What cosmology can tell us about neutrinos

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Prologue

- **Neutrino mass sum**: more precise than $\beta$ (KATRIN) and double $\beta$ decay (GERDA), but more model dependent. Not sensitive to Dirac vs Majorana, mixing angles, phases ...

- **Hierarchy**: not specifically sensitive to the hierarchy like NOvA, DUNE, PINGU, ORCA, Hyper-K, but the IH might be ruled out.

- **Effective number of relativistic degrees of freedom**, $N_{\text{eff}}$, ($\sim$Neutrino number)
Outline

- Neutrino mass sum:
  - State of the art: observables and current bounds
  - Future prospects of constraining the neutrino mass sum and possibly the hierarchy

- $N_{\text{eff}}$:
  - Sterile neutrinos
Observables

- $z = 1100$ (CMB)
- $z \approx 0-1$ (LSS)
- $z = 13$, $\nu = 1.4$ GHz (21cm SKA)
- $z = 0$, $\nu = 100$ MHz (21cm SKA)

Neutral IGM

Cosmic "Dark Ages"

First stars

First galaxies

Reionization

Hubble 2009

Hubble 2012

Big Bang

Recombination
CMB: TT, EE, TE, lensing

$\nu = 1.4 \text{ GHz}$

$z = 13$

$\nu = 100 \text{ MHz}$

$z = 1100$

21cm SKA

LSS

Bkg. effects only at late times: late ISW

Perturb. effects: early ISW.
CMB: TT, EE, TE, lensing

Bkg. effects only at late times: late ISW
Perturb. effects: early ISW.

Suppression of lensing potential

\[ \sum m_\nu < 0.59 \text{ eV} \quad 95\% \text{cl} \]
LSS: BAO, galaxy clustering

BAO geometric information

$P(k)$ shape information: more powerful, but, at the same time, more affected by systematics

$P_m(k,z) = b^2 P_g(k,z)$

$\sum m_\nu < 0.13 \text{ eV} \quad 95\% \text{cl}$

Cuesta, Niro, Verde, Phys. Dark Univ (2016)
LSS: galaxy lensing

Distortion of distant galaxy images by intervening matter

$\sum m_\nu < 0.30 \text{ eV } 95\% \text{cl}$

Leistedt, Peiris, Verde, PRL (2014)
The decrement in cosmologies with massive and massless neutrinos can be understood if we look at Eq. (2006). Using our description of the procedure used to calculate this, we have checked that using a mean redshift $z = 13$, while these have a redshift range $z \sim 0-1$, they cover a redshift range $z = 2014b$, they are $\omega_{b} = 0.05$, $\omega_{m} = 0.25$, and $\omega_{m} = 0.7$, with $z_{\nu} = 3.4$. 

$$P_{21}(k,z) = T_{b}^{2} P_{m}(k,z), \text{ where } T_{b} = T_{b}(\omega_{b}, \omega_{m}, x_{HI})$$

$$\sigma(M_{\nu}) = 56 \text{ meV}$$

Planck+SKA

Mao, Tegmark, McQuinn, Zaldarriaga, Zahn, PRD (2008)
Current $M_\nu$ constraints

The sensitivity is affected by degeneracies, even in the minimal 6+1 parameter model.

- Model dependence of cosmological results.
- Combining different probes at different redshift will provide robust results.

Archidiacono, Brinckmann, Lesgourgues, Poulin, JCAP (2017)
Archidiacono, Brinckmann, Clesse, Lesgourgues, in preparation
Future $M_\nu$ constraints
LSS: Euclid

Galaxy clustering

$$P(k, z) = \left\langle |\delta_m(k, z)|^2 \right\rangle$$

$$\delta_{cdm} \propto a$$

$$\delta_{cdm} \propto a^{1-3/5 f_\nu}$$

$$f_\nu = \frac{\omega_\nu}{\omega_m}$$

Galaxy lensing

Observational + theoretical error

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Observational + theoretical

$M_{ν, ref} = 60 \text{ meV}; M_{ν, fid} = 60 \text{ meV}$

$σ(M_ν) = 17 \text{ meV}$

Preliminary

Archidiacono, Brinckmann, Lesgourgues, Poulin, JCAP (2017)
Archidiacono, Brinckmann, Clesse, Lesgourgues, in preparation
Future $M_\nu$ constraints
21cm SKA

The independent measurement of the epoch of reionization by 21cm surveys may break the degeneracy between the neutrino mass and $\tau_{\text{reio}}$ which appears in combined analyses of future CMB+LSS data.

However, the measurement of the optical depth at reionization $\tau_{\text{reio}}$ by 21-cm surveys will be subject to uncertainties coming from the detailed modelling of very non-linear astrophysical processes, and it is currently difficult to predict the sensitivity of future experiments to this parameter.

Liu et al., PRD (2016)
If nature has chosen the neutrino mass sum to be close to the minimum value allowed by oscillation experiments in the normal hierarchy $M_\nu = 60$ meV, then future cosmological data will detect this value at 4-5σ c.l. This would put some pressure on the inverted hierarchy.

$$k > k_{nr} = 0.018 \left( \frac{m_\nu}{eV} \right)^{1/2} \Omega_m^{1/2} h / Mpc$$

The scale of the non-relativistic transition depends on the single neutrino mass.

Hannestad, Schwetz, JCAP (2016)
\( N_{\text{eff}} \) from Planck

- \( \Lambda \text{CDM} + N_{\text{eff}} \ (N_{\text{eff}}^{\text{standard}} = 3.046) \)
  \[ N_{\text{eff}} = 3.04 \pm 0.18 \ (68\% \text{c.l.}) \ (\text{Planck+BAO}) \]

- \( H_0 = (67.31 \pm 0.96) \text{ km/s/Mpc} \)
  \[ (68\% \text{c.l.}) \ (\text{Planck}) \]
  \[ H_0 = (73.24 \pm 1.74) \text{ km/s/Mpc} \]
  \[ (68\% \text{c.l.}) \ (\text{HST, Riess et al., Apj (2016)}) \]

- \( \sigma_8 \) tension between Planck and CFHTLens
  (Kilbinger at al., MNRAS(2013)), alleviated by DES (Abbott at al., PRD(2016))
$N_{\text{eff}} + m_{\nu, \text{sterile}}^\text{eff}$ from Planck

$\Lambda\text{CDM} + N_{\text{eff}} + m_{\nu, \text{sterile}}^\text{eff}$

$N_{\text{eff}} < 3.7$ & $m_{\nu, \text{sterile}}^\text{eff} < 0.38$ eV (95\%c.l.)

(Planck + BAO)

Planck tension with HST (CFHTLens) does not represent an escape route!

- $\chi^2$ does not improve
- Tension with SBL

Gariazzo, Giunti, Liu, Global fit (2017)

Talk by C. Giunti
Talk by P. Guzowski
Non-standard sterile neutrino self-interactions

- $N_{\text{eff}}$: Secret interactions induce an additional MSW-like potential. If the potential is dominating at $T \geq 1$ MeV, the in medium mixing angle is suppressed and the sterile neutrino production is delayed until after the active neutrino collisional decoupling. The distribution of sterile neutrinos turns out to be partially non-thermal.

- $M_\nu$: Since the collisional term is proportional to $T$, while $H \sim T^2$, sterile neutrinos and light pseudoscalars will re-couple. After the non-relativistic transition, sterile neutrinos will start annihilating into pseudoscalars; the process will last until the final decoupling.

Archidiacono, Hannestad, Hansen, Tram, PRD (2016)
Archidiacono, Gariazzo, Giunti, Hannestad, Hansen, Laveder, Tram, JCAP (2016)
Chu, Dasgupta, Kopp, JCAP (2015)
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Conclusions

• Future galaxy and hydrogen surveys will be able to pin down the neutrino mass sum in the minimal extension of the ΛCDM.

In this case: Inverted Hierarchy is excluded at 2-3 σ.

• Cosmology rules out light sterile neutrinos, unless there are non-standard sterile neutrino self-interactions.

• Take-home message: data tension ➔ model extension!
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