NEUTRINO PROPERTIES FROM COSMOLOGY

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see also Gerbino&Lattanzi2017
Some basic facts

- Standard cosmological model predicts the existence of a background of relic neutrinos ($C_{\nu}B$)
- $\Gamma_w > H(T \geq 1\text{MeV})$ -> Thermal equilibrium with primordial plasma ($T_\nu = T$)
- $T < 1\text{ MeV}$ -> neutrino free stream keeping an equilibrium spectrum ($T_\nu \neq T$, $T_\nu \propto 1/a$):
  \[
  f_\nu(p) = \frac{1}{e^{p/T} + 1}
  \]
- Today $T_\nu = 1.9\text{ K}$ and $n_\nu = 113 \text{ part/cm}^3$ per species
Neutrino phenomenology

Neutrinos were relativistic in the early Universe

\[ \rho_\nu = g_\nu \int p f(p) d^3 p \propto g_\nu T^4_\nu \]

so they contributed to the radiation density

\[ \rho_{rad} = \rho_\gamma + \rho_\nu = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \right] \rho_\gamma \]

with \( \rho_x \propto g_x T^4_x, T_\nu/T_\gamma = (4/11)^{1/3} \)

\[ N_{eff} = \frac{\rho_{rad} - \rho_\gamma}{\rho^\text{st}_\nu} = 3.046 \]

Neff could account for any 'extra' radiation component

Dolgov, 1997
Mangano+, 2005
deSalas & Pastor, 2016
Neutrino phenomenology

Neutrinos are non-relativistic today

\[ \rho_{\nu} = m_{\nu} n_{\nu} = m_{\nu} g_{\nu} \int f(p) d^3 p \propto m_{\nu} g_{\nu} T_{\nu}^3 \]

so they contribute to the matter content

\[ \Omega_{\nu} = \sum_{\nu} \frac{\rho_{\nu}}{\rho_c} = \frac{\sum_{\nu} m_{\nu}}{93.14 h^2 \text{eV}} \]

\[ \rho_c = \frac{3 H^2}{8 \pi G} \]

3 active families, sub-eV masses

Relativistic at early times, non-relativistic today

Peculiar effects on cosmological observables
Effects on background quantities

Expansion rate

$$H(z)^2 = H_0^2 \left[ (\Omega_c + \Omega_b)(1 + z)^3 + \Omega_\gamma (1 + z)^4 + \Omega_\Lambda + \frac{\rho_\nu(z)}{\rho_{\text{crit},0}} \right]$$

modifies the angular size of the sound horizon at recombination

$$\theta_s = \frac{r_s}{D_A}$$

modifies the angular scale of the Silk damping

$$\theta_d = \frac{r_d}{D_A} \propto \frac{1}{\sqrt{H}} \frac{1}{1/H}$$

$$1 + z_{\text{eq}} = \frac{\Omega_c + \Omega_b}{\Omega_\gamma \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right]}$$

Matter-radiation equality
Perturbation effects

$$k_{fs} \approx 0.018 \Omega_m^{1/2} \left( \frac{m_\nu}{1 \text{ eV}} \right) h \text{Mpc}^{-1}$$  \hspace{1cm} \text{Free streaming scale}

$$\delta_m(k \gg k_{fs}) \propto a^{1-(3/5)f_\nu}$$  \hspace{1cm} \text{Suppressed growth}

$$k_p r_s + \phi = p\pi$$  \hspace{1cm} \text{Acoustic phase shift}
Effects on the CMB spectrum

sound horizon at recombination

matter-equality

\[ \Delta D^{TT}_\ell [\mu K^2] \]

Planck collaboration

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Effects on the CMB spectrum

Silk damping

Hou et al, 2014

Credits: M. Lattanzi

Time of matter radiation equality and angle subtended by the sound horizon at LSS are held fixed

Ncuts = 2.5
Ncuts = 2.75
Ncuts = 3.046
Ncuts = 3.25
Ncuts = 3.5

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Effects on the CMB spectrum

Follin et al., 2015

Phase shift

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Effects on the CMB spectrum

CMB lensing

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\[ \ell \]
Effects on the matter spectrum

- free-streaming
- sound horizon at baryon decoupling
- phase shift

(B - P_{\Sigma m_0})/P_{\Sigma m_0} = 0

\(k (h/\text{Mpc})\)

\(\Sigma m_\nu = 0\)
\(\Sigma m_\nu = 50 \text{ meV}\)
\(\Sigma m_\nu = 100 \text{ meV}\)
\(\Sigma m_\nu = 150 \text{ meV}\)

Abazajian+, 2015

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Current limits on the neutrino mass scale

\[ \sum m_\nu [\text{eV}] \]

\[ m_{\text{light}} [\text{eV}] \]

Gerbino & Lattanzi, 2017

- IH
- NH

\[ m_3 \ll m_1 \ll m_2 \]
\[ m_1 \ll m_2 \ll m_3 \]
Current limits on the neutrino mass scale

\[ \sum m_\nu < 0.72 \text{ eV} \]

\[ m_3 \ll m_1 < m_2 \]

\[ m_1 < m_2 \ll m_3 \]
Current limits on the neutrino mass scale

\[ \sum m_\nu < 0.72 \text{ eV} \]

\[ \sum m_\nu < 0.25 \text{ eV} \]

\[ m_3 \ll m_1 < m_2 \]

\[ m_1 < m_2 \ll m_3 \]
Current limits on the neutrino mass scale

\[ \sum m_\nu < 0.72 \text{ eV} \]

\[ \sum m_\nu < 0.37 \text{ eV} \]

\[ \sum m_\nu < 0.25 \text{ eV} \]
Current limits on $N_{\text{eff}}$

**Planck**

$N_{\text{eff}} = 3.13 \pm 0.32$

**Planck+BAO**

$N_{\text{eff}} = 3.15 \pm 0.23$

- Standard value
- Fully-thermalized additional species
Current limits on sterile neutrinos

\[ \text{Planck+lensing + BAO 95\%CL} \]

\[ N_{\text{eff}} < 3.7 \]
\[ m_{\nu, \text{sterile}}^{\text{eff}} < 0.38 \]

\[ m_{\nu, \text{sterile}} = (\Delta N_{\text{eff}})^{3/4} m_{\text{thermal}} \]

thermally distributed (dashed)

\[ m_{\nu, \text{sterile}} = \Delta N_{\text{eff}} m_{\text{sterile}}^{\text{DW}} \]

Dodelson-Widrow (dotted)
Roadmap to the future

| Year | Stage | Sensitivity ($\mu K^2$) | $\sigma(r)$ | $\sigma(N_{\text{eff}})$ | $\sigma(\Sigma m_v)$ |
|------|-------|-------------------------|-------------|-------------------------|---------------------|
| 2015 | Stage 2 | $\geq 10^{-5}$ | 0.035 | 0.14 | 0.15 eV |
| 2016 | Stage 3 | $10^{-5}$ | 0.006 | 0.06 | 0.06 eV |
| 2017 | Stage 4 | $10^{-6}$ | 0.0005 | 0.027 | 0.015 eV |
| 2022 | CMB-S4 | $10^{-8}$ |  |  |  |

Target

CMB Stage-IV white paper
CONCLUSIONS

Determine CnB properties from neutrino peculiar effects on cosmological observables

Strong and robust constraints from cosmology

Neutrino masses: getting closer to the non-degenerate region

Neff: no preference for an additional thermalised species

Next generation surveys will probe the physics of non-instantaneous decoupling and detect the neutrino mass scale with high statistical significance
BACKUP SLIDES
Complementarity with laboratory searches

![Graph showing complementarity with laboratory searches](image)
Complementarity with laboratory searches

\[ m_{\beta\beta}[\text{eV}] \]

\[ m_{\text{light}}[\text{eV}] \]

IH

NH

Future 0ν2β

CORE + BAO, ΛCDM + Σm\text{y},
CORE + BAO, ΛCDM + Σm\text{y}, + Ω\text{K}
CORE, ΛCDM + Σm\text{y},

Gerbino & Lattanzi, 2017

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Joint constraints on $M_{\nu}$ - future

$\Sigma m_{\nu}$ (eV) vs. $m_{\text{lightest}}$ (eV)

- Current Cosmology (95% U.L.)
- KATRIN c. 2020 (95% U.L.)
- CMB-S4 + DESI BAO
- Inverted Hierarchy
- DUNE
- Normal Hierarchy

$\sim 3\sigma$ detection in the minimal mass scenario with S4 surveys
Sensitivity to the hierarchy

Physical effects due to different distribution of the sum of the masses for the 2 hierarchies

Total nu energy density

Matter power spectrum

Are current (and future) data sensitive to these effects? How much?
Sensitivity to the hierarchy

$P(h = NH) : P(h = IH)$

$\cdots \cdots \cdots \cdots 3:2$

$P(h = NH) : P(h = IH)$

$\cdots \cdots \cdots \cdots 0.06\text{eV mass} \rightarrow 9:1$

$\cdots \cdots \cdots \cdots 0.1\text{eV mass} \rightarrow 1:1$

See also Hannestad&Schwetz,2016
The Hubble constant

Compensate a change in the distance to the last scattering surface by modifying the Hubble constant
The reionisation optical depth

- Better determination of tau benefits parameter estimation in general
- Degeneracy between the optical depth and neutrino mass
If $M_{\nu} = 0.1\,\text{eV}$, $\sigma(m_{\beta\beta}) \sim 10\,\text{meV}$ could guarantee $0n2b$ measurement. $0n2b$ could in turn help unravel the hierarchy (wip, extending the results in Gerbino+2015 in the hierarchical bayesian context).
Limits on $N_{\text{eff}}$ from Planck 2015

$N_{\text{eff}} = 3.13 \pm 0.32$ (PlanckTT+lowP)

$N_{\text{eff}} = 3.15 \pm 0.23$ (PlanckTT+lowP+BAO)

$N_{\text{eff}} = 2.99 \pm 0.20$ (PlanckTT,TE,EE+lowP)

$N_{\text{eff}} = 3.04 \pm 0.18$ (PlanckTT,TE,EE+lowP+BAO)

$N_{\text{eff}} = 4$

(one extra thermalized)

excluded at more than $3\sigma$
Limits on $M_{\nu}$ from Planck 2015

| Planck TT & lowP | 2013  | 2015       | 2015 + Planck TE, EE |
|-----------------|-------|------------|----------------------|
| Planck TT & lowP | <0.93 eV | <0.72 eV (23%) | <0.49 eV (48%) |
| Planck TT & lowP & lensing | <1.1 eV | <0.68 eV (38%) | <0.59 eV (47%) |
| Planck TT & lowP & BAO | <0.25 eV | <0.21 eV (16%) | <0.17 eV (36%) |
| Planck TT & lowP & ext | <0.20 eV | <0.15 eV | |
| Planck TT & lowP & lensing & ext | <0.23 eV | <0.19 eV | |

Planck TT & lowP: 
- 95% CL: $M_{\nu} < 0.93$ eV
- Constraints: $M_{\nu} < 0.72$ eV (23%)
- Combined with Planck TE, EE: $M_{\nu} < 0.49$ eV (48%)

Planck TT & lowP & lensing: 
- 95% CL: $M_{\nu} < 1.1$ eV
- Constraints: $M_{\nu} < 0.68$ eV (38%)
- Combined with Planck TE, EE: $M_{\nu} < 0.59$ eV (47%)

Planck TT & lowP & BAO: 
- 95% CL: $M_{\nu} < 0.25$ eV
- Constraints: $M_{\nu} < 0.21$ eV (16%)
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Planck TT & lowP & ext: 
- 95% CL: $M_{\nu} < 0.20$ eV
- Constraints: $M_{\nu} < 0.15$ eV

Planck TT & lowP & lensing & ext: 
- 95% CL: $M_{\nu} < 0.23$ eV
- Constraints: $M_{\nu} < 0.19$ eV

>10x better than current kinematic measurements

Planck collaboration, 2015
Robustness wrt the underlying cosmology

\[ M_\nu \text{ [eV]} \]

- Planck + DESI + Euclid
- CORE-M5 + DESI + Euclid

\[ \Lambda CD M \quad \Lambda CD M + \Omega_k \quad \Lambda CD M + w \]

CORE collaboration (DiValentino et al), 2016
Neutrino unknown: when neutrinos are nuisance

- When accounting for uncertainties in $M_{\nu}$ or $N_{\text{eff}}$, some models are still in agreement with data
- With BAO, more stable contours

Better constraints on neutrino properties will improve constraints on inflation

Need for taking into account neutrino uncertainties to better assess consistency of inflationary models

Gerbino, Freese+, in prep

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Neutrino unknown: when neutrinos are nuisance

StageIV+tauprior

- Better constraints on neutrino properties will improve constraints on inflation
- Need for taking into account neutrino uncertainties to better assess consistency of inflationary models

Gerbino,Freese+,in prep
Neff modifies the expansion rate

\[ H^2 = H_0^2 \left( \frac{\Omega_{\text{rad}}}{a^4} + \frac{\Omega_m}{a^3} + \Omega_\Lambda \right) \]

Impact on Big Bang Nucleosynthesis (neutron-to-proton ratio)

\[ T = 9.9 \times 10^9 \text{ K}, \quad \rho_b = 0.011 \text{ g/cm}^3 \]

Equilibrium n/p ratio

Free neutron decay

BBN starts

\[ t_{\text{BBN}} \approx 4 \rightarrow 24 \text{ min} \]
Limits on Neff from Planck 2015

Agreement between cosmological (2D contours) and astrophysical (bands) measurements

Planck collaboration, 2015

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Gravitational lensing provides new probes for neutrino masses.