

Current and future constraints on neutrino physics from cosmology

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Abstract. In recent years precision cosmology has become an increasingly powerful probe of particle physics. Perhaps the prime example of this is the very stringent cosmological upper bound on the neutrino mass. However, other aspects of neutrino physics, such as their decoupling history and possible non-standard interactions, can also be probed using observations of cosmic structure. Here, we review the current status of cosmological bounds on neutrino properties and discuss the potential of future observations, for example by the recently approved EUCLID mission, to precisely measure neutrino properties.

1. Introduction and bounds on standard model neutrinos

It has long been known that neutrinos are important for cosmological structure formation. Because neutrinos have finite mass and no electromagnetic interactions they are a source of dark matter, albeit with properties very different from cold dark matter. The problem with neutrinos as the sole source of dark matter is that their very small masses and high thermal velocities prevent them from clustering on small scales, in stark contrast to the known properties of the dominant dark matter component.

On the other hand, the fact that neutrinos behave so differently from other sources of matter in the universe also means that precision cosmology can be used to set very tight constraints on the properties of neutrinos, such as their mass and cosmological number density (see e.g. [1, 2] for recent reviews).

With the advent of very large scale cosmological observations, constraints on some neutrino parameters have now reached a precision where they outperform any current or planned terrestrial experiments. For example the combination of cosmic microwave background observations by WMAP [3] with large scale structure surveys such as the Sloan Digital Sky Survey (SDSS) [4] have been able to constrain the mass of standard model neutrinos to below the 1 eV scale, compared to the current upper bound on the sum of neutrino masses from beta decay measurements by the Mainz experiment [5] of around 7 eV.

However, a drawback of using cosmology to probe neutrino masses has consistently been that cosmological neutrino constraints are susceptible to the exact cosmological model used. Depending on the data sets used this may still allow some room for example for the existence of a partly (or perhaps even fully) thermalised sterile neutrino species [6, 7, 8, 9]. Another potential



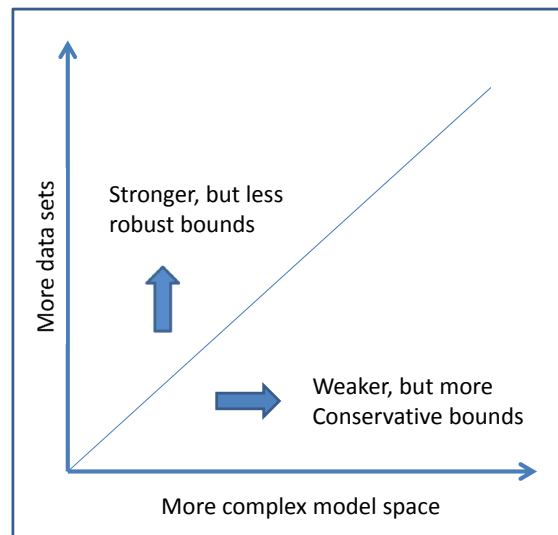


Figure 1. The dependence of cosmological neutrino mass bounds on the choice of model framework and the number of data sets used.

drawback has been that a useful constraint initially could only be derived by combining a variety of different data sets. If just one of these data sets has a systematic bias the result will formally be either a very stringent constraint on the neutrino mass or, conversely, a spurious detection of the neutrino mass. This general trend is illustrated in Figure 1.

One of the main developments during the past decade has been that a useful constraint on neutrino properties can now be gained from either just a single set of data or at most the combination of two data sets with well-understood systematics. An example of this is that an upper bound of typically $\sum m_\nu \sim 0.3 - 0.5$ eV [10, 11] can now be derived from just CMB data combined with almost linear large scale structure data from the SDSS survey and a measurement of the Hubble parameter [12] (see also e.g. [13, 14, 15, 16, 17, 18, 19, 20] for additional recent constraints on the neutrino mass from large scale structure probes). Previously, bounds of the same formal strength were typically derived with the addition of Lyman- α and other auxiliary data (see e.g. [21]). However, this relied on an understanding of baryonic physics in the semi- or non-linear regime of structure formation. More recent Lyman- α analyses have been much more conservative and hence not been able to add much extra information on the properties of light neutrinos [22]. We note that although this is true for light neutrinos, the Lyman- α data still provides an extremely strong constraint on possible keV mass sterile neutrinos which would constitute warm dark matter. [23, 24, 25].

2. Sterile neutrinos

While constraints on pure standard model neutrinos are by now very stringent, there is still the possibility that non-standard neutrino physics could be present. For example, one or more

additional sterile neutrinos might be present. Even though such neutrinos have no standard model interactions they can thermalize through mixing with the active flavours (see e.g. [26, 27] for recent treatments). Full thermalisation occurs for large mass differences and large mixing angles and the usual bound on light neutrino masses strongly constrains the mass of such neutrinos. However, for sufficiently large masses the contribution to the energy density at present can be large even though thermalisation is incomplete - the sterile neutrino warm dark matter limit. This particular case is not subject to the usual cosmological constraints, simply because the free streaming scale is much smaller than the scale measured by CMB and large scale structure surveys. For warm dark matter, more useful constraints can be derived from the Lyman-alpha forest and from the dynamics of small scale non-linear structures such as dwarf galaxies.

From a neutrino oscillation perspective there is no indication of very high mass neutrinos. The mixing angle required for sterile neutrino warm dark matter is much smaller than what is required for detection through oscillation experiments. However, there is an indication from a number of different experiments that a fourth light neutrino species might be needed. Since it must necessarily interact much more weakly than standard model neutrinos it is by construction a sterile neutrino. The evidence for such neutrinos comes through mixing with the active flavours and in fact the best fitting mixing angle is relatively large, leading to complete or almost complete thermalisation in the early Universe. The question is therefore whether sterile neutrinos are compatible with current cosmological bounds. Contrary to naive expectations eV mass sterile neutrinos might actually be allowed, depending somewhat on the specifics of the analysis [6, 7, 8, 9]. In Figure 2 we show an example of a recent analysis of mass constraints on light sterile neutrinos, taken from Ref. [6].

3. Dark radiation

Another question which has recently received significant attention is the possible presence of extra relativistic degrees of freedom in the Universe, not necessarily related to light neutrinos. While some types of sterile neutrinos would behave essentially as dark radiation there are many other models predicting the existence of extra radiation. Examples are new, massless or very light particles such as Majorons, or the presence of early dark energy.

The reason for the current interest is that the relativistic energy measured by WMAP and other CMB experiments point towards a value of higher than predicted in the standard model. The CMB anisotropy spectrum is sensitive to additional relativistic energy density mainly because of two effects: The early integrated Sachs-Wolfe effect leads to an increase in power around the first acoustic peak because matter-radiation equality is delayed, and the small scale peaks are damped because of diffusion [28].

Usually, relativistic, weakly interacting energy density is quantified in terms of the effective number of neutrino species, $N_{\text{eff}} \equiv \rho/\rho_{\nu,0}$ where $\rho_{\nu,0} = (4/11)^{1/3}\rho_\gamma$. Because of finite temperature corrections to the photon propagator as well as a small amount of entropy transfer from electrons and positrons to neutrinos the standard model prediction is $N_{\text{eff}} = 3.046$, instead of exactly 3 (see e.g. [29, 30, 31, 32]). The most recent analysis of WMAP plus auxiliary data gives a result of $N_{\text{eff}} = 4.29^{+1.05}_{-0.96}$ at 95% C.L., i.e. an indication of beyond standard model physics at slightly more than 2σ [33] (see also [3, 11, 34, 35, 8]).

4. Future constraints

The rapid improvement of cosmological neutrino constraints is set to continue in coming years, with new CMB observations by Planck covering both large and small angular scales currently covered by several different experiments (thus with much more well controlled systematics). Even more astounding will be the development in terms of large scale structure surveys. The recently approved ESA mission EUCLID [36] will measure a substantial fraction of the entire

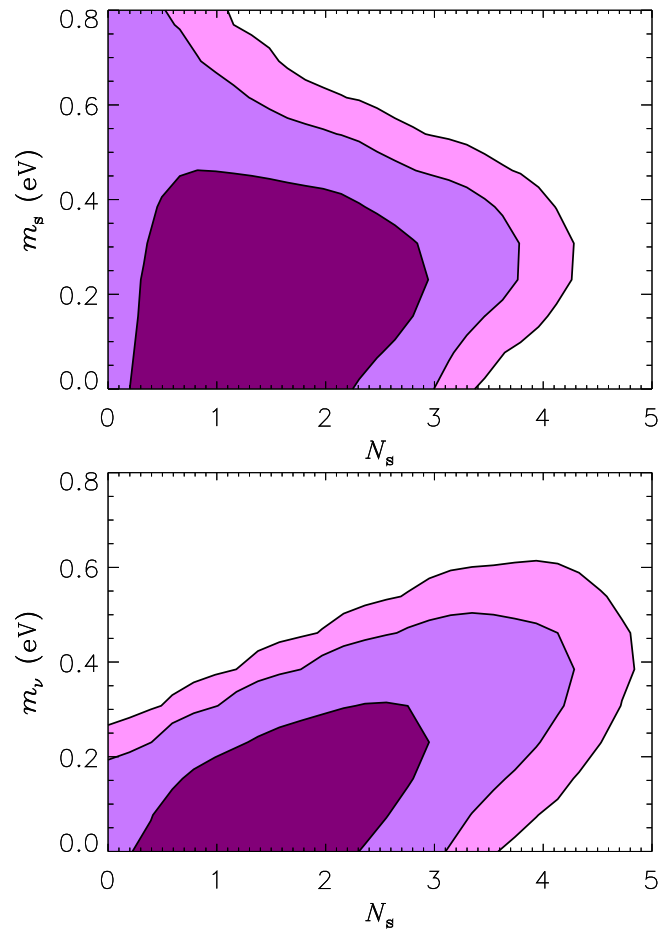


Figure 2. 2D marginalized 68%, 95% and 99% credible regions for the neutrino mass and thermally excited number of degrees of freedom N_s . *Top:* The $3 + N_s$ scheme, in which ordinary neutrinos have $m_\nu = 0$, while sterile states have a common mass scale m_s . *Bottom:* The $N_s + 3$ scheme, where the sterile states are taken to be massless $m_s = 0$, and 3.046 species of ordinary neutrinos have a common mass m_ν . Figure taken from [6].

Hubble volume with a deep photometric survey. In practise, the magnitude and wavelength limitations of the instrument means that the median redshift of galaxies measured by EUCLID will be around 0.8-1, with a substantial tail up to redshifts higher than 2. Because it is a space-based experiment it is not limited by seeing in the atmosphere and therefore the shape of galaxies can be measured exceedingly accurately, making it a perfect instrument for weak lensing. Together with the photometric survey, EUCLID will feature a spectroscopic survey of around 10^7 galaxies which will be important both for calibration of the much larger photometric survey and for precision measurements of the baryon acoustic oscillation feature.

However, in terms of constraining the neutrino mass the most important parameters in the power spectrum are the shape and amplitude, not the acoustic feature. The photometric survey is therefore the most important EUCLID data deliverable. As it turns out the combination of Planck data with either the photometric shear data or the galaxy power spectrum are able to constrain the neutrino mass to approximately 0.02-0.03 eV at 1σ [37]. While this is enough to guarantee that the effect of neutrino mass will be seen in the data (and of course also enough that it is crucial to include massive neutrinos in the analysis), it is not enough to be sure that a genuine detection of the neutrino mass will be made.

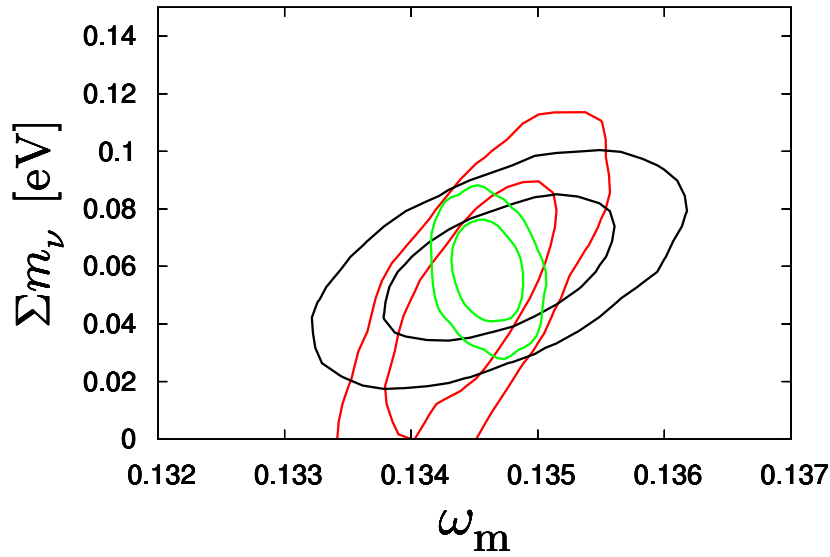


Figure 3. 68% and 95% constraints on the matter density, $\omega_m = \Omega_m h^2$, and the sum of neutrino masses, $\sum m_\nu$, for the combination of Planck CMB data with EUCLID shear data (red curves) and EUCLID galaxy data (black curves), as well as the combination of all three (green curves). The data used corresponds to the “csgx” case in [37].

However, it turns out that the combination of EUCLID shear *and* galaxy measurements breaks the degeneracy between $\sum m_\nu$, ω_m , and h , leading to a significantly tighter constraint on all three parameters [37]. In fact, if galaxy bias can be reliably estimated from the spectroscopic survey, the combined EUCLID data, together with CMB data leads to a much tighter constraint than naively expected. In fact, the combination of CMB, shear, and galaxy data might allow for a 5σ detection of non-zero neutrino masses, even in the normal hierarchy. Figure 3 (taken from [37]) shows the projected constraint on the sum of neutrino masses for the combination of Planck data with EUCLID galaxy and shear data.

Preliminary studies using the dataset called “csgx” in [37] show that going to more complex model spaces does not significantly affect this conclusion. Adding the equation of state parameter for dark energy, w , and the effective number of relativistic species, N_{eff} , as free parameters beyond Λ CDM plus $\sum m_\nu$ only marginally relaxes the constraint which can be achieved from 0.011 eV to 0.012 eV at the 1σ level. Table 1 also shows the corresponding constraints on w and N_{eff} . Interestingly, as can be seen in Figure 4, the degeneracy between $\sum m_\nu$ and w is no longer very strong when the data reaches this level of precision. A similar thing happens for the correlation between $\sum m_\nu$ and N_{eff} . In Figure 5 we show correlations between $\sum m_\nu$, ω_m , and N_{eff} for Planck CMB data, EUCLID shear plus galaxy data, and the two data sets combined. As can be seen in the top panel, the correlation between $\sum m_\nu$ and N_{eff} is almost entirely broken by the combination of the two data sets.

Even though the neutrino mass is the main parameter of interest because it very directly affects the formation of structure, the effective number of neutrino species is an equally important parameter from a neutrino physics point of view. Not only is it a sensitive probe of physics beyond the standard model, the standard model prediction itself is interesting. The predicted value of 3.046 relies on a very precise understanding of standard model physics to an energy scale of more than 1 MeV in the early universe. If data becomes precise enough to distinguish 3.046 from 3 it de facto means that we will, through observations of structure formation in the late time universe, be able to see effects of finite temperature field theory in the early Universe.

Table 1. Estimated 1σ sensitivity of Planck+EUCLID to $\sum m_\nu$, w , and N_{eff} . The data used correspond to the csgx case in [37].

Model	$\sum m_\nu$	w	N_{eff}
Standard Λ CDM + $\sum m_\nu$	0.011	—	—
Standard Λ CDM + $\sum m_\nu + w + N_{\text{eff}}$	0.012	0.02	0.055

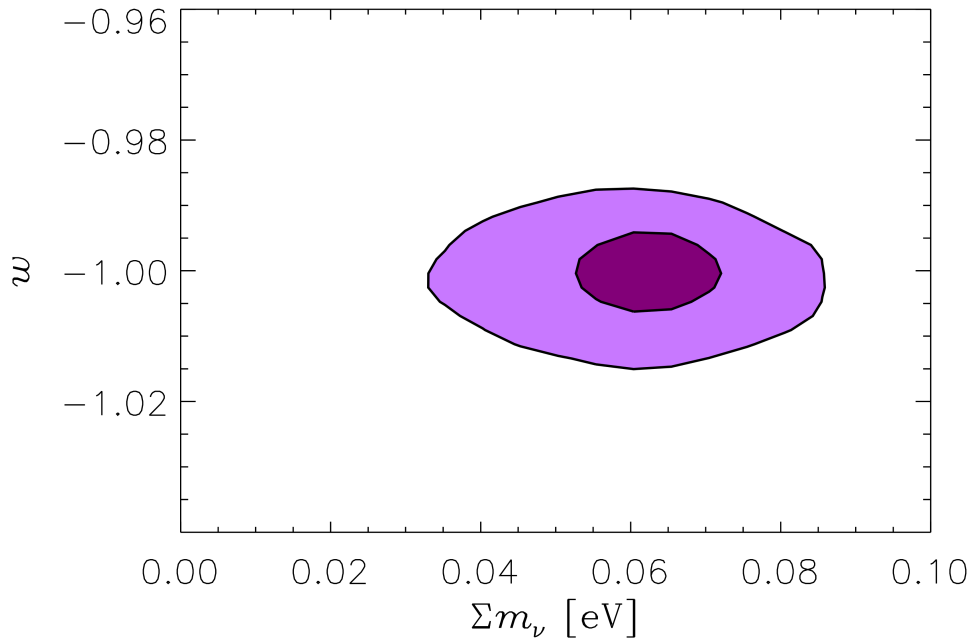


Figure 4. 68% and 95% constraints on the sum of neutrino masses, $\sum m_\nu$, and the dark energy equation of state, w , for the combination of Planck CMB data with EUCLID shear and galaxy data. The data used corresponds to the “csgx” case in [37].

The estimated sensitivity of EUCLID plus Planck data is almost, but not quite at the required level. At 1σ the combined data might reach $\sigma(N_{\text{eff}}) \sim 0.05$ which means that the standard model prediction can only be tested at approximately 1σ .

5. Conclusions

We have reviewed both the current status of neutrino constraints from large scale structure formation, as well as possible future bounds from experiments such as EUCLID.

Even at present epoch late time cosmology provides extremely useful constraints on light neutrinos. The bound on the masses of light, standard model neutrinos is significantly stronger than from direct experiments. While an exact value of the current bound is hard to quantify it is somewhere in the range of 0.3-0.5 eV, depending on the exact data and model space used in the analysis. Any value close to the current bound from beta decay experiments is certainly ruled out at very high significance. However, in the presence of sterile neutrinos the bound does become significantly weaker, and the existence of an additional eV-mass sterile neutrino, as is hinted at by current short baseline oscillation data, may not be excluded.

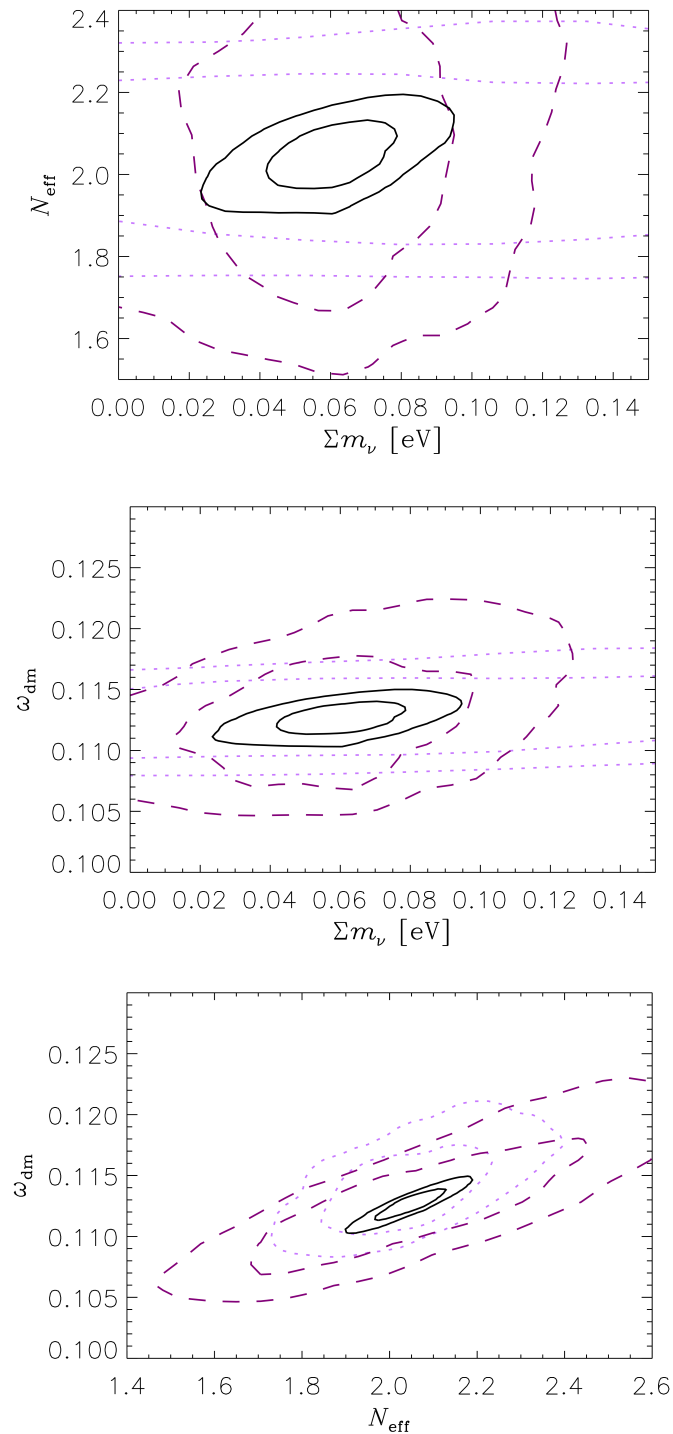


Figure 5. 68% and 95% constraints on the sum of neutrino masses, Σm_ν , the effective number of relativistic species, N_{eff} , and the dark matter density, ω_{dm} , for Planck CMB data (dotted lines), EUCLID shear and galaxy data (dashed lines), and the two combined (full lines). The data used corresponds to the “csgx” case in [37].

In fact, as was also discussed above, there might be an indication from mainly CMB data of the existence of extra radiation beyond what is predicted by the standard model. Light neutrinos would contribute to this energy density because they would still be relativistic at the epoch of recombination where the CMB is formed. Thus, sterile neutrinos might yet be discovered by precision measurements in cosmology. The upcoming data release from the Planck satellite should give a strong indication of whether sterile neutrinos are needed or not.

Finally, we also discussed the ability of the recently approved EUCLID satellite to measure neutrino masses. Interestingly, with Planck and EUCLID data combined it might be possible to not only put an upper limit on the neutrino mass, but make a real measurement at the 5σ level even if the sum of neutrino masses is as low as possible (i.e. in the normal hierarchy with a massless ν_1).

One remaining problem, however, is that it may be difficult to ascertain, based on cosmological data alone, whether the effect seen is due to standard model neutrinos. What the measurement will measure with great precision is the presence of the expected relativistic energy density and rest mass in *some* species that is weakly interacting. That it is weakly interacting follows from the requirement that the energy density is in a component with anisotropic stress. Without an anisotropic stress term the light particle species will behave as a perfect fluid, i.e. a fluid with no viscosity. This in turn leads to a strong enhancement of structure on all scales within the sound horizon on the fluid because free-streaming is absent (see e.g. [38, 39, 40, 41, 42, 43, 44]). Already with the current WMAP data such a scenario is very strongly disfavoured, and with new data from Planck an even stronger bound can be imposed on the interaction strength of the light species.

Since cosmological data based on structure formation can never be sensitive to flavour, it is not possible to “directly” measure the cosmic neutrino background. Therefore it will of course be highly desirable with a corresponding laboratory measurement of neutrino mass even when a non-zero neutrino mass has been detected at more than 5σ significance.

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