Fermilab FERMILAB-FN-0785-A

Constraints on the Relic Neutrino Abundance and Implications for Cosmological Neutrino Mass Limits

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We examine a mechanism which can lead to flavor transformation of neutrino-antineutrino asymmetries in the early universe, a process which is unavoidable when the neutrino mixing angles are large. This sets the best limit on the lepton number of the universe, and hence on the relic neutrino abundance. We also consider the consequences for the relic neutrino abundance if extra neutrino interactions are allowed, e.g., the coupling of the neutrinos to a light (compared to m_ν) boson. For a wide range of couplings not excluded by other considerations, the relic neutrinos would annihilate to bosons at late times, and thus make a negligible contribution to the matter density today. This mechanism evades the neutrino mass limits arising from large scale structure.

I. INTRODUCTION

The discovery of neutrino oscillations confirms that neutrinos have non-zero mass, requiring physics beyond the minimal standard model. The solar and atmospheric oscillation experiments have measured neutrino mass-squared differences $\delta m^2_{21} \simeq 7\times10^{-5}$ eV^2 and $\delta m^2_{32} \simeq 2\times10^{-3}$ eV^2 [1], which implies *lower* limits on at least two neutrino masses of $\sqrt{\delta m^2_{21}}$ and $\sqrt{\delta m^2_{32}}$. The best laboratory limit on neutrino mass arises from tritium beta decay. At the present sensitivity of $m_\nu < 2.2$ eV (at 95% CL) [2], this *upper* limit applies to each of the three mass eigenstates. KATRIN, a proposed next-generation tritium beta decay experiment, will have sensitivity down to $m_\nu \simeq 0.2$ eV [3]. New neutrinoless double beta decay experiments will have even greater sensitivity, if neutrinos are Majorana particles [4]

Neutrino mass can also be measured with cosmology. This is an exciting possibility, since the current cosmological limits on the sum of the neutrino masses range from 0.5 to 2 eV, and future observations should realistically be able to reach the scale $\sqrt{\delta m^2_{23}}$, by which the discovery of neutrino mass is guaranteed [5]. The cosmological approach involves determining the fraction of the dark matter that consists of neutrinos. Although neutrinos are not a dominant component of the dark matter, they can have a significant effect of the growth of large scale structure. Measurement of the large scale structure power spectrum constrains the energy density in neutrinos, $\rho_\nu = \sum m_\nu N_\nu$, and hence sets a neutrino mass limit provided N_ν, the number density of relic neutrinos, is (independently) well determined.

The best constraints on N_ν arise from big bang nucleosynthesis (BBN). We shall explain how knowledge that the solar neutrino mixing angle is large, allows the BBN limit on the relic neutrino abundance to be greatly improved. This is possible because large angle mixing leads to equilibration of the neutrino flavors before the time of BBN, such that all three active neutrino flavors are subject to the stringent constraints that would otherwise apply only to ν_e. Given that cosmological limits on neutrino mass rely on the assumption that the relic neutrinos have the standard abundance, the determination of N_ν from BBN is an important input.

While we may now confidently predict N_ν at the epoch of BBN, its possible that non-standard physics could change this value during the period between BBN and the formation of structure. We shall examine a model in which non-standard interactions keep the neutrinos in equilibrium until late times. Provided the neutrino decouple when they are non-relativistic, their abundance today can be very small, and the cosmological neutrino mass limits evaded.

II. STRINGENT CONSTRAINTS ON RELIC NEUTRINO-ANTINEUTRINO ASYMMETRIES DUE TO FLAVOR EQUILIBRATION

The relic neutrino background has never been directly detected, so we must resort to indirect means to infer its properties. One of the most useful tools available is big bang nucleosynthesis. While our knowledge of both neutrino mixing and cosmology have recently undergone dramatic improvement, there remain open questions. The central question we address in this section is the possibility of a large relic neutrino asymmetry, or equivalently: how big is the universe's lepton number?

While the baryon asymmetry of the universe is well determined, $n_B/n_\gamma \simeq 5 \times 10^{-10}$, the size of the lepton asymmetry is unknown. Given constraints on charge neutrality, any large lepton asymmetry would have to be hidden in the neutrino sector. The simplest assumption is that the baryon and lepton asymmetries are of the same size, as would be the case if $B-L$ were conserved. However, there are viable models in which L may be large while B is small [6], and if confirmed would be a very important clue.

Since neutrinos and antineutrinos should be in chemical equilibrium until they decouple at a temperature $T \sim 2$ MeV, they may be well-described by Fermi-Dirac distributions with equal and opposite chemical potentials:

$$f(p,\xi) = \frac{1}{1+\exp(p/T-\xi)}\,, \tag{1}$$

where p denotes the neutrino momentum, T the temperature, and ξ the chemical potential in units of T. The lepton asymmetry L_α for a given flavor ν_α is related to the chemical potential by

$$L_\alpha = \frac{n_{\nu_\alpha} - n_{\bar\nu_\alpha}}{n_\gamma} = \frac{\pi^2}{12\zeta(3)}\left(\xi_\alpha + \frac{\xi_\alpha^3}{\pi^2}\right)\,, \tag{2}$$

where $\zeta(3) \simeq 1.202$. A nonzero chemical potential results in extra energy density, such that the effective number of neutrinos is increased from the standard model prediction by

$$\Delta N_\nu = \frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4\,. \tag{3}$$

Large chemical potentials affect BBN in two ways:

1. The extra energy density increases the expansion rate of the universe, thus increasing the BBN helium abundance, and also alters the CMB results. This sets the weak bound $|\xi_\alpha| \lesssim 3$, for all three flavors.

2. An additional, much stronger, limit can be placed on the ν_e – $\overline{\nu}_e$ asymmetry, as it directly effects the neutron to proton ratio prior to BBN by altering beta-equilibrium. (Beta-equilibrium is between the weak interactions $n + \nu_e \leftrightarrow p + e^-$ and $p + \bar\nu_e \leftrightarrow n + e^+$.) For example, positive ξ_e increases the ν_e abundance relative to $\bar\nu_e$, thus lowering the neutron to proton ratio and decreasing the helium yield. This sets the limit $|\xi_e| \lesssim 0.04$.

However, it is possible that the two effects compensate for each other, i.e., the effect of a small ξ_e is partially undone by an increased expansion rate due to a large $\xi_{\mu,\tau}$. In this case the bounds become [7]:

$$-0.01 < \xi_e \; < \; 0.22\,, \tag{4}$$

$$|\xi_{\mu,\tau}| \; < \; 2.6\,, \tag{5}$$

where the upper limits are obtained only in tandem.

A. Consequences of Large Angle Mixing

Since we know neutrinos oscillate, the individual lepton numbers L_e, L_μ and L_τ are violated, and only the total lepton number is conserved. It was suggested in Ref. [8] that the large neutrino mixing angles implied by the present data may lead to equilibration of all three flavors in the early universe. If a large asymmetry hidden in $\xi_{\mu,\tau}$ were to be transfered to ξ_e well before weak freezeout at $T \simeq 1$ MeV, the stringent BBN limit on ξ_e would then apply to all three flavors, improving the bounds on $\xi_{\mu,\tau}$ by nearly two orders of magnitude.

This proposal was recently studied in detail in Refs. [9–11], where close to complete equilibration of the asymmetries $\xi_{\mu,\tau}$ with ξ_e was found. We have examined this equilibration mechanism, and in particular, found analytic solutions for the parameters controlling the evolution [11].

B. Flavor Equilibration and Effective Oscillation Parameters

Equilibration of neutrino flavors in the early universe is driven by MSW transitions, which occur when the temperature of the universe is in the MeV range. These MSW transition convert the initial flavor states (which are approximately mass eigenstates at high temperature) into vacuum mass eigenstates as the universe expands and cools. Since the neutrino mixing angles (and most importantly, the solar mixing angle) are large, the final state has large components of all three flavors. Large neutrino mixing angles are thus a crucial ingredient in obtaining flavor equilibrium. (If the solar neutrino mixing angle had been a small angle, equilibration would not be complete.)

Equilibration of ν_e with ν_μ and ν_τ takes place when $T \sim 2$ MeV, via an MSW transition which is driven by the solar mass squared difference. (Equilibration of ν_μ and ν_τ takes place earlier, around $T \sim 10$ MeV, controlled by the atmospheric neutrino mixing parameters.) The MSW transitions which take place are actually more complicated than typical MSW transitions that occur, for example, for solar neutrinos. This is because in addition to a refractive index arising from forward scattering interactions with charged leptons in the plasma, there are also refractive effects caused by forward scattering from *other neutrinos* in the background medium. This neutrino-neutrino forward scattering introduces a non-linear contribution to the effective potential [12]. Surprisingly, the effect of this non-linear term is to synchronize the neutrino ensemble such that all momentum modes go through the MSW resonance together. The entire ensemble behaves as though it had the same effective momentum (which is close to the thermal average.) See [9–11, 13] for details.

Under these conditions, the evolution of the neutrino ensemble must be calculated by solving a quantum Boltzmann equation [14] which describes the evolution of the neutrino density matrix. However, in the limit in which the neutrino-neutrino forward scattering is dominant (which occurs for all parameters of interest) we have calculated effective oscillation parameters which describe the evolution of the entire neutrino ensemble [11]. The evolution is governed by an *effective* matter term, given by

$$Z = \frac{2T}{\delta m_0^2}\left(\frac{V^T}{p/T}\right)\left(\pi^2 + \frac{\xi^2}{2}\right). \tag{6}$$

Here V^T is the thermal potential arising from the finite-temperature modification of the neutrino mass due to the presence of thermally populated charged leptons in the plasma

$$V^T(p) = -\frac{8\sqrt{2}G_{\mathrm{F}}p}{3m_{\mathrm{W}}^2}\left(\langle E_{l^-}\rangle n_{l^-} + \langle E_{l^+}\rangle n_{l^+}\right) . \tag{7}$$

If the mixing angle and mass squared difference in vacuum are θ_0 and δm_0^2 respectively, the effective

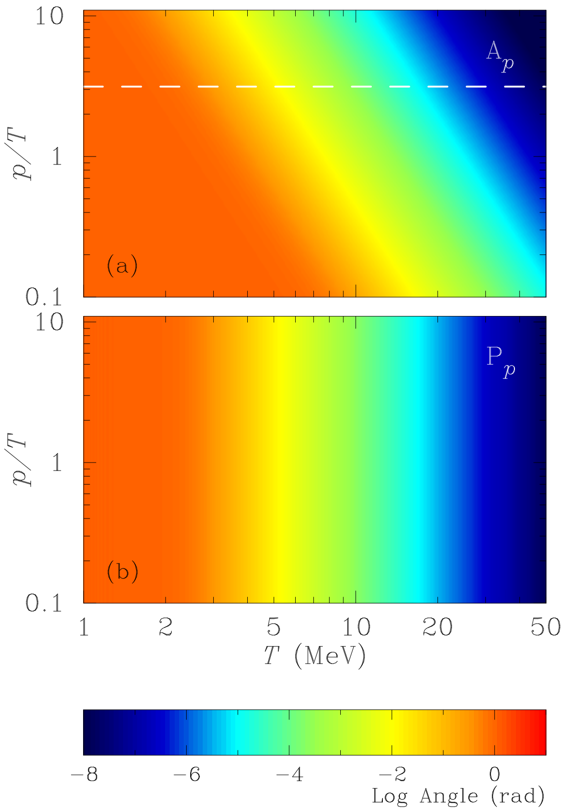

FIG. 1: The color denotes the value of 2θ, where θ is a mixing angle. In the upper panel, we show the value of the matter-affected mixing angle, neglecting the refractive index term arising from neutrino-neutrino forward scattering. In the lower panel, we have included the effects of neutrino-neutrino forward scattering. The result is a dramatic synchronization of the momentum ensemble, to a single effective momentum, $p_{sync}/T \simeq \pi$. That is, *all* of the momentum modes behave as though they have momentum $p/T \simeq \pi$, shown with a white horizontal dashed line.

or "synchronized" oscillation frequency is given by

$$\Delta_{\rm sync} = \xi \frac{\delta m_0^2}{2T} \left(\frac{3/2}{\pi^2 + \xi^2} \right) \sqrt{\sin^2 2\theta_0 + (-\cos 2\theta_0 + Z)^2}. \tag{8}$$

However, it is the effective mixing angle $\theta_{\rm sync}$ that is important in describing when the MSW transformation takes place. This angle is given by

$$\sin^2 2\theta_{\rm sync} = \frac{\sin^2 2\theta_0}{\sin^2 2\theta_0 + (-\cos 2\theta_0 + Z)^2}, \tag{9}$$

and thus we find it is the mixing angle which would correspond to the momentum state

$$\frac{p_{\rm sync}}{T} = \pi \sqrt{1 + \xi^2/2\pi^2} \simeq \pi \tag{10}$$

in the absence of the nonlinear potential. This result indicates a remarkable coincidence. Namely, that the nonlinear potential drives the system to an effective momentum of $p/T \simeq \pi$, which is very close to the thermal average $p/T \simeq 3.15$. Fig. 1 illustrates evolution of the mixing angle as a function of temperature.

C. Discussion and Implications

The synchronized MSW transition takes place in conjunction with collisional processes which tend to decohere superpositions of neutrino flavor states. Through these two effects, very close to complete equilibration of neutrino flavors occurs. Therefore, because asymmetries in any flavor will affect beta-equilibrium, the stringent limits on ν_e can now be applied to all flavors. The limits on the relic neutrino chemical potentials thus become

$$|\xi_e| \sim |\xi_\mu| \sim |\xi_\tau| \lesssim 0.04, \tag{11}$$

and the lepton number

$$|L| = |L_e + L_\mu + L_\tau| \lesssim 0.08. \tag{12}$$

By comparison with the old limits in Eq. 4, this is an improvement by two orders of magnitude.

Flavor equilibration is an important result, as it excludes the possibility of degenerate BBN [15], and is the strongest limit on the total lepton number of the universe and is likely to remain so for the foreseeable future. In terms of extra relativistic degrees of freedom, the limit is impressively tight: If $\xi_{e,\mu,\tau} < 0.04$, then $\Delta N_\nu < 3 \times 0.0007 = 0.002$. One significant implication is that cosmological constraints on (and future measurements of) neutrino masses will not be subject to uncertainty in the relic neutrino density.

Strictly speaking, one version of the degenerate BBN scenario is still possible: It is conceivable that $\xi_e \sim \xi_\mu \sim \xi_\tau \sim 0.2$, provided that another relativistic particle species contributes the extra energy density required to compensate for the large ν_e chemical potential. However, this extra energy density could no longer consist of active neutrinos, so would have to be something more exotic. Such an unnatural scenario could eventually be detected via the CMB.

III. THE NEUTRINOLESS UNIVERSE

Cosmological limits on neutrino mass are possible because neutrinos cause a suppression of the large scale structure power spectrum. When neutrinos are relativistic, they free stream out of density perturbations, reducing the growth of structure. This results in a suppression of the matter power spectrum on all scales below that of the horizon at the time the neutrinos became non-relativistic, after which they act like cold dark matter. The extent to which this lack of clustering affects the distribution of matter today depends on the ratio of the energy density of the non-clustering component (neutrinos) to the total density of matter. The former is

$$\rho_\nu = \Sigma m_\nu n_\nu \rightarrow \frac{\Sigma m_\nu}{93.5 h^2 \text{ eV}} \rho_{\rm cr}, \tag{13}$$

where $\rho_{\rm cr}$ is the critical density associated with a flat universe, and h specifies the Hubble constant, $H_0 = 100h\,\text{km}\,\text{sec}^{-1}\,\text{Mpc}^{-1}$. The limit on the right in Eq. (13) assumes the standard cosmological abundance. Recall that, in the standard scenario, neutrinos couple to the rest of the cosmic plasma until the weak interactions freeze out at $T \sim 1$ MeV. After freeze out, their abundance scales simply as a^{-3} where a is the cosmic scale factor. Thus, in the standard cosmology, there are expected to be roughly as many cosmic neutrinos today as photons in the cosmic microwave background.

Limits from structure formation on the sum of neutrino masses now range from 0.5 to 2 eV, with the spread largely due to different assumptions about the relative bias between the mass and galaxy distributions [16]. Bias is one important issue, but this will be circumvented with future weak lensing surveys, which will measure the mass distribution directly.

Another possible weak link in the cosmological constraint is the assumption that neutrinos have the standard abundance. We have shown that BBN constraints, combined with neutrino mixing data, no longer allow the possibility of a significantly increased n_ν due to a large lepton asymmetry. Are there other ways to alter the relic neutrino abundance, and in particular, to lower it?

If neutrinos have extra interactions so that they remain in equilibrium until late times, they would freeze out when they are non-relativistic, in which case their final abundance would be suppressed by a factor $\propto e^{-m_\nu/T_f}$. We show that new neutrino couplings in the allowed range can lead to a *vanishing relic neutrino density today*, hiding the effects of neutrino masses from cosmological observations. This possibility is falsifiable both directly and with other experiments.

A. Interaction Model

We consider the cosmological consequences of coupling neutrinos to each other with scalar or pseudo-scalar bosons, through tree level couplings of the form

$$\mathcal{L} = h_{ij}\overline{\nu}_i\nu_j\phi + g_{ij}\overline{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}, \tag{14}$$

as in Majoron-type models, for example. The field ϕ is massless (or light compared to m_ν). Viable models of this type have been discussed in Ref. [17]. The solar neutrino [18] and meson decay [19] limits on these couplings are very weak, $|g| \lesssim 10^{-2}$. Stronger limits may obtain in certain circumstances. Neutrinoless double beta decay limits $g_{ee} < 10^{-4}$, but the other couplings may be much larger. Supernova constraints [20] may exclude a narrow range of couplings around $g \sim 10^{-5}$, but the boundaries are model dependent. Scalar couplings could mediate long-range forces with possible cosmological consequences, while pseudoscalar couplings mediate spin-dependent long-range forces, which have no net effect on an unpolarized medium [21]. Since ϕ couples only to neutrinos, we do not consider these effect further, so we shall not distinguish g or h type couplings.

The ϕ boson can be brought into thermal equilibrium through its coupling to the neutrinos, and the $\nu - \phi$ system may stay in thermal contact until late times, through the processes $\nu\phi \leftrightarrow \nu\phi$ and $\nu_i \leftrightarrow \nu_j\phi$. Most important though is $\nu\nu \leftrightarrow \phi\phi$, a process which depletes the total number of neutrinos. In the standard case, the neutrinos decouple from each other and the matter at $T \sim 1$ MeV, but interactions with ϕ may keep neutrinos in equilibrium until they are non-relativistic, $T \sim 1$ eV. In order to accomplish this, g must be sufficiently large; we show below that this requires $g \gtrsim 10^{-5}$, well within the allowed range. If the couplings are this large, then all cosmic neutrinos efficiently annihilate into scalars, leaving no relic neutrinos today, thereby hiding the effects of neutrino mass and evading the cosmological mass limits.

B. Annihilation Rate

The rate for neutrino annihilation is

$$\Gamma = \langle\sigma v\rangle n_{\rm eq}, \tag{15}$$

where the cross section is [22, 23]

$$\sigma = \frac{g^4}{32\pi}\frac{1}{s}\left[\frac{1}{\beta^2}\log\frac{1+\beta}{1-\beta} - \frac{2}{\beta}\right], \tag{16}$$

and $\sqrt{s}$ is the center of mass energy and $\beta^2 = 1 - 4m^2/s$. In the non-relativistic limit the annihilation rate becomes

$$\Gamma(T) = \frac{g^4}{64\pi}\frac{T}{m^3}\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}, \tag{17}$$

where we have used $\langle\beta^2\rangle \simeq 3T/m$.

For sufficiently large g, the annihilation rate will be larger than the expansion rate until the temperature drops well beneath the neutrino mass. Once $T < m_\nu$, the neutrino abundance will become exponentially suppressed, asymptoting to the equilibrium abundance at the freeze out temperature, T_f, defined as the temperature at which the annihilation rate is equal to the expansion rate. If T_f is less than of order $m/7$, the neutrinos will be suppressed from their nominal abundance by a factor greater than 100: they will play no role in subsequent cosmological evolution. We find that as long as $g \gtrsim 10^{-5}$, the annihilation is complete by T_f, with only a negligible amount of neutrinos remaining.

Note that for $g \gtrsim 10^{-5}$, the scalar will be brought into thermal equilibrium before BBN. The energy density of a scalar boson is equivalent to 4/7 that of a neutrino species. Given that current BBN limits are $N_\nu^{\rm eff} < 3.3 - 4$, an additional scalar is allowable. (In the case that the electron neutrinos have a large chemical potential, even $N_\nu^{\rm eff} = 7$ is permitted, provided the extra degrees of freedom do not consist of active neutrinos.)

C. Neutrino-ϕ Energy Density

Even if the neutrinos completely annihilate into massless ϕ's, they still have a small impact on the distribution of matter in the universe today. The energy density in the $\nu - \phi$ system differs from that in the three massless neutrinos of the canonical standard cosmological model and from a model of three massive non-interacting neutrinos. In particular, the epoch of matter domination is delayed in the interacting neutrino scenario outlined above. This delay leads to a small suppression of the matter power spectrum on small scales. To explain this suppression, we first compute the evolution of the energy density in the $\nu - \phi$ system and compare it with the conventional scenarios.

As the neutrinos annihilate, the temperature of the $\nu - \phi$ fluid increases with respect to the photon temperature. To track the temperature evolution, we can use entropy conservation. The entropy density of the $\nu - \phi$ fluid is

$$s_{\nu-\phi} = \frac{2\pi^2}{45} T_\nu^3 \left[1 + 6 \times (7/8) F(m/t)\right], \tag{18}$$

where

$$F(m/T) \equiv \frac{180}{7\pi^2 T^4}(\rho_\nu + P_\nu). \tag{19}$$

When the neutrinos are highly relativistic, $F = 1$, while it is exponentially suppressed at late times when the neutrinos become non-relativistic. Entropy conservation then implies

$$\frac{T_{\nu\phi}}{T_\gamma} = \left(\frac{T_{\nu\phi}}{T_\gamma}\right)_{\rm init} \left[\frac{1 + 21/4}{1 + (21/4)F(m/T)}\right]^{1/3}. \tag{20}$$

If $(T_{\nu\phi}/T_\gamma)_{\rm init}$ takes the standard value, $(4/11)^{1/3}$ at early times, at late times we have $(T_{\nu\phi}/T_\gamma) = (25/11)^{1/3}$. This implies an increase in the radiation energy density, corresponding to an effective number of neutrinos of $N_\nu^{\rm eff} = 6.6$. The evolution of the energy density is shown in Fig. 2.

CMB measurement constrain the number of light relativistic degrees of freedom. The current limit is $N_\nu^{\rm eff} \lesssim 7$ [24], hence does not rule out this scenario. However, one must be careful about interpreting such a limit, as the absence of freestreaming will lead to additional effects [25]. Future high precision CMB experiments may be able to observe these effects.

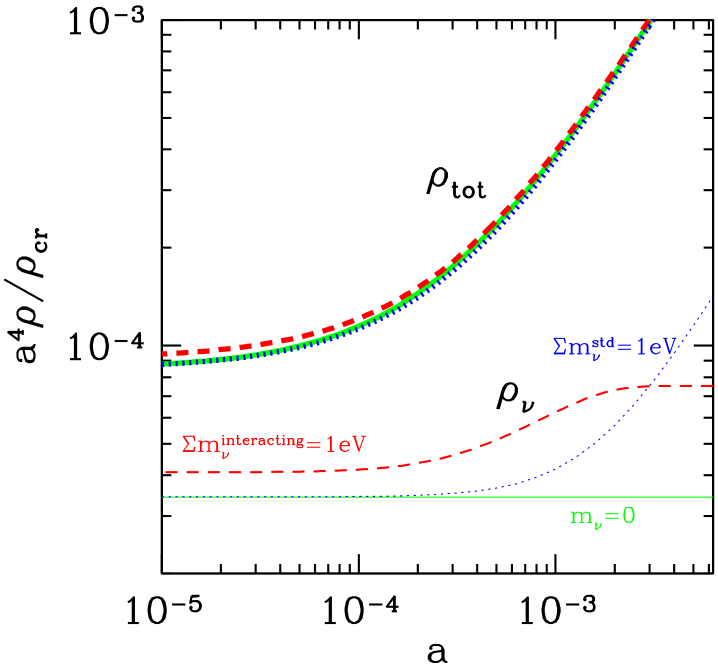

FIG. 2: Evolution of the energy density in three different scenarios, as a function of the scale factor a. Heavy curves at top are total energy density including matter, photons, and neutrinos; light curves at bottom are energy density in neutrino sector (including in the interacting case the ϕ's). Three different scenarios are depicted, differing in neutrino content: three massless neutrinos (solid), three degenerate standard model (non-interacting) neutrinos with $\sum m_\nu = 1$ eV (dotted); and three interacting degenerate neutrinos plus massless ϕ (dashed). Matter domination occurs later in the interacting $\nu - \phi$ scenario. We use the same total matter density, $\Omega_m = 0.3$, throughout.

D. Power Spectrum

We have calculated the large scale structure power spectrum, assuming the limit where neutrino annihilation is complete. We find that the current neutrino mass limits can be completely evaded: all values of neutrino mass are allowed, even those much greater than 1 eV. The results are shown in Fig. 3, where for comparison we have also shown the suppression caused by free streaming in the standard case.

In the interacting scenario, the usual suppression due to neutrino mass is absent, simply because neutrinos make no contribution to the matter density today. However a small suppression of the power spectrum does occur, due to the modified expansion history. Since the ϕ heating leads to an enhanced radiation density, matter radiation equality is delayed (see Fig.2). This means that the potentials for scales which enter the horizon during the radiation dominated epoch will decay for a slightly longer period, leading to a small suppression of the power spectrum on these scales. Note that if the neutrino annihilation is complete well before matter radiation equality, as would be the case for very heavy neutrinos, the full effects of the extra radiation are felt. This corresponds to the bottommost of the solid curves in Fig.3. For very small neutrino masses, $m_\nu \ll 1$eV, the increase in the radiation density due to neutrino annihilation occurs after time of matter radiation equality. At this stage, the universe has already entered the matter dominated regime, where the potentials are dominated by the dark matter, and the radiation is less important. The effects of the extra radiation created by neutrino annihilation are thus quite small. (The power spectrum is slightly suppressed with respect to a standard massless neutrino scenario, since there is still a small amount of extra radiation due the population of ϕ.) For intermediate cases, e.g., $\sum m_\nu = 1$eV, we find a suppression $P/P(m_\nu = 0) \simeq 0.8$, compared to 0.5 in the normal case.

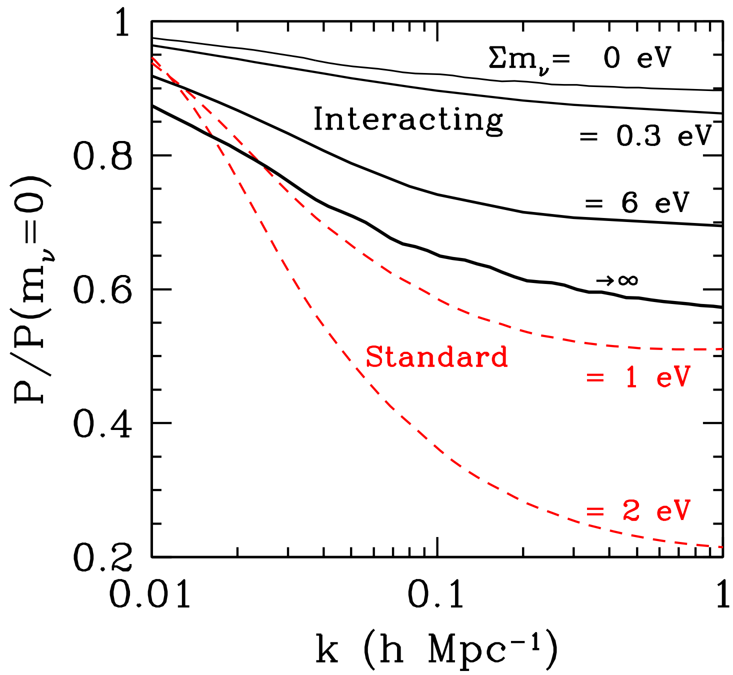

FIG. 3: The ratio of power spectra $P/P(m_\nu = 0)$ where $P(m_\nu = 0)$ is the power spectrum for the standard scenario with massless neutrinos. The solid curves show this ratio for various (degenerate) neutrino masses in the interacting scenario; dashed show the ratio in the standard scenario. Current limits range between the 1 and 2 eV standard curves. Note that masses above the tritium bound are not possible in either case.

E. Discussion

In the interacting scenarino, the present neutrino mass limits from large scale structure are eliminated. Therefore, future laboratory based tests of absolute neutrino mass, such as the KATRIN [3] tritium beta decay experiment, will play a unique and essential role. A comparision between tritium beta decay, neutrinoless beta decay, and cosmological neutrino mass limits will provide complimentary information and allow stringent test of neutrino properties.

The interacting scenario is falsifiable, as these couplings are of the appropriate size to lead to neutrino decay over astronomical distances, which has testable consequences [26]. The scenario may also be tested with future high precision CMB measurements [25].

IV. CONCLUSIONS

We have shown that large angle MSW transitions lead to neutrino flavor equilibration in the early universe. This sets the strongest limit on the universe's lepton number, because stringent constraints on the $\nu_e - \overline{\nu}_e$ asymmetry can now be applied to all three flavors, and the possibility of "degenerate" BBN eliminated. An important consequence is that in the standard cosmological scenario, the relic neutrino number density is now extremely well determined, thereby removing a possible uncertainty in cosmological determinations of neutrino mass.

We have also examined a model in which the relic neutrino density today is vanishing. This may be achieved with extra interactions which keep the neutrinos in thermal equilibrium until they become non-relativistic. In this scenario, the neutrino annihilate into massless bosons at late times, and thus make a negligible contribution to the matter density today. This eliminates the present neutrino mass limits arising from large scale structure.

Acknowledgments

The material presented here is based on work done at Fermilab in collaboration with Kev Abazajian, John Beacom, and Scott Dodelson, and published as:
• *The Neutrinoless Universe*, J. F. Beacom, N. F. Bell and S. Dodelson, astro-ph/0404585.
• *Stringent constraints on cosmological neutrino antineutrino asymmetries from synchronized flavor transformation*, K. N. Abazajian, J. F. Beacom and N. F. Bell, Phys. Rev. D **66**, 013008 (2002).

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