

Planck 2015 constraints on neutrino physics

Massimiliano Lattanzi (on behalf of the *Planck* collaboration)

Dipartimento di Fisica e Scienze della Terra, Università di Ferrara and INFN sezione di Ferrara, Polo Scientifico e Tecnologico - Edificio C Via Saragat, 1, I-44122, Ferrara, Italy

E-mail: lattanzi@fe.infn.it

Abstract. Anisotropies of the cosmic microwave background radiation represent a powerful probe of neutrino physics, complementary to laboratory experiments. Here I review constraints on neutrino properties from the recent 2015 data from the *Planck* satellite.

1. Introduction

Oscillation experiments have by now established that neutrino have a mass [1, 2], a discovery whose importance has been acknowledged by the 2015 Nobel prize in physics. Oscillations cannot however provide information on the absolute scale of neutrino masses. Massive neutrinos affect the evolution of the Universe, modifying cosmological observables that can be used to constrain their mass (as well as other properties) [3, 4]. This approach is complementary to other probes of neutrino masses, namely direct (kinematic) measurements, like in tritium β decay experiments [5], and the study of neutrinoless double β decay [6] (see also Refs. [7, 8] for the possibility of combining data on neutrinoless double β decay with cosmological observations). The subject of this contribution are the limits on neutrino properties that can be obtained from cosmological observables, and in particular from the latest observations of cosmic microwave background (CMB) temperature and polarization anisotropies of the *Planck* satellite¹.

Planck is a third-generation ESA satellite dedicated to the CMB, that observed the microwave and submillimetre sky continuously from 12 August 2009 to 23 October 2013. Its scientific payload consists of an array of 74 detectors in nine frequency bands between ~ 30 GHz and ~ 1 THz, which scanned the sky with angular resolution between $33'$ and $5'$. *Planck* imaged the whole sky with an unprecedented combination of sensitivity, angular resolution and frequency coverage. In February 2015, the third *Planck* data release (the second containing cosmological data) started, that includes products and scientific results based on data collected across the whole mission duration, both in temperature and polarization [9].

This contribution is largely based on Sec. 6.4 of the 2015 *Planck* cosmological parameters paper [10], to which I refer the reader for a more detailed discussion of the results presented here. After reviewing the data and method used in Sec. 2, I report the limits that *Planck* observations put on neutrino masses in Sec. 3. Then in Sec. 4 I report the bounds on the effective number of degrees of freedom, while in the following section I discuss limits on the presence of a fourth,

¹ *Planck* (<http://www.esa.int/Planck>) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states and led by Principal Investigators from France and Italy, telescope reflectors provided through a collaboration between ESA and a scientific consortium led and funded by Denmark, and additional contributions from NASA (USA).



massive neutrino eigenstate. In Sec. 6 the agreement of the behaviour of neutrino perturbations with the standard expectations is briefly discussed. In Sec. 7 I draw a summary.

2. Data and method

The baseline dataset used in the analysis is the *Planck* temperature power spectrum in the whole multipole range $2 \leq \ell \leq 2500$ (denoted as *Planck TT*), complemented with the large-scale ($\ell < 30$) polarization (lowP). The 2015 release also includes the *TE* and *EE* polarization spectra at $\ell \geq 30$, denoted as *Planck TE*, *EE*. The latter spectra are likely to be affected by low-level residual systematics, and the results obtained using high- ℓ polarization are to be regarded as non-conservative. The dataset discussed so far are based on the two-point correlation function of the CMB (of which the power spectrum represents the harmonic transform), and are described in detail (together with the likelihood function used to quantify the agreement between the data and predictions from a given theoretical model) in the 2015 *Planck* power spectra and likelihood paper [11]. *Planck* is also able to measure the connected part of the 4-point *TTTT* correlation function; this is generated by weak gravitational lensing of the CMB anisotropy pattern by large-scale structures, and is proportional to the power spectrum of the lensing potential. The dataset using this information is denoted with “lensing”, and is described in detail in the 2015 *Planck* lensing paper [12]. Even if the measure of the 4-point correlation function is a more direct probe, lensing also affects the *TT*, *TE* and *EE* power spectra by smoothing the peaks and troughs, an effect that can be measured by high-resolution, low-noise observations like *Planck*’s. Lensing, through its effects on both the power spectra and the 4-point correlation function, plays an important role in deriving constraints on the total neutrino mass, given the effect of neutrinos on structure formation. Finally, the analysis made by the *Planck* collaboration also considers auxiliary, external datasets, in particular baryon acoustic oscillations (BAO) measurements [13, 14, 15], observations of Type IA supernovae [16], and astrophysical estimates of the Hubble constant [17, 18], collectively denoted as “external”.

The theoretical models considered here are suitable extensions of the standard, six-parameter Λ CDM model. The parameter constraints reported in the following sections are computed using the *CosmoMC* code [19] as a Monte Carlo engine, interfaced with the Boltzmann code *camb* [20]. Unless otherwise noted, constraints are given in the form mean $\pm$ 68% uncertainty, or as 95% confidence upper limits.

3. *Planck* constraints on neutrino masses

Massive neutrinos affect the cosmological evolution both at the background and at the perturbation level [3, 4]. However, neutrino masses in the sub-eV range (as indicated by laboratory experiments) do not have a *direct* effect on primary CMB anisotropies (those generated at the time of decoupling), since in that case the transition to the non-relativistic regime takes place after the CMB decoupling. Thus their effects on the CMB are confined to those related to the modified background evolution and to secondary anisotropies, that are created while the CMB photons propagate freely after decoupling. Possible background effects include changes in the time of matter-radiation equality, in the angular-diameter distance to the last scattering surface, and in the amount of late-integrated Sachs-Wolfe (ISW) effect. However, even in the minimal extension of the Λ CDM model that includes massive neutrinos, these effects can be at least partially compensated by variations in other cosmological parameters² like the Hubble parameter H_0 . Thus the constraining power deriving from background effects on the CMB anisotropy pattern is somewhat limited. In fact, much of *Planck*’s capability to constrain neutrino masses comes instead from their effect on the evolution of matter perturbations, that

² This is even more evident in more complicated extensions of the standard cosmological model, like those that do not assume spatial flatness.

in turn affect the weak lensing of small-scale CMB anisotropies. Perturbations in the neutrino fluid are erased at small scales due to their large thermal velocities [21]. The overall effect is that density fluctuations are suppressed at scales below the neutrino free-streaming scale (roughly equal to the size of the horizon at the time of the non-relativistic transition) proportionally to the fraction of matter density provided by neutrinos. Since the neutrino energy density is proportional to the sum of the masses $\sum m_\nu$ through $\Omega_\nu h^2 = \sum m_\nu / 94.1 \text{ eV}$, larger neutrino masses imply less power in fluctuations and thus a lesser amount of CMB weak lensing.

Table 1. *Planck* constraints on the total neutrino mass $\sum m_\nu$, for different datasets combination (limits are at 95% CL).

Dataset		+ lensing	+ BAO	+ ext	+ lensing + ext
<i>Planck</i> TT + lowP	$< 0.72 \text{ eV}$	$< 0.68 \text{ eV}$	$< 0.21 \text{ eV}$	$< 0.20 \text{ eV}$	$< 0.23 \text{ eV}$
<i>Planck</i> TT,TE,EE + lowP	$< 0.49 \text{ eV}$	$< 0.59 \text{ eV}$	$< 0.17 \text{ eV}$	$< 0.15 \text{ eV}$	$< 0.19 \text{ eV}$

Constraints on $\sum m_\nu$ from *Planck* are obtained by assuming three species of degenerate massive neutrinos, with an equilibrium Fermi-Dirac distribution with $T_\nu = (4/11)^{1/3} T_{\text{CMB}} \simeq 1.9 \text{ K}$ and zero chemical potential. I report them in Tab. 1 for different combinations of *Planck* and external datasets. The baseline dataset (*Planck*TT+lowP) already constraints $\sum m_\nu < 0.72 \text{ eV}$ at 95% CL. This constrain, that can be regarded as the most conservative from the point of view of *Planck* data, is at the same level of the expected sensitivity of the KATRIN experiment [22], that is of 0.2 eV for the effective electron neutrino mass. Addition of the small-scale polarization information improves the limit down to $\sum m_\nu < 0.49 \text{ eV}$, thus better than KATRIN. I note however that this does not make the information that will be gathered from KATRIN, or any other experiment based on kinematic measurements, any less useful, since this kind of results is very robust and model-independent. Adding the lensing information does not improve significantly - and in the case of small-scale polarization it actually worsens - the results from the baseline dataset, the reason being that the reconstruction of the lensing potential from the four-point correlation function of the CMB prefers a smaller lensing amplitude with respect to what is estimated by fitting the TT power spectrum. This slight tension increases the statistical weight of larger values of the total neutrino mass, once the lensing potential information is folded into the analysis. On the other hand, the geometrical constraint provided by BAO observations greatly improves the bounds on $\sum m_\nu$: the *Planck*TT+lowP+BAO dataset yields $\sum m_\nu < 0.21 \text{ eV}$. When high-ell polarization, lensing or external datasets other than BAO are also considered, the 95% upper limits remain in the range $150 - 230 \text{ meV}$. In particular, the upper limit $\sum m_\nu < 0.23 \text{ eV}$ from the *Planck*TT+lowP+lensing+ext dataset is regarded as the best limit obtained from *Planck*, while still being at the same time reasonably conservative, as it does not use small-scale polarization that might be affected by low-level systematics. In Fig. 1 I show a whiskers plot comparing the limits on $\sum m_\nu$ from *Planck* 2013 and *Planck* 2015, the latter with and without high-ell polarization.

Since the presence of massive neutrinos reduces the power in small-scale fluctuations, they have been proposed as a possible solution to the tension between values of the fluctuations amplitude σ_8 inferred from *Planck*'s CMB measurements, and large scale structures (smaller) determinations of the same parameter. However larger masses also require a lower H_0 , and thus lead to possible tensions with astrophysical measurements of the Hubble constant. Moreover, for the more constraining combination of datasets, the allowed range of neutrino masses is quite

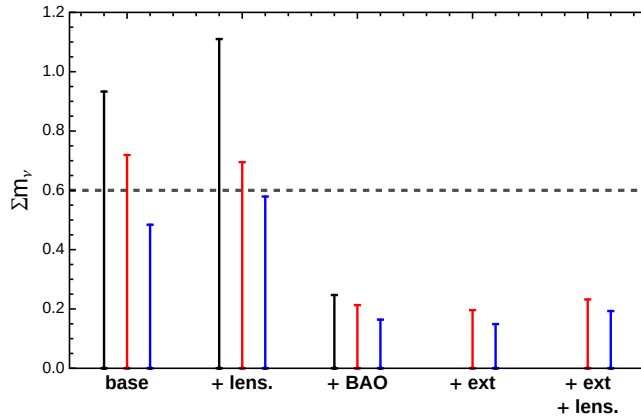


Figure 1. Comparison between constraints on $\sum m_\nu$ from *Planck* 2013 (black) and *Planck* 2015 without (red) and with (blue) small-scale polarization. The baseline always includes the full TT spectrum and the low-ell polarization (taken from WMAP in 2013). The dashed line represents KATRIN sensitivity to the effective electron neutrino mass, translated in terms of $\sum m_\nu$.

small and the impact on σ_8 is not large enough to solve the tension.

4. *Planck* constraints on N_{eff}

The effective number of neutrino families N_{eff} parametrizes the energy density in relativistic species in the early Universe. It is defined as the ratio between the total density ρ_r of relativistic species (excluding photons) and the energy density of a single neutrino family with temperature $T_\nu = (4/11)^{1/3} T_{\text{CMB}}$. Thus $N_{\text{eff}} = 3$ for three standard model neutrinos that are thermalized in the early Universe through weak interactions, and decoupled well before e^+e^- annihilation; the actual prediction is instead $N_{\text{eff}} = 3.046$ because neutrinos decouple shortly before e^+e^- annihilation and thus receive some of the entropy produced in the annihilation [23]. N_{eff} could differ from its standard value for several reasons, like the presence of a (effectively) massless species at decoupling, (e.g., a very light sterile neutrino), non-thermal radiation production via particle decays, or even a non-zero chemical potential for the active neutrinos. In these scenarios, $\Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 > 0$; the case $\Delta N_{\text{eff}} < 0$ is also possible, for example if standard model neutrinos are not fully thermalized, like in low-rehating scenarios. The analysis presented in the *Planck* parameters paper follows a phenomenological approach, considering N_{eff} a free parameter with a flat wide prior, and yields the following constraints for different data combinations (in this analysis the total mass of the active neutrinos is kept fixed to 0.06 eV):

$$N_{\text{eff}} = 3.13 \pm 0.32 \quad \text{PlanckTT} + \text{lowP}, \quad (1a)$$

$$N_{\text{eff}} = 3.15 \pm 0.23 \quad \text{PlanckTT} + \text{lowP} + \text{BAO}, \quad (1b)$$

$$N_{\text{eff}} = 2.99 \pm 0.20 \quad \text{PlanckTT, TE, EE} + \text{lowP}, \quad (1c)$$

$$N_{\text{eff}} = 3.04 \pm 0.18 \quad \text{PlanckTT, TE, EE} + \text{lowP} + \text{BAO}. \quad (1d)$$

Planck is consistent with the standard value of N_{eff} , and excludes $N_{\text{eff}} = 4$ (i.e., a fully-thermalized fourth neutrino state) at a level between 2.7 and 5.3σ ; however, sizeable amounts of extra radiation are still allowed by the data. For example, a fully-thermalized massless boson decoupling before muon annihilation, contributing $\Delta N_{\text{eff}} \simeq 0.39$, is only weakly disfavoured by the data. Allowing also the mass of active neutrinos to vary yields the combined 95% constraints $N_{\text{eff}} = 3.2 \pm 0.5$ and $\sum m_\nu < 0.32 \text{ eV}$ from *Planck*TT+lowP+lensing+BAO.

Due to the correlation between N_{eff} and H_0 , values of $\Delta N_{\text{eff}} > 0$ favour higher values of the Hubble parameter with respect to standard ΛCDM . This alleviates the tension between *Planck* and direct measurements of H_0 . However, models with large N_{eff} and H_0 also have higher values of the fluctuation amplitude σ_8 , and thus increase the tension between *Planck* and large-scale structure data. In general, modifications in the neutrino sector cannot, by themselves, easily solve the tensions between *Planck* and other data.

5. *Planck* constraints on light sterile neutrinos

The existence of extra, sterile neutrino eigenstates is not forbidden by any fundamental symmetry in nature. In particular, light (*i.e.*, $\sim$ eV mass) sterile neutrinos have been proposed as a possible solution to the short-baseline (SBL) neutrino oscillation anomalies (see e.g. Ref. [24] and references therein).

The limits presented in the previous section can be interpreted in terms of a very light ($m_s \ll 1$ eV), *i.e.*, effectively massless, sterile neutrino. In the massive case, instead, a light sterile neutrino model is completely specified - from the point of view of its effects on the late-time cosmological observables like CMB anisotropies - by the energy densities of the particles in the non-relativistic and ultrarelativistic regimes, provided that the distribution function of the particles is proportional to a Fermi-Dirac distribution [25]. *Planck*'s constraints on sterile neutrinos are obtained by considering a single additional massive eigenstate, parametrised through the effective mass $m_s^{\text{eff}} \equiv (94.1 \text{ eV}) \Omega_s h^2$ and its contribution ΔN_{eff} to the energy density in relativistic species. This parametrisation allows to map different cases of interest to a single model, that can be studied through a single analysis. In particular, two cases are considered: (i) the extra eigenstate is thermally distributed with arbitrary temperature T_s ; or (ii) it is distributed proportionally to the active neutrinos with a suppression factor χ_s [this corresponds to the Dodelson-Widrow (DW) scenario of non-resonant production]. The actual mass m_s of the sterile can be recovered from the parameters of the "effective model" by means of $m_s = (T_s/T_\nu)^{-3} m_s^{\text{eff}} = \Delta N_{\text{eff}}^{-3/4} m_s^{\text{eff}}$ for the thermal case, and $m_s = \chi_s^{-1} m_s^{\text{eff}} = \Delta N_{\text{eff}}^{-1} m_s^{\text{eff}}$ for the DW case. The total mass of the active neutrinos is kept fixed at 0.06 eV.

Planck is consistent with no sterile neutrinos. The 95% allowed region in parameter space is $N_{\text{eff}} < 3.7$, $m_s^{\text{eff}} < 0.52$ eV from *Planck*TT + lowP + lensing + BAO. This result has important consequences for the sterile neutrino interpretation of short-baseline anomalies. It has been shown that a sterile neutrino with the large mixing angles required to explain reactor anomalies would thermalize rapidly in the early Universe (see e.g. Refs. [26, 27]), yielding $\Delta N_{\text{eff}} = 1$. The preferred short-baseline solution then corresponds to $m_s \simeq 1$ eV and $\Delta N_{\text{eff}} = 1$ and is strongly excluded (more than 99% confidence) by the above combination of *Planck* and BAO data. Several mechanism to avoid full thermalization and make the SBL solution in agreement with cosmological observations have been proposed, like large lepton asymmetries, new interactions, or particle decays (again see Refs. in [24]).

6. *Planck* constraints on neutrino perturbations

The precision of *Planck* data allows to use them also to test that perturbations in the neutrino fluid evolve according to the standard model prediction for non-interacting relativistic particles. This is done by introducing the effective neutrino sound speed c_{eff} and viscosity c_{vis} [28] and looking for deviations from the standard values $c_{\text{eff}}^2 = c_{\text{vis}}^2 = 1/3$ expected for free-streaming particles. This is an interesting test as it allows to test the robustness of the base Λ CDM model and at the same time to probe for non-standard physics in the neutrino sector, like *e.g.* neutrino couplings to a light scalar particle. *Planck* data are fairly consistent with the standard picture; the *Planck*TT+lowP dataset yields $c_{\text{eff}}^2 = 0.312 \pm 0.011$ and $c_{\text{vis}}^2 = 0.47^{+0.26}_{-0.12}$. Inclusion of the small-scale *Planck* polarization data strengthens the agreement.

7. Summary

I have shown how *Planck* data can be used to constrain neutrino properties. *Planck* does not show evidence for a non-minimal neutrino mass, nor for new physics beyond the standard model of particles; however, it provides the best (albeit model-dependent) bounds to date on the total neutrino mass, as well as tight constraints on the total density of relativistic species, excluding the presence of an additional massless, fully thermalized species, and on the presence of a light

sterile neutrino. In the latter case, *Planck* data exclude with high confidence the preferred SBL solution.

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