Neutrinoless Universe

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We consider the consequences for the relic neutrino abundance if extra neutrino interactions are allowed, e.g., the coupling of 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.

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Introduction.—The discovery of neutrino oscillations means that neutrinos have mass, which requires physics beyond the standard model. The solar and atmospheric oscillation experiments have measured neutrino mass-squared differences $\delta m^2_{21} \simeq 7 \times 10^{-5}$ eV^2 and $\delta m^2_{32} \simeq 2 \times 10^{-3}$ eV^2 [1], which implies *lower* limits on two neutrino masses of $\sqrt{\delta m^2_{21}}$ and $\sqrt{\delta m^2_{32}}$. Since these oscillations have been shown to be dominated by active-flavor neutrino oscillations, the three neutrino masses are connected and become degenerate in mass if any are larger than $\sqrt{\delta m^2_{32}}$ [2]. Thus, at the present sensitivity of $m_\nu < 2.2$ eV (at 95% C.L.) [3], the *upper* limit on neutrino mass from tritium beta decay applies to *each* of the three mass eigenstates. KATRIN, a proposed next-generation tritium beta decay experiment, will have a sensitivity down to $m_\nu \simeq 0.2$ eV [4]. New neutrinoless double beta decay experiments will have an even greater sensitivity, but only if neutrinos are Majorana particles [5].

Neutrino mass can also be measured with cosmological data. When neutrinos are relativistic, they free stream out of density perturbations, reducing the growth of the 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 nonrelativistic, 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 nonclustering component (neutrinos) to the total density of matter. The former is

$$\rho_\nu = \Sigma m_\nu n_\nu = \frac{\Sigma m_\nu}{93.5 h^2 \text{ eV}} \rho_{\rm cr}, \tag{1}$$

where $\rho_{\rm cr} = 3H_0^2/8\pi G$ is the critical density associated with a flat universe; the total density in matter is parametrized as $\Omega_m \rho_{\rm cr}$. Here h specifies the Hubble constant, $H_0 = 100h$ km sec^{-1} Mpc^{-1}. The equality on the right in Eq. (1) 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 neutrinos freeze out, their abundance scales simply as a^{-3} where a is the cosmic scale factor. Thus, in the standard cosmology, there are roughly as many relic neutrinos today as photons in the cosmic microwave background (CMB).

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 [6]. Bias is one important issue, but this will be circumvented with future weak lensing surveys, which will measure the mass distribution directly. Indeed, it has been shown that these observations should realistically be able to reach the scale $\sqrt{\delta m^2_{23}}$, by which the discovery of the neutrino mass is guaranteed [7]. These mass constraints depend on assuming the standard relic neutrino abundance. Big-bang nucleosynthesis (BBN) constraints, combined with neutrino mixing data, no longer allow the possibility of a significantly increased n_ν due to a large lepton asymmetry [8]. Are there other ways to alter the relic neutrino abundance, and specifically to lower it?

If neutrinos have extra interactions so that they remain in equilibrium until late times, they would freeze out when they are nonrelativistic, 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.

Interaction model.—We consider the cosmological consequences of coupling neutrinos to each other with bosons, through tree level scalar or pseudoscalar couplings of the form

$$\mathcal{L} = h_{ij} \bar{\nu}_i \nu_j \phi + g_{ij} \bar{\nu}_i \gamma_5 \nu_j \phi + \text{H.c.}, \tag{2}$$

as in Majoron-like models, for example. The field ϕ is assumed to be massless (or light compared to m_ν). Viable models of this type have been discussed in Ref. [9]. Here we assume that there is just one new boson and that these new couplings are unconnected to the mechanism of neutrino mass generation. Even tiny couplings can cause profound effects, as we show.

The solar neutrino [2,10] and meson decay [11] limits on these couplings are very weak, $|g| \lesssim 10^{-2}$ (here and below we do not distinguish g or h type couplings, nor neutrinos and antineutrinos). Neutrinoless double beta decay limits $g_{ee} < 10^{-4}$, but the other couplings may be much larger. Supernova constraints may exclude a narrow range of couplings around $g \sim 10^{-5}$, but the boundaries are model dependent [12]. 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 [13]. Since these constraints can be evaded, and since in our case ϕ couples only to neutrinos, we do not consider them further.

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 $\nu \leftrightarrow \nu\phi$. 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 nonrelativistic, $T \sim 1$ eV, when the inverse process becomes kinematically prohibited. 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. While neutrino decay requires off-diagonal couplings, the effects considered here can occur with either diagonal or off-diagonal couplings. If the couplings are this large, all relic neutrinos efficiently annihilate into bosons, leaving no relic neutrinos today, thereby hiding the cosmological effects of neutrino mass.

Past models of invisible neutrino decay also allowed a late transfer of energy from nonrelativistic to relativistic particles, altering the expansion rate history [14]. However, the case considered was that of a heavy ($m_\nu \gtrsim 10$ eV) neutrino, enough to be the dark matter, decaying into massless neutrinos. Such scenarios are no longer possible, given laboratory data on the neutrino mass scale and mass differences. For the relevant mass range, if decays occur, the parent and daughter neutrinos are equally relativistic. The possibilities of neutrino annihilation and/or self-interaction have been considered in scenarios in which neutrinos are the dark matter [15,16]. When neutrinos are a fraction of the dark matter, the signatures of this scenario are more subtle and have not been treated elsewhere.

Annihilation.—The neutrino annihilation rate is

$$\Gamma = \langle \sigma v \rangle n_{\rm eq}, \tag{3}$$

with the cross section [16,17]

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

where $\sqrt{s}$ is the center of mass energy and $\beta^2 = 1 - 4m_\nu^2/s$. In the nonrelativistic limit the annihilation rate becomes

$$\Gamma(T) = \frac{g^4}{64\pi}\frac{T}{m_\nu^3}\left(\frac{m_\nu T}{2\pi}\right)^{3/2} e^{-m_\nu/T}, \tag{5}$$

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

For sufficiently large g, the annihilation rate will be larger than the expansion rate until the temperature drops well below the neutrino mass. Once $T_\nu < m_\nu$, 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 $m_\nu/7$, the neutrinos will be suppressed from their nominal abundance by a factor greater than 100: they will play no role in subsequent cosmological evolution. The constraint on the coupling g is thus obtained by solving $\Gamma(T_f) \equiv H(T_f)$ and requiring $T_f < m_\nu/7$. For this estimate, it is sufficient to set $H(T) \sim H_0[\Omega_m(T/T_0)^3 + \Omega_\gamma(T/T_0)^4]^{1/2}$, where T_0 is the standard photon temperature, 2.73 K, and $\Omega_\gamma = 2.47 \times 10^{-5}h^{-2}$ is the ratio of energy density in photons to the critical density [18]. Then, 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 boson 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. Current BBN limits [19–21] are $N_\nu^{\rm eff} < 3.3$–4, so an additional boson is still allowable. In the case that the electron neutrinos have a large lepton asymmetry, even $N_\nu^{\rm eff} = 7$ is permitted, provided the extra degrees of freedom do not consist of active neutrinos [8,20]. Neutrino-majoron interactions may also weaken the constraints on large lepton asymmetries [22].

Neutrino-boson energy density.—We henceforth assume that $g > 10^{-5}$, so the neutrinos completely annihilate into massless bosons. However, there is still a small impact on the distribution of matter in the universe today. The energy density in the $\nu - \phi$ system differs from that of the three massless neutrinos of the canonical standard cosmological model and from a model of three massive noninteracting 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 common temperature of the $\nu - \phi$ fluid does not simply scale as a^{-1}. Rather, it falls less sharply. To track the temperature evolution, we can use entropy conservation. The entropy density of the $\nu - \phi$ fluid is

$$s_{\nu-\phi} = \frac{2\pi^2}{45} T_{\nu\phi}^3 [1 + 6 \times (7/8) F(m_\nu / T_{\nu\phi})], \quad (6)$$

$$F(m_\nu / T_{\nu\phi}) \equiv \frac{180}{7\pi^2 T_{\nu\phi}^4} (\rho_\nu + P_\nu). \quad (7)$$

When the neutrinos are highly relativistic, $F = 1$, while it is exponentially suppressed, $F \simeq 0$, at late times when the neutrinos become nonrelativistic. Entropy conservation then implies

$$\frac{T_{\nu\phi}}{T_\gamma} = \left(\frac{T_{\nu\phi}}{T_\gamma}\right)_{\rm init} \left[\frac{1 + 21/4}{1 + (21/4) F(m_\nu / T_{\nu\phi})}\right]^{1/3}. \quad (8)$$

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. 1.

CMB measurements constrain the number of light relativistic degrees of freedom. The current limit is $N_\nu^{\rm eff} \lesssim 7$ [23] and hence does not rule out this scenario. Further, one must be careful about applying this limit to our model, as interactions will reduce the propagation speed of neutrinos. Some secondary effects on the CMB due to neutrino free streaming (i.e., a phase shift and amplitude reduction) will thus be less striking than in the standard, noninteracting model [24]. These effects are discussed in [25] for a similar model in which a light (but heavier than m_ν) boson is coupled to the neutrinos.

Power spectrum.—We have calculated the large scale structure power spectrum, assuming the limit where the neutrino annihilation is complete. We find that the current neutrino mass limits can be completely removed: all values of $\sum m_\nu$ are allowed, even those much greater than 1 eV. The results are shown in Fig. 2 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, because neutrinos make no contribution to the matter density today. A small suppression does occur, due to the extra radiation present. Even though neutrinos do not free stream, perturbations in the neutrino-ϕ fluid still cannot grow, due to the pressure in this tightly coupled relativistic fluid. The negligible density in neutrinos makes this suppression irrelevant. The effects on the power spectrum are thus entirely due to the modified expansion history.

Matter radiation equality is delayed, since the ϕ heating leads to an enhanced radiation density (see Fig. 1). Therefore, 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. 2. For very small neutrino masses, $m_\nu \ll 1$ eV, the

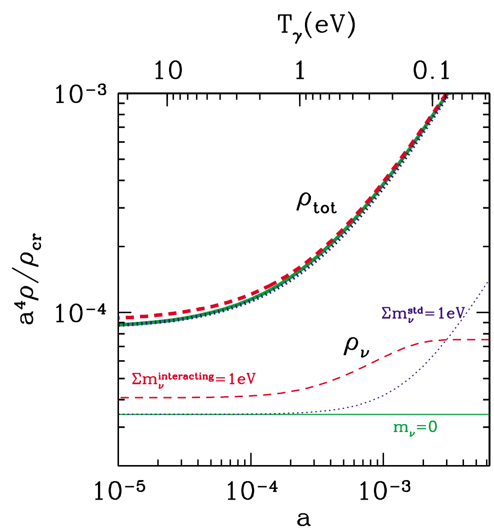

FIG. 1 (color online). Evolution of the energy density as a function of the scale factor a. Heavy curves at the top are total energy density including matter, photons, and neutrinos; light curves at the bottom are energy density in the neutrino sector (including ϕ's in the interacting case). Three different scenarios are depicted, differing in neutrino content: three massless neutrinos (solid line), three degenerate standard model neutrinos with $\sum m_\nu = 1$ eV (dotted line), and three interacting degenerate neutrinos plus massless ϕ (dashed line). We use the same total matter density, $\Omega_m = 0.3$, throughout; ρ_{cr} denotes the critical density *today.*

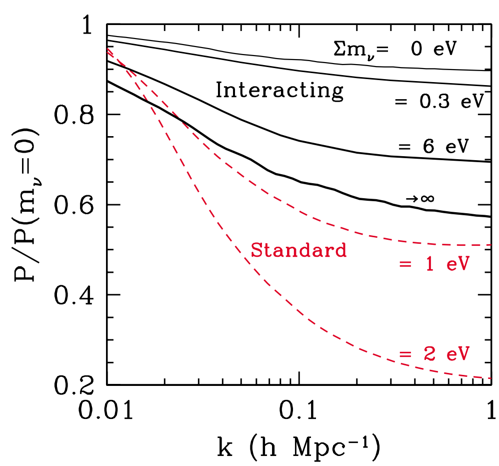

FIG. 2 (color online). The ratio of power spectra $P/P(m_\nu = 0)$ where $P(m_\nu = 0)$ is the power spectrum for the standard scenario with massless neutrinos. The solid curves show this ratio for various (degenerate) neutrino masses in the interacting scenario. Dashed curves show the ratio in the standard scenario, for which the current limit is $\sum m_\nu < 1$–2 eV. Note that the tritium bound, $\sum m_\nu < 6.6$ eV, always applies.

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.

Conclusions.—We have examined a model in which extra couplings allow the neutrinos to annihilate into massless (or light) bosons at late times and thus make a negligible contribution to the matter density today. This evades the present neutrino mass limits arising from a large scale structure. Future tritium beta decay experiments like KATRIN [4] will play a unique and essential role, especially in comparison to cosmology and neutrinoless double beta decay, allowing stringent tests of new neutrino interactions.

The scenario outlined here could be falsified in several ways. First, by a robust discovery of neutrino mass with large scale structure data, if the power spectrum suppression was greater than that allowed for the tritium bound mass in the interacting case (see Fig. 2). This emphasizes the importance of improving the tritium bound. Second, with future precision BBN and CMB data. Third, these couplings could lead to neutrino decay over astronomical distances, which has testable consequences [26].

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