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Neutrino properties from cosmology

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A possible reference point

Particle data group, Neutrinos in Cosmology, Lesgourgues & Verde Chapter 26
https://pdg.lbl.gov/2022/reviews/astro-cosmo.html
(fully updated every 2 years, revised every year*)
What is a neutrino? (for cosmology)

- Behaves like radiation at $T \sim \text{eV}$ (recombination/decoupling)
- Eventually (possibly) becomes non-relativistic, behaves like matter
- Small interactions (not perfect fluid)
- Has a high velocity dispersion (is “HOT”)
Neutrinos

The only known particle behaving as radiation at early time (during the CMB acoustic oscillations) and as dark matter (not cold) at late time (during structure formation).

This has consequences for the background evolution and the structure growth.
Relict neutrinos influence in cosmology

Primordial nucleosynthesis

CMB

Large-scale structure

T ~ MeV

$N_{\text{eff}}$ changes neutron freezeout and hence $Y_{\text{He}}$ & $Y_D$
What do we know and what would we like to know?

How many “neutrinos”? (dark radiation)

Have we really seen the cosmic neutrino background? (i.e. Are we really sure it’s neutrinos?)

Their total mass $M_\nu$ or $\Sigma$
(and are we really sure??)

The individual masses (hierarchy)

Mostly model-dependent statements: measuring cosmological parameters values**
Implications: tldnr

Cosmology is key to determine neutrino masses
Neutrino mass limits

Katrin (detection vs 90% limit)

CMB(Planck) +BAO
+LSS

5% or less effects on P(k)
recap

• There is a CνB
• Cosmology places stringent limits on $\Sigma m_\nu$
• If IH then a measurement is around the corner
• However, IH is under pressure from a Bayesian perspective
• This has important implications
• What if KATRIN measures something?
Boltzmann codes....

- Like CLASS or CAMB have all this (and more in)
- Mostly linear predictions
- They are also shipped with MCMC’s “engines”
- And a suite of data with errors and covariances
- And appropriate likelihoods..... (and non-linear corrections)
- ....to do parameter constraints
What about non-linearities?
$\Sigma m = 0 \text{ eV}$

$\Sigma m = 0.3 \text{ eV}$

$\Sigma m = 1 \text{ eV}$
What about non-linearities?

**Approaches:**
- Analytic i.e. Perturbation theory
- N-body Simulations

**Intermediate:**

**Emulators**

<table>
<thead>
<tr>
<th>Simulate just neutrino masses</th>
<th>Use particles</th>
<th>Use grids</th>
<th>Use hybrid</th>
</tr>
</thead>
</table>

Simulate also hierarchy
Note that non-linearities enhance the signal

This is for MATTER in real space
What about real world effects?

- Baryonic physics (lensing and galaxy surveys)
- Bias (galaxy surveys)
- redshift space (galaxy surveys)
Redundancy is the key
• Cosmic Microwave Background experiments have detected a “dark radiation” (relativistic species which are not photons) with the right abundance to be neutrinos decoupled from the early Universe.
• We want to test if other properties of that fluid are also consistent with neutrinos.
• We want to test that the consistency is robust e.g., against changes in the cosmological parameters.
How many neutrinos?

- Cosmology is sensitive to Neff primarily because energy density in relativistic particles affects directly the universe’s expansion rate during the radiation domination era.
- True for any thermal background of light particles such as axions and axion-like particles, hidden sector photons, majorons, or even gravitons.
- Likewise, any process that alters the thermal abundance of neutrinos (e.g., a low reheating temperature) or affects directly the expansion rate itself (e.g., a time-dependent $G$) can mimic a non-standard Neff.

Degeneracy may not be perfect: effective parameter.
$N_{\text{eff}}$: number of effective species

\[ H^2(t) \simeq \frac{8\pi G}{3} (\rho_\gamma + \rho_\nu) \]

\[ \rho_\nu \propto T^4 N_{\text{eff}} \]

Standard: $N_{\text{eff}}=3.045$

Extra radiation, boosted expansion rate
Any thermal background of light particles,
anything affecting expansion rate

Look at BBN $N_{\text{eff}}$ around 3 to 4

Look at CMB: effects matter-radn equality and so sound horizon at decoupling
\[-\text{degeneracy with } \omega_m \text{ and } H\]

Anisotropic stress,
$z_{\text{eq}}$ on diffusion damping

Main effect: increasing $N_{\text{eff}}$ increases
Silk Damping scale (for fixed $\theta$s),
small phase shifts too

Hou et al 2011
Neutrinos Neff: Physical effects

Neff and the CMB

Naively: changes matter radiation equality but other physics can do that

Keep $z_{eq}$ fixed (and matter to $\Lambda$ fixed, and $wb$) so play with Neff and $H_0$

Increase Silk damping
Neutrinos, Neff: Physical effects

Keep \( \text{zeq} \) fixed (and matter to \( \Lambda \) fixed, and \( \text{wb} \)) so play with Neff and \( H_0 \)

But then you’ve changed

\[
\frac{\Omega_b}{\Omega_c}
\]
Parameter constraints: Neutrino species

Planck collaboration, 2018 paper VI

$H_0$ [$\text{km s}^{-1} \text{Mpc}^{-1}$] vs. $N_{\text{eff}}$

Riess et al. (2018)

$N_{\text{eff}} = 3.11^{+0.44}_{-0.43}$ (95% C.L., TT+lowE+lensing+BAO);

$N_{\text{eff}} = 2.99^{+0.34}_{-0.33}$ (95% C.L., TT,TE,EE+lowE+lensing+BAO).
## Summary $N_{\text{eff}}$ constraints

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>95%CL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CMB alone</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pl18[TT,TE,EE+lowE]</td>
<td>$\Lambda$CDM+$N_{\text{eff}}$</td>
<td>$2.92^{+0.36}_{-0.37}$</td>
</tr>
<tr>
<td><strong>CMB + background evolution + LSS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pl18[TT,TE,EE+lowE+lensing] + BAO</td>
<td>$\Lambda$CDM+$N_{\text{eff}}$</td>
<td>$2.99^{+0.34}_{-0.33}$</td>
</tr>
<tr>
<td></td>
<td>$+$ BAO + R21</td>
<td></td>
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<tr>
<td></td>
<td>$+$5-params.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3.34 \pm 0.14$ (68%CL)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2.85 \pm 0.23$ (68%CL)</td>
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</tr>
</tbody>
</table>
Back a decade

On the other hand…

the cosmic neutrino background has been detected at

$>> 4 \sigma$

99.7% or 0.003
How do you know it’s neutrinos?
“Dark radiation” candidates

- 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)
- other light relics with interactions (self-inter., or with dark sector)
- effects from modified gravity, extra dimensions...

ALL of these scale like radiation!

need EXTRA evidence

Let’s look at the **perturbations**
**The \( \{c^2_{\text{vis}}, c^2_{\text{eff}}\} \) parametrization**

**Background (no anisotropies)**

**Equation of state**
\[
\overline{p} = w_{\text{dr}} \overline{\rho}
\]
\[
\frac{\dot{\rho}}{\rho} = -3(1 + w_{\text{dr}}) \frac{\ddot{a}}{a}
\]

**Sound speed**
\[
\dot{\rho} = c_a^2 \dot{\rho}
\]
\[
c_a^2 = w_{\text{dr}} - \frac{1}{3} \frac{\dot{w}_{\text{dr}}}{1 + w_{\text{dr}}} \left(\frac{\ddot{a}}{a}\right)^{-1}
\]

**First-order Perturbations**

**Isotropic pressure**
\[
\delta p = c_{\text{eff}}^2 \delta \rho
\]

**Anisotropic pressure**
\[
\dot{\sigma} = f \left( c_{\text{vis}}^2 \right)
\]
The $\{c_{\text{vis}}^2, c_{\text{eff}}^2\}$ parametrization

If we can get strong constraints around $c_{\text{vis}}^2 = c_{\text{eff}}^2 = 1/3$ that makes further evidence for neutrino background! Otherwise, alternative dark radiation would be favored.
Effects of $c_{\text{eff}}^2$ on the $\nu$ density perturbations

Perturbations grow as power-law above the sound horizon and begin to oscillate with decaying amplitude below the sound horizon.

Depending on the value of $c_{\text{eff}}^2$ the perturbations will stop growing earlier/later.

Wayne Hu (1998)
Effects of $c^2_{\text{vis}}$ on the $\nu$ density perturbations

$c^2_{\text{vis}}$ mimics the effect of the mean free path of particles in an imperfect fluid with interactions.

The limit $c^2_{\text{vis}} = 0$ corresponds to a negligible mean free path, i.e., to the strongly interacting regime where the pressure remains isotropic.

Wayne Hu (1998)
Effects of $c^2_{\text{vis}}, c^2_{\text{eff}}$ on the T&E
Power spectrum of the CMB

c$^2_{\text{vis}}$ and $c^2_{\text{eff}}$ change the **amplitude** (and shape) of the temperature and polarization power spectra.
c$^2_{\text{vis}}$ and $c^2_{\text{eff}}$ change the **phase** of the acoustic oscillations, especially in the polarization spectra.
The relative effect of $c^2_{\text{vis}}$ and $c^2_{\text{eff}}$ does **not** depend on neutrino mass, at least in the range $\Sigma m_{\nu} < 0.3\text{eV}$.
Effects of $\{c^{2}_{\text{vis}}, c^{2}_{\text{eff}}\}$ on the matter power spectrum

c$^{2}_{\text{eff}}$ modifies power at small scales at the level of several percent. Lyman-alpha forest data should be able to help here!!

These $P(k)$ ratios are again independent of $m_{\nu}$.
### Cosmological constraints

**CMB + CMB lensing**

All cases remain consistent with neutrinos, although in some cases the claim $c^2_{\text{vis}} \neq 0$ weakens.

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**Table:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Lambda$CDM + $c^2_{\text{eff}} + c^2_{\text{vis}}$</th>
<th>$+ N_{\text{eff}}$</th>
<th>$+ m_{\nu}$</th>
<th>$+ w$</th>
<th>$+ \alpha_s$</th>
<th>$+ N_{\text{eff}} + m_{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100 \omega_b$</td>
<td>$2.162^{+0.047}_{-0.052}$</td>
<td>$2.174^{+0.057}_{-0.055}$</td>
<td>$2.124^{+0.048}_{-0.056}$</td>
<td>$2.179^{+0.052}_{-0.056}$</td>
<td>$2.180^{+0.050}_{-0.056}$</td>
<td>$2.136^{+0.060}_{-0.068}$</td>
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<tr>
<td>$\omega_{\text{cdm}}$</td>
<td>$0.1163^{+0.0037}_{-0.0034}$</td>
<td>$0.1181^{+0.0054}_{-0.0051}$</td>
<td>$0.1186^{+0.0037}_{-0.0036}$</td>
<td>$0.1164^{+0.0037}_{-0.0035}$</td>
<td>$0.1163 \pm 0.0035$</td>
<td>$0.1184 \pm 0.0055$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$68.3 \pm 1.1$</td>
<td>$69.6 \pm 2.9$</td>
<td>$63.7^{+1.4}_{-2.6}$</td>
<td>$85.5^{+1.0}_{-4.5}$</td>
<td>$68.3^{+1.1}_{-4.2}$</td>
<td>$65.4^{+1.0}_{-4.2}$</td>
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<tr>
<td>$10^{+9} A_s$</td>
<td>$2.31^{+0.12}_{-0.15}$</td>
<td>$2.34^{+0.12}_{-0.16}$</td>
<td>$2.36 \pm 0.13$</td>
<td>$2.27^{+0.12}_{-0.15}$</td>
<td>$2.35^{+0.13}_{-0.15}$</td>
<td>$2.39 \pm 0.14$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.984^{+0.021}_{-0.012}$</td>
<td>$0.991^{+0.024}_{-0.018}$</td>
<td>$0.981^{+0.018}_{-0.020}$</td>
<td>$0.979^{+0.022}_{-0.021}$</td>
<td>$0.980^{+0.019}_{-0.021}$</td>
<td>$0.987^{+0.025}_{-0.022}$</td>
</tr>
<tr>
<td>$\tau_{\text{reio}}$</td>
<td>$0.090^{+0.012}_{-0.014}$</td>
<td>$0.093^{+0.013}_{-0.014}$</td>
<td>$0.093^{+0.013}_{-0.014}$</td>
<td>$0.088^{+0.012}_{-0.014}$</td>
<td>$0.095^{+0.013}_{-0.016}$</td>
<td>$0.094^{+0.013}_{-0.016}$</td>
</tr>
<tr>
<td>$c^2_{\text{eff}}$</td>
<td>$0.314^{+0.013}_{-0.012}$</td>
<td>$0.314^{+0.013}_{-0.012}$</td>
<td>$0.309^{+0.013}_{-0.014}$</td>
<td>$0.318^{+0.013}_{-0.014}$</td>
<td>$0.320^{+0.014}_{-0.016}$</td>
<td>$0.312^{+0.014}_{-0.013}$</td>
</tr>
<tr>
<td>$c^2_{\text{vis}}$</td>
<td>$0.49^{+0.11}_{-0.22}$</td>
<td>$0.49^{+0.11}_{-0.22}$</td>
<td>$0.49^{+0.11}_{-0.22}$</td>
<td>$0.46^{+0.11}_{-0.23}$</td>
<td>$0.50^{+0.16}_{-0.22}$</td>
<td>$0.56^{+0.14}_{-0.24}$</td>
</tr>
<tr>
<td>$N_{\text{eff}}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>$3.17^{+0.34}_{-0.37}$</td>
</tr>
<tr>
<td>$M_{\nu}$ [eV]</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>$&lt; 1.03$</td>
<td>–</td>
<td>$&lt; 1.05$</td>
</tr>
<tr>
<td>$w$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>$-1.49^{+0.18}_{-0.38}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>$-0.010 \pm 0.010$</td>
<td>–</td>
</tr>
</tbody>
</table>

*Audren et al. JCAP arXiv:1412.5948*
Killing dark radiation candidates

- Background of gravitational waves
- Neutrinos with exotic interactions (self-inter., or with dark sector)
- Effects from modified gravity, extra-dimensions...
- Other light decoupled relics (axions, gravitinos, etc.)
- Scalar field oscillating in quartic potential
- Other light relics with interactions (self-inter., or with dark sector)

courtesy of Julien Lesgourgues
Hierarchy effect on the shape of the linear matter power spectrum

Neutrinos of different masses have different transition redshifts from relativistic to non-relativistic behavior, and their individual masses and their mass splitting change the details of the radiation-domination to matter-domination regime.

\[ \Sigma = 0.1\, \text{eV} \]
\[ \Sigma = 0.06\, \text{eV} \]
How about hierarchy?

In principle there is a signal in LSS, but it is small and at large scales.

Use model-selection techniques (cosmologists do inference so tend to be Bayesian).

Combine with constraints from oscillations.

‘Later or another time’
What is hierarchy?

• There are three masses $m_1$, $m_2$, $m_3$ and therefore only two square mass splitting (measurable quantity). One will be smaller than the other one.
• $m_1, m_2$ refer to the smaller splitting
• $m_3$ can be above (NH) or below (IH) this pair.
• Hierarchy is given by the sign of the larger mass splitting.

Only after the oscillations measurements are in and we find that one mass splitting is much smaller than the other one we can say

One large two small is NH two large one small is IH
Bayesian statistics

The upper limit, $\Sigma \text{meV}/eV < \sim 0.1$ indicate that not all $\Delta$ are possible if neutrinos….

Consistency check!
About the LHS

Let’s dream.....
Bayes
Compute the Bayesian evidence

\[ P(\alpha|D, M) = \frac{P(D|\alpha, M)P(\alpha|M)}{P(D|M)} \]

\[ P(D|M) = \int P(D|\alpha, M)P(\alpha|M)d\alpha \]

\[ P(M|D) = \frac{P(D|M)P(M)}{P(D)} \]

Then take ratios

IT WILL ALWAYS DEPEND ON THE PRIOR

Use oscillations measurements + cosmological limits (assume Gaussian likelihood)
Neutrinos properties from the sky

If it looks like a duck, and quacks like a duck, we have at least to consider the possibility that we have a small aquatic bird of the family anatidae on our hands.

Douglas Adams
English Writer
(1952-2001)
Recap

Cosmic neutrino background, wonderful end-to-end test (indirect)

CMB+LSS limit \[ M_\nu < 0.1 \text{ eV} \]

The pessimist: The inverted hierarchy is under pressure

The optimist: If IH then a measurement of \( M_\nu \) is just around the corner!

IH under pressure, but how much depends on choice of priors

Cosmology is the key to determine neutrino mass scale
It’s challenging: galaxies can be messy, but it’s what we’ve got.
Model dependent statement.
However, a wonderful end-to-end test.
Conclusions

• Precision cosmology means that we can start (or prepare for) constraining interesting physical quantities.

• Neutrino properties: absolute mass scale, number of families, possibly hierarchy.

• My “bet”: $0.06 < \Sigma m_\nu / eV < \sim 0.1$ (95%) Large future surveys mean that sub % effects become detectable, which brings in a whole new set of challenges and opportunities (e.g., mass, hierarchy).

• The (indirect) detection of neutrino masses is within the reach of forthcoming experiments (even for the minimum mass allowed by oscillations).

• Systematic and real-world effects are the challenge, need for in-build consistency checks!

• COMPLEMENTARITY is key.
In summary:

- \( N_{\text{eff}} \) consistent with 3
- These are “light” neutrinos (<0.1* eV at 95% CL)
- More wiggle room: go beyond the minimal LCDM (errors gets slightly larger, but… epicycles)
- Avoid thermalization (some v. radical options)
Implications

Strong Bayesian Evidence for NH, when using the stated priors

Double beta decay experiments: favours experimental techniques reaching multi-ton active mass detectors and very low background

Experiments more sensitive to normal mass hierarchy are much more likely to be successful

Conclusions could be evaded by drastically changing the prior, but you will have to be very convincing

Or by measuring $0\nu\beta\beta$ decay.
Dirac or Majorana? ↔ hierarchy

Are neutrinos their own anti-particle? (are they Majorana or Dirac?)

0νββ (next generation)

Yes

No

Because Dirac OR because below threshold (still unknown)?

Majorana

Dayabay and other