# Cosmology Favoring Extra Radiation and Sub-eV Mass Sterile Neutrinos as an Option

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Precision cosmology and big-bang nucleosynthesis mildly favor extra radiation in the Universe beyond photons and ordinary neutrinos, lending support to the existence of low-mass sterile neutrinos. We use the WMAP 7-year data, small-scale cosmic microwave background observations from ACBAR, BICEP, and QuAD, the SDSS 7th data release, and measurement of the Hubble parameter from HST observations to derive credible regions for the assumed common mass scale $m_s$ and effective number $N_s$ of thermally excited sterile neutrino states. Our results are compatible with the existence of one or perhaps two sterile neutrinos, as suggested by LSND and MiniBooNE, if $m_s$ is in the sub-eV range.

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*Introduction.*—Big-bang nucleosynthesis (BBN) has for many years provided the best inference of the radiation content of the Universe. This inference implies the existence of approximately three neutrino flavors and hence three generations of elementary particles [1,2]. Of course, by the early 1990s, precision measurements of the $Z^0$ decay width at LEP had superseded this early cosmological evidence. More recently, observations of the cosmic microwave background (CMB) anisotropies and the large-scale structure (LSS) distribution have allowed us to probe the radiation density at the CMB decoupling epoch. Since this epoch corresponds to a much later time than the epoch of nucleosynthesis, inference of the radiation content of the Universe from precision CMB/LSS measurements provides an important overall consistency check. The results are surprising on several counts.

First, when analyzing cosmological data in extended scenarios that allow for extra radiation, one consistently finds a trend towards a radiation excess, and this hint has become stronger over the years [3–5]. The cosmic radiation content is usually expressed in terms of $N_{\rm eff}$, representing the effective number of thermally excited neutrino species. The standard value $N_{\rm eff} = 3.046$ slightly exceeds 3 because $e^+e^-$ annihilation provides residual neutrino heating [6]. Most recently, the Wilkinson Microwave Anisotropy Probe (WMAP) Collaboration found a 68% credible interval of $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$ based on their 7-year data release and additional LSS data [7]. A similar study including the Sloan Digital Sky Survey (SDSS) data release 7 (DR7) halo power spectrum found $N_{\rm eff} = 4.78^{+1.86}_{-1.79}$ at 95% confidence [4]; see also Ref. [8]. Most recently the Atacama Cosmology Telecope Collaboration has arrived at similar conclusions [9].

Second, for a good part of the past two decades, BBN and the observed primordial $^4$He abundance suggested $N_{\rm eff} \lesssim 3$ [10]. A large body of literature was devoted to particle-physics constraints, assuming that additional radiation required other novel ingredients such as a $\nu_e$–$\bar{\nu}_e$ asymmetry [1,2]. However, the BBN situation has also changed of late: Two recent studies find a somewhat higher $^4$He abundance of $Y_p = 0.2565 \pm 0.001(\text{stat}) \pm 0.005(\text{syst})$ [11] and $Y_p = 0.2561 \pm 0.011$ [12], respectively, suggesting additional radiation during the BBN epoch.

Taking these hints seriously, one quickly finds that it is not easy to account for additional radiation because well-motivated candidates are lacking. The strong dilution of any preexisting radiation at the quark-hadron phase transition at $T \sim 170$ MeV suggests that a novel radiation component should be produced after the QCD epoch, although there are counterexamples [13]. If neutrinos are Dirac particles there is no obvious way to equilibrate the right-handed states because one needs larger couplings (e.g., magnetic moments or right-handed currents) than allowed by other evidence [14]. Thermal axions can provide only a fractional contribution to $N_{\rm eff}$ [15]. In contrast to earlier findings, it was recently shown that standard neutrinos with primordial asymmetries can provide any value for $N_{\rm eff}$ [16]. No simple mechanism, however, produces the required asymmetries.

If low-mass sterile neutrinos exist and mix with active flavors, they can be thermally excited by the interplay of oscillations and collisions [17]. The prior theoretical motivation for such states is perhaps not strong. However, the signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ flavor conversion in the LSND experiment [18], if interpreted in terms of flavor oscillations, requires low-mass sterile states [19–21]. Later, the MiniBooNE experiment observed excess events in the $\nu_\mu \to \nu_e$ channel that were not compatible with LSND in a two-flavor oscillation model [22,23]. Early MiniBooNE data in the $\bar{\nu}_\mu \to \bar{\nu}_e$ channel were statistically not significant enough to confirm or refute the LSND signature [24]. However, based on 70% more data, a clear excess was recently reported [25]. If interpreted in terms of flavor oscillations, these data require *CP* violation and thus a minimal scenario would involve 2 sterile neutrinos that can interfere appropriately [26,27], although this interpretation causes significant tension with disappearance experiments, notably atmospheric neutrinos. An alternative is 1 sterile state together with nonstandard interactions [28]. Yet another motivation for low-mass sterile neutrinos arises from a combined fit of MiniBooNE and Gallium radioactive source experiments [29].

These scenarios together with the cosmological hints for extra radiation motivate us to reconsider the impact of low-mass sterile neutrinos on cosmological observables. Some recent studies have looked at light sterile states in the context of precision cosmology [30–32], but with emphasis on providing constraints on such models. Furthermore, these papers were written at a time when precision cosmology provided only very weak evidence for $N_{\rm eff} > 3$.

*Scenarios.*—Thermal excitation of sterile neutrinos is complicated because of possible resonant matter effects and *CP* violating phases. However, for the eV mass range and the relatively large mixing angles needed to explain the oscillation experiments, the sterile states are likely strongly thermally excited [31,33]. Note, however, that the presence of even a small neutrino asymmetry can lead to incomplete thermalization [34,35].

In the following we take the number of thermally excited sterile neutrinos, $N_s$, to be an adjustable cosmological fit parameter, while the active neutrinos are assumed to have a fixed abundance ($N_\nu = 3.046$) so that $N_{\rm eff} = 3.046 + N_s$. For the neutrino masses, we consider two schematic scenarios. In the first scenario, the ordinary neutrinos are taken to be massless, while the sterile states have a common mass scale $m_s$ which is free to vary (the "$3 + N_s$" scenario). The second scenario, the "$N_s + 3$" scenario, consists of massless sterile states and active neutrinos that have an adjustable common mass $m_\nu$; i.e., all active species are treated as degenerate in mass. This is a good approximation because current cosmological data are not sensitive to the small mass splittings.

*Cosmological analysis.*—Besides the new parameters $N_s$ and $m_s$ or $m_\nu$, we use a cosmological parameter space consisting of the standard "vanilla" ΛCDM parameters: The baryon density $\omega_b = \Omega_b h^2$, cold dark matter density $\omega_{\rm cdm} = \Omega_{\rm cdm} h^2$, Hubble parameter $H_0$, scalar fluctuation amplitude $A_s$, scalar spectral index $n_s$, and the optical depth to reionization $\tau$. We use either $m_\nu$ or $m_s$ as a fit parameter, depending on the scenario under consideration, from which we calculate the contribution to the matter density as (i) $\Omega_\nu h^2 = N_s \times m_s/(93\ \text{eV})$ in the $3 + N_s$ scheme, and (ii) $\Omega_\nu h^2 = 3.046 \times m_\nu/(93\ \text{eV})$ in the $N_s + 3$ case. We impose flat priors on all parameters, as detailed in Table I. Parameter estimation is performed using a modified version of the COSMOMC package [36].

TABLE I. Priors and standard values for the cosmological fit parameters considered in this work.

| Parameter | Standard | Prior |
|---|---|---|
| $\omega_{\rm cdm}$ | | 0.01–0.99 |
| $\omega_b$ | | 0.005–0.1 |
| $h$ | | 0.4–1.0 |
| $\tau$ | | 0.01–0.8 |
| $\ln(10^{10}A_s)$ | | 2.7–4.0 |
| $n_s$ | | 0.5–1.5 |
| $m_s$, $m_\nu$ (eV) | 0 | 0–3 |
| $N_s$ | 0 | 0–7 |

We use CMB data from WMAP after 7 years of observation [7], as well as from the ACBAR [37], BICEP [38], and QuAD [39] experiments. In addition, we use the halo power spectrum extracted from the SDSS-DR7 luminous red galaxy sample [40]. Finally, we impose a prior on the Hubble parameter based on the Hubble Space Telescope observations [41]. Since recent type Ia supernova (SN) luminosity distance data are plagued by unresolved systematic issues associated with the light-curve fitting methods [42], we do not use them in our default analysis.

In Fig. 1, we show 2D confidence contours for the $3 + N_s$ and $N_s + 3$ cases. We also provide 1D confidence intervals for $N_s$ and $m_\nu$ or $m_s$ for different scenarios in Table II. For $N_s + 3$ ($m_s = 0$ and $m_\nu \neq 0$), the evidence for $N_s > 0$ is beyond 95%, although it is weaker in the opposite scenario $3 + N_s$ where the new states are massive.

The evidence for $N_s > 0$ increases if we include the full SN sample from Ref. [42] using the MLCS2K2-inferred luminosity distances. However, this effect is less pronounced if adopting instead the SALT-II light-curve fitting method (Table II). Independently of SN data, excess radiation is preferred even by our default data sets.

*BBN.*—The relatively large $N_s$ values compatible with this analysis are somewhat restricted by the primordial light-element abundances. We summarize current BBN constraints on $N_s$ in Table III. For the $^4$He abundance we consider both the value found by Izotov and Thuan [11], $Y_p^{\rm IT} = 0.2565 \pm 0.001({\rm stat}) \pm 0.005({\rm syst})$ and the value derived by Aver *et al.* [12], $Y_p^A = 0.2561 \pm 0.011$. We adopt the deuterium abundance of Pettini *et al.* [43], $\log({\rm D/H})_p = 4.56 \pm 0.04$ and the baryon density inferred from our CMB+SDSS+HST analysis, $\omega_b^{\rm CMB} = 0.022\,39 \pm 0.000\,48$. Theoretical primordial element abundances are calculated using PARTHENOPE [44].

It is noteworthy that independently of $^4$He, deuterium alone also provides nontrivial limits when combined with $\omega_b^{\rm CMB}$. All of these results likely contain significant systematic errors. We therefore refrain from a common likelihood analysis and simply remark that both $^4$He and D somewhat prefer $N_s > 0$, but depending on the assumed errors for $Y_p$ it may be difficult to accommodate $N_s = 2$. Of course the oscillation data do not necessarily imply two

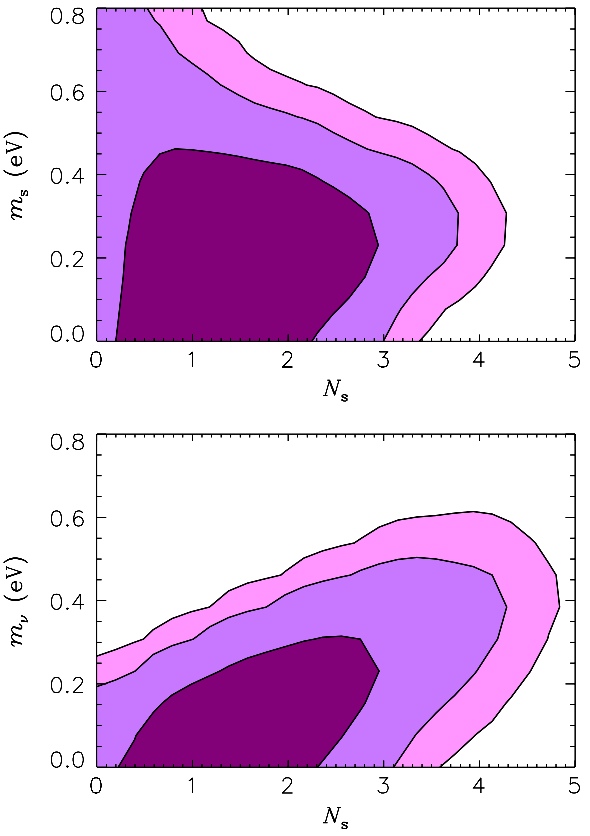

FIG. 1 (color online). 2D marginalized 68%, 95%, and 99% credible regions for the neutrino mass and thermally excited number of degrees of freedom $N_s$. Top: The $3 + N_s$ scheme, in which ordinary neutrinos have $m_\nu = 0$, while sterile states have a common mass scale $m_s$. Bottom: The $N_s + 3$ scheme, where the sterile states are taken to be massless $m_s = 0$, and 3.046 species of ordinary neutrinos have a common mass $m_\nu$.

fully thermalized sterile neutrinos. Indeed, Ref. [31] shows that the degree of sterile state thermalization in a 3 active +2 sterile scenario depends strongly on the neutrino mixing and mass parameters. Another possibility is the presence of a small lepton asymmetry, which can reduce the thermalization efficiency [34,35]. Yet another option is that the oscillation data are explained by 1 sterile state plus new interactions [28]. Still, for reference we provide mass bounds in Table II for the cases of $N_s = 1$ or 2 exactly, besides the variable $N_s$.

TABLE II. 1D marginalized bounds on $N_s$ and neutrino masses. In rows 3–6 we have used $N_s = 1$ or 2 exactly. Two-tailed limits are minimal credible intervals.

| Scenario | Range for $N_s$ | | Range for $m_s$ or $m_\nu$ | |
|---|---|---|---|---|
| | 68% | 95% | 68% | 95% |
| $3 + N_s$ | 0.39–2.21 | <3.10 | 0.01–0.34 eV | <0.66 eV |
| $N_s + 3$ | 0.83–2.77 | 0.05–3.75 | <0.22 eV | <0.42 eV |
| 2 + 3 | | | <0.20 eV | <0.30 eV |
| 3 + 2 | | | <0.29 eV | <0.45 eV |
| 1 + 3 | | | <0.16 eV | <0.24 eV |
| 3 + 1 | | | <0.35 eV | <0.48 eV |
| Including supernova data (MLCS2K2): | | | | |
| $3 + N_s$ | 1.24–3.36 | 0.26–4.31 | 0.17–0.47 eV | 0.09–0.64 eV |
| Including supernova data (SALT-II): | | | | |
| $3 + N_s$ | 0.02–1.54 | <2.57 | <0.28 eV | <0.66 eV |

TABLE III. BBN constraints on $N_s$, using $N_s \geq 0$ as a prior. Maximum of the marginalized posterior and minimal 95% credible interval (C.I.).

| Data | Posterior max | 95% C.I. |
|---|---|---|
| $Y_p^{\mathrm{IT}} + (\mathrm{D/H})_p$ | 0.68 | 0.01–1.39 |
| $Y_p^{\mathrm{A}} + (\mathrm{D/H})_p$ | 0.69 | <2.42 |
| $(\mathrm{D/H})_p + \omega_b^{\mathrm{CMB}}$ | 0.49 | <2.12 |

*Discussion.*—Allowing for extra radiation as a cosmological fit parameter, current cosmological data favor additional radiation compatible with recent hints from BBN. Assuming ordinary neutrinos to have a common mass $m_\nu$ and the extra radiation to be massless, evidence for $N_s > 0$ exceeds 95%, whereas the most constraining upper limit comes from BBN. With currently favored $^4$He and D abundances, it would be difficult to accommodate two fully thermalized additional neutrino states.

The usual degeneracy between extra radiation and the ordinary neutrino mass (Fig. 1) weakens the neutrino mass limits, with 1D credible intervals given in Table II.

However, it is more interesting to assume essentially massless standard neutrinos and attribute a possible mass to sterile neutrinos ($3 + N_s$ scenario). If we assume $N_s = 1$, the 95% allowed mass range is $m_s < 0.48$ eV. For $N_s = 2$ it is 0.45 eV (Table II), although this case would be disfavored by BBN. For $N_s < 1$, the 2D marginalized posterior probability distribution has a long tail so that $m_s \gtrsim 1$ eV is marginally allowed: the fewer sterile states there are, the larger the mass they can possess.

The relatively small masses favored by cosmology are not assured to provide good fits to the short-baseline appearance experiments—in principle a combined analysis as in Ref. [31] is desirable but complicated because of the many parameters involved. Moreover, the degree of thermalization of the additional states would have to be considered in detail. Two fully thermalized states, corresponding to $N_s = 2$, are difficult to accommodate in BBN even with the new helium abundances.

Our main message is that on present evidence, cosmology does not exclude sterile neutrinos if they are not too heavy and thus do not contribute excessive amounts of hot dark matter. Quite on the contrary, both BBN and precision observations would happily welcome some amount of additional radiation corresponding to around one new thermal degree of freedom. Low-mass sterile neutrinos are one natural possibility.

Low-mass sterile neutrinos mixed with active ones can strongly modify the neutrino signal from a core-collapse

SN and $r$-process nucleosynthesis in the neutrino-driven wind [21,45–48]. These effects should be studied in the presence of two sterile flavors and $CP$ violating phases.

The Planck spacecraft, currently taking CMB data, is expected to boost precision determination of cosmological parameters. It is foreseen that Planck data will constrain the cosmic radiation content at CMB decoupling with a precision of $\Delta N_{\mathrm{eff}} \simeq \pm 0.26$ or better, so extra radiation at the level of 2 extra species could be detected with high significance [49,50]. Conversely, if Planck should find $N_{\mathrm{eff}} = 3 \pm 0.26$, this would provide strong arguments against sterile neutrinos. Thus, the ongoing Planck measurements will make or break the new-found friendship between cosmology and sterile neutrinos.

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