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Are cosmological neutrinos free-streaming?

Anders Basbøll, Ole Eggers Bjaelde, Steen Hannestad, and Georg G. Raffelt

1Department of Physics and Astronomy, University of Aarhus, Ny Munkegade, DK-8000 Aarhus C, Denmark
2Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

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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.

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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 \( c_{\text{vis}} \), taken to be independent of redshift. Our study is complementary in that we assume that \( c_{\text{vis}} \) 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

\[
\Theta = (\omega_{\text{CDM}}, \omega_B, H_0, n_s, \alpha_s, \tau, A_s, N_\nu, z_i),
\]

where \( h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) \), and the cold dark matter (CDM) and baryon (B) contents are given by \( \omega_{\text{CDM}} = \Omega_{\text{CDM}}h^2 \) and \( \omega_B = \Omega_Bh^2 \) respectively. We assume spatial flatness, i.e. the dark energy (DE) density is given by \( \Omega_{\text{DE}} = 1 - \Omega_{\text{CDM}} - \Omega_B \). 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 \( \alpha_s \). 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 \( \tau \). 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 \( N_\nu \) 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 \( k = 0.2h \text{ Mpc}^{-1} \) and correct for non-linearity using the shot-noise term \( P_{\text{shot}} \).

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 \( N_\nu \) 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
at a redshift around recombination \((z_r = 1100)\). Marginalizing over \(N_p\) 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 \(N_p\) 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 \(m_{\nu}\) [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 \(N_p = 3.046\).

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 \(N_p\). This is hardly surprising since \(N_p \sim 3\) 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 \(N_p = 3.046\) 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 \(N_p\) 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 we 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 \(m \approx T_R \sim 0.3\) 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 \(N_p\).
neutrino degrees of freedom stop free-streaming at $z_f$. 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 improve by some 6 orders of magnitude [45].

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 disfavor $\tilde{\nu}$ by some 5 orders of magnitude [28].

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].

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