Neutrino Cosmology: Current Results

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on behalf of the Planck Collaboration

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Neutrino Oscillation Workshop 2016
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:

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

\( N_{\text{eff}} = 2.5 \)
\( N_{\text{eff}} = 2.75 \)
\( N_{\text{eff}} = 3.046 \)
\( N_{\text{eff}} = 3.25 \)
\( N_{\text{eff}} = 3.5 \)

(Note I am showing \( \sim l^4 C_l \), not \( l^2 C_l \))
This picture is consistent with current CMB observations:

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

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

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Due to non-instantaneous decoupling, the standard expectation is $N_{\text{eff}} = 3.046$ (updated calculation gives $N_{\text{eff}} = 3.045$; see S. Pastor’s talk on Monday) (note I am showing $\sim l^4 C_l$, not $l^2 C_l$)

Energy density in units of “standard” neutrino density (thermally distributed with $T=1.9$ K)
The Cosmic Neutrino Background

This picture is consistent with current CMB observations:

\[ N_{\text{eff}} = 3.15 \pm 0.23 \text{ (PlanckTT+lowP+BAO)} \]

(Planck 2015 XIII)
Planck is a 3rd generation ESA satellite devoted to CMB
Ultimate characterization of the temperature anisotropies
74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz
angular resolution between 30' and 5', $\Delta T/T \sim 2 \times 10^{-6}$
PLANCK: TEMPERATURE ANISOTROPIES
Definitive measurement of the CMB temperature anisotropies
PLANCK: POLARIZATION ANISOTROPIES
Two independent components: a grad-like (E) and a curl-like (B) mode
Different behaviour under parity
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Different behaviour under parity

Still a wealth of information to be extracted
*Planck* has just scratched the surface
PLANCK: LENSING POTENTIAL
Most significant detection on CMB lensing to date
Reconstructed from the temperature and polarization maps
**Planck: Lensing Potential**

Most significant detection on CMB lensing to date
Reconstructed from the temperature and polarization maps

Measures deflection of light due to intervening structures
(average deflection angle is ~2.5 arcmin)
Gives integrated information about the matter distribution between us and the last scattering surface
The information in the maps can be compressed by computing the 2-point correlation functions (i.e., spectra).
The red curve is a fit of the 6-parameters $\Lambda$CDM model to the TT data only.
Planck baseline cosmological dataset uses the full TT spectrum + large scale (l < 30) polarization (not shown) (*PlanckTT+lowP*)
Can be extended to include the full polarization information \((\text{PlanckTTTEEE+lowP})\).

Less conservative: high-ell polarization could be affected by residual systematics.
All the previous can be complemented by the lensing power spectrum (+Planck lensing)
Beware that lensing information is present also in the damping tail of the temperature and polarization power spectra, so we have sensitivity to the matter distribution even without using $\phi\phi$. 
What we compute

Planck collaboration

SDSS-BOSS collaboration
HOW HEAVY?

$H_0$ and $\Omega_{\Lambda}$ are varied to keep $z_{eq}$ and $\theta_s$ constant.

Background: change in MR equality, angular-diameter distance to LSS
**Background:** change in MR equality, angular-diameter distance to LSS can be mostly compensated by acting on other parameters (e.g. $H_0$)

$H_0$ and $\Omega_\Lambda$ are varied to keep $z_{eq}$ and $\theta_s$ constant.

How heavy?

$\Sigma m_\nu = 0.06 \text{ eV}$
$\Sigma m_\nu = 0.2 \text{ eV}$
$\Sigma m_\nu = 0.4 \text{ eV}$
$\Sigma m_\nu = 0.6 \text{ eV}$
$\Sigma m_\nu = 0.8 \text{ eV}$
$H_0$ and $\Omega_{\Lambda}$ are varied to keep $z_{eq}$ and $\theta_s$ constant.

Perturbations: free streaming, damping of small-scale perturbations.
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Net effect is to decrease lensing

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- proportional to the neutrino energy density

- the effect is larger for larger masses
**HOW HEAVY?**

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## How Heavy?

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<th>95% constraints on total mass</th>
<th>PlanckTT</th>
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The table shows the 95% constraints on the total mass of neutrinos for different combinations of data sets.

**Planck**
- **Planck TT + lowP**: The constraints are shown in blue.
- **Planck TT + lowP + lensing**: The constraints are shown in red.
- **Planck TT, TE, EE + lowP**: The constraints are shown in green.
- **Planck TT + lowP + BAO**: The constraints are shown in blue dotted.
- **Planck TT + lowP + lensing + BAO**: The constraints are shown in red dotted.
- **Planck TT + lowP + lensing + ext**: The constraints are shown in green dotted.
- **Planck TT + lowP + lensing + BAO + ext**: The constraints are shown in blue dotted.

These figures illustrate the impact of different additional data sets on the constraints on the total mass of neutrinos.
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Larger mass can partly alleviate the tension with LSS probes (smaller $\sigma_8$) but increases tension with direct measurements of the Hubble constant.
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**Planck 2015 + BOSS Lyman-α:**
\[ \sum m_\nu < 0.12 \text{ eV (@95%)} \]
(Palanque-Delabrouille et al. 2015)

**Planck 2015 + BOSS DR12 (BAO+shape):**
\[ \sum m_\nu < 0.16 \text{ eV (@95%)} \]
(BOSS collab., arXiv:1607.03155)
IMPLICATIONS FOR MASS PARAMETERS

Adapted from Gerbino, ML, Melchiorri

PlanckTTTEEE + lowP+BAO +osc

KATRIN (90%)

NH
IH

KamLAND–Zen (90%)

$\beta\beta$ [eV]

$\beta\beta$ [eV]
New large-scale polarization data has been released in May 2016.

Large-scale polarization mainly fixes the reionization redshift (i.e. the reionization optical depth)

PlanckTT+lowP (2015)
\[ \tau = 0.078 \pm 0.019 \]

PlanckTT + 2016 low-ell pol.
\[ \tau = 0.058 \pm 0.009 \]
New large-scale polarization data has been released in May 2016

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

Tighter constraints on neutrino mass:

$\Sigma m_\nu < 0.59$ eV (PlanckTT+2016lowP)

$\Sigma m_\nu < 0.34$ eV (PlanckTTTEEE +2016lowP)
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.
Planck constraints on $N_{\text{eff}}$ alone (can be regarded as a massless limit for the sterile)

\[ N_{\text{eff}} = 3.13 \pm 0.32 \text{ (PlanckTT+lowP)} \]

\[ N_{\text{eff}} = 3.15 \pm 0.23 \text{ (PlanckTT+lowP+BAO)} \]

\[ N_{\text{eff}} = 2.99 \pm 0.20 \text{ (PlanckTT,TE,EE+lowP)} \]

\[ N_{\text{eff}} = 3.04 \pm 0.18 \text{ (PlanckTT,TE,EE+lowP+BAO)} \]

(uncertainties are 68% CL)

$N_{\text{eff}} = 4$ (i.e., one extra thermalized massless neutrino) is excluded at between ~ 3 and 5 sigma.
**Effective Number of Neutrino Families**

Planck 2015 + BOSS DR12 (BAO+shape):

\[ N_{\text{eff}} = 3.03 \pm 0.18 \]

Planck 2015 + BOSS DR12 (BAO+shape) + \( H_0 \):

\[ N_{\text{eff}} = 3.28 \pm 0.16 \]

(BOSS collab., arXiv: 1607.03155)
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

Lines of constant \( m_s \) (thermal)

Lines of constant \( m_s \) (DW)
Planck constraints on massive sterile neutrinos

- $m_s \sim 1$ eV is allowed by cosmology
- **BUT** the SBL best-fit for $\theta$ would lead to complete thermalization ($\Delta N_{\text{eff}} = 1$)
- Excluded by Planck!

- One sterile eigenstate; total active mass fixed to 0.06 eV
- $m_s \leq 0.52$ eV

Lines of constant $m_s$ (thermal)

Lines of constant $m_s$ (DW)

Amplitude of density fluctuations

$N_{\text{eff}}$ vs. $m_{\nu, \text{sterile}}$ [eV]
Planck constraints on massive sterile neutrinos

One sterile eigenstate; total active mass fixed to 0.06 eV

$m_s \sim 1$ eV is allowed by cosmology

**BUT** the SBL best-fit for $\theta$ would lead to complete thermalization ($\Delta N_{\text{eff}} = 1$)

Excluded by Planck!

Possible solutions: large lepton asymmetries; secret interactions

See S. Gariazzo’s talk on Monday

Amplitude of density fluctuations

Lines of constant $m_s$ (thermal)

Lines of constant $m_s$ (DW)
**Neutrino Perturbations**

Parameterized by the effective $\nu$ sound speed and viscosity

*Consistent with free-streaming neutrinos ($c_{\text{vis}}^2 = c_{\text{eff}}^2 = 1/3$)*

- **Planck TT+lowP+BAO**
  - $c_{\text{eff}}^2 = 0.316 +/- 0.010$
  - $c_{\text{vis}}^2 = 0.44^{+0.15}_{-0.10}$

- **Planck TT,TE,EE+lowP+BAO**
  - $c_{\text{eff}}^2 = 0.3242 +/- 0.0059$
  - $c_{\text{vis}}^2 = 0.331 +/- 0.037$
Parameterized by the effective $\nu$ sound speed and viscosity

*Consistent with free-streaming neutrinos* ($c^2_{\text{vis}} = c^2_{\text{eff}} = 1/3$)

A different approach based on inserting a collision term in the Boltzmann equation gives results consistent with free streaming $\nu$’s (see F. Forastieri talk on Monday)

**Planck TT + lowP + BAO**

$c^2_{\text{eff}} = 0.316 +/- 0.010$
$c^2_{\text{vis}} = 0.44^{+0.15}_{-0.10}$

**Planck TT, TE, EE + lowP + BAO**

$c^2_{\text{eff}} = 0.3242 +/- 0.0059$
$c^2_{\text{vis}} = 0.331 +/- 0.037$
• 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. PlanckTT+lowP+BAO gives $\Sigma m_\nu < 0.21 \text{ eV}$
• Planck is compatible with 3 neutrino families; $N_{\text{eff}} = 4$ is excluded at between 3 and 5 sigma, depending on the dataset
• Consistent with standard BBN
• Neutrino perturbations consistent with free-streaming nu’s
BACKUP SLIDES
The ΛCDM model assumes:

- neutrinos have only weak and gravitational interactions;
- no sterile neutrinos or other light relics;
- negligible lepton asymmetry (zero chemical potential);
- no entropy generation after neutrino decoupling beyond e^+e^- annihilation;
- neutrinos are stable;
- in general, no interactions that could lead to neutrino scattering/annihilation/decay at late times;
- “high” (T >> 1 MeV) reheating temperature.
- + general relativity....
Primordial nucleosynthesis

Consistent with measurements of the primordial abundances.