Neutrino mass limits from galaxy surveys and implications for particle physics

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based on A. J. Cuesta, VN, L. Verde, arXiv:1511.05983 [astro-ph.CO]
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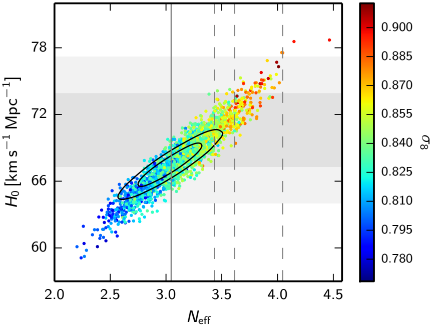
Outline

Neutrinos in cosmology I

Planck TT+lowP (coloured points) and Planck TT,TE,EE+lowP+BAO (solid black contours) *Planck collaboration, arXiv:1502.01589*

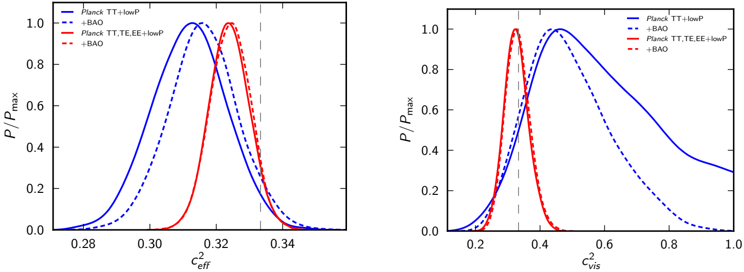


$N_{\rm eff} = 3.13 \pm 0.32$ (TT+lowP)
$N_{\rm eff} = 3.15 \pm 0.23$ (TT+lowP+BAO)
$N_{\rm eff} = 2.99 \pm 0.20$ (TT+TE+EE+lowP)

$N_{\rm eff} = 3.04 \pm 0.18$ (TT+TE+EE+lowP+BAO)

Neutrinos in cosmology II

1D posterior distributions for the neutrino perturbation parameters $c^2_{\rm eff}$ and $c^2_{\rm vis}$



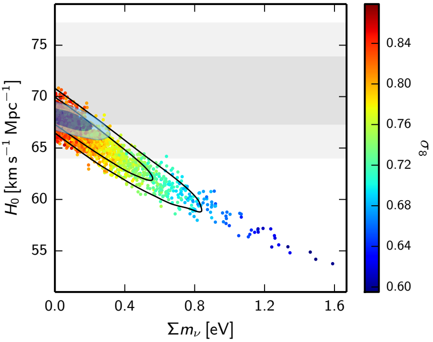
Parameters	TT+TE+EE+lowP	TT+TE+EE+lowP+BAO
$c^2_{\rm eff}$	0.3240 ± 0.0060	0.3242 ± 0.0059
$c^2_{\rm vis}$	0.327 ± 0.037	0.331 ± 0.037

Planck collaboration, arXiv:1502.01589

Neutrino mass information from cosmology

Planck results on neutrino mass

Planck TT+lowP (coloured points): $M_\nu < 0.72$ eV; *Planck collaboration, arXiv:1502.01589*
Planck TT+lowP+lensing (solid black contours): $M_\nu < 0.68$ eV;
Planck TT+lowP+lensing+BAO (filled contours): $M_\nu < 0.25$ eV;



M_ν <0.49 eV (TT+TE+EE+lowP) M_ν <0.17 eV (TT+TE+EE+lowP+BAO)
M_ν <0.14 eV (TT+TE+EE+SimLow+lensing) *Planck collaboration, arXiv:1605.02985*

Neutrino mass information from oscillation experiments

- Neutrino oscillation experiments require that neutrinos have mass
  But still unknown: IH or NH; M_ν

- the current minimum value allowed for an IH is:

$$M_\nu = (0.0982 \pm 0.0010)\ \mathrm{eV}\ (68\%\mathrm{C.L.})$$

  If the lightest state, m_3, is massless, then $m_2^2 = |\Delta m_{32}^2|$ and $m_1^2 = |\Delta m_{32}^2| - \Delta m_{21}^2$ with the best-fit for $|\Delta m_{32}^2|$ and Δm_{21}^2 equal respectively to $2.449 \times 10^{-3}\ \mathrm{eV}^2$ and $7.5 \times 10^{-5}\ \mathrm{eV}^2$.

  M. C. Gonzalez-Garcia, M. Maltoni, and T. Schwetz, arXiv:1409.5439

- strongest constraint on M_ν is obtained from CMB15, BAO and Lyman-α forest data: Palanque-Delabrouille et al., arXiv:1506.05976 [astro-ph.CO]

$$M_\nu < 0.12\ \mathrm{eV}\ (95\%\ \mathrm{C.L.})$$

  From CMB13 results: Palanque-Delabrouille et al., arXiv:1410.7244 [astro-ph.CO]

$$M_\nu < 0.15\ \mathrm{eV}\ (\mathrm{including\ BAO} : 0.14\ \mathrm{eV})\ (95\%\ \mathrm{C.L.})$$

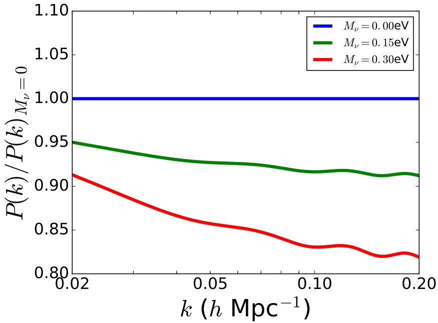
Our analysis: neutrino mass bounds from galaxy surveys

Galaxy surveys

Massive neutrinos lead to a suppression on the matter power spectrum at small scales (neutrinos do not cluster gravitationally on small scales)

$\Rightarrow$ measurements of the full shape of the matter power spectrum are of great importance for neutrino physics since they are able to put tight constraints on the sum of neutrino masses

W. Hu, D. J. Eisenstein, M. Tegmark, astro-ph/9712057; J. Lesgourgues, S. Pastor, astro-ph/0603494

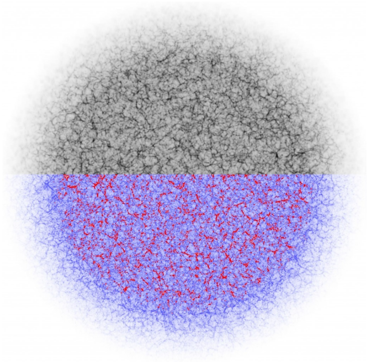


Data sets used in the analysis

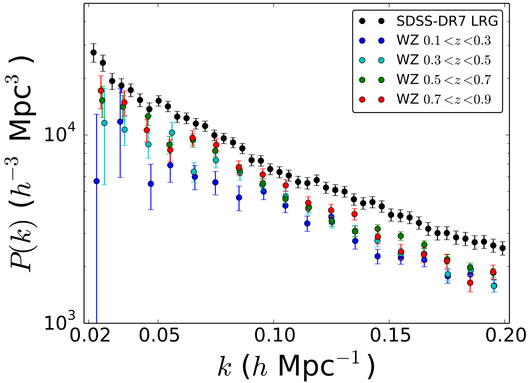
Power spectrum $P(k)$:

- extreme test by considering luminous red galaxies (LRG in DR7) and emission line galaxies (WZ).
  LRG are mostly passively evolving, massive galaxies thought to inhabit preferentially the centre of cluster-size dark matter halos.
  The WZ galaxies are star-forming blue galaxies which tend to avoid the densest regions.

Credit: 4MOST



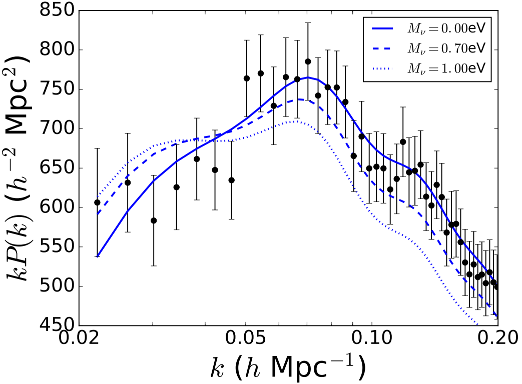
The LRG data are at $z \sim 0.35$ *B. A. Reid, et al., arXiv:0907.1659*.
The WZ data are separated in four redshift bins at effective redshifts $z = 0.22, 0.41, 0.6, 0.78$. *D. Parkinson, et al., arXiv:1210.2130*.
Only band powers with $k < 0.2\ h$ Mpc^{-1} are used.



NOTE: A visual comparison of the two data sets might be misleading since the galaxy samples and the window functions of the two surveys are different.

Effect of neutrino masses

Power spectrum from LRG after applying the window function of the survey.



Data sets used in the analysis

Cosmic Microwave Background:
We use information on the CMB from the Planck 2015 data releases.

Baryon Acoustic Oscillations:
BAO measurements help to lift cosmological parameters degeneracies (ex: ruling out small values of H_0 allowed by the CMB-only case).

$r_s(z_d)$: the comoving sound horizon at the baryon drag epoch;
$D_V(z) = [(1+z)^2 D_A^2 cz/H(z)]^{1/3}$, with D_A the angular diameter distance.

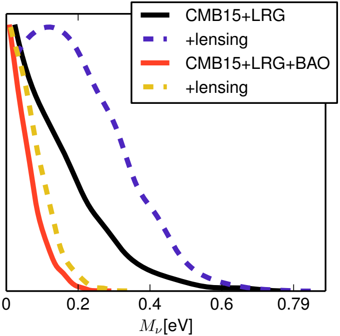
Survey	Measurement
6dFGS	$r_{\rm drag}/D_V(z=0.106)$: 0.327 ± 0.015 Beutler et al, 2011
SDSS-MGS	$D_V(z=0.15)/r_{\rm drag}$: 4.47 ± 0.16 Ross et al, 2014
BOSS-LOWZ	$D_V(z=0.32)/r_{\rm drag}$: 8.47 ± 0.17 Anderson et al, 2013
BOSS-CMASS	$D_V(z=0.57)/r_{\rm drag}$: 13.77 ± 0.13 Anderson et al, 2013

Results

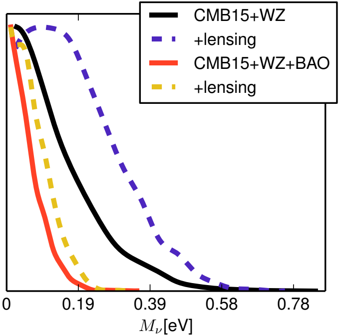
Data sets	M_ν at 95% CL
CMB15 + LRG	0.38 eV
CMB15 + WZ	0.37 eV
CMB15 + LRG + WZ	0.30 eV
CMB15 + LRG + BAO	0.13 eV
CMB15 + WZ + BAO	0.14 eV
CMB15 + LRG + WZ + BAO	0.14 eV
CMB15 + LRG + lensing	0.44 eV
CMB15 + WZ + lensing	0.43 eV
CMB15 + LRG + WZ + lensing	0.38 eV
CMB15 + LRG + BAO + lensing	0.17 eV
CMB15 + WZ + BAO + lensing	0.17 eV
CMB15 + LRG + WZ + BAO + lensing	0.18 eV

CMB15: Planck TT,TE,EE + lowP data; LRG and WZ: the full shape of the matter power spectra as reported by SDSS-DR7 and WiggleZ survey respectively.

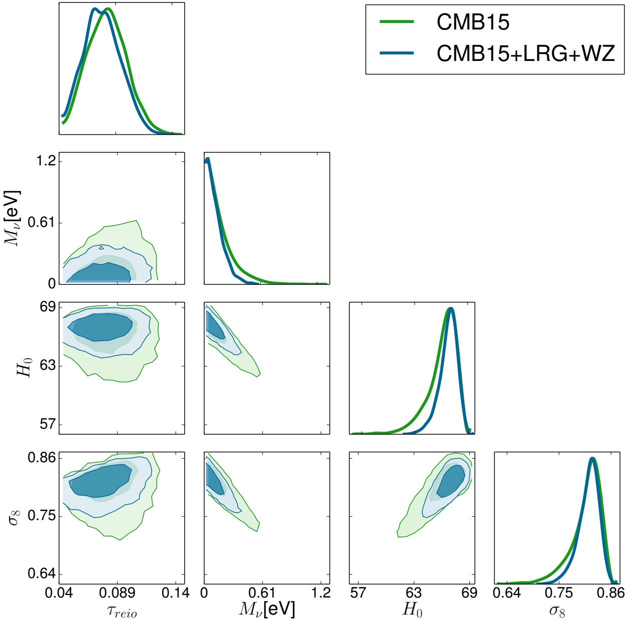
Results

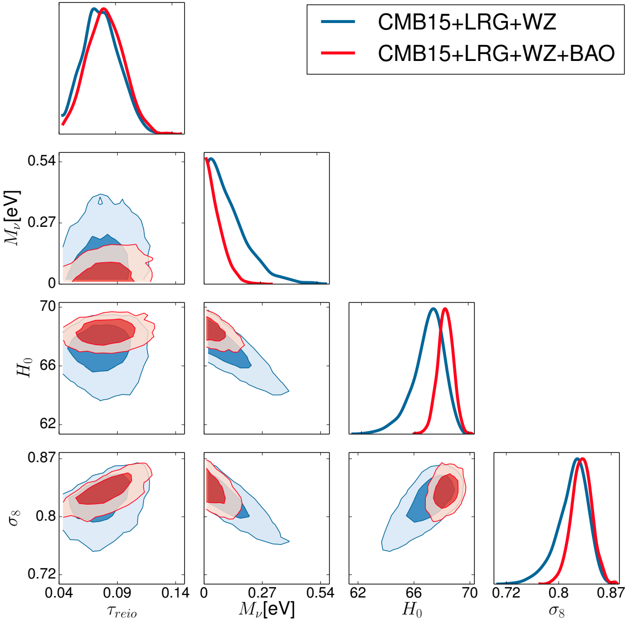


LRG galaxies



WZ galaxies


CMB15
CMB15+LRG+WZ
M_ν[eV]
H_0
σ_8
τ_{reio}
1.2
0.61
0
69
63
57
0.86
0.75
0.64
0.04
0.089
0.14
0
0.61
1.2
57
63
69
0.64
0.75
0.86


CMB15+LRG+WZ
CMB15+LRG+WZ+BAO
0.54
0.27
0
M_ν[eV]
70
66
62
H_0
0.87
0.8
0.72
σ_8
0.04
0.09
0.14
τ_{reio}
0
0.27
0.54
M_ν[eV]
62
66
70
H_0
0.72
0.8
0.87
σ_8

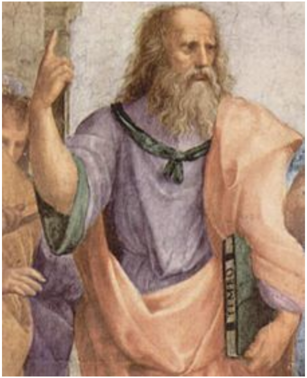
(Comment: including H_0 determination)

Neutrino mass constraints if we also add the local determination of $H_0 = 73.0 \pm 2.4$ km s^{-1} Mpc^{-1}.

Data sets	M_ν at 95% CL
CMB15 + BAO + H_0	0.11 eV
CMB15 + LRG + H_0	0.19 eV
CMB15 + WZ + H_0	0.18 eV
CMB15 + LRG + WZ + H_0	0.175 eV
CMB15 + LRG + BAO + H_0	0.11 eV
CMB15 + WZ + BAO + H_0	0.11 eV
CMB15 + LRG + WZ + BAO + H_0	0.12 eV
CMB15 + LRG + lensing + H_0	0.23 eV
CMB15 + WZ + lensing + H_0	0.21 eV
CMB15 + LRG + WZ + lensing + H_0	0.21 eV
CMB15 + LRG + BAO + lensing + H_0	0.135 eV
CMB15 + WZ + BAO + lensing + H_0	0.14 eV
CMB15 + LRG + WZ + BAO + lensing + H_0	0.14 eV

NOTE: a tension has been claimed between the CMB and H_0 measurements within the standard ΛCDM model and its simple extensions.

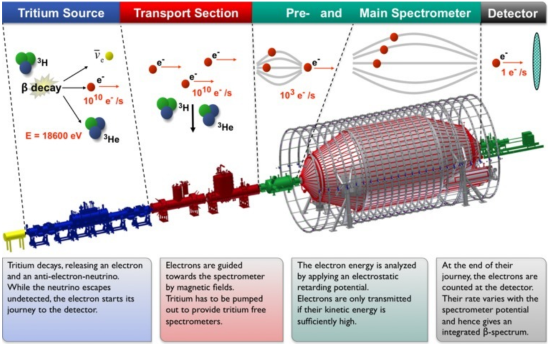
Cosmology versus laboratory experiments



Tritium β decay

The KArlsruhe TRItium Neutrino (KATRIN) experiment:
limit down to 0.2 eV (90% CL) or discover the actual mass, if it is larger than 0.35 eV.

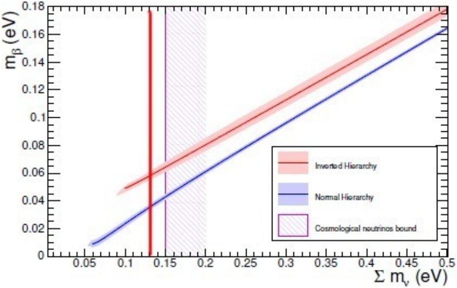
$$^3H \rightarrow \, ^3He + e^- + \bar{\nu}_e$$



https://www.katrin.kit.edu/

Tritium β decay

$$m_{\nu_e}^2 = \sum_i m_i^2 |U_{ei}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$



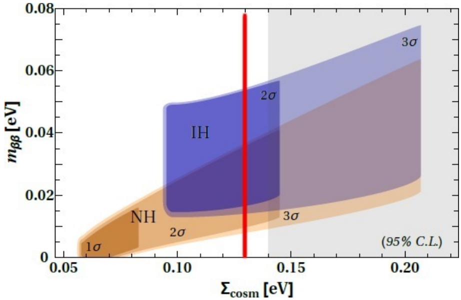
Palanque-Delabrouille et al., arXiv:1410.7244 [astro-ph.CO]

$0\nu2\beta$ decay

Neutrinoless double beta decay: are neutrinos Majorana particles?

$$m_{ee} = |\sum_i m_i U_{ei}^2| = |m_1 c_{13}^2 c_{12}^2 e^{i2\alpha_1} + m_2 c_{13}^2 s_{12}^2 e^{i2\alpha_2} + m_3 s_{13}^2 e^{-i2\delta}|$$

GERDA (^{76}Ge), KamLAND-Zen (^{136}Xe) and EXO-200 have set a limit on $m_{ee} \lesssim 0.2 - 0.4$ eV at 90% C.L.
New experiments (ton scale): $m_{ee} \sim 0.01$ eV



S. Dell'Oro, S. Marcocci, M. Viel, F. Vissani, arXiv:1505.02722 [hep-ph]

Future surveys

Future surveys

- expect a sensitivity $\sigma(M_\nu)$ close to 0.02 eV (1-sigma) around the year 2025 for a survey like Euclid combined with Planck (planned launch date for Euclid 2020)

  B. Audren, J. Lesgourgues, S. Bird, M. G. Haehnelt and M. Viel, arXiv:1210.2194

  CMB satellite of next generation like Core+ combined with Euclid could further improve the sensitivity

- Other surveys, like DESI, can reach similar sensitivity on M_ν.
  DES can reach a sensitivity $\sigma(M_\nu)$ close to 0.06 eV

  A. Font-Ribera, et al., arXiv:1308.4164 [astro-ph.CO]

  O. Lahav, et al., arXiv:0910.4714 [astro-ph.CO]

- Good prospects to detect the absolute neutrino mass scale with cosmology, and even to exclude the IH scenario

Conclusions

- Oscillation experiments impose a minimum M_ν for IH $\gtrsim 0.1$ eV, and cosmological bounds are now reaching this level of accuracy
- Tracers affected by bias/astrophysics
  $\Rightarrow$ The neutrino mass constraints should be shown to be also robust: LRG vs WZ galaxies
- The tighter upper limit (0.13 eV) obtained with SDSS-DR7 LRG is very close to the one obtained using Lyman-alpha clustering data
- A small region of parameter space for IH is still allowed
- We are in the era of precision cosmology:
  $\Rightarrow$ interesting results to come and nice interplay between cosmology and particle physics

Thank you!

The School of Athens, Raphael