Neutrinos

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Motivations

- Neutrino oscillations prove that there is a mass mixing matrix:

\[
\begin{pmatrix}
\nu_e & \nu_\mu & \nu_\tau \\
\end{pmatrix}
\begin{pmatrix}
* & * & * \\
* & * & * \\
* & * & * \\
\end{pmatrix}
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix}
\]

- Propagating mass eigenstates

- Flavor eigenstates: \(m_1, m_2, m_3, \theta_{12}, \theta_{23}, \theta_{13}, \delta\)

- Right-handed (Dirac) or self-conjugate (Majorana)

- Laboratory experiments measured:
  - 2 squared mass differences, 3 angles, bounds on phase
  - One missing mass! Knowing one new combination would fix everything (maybe up to ordering option) …

- Normal and inverted hierarchy:

\[
\begin{align*}
M_\nu > 0.11 \text{ eV} \\
0.06 \text{ eV}
\end{align*}
\]
Motivations

... for measuring total neutrino mass $M_N$ with cosmology:

- **For particle physicists**
  - More sensitive than $\beta$- and double-$\beta$- decay (KATRIN, GERDA, ...), works for Dirac and Majorana
  - Complementary to $\beta$-decay which contains independent information (on phases, angles, Dirac/Majorana...)
  - Can lead to full understanding of neutrino sector (or give hint of extensions to e.g. sterile neutrinos)
  - Hints on seesaw, leptogenesis, baryogenesis...
Motivations

... for measuring total neutrino mass $M_\nu$ with cosmology:

- **For cosmologists**
  - **Safest output/reward of current observational efforts**
  - Neglect neutrinos would **bias** results; e.g.:
    - neglecting $>5\%$ effect in small-scale power spectrum would point incorrectly to running, modified gravity etc…
    - At least $1\%$ impact on $H_0$ value inferred from CMB (through angular diameter distance)
  - Excluding $M_\nu \sim 0.11$eV would **rule out IH**
  - Excluding $M_\nu \sim 0.06$ eV would **point out at new physics or cosmology**
    - Neutrinos decay or interact strangely
    - Standard neutrino decoupling does not apply (low-temperature reheating, entropy production, etc.)
Neutrino mass detection with CMB

A. Background effects:

1. for same equality redshift, peak scale, \( z_{\text{reio}} \), change \( H_0, \Omega_\Lambda \): late Integrated Sachs-Wolfe, shifted \( \tau_{\text{reio}} \), ...

   Constant peak angular scale: \( \Delta H_0 / [1 \text{ km/s/Mpc}] = - \Delta M_\nu / [0.1\text{eV}] \)

   \( \Delta H_0 = 0.6 \text{ km/s/Mpc} \) coming from different choice of fiducial model \( (M_\nu = 0 \rightarrow 0.06\text{eV}) \)

2. also small background effect on recombination history [Grohs et al. 1412.6875]

B. Perturbation effects:

3. early Integrated Sachs-Wolfe effect when neutrinos become non-relativistic at \( 500 < z < 1000 \)

   produces a feature in temperature spectrum for \( 10 < l < 200 \)

4. fraction of neutrinos already non-relativistic at decoupling: slightly modified neutrino-photon gravitational interaction (very small)

5. reduced CMB lensing (spectrum of temperature, polarisation, extracted lensing potential):

   dominant effects
Neutrino mass detection with CMB

TT, minimal NH, $M_{\nu} = 0.06$ eV

- primary
- primary+ISW
- primary+ISW+lensing

Cosmic Variance

CORE+

(1) (3) (5)
Neutrino mass detection with CMB

EE, minimal NH, $M_\nu=0.06$ eV

Primary+ISW
Primary+ISW+lensing

LiteCORE-120cm
LiteCORE-150cm
CORE+
Cosmic Variance

(1)
Neutrino mass detection with CMB

BB, minimal NH, $M_\nu=0.06$ eV (simplifying gaussian approximation)

LiteCORE-120cm
LiteCORE-150cm
CORE+
Cosmic Variance
Neutrino mass detection with CMB

DD, minimal NH, $M_\nu=0.06$ eV

- LiteCORE-120cm
- LiteCORE-150cm
- CORE+
- Cosmic Variance

$L^2$ maps for different experiments
Suite of 81 MCMC MontePython forecasts

at TTK (RWTH Aachen),

with Thejs Brinckmann and Sébastien Clesse.
### Suite of 81 MCMC MontePython forecasts

**A. Instruments:** Core+ / LiteCore 150cm / LiteCore 120cm

<table>
<thead>
<tr>
<th>Channel [GHz]</th>
<th>FWHM [arcmin]</th>
<th>$\Delta T$ [$\mu K$ arcmin]</th>
<th>$\Delta P$ [$\mu K$ arcmin]</th>
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</thead>
<tbody>
<tr>
<td><strong>LiteCORE-120, $l_{\text{max}} = 3000$, $f_{\text{sky}} = 0.7$</strong></td>
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Suite of 81 MCMC MontePython forecasts

A. Instruments: Core+ / LiteCore 150cm / LiteCore 120cm

B. Likelihoods:
   - Unlensed TT, TE, EE
   - Lensed TT, TE, EE, BB (*neglecting intrinsic non-gaussianity; delensing irrelevant*)
   - Lensed TT, TE, EE + extracted deflection field DD
Suite of 81 MCMC MontePython forecasts

A. **Instruments:** Core+ / LiteCore 150cm / LiteCore 120cm

B. **Likelihoods:**
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C. **Fiducial models:** minimal NH, minimal IH

D. **Fitted models:** $\Lambda$CDM extensions:
   - 7 params ($M_\gamma$),
   - 8 params ($Y_{He}$, $r$, $w$, $N_{eff}$, running, $\Omega_k$)
Suite of 81 MCMC MontePython forecasts

First conclusion: even with Core+, mass splitting is irrelevant

<table>
<thead>
<tr>
<th>Fiducial model</th>
<th>Fitted model</th>
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<td>NH (minimal $M_\nu \sim 0.06\text{eV}$)</td>
<td>Degenerate ($M_\nu &gt;0$)</td>
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Suite of 81 MCMC MontePython forecasts

Second conclusion: same results with lensed BB or lensing extraction, excepted for $\Lambda$CDM + $M_\nu + \Omega_k$ (while without lensing at all: 4 times worse)
Suite of 81 MCMC MontePython forecasts

Third conclusion: minor impact of resolution / sensitivity, in most cases $\sigma(M_\nu) \sim 44$ meV

Results based on runs with lensing extraction:

<table>
<thead>
<tr>
<th>Symmetrised $\sigma(M_\nu)$ in meV</th>
<th>LiteCore120</th>
<th>LiteCore150</th>
<th>Core+</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$CDM + $M_\nu$</td>
<td>45</td>
<td>44</td>
<td>43</td>
</tr>
<tr>
<td>$\Lambda$CDM + $M_\nu + \Delta N_{\text{eff}}$</td>
<td>45</td>
<td>44</td>
<td>44</td>
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<tr>
<td>$\Lambda$CDM + $M_\nu + w$</td>
<td>36</td>
<td>36</td>
<td>35</td>
</tr>
<tr>
<td>$\Lambda$CDM + $M_\nu + Y_{\text{He}}$</td>
<td>45</td>
<td>44</td>
<td>44</td>
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<tr>
<td>$\Lambda$CDM + $M_\nu + \text{running}$</td>
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<tr>
<td>$\Lambda$CDM + $M_\nu + r$</td>
<td>43</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>$\Lambda$CDM + $M_\nu + \Omega_k$</td>
<td>92</td>
<td>88</td>
<td>84</td>
</tr>
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volume effect in Bayesian parameter inference: $w>-1$ or $r>0$ requires smaller $M_\nu$
Conclusions

• LiteCore / Core+ alone:
  • robust errorbar $\sigma(M_\nu) \sim 44$ meV
  • (excepted with free $\Omega_k$ : twice worse sensitivity)

• Very useful probe in combination with LSS experiments
  • Planck + Euclid : $\sigma(M_\nu) = 25$-$30$ meV : at least 2 sigma detection
  • Core+ / LiteCore + Euclid : $\sigma(M_\nu) = 15$-$20$ meV: at least 3-$4$ sigma detection
  • Even better with SKA?
Core+ with lensed BB or lensing extraction

$\Lambda$CDM + $M_\nu + \Delta N_{\text{eff}}$
Core+ with lensed BB or lensing extraction
\( \Lambda CDM + M_\nu + w \)
Core+ with lensed BB or lensing extraction
$\Lambda CDM + M_\nu + Y_{\text{He}}$
Core+ with lensed BB or lensing extraction
\( \Lambda CDM + M_\nu + \text{running} \)
Core+ with lensed BB or lensing extraction

$\Lambda$CDM + $M_\nu + \Omega_k$
LiteCore 150cm with lensed BB or lensing extraction
$$\Lambda CDM + M_\nu + \Omega_k$$
LiteCore 120cm with lensed BB or lensing extraction
$\Lambda$CDM + $M_\nu + \Omega_k$