Is Cosmology Compatible with Sterile Neutrinos?

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By combining data from cosmic microwave background experiments (including the recent WMAP third year results), large scale structure, and Lyman-α forest observations, we constrain the hypothesis of a fourth, sterile, massive neutrino. For the 3 massless + 1 massive neutrino case, we bound the mass of the sterile neutrino to $m_s < 0.26$ eV (0.44 eV) at 95% (99.9%) C.L., which excludes at high significance the sterile neutrino hypothesis as an explanation of the LSND anomaly. We generalize the analysis to account for active neutrino masses and the possibility that the sterile abundance is not thermal. In the latter case, the contraints in the (mass, density) plane are nontrivial. For a mass of >1 or <0.05 eV, the cosmological energy density in sterile neutrinos is always constrained to be $\omega_\nu < 0.003$ at 95% C.L., but for a mass of ~0.25 eV, ω_ν can be as large as 0.01.

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Introduction.—Recent cosmological data coming from measurements of the cosmic microwave background (CMB) anisotropies (see, e.g., [1,2]), galaxy clustering (see, e.g., [3]) and Lyman-alpha forest clouds [4] are in spectacular agreement with the expectations of the so-called standard model of structure formation, based on primordial adiabatic inflationary perturbations and a cosmological constant.

Since the model works so well, the ambitious idea of using cosmology to test aspects of particle physics is becoming a reality. An excellent example of this comes from the new cosmological constraints on neutrino physics.

Cosmological neutrinos have a profound impact on cosmology since they change the expansion history of the Universe and affect the growth of perturbations (see [5] for a detailed account). Recent analyses (see, e.g., [4,6]) have indeed constrained the neutrino mass in the context of three-flavor mixing to be $m_\nu < 0.16$ eV ($m_\nu < 0.45$ eV without Lyman-α forest data) with a greater accuracy than laboratory beta decay experiments which suggest $m_\nu < 2.2$ eV (see [6], and references therein).

A possible discrepancy between cosmology and beta decay or neutrino oscillation experiments might provide valuable information for the presence of systematics or new physics. At the moment, the claimed and highly debated detection of a neutrino mass in the range $0.17\ \mathrm{eV} < m_{\beta\beta} < 2.0\ \mathrm{eV}$ at 99% C.L. [7] from the Heidelberg-Moscow double beta decay experiment is at odds with the cosmological bound.

While the neutrino masses are very difficult to measure experimentally, mass differences between neutrino mass eigenstates (m_1, m_2, m_3) have now been measured in oscillation experiments. Observations of atmospheric neutrinos suggest a squared mass difference of $\Delta m^2 \sim 3 \times 10^{-3}\ \mathrm{eV}^2$, while solar neutrino observations, together with results from the KamLAND reactor neutrino experiment, point towards $\Delta m^2 \sim 5 \times 10^{-5}\ \mathrm{eV}^2$. The two measured mass differences are easily accommodated in simple extensions of the standard model by giving masses to at least two of the neutrinos. If these masses are greater than ~0.1 eV, all three neutrinos must be nearly degenerate, with small differences accounting for the observations.

Results from the Liquid Scintillator Neutrino Detector (LSND) [8] challenge the simplicity of this picture. The LSND experiment reported a signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the appearance of $\bar{\nu}_e$ in an originally $\bar{\nu}_\mu$ beam. To reconcile the LSND anomaly with results on neutrino mixing and masses from atmospheric and solar neutrino oscillation experiments, one needs additional mass eigenstates. One possibility is that these additional states are related to right-handed neutrinos, for which bare mass terms ($M\nu_R\nu_R$) are allowed by all symmetries. These would are *sterile*, i.e., not present in $SU(2)_L \times U(1)_\gamma$ interactions. The "3 + 1 sterile" neutrino explanation assumes that the $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation goes through $\bar{\nu}_\mu \to \bar{\nu}_s \to \bar{\nu}_e$. The additional sterile state is separated by the three active states by a mass scale in the range of $0.6\ \mathrm{eV}^2 < \Delta m^2_{\mathrm{LSND}} < 2\ \mathrm{eV}^2$. Constraints from long baseline experiments are threatening this interpretation [9–14]; it is possible that more than one sterile neutrino is necessary to explain LSND [15]. The LSND signal will be soon tested by the MINI-BOONE experiment, expected to release the first results at the beginning of the next year.

In the meantime, given the increased quality in the data, it is timely to test the sterile neutrino hypothesis using cosmological observations. Several recent analyses have already provided interesting cosmological constraints on a fourth massive neutrino [4,16,17]. Here we generalize these in several ways: First, while previous work has considered the case of 3(massless) + 1(massive) neutrinos, here we also allow masses for the standard 3 neutrinos, as required by oscillation experiments. Second, we use updated cosmological data sets, including the new results from the WMAP satellite [1,2] and BOOMERANG-2K2 experiment [18]. Finally, the strength of the interactions of a neutrino determines its cosmological abundance. Given how little we know about sterile neutrino interactions (or mass mixing), it therefore seems reasonable to allow the sterile abundance to be a free parameter. Of course, if a sterile neutrino can have any abundance (including zero), there is no mass limit. However, we will see that the constraints in the (mass, density) plane are highly nontrivial.

Cosmology.—The three active neutrinos interact via the well-measured weak interactions. These interactions ensure that they were in thermal equilibrium at early times until they decouple from the primordial plasma slightly before electron-positron annihilation. After decoupling, they maintain an equilibrium distribution of a massless fermion with a temperature lower than the photon temperature by a factor of $(4/11)^{1/3}$. This introduces a well-known relation between the energy density of the active neutrinos and their total mass: $\omega_\nu \equiv (\rho_\nu/\rho_{\rm cr})h^2 = 0.0106(m_\nu/{\rm eV})$, where $\rho_{\rm cr}$ is the critical energy density, h parametrizes the Hubble constant via $H_0 = 100h$ km sec^{-1} Mpc^{-1}, and here and throughout m_ν refers to the sum of all *active* neutrino masses. So, for example, if the three neutrinos are nearly degenerate, they each have a mass approximately equal to $m_\nu/3$.

While sterile neutrinos, by defintion, do not have weak interactions, they are not pure mass eigenstates. As such, oscillations in the early Universe can transform the thermal active neutrinos into a sterile neutrino [19,20]. Thermalization occurs if $\Delta m^2_{\rm LSND}\sin^4\theta > 3\times 10^{-6}$ eV^2, where θ is an effective mixing angle. In the simplest models with one sterile neutrino, this condition is satisfied, so $\omega_s = 0.0106(m_s/{\rm eV})$, but there are many ways of evading thermalization [21]. Indeed, if one light sterile neutrino exists, there is every reason to expect one or two more, and these considerably complicate the thermalization analysis. It is, for example, possible to have superthermal abundances if a heavier sterile state decays at relatively late times to a lighter state. In short, if a sterile neutrino exists, its cosmological density is much more uncertain than that of the active neutrinos.

Sterile neutrinos influence the development of inhomogeneities and anisotropies in the Universe by changing the epoch of equality and by suppressing perturbations via freestreaming. The epoch at which the energy density in nonrelativistic matter equals that in radiation dictates when structure begins to grow. This leaves an imprint on the matter power spectrum [22]: There is a peak at the scale equal to the horizon at the epoch of equality. If this epoch is close to recombination, the residual radiation causes gravitational potentials to decay, and this time variation produces an early intergated Sachs-Wolfe (ISW) effect, boosting the power on scales near the horizon. The main effect of freestreaming is a suppression of power on scales smaller (wave number k larger) than $k_{\rm fs} = 0.01(m_s/{\rm eV})^{1/2}$ Mpc^{-1} with suppression proportional to ω_s/ω_m, where $\omega_m \equiv \Omega_m h^2$, and Ω_m is the total energy density of nonrelativistic matter (baryons plus cold dark matter) in units of the critical density.

In the standard cosmology, with three massless neutrinos, the scale factor at equality is $a_{\rm EQ} = 2.82\times 10^{-4}(0.15/\omega_m)$. A sterile neutrino is relativistic until its temperature drops beneath its mass, so masses of the order of an eV raise the question: What does it count as, matter or radiation? Since the Hubble rate scales as a^{-2} in a radiation dominated universe and $a^{-3/2}$ in a matter dominated universe, we define the epoch of equality as the moment when $\frac{d\ln H}{d\ln a}(a_{\rm eq}) = -\frac{7}{4}$. This definition agrees well with the standard definition for massless neutrinos. The dependence of $a_{\rm eq}$ on the sterile neutrino parameters m_s and ω_s is plotted in Fig. 1. This figure suggests that in the limit of very small m_s, any appreciable ω_s will be excluded because neutrinos behave essentially as radiation and shift the redshift of matter-radiation equality significantly, producing an unacceptably large ISW effect.

The amount of suppression due to freestreaming increases as the density increases (from top to bottom in Fig. 1), but the large scales (from which constraints derive) cease to be affected as the neutrino mass increases (from left to right). Therefore, at fixed ω_s, constraints from freestreaming are tighter for *small* neutrino masses. Note that this differs from the thermal case (dashed curve in Fig. 1). In that case, the neutrino density increases with the mass, so there is *more* suppression at high masses.

Data analysis and results.—To obtain constraints on sterile neutrino parameters, we use the publicly available

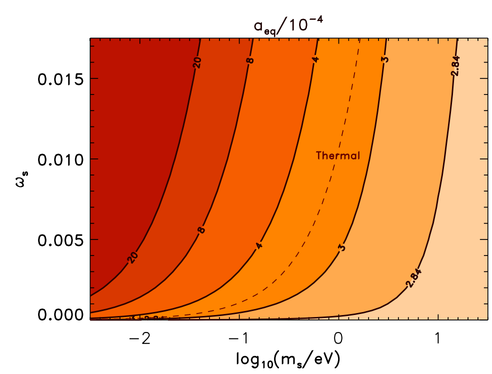

FIG. 1 (color online). The epoch of equality $a_{\rm eq}$ as a function of mass of a sterile neutrino and its energy density. The nonrelativistic matter density here is fixed to $\omega_m = 0.15$, so that in the standard 3-neutrino model, $a_{\rm EQ} = 2.82\times 10^{-4}$. Notice that, at fixed ω_s, $a_{\rm eq}$ rises very rapidly for lower masses since the neutrinos behave as radiation. Thermalized neutrinos lie along the dashed curve.

Markov chain Monte Carlo (MCMC) package COSMOMC [23]. The linear perturbations engine CAMB [24] of the software has been generalized in several ways. First, we allow for a nonthermal sterile neutrino density. Second, we allow for the possibility that the active neutrinos have mass different than the sterile neutrino.

In the MCMC, we sample the following 8-dimensional set of cosmological parameters, adopting flat priors on them: The log mass of thermal sterile neutrinos $\log m_s$ and ω_ν, the energy density of 3 degenerate standard massive neutrinos $\omega_\nu = m_\nu/(94.1\ \mathrm{eV})$, the physical baryon and cold dark matter densities, $\omega_b = \Omega_b h^2$ and $\omega_c = \Omega_c h^2$, the ratio of the sound horizon to the angular diameter distance at decoupling, Θ_s, the scalar spectral index and the overall normalization of the spectrum n_s and A_s, and, finally, the optical depth to reionization τ_r. We consider purely adiabatic initial conditions, impose flatness, and do not include gravitational waves.

We include the WMAP three-year data [1,2] (temperature and polarization) with the routine for computing the likelihood supplied by the WMAP team [25], as well as the CBI [26], VSA [27], ACBAR [28], and BOOMERANG-2K2 [18] measurements of the CMB on scales smaller than those sampled by WMAP. In addition to the CMB data, we also consider the constraints on the real-space power spectrum of galaxies from the SLOAN galaxy redshift survey (SDSS) [29] and the 2dF galaxy redshift survey [30] and Lyman-alpha forest clouds [31,32] from the SDSS, the gold sample of the recent supernova type Ia data [33], the latest supernovae legacy survey supernovae data [34], and the constraints from the baryonic acoustic oscillations detected in the Luminous Red Galaxies (LRG) sample of the SDSS [35]. (There is a negligible overlap between the constraints from the 2dFGRS, SDSS, and SDSS LRG analysis, as there are galaxies in common in all three data sets.)

The details of the analysis are the same as those in Ref. [36], and the reader is invited to check that paper to examine what constraints the above data sets give for other models including the standard 3 degenerate massive neutrinos case.

If the active neutrino masses are fixed to zero and the sterile neutrino abundance is thermal (similar to the assumptions imposed in Ref. [4]), the upper limit on the sterile neutrino mass is 0.26 eV (0.44 eV) [all at 95% (99.9%) C.L.]. Of course, the active neutrino masses are not zero. Taking them as a free parameter leads to an upper limit on the sterile neutrino mass of 0.23 eV (0.42 eV). This is marginally tighter than the $m_\nu = 0$ constraint, because the limit is really on the sum of all neutrino masses. Fixing the active masses to zero allows the maximum m_s. Relaxing this restriction leaves less room for a large m_s. We have found some sensitivity to the mass *difference* of the sterile and active states (and this might be measurable with future data), but current data really constrain only the sum of all neutrino masses.

We now generalize further and allow the sterile neutrino abundance ω_s to vary. Figure 3 shows the constraints in the ω_s-m_s plane. Note the distinct peak around the region of $m_s \sim 0.25$ eV, presenting an allowed region of parameter space with anomalously large values of ω_s. To the left of this peak, a_{EQ} is very large and the resulting ISW effect precludes agreement with CMB data. When m_s is in the allowed regime, a_{EQ} would still be too large were ω_m fixed. However, a model with larger $\omega_m(\sim 0.18)$ leads to an even smaller, acceptable a_{EQ}. Fortuitously, the enhanced cold matter density also mitigates the freestreaming suppression (which scales as ω_c^{-1}). At a larger neutrino mass ($\sim$1 eV), additional cold matter would make a_{EQ} too small, so ω_m must be closer to 0.13 and the freestreaming suppression becomes relevant again, preventing agreement with large scale structure. This is illustrated in Fig. 2. Here we show the angular CMB anisotropy and matter power spectrum for different masses at fixed ω_s. The suppression due to freestreaming is evident in the power spectrum and clearly becomes more severe for smaller masses. However, increasing dark matter density to match the epoch of matter-radiation equality opposes this effect. Crucial to this interpretation is the realization that the matter-radiation equality is very thoroughly measured by the

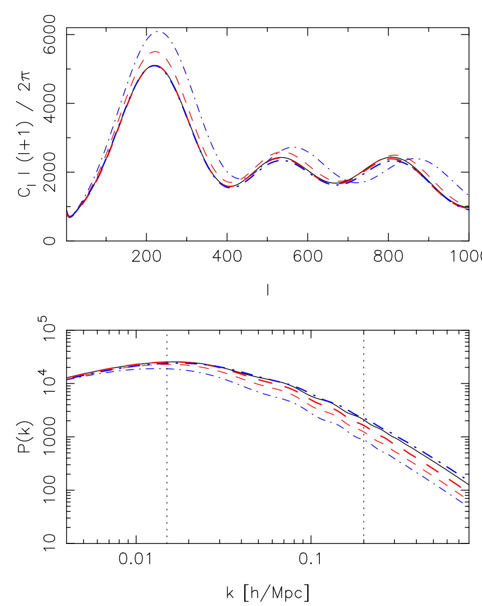

FIG. 2 (color online). Effect of an extra sterile neutrino on the CMB (top) and LSS (bottom) power spectra. The thin lines correspond to a standard model, sterile neutrino of mass $m = 1$ eV (dashed line), $m = 0.3$ eV (dotted-dashed line), and fixed sterile density $\omega_s = 0.01$. These curves are normalized to large scale C_ℓ. The thick dashed and dotted-dashed curves correspond to models which, in addition to having sterile mass, have had dark matter density increased to match standard a_{eq} and h increased to match CMB peak positions and were normalized at the first peak. The dotted vertical lines in the bottom plot enclose the area where LSS experiments are currently sensitive to, with thick line normalizations chosen to illustrate the fact that the 1 eV model is a poorer fit than 0.3 eV model. See text for discussion.

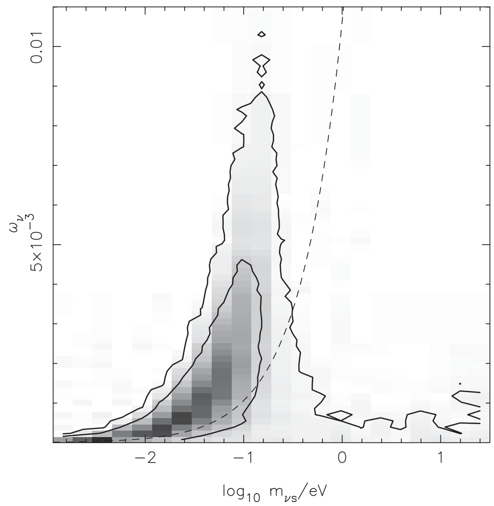

FIG. 3. $1, 2$-σ constraints on the sterile neutrino mass and abundance.

present-day experiments with little model dependence. The constraint can be summarized in $a_{\rm eq} \sim (2.95 \pm 0.13) \times 10^{-4}$.

Conclusions.—By combining data from cosmic microwave background experiments, galaxy clustering, and Ly-alpha forest observations, we have constrained the hypothesis of a fourth, sterile, massive neutrino, as an explanation of the LSND anomaly. For the 3 massless + 1 massive thermal neutrino case, we bound the mass of the sterile neutrino to $m_\nu < 0.26$ eV (0.44 eV) at 95% (99.9%) C.L. Marginalizing over active neutrino masses improves the limit to $m_\nu < 0.23$ eV (0.42 eV). These limits are incompatible at more than 3σ with the LSND result $0.6\ {\rm eV}^2 < \Delta m^2_{\rm LSND} < 2\ {\rm eV}^2$ (95% C.L.). Moreover, our analysis renders the LSND anomaly incompatible at high significance with a degenerate active neutrino scenario and vice versa. If we allow for the possibility of a nonthermal sterile neutrino, we find that the upper limit of allowed energy density in the sterile neutrino is a strong function of mass. In particular, for $m_s < 1$ or >0.05 eV, the cosmological energy density in sterile neutrinos is always constrained to be $\omega_s < 0.003$, but that for a sterile neutrino mass of $\sim$0.25 eV, ω_s can be as large as 0.01 eV.

The results presented in this Letter rely on the assumption that systematics in the public data sets we analyzed (WMAP, Lyman-α, etc.) are under control. We argue that this is likely: The data sets are large enough that detailed systematics checks—e.g., dividing the data into multiple subsets, constructing *quiet* channels that should see nothing, and cross correlating different bands to reduce noise—have been performed. We also checked that if we drop either small scale CMB, large scale structure (LSS), or Lyman-α data set from the analysis, the constraints simply weaken without any systematic change in the results.

The results presented here also rely on the assumption of a theoretical cosmological model based on a large but limited set of parameters. Extensions of the parameter space (such as an isocurvature component, etc.) may modify our conclusions, but they are not required by the current data. If the LSND anomaly is confirmed by MINIBOONE, we will have been proved wrong, and cosmologists will need to reexamine the entire framework on which these very tight constraints rest.

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