Neutrino cosmology from Planck 2014

J. Lesgourgues (CERN, LAPTh) on behalf of the Planck Collaboration
• Have we detected the Cosmic Neutrino Background
  ▪ through its average density?
  ▪ through its perturbations/anisotropies?

• Have we detected something more than the CNB (extra light relics)?
The Cosmic Neutrino Background (CNB)

Predicted in 1953 with correct temperature \( T_\nu = (4/11)^{4/3} T_\gamma \) by Alpher, Follin & Herman:

Physical Conditions in the Initial Stages of the Expanding Universe*,

RALPH A. ALPHER, JAMES W. FOLLIN, JR., AND ROBERT C. HERMAN

Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

(Received September 10, 1953)
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61 years later...
The Cosmic Neutrino Background (CNB)

Predicted in 1953 with correct temperature \((T_\nu = (4/11)^{1/3} T_\gamma)\) by Alpher, Follin & Herman:

61 years later...

... are we sure that it exists?
1. Probing the CNB average density

Alpher et al.’s prediction with refined neutrino decoupling at ~ 1 MeV, and update to 3 $\nu$ s, leads to:

$$\omega_R = \omega_\gamma \left( 1 + N_{\text{eff}} \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \right) \quad \text{with } N_{\text{eff}} = 3.046$$

in relativistic regime, and contribution to matter density for $T_\nu < m_\nu$:

$$\omega_M = \omega_b + \omega_{\text{CDM}} + (\Sigma m_\nu) / 93.14 \text{ eV}$$
1. Probing the CNB average density

*Alpher et al.*’s prediction with refined neutrino decoupling at \( \sim 1 \) MeV, and update to 3 \( \nu \) s, leads to:

\[
\omega_R = \omega_{\gamma} \left( 1 - \frac{N_{\text{eff}} \times 7/8 (4/11)^{4/3}}{4} \right) \quad \text{with} \quad N_{\text{eff}} = 3.046
\]

in relativistic regime, and contribution to matter density for \( T_\nu < m_\nu \):

\[
\omega_M = \omega_b + \omega_{\text{CDM}} + \frac{(\sum m_\nu)}{93.14 \text{ eV}}
\]

10 to 17\( \sigma \) evidence, from different combinations of Planck Temp., Pol. and BAOs
1. Probing the CNB average density

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$$\omega_R = \omega_\gamma \left(1 - \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} \cdot N_{\text{eff}}\right)$$

with $N_{\text{eff}} = 3.046$

in relativistic regime, and contribution to matter density for $T_\nu < m_\nu$:

$$\omega_M = \omega_b + \omega_{\text{CDM}} + \frac{(\sum m_\nu)}{93.14 \text{ eV}}$$

10 to 17$\sigma$ evidence, from different combinations of Planck Temp., Pol. and BAOs

Impact on $d_{\text{Arec}}$, $\theta_s$ can be compensated by decreasing $H_0$

Impact on Late ISW below cosmic variance

no evidence so far
1. Probing the CNB average density

• How can we test the density of radiation?
1. Probing the CNB average density

- An increase of radiation only would have obvious consequences:

![Graph showing the evolution of matter and radiation density with scale factor](image)
1. Probing the CNB average density

• An increase of all densities is more subtle to detect:

\[ \log \rho \]

\[ \log a \]

- radiation
- matter

• Or in other word, a simultaneous increase of \( (H_0, N_{\text{eff}}) \), with \( \Omega_b, \Omega_{\text{cdm}}, \Omega_\Lambda \) fixed
1. Probing the CNB average density

- Keeping $\Omega_i$ fixed and increasing $(H_0, N_{\text{eff}})$ preserves all characteristic redshifts
- But increase in $H_0$ changes peak-scale-to-damping-scale ratio!

larger $(H_0, N_{\text{eff}})$, more damping
1. Probing the CNB average density

\[ N_{\text{eff}} = 3.13 \pm 0.32 \quad (\text{Planck TT+lowP}) \]
\[ N_{\text{eff}} = 3.15 \pm 0.23 \quad (\text{Planck TT+lowP+BAO}) \]
\[ N_{\text{eff}} = 2.98 \pm 0.20 \quad (\text{Planck TT,TE,EE+lowP}) \]
\[ N_{\text{eff}} = 3.04 \pm 0.18 \quad (\text{Planck TT,TE,EE+lowP+BAO}) \]

(all at 68\% CL, BAO from 6dFGS, SDSS-MGS, BOSS-LOWZ, BOSS-CMASS-DR11)
1. Probing the CNB average density

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\( N_{\text{eff}} \) compatible with standard model, > 0 at 10 to 17\( \sigma \) (was ~ 10 to 12\( \sigma \) with Planck 2013)
1. Probing the CNB average density

Are we sure that observed $N_{\text{eff}} \sim 3$ comes from neutrinos? Could be anything scaling like radiation:

- background of gravitational waves
- other light decoupled relics (axions, gravitinos, etc.)
- scalar field oscillating in quartic potential
- standard neutrinos
- neutrinos with exotic interactions (self-inter., or with dark sector)
- effects from modified gravity, extra dimensions...
- other light relics with interactions (self-inter., or with dark sector)
1. Probing the CNB average density

Standard neutrinos have the strongest theoretical motivations.

- Only species giving a definite prediction of $N_{\text{eff}} \sim 3$.
- But can we get extra observational evidence?
- Maybe at level of perturbations?

- gravitational waves
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Standard neutrinos have the strongest theoretical motivations. Only species giving a definite prediction of $N_{\text{eff}} \sim 3$. But can we get extra observational evidence? Maybe at level of perturbations?
2. Probing the CNB \textit{perturbations / anisotropies}

- Until photon decoupling \textit{neutrino perturbations} governed by Vlasov equation, like any decoupled (\textit{free-streaming}) relativistic relic.
- Their density/pressure perturbations, energy flux and anisotropic pressure/shear act as sources in Einstein equations: \textit{gravitational interactions with photons, baryons}.
- Affects the amount of gravitational boost of CMB acoustic oscillations just after Hubble crossing.
- Controls \textit{amplitude and phase of CMB acoustic oscillations}.

Can we observe these free-streaming effects?
2. Probing the CNB perturbations / anisotropies

- Until photon decoupling *neutrino perturbations* governed by Vlasov equation, like any decoupled *(free-streaming)* relativistic relic.

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Can we observe these free-streaming effects?

- later on \(T_\nu<m_\nu\), non-relativistic transition modifies evolution of density perturbations.

Can we see these additional effects of the masses?
Define two phenomenological parameters changing the perturbation equations:

1) Effective sound speed: $\delta p = c_{\text{eff}}^2 \delta \rho$

2) Effective viscosity speed $c_{\text{vis}}$ controlling the amount of anisotropic pressure / shear

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*Archidiacono et al. 2011*

inspired from *Hu 1998, Trotta & Melchiorri 2004...*

---

other Dark Radiation candidates, maybe interacting (EFFECTIVE)

scalar field oscillating in quartic potential (EXACT)
2. Probing the CNB *perturbations / anisotropies*

Effect of varying \((c_{\text{eff}}^2, c_{\text{vis}}^2)\) on CMB spectrum:

![Graph showing the effect of varying\((c_{\text{eff}}^2, c_{\text{vis}}^2)\) on CMB spectrum.](image)

- **Temperature**
- **Polarisation**

Audren et al., arXiv:1412.xxxx (in preparation)
2. Probing the CNB perturbations / anisotropies

If we could prove that \((c_{\text{eff}}^2, c_{\text{vis}}^2) = (1/3, 1/3)\): evidence for CNB anisotropies (through the CMB ones)

If we could prove that \((c_{\text{eff}}^2, c_{\text{vis}}^2) \neq (1/3, 1/3)\): very strong result in favor of alternative Dark Radiation

- Standard neutrinos
- Other light decoupled relics (axions, gravitinos, etc.)
- Scalar field oscillating in quartic potential
- Neutrinos with exotic interactions (self-inter., or with dark sector)
- Effects from modified gravity, extra-dimensions…
- Other light relics with interactions (self-inter., or with dark sector)
- Background of gravitational waves
2. Probing the CNB perturbations / anisotropies

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Parameter & TT+lowP & TT+lowP+BAO & TT,TE,EE+lowP & TT,TE,EE+lowP+BAO \\
\hline
$C_{\text{vis}}^2$ & & & & \\
\hline
$C_{\text{eff}}^2$ & & & & \\
\hline
\end{tabular}
\end{table}

68%CL
2. Probing the CNB perturbations / anisotropies

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<tbody>
<tr>
<td>$c_{\text{vis}}^2$</td>
<td>$0.47^{+0.26}_{-0.12}$</td>
<td>$0.44^{+0.15}_{-0.10}$</td>
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Preliminary

68%CL
2. Probing the CNB perturbations / anisotropies

With polarisation data, Planck detects signature of neutrinos anisotropies with high significance!

68%CL

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2. Probing the CNB *perturbations* / *anisotropies*

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**Can we observe these free-streaming effects?** YES !!!

- later on (*T_ν< m_ν*), non-relativistic transition modifies evolution of density perturbations.

**Can we see these additional effects of the masses?**
2. Probing the CNB *perturbations / anisotropies*

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**Can we observe these free-streaming effects?**  YES !!!

- later on (*T_ν<m_ν*), non-relativistic transition modifies evolution of density perturbations.

**Can we see these additional effects of the masses?**  NOT YET
2. Probing the CNB *perturbations / anisotropies*

Effect of neutrino masses on CMB Temp. for a constant $d_A(\text{dec})$ and fixed "early cosmology" (densities at $T_\nu > m_\nu$):

Also effects on **lensing spectrum** probed by lensing extraction: reduction of power on small scales.
2. Probing the CNB perturbations / anisotropies

- Without lensing extraction:
  
  \[
  m_1 < 0.72 \text{ eV} \quad (\text{Planck } TT + \text{lowP})
  \]
  
  \[
  m_1 < 0.21 \text{ eV} \quad (\text{Planck } TT + \text{lowP} + \text{BAO})
  \]
  
  \[
  m_1 < 0.48 \text{ eV} \quad (\text{Planck } TT, TE, EE + \text{lowP})
  \]
  
  \[
  m_1 < 0.16 \text{ eV} \quad (\text{Planck } TT, TE, EE + \text{lowP} + \text{BAO}) \quad \text{strongest bound}
  \]
2. Probing the CNB perturbations / anisotropies

- With lensing extraction:

\[
\begin{align*}
\hat{m}_1 &< 0.70 \text{ eV} \quad (95\%, \text{Planck TT+lowP+lensing}). \\
\hat{m}_1 &< 0.58 \text{ eV} \quad (95\%, \text{Planck TT,TE,EE+lowP+lensing}). \\
\hat{m}_1 &< 0.23 \text{ eV} \quad (95\%, \text{Planck TT+lowP+lensing+ext}). \\
\end{align*}
\]

final conservative bound
2. Probing the CNB perturbations / anisotropies

... but small tensions with data preferring a low $\sigma_8$ : SZ clusters, galaxy weak lensing, and RSD...
Answer to first question:

We are confident that we have detected the Cosmic Neutrino Background because we can probe with high significance:

1) its background density: $N_{\text{eff}} \sim 3$ matching old theoretical predictions (0 excluded at $17\sigma$)

2) its perturbations in the relativistic regime: $(c_{\text{eff}}^2, c_{\text{vis}}^2) \sim (1/3, 1/3)$ ($c_{\text{vis}}^2=0$ excluded at $9\sigma$)

We don't see yet its perturbations in the non-relativistic regime, but detection of $\Sigma m_\nu$ expected to be just around the corner.
Answer to first question:

We are confident that we have detected the Cosmic Neutrino Background because we can probe with high significance:

1) its background density: $N_{\text{eff}} \sim 3$ matching old theoretical predictions (0 excluded at $17\sigma$)
2) its perturbations in the relativistic regime: $(c_{\text{eff}}^2, c_{\text{vis}}^2) \sim (1/3, 1/3)$ ($c_{\text{vis}}^2=0$ excluded at $8\sigma$)

We don't see yet its perturbations in the non-relativistic regime, but detection of $\Sigma m_\nu$ expected to be just around the corner

Second question: do we see extra light relics?
3. Are there extra light relics?

- Lots of well-motivated candidates for extra relativistic relics. What does active neutrino mass bounds become in this context?

- These candidates could be light instead of ultra-relativistic. Contribute to both $N_{\text{eff}}$ and $M_\nu$. What are bounds on their mass?

- Short baseline oscillation anomaly (LSND, MiniBoone, reactor data…)

  Is one light sterile neutrino with $m \sim 1\text{eV}$ compatible with Planck?
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  Is one light sterile neutrino with $m \sim 1\text{eV}$ compatible with Planck?

- Model dependent analysis. To catch most of the cases, either exactly or approximately, study one case (one massive extra species) but display results in terms of:
  - $N_{\text{eff}}$: parameter for relativstic density at early times
  - $m_{\text{eff}}$: parameter for non–relativistic mass of HDM today ($\omega_{\text{HDM}} = m_{\text{eff}} / 93.14\text{eV}$)
3. Are there extra light relics?

One thermalised sterile neutrino species

Physical masses
(DW sterile neutrino)
(early decoupled thermal particle)

Prior m < 10eV to avoid degeneracy with CDM
3. Are there extra light relics?

- Several datasets prefer low $\sigma_8$ (SZ clusters, galaxy weak lensing, …) but are also sensitive to $H_0$ and $\Omega_m$.
- Direct measurements of Hubble rate prefer high $H_0$.

Assuming massive neutrinos and/or extra radiation brings very marginal reduction of tensions.
3. Are there extra light relics?

No convincing evidence, and stronger bounds than in 2013.
3. Are there extra light relics?

Still, with high-$H_0$ prior from LMC and MW cepheids (Efstathiou 2014):

\[
\begin{align*}
N_{\text{eff}} &= 3.46 \pm 0.25 \\
H_0 &= 71.1 \pm 2.1
\end{align*}
\]

(68\%, Planck TT+lowP+ high $H_0$)