Massive Neutrinos in Cosmology

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The presence of a background of relic neutrinos ($C_{\nu B}$) is a basic prediction of the standard cosmological model

• Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until $T \sim 1$ MeV ($z \sim 10^{10}$);

• Below $T \sim 1$ MeV, neutrino free stream keeping an equilibrium spectrum:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$

• Today $T_\nu = 1.9$ K and $n_\nu = 113$ part/cm$^3$ per species
This picture is consistent with current CMB observations:

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

(note I am showing \( \sim l^4 C_l \), not \( l^2 C_l \))
The Cosmic Neutrino Background

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

\[ N_{\text{eff}} = 2.5 \]
\[ N_{\text{eff}} = 2.75 \]
\[ N_{\text{eff}} = 3.046 \]
\[ N_{\text{eff}} = 3.25 \]
\[ N_{\text{eff}} = 3.5 \]

Energy density in units of “standard” neutrino density (thermally distributed with T=1.9 K)

(note I am showing \( \sim l^4 C_l \), not \( l^2 C_l \))
The Cosmic Neutrino Background

This picture is consistent with current CMB observations:

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

Due to non-instantaneous decoupling, the standard expectation is \( N_{\text{eff}} = 3.046 \) (updated calculation gives \( N_{\text{eff}} = 3.045 \); see de Salas & Pastor 2016) (note I am showing \( \ell^4 C_\ell \), not \( \ell^2 C_\ell \))

Energy density in units of “standard” neutrino density (thermally distributed with T=1.9 K)
Background effects can be mostly reabsorbed by varying other parameters

Perturbations: free streaming, damping of small-scale perturbations

Net effect is to **decrease lensing**

- proportional to the neutrino energy density
- the effect is larger for larger masses
LARGE SCALE STRUCTURES

What we compute
Planck collaboration
SDSS-BOSS collaboration

Image Credit: M. Blanton and the Sloan Digital Sky Survey.

Eisenstein et al (2005)
Full shape of the matter power spectrum:
Power at small scales is affected by the presence of neutrinos (due to free streaming)
issues: non-linearities, scale-dependent bias

Image Credit: M. Blanton and the Sloan Digital Sky Survey.

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Image Credit: M. Blanton and the Sloan Digital Sky Survey.

Eisenstein et al (2005)
Baryon acoustic oscillations (BAO): Imprint of a characteristic scale (the sound horizon at the drag epoch) on the matter two-point CF
Standard ruler: BAO allow to constrain the expansion history and solve geometrical degeneracies
Less affected by systematics (e.g. nonlinear evolution)
Planck 2015 constraints on neutrino mass

PLANCK TT + lowP + lensing
\[ \Sigma m_\nu < 0.68 \text{ eV} \]

~ one order of magnitude better than present kinematic constraints already at the same level than near-future expectations for e.g. KATRIN

Inclusion of external data like BAO allows to better constrain the expansion history and reduce degeneracy with H0:

PLANCK TT + lowP + lensing + BAO
\[ \Sigma m_\nu < 0.23 \text{ eV} \]

Note that non-zero neutrino mass does not alleviate tension with direct measurements of H0

(Planck 2015 XIII)
### How heavy?

<table>
<thead>
<tr>
<th>95% constraints on total mass</th>
<th>PlanckTT</th>
<th>PlanckTTTEEE</th>
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<tbody>
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<td>+lowP</td>
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<td>+lowP+BAO</td>
<td>&lt;0.21 eV</td>
<td>&lt;0.17 eV</td>
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<td>&lt;0.23 eV</td>
<td>&lt;0.19 eV</td>
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Planck 2015 + BOSS Lyman-α:

\[
\sum m_\nu < 0.12 \text{ eV (at 95%)}
\]

(Palanque-Delabrouille et al. 2015)

Planck 2015 + BOSS DR12 (BAO+shape):

\[
\sum m_\nu < 0.16 \text{ eV (at 95%)}
\]

(BOSS collab., arXiv:1607.03155)
Cosmology constraints can be combined with data from oscillation experiments.

\[ m_\beta \equiv \left[ \sum |U_{ei}|^2 m_i^2 \right]^{1/2} \]

\[ m_{\beta\beta} \equiv \left| \sum U_{ei}^2 m_i \right| \]

Adapted from Gerbino, ML, Melchiorri, 2016
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Adapted from Gerbino, ML, Melchiorri, 2016.

See M. Gerbino’s talk on Wednesday.

PlanckTTTEEE + lowP (2015) + BAO + osc

KATRIN (90%)

NH
IH

KamLAND–Zen (90%)
New large-scale polarization data has been released in May 2016 (Planck int. res. XLVI)

![Diagram](image)

Smaller $\tau$ means less overall power (thus smaller fluctuations) and less lensing
New large-scale polarization data has been released in May 2016 (Planck int. res. XLVI)

Smaller $\tau$ means less overall power (thus smaller fluctuations) and less lensing

Tighter constraints on neutrino mass:

$\Sigma m_\nu < 0.59 \text{ eV} \ (\text{Planck TT} + 2016\text{lowP})$

$\Sigma m_\nu < 0.34 \text{ eV} \ (\text{Planck TT TEEE} + 2016\text{lowP})$
Update using latest data (limits are 95% CL)

\[ M_\nu < 0.19 \text{ eV (PlanckTT+lowP+BAO)} \]

\[ M_\nu < 0.15 \text{ eV (PlanckTT+lowP2016+BAO)} \]

\[ M_\nu < 0.09 \text{ eV (PlanckTTTEEE+lowP2016+BAO+H0)} \]
Update using latest data (limits are 95% CL)

$M_\nu < 0.19$ eV (PlanckTT+lowP+BAO)

$M_\nu < 0.15$ eV (PlanckTT+lowP2016+BAO)

$M_\nu < 0.09$ eV
(PlanckTTTEEE+lowP2016+BAO+H0)

Normal hierarchy is favoured with odds ~3:1 for the most constraining dataset combinations
DES Year-1 results (arXiv:1708.01530)

M$_\nu$ < 0.29 eV
DES-Y1+Planck+JLA+BAO

Constraints are looser by ~20% when DES is added

This is related to the reduced clustering amplitude that is preferred by DES (wrt Planck)

See E. Krause’s plenary talk on Wednesday
Higher values of $N_{\text{eff}}$ can help relieve the tension with astrophysical measurements of $H_0$. However, they imply a larger $\sigma_8$ and thus worsen the tension with LSS probes.

$N_{\text{eff}} = 3.15 \pm 0.23$

(Planck 2015 XIII)
**Neutrino Masses from CORE-M5**

Expected uncertainty on $\Sigma m_\nu$ from CORE (+LSS) in $\Lambda$CDM+$M_\nu$

$\sigma(m_\nu) = 0.044 (0.016)$ eV

Uncertainty from CORE+LSS degrades to 0.02 eV in some extended models

*In combination with LSS, guarantees at least a 4$\sigma$ detection*

However, beware that all forecast shown here and in the following assume perfect control of systematics
The future: ground-based experiments

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>Sensitivity ($\mu K^2$)</th>
<th>$\sigma(r)$</th>
<th>$\sigma(N_{\text{eff}})$</th>
<th>$\sigma(\Sigma m_\nu)$</th>
<th>Dark Energy F.O.M</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>1000</td>
<td>$\approx 10^{-5}$</td>
<td>0.035</td>
<td>0.14</td>
<td>0.15 eV</td>
<td>~180</td>
</tr>
<tr>
<td>2016</td>
<td>Stage 3</td>
<td>10,000</td>
<td>$10^{-6}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06 eV</td>
<td>~300-600</td>
</tr>
<tr>
<td>2018</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>1250</td>
</tr>
<tr>
<td>2021</td>
<td></td>
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</table>

CMB-S4 Science Book (arXiv: 1610:02743)
## Future Prospects

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<tr>
<th>Scenario</th>
<th>$\sigma(\sum m_\nu)$ [meV]</th>
<th>$\sigma(N_{\text{eff}})$</th>
</tr>
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<tbody>
<tr>
<td>CMB Stage IV</td>
<td>45</td>
<td>0.021</td>
</tr>
<tr>
<td>CMB Stage IV + DESI BAO</td>
<td>16</td>
<td>0.020</td>
</tr>
<tr>
<td>Planck + Euclid</td>
<td>25 - 30</td>
<td>-</td>
</tr>
<tr>
<td>CORE</td>
<td>44</td>
<td>0.04</td>
</tr>
<tr>
<td>CORE + LSS</td>
<td>15 - 20</td>
<td>0.04</td>
</tr>
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Comparing with Lab

The absolute mass scale can be measured through:
(numbers on the right are current upper limits)

- tritium beta decay
\[ m_\beta \equiv \left[ \sum |U_{ei}|^2 m_i^2 \right]^{1/2} \quad (2.05 - 2.3 \text{ eV @ 95\%CL}) \quad \text{(Troisk-Mainz)}

- neutrinoless double beta decay
\[ m_{\beta\beta} \equiv \left| \sum U_{ei}^2 m_i \right| \quad (0.06 - 0.16 \text{ eV @ 90\%CL}) \quad \text{(Kamland-Zen)}

- cosmological observations
\[ \sum m_\nu \equiv \sum_i m_i \quad (0.2 - 0.7 \text{ eV @ 95\%CL}) \quad \text{(Planck)}

U is the neutrino mixing matrix:
\[ |\nu_\alpha > = \sum_i U_{\alpha i}^* |\nu_i > \]
The absolute mass scale can be measured through:
(numbers on the right are forecast for future sensitivities)

- tritium beta decay
  \[ m_\beta \equiv \left[ \sum |U_{ei}|^2 m_i^2 \right]^{1/2} \]  
  \( (200 \text{ meV @ 68}\% \text{CL}) \)  
  (Katrin)

- neutrinoless double beta decay
  \[ m_{\beta\beta} \equiv \left| \sum U_{ei}^2 m_i \right| \]  
  \( (8 \text{ – } 20 \text{ meV @ 90}\% \text{CL}) \)  
  (nEXO, 5-year exposure)

- cosmological observations
  \[ \sum m_\nu \equiv \sum_i m_i \]  
  \( (16 \text{ – } 45 \text{ meV @ 68}\% \text{CL}) \)  
  (CORE, CORE+LSS)
A window on new physics: neutrino self-interactions in the CMB

See I. Oldengott’s and F. Forastieri’s talks!

\( \ell^3(\ell+1)C_\ell^T / 2\pi \) [\( \mu K^2 \)]

\( \langle \rho_n \rangle \)

(Prob. density (coupling constant))

\( \gamma_{\nu\nu} \times 10^{27} \) (coupling constant)
Summary

- Cosmological data can be used to constrain neutrino properties
- Until now, no deviation from standard expectations (i.e. LCDM) has been observed
- Planck can constrain neutrino masses mainly thanks to the lensing of the power spectrum. From PlanckTT+lowP: $\Sigma m_\nu < 0.72$ eV
- Geometrical probes (e.g. BAO) can greatly improve the constraints: PlanckTT+lowP+BAO gives $\Sigma m_\nu < 0.21$ eV
- Cosmological observations, combined with information from oscillation experiments, also give tight constraints on $m_\beta$ and $m_{\beta\beta}$
- Present data show a weak (odds 3:2) preference for normal hierarchy – this is mainly driven by the preference for small neutrino mass
- Planck is compatible with 3 neutrino families; $N_{\text{eff}} = 4$ is excluded at between 3 and 5 sigma, depending on the dataset
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
BACKUP SLIDES
**PLANCK CONSTRAINTS ON MASSIVE STERILE NEUTRINOS**

Planck TT+lowP+ lensing+BAO

\[ N_{\text{eff}} < 3.7 \]
\[ m_{\nu, \text{sterile}}^{\text{eff}} < 0.52 \text{ eV} \]

One sterile eigenstate; total active mass fixed to 0.06 eV

Present-day energy density

Amplitude of density fluctuations

Planck 2015 XVI
Planck constraints on massive sterile neutrinos

- Planck TT+lowP+lensing+BAO
- $N_{\text{eff}} < 3.7$
- $m_{\nu,\text{sterile}}^{\text{eff}} < 0.52 \text{ eV}$

One sterile eigenstate; total active mass fixed to 0.06 eV

- Early energy density
- Present-day energy density
- Amplitude of density fluctuations
- Lines of constant $m_s$ (thermal)
- Lines of constant $m_s$ (DW)

Planck 2015 XVI
Planck constraints on massive sterile neutrinos

Planck TT+lowP+lensing+BAO

$N_{\text{eff}} < 3.7$

$m_{\text{eff}}^{\text{sterile}} < 0.52 \text{ eV}$

One sterile eigenstate; total active mass fixed to 0.06 eV

$m_s \sim 1 \text{ eV}$ is allowed if either $T_s < T_\nu$

or if distribution is a gray body

Planck 2015 XVI
## How Heavy?

### 95% Constraints on Total Mass

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### Diagram

- **Planck TT + lowP**
- +lensing
- +BAO + $H_0$ + JLA
- **Planck TT, TE, EE + lowP**
- +lensing
- +BAO + $H_0$ + JLA

(Planck 2015 XIII)
Recently a paper from Simpson et al. claimed "strong" evidence in favour of NH (odds of 42:1) from cosmological data. (Simpson et al., arXiv:1703.03425)

The results in the paper are based on the choice of a gaussian prior over $\log(m_i)$, that is further marginalized over. This is motivated as "less informative", as it assigns equal probabilities to different orders of magnitude in the masses.
The fact that NH is favored by a log prior is perfectly natural in the framework of Bayesian statistics.

Oscillation experiments single out regions in the $(m_1, m_2, m_3)$ plane.

The regions singled out in NH or IH are different BUT they occupy the same volume in $(m_1, m_2, m_3)$.

They do not occupy the same volume in Log$[(m_1, m_2, m_3)]$. 
$|x - 1| = 0.5 \pm 0.1$
$|x - 1| = 0.5 +/- 0.1$

The two models ($x - 1 > 0$ vs $x - 1 < 0$) occupy the same volume in parameter space.
\[ |x - 1| = 0.5 \pm 0.1 \]

The two models \((x-1 > 0 \text{ vs } x-1 < 0)\) occupy the same volume in parameter space.

Here, two models \((x-1 > 0 \text{ vs } x-1 < 0)\) occupy different volumes in parameter space (we would prefer the \(x-1 < 0\) hypothesis).