

Neutrinos with refractive masses and the DESI baryon acoustic oscillation results

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Due to interactions with dark matter, neutrinos can acquire refractive masses which explain the data from oscillation experiments. We study the effects of relic neutrinos with refractive masses on structure formation in the Universe. In the model with a light fermionic mediator, above the resonance energy, E_R , associated with the mass of the mediator, refractive masses have all the properties identical to the usual vacuum masses. Below the resonance, refractive masses decrease with neutrino energy, however, they cannot be used in the same way as usual masses. We study the dispersion relations and group velocities of such neutrinos and their dependence on redshift. We show that in the epoch of structure formation, relic neutrinos were ultrarelativistic and essentially massless particles for $E_R = (10 - 10^5)$ eV. This allows us to reconcile the values of masses extracted from oscillation experiments with the stringent bounds on sum of neutrino masses from cosmological surveys.

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I. INTRODUCTION

Origins of neutrino masses, nature of dark matter (DM), and possible interactions between neutrinos and DM are among the major outstanding issues in particle physics and cosmology. Recent measurements of baryonic acoustic oscillations (BAO) from the first year of operation of the Dark Energy Spectroscopic Instrument (DESI) [1], along with measurements of the cosmic microwave background (CMB) polarization, temperature and lensing by PLANCK [2], as well as data from the ACT [3], constrain the sum of neutrino masses $\sum m_\nu^{\text{cosm}} < 0.072$ eV at 95% confidence level (CL). This bound disfavors the inverted mass ordering (IO) of neutrinos at 3σ . Furthermore, the posterior distribution of $\sum m_\nu^{\text{cosm}}$ peaks at zero, thus indicating a slight tension with even normal mass ordering (NO). A more stringent bound, $\sum m_\nu < 0.043$ eV at 2σ CL, was obtained by combining DESI BAO and CMB results with supernova Ia, GRB and x-ray observations [4].

Recall that oscillation data being sensitive to neutrino mass-squared differences allows one to get a lower bound on neutrino masses. In the case of normal mass ordering (NO), $m_3 \geq \sqrt{\Delta m_{31}^2}$ and $m_2 \geq \sqrt{\Delta m_{21}^2}$. This leads to a lower bound on the sum of masses: $\sum m_\nu^{\text{osc}} \approx 0.057$ eV. In

the case of inverted ordering (IO), $m_1 \approx m_2 \geq \sqrt{\Delta m_{31}^2}$, we obtain $\sum m_\nu^{\text{osc}} = 0.11$ eV. Thus,

$$\sum m_\nu^{\text{osc}} > \sum m_\nu^{\text{cosm}} \quad (1)$$

for IO and even for NO in the peak of posterior distribution. Future observations can further strengthen the cosmological bound. The reason of this tension could be some cosmological uncertainties. In Ref. [5], it was claimed that the DESI measurement seems to favor $\sum m_\nu < 0$, if a positive $\sum m_\nu$ is not imposed *a priori*. Such a measurement, if confirmed, can point to enhanced matter clustering, and can be explained in a scenario where DM interacts with itself through long-range forces.

Does the inequality in Eq. (1) make sense? Can the sum of neutrino masses determined in oscillation experiments be reconciled with the strong cosmological bound? Notice that the oscillation masses are determined at present epoch, $z = 0$, at neutrino energies $E > 0.1$ MeV, and in the solar system. In contrast, the cosmological bound concerns the average neutrino mass in the Universe during the epoch of structure formation, $z = 10-1000$ and at low neutrino energies, $E = (0.01-1)$ eV. Can this difference explain the inequality in Eq. (1)? Of course, usual neutrino masses generated by the Higgs vacuum expectation value (VEV) in local interactions should not change with E , z and location.

There are several possibilities which could explain the inequality in Eq. (1). Neutrinos can be massless in the early Universe and pick up a mass later due to a late phase transition [6–8]. Neutrino masses can be time-varying, either as a result of coupling directly with ultralight scalar

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fields, or through mixing with sterile neutrinos, which in turn, interact with an ultralight scalar [9]. In these scenarios, neutrino masses are small in the early Universe, but later, after neutrinos become nonrelativistic, the masses grow to the present values. Other ideas include neutrino decays or annihilation to lighter particles, thereby reducing the energy density in massive neutrinos, or cooling the neutrinos, through new interactions with DM [5].

Thus, the cosmological surveys raise an important question on the nature of the neutrino mass: is it generated through a vacuum expectation value (VEV) in a short range interaction, or does it have a dynamical or refractive origin?

In this paper, we explore the possibility that the cosmological bound on the sum of neutrino masses can be stronger than the lower bound from oscillations. We assume that neutrino masses have a dynamical nature, such that the effective masses of the relic neutrinos were smaller in the epoch of structure formation in the Universe than now. Scenarios in which neutrinos acquire masses partially or completely through interactions with light dark matter have been considered in [10–24]. However, the cosmological consequences of refractive neutrino masses have not been studied in detail before.

We use the scenario studied in [25], where neutrinos acquire an effective mass-squared via scattering on ultralight dark matter (ULDM), mediated by a light fermion. We consider the evolution of relic neutrinos with refractive masses and show that in the epoch of structure formation, they appear essentially as massless particles, thus allowing us to satisfy the cosmological bound and the inequality in Eq. (1). The key new result of the paper is that refractive mass at low energies (in contrast to high energies) cannot be considered as usual mass and therefore the cosmological consequences of neutrinos with refraction on dark matter should be treated differently from the beginning. In Sec. II, we consider the neutrino potential generated by interactions with DM and its dependence on the redshift z , the resonance energy, and the C-asymmetry of the DM. In Sec. III, we study the key elements relevant for structure formation: the dispersion relations of neutrinos and antineutrinos, the group velocities of relic neutrinos and their evolution, the relativistic to nonrelativistic transition. In Sec. IV, we discuss the obtained results and conclude.

II. NEUTRINO POTENTIAL AND REFRACTIVE MASS AND THEIR EVOLUTION

We assume that massless neutrinos interact with ULDM composed of scalar bosons ϕ , via a light fermionic mediator χ , through the effective Yukawa interaction $g\bar{\chi}\nu\phi + \text{H.c.}$ ¹

¹This effective interaction is not gauge invariant, but can be generated after electroweak symmetry breaking. Examples of UV complete gauge invariant models that lead to such interactions can be found in [14,26].

Elastic forward scattering of neutrinos on the cold gas of ϕ produces an effective potential [25]

$$V = \frac{m_{\text{asy}}^2}{2E_R} \frac{y - \epsilon}{y^2 - 1}, \quad m_{\text{asy}}^2 \equiv \frac{g^2(n_\phi + \bar{n}_\phi)}{m_\phi}. \quad (2)$$

Here m_{asy}^2 is the effective mass-squared, $n_\phi(\bar{n}_\phi)$ is the number density of ULDM particles (antiparticles) and m_ϕ is the ULDM mass. We define $y \equiv E_\nu/E_R$. The resonance energy $E_R = m_\chi^2/(2m_\phi)$, where m_χ is the mass of the mediator and $\epsilon \equiv (n_\phi - \bar{n}_\phi)/(n_\phi + \bar{n}_\phi)$ is the C-asymmetry of DM, see [27] for example for models of light asymmetric DM. For nonrelativistic DM, the energy density equals $\rho_\phi \simeq m_\phi(n_\phi + \bar{n}_\phi)$, and hence $m_{\text{asy}}^2 = g^2\rho_\phi/m_\phi^2$ [25]. The potential for antineutrinos is given by the same expression as Eq. (4) with the substitution $\epsilon \rightarrow -\epsilon$. Similarly, due to interaction with DM and ν , the fermion χ also picks up a refraction mass, which is of the same order as the neutrino refractive mass [25].

At energies much above the resonance, $y \gg 1$, the potential becomes $V \approx m_{\text{asy}}^2/2E$, thus reproducing the standard term due to neutrino mass in the Hamiltonian of flavor evolution of neutrinos. Therefore, m_{asy}^2 can be identified with the mass-squared extracted from the oscillation experiments, e.g., $m_{\text{asy}}^2 \approx \Delta m_{31}^2$, etc. There are two viable regions of parameters of the model in which the observed values of oscillation parameters can be reproduced and all the existing bounds are satisfied [25]: (i) $m_\phi \sim 10^{-10}$ eV, $g \sim 10^{-10}$, $m_\chi \sim 10^{-4}$ eV, and (ii) $m_\phi \sim 10^{-22}$ eV, $g \sim 10^{-21}$, $m_\chi \sim 10^{-10}$ eV.

In the opposite case, $y \ll 1$, relevant for the relic neutrinos, we have

$$V \approx \frac{m_{\text{asy}}^2}{2E_R} \epsilon = \frac{g^2}{m_\chi^2} (n_\phi + \bar{n}_\phi) \epsilon = \frac{g^2}{m_\chi^2} (n_\phi - \bar{n}_\phi), \quad (3)$$

which coincides with the Wolfenstein potential [28].

Let us consider the evolution of the average potential in the Universe for relic neutrinos (see Fig. 1). The potential is proportional to the number density of dark matter and therefore it increases with z as $(1+z)^3$:

$$V(z) = \frac{m_{\text{asy}}^2}{2E_R} \xi(1+z)^3 \frac{y(z) - \epsilon}{y(z)^2 - 1}. \quad (4)$$

Here $y(z) = y_0(1+z)$, $y_0 = E_0/E_R$, and $E_0 = 5 \times 10^{-4}$ eV is the present ($z = 0$) average energy of relic neutrinos. In Eq. (4), $\xi^{-1} \simeq 10^5$ is the local overdensity of DM. For $\epsilon \neq 0$ and $y \ll 1$, the expression in Eq. (4) simplifies as

$$V(z) \approx \frac{m_{\text{asy}}^2}{2E_R} \epsilon \xi(1+z)^3, \quad (5)$$

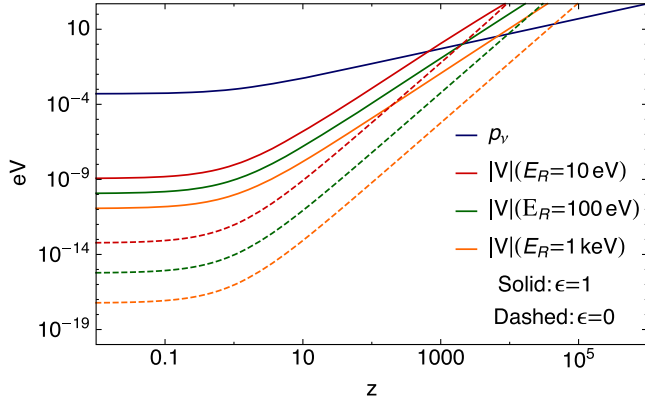


FIG. 1. Dependence of the neutrino momentum and the effective potential on redshift z for different values of the resonant energy E_R and DM charge asymmetry, $\epsilon = 1$ (solid lines) and $\epsilon = 0$ (dashed lines). We take $m_{\text{asy}} = \sqrt{\Delta m_{31}^2} = 0.05$ eV.

that is, it does not depend on the energy of the neutrino. In the case of $\epsilon = 0$, we obtain from Eq. (4),

$$V(z) = -\frac{m_{\text{asy}}^2}{2E_R} y_0 \xi (1+z)^4. \quad (6)$$

The moduli of this potential increases with z faster than that in Eq. (4), but has much smaller value at $z = 0$ (see Fig. 1).

We can introduce the refractive mass-squared as $\tilde{m}^2 \equiv 2yVE_R = 2VE$. It is proportional to the DM density and hence depends on space-time coordinates. For $y \gg 1$, the refractive mass-squared has all the properties identical to the vacuum mass-squared. Below the resonance, $y < 1$, the mass-squared decreases as $y\epsilon$ for $\epsilon \neq 0$ and as y^2 for $\epsilon = 0$, i.e., a sharper decline. Furthermore, the effective mass-squared has opposite signs for neutrinos and antineutrinos. This decrease of modulus of the potential indicates that the bound on sum of usual neutrino masses can be avoided. However, as we will see later, below resonance, the refractive mass cannot be used in the same way as the usual mass, and, in particular, it cannot be used in consideration of cosmological bound.

The decrease of mass with energy also affects kinematical measurements of neutrino mass in the beta decay, in particular, of 3H as used by the KATRIN collaboration [29]. The decay rate depends on the neutrino mass via the neutrino momentum p_ν : $\Gamma \propto p_\nu$. In the case of the usual mass, we have $\sqrt{E_\nu^2 - m_\nu^2} = \sqrt{(Q_e - T_e)^2 - m_\nu^2}$, where Q_e is the end point of spectrum and T_e is the kinetic energy of electron. In the refractive mass case, $p_\nu = Q_e - T_e - V$. This would be equivalent to $m_\nu^2 = 2p_\nu V$, and the latter can be negative. For $E_R = 100$ eV, $|m_{\text{asy}}^2| = \Delta m_{21}^2$ relevant for beta decay and $p_\nu = 1$ eV, this gives $|m_\nu| \sim 10^{-3}$ eV—much below the KATRIN sensitivity.

Note that we consider scalar DM-fermionic mediator case for defineness and simplicity. In principle, a vector

boson like a light dark photon, can also be considered as a mediator [14]. An ultralight fermionic DM is difficult to accommodate due to strong constraints on their number density from the exclusion principle. The DM can also be an ultralight vector boson, as considered in [13].

III. NEUTRINOS WITH REFRACTIVE MASS AND DESI OBSERVATIONS

The cosmological limit on the sum of neutrino masses rely on a determination of the amount of matter clustering during structure formation. The information about clustering is obtained through an accurate measurement of the CMB lensing power spectra (from PLANCK and ACT) and the net amount of nonrelativistic matter content from the BAO, recently observed by DESI with high precision.

Let us first outline how neutrinos with usual vacuum mass affect structure formation. Neutrino masses determine the scale of free streaming, $\lambda_{\text{FS}}(t) \sim v_g(t, m)/H(t)$, where v_g is the group velocity and H is the Hubble constant. At smaller scales, $\lambda < \lambda_{\text{FS}}$, neutrinos do not cluster and damp density perturbations of DM and baryons. Correspondingly, neutrinos erase perturbations with wave numbers k bigger than free streaming wave number, $k_{\text{FS}} \sim 1/\lambda_{\text{FS}}$. Essentially, neutrino masses start affecting the power spectrum of perturbations, $P_m(k)$, at k_{nr} , which corresponds to a transition to nonrelativistic regime, when $p_\nu = m_\nu$. The damping effect of the power spectrum is determined by $f_\nu \equiv (\rho_\nu + \rho_{\bar{\nu}})/\rho_m$ —the fraction of energy density in neutrinos and antineutrinos in the total matter energy density, ρ_m . In the nonrelativistic case, $\rho_\nu \simeq m_\nu n_\nu$, where n_ν ($\bar{n}_\nu$) is the number density of neutrinos (antineutrinos). There are two main reasons of suppression of the power spectrum at $k > k_{\text{nr}}$: (i) since neutrinos do not cluster, their fraction f_ν should be subtracted from the power spectrum, and (ii) neutrinos reduce the rate of growth of perturbation by contributing to expansion rate of the Universe (thus weakening the gravitational clustering) but not clustering themselves. As a result, a suppression of power spectrum equals approximately [30]

$$\frac{P_{m_\nu}(k)}{P_0(k)} = 1 - 8f_\nu, \quad (7)$$

where $P_0(k)$ is the spectrum in the case of massless neutrinos. Increase of f_ν due to increase of neutrino mass leads to stronger suppression of the power spectrum. Hence, to estimate the effect of neutrinos with refractive mass on structure formation, we need to find their group velocities, energy density and explore the relativistic to nonrelativistic transition.

For massless neutrinos with refraction effect, the dispersion relation reads

$$E = p_\nu + V. \quad (8)$$

Figure 1 shows the dependence of p_ν and V on z . For small redshift, one finds $V \ll p_\nu$, but as z increases, V increases faster than p_ν and they become comparable at $z \gtrsim 10^3$. An important quantity is the ratio V/p which determines the perturbativity of approach [25]. For $y \ll \epsilon \leq 1$, we have

$$\frac{V(z)}{p(z)} = \frac{m_{\text{asy}}^2}{2E_R E_0} \xi \epsilon (1+z)^2. \quad (9)$$

According to Eq. (9), the perturbativity condition $V(z)/p(z) \leq 0.1$ gives

$$(1+z) \leq 6.3 \times 10^3 \sqrt{\frac{E_R}{(10^2 \text{ eV}) \epsilon}}. \quad (10)$$

For $\epsilon = 0$, we obtain

$$\frac{V(z)}{p(z)} = -\frac{m_{\text{asy}}^2}{2E_R^2} \xi (1+z)^3, \quad (11)$$

and the inequality $|V/p| \leq 0.1$ leads to

$$(1+z) \leq 3 \times 10^4 \left(\frac{E_R}{10^2 \text{ eV}} \right)^{2/3}. \quad (12)$$

For a given z , the perturbativity conditions, Eqs. (10) and (12), constrain from below the values of E_R .

According to Eq. (8), the group velocity of neutrinos equals

$$v_g = \frac{dE_\nu}{dp_\nu} = 1 - \frac{dV}{dp}. \quad (13)$$

Using the expression for $V(z)$ from Eq. (4), we find the deviation of v_g from 1 in the epoch z ,

$$1 - v_g = \frac{\tilde{m}_{\text{asy}}^2}{2E_R^2} \xi (1+z)^3 \frac{1 + y(z)^2 - 2\epsilon y(z)}{[1 - y(z)^2]^2}. \quad (14)$$

Dependence of the deviation $1 - v_g$ on z is shown in Fig. 2 for different values of E_R . It is compared with the standard mass case $1 - v_g = p/E \approx m^2/2E^2$. For small y (realized for parameters in this plot), the deviation in Eq. (14) does not depend practically on ϵ , in contrast to V and $\tilde{m}^2$. Indeed, for $y \ll 1$, Eq. (14) gives

$$1 - v_g = \frac{\tilde{m}_{\text{asy}}^2}{2E_R^2} \xi (1+z)^3. \quad (15)$$

The deviation does not depend on energy. Ratio of the deviations for refractive and usual masses equals $\xi(1+z)^3 E^2/E_R^2$, which is small for $E^2 \ll E_R^2$. For $m_{\text{asy}}^2 = m^2 = \Delta m_{31}^2$, they become comparable only for $z > 1000$. According to Fig. 2, neutrinos with refractive

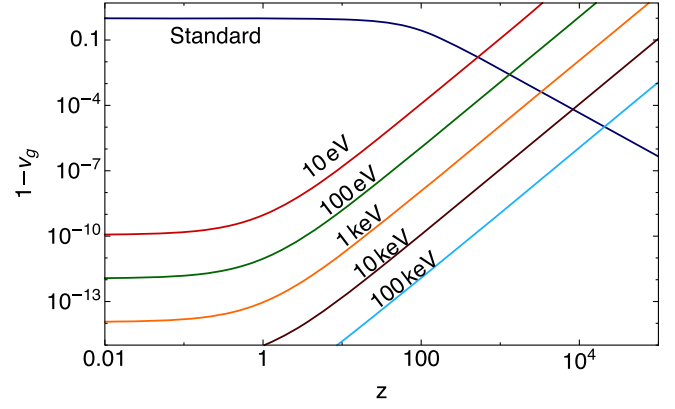


FIG. 2. The deviation of the group velocity of neutrinos from 1 as a function of the redshift for different values of E_R (numbers on top of the curves). The lines for $\epsilon = 0$ and $\epsilon = 1$ practically coincide. The standard case for relativistic neutrinos is also shown. We use $m_{\text{asy}} = \sqrt{\Delta m_{31}^2} = 0.05 \text{ eV}$.

mass $\sim 0.05 \text{ eV}$ are ultrarelativistic in whole time interval of structure formation up to $z = 10^3$ for $E_R > 10 \text{ eV}$.

Group velocities of neutrinos with usual and refractive masses have an opposite dependence on z : in the usual case, with increase of z , one has $v_g \rightarrow 1$ and neutrinos become relativistic; on the other hand, in the refractive case, $v_g \rightarrow 0$ and neutrinos become nonrelativistic. The latter may happen in the epoch of radiation-dominated Universe.

The deviation, Eq. (14), differs from the one obtained by naive substitution $m^2 \rightarrow \tilde{m}^2$ in the standard formula for the group velocity: $1 - v_g = \tilde{m}^2/(2p^2) = V/p$. This is bigger than the estimation in Eq. (14) by the factor $\epsilon E_R/p$. This shows that $\tilde{m}^2$ cannot be used in the same way as usual mass-squared.

The energy densities in neutrinos and antineutrinos equal

$$\begin{aligned} \rho_\nu &= E_\nu n_\nu = (p_\nu + V) n_\nu, \\ \rho_{\bar{\nu}} &= E_{\bar{\nu}} \bar{n}_\nu = (p_\nu - V) \bar{n}_\nu. \end{aligned} \quad (16)$$

Their sum does not depend on V for $n_\nu = \bar{n}_\nu$, being the same as in the case for massless neutrinos. For nonzero lepton asymmetry, $\Delta L \equiv (n_\nu - \bar{n}_\nu)/(n_\nu + \bar{n}_\nu)$, we have

$$\rho_{\text{tot}} = \rho_\nu + \rho_{\bar{\nu}} = p_\nu (n_\nu + \bar{n}_\nu) \left[1 + \frac{V}{p} \Delta L \right]. \quad (17)$$

The key parameters relevant for cosmology are E_R , $(1+z)$ and ϵ . Different bounds in the $E_R - (1+z)$ plane are shown in Fig. 3. We present the lines $V(z)/p(z) = 0.1$ for $\epsilon = 0$ and $\epsilon = 1$ which restrict the region of perturbativity (colored regions are excluded). The bounds—lower on E_R and upper on $(1+z)$ —are stronger in the case of $\epsilon = 1$.

Interestingly, for $E_R = (10 - 10^5) \text{ eV}$, neutrinos with refractive mass are in the perturbation regime at energies

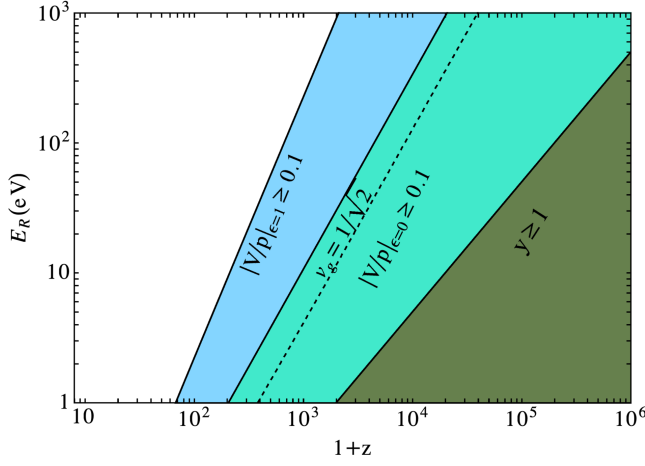


FIG. 3. Perturbativity constraints $V/p \leq 0.1$ in the $E_R - (1+z)$ plane for $\epsilon = 0$ and $\epsilon = 1$. The colored parts show the excluded regions. The dashed line corresponds to the group velocity $v_g = 1/\sqrt{2}$ or, equivalently to $(1+z)_{\text{nr}}$. Also shown is the region of neutrino energies above resonance given by $y \geq 1$.

relevant for both oscillations [25] and for relic neutrinos in epoch of structure formation.

The resonance condition $y = 1$ yields $E_R = E_0(1+z)$. According to Fig. 3, the perturbativity requirement is more stringent than $y \leq 1$. So, in the region $V(z) < p(z)$, we have $y \ll 1$, which justifies, in particular, the use of expression in Eq. (15).

Figure 3 also shows the line corresponding to $v_g = 1/\sqrt{2}$, or $p = m$ in usual mass case, that is, the transition to the nonrelativistic regime. Using Eq. (15), we find an analytical expression of this line

$$(1+z)_{\text{nr}} = \left(0.6 \frac{E_R^2}{\xi m_{\text{asy}}^2} \right)^{1/3}. \quad (18)$$

It is shifted by a factor of $3^{1/3}$ to larger values of $(1+z)$ with respect to the border line of the perturbativity condition for $\epsilon = 0$. For bigger values E_R or smaller values of $(1+z)$ with respect to this line, neutrinos can be considered as relativistic. In this region, the situation for structure formation is similar to that for massless neutrinos.

From Fig. 3, for a given E_R at a large z , we have $(1+z) > (1+z)_{\text{nr}}$, implying that neutrinos are nonrelativistic, with $v_g \ll 1$, and consequently, small free-streaming scale. This would correspond to $f_\nu \approx 0$ and neutrino contributing to cold DM. As z decreases, $(1+z) < (1+z)_{\text{nr}}$, neutrinos become relativistic and $f_\nu \simeq f_\nu(m=0)$. For $E_R \sim 1$ eV, the transition from nonrelativistic to relativistic cases occurs at $z = 10^2 - 10^3$, thus affecting structure formation. This may appear as some effect of neutrino mass but distortion of the power spectrum is expected to be different. Note, however, that for $\epsilon = 0$, we have $V/E = 0.5$ along the

border line $(1+z)_{\text{nr}}$, so perturbative consideration may not work well in this range.

Notice that the effective neutrino mass can be defined via the group velocity as $m_{\text{eff}} = p(v_g^{-2} - 1)^{1/2}$ as in the standard case. Using this equation and Eq. (15) for $(1 - v_g) \ll 1$, we obtain

$$m_{\text{eff}} \approx p \sqrt{2(1 - v_g)} \approx m_{\text{asy}} \frac{p}{E_R} \sqrt{\xi(1+z)^3}. \quad (19)$$

It should be compared with $\tilde{m} = \sqrt{\tilde{m}^2} = \sqrt{2pV}$. Following Eq. (13), one can write $m_{\text{eff}} = p \sqrt{2dV/dp} = \sqrt{2p^2 dV/dp}$. Explicitly, the ratio of these masses equals

$$\frac{m_{\text{eff}}}{\tilde{m}} = \sqrt{\frac{p(z)}{E_R}}. \quad (20)$$

So, m_{eff} can be orders of magnitude smaller than the refractive mass $\tilde{m}$. This shows again that refractive mass cannot be used at low energies for description of structure formation. Correspondingly, the cosmological bound on the parameter space of the model is weaker than that obtained in [25].

IV. CONCLUSION

We studied the cosmological evolution of neutrinos with refractive masses and their influence on structure formation in the Universe. In the model with a light fermionic mediator, below the resonance energy, the refractive masses decrease with E_ν , indicating that cosmological bound on the sum of neutrino masses can be avoided. However, below resonance, one cannot use the refractive masses in the same way as the usual (vacuum) masses. Therefore, the effects of neutrinos on structure formation should be considered directly without invoking the refractive masses.

Using the dispersion relations, we computed the group velocity of neutrinos and studied its properties. We showed that for $z \leq 10^3$ and $E_R > 100$ eV, the deviation $1 - v_g \ll 1$, i.e., neutrinos are ultrarelativistic. Furthermore, in this range of E_R and z , one finds $V/p \ll 1$, so that both the dispersion relation and the total energy practically coincide with those for massless neutrinos. Neutrinos with refractive masses appear as massless particles in the epoch of structure formation and therefore the cosmological analysis, if interpreted in terms of usual neutrino mass, would give zero mass. This removes the tension, Eq. (1), between the sum of neutrino masses determined from oscillation results and the bounds derived from cosmology. As a result, not only normal ordering and inverted ordering mass spectra but also quasidegenerate spectrum is allowed.

Searches of nonzero neutrino masses in cosmology is a test of nature of neutrino masses, and in particular,

their possible refraction origins. That would be the case if future cosmological surveys confirm the inequality in Eq. (1). Establishing the refraction origins of neutrino mass would also imply discovery of the nature of dark matter.

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