Testing neutrino physics with cosmology

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Neutrinos Underground & in the Heavens II, 2016
Copenhagen, Denmark

NORDITA
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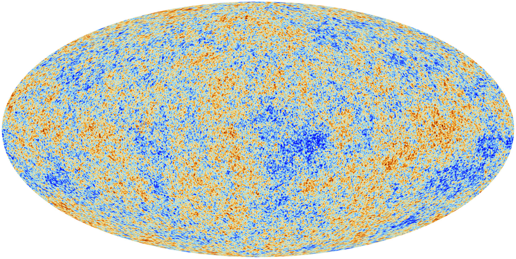
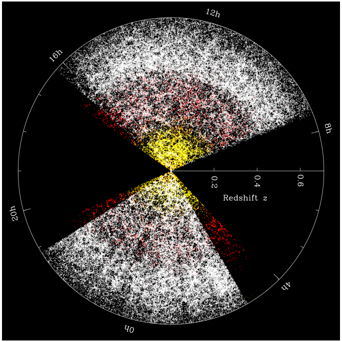
Recap - Neutrinos in cosmology

- Decouple at $T \simeq 1\ \mathrm{MeV}$ (and possibly another time much earlier)
- About 334 neutrinos$/cm^3$
- Highly relativistic in the early Universe and behave as radiation
- Currently at least two neutrino species are non-relativistic and behave as matter
- Neutrino free-streaming washes out structure on small scales
- To leading order, cosmology is sensitive to the sum of neutrino masses, but in principle it could be sensitive to individual masses
- Cosmology bounds are the tightest but also strongly **model-dependent**

Cosmological observations



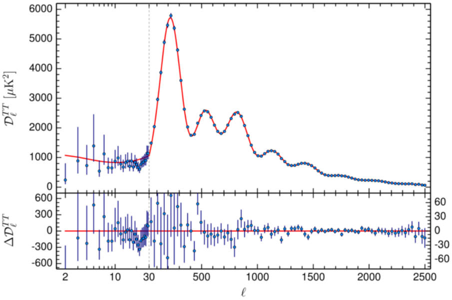
Cosmic Microwave Background (CMB)



Large Scale Structure (LSS)

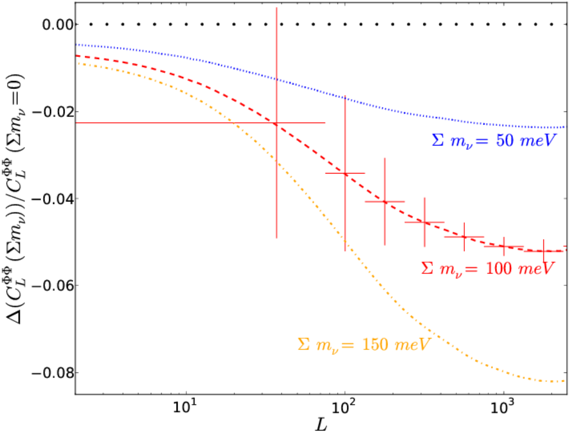
Sub-eV massive neutrinos signatures in cosmology - 1.

- CMB: many degeneracies in parameter space Efstathiou & Bond, MNRAS 1999
- A delay in matter-radiation equality can lead to an enhanced EISW effect $\implies$ boosts the first acoustic peak
- Similarly neutrinos will affect LISW, and also slightly the damping tail
- In principle the change in EISW depends on individual masses, in practice the effect is sub-mill and hence impossible to measure
- In practice CMB is used to mostly constrain values of other cosmological parameters



Sub-eV massive neutrinos signatures in cosmology - 2.

Suppression of the lensing potential. Increase $\sum m_\nu \implies$ suppressed clustering on scales below $k_{\rm nr} \implies$ less structures which can lens $\implies$ suppressed lensing potential Abazajian et al., Astropart. Phys. 2015



Sub-eV massive neutrinos signatures in cosmology - 3.

Together with CMB power spectrum and lensing potential, neutrinos affect large-scale structure

- Free-streaming of neutrinos washes out structure on small scales, below:

$$k_{\rm nr} \simeq 0.018\Omega_m^{\frac{1}{2}} \left(\frac{m}{1\ \mathrm{eV}}\right)^{\frac{1}{2}}\ h\ Mpc^{-1}$$

- Steplike suppression in power, maximum depletion approximately:

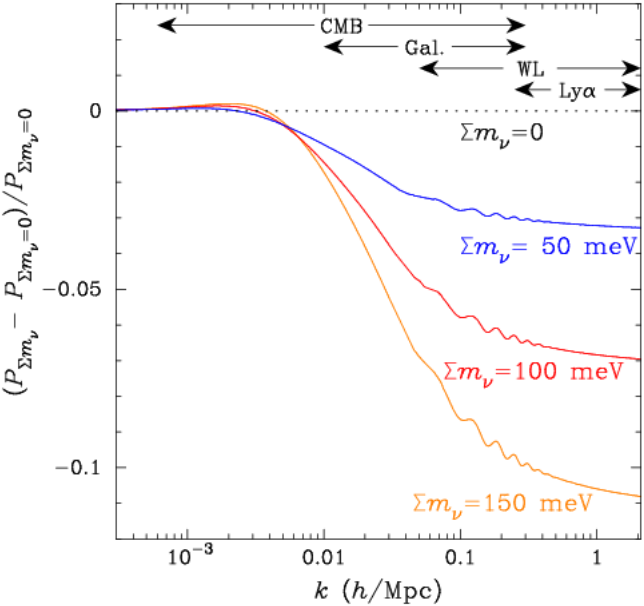
$$\frac{\Delta P(k)}{P(k)} \simeq -8f_\nu\,,\, f_\nu \equiv \frac{\Omega_\nu}{\Omega_m}$$

- Change in the scale-factor dependence of the growth function:

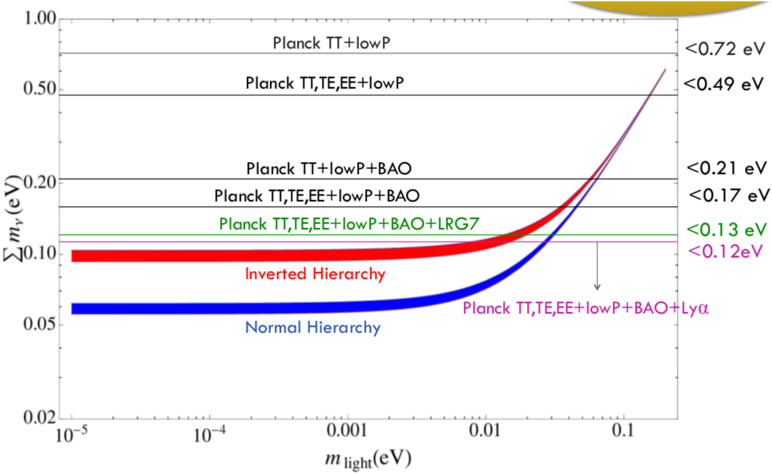
$$D(a) \propto a^{1-\frac{3}{5}f_\nu}$$

Lesgourgues and Pastor, Phys. Rept. 2006; Wong, Annu. Rev. Nucl. Part. Sci. 2011; Lesgourgues and Pastor, Adv. High Energy Phys. 2012

Matter power spectrum suppression

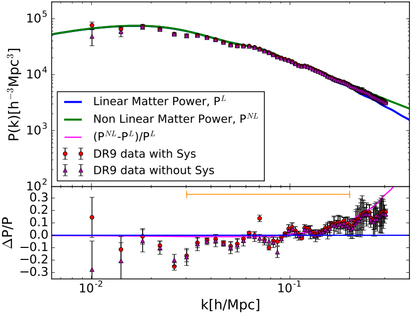


2016 state of the art 95% CL bounds



Cosmological datasets

- *Base*: low-l temperature and polarization spectra, and high-l temperature spectrum Planck coll., 2015
- *Basepol*: in addition to *Base*, high-l TE and EE polarization spectra
- BOSS Data Release 9 CMASS sample full-shape power spectrum monopole (on scales $0.01 < k/(hMpc^{-1}) < 0.2$) Ahn et al. (SDSS coll.), ApJ 2012



Datasets - Continued

- BAO geometrical information: measurements of D_v/r_s from different surveys
  - WiggleZ measurements at $z = 0.44, 0.60, 0.73$ Blake et al., MNRAS 2011
  - 6dFGS measurements at $z = 0.106$ Beutler et al., MNRAS 2011
  - BOSS DR11 LOWZ sample measurement at $z = 0.32$ Anderson et al. (BOSS coll.), MNRAS 2014
- Hubble parameter measurements:
  - *H073p02*: $H_0 = 73.02 \pm 1.79\ km/s/Mpc$ Riess et al. 2016
  - *H070p6*: $H_0 = 70.6 \pm 3.3\ km/s/Mpc$ Efstathiou, MNRAS 2014
  - *H072p5*: $H_0 = 72.5 \pm 2.5\ km/s/Mpc$ Efstathiou, MNRAS 2014
- Could add recent prior on $\tau = 0.058 \pm 0.012$ (exploring in current work) Planck coll., 2016
- Could also add SZ measurements (exploring in current work)

Clustering modelling

We consider an extra free parameter S (with an uniform prior between -1 and 1) to account for systematics in measured power spectrum:

$$P_{\mathrm{meas}}(k) = P_{\mathrm{meas,w}}(k) - S[P_{\mathrm{meas,nw}}(k) - P_{\mathrm{meas,w}}(k)]$$

Giusarma et al. PRD 2013, Giusarma et al. 2016

Theoretical model for galaxy power spectrum with bias and shot noise:

$$P^{g}_{\mathrm{th}}(k,z) = b^2_{\mathrm{HF}} P^{m}_{\mathrm{HF}\nu}(k,z) + P^{s}_{\mathrm{HF}}$$

Bird et al., MNRAS 2012

Results without high-l polarization

Dataset	*1 massive state*			*2 massive states*			*Degenerate spectrum*		
	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0
Planck TT	< 0.662	$0.080^{+0.038}_{-0.037}$	$65.5^{+3.7}_{-4.3}$	< 0.724	$0.081^{+0.039}_{-0.038}$	$65.4^{+4.2}_{-5.3}$	< 0.720	$0.080^{+0.038}_{-0.037}$	$65.6^{+4.2}_{-5.7}$
base	< 0.269	0.073 ± 0.037	$66.8^{+2.1}_{-2.3}$	< 0.281	$0.073^{+0.037}_{-0.036}$	$66.8^{+2.1}_{-2.3}$	< 0.297	$0.073^{+0.036}_{-0.037}$	$66.8^{+2.1}_{-2.3}$
base+BAO	< 0.183	0.075 ± 0.036	$67.5^{+1.4}_{-1.6}$	< 0.191	$0.075^{+0.037}_{-0.036}$	$67.6^{+1.4}_{-1.6}$	< 0.202	$0.075^{+0.037}_{-0.038}$	67.6 ± 1.5
base+H070p6	< 0.230	0.074 ± 0.036	$67.1^{+1.9}_{-2.1}$	< 0.238	$0.074^{+0.037}_{-0.036}$	$67.2^{+1.9}_{-2.0}$	< 0.255	$0.074^{+0.039}_{-0.037}$	$67.1^{+1.9}_{-2.1}$
base+H072p5	< 0.182	$0.076^{+0.037}_{-0.036}$	$67.6^{+1.7}_{-1.8}$	< 0.195	0.076 ± 0.037	$67.6^{+1.7}_{-1.8}$	< 0.201	$0.076^{+0.038}_{-0.037}$	$67.6^{+1.6}_{-1.8}$
base+H073p02	< 0.137	$0.078^{+0.035}_{-0.036}$	$68.2^{+1.4}_{-1.6}$	< 0.145	0.079 ± 0.037	$68.2^{+1.4}_{-1.6}$	< 0.153	$0.079^{+0.037}_{-0.036}$	68.2 ± 1.5
base+BAO+H070p6	< 0.175	0.076 ± 0.036	$67.7^{+1.4}_{-1.5}$	< 0.180	0.075 ± 0.036	$67.7^{+1.4}_{-1.5}$	< 0.187	$0.076^{+0.036}_{-0.037}$	$67.7^{+1.4}_{-1.5}$
base+BAO+H072p5	< 0.151	0.077 ± 0.036	$67.9^{+1.3}_{-1.4}$	< 0.160	$0.078^{+0.036}_{-0.035}$	$68.0^{+1.3}_{-1.4}$	< 0.168	$0.077^{+0.036}_{-0.037}$	$67.9^{+1.3}_{-1.4}$
base+BAO+H073p02	< 0.125	0.079 ± 0.036	$68.3^{+1.2}_{-1.3}$	< 0.135	$0.079^{+0.037}_{-0.037}$	68.3 ± 1.3	< 0.139	0.079 ± 0.036	68.3 ± 1.3

TABLE I. 95% CL upper bounds on $\sum m_\nu$ (in eV), mean values and their associated 95% CL errors of the reionization optical depth τ and the Hubble constant parameter H_0 (in km s^{-1} Mpc^{-1}) for different combination of cosmological datasets. The first, second and third column show the results for 1, 2 and 3 massive neutrino states, respectively. The *base* case refers to the combination of *Planck TT* plus DR9, with bias, shot, and a gaussian prior on systematics included.

Results with high-l polarization

Dataset	1 massive state			2 massive states			Degenerate spectrum		
	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0
Planck pol	< 0.623	$0.083^{+0.033}_{-0.034}$	$65.7^{+3.1}_{-3.8}$	< 0.620	$0.084^{+0.036}_{-0.034}$	$65.6^{+3.2}_{-4.3}$	< 0.487	$0.082^{+0.035}_{-0.034}$	$65.2^{+2.9}_{-3.8}$
basepol	< 0.256	$0.075^{+0.035}_{-0.033}$	$66.8^{+1.8}_{-2.0}$	< 0.270	0.075 ± 0.034	$66.8^{+1.8}_{-2.1}$	< 0.276	$0.076^{+0.035}_{-0.034}$	$66.8^{+1.8}_{-2.0}$
basepol+BAO	< 0.176	$0.076^{+0.033}_{-0.034}$	$67.4^{+1.3}_{-1.5}$	< 0.194	0.076 ± 0.033	$67.5^{+1.4}_{-1.5}$	< 0.185	$0.077^{+0.033}_{-0.034}$	$67.5^{+1.3}_{-1.4}$
basepol+H070p6	< 0.220	$0.077^{+0.033}_{-0.034}$	$67.0^{+1.7}_{-1.9}$	< 0.224	$0.075^{+0.033}_{-0.033}$	$67.1^{+1.6}_{-1.8}$	< 0.223	$0.076^{+0.033}_{-0.034}$	$67.1^{+1.6}_{-1.7}$
basepol+H072p5	< 0.175	$0.077^{+0.034}_{-0.036}$	67.4 ± 1.5	< 0.186	$0.075^{+0.035}_{-0.033}$	$67.5^{+1.5}_{-1.6}$	< 0.198	$0.076^{+0.032}_{-0.034}$	$67.1^{+1.6}_{-1.7}$
basepol+H073p02	< 0.125	$0.079^{+0.033}_{-0.034}$	67.9 ± 1.3	< 0.131	$0.079^{+0.034}_{-0.033}$	$67.9^{+1.4}_{-1.3}$	< 0.143	$0.078^{+0.33}_{-0.034}$	67.9 ± 1.3
basepol+BAO+H070p6	< 0.153	$0.076^{+0.033}_{-0.034}$	$67.6^{+1.3}_{-1.2}$	< 0.157	0.072 ± 0.033	$67.6^{+1.1}_{-1.2}$	< 0.166	0.077 ± 0.033	$67.6^{+1.2}_{-1.3}$
basepol+BAO+H072p5	< 0.135	$0.078^{+0.033}_{-0.034}$	67.8 ± 1.2	< 0.140	$0.078^{+0.033}_{-0.031}$	$67.7^{+1.1}_{-1.2}$	< 0.149	$0.078^{+0.031}_{-0.032}$	$67.6^{+1.1}_{-1.2}$
basepol+BAO+H073p02	< 0.123	$0.078^{+0.032}_{-0.033}$	$68.1^{+1.1}_{-1.2}$	< 0.113	$0.079^{+0.033}_{-0.034}$	68.0 ± 1.1	< 0.124	$0.079^{+0.033}_{-0.032}$	$68.0^{+1.0}_{-1.1}$

TABLE II. As Tab. I but for the *basepol* case, which refers to the combination of *Planck pol* plus DR9, with bias, shot, and a gaussian prior on systematics included, see text for details.

What about the hierarchy?

Hannestad & Schwetz, 2016

- If we take results seriously, they are starting to disfavour the inverted hierarchy, however...
- ...need to perform a proper Bayesian comparison (i.e. calculate posterior odds of NH vs IH)
- Simple approach (where $\mathcal{L}(D \mid m_0, O)$ is likelihood marginalized over cosmological parameters):

$$p_O \equiv p(O \mid D) = \frac{\pi(O) \int_0^\infty \mathcal{L}(D \mid m_0, O)}{\pi(N) \int_0^\infty \mathcal{L}(D \mid m_0, N) + \pi(I) \int_0^\infty \mathcal{L}(D \mid m_0, I)}$$

- When only considering cosmological data, posterior odds for NH vs IH 2:1
- When considering also oscillation data, odds become 3:2
- In order to exclude IH at 95% CL, need accuracy of 0.02 eV or better

Conclusions

- Latest cosmological data is providing strong bounds on the sum of neutrino masses...
- ...but these are highly model-dependent
- In principle individual masses could be detectable in future surveys
- Importance of low-redshift priors (H_0, τ)
- Current bounds appear to be disfavouring the inverted hierarchy...
- ...but a proper Bayesian comparison needs to be done