Are cosmological neutrinos free-streaming?

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Precision data from cosmology suggest neutrinos stream freely and hence interact very weakly around the epoch of recombination. We study this issue in a simple framework where neutrinos recouple instantaneously and stop streaming freely at a redshift z_i. The latest cosmological data imply $z_i \lesssim 1500$, the exact constraint depending somewhat on the assumed prior on z_i. This bound can be translated into a bound on the coupling strength between neutrinos and majoronlike particles.

I. INTRODUCTION

With the advent of high-precision cosmology it has become feasible to probe progressively more detailed aspects of the cosmic neutrino background radiation [1,2]. In the standard model, neutrinos provide relativistic energy density which influences the cosmic microwave background (CMB) radiation mainly via the early integrated Sachs-Wolfe (ISW) effect and the matter fluctuation spectrum via the relation between neutrino energy density and the epoch of matter-radiation equality. The existence of a cosmological background of relativistic energy density has been unambiguously detected in the fifth-year Wilkinson Microwave Anisotropy Probe (WMAP5) data [3] and was already previously detected using the combination of CMB and Large Scale Structure (LSS) data [4–8]. Furthermore, cosmological data provide a restrictive upper bound on the sum of neutrino masses of 0.2–1 eV, depending on the specific choice of data sets and model space [1,9–16].

The present level of precision allows us to turn to more subtle issues. For example, it is timely to probe the possibility that neutrinos have nonstandard interactions where one case in point is an interaction with the Nambu-Goldstone boson of a new, broken $U(1)$ symmetry as in majoron models [17–19]. Such an interaction would recouple the neutrinos to each other at some "interaction redshift" z_i, whereas at earlier epochs they would behave in the same way as standard-model neutrinos. For the cases of interest, this recoupling occurs much later than the electroweak decoupling. Therefore, in the limit of relativistic neutrinos the total energy density in the combined fluid of neutrinos and majorons is conserved, preventing any direct impact on cosmological observables.

However, neutrinos lose their free-streaming property if the interaction is sufficiently strong. As a consequence, any anisotropic stress components in the Boltzmann hierarchy are suppressed, effectively truncating the Boltzmann hierarchy at first order, equivalent to the equations for a perfect fluid [20–28]. (See Ref. [29] for a detailed description of the Boltzmann hierarchy.)

The impact of neutrino free-streaming on cosmological observables was recently studied in Ref. [28]. The fit parameter was the effective viscosity $c_{\rm vis}^2$, taken to be independent of redshift. Our study is complementary in that we assume that $c_{\rm vis}^2$ drops instantaneously at z_i from the free-streaming value $1/3$ to the perfect-fluid value 0. Our conclusion that neutrinos should stream freely around the epoch of recombination is perfectly consistent with Ref. [28]. However, our approach lends itself more directly to an interpretation in terms of a specific interaction model where the recoupling redshift is related to a dimensionless coupling constant g. Therefore, we can translate our limits on z_i into limits on g.

From flavor oscillation experiments we know that neutrinos have masses which therefore are unavoidable cosmological fit parameters. The usual cosmological limits on the sum of neutrino masses imply that any single mass eigenstate should obey $m \lesssim 0.2$–0.3 eV so that all neutrinos would be relativistic around the recombination epoch. Treating them as massless is therefore a reasonable approximation for the simple problem addressed here. On the other hand, a strong majoron-type interaction can lead to the annihilation of "heavy" neutrinos into majorons ("neutrinoless universe" [22]). Such scenarios lead to a complicated evolution of the neutrino-majoron fluid that we are not investigating, although it would have a strong impact on cosmological observables. In any event, our constraint on the free-streaming nature of the relevant radiation at recombination does not depend on the physical nature of the radiation.

Eventually the KATRIN experiment, unless it detects a significant neutrino mass, will constrain the neutrino mass scale to $m \lesssim 0.2$ eV [30]. Such a bound would imply that neutrinos cannot have disappeared at the recombination epoch and our constraint indeed applies to neutrinos. In this sense the anticipated KATRIN limit will strengthen the case for translating our limit on z_i into a limit on exotic neutrino interactions.

We begin in Sec. II with a description of our model space, data sets, and statistical methodology. In Sec. III we

provide our bounds on z_i, and in Sec. IV we conclude with a discussion.

II. MODELS, DATA, AND METHODOLOGY

Our parameter constraints will be based on a reasonably general 10-parameter model consisting of

$$\Theta = (\omega_{\mathrm{CDM}}, \omega_{\mathrm{B}}, H_0, n_s, \alpha_s, \tau, A_s, N_\nu, z_i), \qquad (1)$$

where $h = H_0/(100 \ \mathrm{km \ s}^{-1} \ \mathrm{Mpc}^{-1})$, and the cold dark matter (CDM) and baryon (B) contents are given by $\omega_{\mathrm{CDM}} = \Omega_{\mathrm{CDM}} h^2$ and $\omega_{\mathrm{B}} = \Omega_{\mathrm{B}} h^2$ respectively. We assume spatial flatness, i.e. the dark energy (DE) density is given by $\Omega_{\mathrm{DE}} = 1 - \Omega_{\mathrm{CDM}} - \Omega_{\mathrm{B}}$. For the dark energy we assume a constant equation of state parameter w. The primordial fluctuations are assumed to be adiabatic and described by the scalar amplitude A_s, the spectral index n_s, and the running α_s. We do not consider the presence of tensor modes or an isocurvature component. Finally, we include the present Hubble parameter H_0 and the optical depth to reionization τ. As discussed in the previous section we assume massless neutrinos.

In order to keep our study on the properties of the radiation as general as possible, we will sometimes use the effective number of neutrino flavors N_ν as a fit parameter to express the radiation content in the usual way. The standard value is $N_\nu = 3.046$ [31].

Neutrino interactions are assumed to recouple instantaneously at a redshift z_i. Here our standard prior is linear (i.e. uniform) in z_i, but we will also test an alternative case where a linear prior is used on $\log(z_i + 1)$.

The priors on our model parameters are listed in Table I, including the alternatives that we use in some cases.

We use CMB data from WMAP5 [3,32–34] and measurements of the matter power spectrum based on the Sloan Digital Sky Survey-Luminous Redshift Galaxies (SDSS-LRG) [35] and 2-degree-Field (2dF) galaxy samples [36]. In addition we include the Supernova Type Ia (SN-Ia) data from Ref. [37], the SDSS-LRG Baryon Acoustic

Oscillation measurement (SDSS-LRG BAO) from Ref. [38], and the Hubble Space Telescope (HST) key project measurement of H_0 [39].

Our treatment of nonlinear corrections to the LSS power spectra follows the prescription given in Ref. [40], i.e., we include data up to $k = 0.2h \ \mathrm{Mpc}^{-1}$ and correct for nonlinearity using the shot-noise term P_{shot}.

In order to derive constraints on our model parameters we have modified the publicly available CAMB code [41] to allow for neutrino interactions and combined it with the Markov Chain Monte Carlo software COSMOMC [42]. Credible intervals are calculated using Bayesian inference as implemented in the GETDIST routine of COSMOMC.

III. LIMIT ON RECOUPLING REDSHIFT

Following the approach described in the previous section we have calculated 68% and 95% credible regions in the two-dimensional parameter space of N_ν and z_i that we show in Fig. 1. In the upper panel we have used the linear prior on z_i described in Table I. The cosmological precision data show (i) strong evidence for the existence of relativistic energy density and (ii) that it must be freely streaming
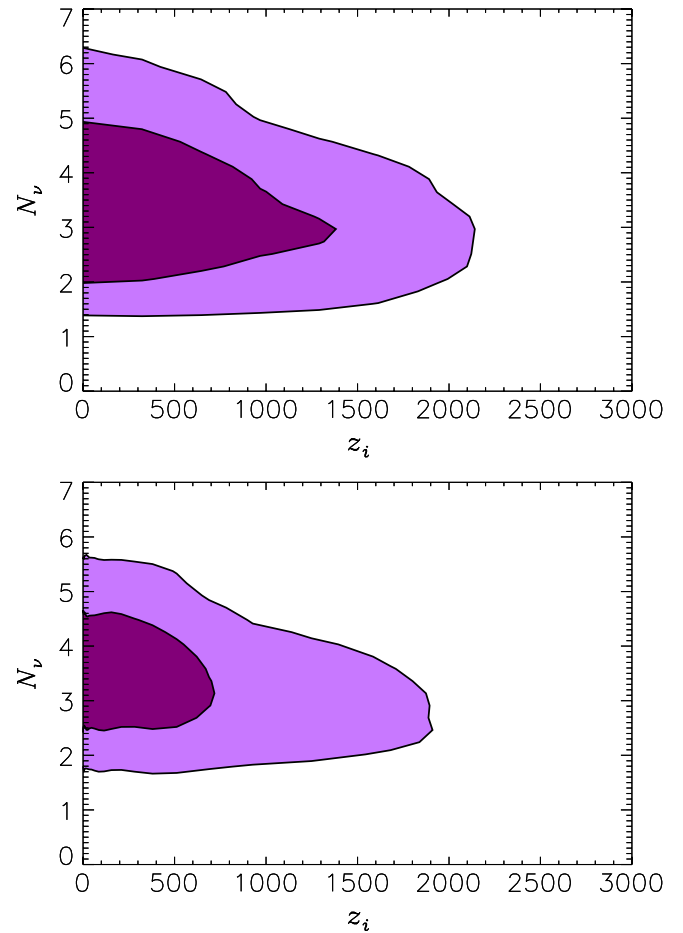
TABLE I. Priors on the model parameters. Note that for N_ν we use the prior $0 \le N_\nu \le 50$ for Figs. 1 and 2, and $N_\nu = 3.046$ everywhere else.

Parameter	Standard (linear) prior	Alternative (log) prior
ω_{CDM}	0.01–0.9	0.01–0.9
ω_{B}	0.005–0.1	0.005–0.1
H_0	40–100	40–100
w	-2–0	-2–0
n_s	0.5–1.5	0.5–1.5
α_s	-0.2–0.2	-0.2–0.2
$\log[10^{10} A_s]$	2.5–4	2.5–4
τ	0–1	0–1
N_ν	3.046/0–50	3.046/0–50
z_i	0–10^4	$\cdots$
$\log(1 + z_i)$	$\cdots$	0–4

FIG. 1 (color online). Two-dimensional marginal 68% and 95% contours for z_i and N_ν. Top: Linear prior for z_i. Bottom: Logarithmic prior, i.e., linear in $\log(1 + z_i)$.

at a redshift around recombination ($z_r \approx 1100$). Marginalizing over N_ν we find $z_i < 1500$ at 95% C.L.

We have repeated the same exercise for a logarithmic prior on z_i, i.e., one that is uniform in $\log(z_i + 1)$. The corresponding credible regions are shown in the lower panel of Fig. 1. Marginalizing once more over N_ν we find $z_i < 795$ at 95% C.L. The difference arises because the effective volume at low z_i becomes larger for the logarithmic prior and therefore integration favors slightly lower values of z_i. This effect is well-known for parameters with a highly non-Gaussian likelihood, other notable examples being neutrino mass m_ν [16] and the tensor to scalar ratio r [43,44].

While the exact redshift at which neutrinos can become strongly interacting depends on assumptions about priors, we find that neutrinos which were strongly interacting significantly before recombination are excluded by data at much more than 95% C.L., a conclusion which is fully consistent with Ref. [28].

Our results pertain to any form of radiation present around recombination. However, we ultimately want to test the interactions of ordinary neutrinos. The cosmic standard radiation content is given by $N_\nu = 3.046$.
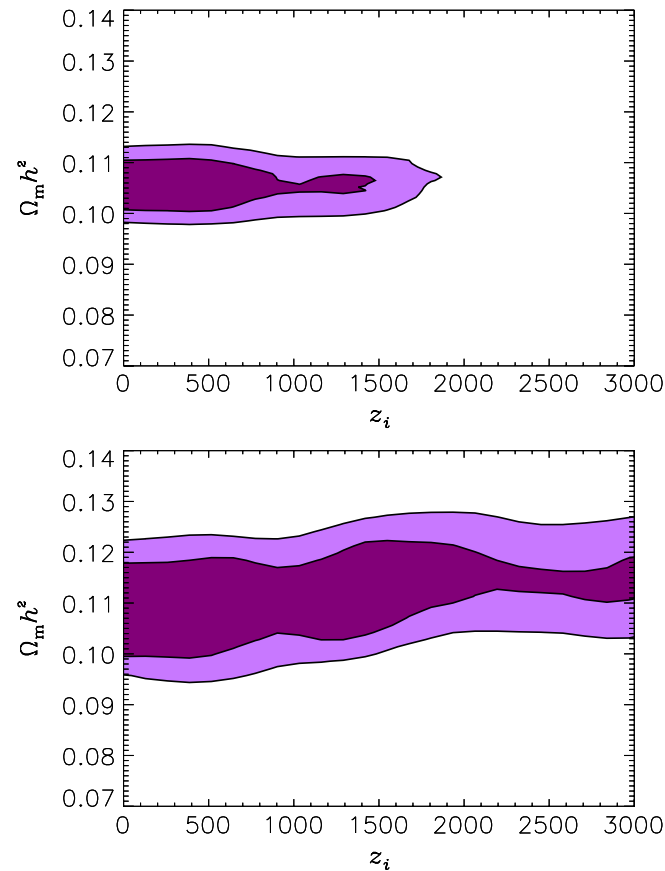

Repeating the above exercises with this fixed prior we find $z_i < 1520$ for the linear z_i prior and $z_i < 790$ for the logarithmic prior. These limits are almost identical to those where we marginalized over N_ν. This is hardly surprising since $N_\nu \sim 3$ allows the largest values of z_i.

In order to test more quantitatively how disfavored strongly coupled neutrinos are we have performed a high-precision run with $N_\nu = 3.046$ and the more conservative linear z_i prior to calculate a sequence of progressively higher confidence limits. We find $z_i < 1910$ at 99% C.L. and 2230 at 99.7% C.L. At even higher confidence limits the Markov chains show signs of incomplete convergence and we refrain from quoting bounds.

We also show two-dimensional credible regions in the plane spanned by the matter density $\Omega_M = \Omega_{CDM} + \Omega_B$ and z_i in Fig. 2 where the conservative linear z_i prior was used and N_ν kept as a fit parameter. In the top panel we have used the full data set as in Fig. 1 and find consistent results. In the bottom panel have used only WMAP5 data and thus confirm with our method that WMAP5 data alone do not significantly constrain z_i [28].

IV. DISCUSSION

We have studied a model in which neutrinos free-stream after the weak decoupling temperature around 1 MeV, but subsequently become strongly interacting at some later epoch. In this model neutrino free-streaming is shut off at some redshift z_i after which they behave like a perfect fluid.

Our approach of neutrinos recoupling at some redshift z_i was motivated by a majoron-type interaction model where neutrinos interact with a new massless pseudoscalar by virtue of a dimensionless Yukawa coupling g. In the framework of such a model we can translate our limit on z_i into a limit on g in analogy to a previous paper by two of us [24]. When considering the scattering process the bound applies to any component of g_{ij}, the indices referring to the different neutrino flavors. The off-diagonal parts, however, are much more tightly constrained by the decay process $\nu_i \rightarrow \nu_j \phi$ [24].

At $z \sim 1500$ the Universe is matter dominated and to a good approximation $H \propto T^{3/2}$. Since for scattering the rate is $\Gamma \sim g^4 T$, we can translate the condition for strong interaction $\Gamma/H \gtrsim 1$ to a bound on g [24]. Since $\Gamma/H \propto g^4 T^{-1/2}$, and in the previous paper we effectively used $z_i = 1088$ to obtain $g < 10^{-7}$ we now get $g < 10^{-7}(1500/1088)^{1/8} \sim 1.05 \times 10^{-7}$, i.e. a negligible 5% difference compared with our previous result.

It should be noted that, for masses below the recombination temperature $m \lesssim T_R \sim 0.3$ eV, our bound applies equally well to the case of neutrino decay and inverse decay [24]. Again, the quantitative difference with respect to our earlier result is negligible.

We finally note that the translation of z_i into a bound on g in our model depends on the assumption that all N_ν

FIG. 2 (color online). Two-dimensional marginal 68% and 95% contours for z_i and $\Omega_M h^2$, using the linear prior for z_i and using N_ν as a fit parameter. Top: Full data set. Bottom: WMAP5 data only.

neutrino degrees of freedom stop free-streaming at z_i. In terms of g this means that for the diagonal terms the bound on g applies only if all g_{ii} are comparable in magnitude. Likewise, for the off-diagonal components we require that the g_{ij} are such that one of the states is not completely decoupled from the interaction. In the case where one or more states are decoupled the bound can be expected to weaken [10,27].

One way to improve this limit in the future is by actually detecting neutrino hot dark matter in cosmological precision data. In decay scenarios involving massless pseudo-scalars and for a mass of 50 meV, the lifetime limit would improve by some 6 orders of magnitude [45].

Our more general conclusion is that neutrinos which are strongly interacting around recombination are strongly disfavored by data. The present data strongly support the conclusion that the cosmic neutrino background (i) exists around the epoch of recombination and (ii) that its fluctuations do have an anisotropic stress component. In the future, CMB data alone will likely suffice to reach the same or better sensitivity so that the bound on g can be expected to improve significantly [25,28].

[1] S. Hannestad, Annu. Rev. Nucl. Part. Sci. **56**, 137 (2006).
[2] J. Lesgourgues and S. Pastor, Phys. Rep. **429**, 307 (2006).
[3] E. Komatsu *et al.*, arXiv:0803.0547 [Astrophys. J. Suppl. Ser. (to be published)].
[4] S. Hannestad, Phys. Rev. D **64**, 083002 (2001).
[5] S. Hannestad, J. Cosmol. Astropart. Phys. 01 (2006) 001.
[6] K. Ichikawa, M. Kawasaki, and F. Takahashi, J. Cosmol. Astropart. Phys. 05 (2007) 007.
[7] G. Mangano, A. Melchiorri, O. Mena, G. Miele, and A. Slosar, J. Cosmol. Astropart. Phys. 03 (2007) 006.
[8] J. Hamann, S. Hannestad, G. G. Raffelt, and Y. Y. Y. Wong, J. Cosmol. Astropart. Phys. 08 (2007) 021.
[9] C. Zunckel and P. G. Ferreira, J. Cosmol. Astropart. Phys. 08 (2007) 004.
[10] M. Cirelli and A. Strumia, J. Cosmol. Astropart. Phys. 12 (2006) 013.
[11] A. Goobar, S. Hannestad, E. Mörtsell, and H. Tu, J. Cosmol. Astropart. Phys. 06 (2006) 019.
[12] J. R. Kristiansen, H. K. Eriksen, and O. Elgaroy, Phys. Rev. D **74**, 123005 (2006).
[13] U. Seljak, A. Slosar, and P. McDonald, J. Cosmol. Astropart. Phys. 10 (2006) 014.
[14] G. L. Fogli *et al.*, Phys. Rev. D **75**, 053001 (2007).
[15] S. Hannestad, J. Cosmol. Astropart. Phys. 05 (2003) 004.
[16] S. Hannestad, arXiv:0710.1952.
[17] G. B. Gelmini and M. Roncadelli, Phys. Lett. **99B**, 411 (1981).
[18] Y. Chikashige, R. N. Mohapatra, and R. D. Peccei, Phys. Lett. **98B**, 265 (1981).
[19] J. Schechter and J. W. F. Valle, Phys. Rev. D **25**, 774 (1982).
[20] G. Raffelt and J. Silk, Phys. Lett. B **192**, 65 (1987).
[21] F. Atrio-Barandela, and S. Davidson, Phys. Rev. D **55**, 5886 (1997).
[22] J. F. Beacom, N. F. Bell, and S. Dodelson, Phys. Rev. Lett. **93**, 121302 (2004).
[23] S. Hannestad, J. Cosmol. Astropart. Phys. 02 (2005) 011.
[24] S. Hannestad and G. Raffelt, Phys. Rev. D **72**, 103514 (2005).

[25] A. Friedland, K. M. Zurek, and S. Bashinsky, arXiv:0704.3271.
[26] R. F. Sawyer, Phys. Rev. D **74**, 043527 (2006).
[27] N. F. Bell, E. Pierpaoli, and K. Sigurdson, Phys. Rev. D **73**, 063523 (2006).
[28] F. De Bernardis, L. Pagano, P. Serra, A. Melchiorri, and A. Cooray, J. Cosmol. Astropart. Phys. 06 (2008) 013.
[29] C. P. Ma and E. Bertschinger, Astrophys. J. **455**, 7 (1995).
[30] G. Drexlin (KATRIN Collaboration), Nucl. Phys. B, Proc. Suppl. **145**, 263 (2005).
[31] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, and P. D. Serpico, Nucl. Phys. **B729**, 221 (2005).
[32] Legacy Archive for Microwave Background Data Analysis (LAMBDA), http://lambda.gsfc.nasa.gov.
[33] M. R. Nolta *et al.*, arXiv:0803.0593 [Astrophys. J. Suppl. Ser. (to be published)].
[34] J. Dunkley *et al.* (WMAP Collaboration), arXiv:0803.0586 [Astrophys. J. Suppl. Ser. (to be published)].
[35] M. Tegmark *et al.*, Phys. Rev. D **74**, 123507 (2006).
[36] S. Cole *et al.* (2dFGRS Collaboration), Mon. Not. R. Astron. Soc. **362**, 505 (2005).
[37] T. M. Davis *et al.*, Astrophys. J. **666**, 716 (2007).
[38] D. J. Eisenstein *et al.* (SDSS Collaboration), Astrophys. J. **633**, 560 (2005); see also Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies, http://cmb.as.arizona.edu/~eisenste/acousticpeak.
[39] W. L. Freedman *et al.*, Astrophys. J. **553**, 47 (2001).
[40] J. Hamann, S. Hannestad, A. Melchiorri, and Y. Y. Y. Wong, J. Cosmol. Astropart. Phys. 07 (2008) 017.
[41] Physics and Cosmology, http://cosmologist.info.
[42] A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002).
[43] W. Valkenburg, L. M. Krauss, and J. Hamann, Phys. Rev. D **78**, 063521 (2008).
[44] H. Peiris and R. Easther, J. Cosmol. Astropart. Phys. 07 (2006) 002.
[45] P. D. Serpico, Phys. Rev. Lett. **98**, 171301 (2007).