?$), (3) the absolute value of the neutrino mass, will provide us the additional knowledge about the precise nature of this new physics, have the potential to unravel some of the deepest and most long-standing mysteries of cosmology and astrophysics, such as the origin of matter, the origin of heavy elements, and even the nature of dark-energy.

The global analysis of the solar and KamLAND data $[1]$ and super-Kamiokande atmospheric data $[2]$ provide the two independent neutrino mass-squared differences: $\Delta m^2_{\text{sol}} \sim \Delta m^2_{\text{atm}} = (7.9^{+2.8}_{-2.9}) \times 10^5 \text{eV}^2$, $\Delta m^2_{\text{atm}} \simeq (2.6 \ 0.2) \times 10^3 \text{eV}^2$, and

\begin{align*}
\Delta m^2_{\text{atm}} \simeq (2.6 \ 0.2) \times 10^3 \text{eV}^2,
\end{align*}

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mixing angles: \( \theta_{12} = \theta_3 = 33^\circ \), \( \theta_{23} = \theta_1 = 43^\circ \), and \( \theta_{13} = 7^\circ \). Above results tell us a substantial evidence that the three known neutrinos have a combined mass \( \Sigma = \sum_{i=1}^{3} m_{\nu_i} \) of at least \( \Delta m_{21}^2 = 0.05 \text{ eV} \). Since neutrino oscillations are only sensitive to mass-squared differences, three possible neutrino mass spectrum are allowed as: \( m_1 \ m_2 \ m_3 \) (normal hierarchy), or \( m_3 \ m_1 \ m_2 \) (inverted hierarchy), or \( m_1' \ m_2' \ m_3 \) (quasi-degenerate), depending on whether the light eigenmass is close to 0 or \( \Delta m_{21}^2 \) respectively.

The nature of spectrum is important to neutrino mass model-building, the combination of neutrinos to dark-matter, and the viability of observing neutrinoless double beta decay (0\(\nu\beta\beta\)) if neutrinos are Majorana [3, 4, 5].

There are three well known ways to get the direct information on the absolute mass of neutrinos by using: Tritium \( \beta \)-decay experiment, neutrinoless double beta decay experiment, and astrophysical observations.

**(A) Neutrinoless Double Beta Decays:**

The standard method for the measurement of the absolute value of the neutrino mass is based on the detailed investigation of the high-energy part of the \( \beta \)-spectrum of the decay of tritium:

\[
^3H \rightarrow ^3He + e^- + \bar{\nu}_e
\]

This decay has a small energy release \( E_0 = 18.7 \text{ keV} \) and a convenient life time \( T_{1/2} = 12.3 \text{ years} \). Since the flavour eigenstates are different from mass eigenstates in neutrino sector, in general, electron neutrino can be expressed as

\[
\nu_e = \sum_i U_{ei} \nu_i
\]

Neglecting the recoil of the final nucleus, the spectrum of the electrons is given:

\[
\frac{d\Gamma}{dE} = \sum_i U_{ei} \frac{d\Gamma_i}{dE}
\]

and the resulting spectrum can be analyzed in term of a single mean-squared electron neutrino mass

\[
\langle m_{\beta} \rangle^2 = \sum_j m_j^2 U_{ej}^2 = m_1^2 U_{e1}^2 + m_2^2 U_{e2}^2 + m_3^2 U_{e3}^2
\]

If the neutrino mass spectrum is practically degenerate: \( m_1' \ m_2' \ m_3 \), the neutrino mass can be measured in these experiments. Present-day tritium experiments Mainz[6] and Troitsk[7] gave the following results:

\[
m_1^2 = (1.2 \ 2.2 \ 2.7 \ 2.1) \text{ eV} \quad \text{(Mainz)};
\]

\[
m_1^2 = (2.3 \ 2.5 \ 2.0 \ 2.0) \text{ eV} \quad \text{(Troitsk)};
\]
This value corresponds to the upper bound

$$m_1 < 2.2 \, \text{eV} \quad (95\% \text{C.L.:})$$

(7)

Another useful method is by using the neutrinoless double beta decay. The search for neutrinoless double $\beta$-decay

$$\langle A;Z \rangle \rightarrow \langle A;Z_2 \rangle + e^- + e^-$$

(8)

for some even-even nuclei is the most sensitive and direct way of investigating the nature of neutrinos with definite masses. In this process, total lepton number is violated ($\Delta L = 2$) and is allowed only if massive neutrinos are Majorana particles. The rate of $0\nu\beta\beta$ is approximately

$$\frac{1}{T_{1-2}^{0\nu}} = G_{0\nu} (Q_{\beta\beta};Z) \mathcal{M}_{0\nu} \frac{1}{2} \langle m_{\beta\beta} \rangle^2 ;$$

(9)

where $G_{0\nu}$ is the phase space factor for the emission of the two electrons, $\mathcal{M}_{0\nu}$ is nuclear matrix elements, and $\langle m_{\beta\beta} \rangle$ is the effective Majorana mass of the electron neutrino:

$$\langle m_{\beta\beta} \rangle = \sum_i U_{ei}^2 m_i.$$  

(10)

We can write eq.(10), for normal and inverted hierarchy respectively, in terms of mixing angles and $\Delta_m^2 = m_2^2 - m_1^2 = (7 \, 9 \, 2 \, 8) \, 10^3 \, \text{eV}^2$, $\Delta_a = (m_3^2 - m_2^2),$ (2 \, 6 \, 0 \, 2) $10^3 \, \text{eV}^2$ and CP phases as follows:

$$\langle m_{ee} \rangle = c_{2 \, 3}^2 c_{1 \, 3} m_1 + c_{2 \, 3}^2 s_{1 \, 3}^2 e^{i \phi_3} \Delta_2 + m_2^2 + s_{2 \, 3}^2 e^{i \phi_3} \Delta_2 + m_1^2 ; \quad \text{(normal hierarchy);}$$

$$\langle m_{ee} \rangle = s_{2 \, 3}^2 m_1 + c_{2 \, 3}^2 s_{1 \, 3}^2 e^{i \phi_3} \Delta_2 \Delta_2 + m_1^2 + s_{2 \, 3}^2 e^{i \phi_3} ; \quad \text{(inverted hierarchy);}$$

(11)

From above relations, we can have the correlation plot between $m_{\text{light}}$ and $\langle m_{\beta\beta} \rangle$ with current observed data sets of mixing angles and $\Delta_\mu^2$ from neutrino oscillation experiments. However, $0\nu\beta\beta$ decays have not yet been seen experimentally.

The most stringent lower bounds for the time of life of $0\nu\beta\beta$-decay were obtained in the Heidelberg-Moscow[8] and IGEX[9] $^{76}\text{Ge}$ experiments:

$$T_{1-2}^{0\nu} = 1.9 \, \text{years} \quad (90\% \text{C.L.:}) \quad \text{Heidelberg Moscow};$$

(12)

$$T_{1-2}^{0\nu} = 1.57 \, \text{years} \quad (90\% \text{C.L.:}) \quad \text{IGEX}.$$  

(13)

Taking into account different calculation of the nuclear matrix elements, from these results the following upper bounds were obtained for the effective Majorana mass:

$$\langle m_{\beta\beta} \rangle < (0.35 \, 1.24) \, \text{eV}$$

(14)
TABLE 1. The current upper limits on effective Majorana neutrino mass $\bar{m}_{\beta\beta}$ and the sensitivities of the future $0\nu\beta\beta$-decay experiments. We used the matrix elements $M^{0\nu}$ with reduced uncertainty [12]. $T_{1/2}^{0\nu}$ denotes the current lower limit on the $0\nu\beta\beta$-decay half-life or the sensitivity of planned $0\nu\beta\beta$-decay experiments.

| Nucl. | $M^{0\nu}$ | $T_{1/2}^{0\nu}$ (years) | Experiment | $\bar{m}_{\beta\beta}$ (eV) |
|-------|------------|--------------------------|------------|--------------------------|
| $^{76}$Ge | 2.40 | 1.9 $10^{9}$ | Hiedelberg-Moscow | 0.55 |
| | | 3 $10^{9}$ | Majorana | 0.044 |
| | | 7 $10^{9}$ | GEM | 0.028 |
| | | 1 $10^{9}$ | GENIUS | 0.023 |
| $^{100}$Mo | 1.16 | 6 $10^{9}$ | NEM03 | 7.8 |
| | | 4 $10^{9}$ | NEM03 | 0.92 |
| | | 1 $10^{9}$ | MOON | 0.058 |
| $^{130}$Te | 1.50 | 1.4 $10^{9}$ | CUORE | 3.9 |
| | | 2 $10^{9}$ | CUORE | 0.10 |
| $^{136}$Xe | 0.98 | 1.2 $10^{9}$ | DAMA | 2.3 |
| | | 3 $10^{9}$ | XMASS | 0.10 |
| | | 2 $10^{9}$ | EXO(1t) | 0.055 |
| | | 4 $10^{9}$ | EXO(10t) | 0.012 |

Many new experiments (including CAMEO, CUORE, COBRA, EXO, GENIUS, MAJORANA, MOON and XMASS experiments) on the search for the neutrinoless double $\beta$-decay are in preparation at present. In these experiments the sensitivities are expected to be achieved. The detail upper limit of $\bar{m}_{\beta\beta}$ and the sensitivities of the future $0\nu\beta\beta$-decay experiments are summerized in table 1. It is very difficult to confirm the normal hierarchy pattern of neutrino mass when $m_1 < 1.7 \times 10^{-3}$ eV, however for the inverted case, it can be detected if $m_3 < 8.9 \times 10^{-3}$ eV and $m_{ee} > 0.012$ eV.

(B) Cosmological Constrains within the Standard Cosmology:

Within the standard cosmological model, the relic abundance of neutrinos at present epoch was come out straightforwardly from the fact that they follow the Fermi-Dirac distribution after freeze out, and their temperature is related to the CMB radiation temperature $T_{CMB}$ today by $T_\nu = (4 = 11)^{1/3} T_{CMB}$ with $T_{CMB} = 2.726$ K, providing

$$n_\nu = \frac{6 \zeta(3)}{11 \pi^2} T_{CMB}^3,$$

where $\zeta(3) \approx 1.202$, which gives $n_\nu \approx 112 cm^{-3}$ for each family of neutrinos at present. By now the massive neutrinos become non-relativistic, and their contribution to the mass
density ($\Omega_\nu$) of the universe can be expressed as

$$\Omega_\nu h^2 = \frac{\Sigma}{93.14 \text{eV}};$$

(17)

where $\Sigma$ stands for the sum of the neutrino masses. In this relation, we include the effect of three neutrino oscillation [10]. We should notice that when obtaining the limit of neutrino masses one usually assumes:

• the standard spatially flat $\Lambda$CDM model with adiabatic primordial perturbations,

• they have no non-standard interactions,

• neutrinos decoupled from the thermal background at the temperatures of order 1 MeV.

These simple conditions can be modified from several effects: due to a sizable neutrino-antineutrino asymmetry, due to additional light scalar field coupled with neutrinos [13], and due to the light sterile neutrino [14]. However, analysis of WMAP and 2dFGRS data gave independent evidence for small lepton asymmetries [15, 16], and such a scenario with a light scalar field is strongly disfavored by the current CMB power spectrum data [17]. We will not therefore take into account such non-standard couplings of neutrinos in the following. In addition, current cosmological observations are sensitive to neutrino masses $0.1 \text{eV} < \Sigma < 2 \Omega \text{eV}$. In this mass scale, the mass-square differences are small enough and all three active neutrinos are nearly degenerate in mass. Therefore we take the assumption of degenerate mass hierarchy. Even if we consider different mass hierarchy pattern, it will be very difficult to distinguish such hierarchy patterns from cosmological data alone [18].

After neutrinos decoupled from the thermal background, they stream freely and their density perturbations are damped on scale smaller than their free streaming scale. Consequently the perturbations of cold dark matter (CDM) and baryons grow more slowly because of the missing gravitational contribution from neutrinos. The free streaming scale of relativistic neutrinos grows with the hubble horizon. When the neutrinos become non-relativistic, their freestreaming scale shrinks, and they fall back into the potential wells. The neutrino density perturbation with scales larger than the freestreaming scale resumes to trace those of the other species. Thus the free streaming effect suppresses the power spectrum on scales smaller than the horizon when the neutrinos become non-relativistic. The co-moving wavenumber corresponding to this scale is given by

$$k_{nr} = 0.026 \frac{m_\nu}{1 \text{eV}} \Omega_\nu^{1/2} h \text{Mpc}^{-1};$$

(18)

for degenerated neutrinos, with almost same mass $m_\nu$. The growth of fourier modes with $k > k_{nr}$ will be suppressed because of neutrino free-streaming. The power spectrum of matter fluctuations can be written as

$$P_m(k; z) = P(k)T^2(k; z);$$

(19)

where $P(k)$ is the primordial spectrum of matter fluctuations, to be a simple power law $P(k) = Ak^n$, where A is the amplitude and n is the spectral index. Here the transfer
TABLE 2. Recent cosmological neutrino mass bounds (95% C.L.)

| Cosmological Data Set                      | Σ bound (2σ) | References                  |
|-------------------------------------------|--------------|------------------------------|
| CMB (WMAP-3 year alone)                   | < 2.0 eV     | Fukugita et al.[21]         |
| LSS[2dFGRS]                               | < 1.8 eV     | Elgaroy et al.[22]         |
| CMB + LSS[2dFGRS]                         | < 1.2 eV     | Sanchez et al.[23]          |
| "                                        | < 1.0 eV     | Hannestad[24]               |
| CMB + LSS + SN1a                          | < 0.75 eV    | Barger et al.[25]           |
| "                                        | < 0.68 eV    | Spergel et al.[26]          |
| CMB + LSS + SN1a + BAO                    | < 0.62 eV    | Goobar et al.[27]           |
| "                                        | < 0.58 eV    |                             |
| CMB + LSS + SN1a + Ly-α                   | < 0.21 eV    | Seljak et al.[28]           |
| CMB + LSS + SN1a + BAO + Ly-α             | < 0.17 eV    | Seljak et al.[28]           |

function $T(k,z)$ represents the evolution of perturbation relative to the largest scale. If some fraction of the matter density (e.g., neutrinos or dark energy) is unable to cluster, the speed of growth of perturbation becomes slower. Because the contribution to the fraction of matter density from neutrinos is proportional to their masses (Eq. (17)), the larger mass leads to the smaller growth of perturbation. The suppression of the power spectrum on small scales is roughly proportional to $f_\nu$ [19]:

$$\frac{\Delta P_m(k)}{P_m(k)} = 8f_\nu,$$

where $f_\nu = \Omega_\nu/\Omega_M$ is the fractional contribution of neutrinos to the total matter density. This result can be understood qualitatively from the fact that only a fraction $(1-f_\nu)$ of the matter can cluster when massive neutrinos are present [20]. Analyses of CMB data are not sensitive to neutrino masses if neutrinos behave as massless particles at the epoch of last scattering. According to the analytic consideration in [29], since the redshift when neutrino becomes non-relativistic is given by $1 + z_{nr} = 6.24\Omega_\nu h^2$ and $z_{rec} = 1088$, neutrinos become non-relativistic before the last scattering when $\Omega_\nu h^2 > 0.017$ (i.e. $\Sigma > 1.6eV$). Therefore the dependence of the position of the first peak and the height of the first peak on $\Omega_\nu h^2$ has a turning point at $\Omega_\nu h^2 = 0.017$. This value also affects CMB anisotropy via the modification of the integrated Sachs-Wolfe effect due to the massive neutrinos. However an important role of CMB data is to constrain other parameters that are degenerate with $\Sigma$. Also, since there is a range of scales common to the CMB and LSS experiments, CMB data provides an important constraint on the bias parameters. We summarize some of the recent cosmological neutrino mass bounds within the flat-$\Lambda$CDM model in table 2.

**NEUTRINO MASS BOUNDS IN INTERACTING NEUTRINO-DARK ENERGY MODEL**

With our previous works [30, 31, 32], we investigate the cosmological implication of an idea of the dark-energy interacting with neutrinos [33, 34]. For simplicity, we consider the case that dark-energy and neutrinos are coupled such that the mass of the neutrinos
is a function of the scalar field which drives the late time accelerated expansion of the universe.

In our scenario, Equations for quintessence scalar field are given by

\begin{align}
\ddot{\phi} + 2\mathcal{H} \dot{\phi} + a^2 \frac{dV_{\text{eff}}(\phi)}{d\phi} &= 0 ; \\
V_{\text{eff}}(\phi) &= V(\phi) + V_1(\phi) ; \\
V_1(\phi) &= a^4 \frac{d^3 q}{(2\pi)^3} \frac{q^2}{q^2 + a^2 m_\nu^2(\phi) f(q)} ; \\
m_\nu(\phi) &= \bar{m}_\nu e^{-\frac{\phi}{M_{\text{pl}}}^\beta} ;
\end{align}

where \( V(\phi) \) is the potential of quintessence scalar field, \( V_1(\phi) \) is additional potential due to the coupling to neutrino particles [34, 35], and \( m_\nu(\phi) \) is the mass of neutrino coupled to the scalar field, where we assume the exponential coupling with a coupling parameter \( \beta \). \( \mathcal{H} \) is \( \frac{d}{dt} \), where the dot represents the derivative with respect to the conformal time \( \tau \).

Energy densities of mass varying neutrino (MaVaNs) and quintessence scalar field are described as

\begin{align}
\rho_\nu &= a^4 \frac{d^3 q}{(2\pi)^3} \frac{q^2}{q^2 + a^2 m_\nu^2 f_0(q)} ; \\
3P_\nu &= a^4 \frac{d^3 q}{(2\pi)^3} \frac{q^2}{q^2 + a^2 m_\nu^2} f_0(q) ; \\
\rho_\phi &= \frac{1}{2a^2} \dot{\phi}^2 + V(\phi) ; \\
P_\phi &= \frac{1}{2a^2} \dot{\phi}^2 V(\phi) ;
\end{align}

From equations (25) and (26), the equation of motion for the background energy density of neutrinos is given by

\begin{align}
\dot{\rho}_\nu + 3\mathcal{H}(\rho_\nu + P_\nu) &= \frac{\partial \ln m_\nu}{\partial \phi} \phi (\rho_\nu + 3P_\nu) ;
\end{align}

Here we consider three different types of the quintessence potential \( V(\phi) \): (1) inverse power law potentials (Model I), (2) SUGRA type potential models (Model II), (3) exponential type potentials (Model III), which are given by, respectively:

\begin{align}
V(\phi) &= M^4 \frac{M_{\text{pl}}}{\phi} \alpha ; \\
V(\phi) &= M^4 \frac{M_{\text{pl}}}{\phi} \alpha e^{3\phi^2 - 2M_{\text{pl}}^2} ; \\
V(\phi) &= M^4 e^{\frac{\phi}{M_{\text{pl}}}^\alpha} ;
\end{align}

The coupling between cosmological neutrinos and dark energy quintessence could modify the CMB and matter power spectra significantly. It is therefore possible and also important to put constraints on coupling parameters from current observations. For this purpose, we use the WMAP3 [36, 37] and 2dFGRS [38] data sets.
FIGURE 1. (Left panel): Contours of constant relative probabilities in two dimensional parameter planes for inverse power law models. Lines correspond to 68% and 95.4% confidence limits; (Right panel): Same as Fig.1-a, but for exponential type models.

The flux power spectrum of the Lyman-α forest can be used to measure the matter power spectrum at small scales around \( z < 3 \) [39, 40]. It has been shown, however, that the resultant constraint on neutrino mass can vary significantly from \( \sum m_\nu < 0.2 \text{eV} \) to \( 0.4 \text{eV} \) depending on the specific Lyman-α analysis used [41]. The complication arises because the result suffers from the systematic uncertainty regarding to the model for the intergalactic physical effects, i.e., damping wings, ionizing radiation fluctuations, galactic winds, and so on [42]. Therefore, we conservatively omit the Lyman-α forest data from our current analysis.

Because there are many other cosmological parameters than the MaVaNu parameters, we follow the Markov Chain Monte Carlo (MCMC) global fit approach [43] to explore the likelihood space and marginalize over the nuisance parameters to obtain the constraint on parameters we are interested in. Our parameter space consists of

\[
P(\Omega_b h^2; \Omega_c h^2; H; \tau; A_s; n_s; m_i; \alpha; \beta)
\]

where \( \Omega_b h^2 \) and \( \Omega_c h^2 \) are the baryon and CDM densities in units of critical density, \( H \) is the hubble parameter, \( \tau \) is the optical depth of Compton scattering to the last scattering surface, \( A_s \) and \( n_s \) are the amplitude and spectral index of primordial density fluctuations, and \( (m_i; \alpha; \beta) \) are the parameters of MaVaNs. As an example, allowed parameter’s space are shown in Figs. (1) for the model I and III. In these figures we do not observe the strong degeneracy between the introduced parameters. This is why one can put tight constraints on MaVaNs parameters from observations. For both models we consider, larger \( \alpha \) leads larger \( \omega \) at present. Therefore large \( \alpha \) is not allowed due to the same reason that larger \( \omega \) is not allowed from the current observations. We find no observational signature which favors the coupling between MaVaNs and quintessence scalar field, and obtain the upper limit on the coupling parameter as shown in table 3.

\[
\beta < 0.46 \pm 0.58 (1 \sigma); [1.12; 1.36; 1.53 (2 \sigma)]
\]
TABLE 3. Global analysis data within 2σ deviation for different types of the quintessence potential.

| Quantities | Model I | Model II | Model III | WMAP-3 data (ΛCDM) |
|------------|---------|----------|-----------|---------------------|
| α          | < 4.38  | 0.10 – 11.82 | < 1.41    | —                   |
| β          | < 1.12  | < 1.36   | < 1.53    | —                   |
| Ω_νh^2[10^2] | 2.09–2.36 | 2.09–2.35 | 2.08–2.34 | 2.23 0.07         |
| Ω_{CDM}h^2[10^2] | 9.87 – 12.30 | 9.85–12.40 | 9.84–12.33 | 12.8 0.8          |
| H_0        | 58.39 – 72.10 | 58.55–71.70 | 58.99–71.58 | 72 8              |
| Z_re       | 6.13 – 14.94 | 4.00–14.78 | 6.64–14.78 | —                  |
| n_s        | 0.92–0.99 | 0.92–0.98 | 0.92–0.98 | 0.958 0.016       |
| A_s[10^10] | 18.25 – 23.41 | 18.20–23.32 | 18.33–23.27 | —                |
| Ω_Q[10^2]  | 57.43 – 75.60 | 57.59–75.02 | 58.45–75.05 | 71.6 5.5          |
| Age=Gyrs   | 13.59 – 14.40 | 13.59–14.35 | 13.61–14.36 | 13.73 0.16        |
| Ω_{MVN}h^2[10^2] | < 0.95 | < 0.91 | < 0.84 | < 1.97 95% C.L.: |
| τ          | 0.031–0.143 | 0.028–0.139 | 0.032–0.140 | 0.089 0.030       |

FIGURE 2. Examples of the total mass contributions in the matter power spectrum in Model I (Left panel) and Model III (Right panel). For both panels we plot the best fitting lines (green dashed), lines with larger neutrino masses M_ν = 0.3 eV (blue dotted) and M_ν = 1.0 eV (cyan dot-dashed) with the other parameters fixed to the best fitting values. Note that while lines with M_ν = 0.3 eV can fit to the data well by arranging the other cosmological parameters, lines with M_ν = 1.0 eV cannot.

and the present mass of neutrinos is also limited to

Ω_νh^2_{today} < 0.0044; 0.0048; 0.0048 (1σ); [0.0095; 0.0090; 0.0084 (2σ)]; (33)

for models I, II and III, respectively. When we apply the relation between the total sum of the neutrino masses M_ν and their contributions to the energy density of the universe: Ω_νh^2 = M_ν=(93 ±4 eV), we obtain the constraint on the total neutrino mass: M_ν < 0.45 eV (68% C.L.) [0.87 eV (95% C.L.):] in the neutrino probe dark-energy model. The total neutrino mass contributions in the power spectrum is shown in Fig 2, where we can see the significant deviation from observation data in the case of large neutrino masses.
Beyond the scope of our current analysis, there are other possibilities in cosmological probes of neutrino masses:

- the evolution of cluster abundance with redshift may provide further constraints on neutrino masses,
- the Lyman-\(\alpha\) forest provides constraints on the matter power spectrum on scale of \(k \sim 1 \, hMpc^{-1}\), where the effect of massive neutrinos is most viable,
- Deep and wide weak lensing survey will make it possible, in the future, to perform weak lensing tomography of the matter density field.

As shown in Fig.3, the combination of weak lensing tomography and high-precision CMB-polarization experiments may reach sensitivities down to the lower bound of 0.06 eV on the sum of the neutrino masses [44, 45, 46]. In this case, normal hierarchy pattern will be detectable.

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