

# Sterile neutrino constraints from cosmology

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**Abstract.** The presence of light particles beyond the standard model's three neutrino species can profoundly impact the physics of decoupling and primordial nucleosynthesis. I review the observational signatures of extra light species, present constraints from recent data, and discuss the implications of possible sterile neutrinos with O(eV)-masses for cosmology.

## 1. Introduction

There is mounting evidence from reactor and short-baseline neutrino oscillation experiments suggesting the existence of one or two sterile neutrinos with mass splittings relative to the active flavours in the neighbourhood of  $\Delta m^2 \sim 1 \text{ eV}^2$  and fairly large mixing parameters (see, e.g., [1] for a review and global interpretation, and [2–4] for other recent analyses). In the early universe, flavour oscillations would bring these sterile states into thermal equilibrium prior to neutrino decoupling at  $T \sim 1 \text{ MeV}$ , thereby increasing the relativistic energy density

$$\rho_r = \frac{\pi^2}{15} T_\gamma^4 \left[ 1 + (3.046 + \Delta N_{\text{eff}}) \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \right], \quad (1)$$

where  $T_\gamma$  is the cosmic microwave background (CMB) temperature and  $N_{\text{eff}} \equiv (3.046 + \Delta N_{\text{eff}})$  is the effective number of relativistic neutrino degrees of freedom. The presence of a non-zero  $\Delta N_{\text{eff}}$  due to sterile neutrinos would modify the cosmic expansion rate and affect the big-bang nucleosynthesis (BBN) of light elements, the CMB anisotropies, and the formation of large-scale structures (LSS). Additionally, these eV-mass sterile neutrinos would later play the role of a non-negligible hot-dark matter component.

## 2. CMB and LSS

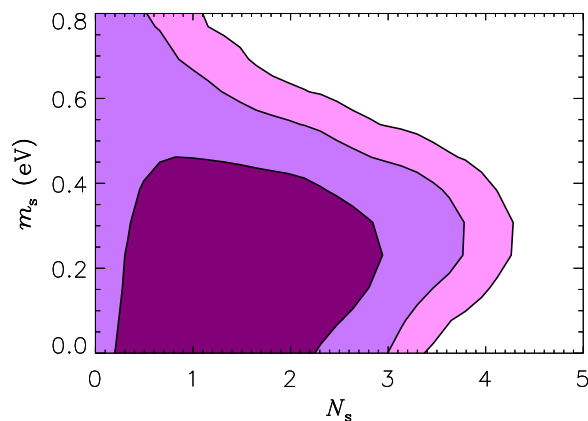
The additional radiation energy provided by light sterile neutrinos impacts the evolution of the CMB anisotropies in four ways: by shifting the redshift of matter-radiation equality  $z_{\text{eq}}$ , changing the ratio of sound horizon to angular diameter distance at decoupling  $\theta_s$ , through the anisotropic stress of the neutrino fluid, and finally, by modifying the thickness of the surface of last scattering [5, 6]. Individually, these effects can be mimicked by other parameters (such as

the matter density for  $z_{\text{eq}}$ ). WMAP data [7] by themselves are not able to completely break all parameter degeneracies, so in order to arrive at meaningful constraints, they need to be supplemented by external data, e.g., measurements of the LSS, or the CMB damping tail.

Current CMB and LSS observations show a consistent preference for additional relativistic degrees of freedom beyond the standard model expectation of  $N_{\text{eff}} = 3.046$ . The significance of this preference depends on the combination of data used; typically, the posterior probability for  $N_{\text{eff}} > 3.046$  ranges from  $\sim 90$ -98.4% [6, 8, 9]. Contrary to recent claims [10], it has been shown in [11] that the excess is not simply a statistical artifact due to the choice of prior probabilities.

All of the above-mentioned analyses assume both standard neutrinos and the particles making up the extra radiation to be massless – if we are to interpret the extra radiation in terms of sterile neutrinos however, their masses would need to be taken into account as well [12, 13].

For our analysis we consider a combination of the WMAP 7-year data release [7], ACBAR [14], BICEP [15], and QuAD [16] data. In addition, we use the halo power spectrum extracted from the SDSS-DR7 luminous red galaxy sample [17], type Ia supernova data from the Union-2 compilation [18], and we impose a constraint on the Hubble parameter based on the Hubble Space Telescope observations [19]. Approximating the three active neutrino species to be massless, the joint constraints on the sterile neutrino mass  $m_s$  and the effective number of sterile species  $N_s$  is shown in figure 1. As long as  $N_s$  is small, eV-masses are compatible with the data, but one or two sterile states that have masses and mixing parameters favoured by a global analysis of the laboratory data (and would hence fully thermalise, unless otherwise suppressed) are disfavoured.



**Figure 1.** Joint 2D marginal 68%-, 95%- and 99%-credible regions in the  $(N_s, m_s)$ -plane [12].

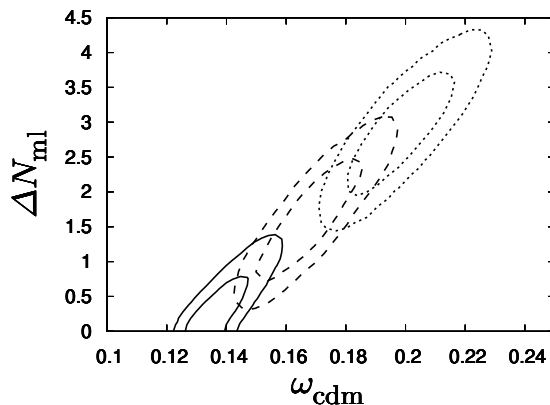
This analysis assumed a minimal extension of the standard  $\Lambda$ CDM-model though, so one may want to ask whether the same conclusion also holds in more complex models [20]. Exploiting known parameter degeneracies of the neutrino mass, we consider a model with one massive sterile neutrino with mass (0,1,2) eV, and an extra  $\Delta N_{\text{ml}}$  massless degrees of freedom ( $\Lambda$ CDM+ $\Delta N$ ), and a model in which additionally the dark energy equation of state parameter  $w$  is allowed to vary ( $w$ CDM+ $\Delta N$ ). As shown in table 1, the best-fit of these models is comparable, or even slightly better than standard  $\Lambda$ CDM, at the cost of  $\sim 1$ -2 extra massless species and/or  $w < -1$ . Thus the mass problem is slightly alleviated, but even in the extended models lower neutrino masses are preferred. If eV-mass steriles were indeed present, the inference of other cosmological parameters would be affected as well, most notably the dark matter density (see figure 2).

### 3. Big bang nucleosynthesis

While not sensitive to the masses of neutrinos, BBN has long been used to probe the radiation content of the Universe at temperatures of order 1 MeV [22, 23]. In this section, we explore the

**Table 1.** Best-fit  $\Delta\chi_{\text{eff}}^2$  relative to standard  $\Lambda\text{CDM}$ . We also show the best-fit values and 95%-credible upper and lower limits on  $\omega_{\text{cdm}}$ , and, where appropriate, on  $\Delta N_{\text{ml}}$  and  $w$ .

Framework	Neutrino sector	$\Delta\chi_{\text{eff}}^2$	$\Delta N_{\text{ml}}$	$w$	$\omega_{\text{cdm}}$
$\Lambda\text{CDM}$	3 massless	0	–	–	$0.1132^{+0.0036}_{-0.0082}$
	3 massless + 1 sterile (0 eV)	–3.16	–	–	$0.1299^{+0.0069}_{-0.0066}$
	3 massless + 1 sterile (1 eV)	4.20	–	–	$0.1398^{+0.0061}_{-0.0074}$
	3 massless + 1 sterile (2 eV)	21.41	–	–	$0.1473^{+0.0075}_{-0.0064}$
$\Lambda\text{CDM}+\Delta N$	$3+\Delta N_{\text{ml}}$ massless + 1 sterile (0 eV)	–3.54	$0.01^{+1.12}_{-0.01}$	–	$0.133^{+0.023}_{-0.005}$
	$3+\Delta N_{\text{ml}}$ massless + 1 sterile (1 eV)	2.26	$1.49^{+1.11}_{-0.73}$	–	$0.166^{+0.026}_{-0.017}$
	$3+\Delta N_{\text{ml}}$ massless + 1 sterile (2 eV)	12.82	$2.57^{+1.24}_{-0.59}$	–	$0.192^{+0.031}_{-0.015}$
$w\text{CDM}+\Delta N$	$3+\Delta N_{\text{ml}}$ massless + 1 sterile (0 eV)	–5.38	$0.09^{+1.61}_{-0.09}$	$-1.00^{+0.18}_{-0.12}$	$0.132^{+0.032}_{-0.006}$
	$3+\Delta N_{\text{ml}}$ massless + 1 sterile (1 eV)	–0.78	$1.23^{+1.61}_{-0.75}$	$-1.11^{+0.18}_{-0.21}$	$0.164^{+0.035}_{-0.015}$
	$3+\Delta N_{\text{ml}}$ massless + 1 sterile (2 eV)	7.80	$2.48^{+1.71}_{-0.79}$	$-1.17^{+0.23}_{-0.22}$	$0.198^{+0.032}_{-0.019}$



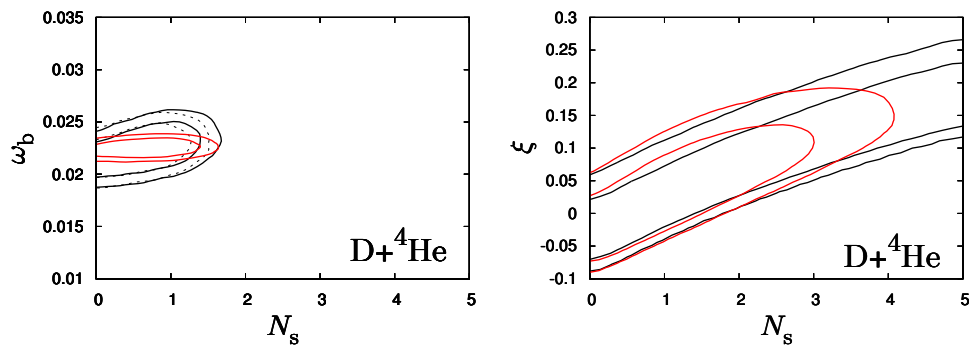
**Figure 2.** 2D marginal 68%- and 95%-credible regions in the  $(\Delta N_{\text{ml}}, \omega_{\text{cdm}})$ -plane for three  $\Lambda\text{CDM}+\Delta N$  class models containing one thermalised sterile species of mass  $m_s = 0$  eV (solid), 1 eV (dashed), and 2 eV (dotted) [21].

implications of the latest primordial element abundance measurements (D [25] and  $^4\text{He}$  [26]) on the sterile neutrino scenario. We consider a general BBN model with three free parameters: the baryon density  $\omega_b$ , an extra  $N_s$  effective sterile neutrino species on top of the usual three fully thermalised standard neutrinos, and a common neutrino chemical potential  $\xi$ . We denote the  $\xi = 0$  case as  $\text{BBN}+N$  and the free  $\xi$  case as  $\text{dBBN}+N$ .

Taking into account uncertainties in the measurements, the nuclear rates and the free neutron lifetime, the inferred constraints on  $N_s$  are plotted in figure 3. The left panel shows that in the  $\text{BBN}+N$  scenario one extra relativistic species is actually preferred over none, with a best-fit of  $N_s = 0.86$ , but two are ruled out at high significance, the 95%-credible upper limit being  $N_s < 1.26$ . As one can see in the right panel, the upper limit can be relaxed quite a bit if a lepton asymmetry is allowed. At the cost of having to introduce a small  $\mathcal{O}(0.1)$  neutrino chemical potential, up to three extra species can easily be accommodated by the data.

#### 4. Conclusions

We have shown that present cosmological data show a slight preference for additional radiation. However, an interpretation in terms of the 3+2 sterile neutrino scenario motivated by LSND/MiniBooNE/reactor data is problematic if one tries to implement the neutrinos in the minimal  $\Lambda\text{CDM}$  model of cosmology. Compatibility with cosmological data would require either significant modifications to the  $\Lambda\text{CDM}$ -model, with accompanying changes to the values of



**Figure 3.** Joint 2D marginal 90%- and 99%-credible regions. Solid (dashed) black contours denote results from D and  ${}^4\text{He}$  data for  $\tau_n = 878.5$  s ( $\tau_n = 885.7$  s). Red contours additionally include a CMB+LSS prior on  $\omega_b$ . *Left:* BBN+N scenario. *Right:* dBBN+N scenario [21].

other cosmological parameters such as the matter density, or a mechanism to suppress the thermalisation of the sterile neutrinos. Observationally, the precision measurement of  $\Delta N_{\text{eff}}$  by Planck [27, 28] remains one of the most promising windows to beyond-standard-model physics.

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