Neutrinos and Cosmology

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Introduction to cosmology

The Universe originates from a hot Big Bang. The primordial plasma in thermodynamic equilibrium cools with the expansion of the Universe. It passes through the phase of recombination, where electrons and protons combine into hydrogen atoms, and decoupling, in which the Universe becomes transparent to the motion of photons.

The Cosmic Microwave Background (CMB) is the radiation coming from the recombination, emitted about 13 billion years ago, just 400,000 years after the Big Bang.

The CMB provides an unexcelled probe of the early Universe and today it is a black body a temperature $T=2.726\text{K}$. 
An important tool of research in cosmology is the angular power spectrum of CMB temperature anisotropies.

\[
\left\langle \frac{\Delta T}{T} (\mathbf{\gamma}_1) \frac{\Delta T}{T} (\mathbf{\gamma}_2) \right\rangle = \frac{1}{2\pi} \sum_{\ell} (2\ell + 1) C_{\ell} P_{\ell} (\mathbf{\gamma}_1 \cdot \mathbf{\gamma}_2)
\]
Introduction to CMB

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

We can extract 4 independent angular spectra from the CMB:

- Temperature
- Cross Temperature Polarization type E
- Polarization type E (density fluctuations)
- Polarization type B (gravitational waves)
From one side we have very accurate theoretical predictions on their angular power spectra while on the other side we have extremely precise measurements, culminated with the recent 2018 legacy release from the Planck satellite experiment.
Planck satellite experiment

- Frequency range of 30GHz to 857GHz;
- Orbit around L2;
- Composed by 2 instruments:
  - LFI → 1.5 meters telescope; array of 22 differential receivers that measure the signal from the sky comparing with a black body at 4.5K.
  - HFI → array of 52 bolometers cooled to 0.1K.
Planck satellite experiment

The theoretical spectra in light blues are computed from the best-fit base-LCDM theoretical spectrum fit to the Planck TT,TE,EE+lowE+lensing likelihood.

Residuals with respect to this theoretical model are shown in the lower panel in each plot.
The Cosmic Neutrino Background

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.
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:

\[ T_{\text{dec}} \approx 1 \text{MeV} \]

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:

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

With a number density of:

\[
n_f = \frac{3 \, \zeta(3)}{4 \, \pi^2} \, g_f \, T_f^3 \rightarrow n_{\nu_k, \bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 \text{cm}^{-3}
\]
Total neutrino mass

If the total neutrino mass is of the order of 1 eV, neutrinos are radiation at the time of equality, and non-relativistic matter today.

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

When neutrinos are relativistic, will contribute to the radiation content of the universe, through the effective number of relativistic degrees of freedom $N_{\text{eff}}$.

When they become non-relativistic, will only cluster at scales larger than their free streaming scale, suppressing therefore structure formation at small scales, and affecting the large scale structures.
When they become non-relativistic, will only cluster at scales larger than their free streaming scale, suppressing therefore structure formation at small scales, and affecting the large scale structures.
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.

Varying their total mass we vary:

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

\[ \omega_M = \omega_b + \omega_{\text{CDM}} + \left( \Sigma m_\nu \right) / 93.14 \text{ eV} \]
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.

![Graph showing the impact of neutrino mass on the CMB spectrum.](image)
Total neutrino mass

$\Sigma m_\nu = 0 \text{ eV}$
$\Sigma m_\nu = 0.3 \text{ eV}$
$\Sigma m_\nu = 0.6 \text{ eV}$
$\Sigma m_\nu = 0.9 \text{ eV}$

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
Total neutrino mass

The shape of the matter power spectrum is the key observable for constraining the neutrino masses with cosmological methods. This is defined as the two-point correlation function of the non-relativistic matter fluctuation in Fourier space:

\[ P(k, z) = \langle |\delta_m(k, z)|^2 \rangle \]

\[ \delta_m = \frac{\sum_i \bar{\rho}_i \delta_i}{\sum_i \bar{\rho}_i} \]
Imposing a flat Universe

Total neutrino mass

\[ \Sigma m_\nu = 0 \text{ eV} \]
\[ \Sigma m_\nu = 0.3 \text{ eV} \]
\[ \Sigma m_\nu = 0.6 \text{ eV} \]
\[ \Sigma m_\nu = 0.9 \text{ eV} \]
From Planck 2018 we have a very important upper limit on the total neutrino mass.
If primary CMB anisotropies form at recombination, when the CMB was at a temperature of $T \sim 0.3$ eV, and a neutrino with a mass of $\sim (0.26/3) \sim 0.09$ eV is still relativistic at that epoch, how can we have with CMB data this amazing upper limit?

$$\sum m_\nu < 0.26 \text{ eV} \quad (95\% \text{, Planck TT,TE,EE+lowE})$$
The gravitational effects of intervening dark matter fluctuations bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB.

This affects the CMB anisotropy angular spectrum by smearing the high $l$ peaks.
The CMB lensing

A simulated patch of CMB sky – **before dark matter lensing**
A simulated patch of CMB sky - after dark matter lensing
Massive neutrinos

\[ \sum m_\nu < 0.26 \text{ eV} \quad (95 \%, \text{Planck TT,TE,EE+lowE}) \]


These strong limits are completely due to the CMB lensing, indicating that we have a clear detection of the lensing signal in the CMB spectra.

In fact, massive neutrinos practically do not form structure. More massive is the neutrino less structure we have, less will be the CMB lensing. So a larger signal of lensing means a smaller neutrino mass.
The inclusion of additional low redshift probes is mandatory in order to sharpen the CMB neutrino bounds. The most stringent bound is obtained when adding the BAO data that are directly sensitive to the free-streaming nature of neutrinos. Moreover, the geometrical information they provide helps in breaking the degeneracies among cosmological parameters.
Mass ordering

In the cosmological analysis, 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 (in the unphysical region). Although the CMB is essentially blind to the mass splitting, now the bounds are strong enough that the neutrino mass-squared splitting can no longer be considered negligible.

The masses \(m_i\) entering in the definition of \(\Sigma\) obey the \(\delta m^2\) and \(\Delta m^2\) constraints in:

\[
\begin{align*}
\delta m^2 &= m_2^2 - m_1^2 > 0, \\
\Delta m^2 &= m_3^2 - \frac{m_2^2 + m_1^2}{2}
\end{align*}
\]

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

The absolute \(\nu\) masses are unknown. However, lower bounds are set by oscillation data by zeroing the lightest \(m_i\):

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

Therefore, we have these corresponding lower bounds:

\[
\Sigma = m_1 + m_2 + m_3 \gtrsim \begin{cases} 
0.06 \text{ eV} & \text{(NO)} \\
0.10 \text{ eV} & \text{(IO)}
\end{cases}
\]
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 $\Sigma$ obey the $\delta m^2$ and $\Delta m^2$ 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 2$\sigma$ level) on the sum of neutrino masses $\Sigma$ for NO and IO.

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

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 ($\Sigma < 0.2 \text{ eV at } 2\sigma$).
By combining the cosmology with oscillation (T2K and NOvA, Daya Bay and Super-Kamiokande phase IV) and non-oscillation (0νββ decay bounds from the KamLAND-Zen experiment) data, using a frequentist analysis, we find the global preference for NO at the typical level of $\Delta \chi^2 \approx 4$ (i.e., 2σ).
A complete and self-consistent Bayesian analysis using neutrino oscillation data, $0\nu\beta\beta$ decay searches and CMB cosmological observations, points to weak evidence for NO, is entirely due to neutrino oscillation data.

In case B, the lightest neutrino mass is the one to vary, while $\Sigma m_\nu$ is a derived parameter, imposing the oscillation mass splitting for the NO and IO.
The Bayesian evidence against IO claimed by Simpson et al, JCAP 06 (2017) 029 (odds of 42:1 in favour of the normal hierarchy) arises by the choice of a logarithm prior, because of the changes in the volume of $m_2$ between the two mass orderings, as this parameter is limited from below by $|\Delta m_{21}^2|$ in NO but by $|\Delta m_{31}^2|$ in IO.

In case A, $\Sigma m_\nu$ is varying and the Bayes factor is not stable by changing prior.
These constraints are for Planck 2018 TTTEEE+lowE+lensing+BAO. Here the lightest neutrino mass $m_0$ is free to vary in the range [0,1] and $\Sigma m_\nu$ is a derived parameter imposing the oscillation mass splitting:

\[
\Sigma m_\nu = m_0 + \sqrt{\Delta m_{32}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2}
\] (NH),

\[
\Sigma m_\nu = m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{31}^2| - \Delta m_{21}^2 + m_0^2}
\] (IH).

Therefore, we have $\Sigma m_\nu > 0.0589\ eV$ for NO or $\Sigma m_\nu > 0.0995\ eV$ for IO. The normal hierarchy is very mildly preferred relative to the inverted:

\[
\Delta \chi^2 = -0.95
\] with a bayesian analysis.
The addition of the eBOSS Lyman-α forest (S. Chabanier et al., 1812.03554) improves the total neutrino mass constraints, ruling out the IO at 95% CL.

The Lyman-α forest 1D flux power spectrum is a powerful tool to study clustering in the universe at redshifts 2 to 6, on scales that are strongly non-linear today, but were only mildly non-linear at such high redshifts.

Therefore, the Lyman-α forest is strongly sensitive to the matter power spectrum on scales where the suppression caused by neutrinos is expected to be significant. However, these measurements are substantially difficult to perform and interpret.
The relativistic neutrinos contribute to the present energy density of the Universe:

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

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

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

The expected value is \( \text{Neff} = 3.046 \), 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, de Salas and Pastor arXiv:1606.06986 [hep-ph]).
The Neutrino effective number

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

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

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 (Silk damping scale):

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

CMB acoustic peaks are shifted and smeared
The Neutrino effective number

Varying $N_{\text{eff}}$ changes the time of the matter radiation equivalence: a higher radiation content due to the presence of additional relativistic species leads to a delay in $z_{\text{eq}}$:

$$1 + z_{\text{eq}} = \frac{\Omega_m}{\Omega_r} = \frac{\Omega_m h^2}{\Omega_{\gamma} h^2} \frac{1}{1 + 0.2271 N_{\text{eff}}},$$

This implies that at the time of decoupling the radiation is still a subdominant component and the gravitational potential is still slowly decreasing.

This shows up as an enhancement of the early Integrated Sachs Wolfe (ISW) effect that increases the CMB perturbation peaks at $l \sim 200$. 

The main reason for this good accuracy is due to the lack of the early integrated Sachs Wolfe effect in polarization data. The inclusion of polarization helps in determining the amplitude of the eISW and Neff.
CMB constraints on the neutrino effective number and the total neutrino mass

\[
\begin{align*}
N_{\text{eff}} &= 2.96^{+0.34}_{-0.33}, \\
\sum m_\nu &< 0.12 \text{ eV,}
\end{align*}
\]

95\%, Planck TT,TE,EE+lowE +lensing+BAO.


When varying also \( N_{\text{eff}} \), the bounds on the total neutrino mass doesn’t change and the neutrino effective number is totally consistent with its standard value 3.046. The bounds remain very close to the bounds we have in 7-parameter models, showing that the data clearly differentiate between the physical effects generated by the addition of these two parameters.
The sterile neutrino

We can completely rule out a fully thermalised 4th sterile neutrino, but we can still have other possibilities. 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 $N_{\text{eff}}$ and $m_{\text{eff}}$ is model dependent.

- Thermally distributed

$$m_{\text{thermal}}\text{ sterile} = (\Delta N_{\text{eff}})^{-3/4} m_{\text{eff}}^{\nu, \text{sterile}}$$

- Produced via the mechanism described by Dodelson & Widrow, 1994, PRL, 72,17.

$$m_{\text{DW}}\text{ sterile} = (\Delta N_{\text{eff}})^{-1} m_{\text{eff}}^{\nu, \text{sterile}}$$

For low $\Delta N_{\text{eff}}$ the physical mass can therefore become large and in that case the particles behave as cold dark matter. For this reason in Planck are excluded all the sterile neutrino masses $>10\text{eV}$. 
The physical mass for thermally-produced sterile neutrinos is constant along the grey lines labelled by the mass in eV, while the equivalent result for sterile neutrinos produced via the Dodelson-Widrow mechanism is shown by the adjacent thinner lines. The dark grey shaded region shows the part of parameter space excluded by the default prior $m_{\text{thermal\ sterile}} < 10$ eV.
The sterile neutrino

Contribution of the sterile neutrino when it is massless.

Contribution of the sterile neutrino when it is massive.

\[ N_{\text{eff}} < 3.34, \quad m_{\nu,\text{sterile}} < 0.23 \text{ eV}, \]

\[ 95\%, \text{ Planck TT,TE,EE+lowE +lensing+BAO.} \]

However the constraints depend on the choice of the prior: adopting a stronger prior of \( m_{\text{thermal \ sterile}} < 2 \text{ eV} \), we obtain a stronger constraint.

One thermalized sterile neutrino with $\Delta N_{\text{eff}} = 1$ is excluded at about $6\sigma$ irrespective of its mass. Its presence is in strong contradiction with cosmological data, so that the production of sterile neutrinos possibly explaining the neutrino short baseline (SBL) anomaly would need to be suppressed by some non-standard interactions (Archidiacono et al. 2016, JCAP, 1608, 067; Chu et al. 2015, JCAP, 1510, 011), low-temperature reheating (de Salas et al. 2015, Phys. Rev., D92, 123534), or another special mechanism.
Since the Planck constraints are model dependent, therefore changing the cosmological scenario we can end with different conclusions.

In fact, anomalies and tensions between Planck and other cosmological probes are present well above the 3 standard deviations. These discrepancies, already hinted in previous Planck data releases, have persisted and strengthened despite several years of accurate analyses.

If not due to systematics, the current anomalies could represent a crisis for the standard cosmological model and their experimental confirmation can bring a revolution in our current ideas of the structure and evolution of the Universe.

These tensions can indicate a failure in LCDM model.
The H0 tension at more than 4σ

The cosmological constraints obtained from Planck are assuming a cosmological model and are therefore model dependent. Moreover these bounds are also affected by the degeneracy between the parameters that induce similar effects on the observables. Therefore the Planck constraints can change when modifying the assumptions of the underlying cosmological model.

\[ H_0 = 67.27 \pm 0.60 \text{ km/s/Mpc in } \Lambda\mathrm{CDM} \]

The last local measurement of the Hubble constant given by the SH0ES collaboration and obtained using Hubble Space Telescope observations of 70 long-period Cepheids in the Large Magellanic Cloud is in tension at 4.4σ with Planck in \( \Lambda\mathrm{CDM} \).

\[ H_0 = 74.03 \pm 1.42 \text{ km/s/Mpc} \]
**The H0 tension at more than 5σ**

**CMB:** \( H_0 = 67.27 \pm 0.60 \) km/s/Mpc in \( \Lambda \)CDM

**BAO+Pantheon+BBN+\( \theta_{MC} \), Planck:** \( H_0 = 67.9 \pm 0.8 \) km/s/Mpc


**SH0ES:** \( H_0 = 74.03 \pm 1.42 \) km/s/Mpc


**Strong Lensing:** Multiply-imaged quasar systems through strong gravitational lensing made by the H0liCOW collaboration

\( H_0 = 73.3 \pm 1.7 \) km/s/Mpc

**Wong et al. arXiv:1907.04869v1**
The $H_0$ value is very important for the determination of the total neutrino mass. In fact, there exist a very important negative correlation between the Hubble constant and the sum of the neutrino masses.
Moreover, there is a very strong positive correlation between $H_0$ and the neutrino effective number. Therefore, imposing an $H_0$ prior as obtained by R19 can give an indication for extra particles at recombination.

The lensing amplitude $A_L$ parametrizes the rescaling of the lensing potential $\phi(n)$, then the power spectrum of the lensing field:

$$C_{\ell}^{\phi \phi} \rightarrow A_L C_{\ell}^{\phi \phi}$$

The gravitational lensing deflects the photon path by a quantity defined by the gradient of the lensing potential $\phi(n)$, integrated along the line of sight $n$, remapping the temperature field.
Its effect on the power spectrum is the smoothing of the acoustic peaks, increasing $A_L$.

Interesting consistency checks is if the amplitude of the smoothing effect in the CMB power spectra matches the theoretical expectation $A_L = 1$ and whether the amplitude of the smoothing is consistent with that measured by the lensing reconstruction.

If $A_L = 1$ then the theory is correct, otherwise we have a new physics or systematics.

Calabrese et al., Phys. Rev. D, 77, 123531
The lensing amplitude

The distributions of AL inferred from the CMB power spectra alone indicate a preference for AL > 1.

The joint combined likelihood shifts the value preferred by the TT data downwards towards AL = 1, but the error also shrinks, increasing the significance of AL > 1 to 2.8σ.

The preference for high AL is not just a volume effect in the full parameter space, with the best fit improved by Δχ²~9 when adding AL for TT+lowE and 10 for TTTEEE+lowE.

\[ AL = 1.243 \pm 0.096 \quad (68\%, \text{Planck TT+lowE}), \]
\[ AL = 1.180 \pm 0.065 \quad (68\%, \text{Planck TT,TE,EE+lowE}), \]
There is a very strong positive correlation between $A_{\text{Lens}}$ and the total neutrino mass. Therefore, to be conservative, we need to take into account this wrong amount of lensing when constraining $\Sigma m_\nu$. 

For example, when $A_{\text{lens}}$ is free to vary, because of their correlation, the bounds on the total neutrino mass are strongly weakened, up to a factor of $\sim 2$.

As a consequence, in these cases there is no more the preference for the normal ordering we have in the LCDM scenario.

The $\Lambda$CDM model assumes that the universe is specially flat. The combination of the Planck temperature and polarization power spectra gives

$$\Omega_K = -0.044^{+0.018}_{-0.015} \quad (68\% \text{, Planck TT,TE,EE+lowE}),$$

a detection of curvature at about $3.4\sigma$.

Planck favours a closed Universe ($\Omega_k < 0$) with $99.985\%$ probability. A closed Universe with $\Omega K = -0.0438$ provides a better fit to PL18 with respect to a flat model, improving the best-fit $\Delta \chi^2$ of -11 compared to base $\Lambda$CDM when adding the one additional curvature parameter.
There is a positive correlation between the curvature and the total neutrino mass.

Curvature of the universe

This is a plot of the acoustic-scale distance ratio, $DV(z)/r_{\text{drag}}$, as a function of redshift, taken from several recent BAO surveys, and divided by the mean acoustic-scale ratio obtained by Planck adopting a model. $r_{\text{drag}}$ is the comoving size of the sound horizon at the baryon drag epoch, and $DV$, the dilation scale, is a combination of the Hubble parameter $H(z)$ and the comoving angular diameter distance $DM(z)$.

In a $\Lambda$CDM model the BAO data agree really well with the Planck measurements...
Curvature of the universe

… but when we let curvature to vary there is a striking disagreement between Planck spectra and BAO measurements!

Therefore, the strong constraint on the total neutrino mass we find combining BAO and Planck data under the assumption of a flat Universe can change drastically if a curvature is considered.

\[ \sum m_\nu < 0.13 \text{ eV} \quad (95\%, \text{Planck TT,TE,EE+lowE +BAO}), \]

How much these constraints should be improved in the future?
CMB-S4 is, at the moment, the proposal with the highest probability of being realised. 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.

\[ \sigma(M_\nu) = 59 \text{ meV} \]
\[ \sigma(N_{\text{eff}}) = 0.048 \]

Errard et al, JCAP03(2016)052

Constraints at 68% cl.
CORE-M5 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.
PICO + future BAO (DESI or Euclid) should reach $\sigma (\sum m_\nu) = 14$ meV, i.e. a 4$\sigma$ detection of the minimum sum for the NO. Moreover, it should constrain the constrain $\Delta N_{\text{eff}} < 0.06$ at 95% CL.
All previous forecast assumes linear or mildly non-linear perturbation theory (k_{max}=1.5 \, h\text{Mpc}^{-1}). But if future developments in treatment of linearities could let us to move to even more non linear regime (k_{max}=5 \, h\text{Mpc}^{-1}) we may learn a lot more.

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

All previous forecasts assume linear or mildly non-linear perturbation theory ($k_{\text{max}}=1.5 \, \text{hMpc}^{-1}$). But if future developments in treatment of linearities could let us move to even more non-linear regime ($k_{\text{max}}=5 \, \text{hMpc}^{-1}$) we may learn a lot more.

CORE+Euclid can reach $0.003 \, \text{eV}$ sensitivity on the sum of neutrino masses.


CORE+Euclid can reach $0.003 \, \text{eV}$ sensitivity on the sum of neutrino masses.
Summary:
With cosmology we can constrain two important neutrino parameters:
- the total neutrino mass;
- 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 2018+BAO: \( \Sigma m_\nu < 0.13 \text{eV} \) at 95% CL.

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 favoured with respect to IO at the level of 2\( \sigma \), 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.

The most stringent bound we have on the sterile neutrino mass is when considering Planck2018+lensing+BAO: \( m_{\text{eff}} < 0.65 \text{eV} \) at 95% CL.

Warning!!
Some indication for anomalies and tensions are present and could significantly affect current Planck constraints on neutrino masses. Until the nature of these anomalies (if new physics or systematics) is clear, we should be very conservative when considering cosmological constraints on the neutrino sector.
Thank you!

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BAO

Acoustic-scale distance measurements divided by the corresponding mean distance ratio from Planck TT,TE,EE+lowE+lensing in the base-LCDM model. The points, with their 1 error bars are as follows:

- **green star, 6dFGS** (Beutler et al. 2011, MNRAS, 416, 3017);
- **magenta square, SDSS MGS** (Ross et al. 2015, MNRAS, 449, 835);
- **small blue circles, WiggleZ** (as analysed by Kazin et al. 2014, MNRAS, 441, 3524);
- **large dark blue triangle, DES** (DES Collaboration arXiv:1712.06209);
- **cyan cross, DR14 LRG** (Bautista et al. arXiv:1712.08064);
- **red circle, SDSS quasars** (Ata et al. arXiv:1705.06373);
- The green point with magenta dashed line is the 6dFGS and MGS joint analysis result of Carter et al. arXiv:1803.01746.

All ratios are for the averaged distance DV(z), except for DES and BOSS Lyman-α, where the ratio plotted is DM. The grey bands show the 68% and 95% confidence ranges allowed for the ratio DV(z)=rdrag by Planck TT,TE,EE+lowE+lensing.
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 $\chi^2$ difference:

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

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.

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. ($<0.18$ eV at $2\sigma$ and $<0.27$ eV at $3\sigma$).

\[ \Delta \chi^2 = -4.26 \] is due to the addition of R19 that is in tension with Planck.
A tension on $S_8$ at more than $2.5\sigma$ is present between the Planck data in the $\Lambda$CDM scenario and cosmic shear data and Ly-$\alpha$ (sharing a similar range of scales).
The S8 tension

This is mainly due to the anomalous value of $A_L$.

We find that the CMB and cosmic shear datasets, in tension in the standard LCDM model, are still in tension adding massive neutrinos.

However, if we include the additional scaling parameter on the CMB lensing amplitude $A_L$, we find that this can put in agreement the Planck 2015 with the cosmic shear data.

$A_L$ is a phenomenological parameter that is found to be more than 2σ higher than the expected value in the Planck 2015 data, suggesting a higher amount of lensing in the power spectra, not supported by the trispectrum analysis.

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