Neutrinos in Cosmology

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Rencontres de Blois

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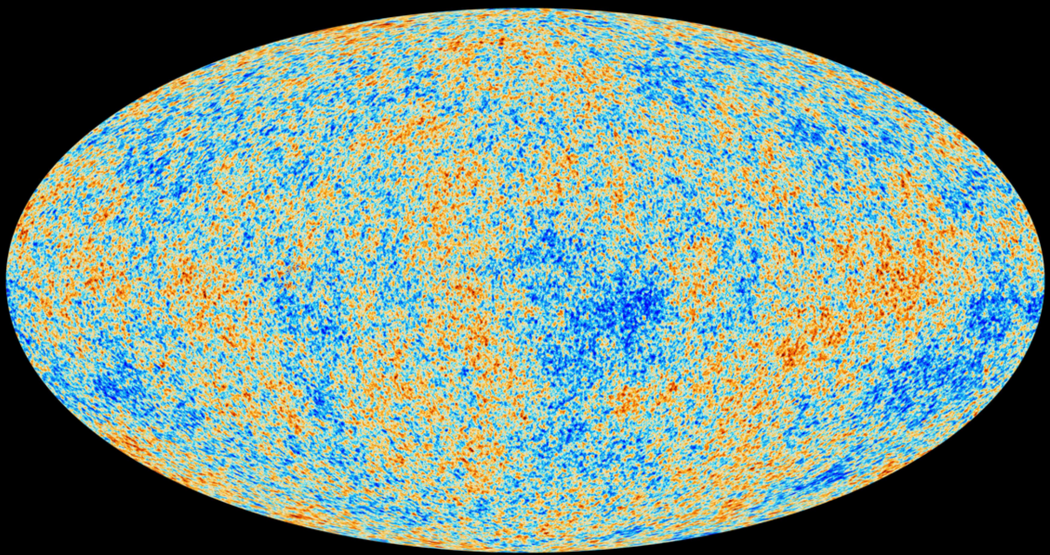
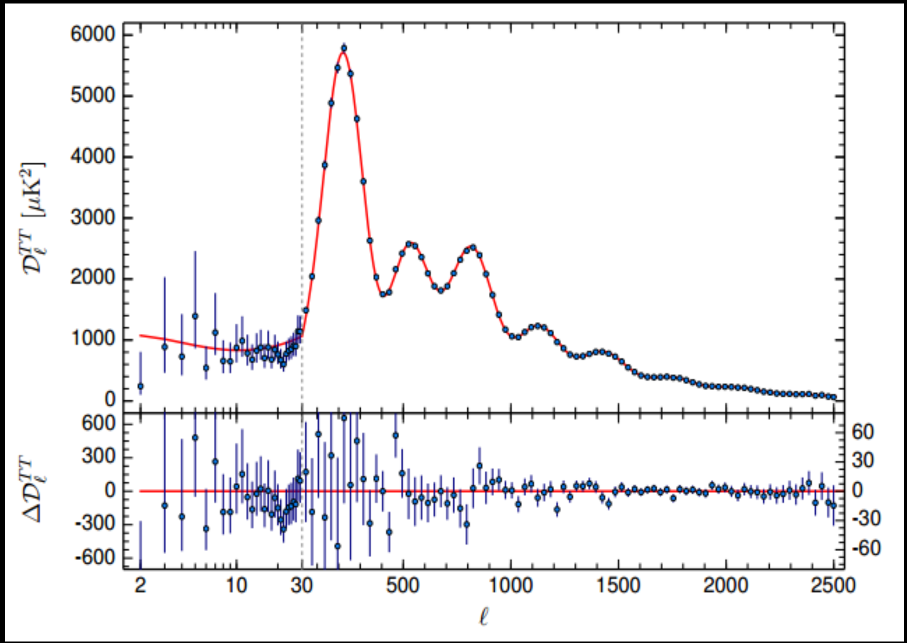
Introduction to CMB





Planck collaboration, 2015

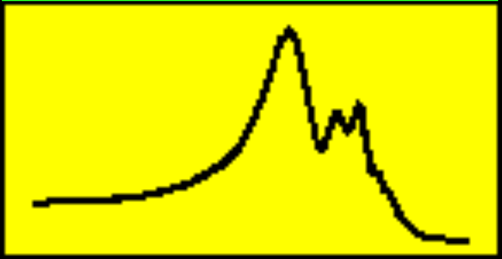
An important tool of research in cosmology is the angular power spectrum of CMB temperature anisotropies.

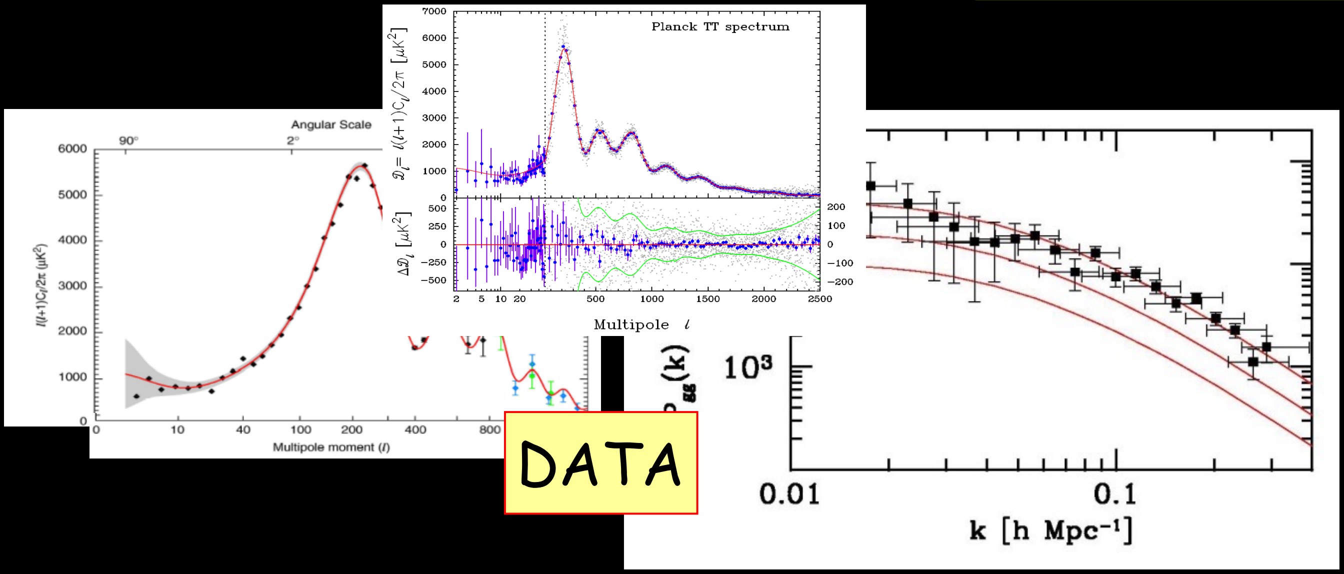
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

Introduction to CMB

Cosmological parameters:
$(\Omega_b h^2, \Omega_m h^2, h, n_s, \tau, \Sigma m_\nu)$

Theoretical model





PARAMETER
CONSTRAINTS

The Cosmic Neutrino Background

When the rate of the weak interaction reactions, which keep neutrinos in equilibrium with the primordial plasma, becomes smaller than the expansion rate of the Universe, neutrinos decouple at a temperature of about:

$$T_{dec} \approx 1 MeV$$

After neutrinos decoupling, photons are heated by electrons-positrons annihilation. After the end of this process, the ratio between the temperatures of photons and neutrinos will be fixed, despite the temperature decreases with the expansion of the Universe. We expect today a Cosmic Neutrino Background (CNB) at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945 K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a number density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k, \bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

Neutrino cosmology

With the CMB data, in combination with other cosmological probes, we can constrain in the neutrino sector the total neutrino mass and the neutrino effective number.

If the total neutrino mass is less than 1 eV, then the three active neutrinos are still relativistic at the time of recombination.

We expect the transition to the non-relativistic regime after the time of the photon decoupling.

Because the shape of the CMB spectrum is related mainly to the physical evolution before recombination, the effect of the neutrino mass, can appear through a modified background evolution and some secondary anisotropy corrections as weak lensing.

Sum of active neutrino masses

These neutrinos are radiation at the time of equality, and non-relativistic matter today.

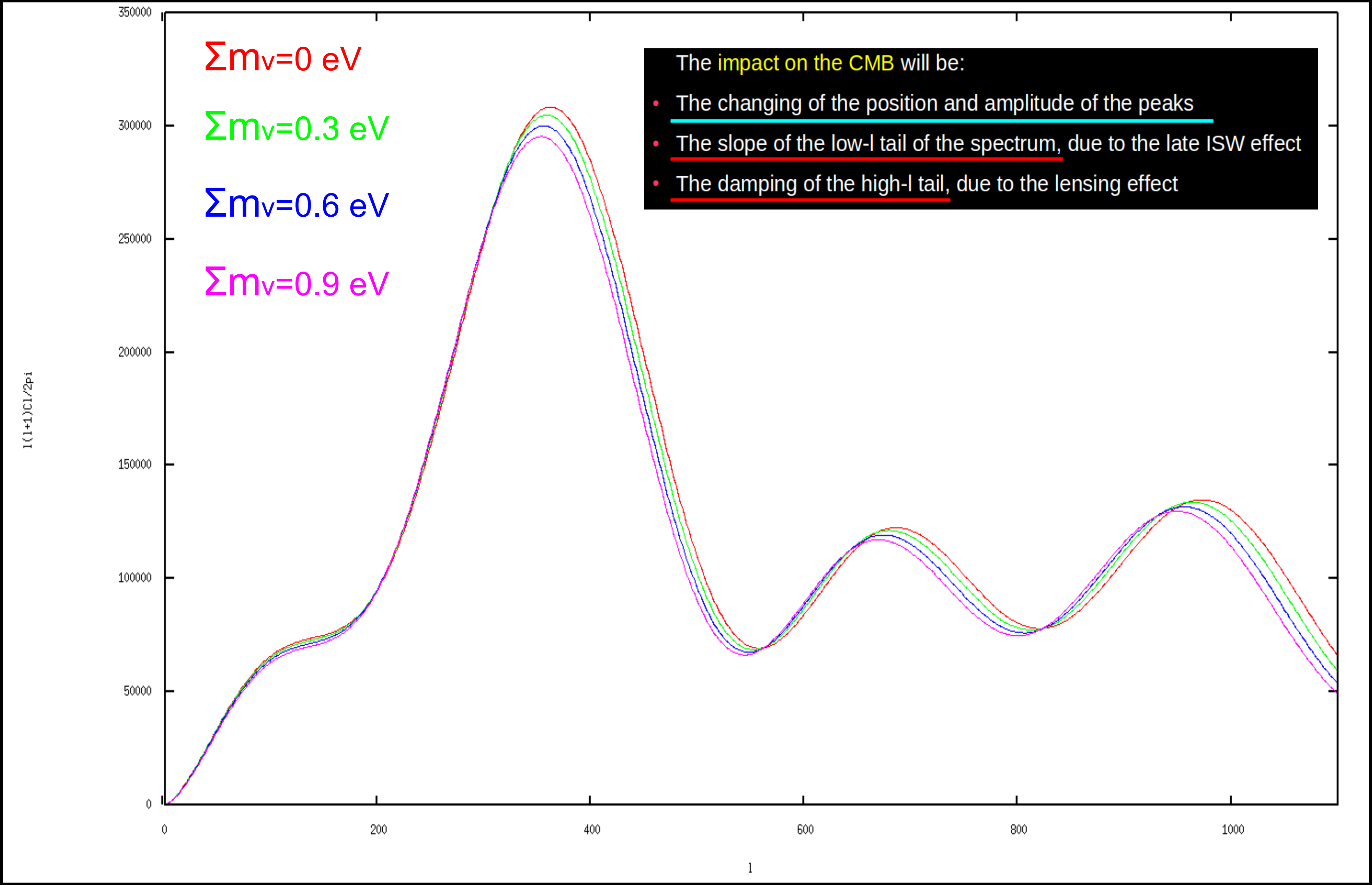
Varying their total mass we vary:

- The redshift of the matter-to-radiation equality z_{eq};
- The amount of matter density today.

The impact on the CMB will be:

- The changing of the position and amplitude of the peaks;
- The slope of the low-l tail of the spectrum, due to the late ISW effect;
- The damping of the high-l tail, due to the lensing effect.

Sum of active neutrino masses



CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck	Planck pol	Planck +BAO	Planck pol +BAO	Planck +H070p6	Planck pol +H070p6	Planck +H073p0	Planck pol +H073p0
$\Omega_c h^2$	$0.1202^{+0.0047}_{-0.0044}$	$0.1200^{+0.0031}_{-0.0030}$	$0.1188^{+0.0028}_{-0.0029}$	$0.1192^{+0.0023}_{-0.0023}$	$0.1193^{+0.0042}_{-0.0041}$	$0.1196^{+0.0028}_{-0.0028}$	$0.1179^{+0.0040}_{-0.0041}$	$0.1189^{+0.0029}_{-0.0028}$
Σm_ν [eV]	< 0.754	< 0.497	< 0.220	< 0.175	< 0.337	< 0.291	< 0.195	< 0.180
H_0	$65.5^{+4.4}_{-5.9}$	$66.3^{+2.9}_{-3.8}$	$67.6^{+1.3}_{-1.3}$	$67.5^{+1.1}_{-1.2}$	$67.1^{+2.8}_{-3.1}$	$67.0^{+2.1}_{-2.4}$	$68.2^{+2.0}_{-2.3}$	$67.7^{+1.7}_{-1.7}$
σ_8	$0.79^{+0.08}_{-0.11}$	$0.811^{+0.058}_{-0.076}$	$0.825^{+0.039}_{-0.042}$	$0.832^{+0.033}_{-0.034}$	$0.819^{+0.049}_{-0.057}$	$0.824^{+0.043}_{-0.049}$	$0.829^{+0.038}_{-0.040}$	$0.831^{+0.035}_{-0.036}$
Ω_m	$0.340^{+0.088}_{-0.063}$	$0.329^{+0.052}_{-0.039}$	$0.311^{+0.017}_{-0.016}$	$0.312^{+0.015}_{-0.014}$	$0.318^{+0.041}_{-0.037}$	$0.319^{+0.031}_{-0.027}$	$0.304^{+0.029}_{-0.028}$	$0.310^{+0.023}_{-0.022}$
τ	$0.080^{+0.038}_{-0.038}$	$0.081^{+0.033}_{-0.034}$	$0.082^{+0.038}_{-0.037}$	$0.083^{+0.033}_{-0.032}$	$0.082^{+0.038}_{-0.037}$	$0.082^{+0.034}_{-0.034}$	$0.085^{+0.039}_{-0.038}$	$0.083^{+0.032}_{-0.033}$

From Planck TTTEEE+lowTEB alone we have a very important upper limit on the total neutrino mass.

Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527

CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck	Planck pol	Planck +BAO	Planck pol +BAO	Planck +H070p6	Planck pol +H070p6	Planck +H073p0	Planck pol +H073p0
$\Omega_c h^2$	$0.1202^{+0.0047}_{-0.0044}$	$0.1200^{+0.0031}_{-0.0030}$	$0.1188^{+0.0028}_{-0.0029}$	$0.1192^{+0.0023}_{-0.0023}$	$0.1193^{+0.0042}_{-0.0041}$	$0.1196^{+0.0028}_{-0.0028}$	$0.1179^{+0.0040}_{-0.0041}$	$0.1189^{+0.0029}_{-0.0028}$
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σ_8	$0.79^{+0.08}_{-0.11}$	$0.811^{+0.058}_{-0.076}$	$0.825^{+0.039}_{-0.042}$	$0.832^{+0.033}_{-0.034}$	$0.819^{+0.049}_{-0.057}$	$0.824^{+0.043}_{-0.049}$	$0.829^{+0.038}_{-0.040}$	$0.831^{+0.035}_{-0.036}$
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τ	$0.080^{+0.038}_{-0.038}$	$0.081^{+0.033}_{-0.034}$	$0.082^{+0.038}_{-0.037}$	$0.083^{+0.033}_{-0.032}$	$0.082^{+0.038}_{-0.037}$	$0.082^{+0.034}_{-0.034}$	$0.085^{+0.039}_{-0.038}$	$0.083^{+0.032}_{-0.033}$

The most stringent bound on the sum of neutrino masses is obtained when considering Planck TTTEEE+lowTEB+BAO. In fact BAO data are directly sensitive to the free-streaming nature of neutrinos.
Moreover, the geometrical information they provide helps breaking degeneracies among cosmological parameters.
The Baryon Acoustic Oscillations we include are the 6dFGS, SDSS-MGS, BOSSLOWZ and CMASS-DR11 surveys, as done by the Planck collaboration.

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CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+tau6	Planck pol +BAO+SZ+tau5	Planck pol H073p0+SZ+tau6	Planck pol H073p0+SZ+tau5	Planck pol+BAO +H073p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.116	< 0.112	< 0.107	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.9^{+1.3}_{-1.4}$	$67.8^{+1.2}_{-1.4}$	$67.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$0.818^{+0.022}_{-0.023}$	$0.824^{+0.022}_{-0.023}$	$0.819^{+0.021}_{-0.022}$	$0.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

Depending on the choice of the low redshift priors, we start to exclude the inverted hierarchy with cosmology…

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CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+tau6	Planck pol +BAO+SZ+tau5	Planck pol H073p0+SZ+tau6	Planck pol H073p0+SZ+tau5	Planck pol+BAO +H073p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.116	< 0.112	< 0.107	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.9^{+1.3}_{-1.4}$	$67.8^{+1.2}_{-1.4}$	$67.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$0.818^{+0.022}_{-0.023}$	$0.824^{+0.022}_{-0.023}$	$0.819^{+0.021}_{-0.022}$	$0.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

The low redshift probes that we are considering in this case are:

- The Hubble constant, H_0=73.0+/-2.4:
- The Planck SZ clusters count,
- The reionization optical depth, τ=0.05+/-0.01.

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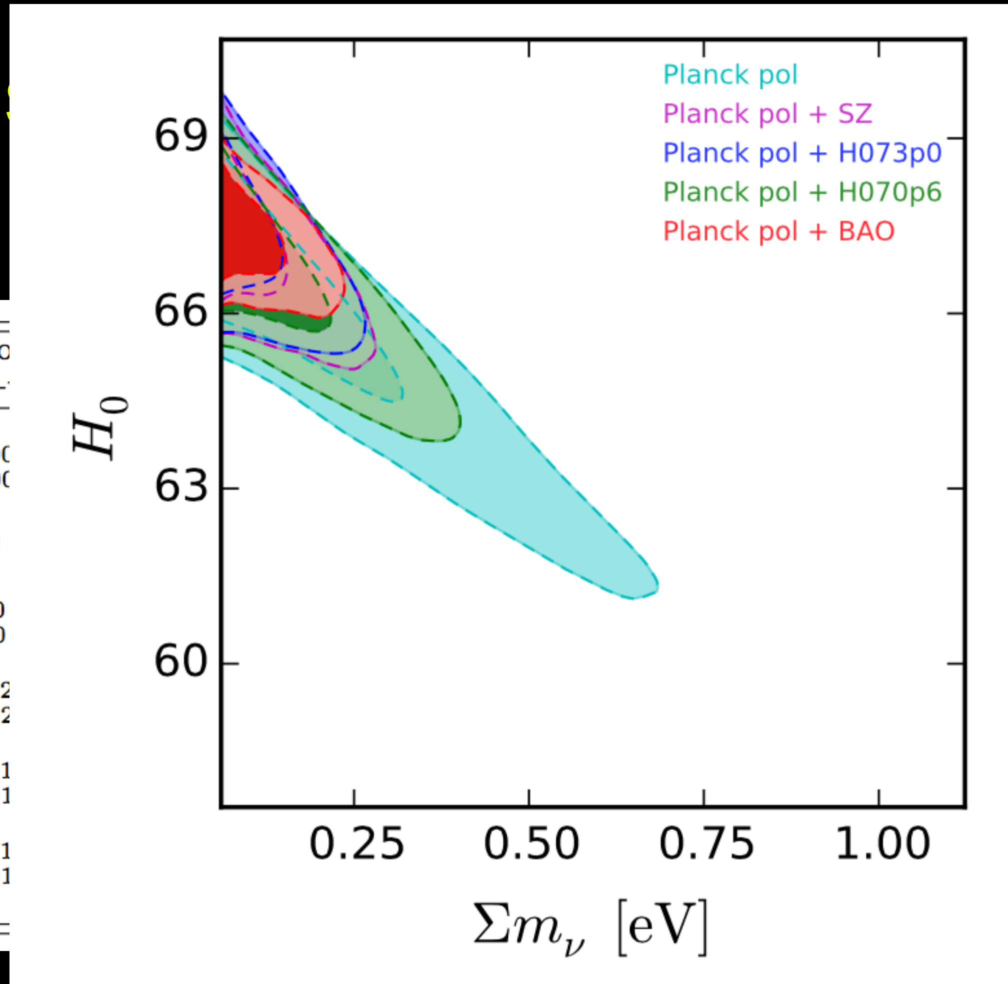
CMB cons rino mass

Constraints at 95% cl.

	Planck po +BAO+SZ+	ck pol+BAO 3p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.00}_{-0.00}$	$190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.02}_{-0.02}$	$324^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.01}_{-0.01}$	$308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.01}_{-0.01}$	$067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$



The low redshift probes that we are considering in this case are:

- The Hubble constant, H_0=73.0+/-2.4:
  - There exists a strong, well-known degeneracy between the neutrino mass and the Hubble constant. In the absence of an independent measurement of H_0, the change in the CMB temperature anisotropies induced by the presence of massive neutrinos can be easily compensated by a smaller value of the Hubble constant. Riess et al. in arXiv:1604.01424v3 confirm the value of H_0=73.24 +/- 1.74 Km/s/Mpc.

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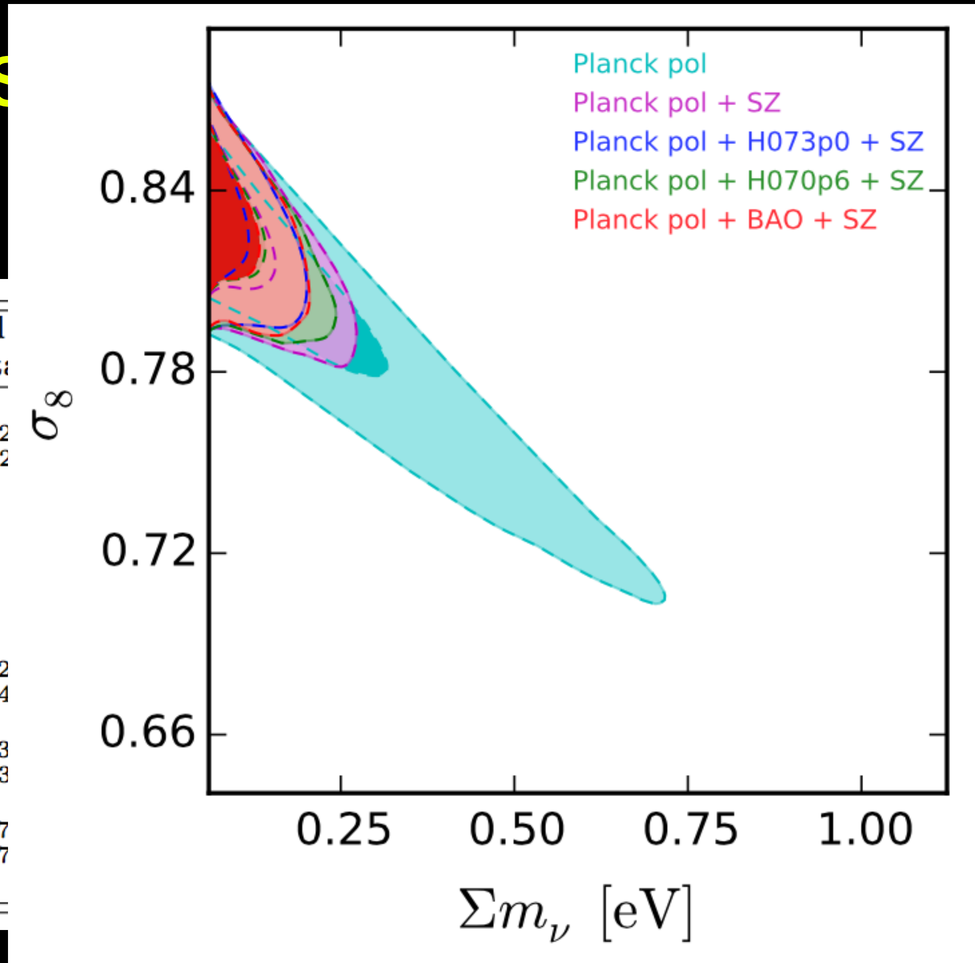
CMB cons... rino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+ta	...ck pol+BAO ...73p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.002}_{-0.002}$	$1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$57.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$



The low redshift probes that we are considering in this case are:

- The Planck SZ clusters count:

  \- Cluster surveys usually focus on the cluster number count function dN/dz, which measures the number of clusters of a certain mass M over a range of redshift, and it depends on the underlying cosmological model. The main uncertainties arise from the cluster mass bias. In our work the cluster mass bias is a free parameter, determined with a bayesian statistics.

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CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+tau6	Planck pol +BAO+SZ+tau5	Planck pol H073p0+SZ+tau6	Planck pol H073p0+SZ+tau5	Planck pol+BAO +H073p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
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Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

The low redshift priors that we are considering in this case are:

- The reionization optical depth, τ=0.05+/-0.01:

  - This prior is motivated by hints from high-redshift quasar absorption and Lyman α emitters. CMB measurements provide constraints via the integrated optical depth τ on when and how cosmic reionization takes place. The Planck collaboration provided the value of τ=0.055 +/- 0.009 from HFI data in arXiv: 1605.02985.

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Mass ordering

Since the cosmological constraints on the total neutrino mass are model dependent and now very close to test the neutrino mass scale, we have to be careful about the assumptions made on the neutrino hierarchy. Usually the neutrino masses are assumed to be degenerate ($m_i=m\geq0$) and the lower bound of total neutrino mass ($\Sigma=m_1+m_2+m_3$) is placed to 0. Although the CMB is essentially blind to the mass splitting, the possibility of allowing best-fit results around $\Sigma\simeq0$ (in the unphysical region) could induce a somewhat artificial preference for the normal ordering (NO) over the inverted ordering (IO), just because NO allows Σ values lower than IO.

For this reason, in Capozzi et al., Phys. Rev. D **95**, 096014 (2017), arXiv:1703.04471 we consider separately the NO and IO cases.

Neutrino oscillation experiments have established that the three known flavor states ν_α (α = e, μ, τ) are linear combinations of three massive states ν_i (i = 1, 2, 3) with different masses m_i, via a mixing matrix $U_{\alpha i}$ characterized by three non-zero angles θ_{ij}.

The masses m_i entering in the definition of Σ obey the δm^2 and Δm^2 constraints in:

$$\begin{aligned}\delta m^2 &= m_2^2 - m_1^2 > 0\ ,\\ \Delta m^2 &= m_3^2 - (m_2^2 + m_1^2)/2\end{aligned}$$

where Δm^2 can be either positive or negative according to the so-called normal ordering (NO) or inverted ordering (IO) for the neutrino mass spectrum.

Mass ordering

Since the cosmological constraints on the total neutrino mass are model dependent and now very close to test the neutrino mass scale, we have to be careful about the assumptions made on the neutrino hierarchy. Usually the neutrino masses are assumed to be degenerate ($m_i = m \geq 0$) and the lower bound of total neutrino mass ($\Sigma = m_1 + m_2 + m_3$) is placed to 0. Although the CMB is essentially blind to the mass splitting, the possibility of allowing best-fit results around $\Sigma \simeq 0$ (in the unphysical region) could induce a somewhat artificial preference for the normal ordering (NO) over the inverted ordering (IO), just because NO allows Σ values lower than IO.

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The absolute ν masses are unknown. However, lower bounds are set by oscillation data by zeroing the lightest m_i:

$$(m_1, m_2, m_3) \geq \begin{cases} \left(0,\ \sqrt{\delta m^2},\ \sqrt{|\Delta m^2| + \delta m^2/2}\right) & \text{(NO)} \\ \left(\sqrt{|\Delta m^2| - \delta m^2/2},\ \sqrt{|\Delta m^2| + \delta m^2/2},\ 0\right) & \text{(IO)} \end{cases}$$

Therefore, we assume in our analysis these corresponding lower bounds:

$$\Sigma = m_1 + m_2 + m_3 \gtrsim \begin{cases} 0.06\ \text{eV} & \text{(NO)} \\ 0.10\ \text{eV} & \text{(IO)} \end{cases}$$

CMB constraints on the total neutrino mass and their ordering

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
1	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT + τ_{HFI}	< 1.08	< 1.08	-0.1
8	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

In order to understand in which way our results depend on the combination of datasets considered and on the theoretical framework assumed, we consider two different scenarios:

- The standard ΛCDM + Σ model.
- An extended scenario, considering variation also in the lensing amplitude A_{lens} that controls the effects of the gravitational lensing in the angular power spectra. The Planck data analysis shows a preference for values $A_{lens}>1$, the expected value, at more than 95% c.l., and the reason is unknown (systematics or new physics?). Since its correlation with Σ strongly weakens the cosmological constraints on neutrino masses, we expect the scenario with extra A_{lens} parameter to yield more conservative results.

Capozzi et al., Phys. Rev. D **95**, 096014 (2017), arXiv:1703.04471

CMB constraints on the total neutrino mass and their ordering

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3	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI}	< 1.08	< 1.08	-0.1
8	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

We implement separately the NO and IO options in the code used for the analysis, so the masses m_i entering in the definition of Σ obey the δm^2 and Δm^2 constraints. The obtained posterior probability functions $p(\Sigma)$ in NO and IO, are transformed into $\chi^2(\Sigma)$ functions by applying the standard Neyman construction and the Feldman-Cousins method. The main cosmological fit results, obtained in this way, are summarized in the table, in terms of upper bounds (at 2σ level) on the sum of neutrino masses Σ for NO and IO.

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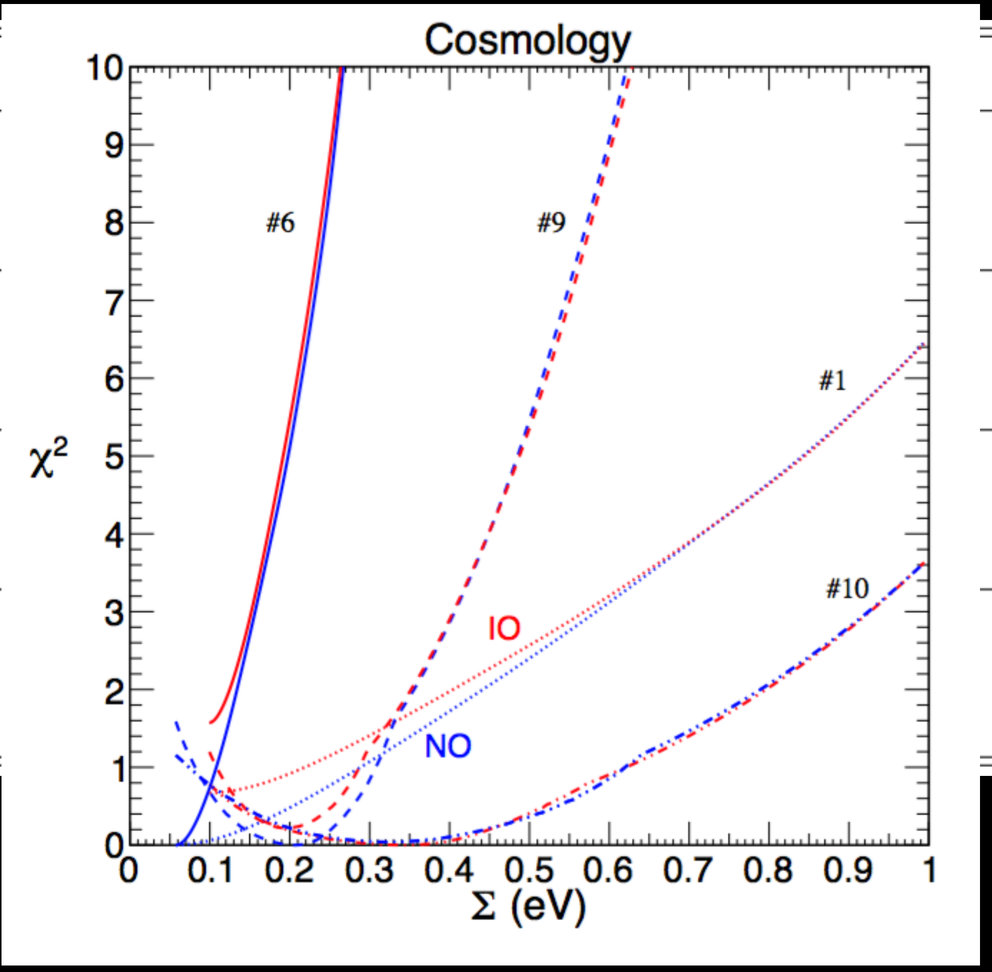
CMB constraints on the total neutrino mass and their ordering

#	Model	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
1	$\Lambda\mathrm{CDM} + \Sigma$	< 0.80	0.7
2	$\Lambda\mathrm{CDM} + \Sigma$	< 0.63	0.2
3	$\Lambda\mathrm{CDM} + \Sigma$	< 0.23	1.2
4	$\Lambda\mathrm{CDM} + \Sigma$	< 0.48	0.6
5	$\Lambda\mathrm{CDM} + \Sigma$	< 0.47	0.3
6	$\Lambda\mathrm{CDM} + \Sigma$	< 0.20	1.6
7	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	< 1.08	-0.1
8	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	< 0.93	0.0
9	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	< 0.46	0.2
10	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	< 1.03	0.0
11	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	< 0.89	0.1
12	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	< 0.32	0.3



For any scenario and combination of cosmological datasets, our CMB fit leads to different best-fit values for Σ, now in the physical region, and an associated values of χ^2_{min} in NO and IO. The value of $\Delta\chi^2_{\mathrm{IO-NO}}$ correctly quantifies the overall preference of the fitted cosmological dataset for one mass ordering. We have also verified that, for any given cosmological data set, the resulting $\chi^2(\Sigma)$ curves for NO and IO converge for increasing Σ as they should (up to residual numerical artifacts at the level of $\delta\chi^2 < 0.1$).

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CMB constraints on the total neutrino mass and their ordering

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
1	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	$\Lambda\mathrm{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT + τ_{HFI}	< 1.08	< 1.08	-0.1
8	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

Although we can see, as expected, a weak sensitivity of cosmological data to the mass ordering, the normal ordering is generally preferred.

There are a few cases where $\Delta\chi^2_{\mathrm{IO-NO}}$ is either negligible or slightly negative, corresponding to the extended and conservative scenarios in which the A_{lens} parameter is varying. In fact, in these cases with A_{lens} free, the bounds are largely weakened, up to a factor of ~2, so the $\chi^2(\Sigma)$ curves are expected to converge.

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CMB constraints on the total neutrino mass and their ordering

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
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12	$\Lambda\mathrm{CDM} + \Sigma + A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

Moreover, the overall preference for NO from cosmological data exceeds 1σ when using the BAO data, and they are associated with the strongest constraints on the sum of neutrino masses ($\Sigma < 0.2$ eV at 2σ).

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CMB constraints on the total neutrino mass and their ordering

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
1	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
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12	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

By combining the cosmology with oscillation (updated with the latest results as available at the beginning of 2017) and non-oscillation ($0\nu\beta\beta$ decay bounds from the KamLAND-Zen experiment) data,

we find the global preference for NO at the typical level of $\Delta\chi^2 \simeq 4$ (i.e., 2σ).

#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	4.3	3.8	4.4	4.2	3.9	$\boxed{4.4}$	$\boxed{3.6}$	3.7	3.8	3.7	3.8	3.9

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Mass ordering

Oscillation data we considered are:

- the latest results from the long-baseline accelerator experiments T2K and NOvA;
- the latest far/near spectral ratio from the reactor neutrino experiment Daya Bay;
- the most recent atmospheric neutrino data from the Super-Kamiokande (SK) phase IV.

Performing our oscillation data analysis, we find an overall preference for NO, quantified by the χ^2 difference:

$$\Delta\chi^2_{\mathrm{IO-NO}} = 3.6 \text{ (all oscill. data)}$$

The values below are not always equal to the algebraic sum of the $\Delta\chi^2$ contributions, since the best-fit points may be slightly readjusted in NO and IO in the global combination.

By combining the cosmology with oscillation (updated with the latest results as available at the beginning of 2017) and non-oscillation ($0\nu\beta\beta$ decay bounds from the KamLAND-Zen experiment) data,

we find the global preference for NO at the typical level of $\Delta\chi^2 \simeq 4$ (i.e., 2σ).

#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	4.3	3.8	4.4	4.2	3.9	$\boxed{4.4}$	$\boxed{3.6}$	3.7	3.8	3.7	3.8	3.9

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Mass ordering

Non-oscillation data:

the strongest $m_{\beta\beta}$ limit to date is provided by the KamLAND-Zen experiment with ^{136}Xe. If the three known neutrinos are Majorana fermions, the rare process of $0\nu\beta\beta$ decay is expected to occur with half life T given by:

$$T^{-1} = G\,|M|^2\,m^2_{\beta\beta}$$

We build a general $\chi^2(m_{\beta\beta})$ function by using:

- the experimental $\chi^2(T)$ curve presented by the KamLAND-Zen collaboration
- our conservative evaluation of nuclear matrix elements and their uncertainties.

We get $m_{\beta\beta} < 0.15$ eV at 90% C.L. (<0.18eV at 2σ and <0.27eV at 3σ).

By combining the cosmology with oscillation (updated with the latest results as available at the beginning of 2017) and non-oscillation ($0\nu\beta\beta$ decay bounds from the KamLAND-Zen experiment) data,

we find the global preference for NO at the typical level of $\Delta\chi^2 \simeq 4$ (i.e., 2σ).

#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	4.3	3.8	4.4	4.2	3.9	4.4	3.6	3.7	3.8	3.7	3.8	3.9

Capozzi et al., Phys. Rev. D **95**, 096014 (2017), arXiv:1703.04471

Constraints on the absolute neutrino mass

We can now see which are the constraints on the absolute mass observables (Σ, $m_{\beta\beta}$) in the (sub)eV range, and the implications for the discovery potential of β-decay searches (for example for the experiment KATRIN, designed to probe the range m_{β}>0.2 eV), obtained by combining the χ^2 from oscillation data with the χ^2 from $0\nu\beta\beta$ and then with the χ^2 from cosmological data.
For the sake of brevity, we consider only two representative cosmological data sets, #10 and #6, that lead to conservative and aggressive bounds on Σ, respectively.

#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	4.3	3.8	4.4	4.2	3.9	4.4	3.6	3.7	3.8	3.7	3.8	3.9

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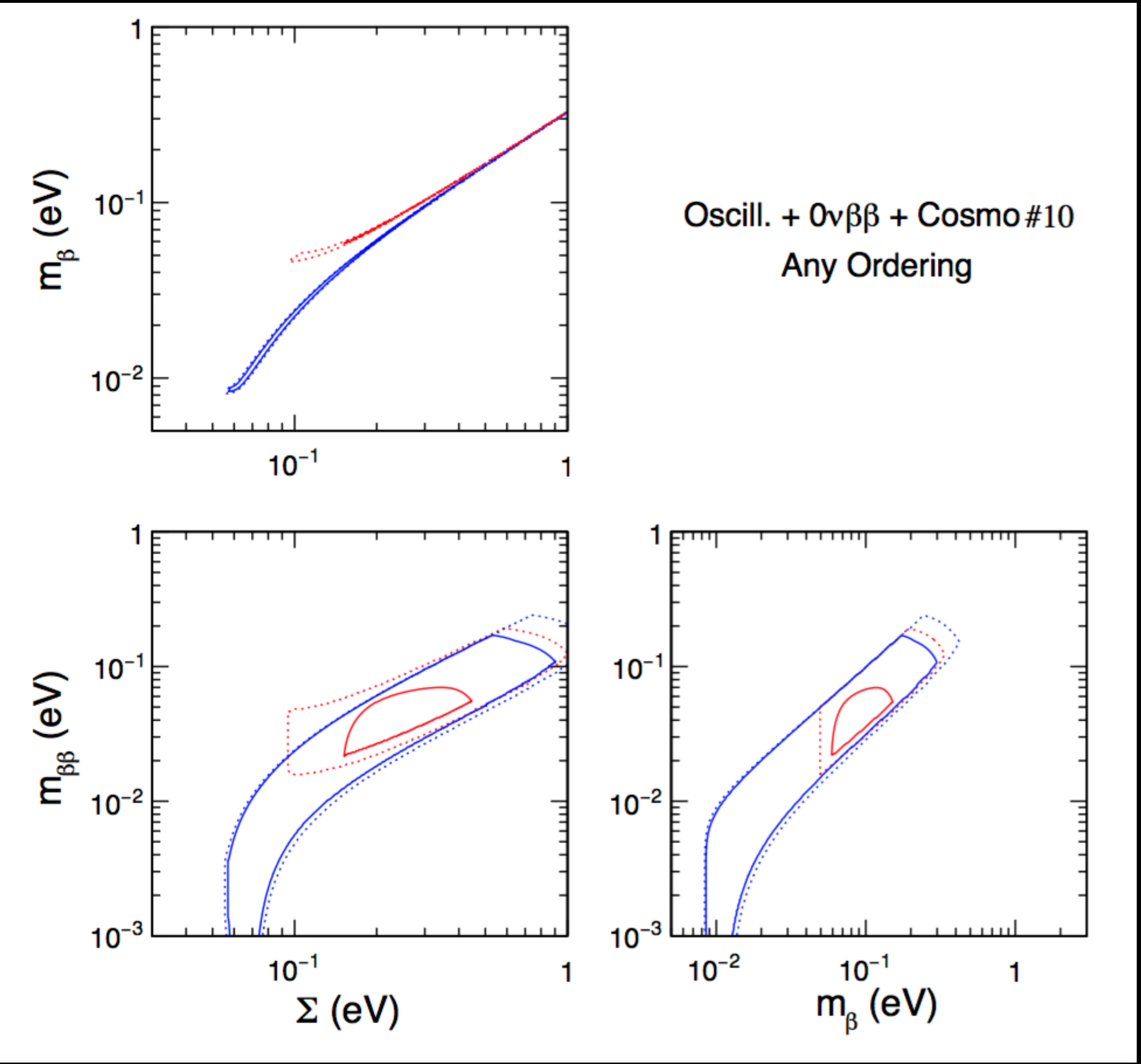
Constraints on the absolute neutrino mass



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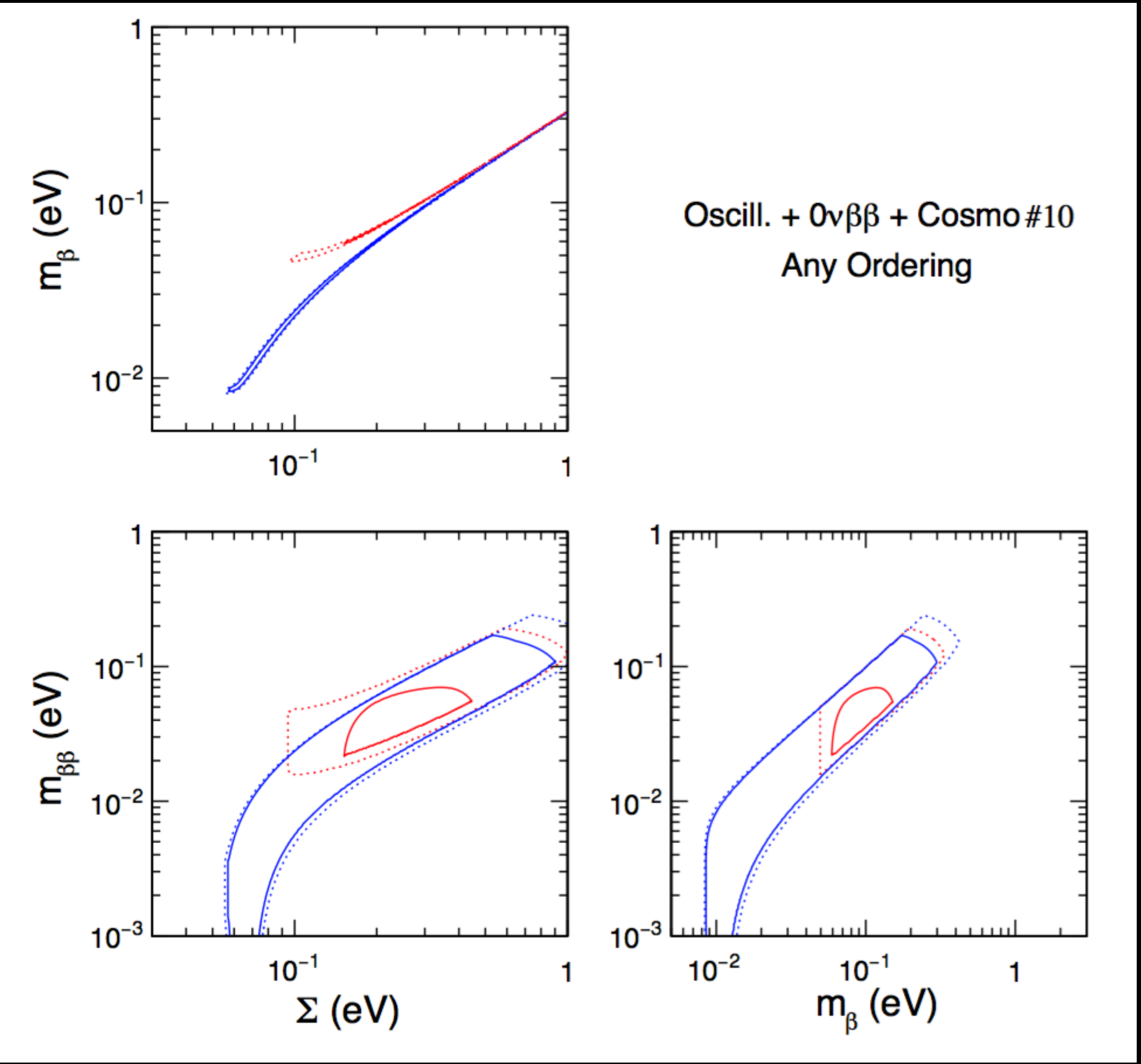
In these plots are shown the constraints in terms of 2σ (solid) and 3σ (dotted) allowed regions for NO (blue) and IO (red).

In the $(\Sigma, m_{\beta\beta})$ plane, we can see a synergic effect of $0\nu\beta\beta$ and cosmological data in setting a joint 2σ bound on Σ at the level of 0.9 eV, to be compared with the $0\nu\beta\beta$ bound <0.18eV at 2σ and the cosmological bound <1.04eV at 2σ.

A more subtle synergy emerges from the fact that, for this case where A_{lens} is varying, the $\chi^2(\Sigma)$ function is minimized at ~ 0.3 eV, showing an indication for a total neutrino mass different from zero. Such a (relatively high) best-fit value for Σ implies preferred values $m_{\beta\beta}$ around few × 10^{-2} eV, as apparent for the IO region allowed at 2σ. This relatively small IO 2σ region illustrates qualitatively how the constraints on $(\Sigma, m_{\beta\beta})$ would appear in the presence of a cosmological measurement (rather than of just upper bounds) for Σ.

Constraints on the absolute neutrino mass



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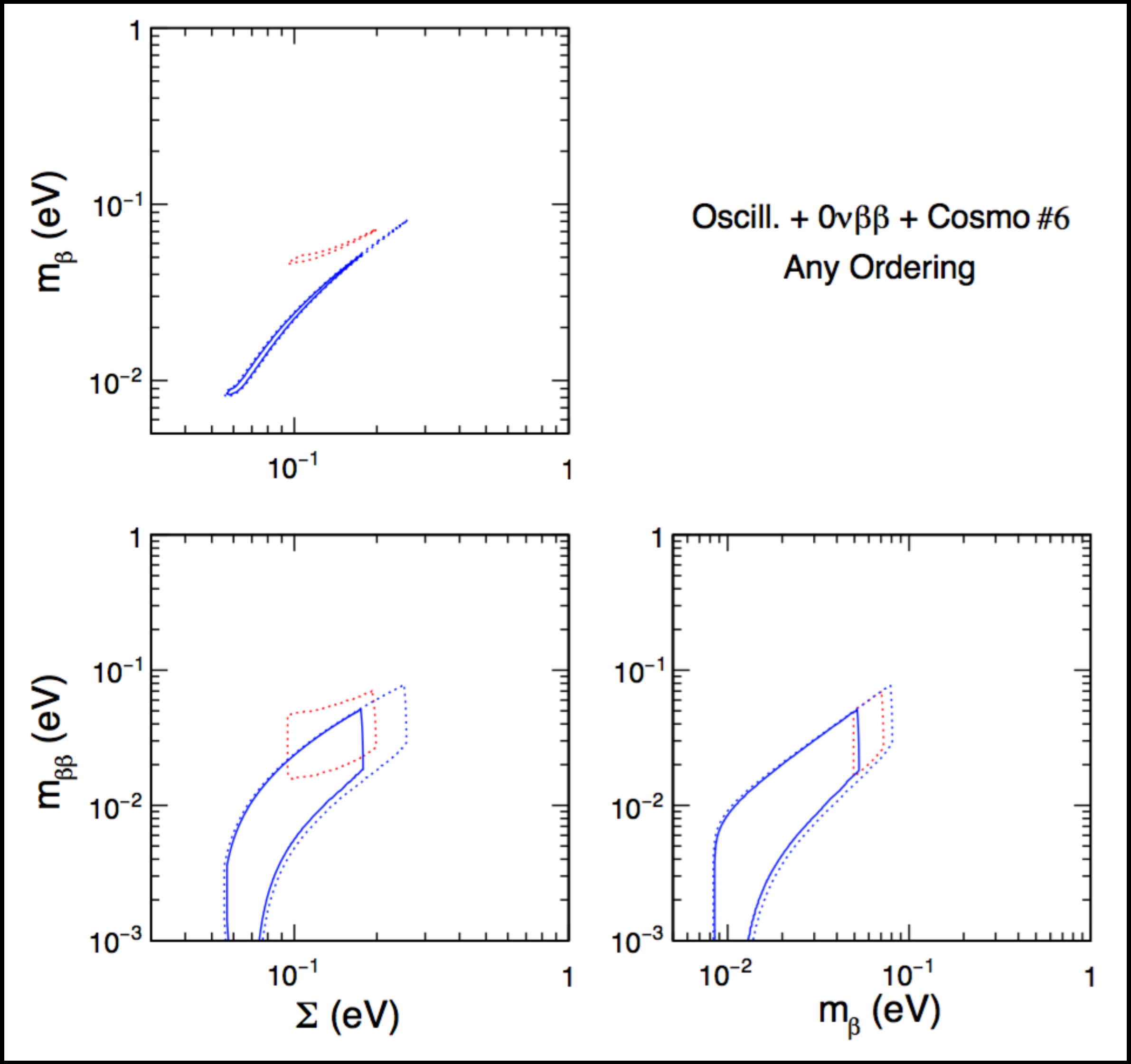
The allowed values of m_β extend up to ~ 0.3 eV (2σ) and ~ 0.4 eV (3σ), in the range testable by KATRIN; however, a large fraction of the m_β allowed range, including the preferred IO region at 2σ, is below the 0.2 eV sensitivity goal of this experiment.

In these plots are shown the constraints in terms of 2σ (solid) and 3σ (dotted) allowed regions for NO (blue) and IO (red).

Constraints on the absolute neutrino mass



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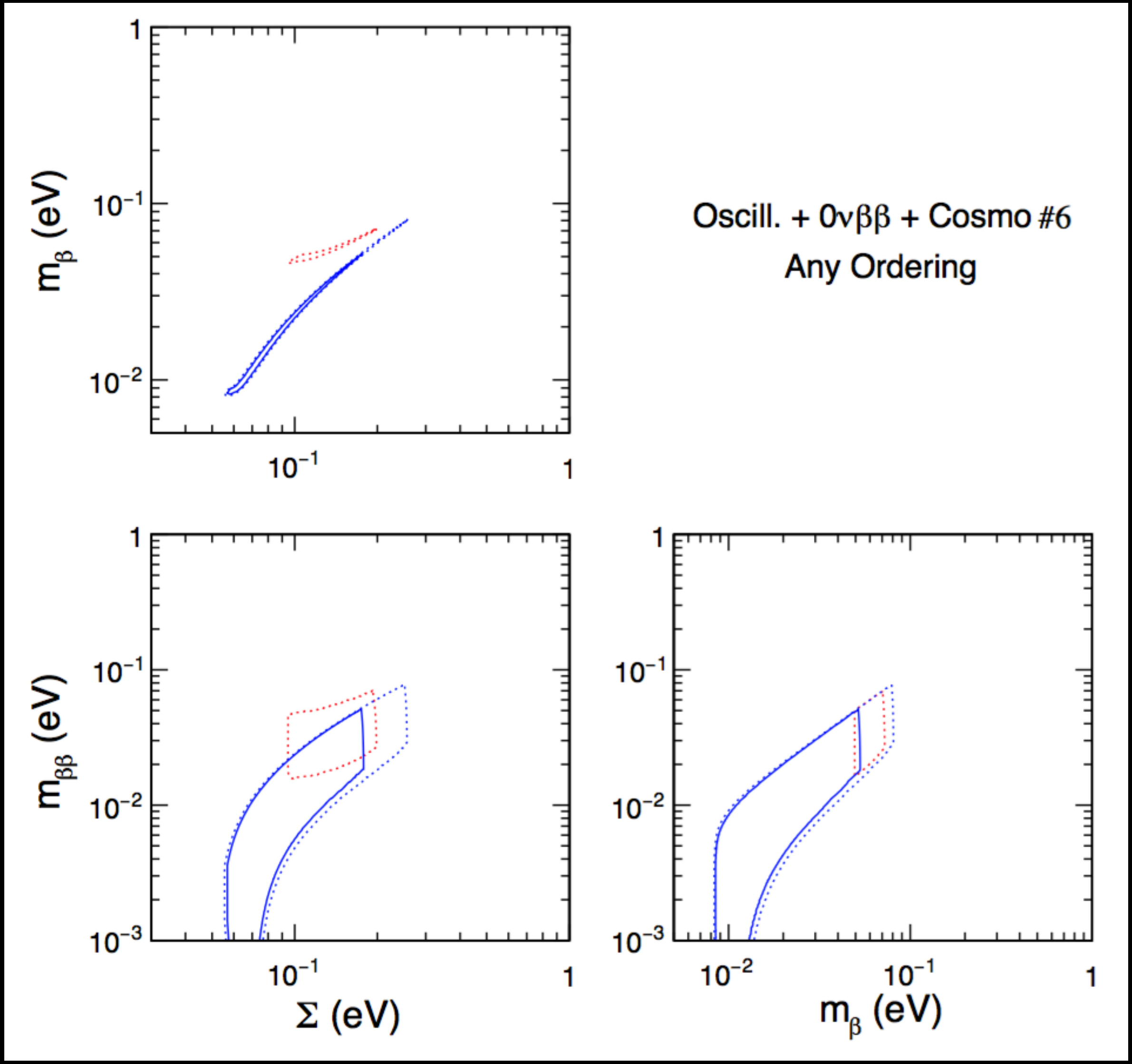
In these plots are shown the constraints in terms of 2σ (solid) and 3σ (dotted) allowed regions for NO (blue) and IO (red).

In the $(\Sigma, m_{\beta\beta})$ plane, in this most constraining cosmological case , the allowed bands are almost vertically cut by the upper bounds on Σ from cosmological data only, with no significant contribution from 0νββ constraints. Indeed, the allowed values of $m_{\beta\beta}$ are well below the 0νββ bounds. Moreover, there is no region allowed at 2σ for IO, since the the global $\Delta\chi^2_{IO-NO}$ exceeds 4 units.

Constraints on the absolute neutrino mass



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In this case, the upper bound on Σ is very strong, and so is the bound on m_β. Indeed, in the (Σ, m_β) plane, the two allowed branches for NO and IO are completely disconnected and could, in principle, be conclusively discriminated via precise measurements of Σ and m_β. Unfortunately, the values of m_β required by such test are entirely below the KATRIN sensitivity.

In these plots are shown the constraints in terms of 2σ (solid) and 3σ (dotted) allowed regions for NO (blue) and IO (red).

The effective number of relativistic degrees of freedom

The relativistic neutrinos contribute to the present energy density of the Universe:

$$\rho_{rad} = \rho_\gamma + \rho_\nu = g_\gamma \left(\frac{\pi^2}{30}\right) T_\gamma^4 + g_\nu \left(\frac{\pi^2}{30}\right)\left(\frac{7}{8}\right) T_\nu^4$$

$$\rho_{rad} = \left(1 + \left(\frac{7}{8}\right)\left(\frac{4}{11}\right)^{\frac{4}{3}}\left(\frac{g_\nu}{g_\gamma}\right)\right)\rho_\gamma$$

We can introduce the effective number of relativistic degrees of freedom:

$$\rho_{rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right]\rho_\gamma$$

The expected value is $N_{eff} = 3.046$, if we assume standard electroweak interactions and three active massless neutrinos. The 0.046 takes into account effects for the non-instantaneous neutrino decoupling and neutrino flavour oscillations (Mangano et al. hep-ph/0506164).

The effective number of relativistic degrees of freedom

If we measure a Neff>3.046, we are in presence of extra, dark radiation. This extra radiation, essentially, increases the expansion rate H:

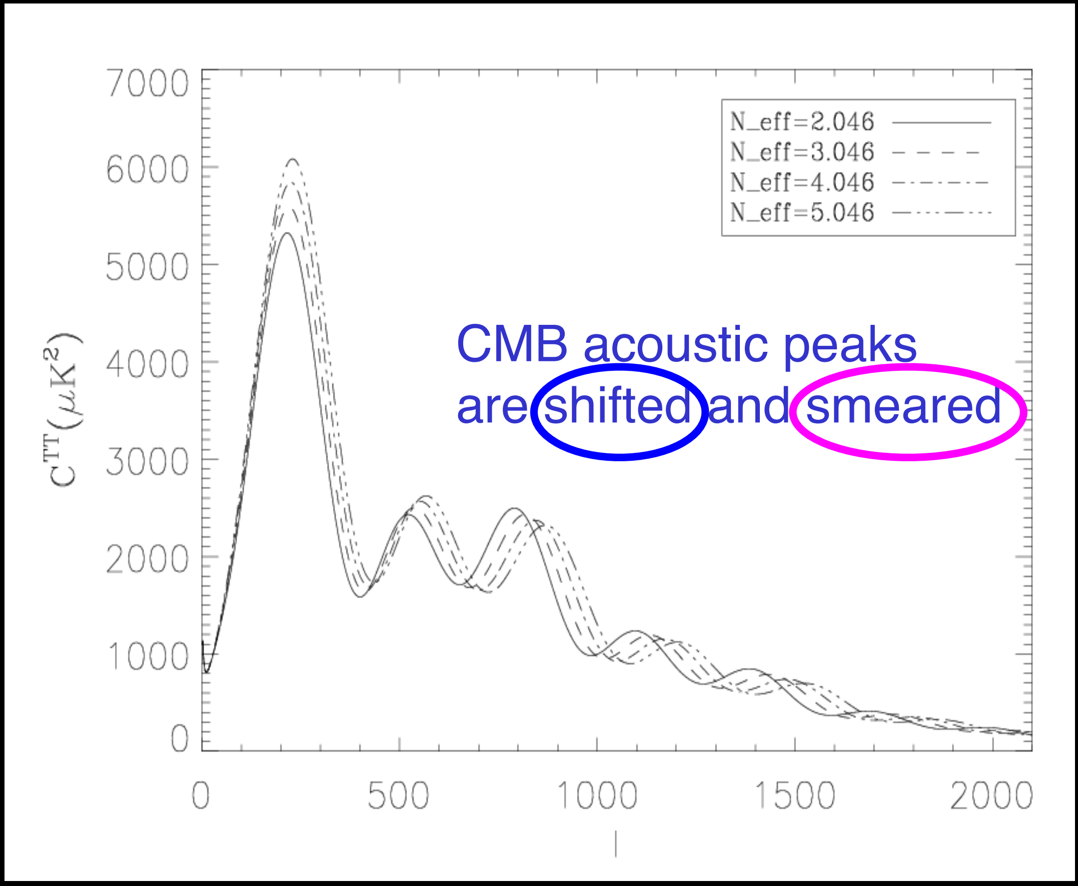
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left(\frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

and it decreases the sound horizon at recombination,

$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}$$

and the diffusion distance (damping scale):

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H}\left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)}\right]$$



CMB constraints on the neutrino effective number

Constraints at 95% cl.

	Planck	Planck pol	Planck +BAO	Planck pol +BAO	Planck +H070p6	Planck Pol +H070p6	Planck +H073p0	Planck Pol +H073p0
$\Omega_c h^2$	$0.1205^{+0.0080}_{-0.0077}$	$0.1192^{+0.0060}_{-0.0057}$	$0.1212^{+0.0077}_{-0.0071}$	$0.1193^{+0.0062}_{-0.0058}$	$0.1222^{+0.0074}_{-0.0073}$	$0.1190^{+0.0062}_{-0.0060}$	$0.1235^{+0.0071}_{-0.0070}$	$0.1215^{+0.0053}_{-0.0054}$
Σm_ν [eV]	< 0.796	< 0.582	< 0.289	< 0.224	< 0.417	< 0.365	< 0.337	< 0.249
N_{eff}	< 3.592	< 3.359	< 3.636	< 3.384	< 3.707	< 3.374	< 3.961	< 3.539
H_0 [km s^{-1} Mpc^{-1}]	$64.9^{+7.2}_{-8,4}$	$65.0^{+4.4}_{-5.0}$	$68.4^{+3.0}_{-2.8}$	$67.4^{+2.4}_{-2.3}$	$68.2^{+4.6}_{-4.7}$	$66.6^{+3.2}_{-3.5}$	$70.5^{+4.2}_{-4.1}$	$68.2^{+2.7}_{-2.8}$
σ_8	$0.781^{+0.091}_{-0.119}$	$0.794^{+0.067}_{-0.085}$	$0.823^{+0.042}_{-0.044}$	$0.823^{+0.037}_{-0.039}$	$0.819^{+0.057}_{-0.062}$	$0.813^{+0.047}_{-0.055}$	$0.835^{+0.047}_{-0.053}$	$0.831^{+0.038}_{-0.043}$
Ω_{m}	$0.351^{+0.104}_{-0.080}$	$0.342^{+0.061}_{-0.046}$	$0.310^{+0.019}_{-0.017}$	$0.315^{+0.017}_{-0.016}$	$0.316^{+0.044}_{-0.043}$	$0.326^{+0.035}_{-0.031}$	$0.298^{+0.034}_{-0.032}$	$0.313^{+0.024}_{-0.024}$
τ	$0.081^{+0.035}_{-0.035}$	$0.086^{+0.031}_{-0.034}$	$0.088^{+0.039}_{-0.038}$	$0.079^{+0.035}_{-0.046}$	$0.088^{+0.044}_{-0.041}$	$0.083^{+0.035}_{-0.035}$	$0.098^{+0.044}_{-0.041}$	$0.091^{+0.034}_{-0.035}$

When varying also N_{eff}, the bounds on the total neutrino mass are less stringent, due to the large degeneracy between Σm_ν and N_{eff}, in order to leave unchanged both the matter-to-radiation equality era and the location of the CMB acoustic peaks.

The neutrino effective number is totally consistent with its standard value 3.046.

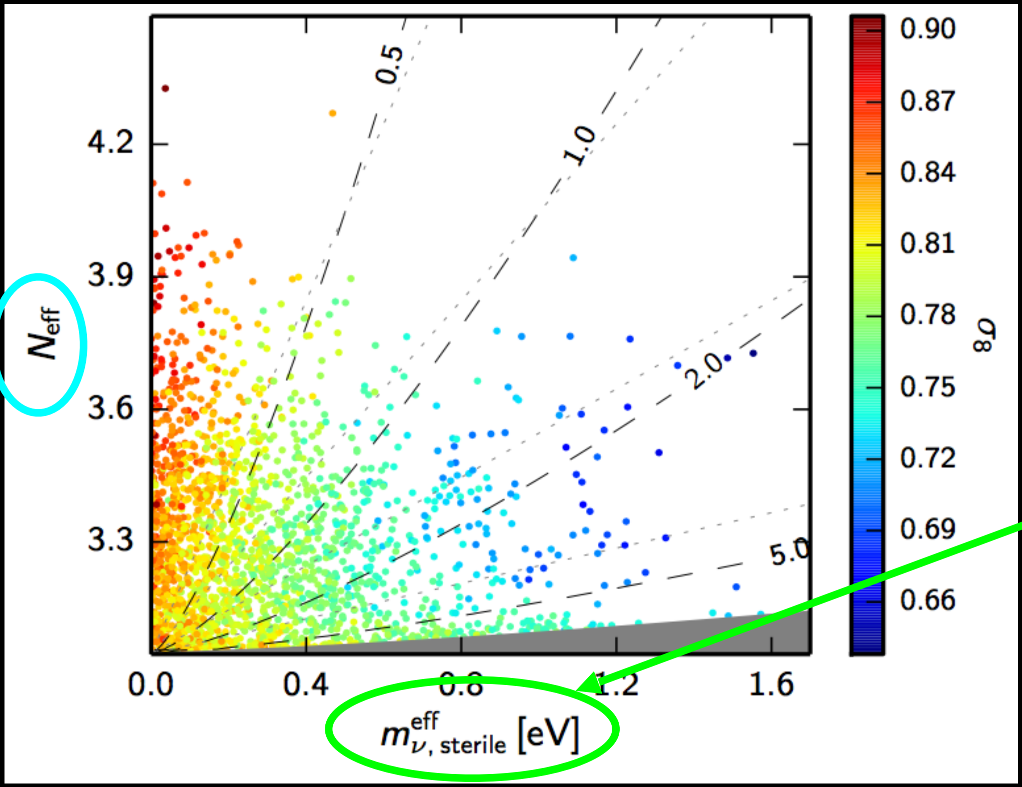
Anyway, there is still the possibility to have some relic components.

Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527

The sterile neutrino

The main candidate to explain the extra dark radiation is a sterile neutrino.
With the CMB we can only constrain the effective sterile neutrino mass, but fixing the model, we can infer also the physical mass of the particle.
The relationship between Neff and meff is model dependent.

Contribution of the sterile neutrino when it is massless.



Contribution of the sterile neutrino when it is massive.

(Planck collaboration 2015)

Thermally distributed

$$m_s^{\rm eff} = (T_s/T_\nu)^3 m_s = (\Delta N_{\rm eff})^{3/4} m_s$$

CMB constraints on the sterile neutrino mass

Constraints at 95% cl.

	Planck	Planck pol	Planck +BAO	Planck pol + BAO	Planck +H070p6	Planck Pol +H070p6	Planck +H073p0	Planck Pol +H073p0
$\Omega_c h^2$	$0.1215^{+0.0090}_{-0.0105}$	$0.1207^{+0.0061}_{-0.0071}$	$0.1214^{+0.0081}_{-0.0081}$	$0.1189^{+0.0068}_{-0.0081}$	$0.1217^{+0.0088}_{-0.0107}$	$0.1205^{+0.0068}_{-0.0077}$	$0.1235^{+0.0090}_{-0.0082}$	$0.1205^{+0.0064}_{-0.0071}$
Σm_ν [eV]	< 0.676	< 0.528	< 0.263	< 0.199	< 0.422	< 0.337	< 0.291	< 0.321
$m_s^{\rm eff}$ [eV]	< 0.972	< 0.820	< 0.449	< 0.694	< 0.822	< 0.773	< 0.462	< 0.630
$N_{\rm eff}$	< 3.648	< 3.401	< 3.762	< 3.405	< 3.705	< 3.445	< 3.961	< 3.434
H_0[km s^{-1} Mpc^{-1}]	$65.7^{+5.7}_{-6.1}$	$65.5^{+3.2}_{-3.7}$	$67.7^{+1.8}_{-1.6}$	$68.7^{+2.8}_{-2.4}$	$67.4^{+4.4}_{-4.2}$	$66.5^{+2.7}_{-2.8}$	$70.0^{+4.6}_{-4.2}$	$67.4^{+2.3}_{-2.1}$
σ_8	$0.762^{+0.095}_{-0.107}$	$0.768^{+0.077}_{-0.087}$	$0.801^{+0.051}_{-0.058}$	$0.806^{+0.048}_{-0.054}$	$0.786^{+0.076}_{-0.083}$	$0.785^{+0.066}_{-0.075}$	$0.818^{+0.064}_{-0.068}$	$0.803^{+0.056}_{-0.062}$
Ω_m	$0.350^{+0.083}_{-0.069}$	$0.347^{+0.054}_{-0.045}$	$0.311^{+0.017}_{-0.017}$	$0.316^{+0.015}_{-0.015}$	$0.328^{+0.051}_{-0.045}$	$0.334^{+0.037}_{-0.034}$	$0.305^{+0.038}_{-0.037}$	$0.323^{+0.023}_{-0.027}$
τ	$0.088^{+0.043}_{-0.041}$	$0.087^{+0.035}_{-0.036}$	$0.095^{+0.041}_{-0.040}$	$0.089^{+0.034}_{-0.034}$	$0.090^{+0.042}_{-0.040}$	$0.087^{+0.035}_{-0.035}$	$0.103^{+0.043}_{-0.044}$	$0.091^{+0.036}_{-0.035}$

When varying also the sterile neutrino mass, the bounds on the total neutrino mass and on the neutrino effective number are less stringent.

The strongest bound we have on the sterile neutrino mass is when considering PlanckTT+lowTEB+BAO.

Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527

Summary:

With the cosmology we can constrain two important neutrino parameters:
- the total neutrino mass, starting to be careful about their ordering;
- the neutrino effective number (and the mass of possible relic components).

The most stringent bound on the sum of neutrino masses is obtained when considering Planck TTTEEE+lowTEB+BAO: $\Sigma m_\nu<0.175$eV. By adding some low redshift priors, in agreement with recent measurements, we can start to exclude the inverted hierarchy. We obtain that $\Sigma m_\nu<0.0993$eV by adding $H_0=73.0\pm2.4$, $\tau=0.05\pm0.01$ and Planck SZ cluster counts. Therefore, we are close to test the neutrino mass hierarchy with existing cosmological probes.

Since data are now very sensitive to the neutrino mass scale, we have to be very careful about the assumptions made on the neutrino hierarchy in cosmology. NO appears to be somewhat favored with respect to IO at the level of 1.9–2.1σ, mainly by neutrino oscillation data (especially atmospheric), corroborated by cosmological data in some cases.

The neutrino effective number is consistent with its standard value 3.046. Anyway, there is still the possibility to have some relic components, as for example a sterile neutrino. The most stringent bound we have on the sterile neutrino mass is when considering PlanckTT+lowTEB+BAO, and it is $m_{eff}<0.449$eV.

Thank you!

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How much these constraints should be improved in the future?

Constraints at 68% cl.

Ground based CMB experiments

$$\sigma(M_\nu) = 3.0 \times 10^2$$
$$\sigma(N_{\rm eff}) = 0.16$$

BICEP3+Keck Array+ Planck

$$\sigma(M_\nu) = 78$$
$$\sigma(N_{\rm eff}) = 0.060$$

AdVActPol+Planck

$$\sigma(M_\nu) = 96$$
$$\sigma(N_{\rm eff}) = 0.076$$

Simons Array + Planck

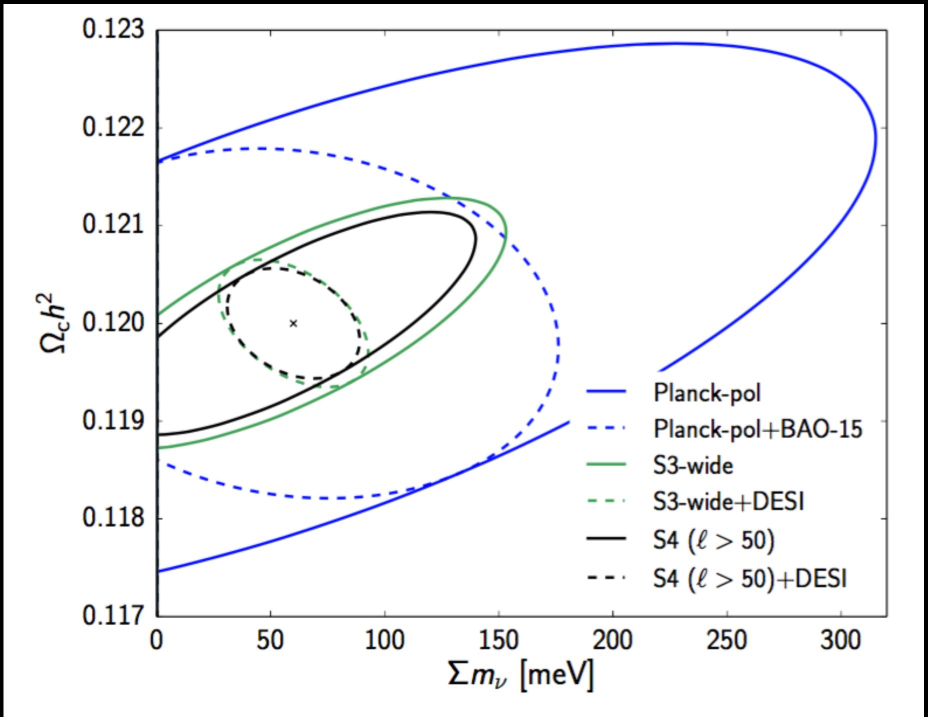
$$\sigma(M_\nu) = 1.0 \times 10^2$$
$$\sigma(N_{\rm eff}) = 0.097$$

SPT-3G+Planck

$$\sigma(M_\nu) = 59$$
$$\sigma(N_{\rm eff}) = 0.048$$

Stage IV

Errard et al, JCAP03(2016)052



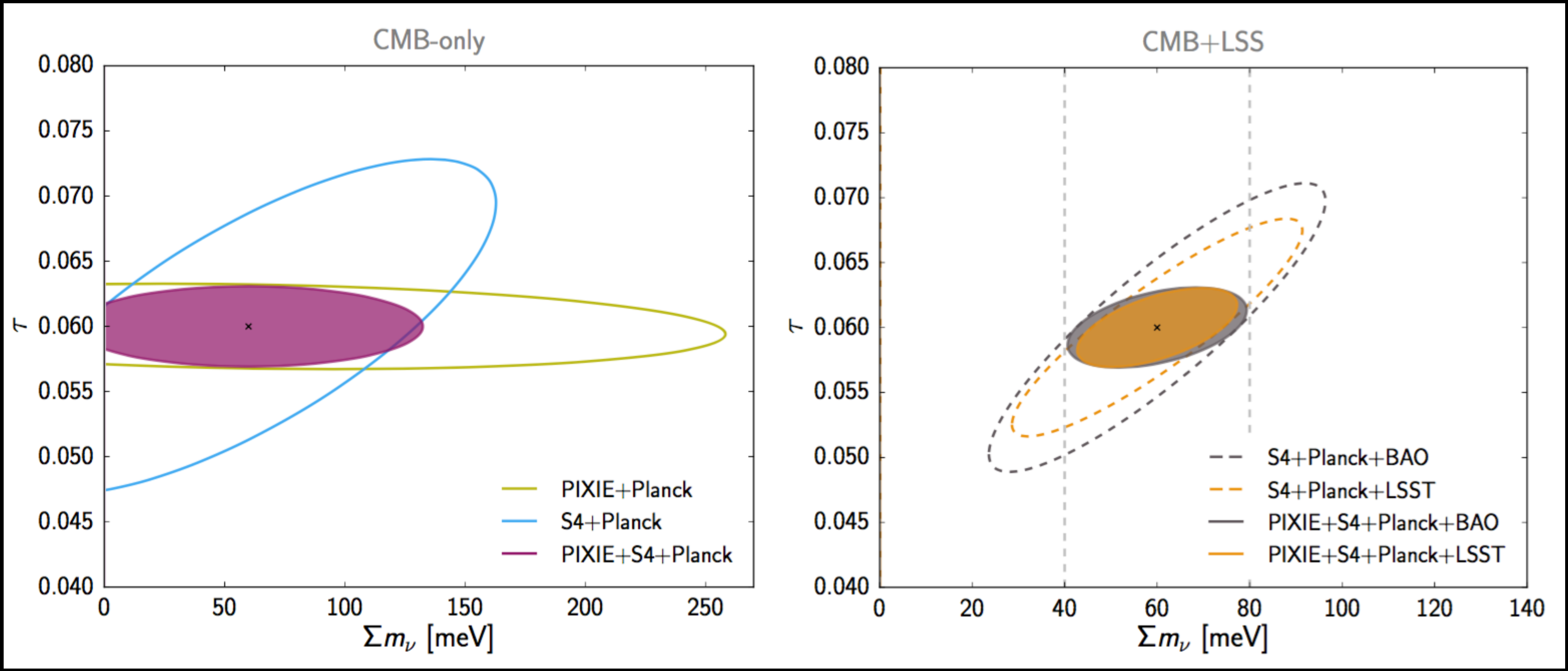
Allison et al, arXiv:1509.04471

Stage IV is, at the moment, the proposal with the highest probability of being realized.

However, it needs large angular scale measurements (as Planck or future experiments) and a perfect a priori knowledge of the foregrounds.

Ground based experiments lack high frequencies so we should be extremely careful with these forecasts.

PIXIE + S4 + Planck



PIXIE alone measures only the optical depth from large-scale polarization, while S4 gets an estimate of both parameters via lensing. A cosmic-variance-limited measurement of τ is reached with PIXIE ($\sigma(\tau)$ = 0.002) when anchoring the amplitude parameter, A_S, with Planck or S4. This τ limit then enables a better neutrino mass measurement, reaching $\sigma(\Sigma m_\nu)$ = 46 meV from CMB alone.

Adding information on the growth of structure and the expansion history at low redshifts, by e.g., BAO from DESI or galaxy shear and clustering from LSST, tightens the m_ν bound even further, with $\sigma(\Sigma m_\nu)$ ≈ 12 meV and a 5σ detection of the neutrino mass.

Calabrese et al. arXiv:1611.10269

CORE

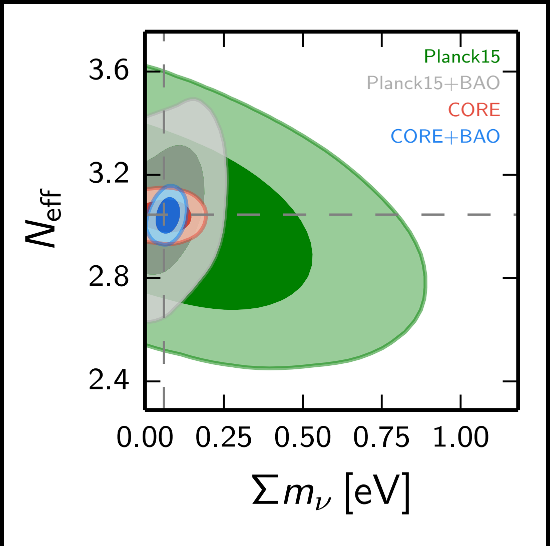
Parameter	Description	Current results (Planck 2015+Lensing)	CORE expected uncertainties
ΛCDM			
$\Omega_b h^2$	Baryon Density	$\Omega_b h^2 = 0.02226 \pm 0.00016$ (68 % CL) [12]	$\sigma(\Omega_b h^2) = \mathbf{0.000037}$ {4.3}
$\Omega_c h^2$	Cold Dark Matter Density	$\Omega_c h^2 = 0.1193 \pm 0.0014$ (68 % CL) [12]	$\sigma(\Omega_c h^2) = \mathbf{0.00026}$ {5.4}
n_s	Scalar Spectral Index	$n_s = 0.9653 \pm 0.0048$ (68 % CL) [12]	$\sigma(n_s) = \mathbf{0.0014}$ {3.4}
τ	Reionization Optical Depth	0.063 ± 0.014 (68 % CL) [12]	$\sigma(\tau) = \mathbf{0.002}$ {7.0}
H_0 [km/s/Mpc]	Hubble Constant	$H_0 = 67.51 \pm 0.64$ (68 % CL) [12]	$\sigma(H_0) = \mathbf{0.11}$ {5.8}
σ_8	r.m.s. mass fluctuations	$\sigma_8 = 0.8150 \pm 0.0087$ (68 % CL) [12]	$\sigma(\sigma_8) = \mathbf{0.0011}$ {7.9}
Extensions			
Ω_k	Curvature	$\Omega_k = -0.0037^{+0.0083}_{-0.0069}$ (68 % CL) [12]	$\sigma(\Omega_k) = \mathbf{0.0019}$ {4}
$N_{\rm eff}$	Relativistic Degrees of Freedom	$N_{\rm eff} = 2.94 \pm 0.20$ (68 % CL) [12]	$\sigma(N_{\rm eff}) = \mathbf{0.041}$ {4.9}
M_ν	Total Neutrino Mass	$M_\nu < 0.315\,\mathrm{eV}$ (68 % CL) [12]	$\sigma(M_\nu) = \mathbf{0.043}$ eV {7.3}
(m_s^{eff}, N_s)	Sterile Neutrino Parameters	$(m_s^{eff} < 0.33eV, N_s < 3.24)$ (68 % CL) [12]	$\sigma(m_s^{eff}, N_s) = (\mathbf{0.037}eV, \mathbf{0.053})$ {8.9, 4.5}
Y_p	Primordial Helium abundance	$Y_p = 0.247 \pm 0.014$ (68 % CL) [12]	$\sigma(Y_p) = \mathbf{0.0029}$ {4.8}
Y_p	Primordial Helium (free N_{eff})	$Y_p = 0.259^{+0.020}_{-0.017}$ (68 % CL) [12]	$\sigma(Y_p) = \mathbf{0.0056}$ {3.2}
τ_n [s]	Neutron Life Time	$\tau_n = 908 \pm 69$ (68 % CL) [164]	$\sigma(\tau_n) = \mathbf{13}$ {5.3}
w	Dark Energy Eq. of State	$w = -1.42^{+0.25}_{-0.47}$ (68 % CL) [12]	$\sigma(w) = \mathbf{0.12}$ {3}
T_0	CMB Temperature	Unconstrained [12]	$\sigma(T_0) = \mathbf{0.018}$ K
p_{ann}	Dark Matter Annihilation	$p_{ann} < 3.4 \times 10^{-28}$ $cm^3/GeV/s$ (68 % CL) [12]	$\sigma(p_{ann}) = \mathbf{5.3 \times 10^{-29}}$ $cm^3/GeV/s$ {6.4}
$g_{\rm eff}^4$	Neutrino self-interaction	$g_{\rm eff}^4 < 0.22 \times 10^{-27}$	$\sigma(g_{\rm eff}^4) = 0.34 \times 10^{-28}$ {6.4}
α/α_0	Fine Structure Constant	$\alpha/\alpha_0 = 0.9990 \pm 0.0034$ (68 % CL)	$\sigma(\alpha/\alpha_0) = \mathbf{0.0007}$ {4.8}
$\Sigma_0 - 1$	Modified Gravity	$\Sigma_0 - 1 = 0.10 \pm 0.11$ (68 % CL) [53]	$\sigma(\Sigma_0 - 1) = \mathbf{0.044}$ {2.5}
$A_{2s1s}/8.2206$	Recombination 2 photons rate	$A_{2s1s}/8.2206 = 0.94 \pm 0.07$ (68 % CL) [12]	$\sigma(A_{2s1s}/8.2206) = \mathbf{0.015}$ {4.7}
$\Delta(z_{reio})$	Reionization Duration	$\Delta(z_{reio}) < 2.26$ (68 % CL) [35]	$\sigma(\Delta z_{reio}) = \mathbf{0.58}$ {3.9}

Numbers in curly brackets {...} give the improvement in the parameter constraint when moving from Planck 2015 to CORE-M5, defined as the ratio of the uncertainties $\sigma^{\rm Planck}/\sigma^{\rm CORE}$.

Di Valentino et al., CORE collaboration, arXiv:1612.00021.

Constraints at 68% cl.

CORE



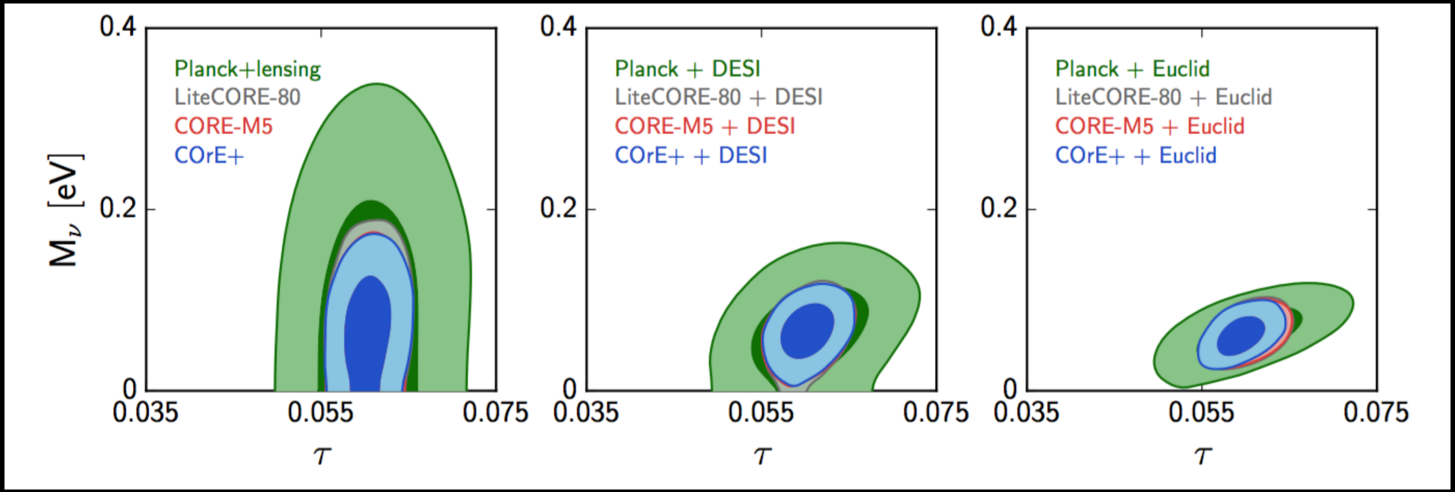
CORE alone should reach 0.05 eV sensitivity on the sum of neutrino masses, and 0.015 eV if combined with LSS experiments.

Moreover, it should constrain the dark radiation with a sensitivity of 0.04.

Parameter	Planck, TEP	LiteCORE-80, TEP	LiteCORE-120, TEP	CORE-M5, TEP	COrE+, TEP
$\Delta N_{\mathrm{eff}}^{\mathrm{massless}}$	< 0.19 (68%CL)	< 0.062 (68%CL)	< 0.045 (68%CL)	< 0.040 (68%CL)	< 0.036 (68%CL)
M_ν (meV)	< 310 (68%CL)	77^{+37}_{-59}	72^{+34}_{-56}	71^{+34}_{-54}	70^{+35}_{-53}

Parameter	Planck, TEP + DESI	LiteCORE-80, TEP + DESI	LiteCORE-120, TEP + DESI	CORE-M5, TEP + DESI	COrE+, TEP + DESI
$\Delta N_{\mathrm{eff}}^{\mathrm{massless}}$	< 0.15 (68%CL)	< 0.061 (68%CL)	< 0.042 (68%CL)	< 0.038 (68%CL)	< 0.033 (68%CL)
M_ν (meV)	85^{+41}_{-50}	72 ± 24	71^{+23}_{-20}	70^{+23}_{-20}	65^{+22}_{-20}

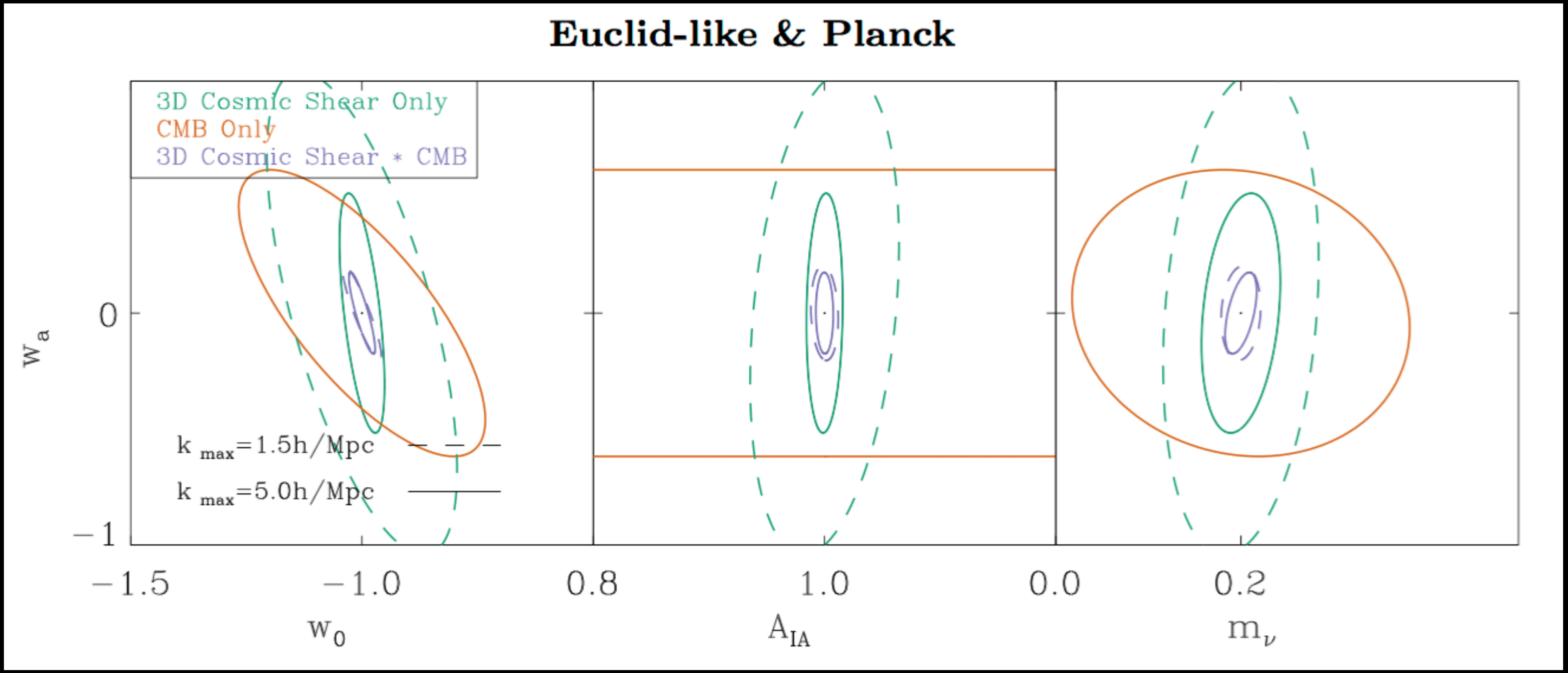
Parameter	Planck, TEP + DESI + Euclid	LiteCORE-80, TEP + DESI + Euclid	LiteCORE-120, TEP + DESI + Euclid	CORE-M5, TEP + DESI + Euclid	COrE+, TEP + DESI + Euclid
$\Delta N_{\mathrm{eff}}^{\mathrm{massless}}$	< 0.111 (68%CL)	< 0.054 (68%CL)	< 0.040 (68%CL)	< 0.038 (68%CL)	< 0.032 (68%CL)
M_ν (meV)	84^{+25}_{-28}	71^{+16}_{-18}	68^{+15}_{-18}	68^{+15}_{-17}	67^{+14}_{-17}



Di Valentino et al., CORE collaboration, arXiv:1612.00021.

EUCLID+Planck

All previous forecast assumes linear or mildly non-linear perturbation theory (kmax=1.5 hMpc^-1). But if future developments in treatment of linearities could let us to move to even more non linear regime (kmax=5 hMpc^-1) we may learn a lot more.

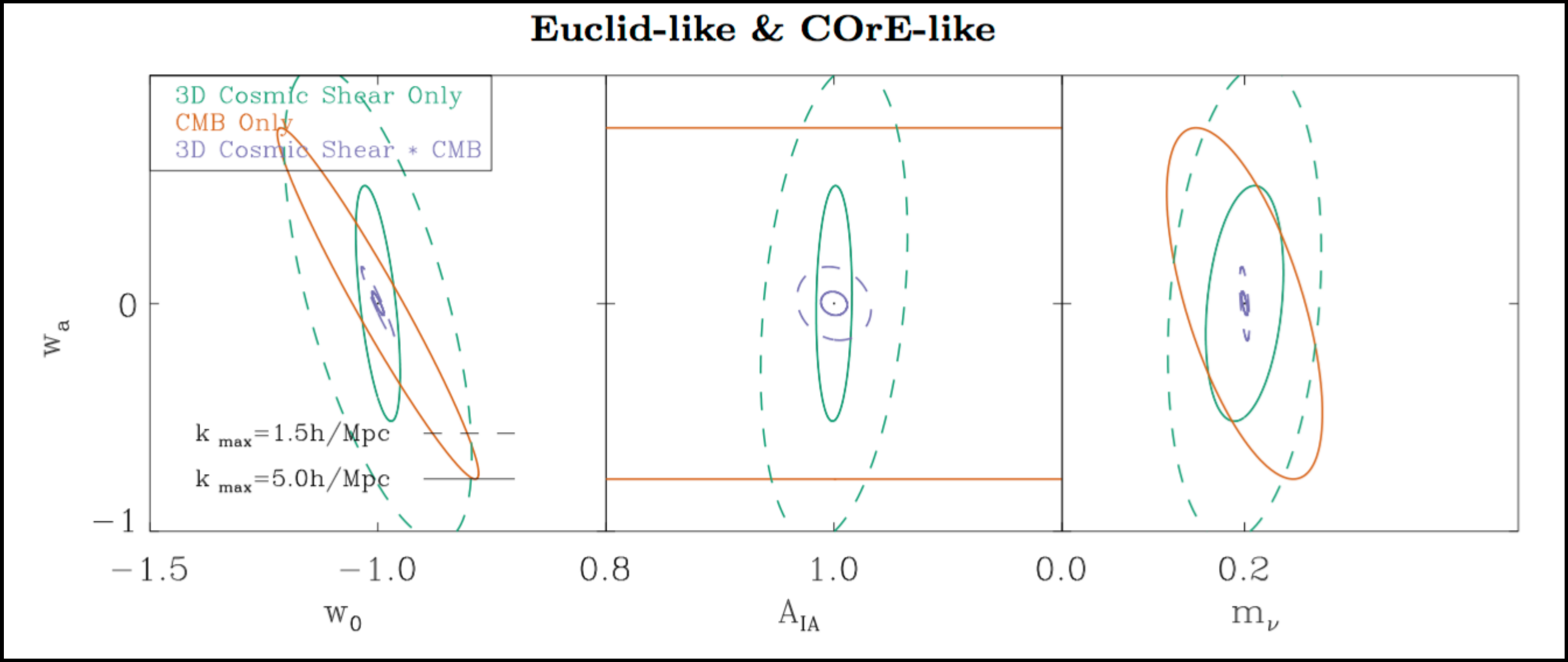


Kitching, Heavens, Das, arXiv:1408.7052

Planck+Euclid can reach 0.015 eV sensitivity on the sum of neutrino masses.

EUCLID+CORE

All previous forecast assumes linear or mildly non-linear perturbation theory (kmax=1.5 hMpc^-1). But if future developments in treatment of linearities could let us to move to even more non linear regime (kmax=5 hMpc^-1) we may learn a lot more.



Kitching, Heavens, Das, arXiv:1408.7052

CORE+Euclid can reach 0.003 eV sensitivity on the sum of neutrino masses.

CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+tau6	Planck pol +BAO+SZ+tau5	Planck pol H073p0+SZ+tau6	Planck pol H073p0+SZ+tau5	Planck pol+BAO +H073p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.116	< 0.112	< 0.107	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.9^{+1.3}_{-1.4}$	$67.8^{+1.2}_{-1.4}$	$67.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$0.818^{+0.022}_{-0.023}$	$0.824^{+0.022}_{-0.023}$	$0.819^{+0.021}_{-0.022}$	$0.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

The reionization optical depth is the most important parameter in constraining the total neutrino mass. In fact, also by removing the H0 prior would result in a bound of Σm_ν <0.0926 eV at 90% CL.

Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527