Neutrino mass and mass hierarchy from cosmology

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Based On...

- **Updated results on neutrino mass and mass hierarchy from cosmology with Plank 2018 liklelihoods**, **S. Roy Choudhury** and S. Hannestad, **JCAP 2007 (2020) 037**, arXiv: 1907.12598.

Introduction

- **Neutrino masses are the only direct evidence for Beyond Standard Model physics.**
- Active neutrinos have three mass eigenstates (ν_1, ν_2, and ν_3) which are quantum superpositions of the 3 flavour eigenstates (ν_e, ν_μ, and ν_τ).
- Cosmology is sensitive to:

$$\sum m_\nu \equiv m_1 + m_2 + m_3, \tag{1}$$

- Tightest bounds on $\sum m_\nu$ come from cosmology.

Introduction

- Flavour transition probability in vacuum: $P_{\alpha\to\beta} \propto sin^2\left(\frac{\Delta m^2 L}{E}\right)$
- $\Delta m^2_{21} \equiv m_2^2 - m_1^2 \simeq 7.6 \times 10^{-5}$ eV^2
- $|\Delta m^2_{31}| \equiv |m_3^2 - m_1^2| \simeq 2.5 \times 10^{-3}$ eV^2
- **At least 2 out of 3 eigenstates are massive.**
- **Since the sign of Δm^2_{31} is not known** $\rightarrow$ two possible orderings.
  +ve:
  normal hierarchy (NH) with $m_1 < m_2 \ll m_3$,
  or -ve:
  inverted hierarchy (IH) with $m_3 \ll m_1 < m_2$.
- **In cosmology we use the degenerate hierarchy approximation** (DH): $m_1 = m_2 = m_3 = \sum m_\nu/3$.

Introduction

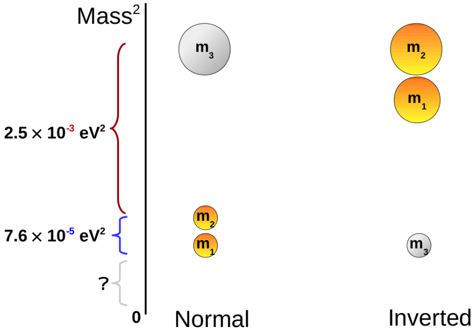


Figure: Image credit: Hyper-Kamiokande Collaboration

Our Method

- **We implement the neutrino hierarchy cases separately:** DH, NH, IH.
- **The lightest neutrino mass** m_0 is **used as a free parameter**. Allows room for further analysis combining with oscillations data.
- To implement the normal and inverted hierarchy, we use the mean values of the mass squared splittings and define m_1, m_2, and m_3
- $\sum m_\nu$ **is a derived parameter.** For DH, $\sum m_\nu = 3m_0$.
- **Flat prior on** m_0 **translates to an implicit near-flat prior on** $\sum m_\nu$:

$$\sum m_\nu \geq 0 \text{ eV (DH)},$$

$$\sum m_\nu \geq 0.06 \text{ eV (NH)},$$

$$\sum m_\nu \geq 0.10 \text{ eV (IH)}.$$

Implicit prior on $\sum m_\nu$

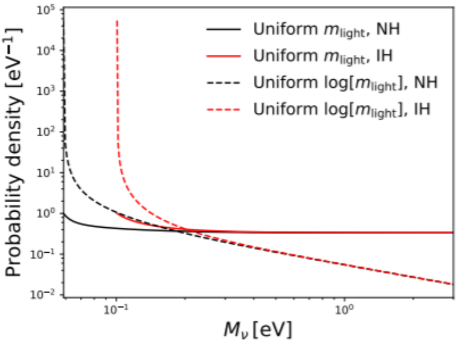


Figure A.6: Prior probability distribution of the sum of the neutrino masses M_ν in the case of uniform prior over $m_{\rm light}$ (solid) and $\log(m_{\rm light})$ (dashed) when assuming either normal (black) or inverted (red) hierarchical mass scenarios.

Figure: Image credit: M. Gerbino et al, Phys.Lett. B775 (2017) 239-250, arXiv: 1611.07847

Origin of some parameter degeneracies with $\sum m_\nu$:

- **$\sum m_\nu$ is degenerate with H_0, $w_{DE}(z) = w_0 + w_a z/(1+z)$, Ω_k.**
- **Origin is the angular diameter distance to the last scattering surface**:

$$D_A(z^*) \equiv \sin\left(\sqrt{K\chi(z^*)}\right)/\sqrt{K}; \quad \text{with} \quad \chi(z^*) = \int_0^{z^*} dz/H(z). \tag{2}$$

where $K = -\Omega_K H_0^2$

- **It is well-constrained by the Planck data given pre-recombination physics is not affected**

$$H^2(z) = \omega_\gamma(1+z)^4 + (\omega_c+\omega_b)(1+z)^3 + \omega_{DE}(z) + \omega_k(1+z)^2 + \omega_\nu(z). \tag{3}$$

- At late times, $\omega_\nu(z) = \Omega_\nu(z)h^2 \propto \sum m_\nu$.
- $$\Omega_{DE}(z) = \Omega_{DE}(0)(1+z)^{3(1+w_0+w_a)}\exp\left(-3w_a\frac{z}{1+z}\right). \tag{4}$$
- For ΛCDM: $w(z) = -1$. For wCDM: $w(z) = w$.

Degenracies: wCDM + $\sum m_\nu$

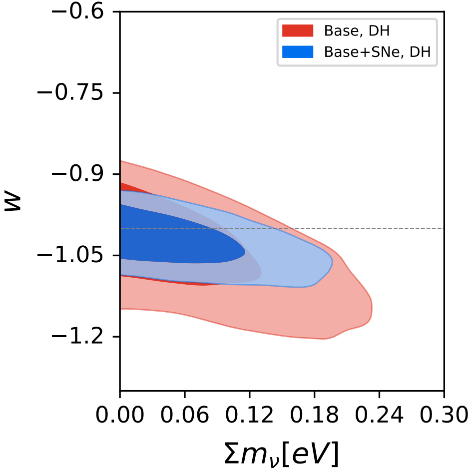


Figure: Base ≡ Planck 2018 TT,TE,EE+ lowE + lensing + BAO

Degenracies: $w_0 w_a \mathrm{CDM} + \sum \mathrm{m}_\nu$

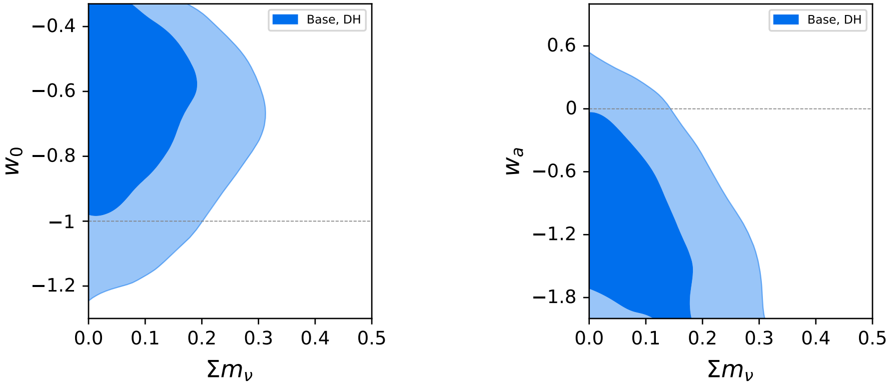
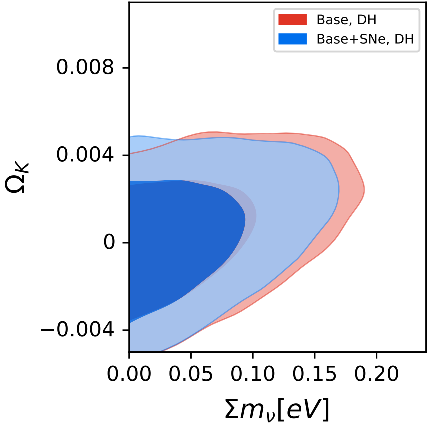


Figure: Base ≡ Planck 2018 TT,TE,EE+ lowE + lensing + BAO

Degenracies: $\Lambda\text{CDM} + \sum m_\nu + \Omega_k$



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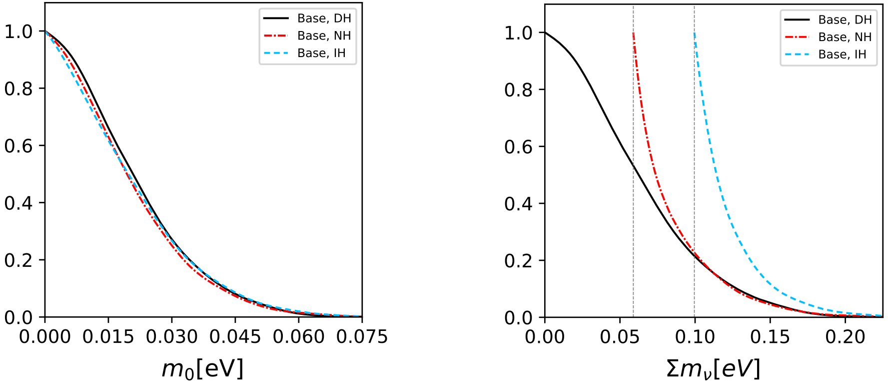

Figure: Base ≡ Planck 2018 TT,TE,EE+ lowE + lensing + BAO

Results: 95% C.L. bounds on $\sum m_\nu$ (eV)

	Base		
	DH	NH	IH
ΛCDM $+ \sum m_\nu$	< 0.12	< 0.15	< 0.17
wCDM $+ \sum m_\nu$	< 0.19	< 0.21	< 0.23
$w_0 w_a$CDM $+ \sum m_\nu$	< 0.25	< 0.26	< 0.28
ΛCDM $+ \sum m_\nu + \Omega_k$	< 0.15	< 0.17	< 0.20

Table: Base $\equiv$ Planck 2018 TT,TE,EE+ lowE + lensing + BAO

Model comparison

- With $\Lambda\mathrm{CDM} + \sum \mathrm{m}_\nu$ with Base data, $\Delta\chi^2_{\mathrm{NH-IH}} = -0.95$.
- Bayesian Odds(NH:IH) = 1.43 : 1 (from Bayesian evidence calculations) $\rightarrow$ **Inconclusive**.
- **Preference for NH from cosmological data is mild.** Similar results in extended models.

Some key points

- Currently no evidence for non-zero neutrino masses from Cosmology.
- Mild preference for NH driven by prior volume effects, not physical effects.
- However, upper bound on $\sum m_\nu$ from Cosmology is quite strong in the ΛCDM model ($\sum m_\nu < 0.12$ eV at 95% C.L. with DH).
- Bounds can relax up to a factor 2 in simple extensions to ΛCDM.
- Upper bounds change from DH to NH to IH, again due to prior volume effects, not physical effects.

Next Decade: Possible improvements on $\sum m_\nu$ bounds

- **CMB-S4**: improved measurements on CMB Polarization, lensing.
- **LiteBIRD, PIXIE**: improved measurement of τ, CMB B-mode.
- **Euclid, Vera C. Rubin Observatory** (formerly LSST), **Nancy Grace Roman Space Telescope** (formerly WFIRST): improved BAO and matter power spectrum.
- Cosmology might be able to detect normal hierarchy at 2σ if true value of $\sum m_\nu < 0.1$ eV and we have a sensitivity of $\sigma_{m_\nu} < 0.02$ eV.
- **This seems possible within the next decade. Let us hope for the best!**

Thank you.