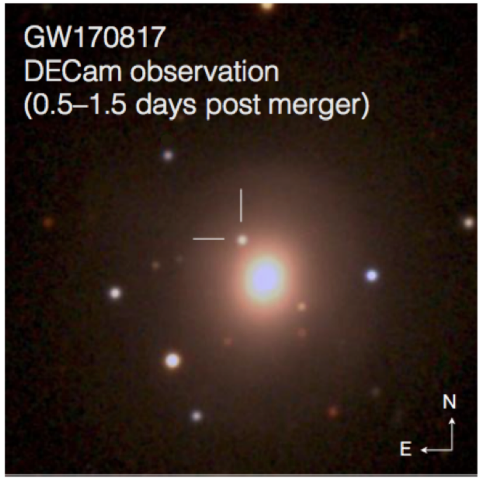
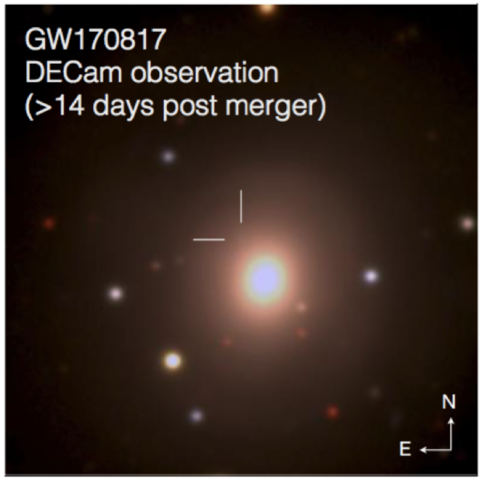
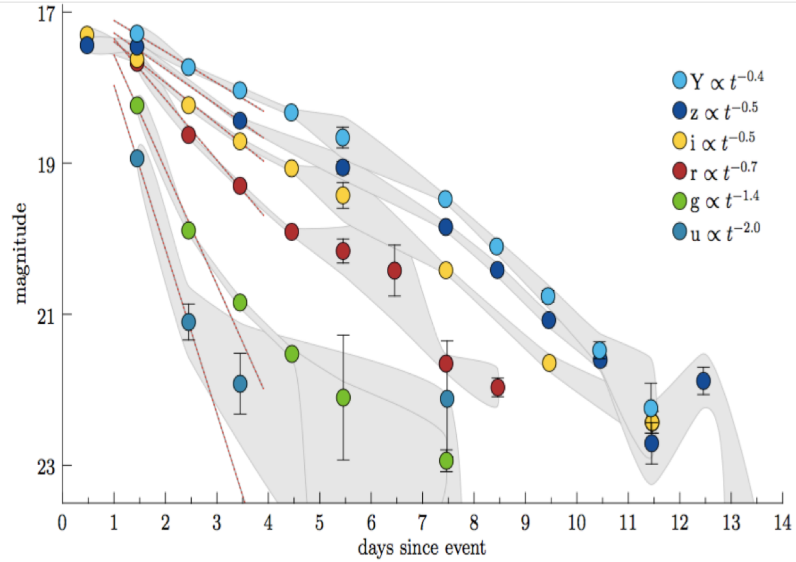
DECam/DES image of GW170817 in galaxy NGC4993 (40 Mpc away)

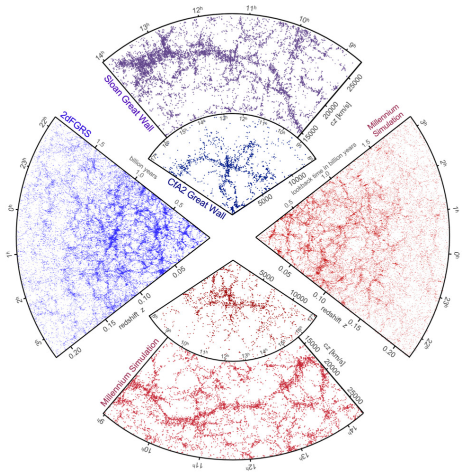


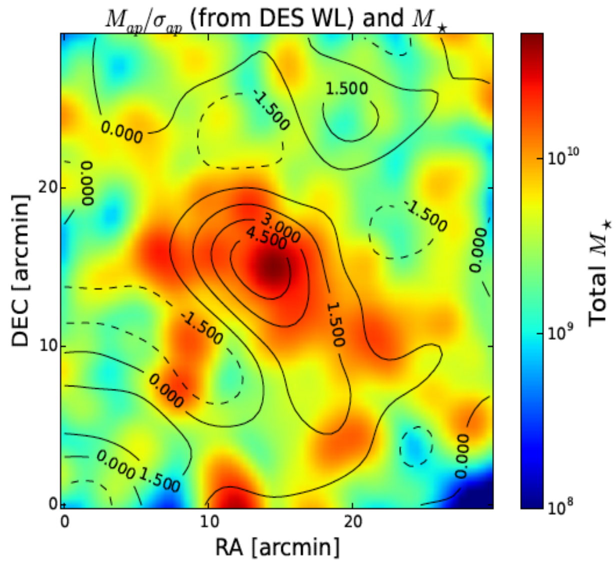




Soares-Santos & DES collaboration
(today 16 Oct 2017 !)

Neutrino mass from cosmological surveys





Ofer Lahav (UCL)

Outline

- Brief History of Hot Dark Matter
- Improvement by a factor 10 on neutrino mass upper limit over 15 years: current galaxy & Ly-alpha (BOSS), CMB (Planck)
- Forecast for future surveys: DES, DESI, Euclid, LSST, SKA
- How to control systematics?
- Beyond 2pt statistics: the cosmic web
- Combining cosmological + terrestrial experiments
- What's next?

The Big Neutrino Questions

- What is the absolute sum of neutrino mass?

(given the lower limit 0.06 eV from oscillations)

- What is the hierarchy – Normal or Inverted?
- Is $N_{eff} = 3.045$,

  or larger (Sterile neutrino /'dark radiation')?
- Is the neutrino its anti-particle (Majorana)?

Brief History of ‘Hot Dark Matter’

* 1970s : Top-down scenario with massive neutrinos (HDM) - Zeldovich Pancakes

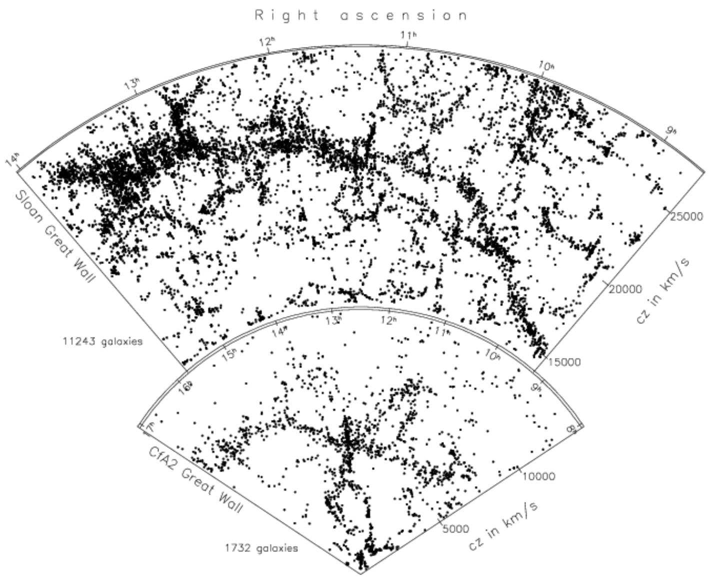
* 1980s: HDM - Problems with structure formation

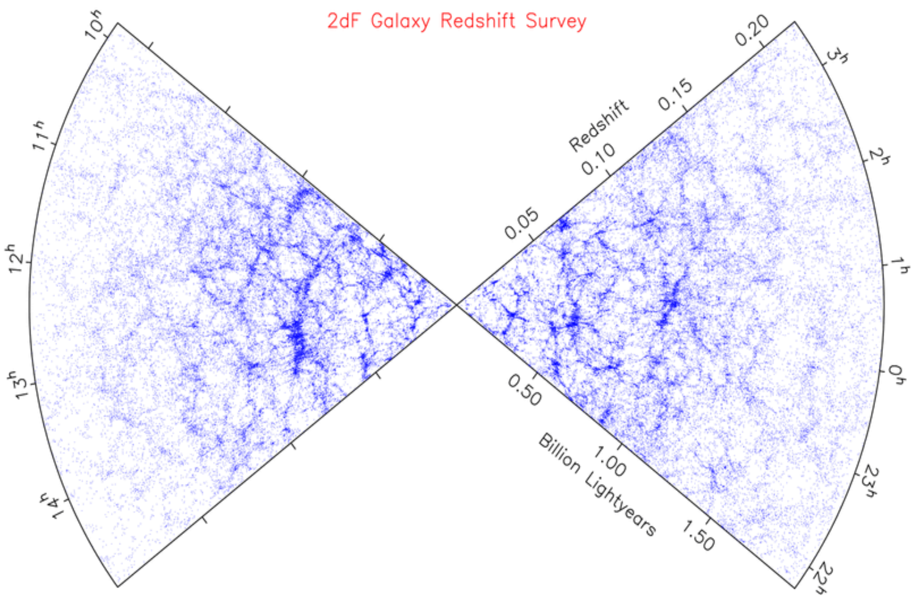
* 1990s: Mixed CDM (80%) + HDM (20%)

* 2000s: Baryons (4%) + CDM (26%) +Lambda (70%):

But now we know HDM exists!
How much?

Tiny Neutrino Masses from Great Walls



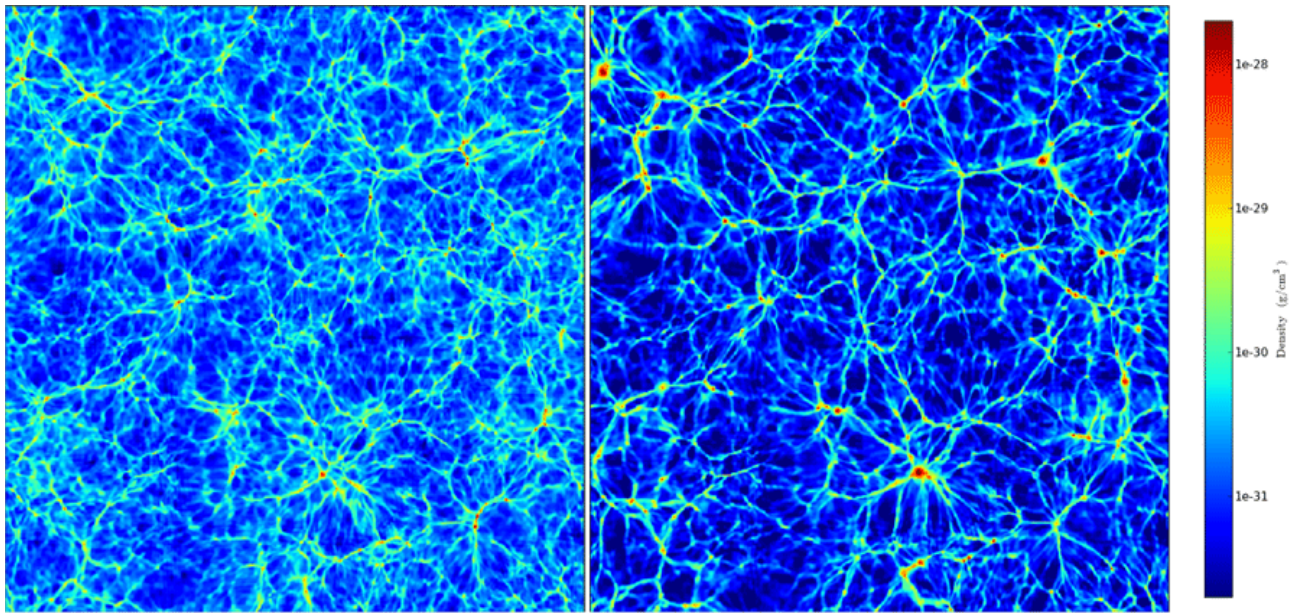


Neutrino Mass from Cosmology

Neutrinos decoupled when they were still relativistic, hence they wiped out structure on small scales

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

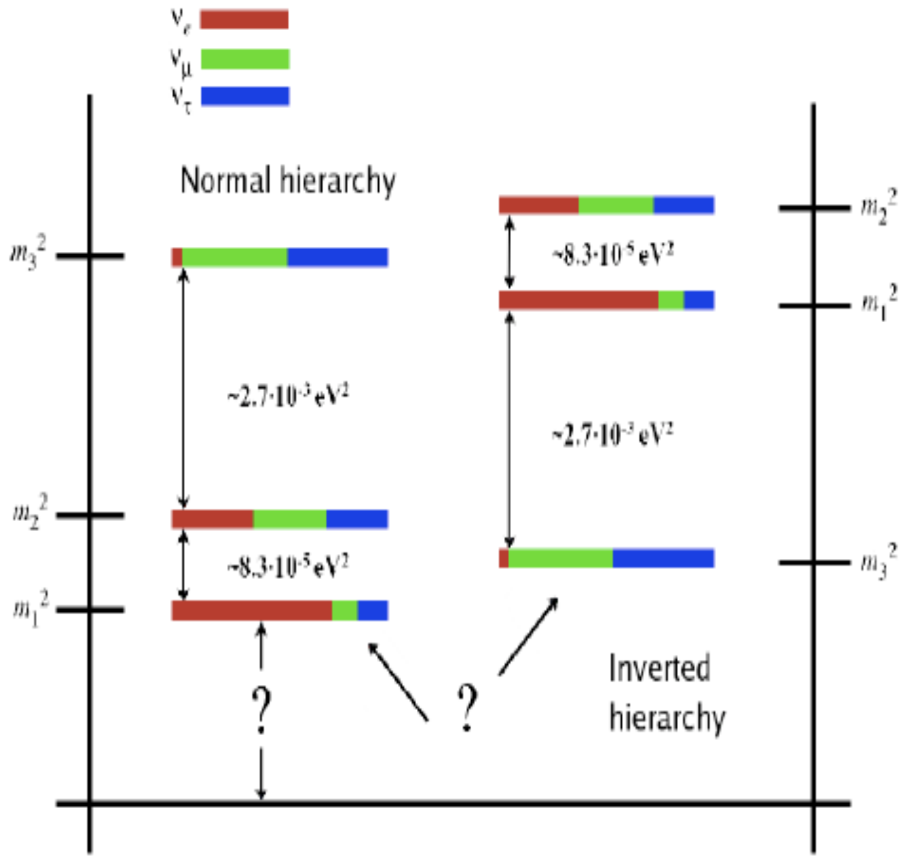
$\Omega_\nu h^2 = M_\nu/(93\ \mathrm{eV})$



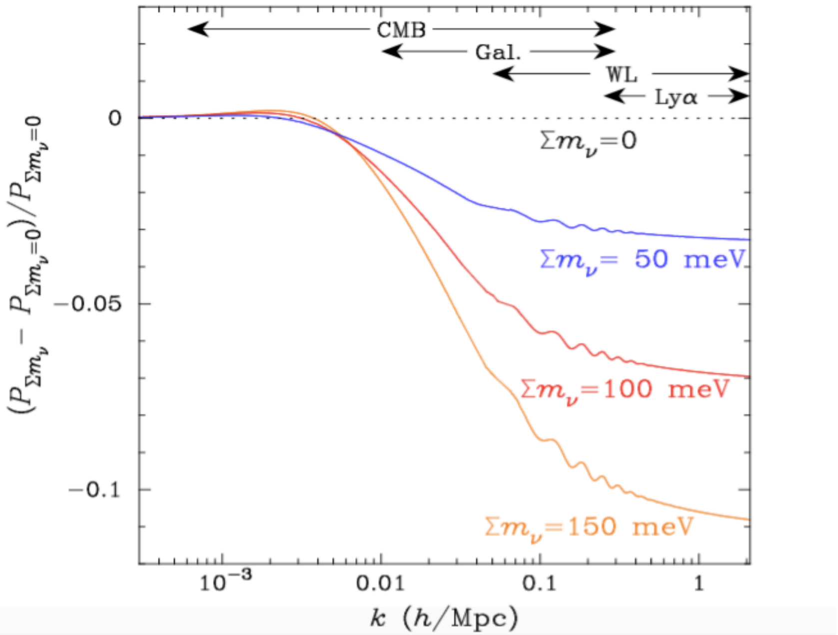
CDM+ 1.9 eV neutrinos. structure 'washed out' ***CDM***

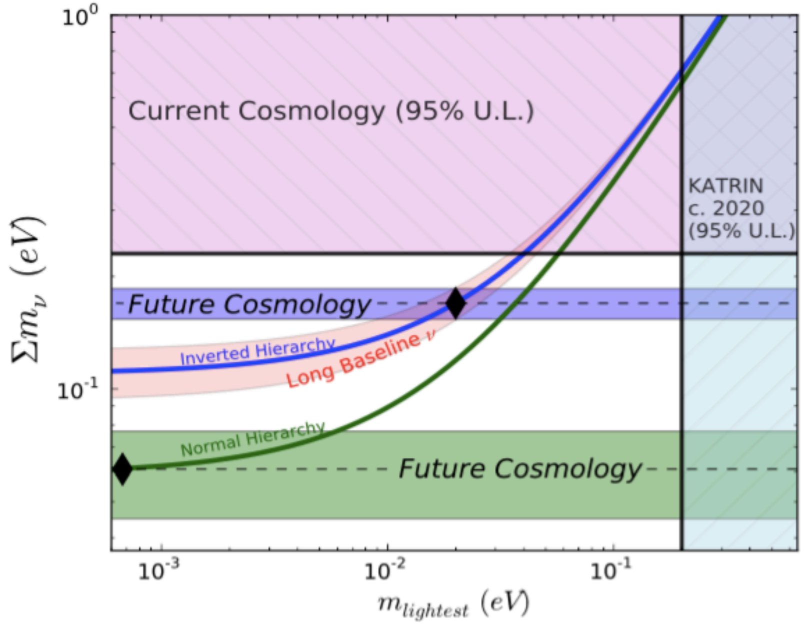
Agarwal & Feldman 2010

Neutrino Mass Hierarchy



The sub-eV Neutrino Cosmology



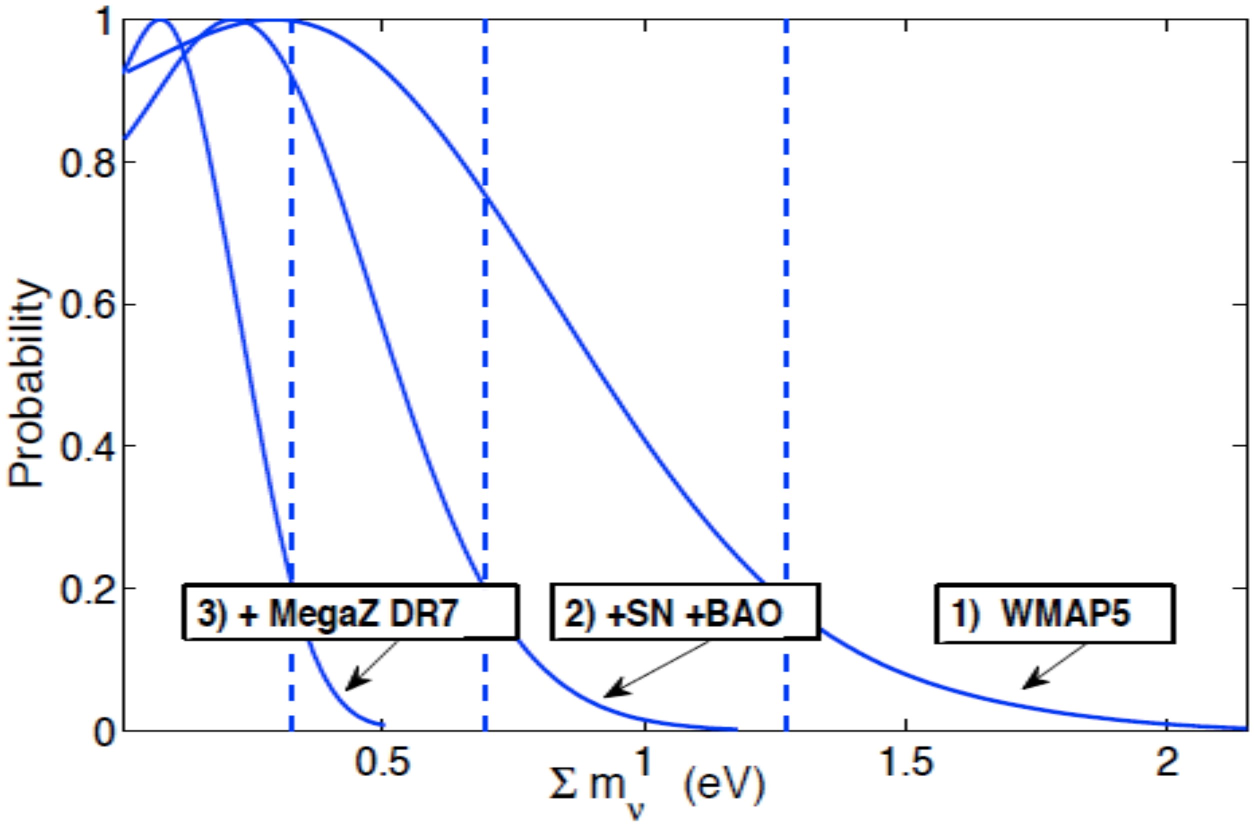


Abazajian et al. 1309.5383

Neutrino mass from MegaZ-LRG

700,000 galaxies within 3.3 (Gpc/h)^3

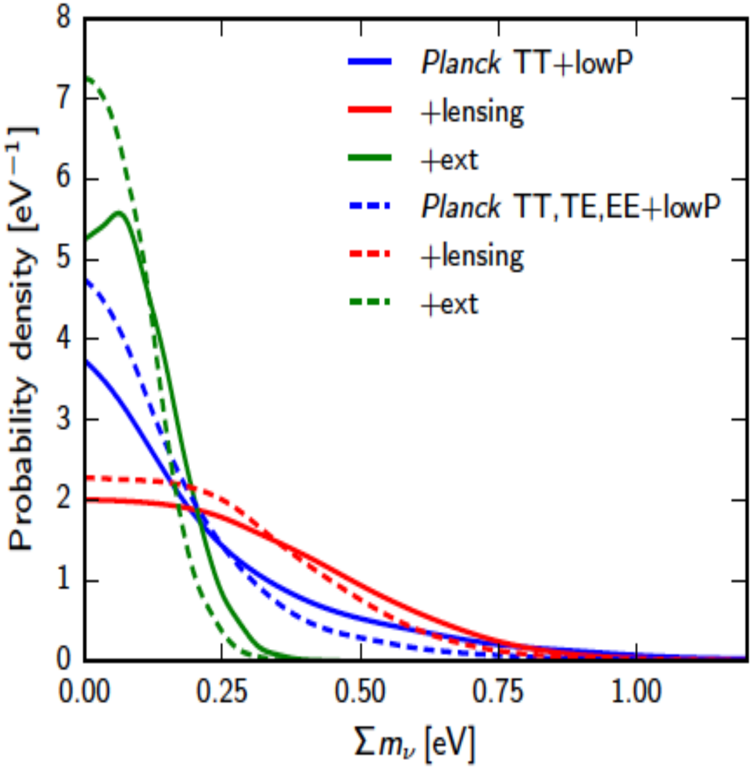
0.06 <Total mass < 0.28 eV (95% CL)



Thomas, Abdalla & Lahav (PRL, 2010)

cf. Reid et al. (2010) ; Planck++ (2015) give < 0.23 eV

Planck 2015 ++
(arXiv:1502.01589)



$$\left.\begin{array}{l}\sum m_\nu < 0.23 \text{ eV} \\ \Omega_\nu h^2 < 0.0025\end{array}\right\} \text{95\%, } \textit{Planck} \text{ TT+lowP+lensing+ext.}$$

N_{eff} = 3.15 +- 0.46 (95% CL)
Consistent with standard 3.046

Methodology: health warnings

- Analysis is done within the Λ-CDM scenario, subject to priors.
- Some probes are sensitive to the neutrino mass directly (e.g. the shape of the power spectrum).
- Other probes just constrain better the other N-1 parameters in the cosmological model (eg SN Ia, BAO).
- The selection of "best data sets" is somewhat subjective.
- Mismatch of data sets could lead to spurious "new Physics".

N_{eff} from Planck++
[vs. standard N_{eff} =3.045]

Table 1.1: Summary of $N_{\rm eff}$ constraints.

	Model	68%CL	Ref.
CMB alone			
Pl15[TT+lowP]	ΛCDM+$N_{\rm eff}$	3.13 ± 0.32	[23]
Pl15[TT,TE,EE+lowP]	ΛCDM+$N_{\rm eff}$	2.99 ± 0.20	[23]
Pl15[TT+lowP]	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	3.08 ± 0.31	[24]
CMB + probes of background evolution			
Pl15[TT+lowP] + BAO	ΛCDM+$N_{\rm eff}$	3.15 ± 0.23	[23]
Pl15[TT,TE,EE+lowP] + BAO	ΛCDM+$N_{\rm eff}$	3.04 ± 0.18	[23]
Pl15[TT+lowP] + JLA	ΛCDM+$N_{\rm eff}$	$3.18^{+0.28}_{-0.32}$	[24]
Pl15[TT+lowP] + BAO	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	$3.18^{+0.24}_{-0.27}$	[24]
CMB + probes of background evolution + LSS			
Pl15[TT+lowP+lensing]	ΛCDM+$N_{\rm eff}$	$3.13^{+0.29}_{-0.34}$	[24]
— + BAO	ΛCDM+$N_{\rm eff}$	$3.08^{+0.22}_{-0.24}$	[24]
— + BAO + JLA + HST	ΛCDM+$N_{\rm eff}$	3.41 ± 0.22	[25]
— + BAO	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	3.2 ± 0.5	[23]
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$N_{\rm eff}$+5-params.	$2.93^{+0.51}_{-0.48}$	[32]

RPP 2017
Lesgourgues & Verde

2-sigma Neutrino mass upper limits from existing data

Data	Authors	$M_{\nu} = \Sigma m_i$
2dFGRS MegaZ-LRG + WMAP	Elgaroy, OL et al. (2002) Thomas et al. (2010)	< 1.8 eV < 0.28 eV
Planck13+robust surveys	Leistedt et al. (2014)	< 0.3 eV
Planck15++	Planck collaboration 2015	< 0.23 eV
BOSS Ly-alpha + Planck15	Palanque-Delabrouille etal. (2015)	< 0.12 eV
DES Y1 + Planck15+JLA+BAO	DES collaboration (2017)	< 0.29 eV

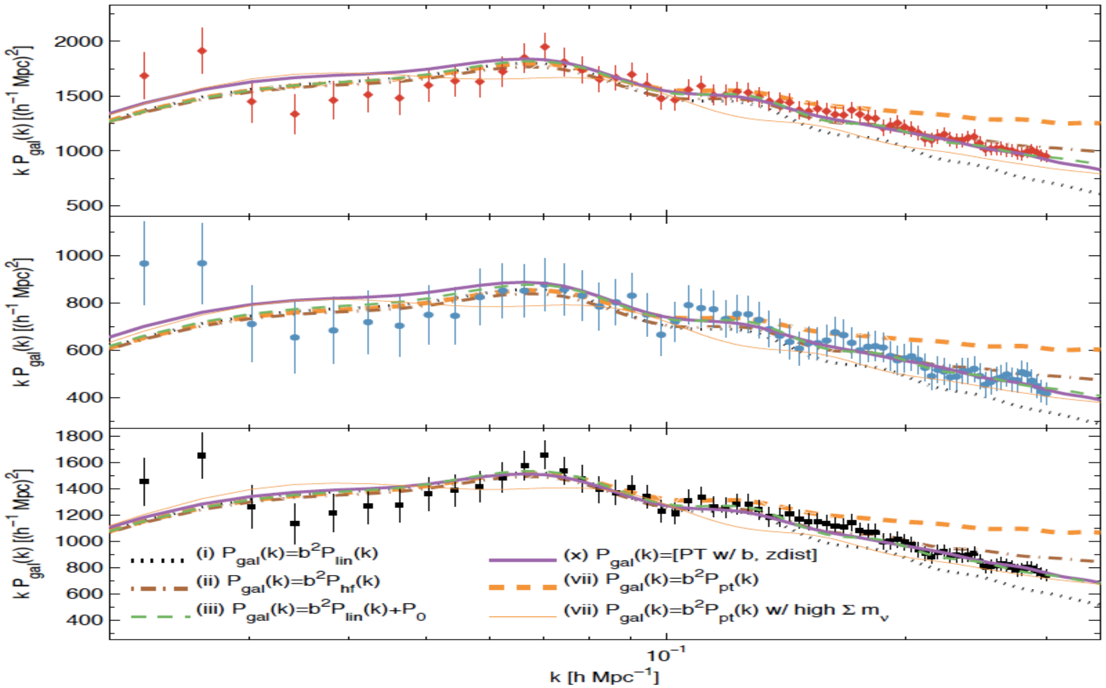
All upper limits 95% CL, but different assumed priors !

2-sigma errors on Neutrino mass – forecast for future surveys

Data	Authors	Error (Σ)
DES (LSS) + Planck DES (LSS+WL) + Planck	OL et al. (2010) Font-Ribera et al. (2014)	0.1 eV 0.08 eV
Euclid (LSS/WL) + Planck	Amendola et al. 2016	0.04 eV 0.05 eV
LSST (WL) +Planck	Abazajian et al. 2014	0.04 eV
DESI++	Font-Ribera et al. 2014	0.04 eV
SKA++	Abdalla & Rawling 2007	0.05 eV

Errors 95% CL, but different assumed priors !

Controlling systematics Neutrino mass from red vs blue SDSS galaxies



red

blue

all

upper limit in the range 0.5-1.1 eV

red and blue within 1–sigma

Swanson, Percival & OL (2010)

The Dark Energy Survey

DARK ENERGY SURVEY

* Multi-probe approach
  Wide field: Cluster Counts,
  Weak Lensing, Large Scale Structure
  Time domain: Supernovae

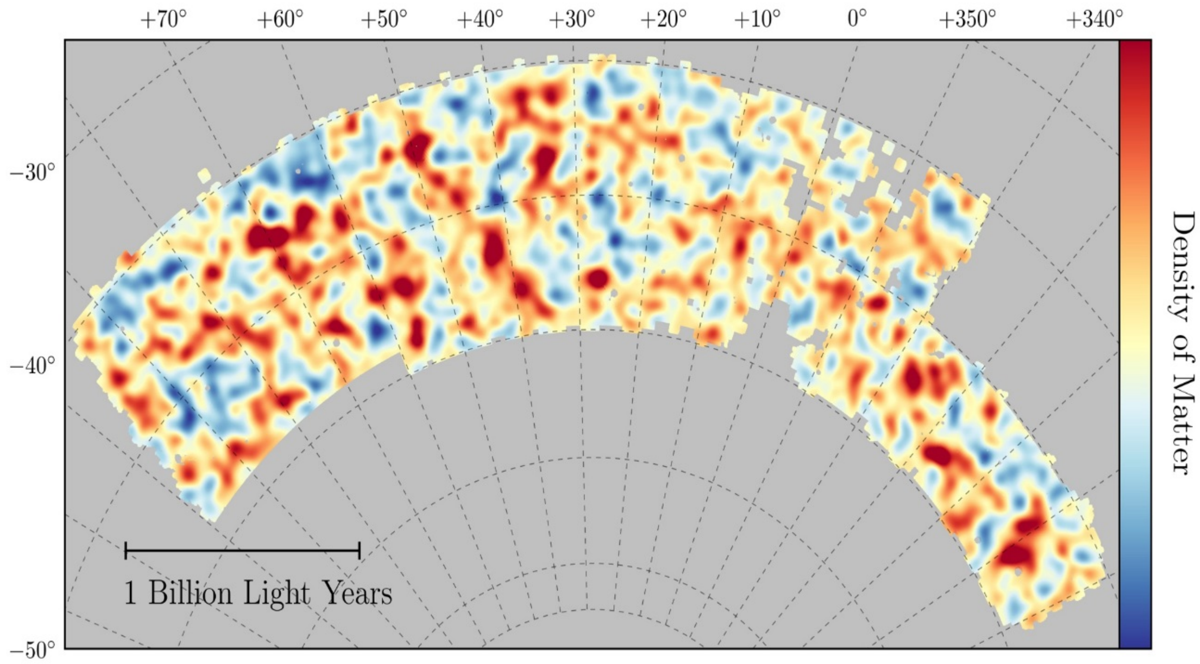
* Survey strategy
  300 million photometric redshifts (grizY)
  over 5000 deg^2
  + 2500 SN Ia (over 27 sq deg fields)
  overlap with VHS + SPT+ OzDES + …

* Currently 5^{th} (last) year of observations

* About 120 DES papers on the arXiv

* Over 400 scientists from 7 countries

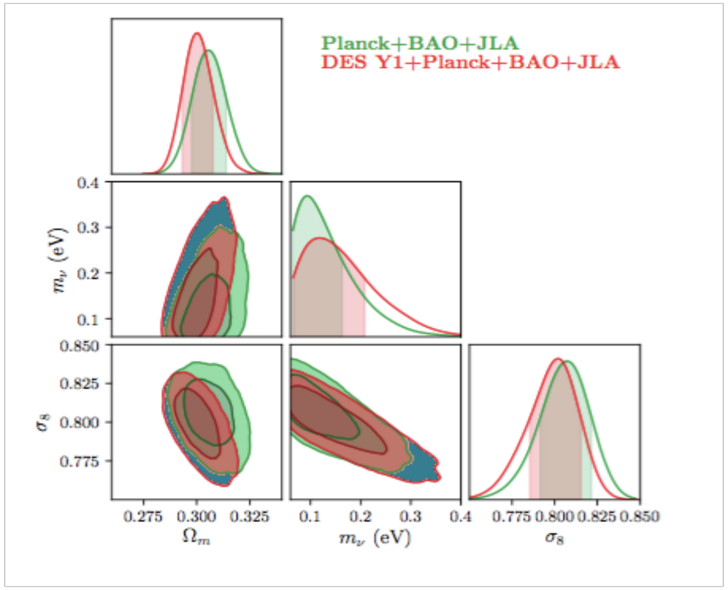
Dark Matter map from DES Weak Lensing

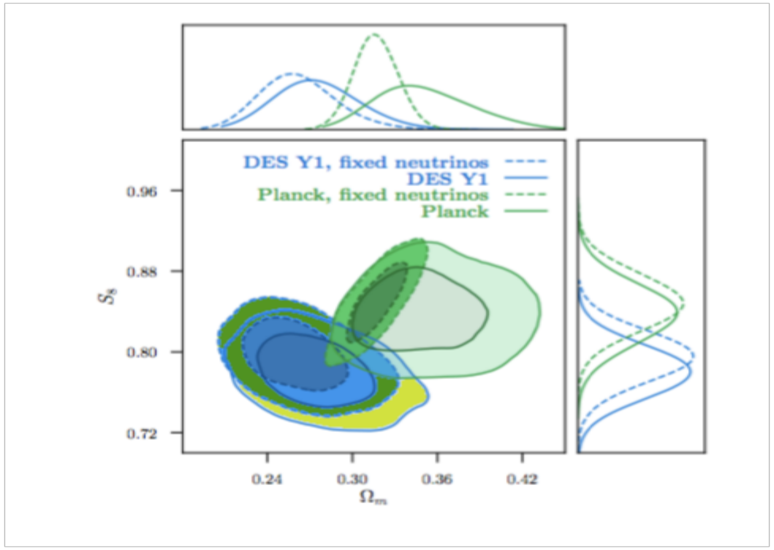


Chang & DES collaboration (2017)

Neutrino mass from DES Year1 2017

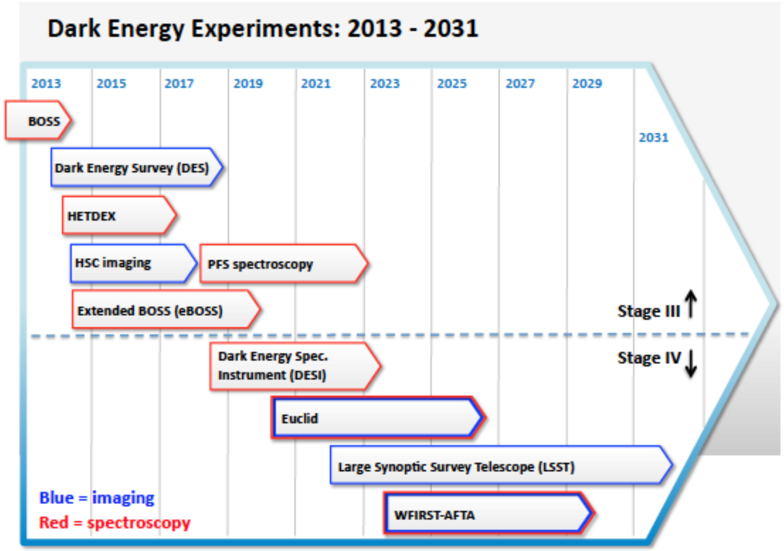
DES collaboration arXiv:1708.01530

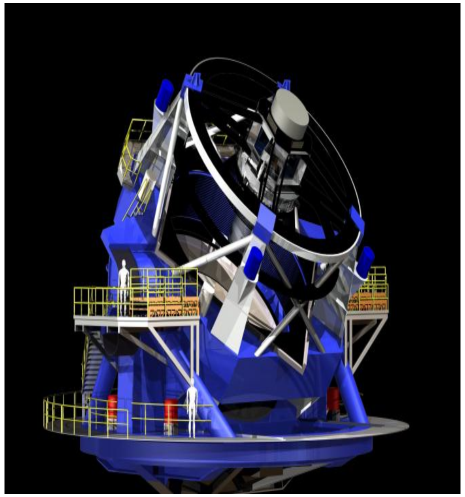


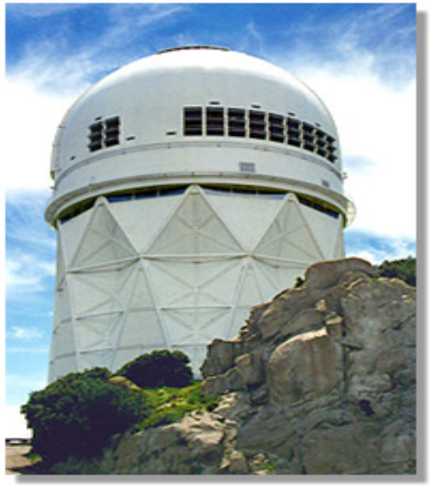


To fix or not to fix
to minimal oscillations
M_{nu} = 0.06 eV ?

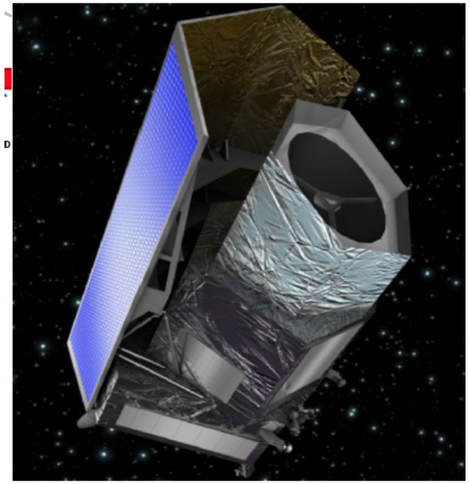
The era of DESI, Euclid, LSST,…







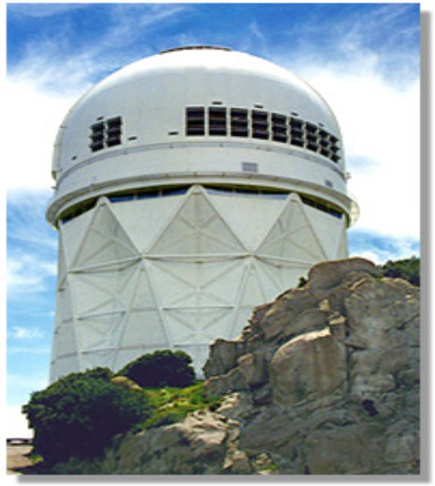
Mayall 4-Meter Telescope



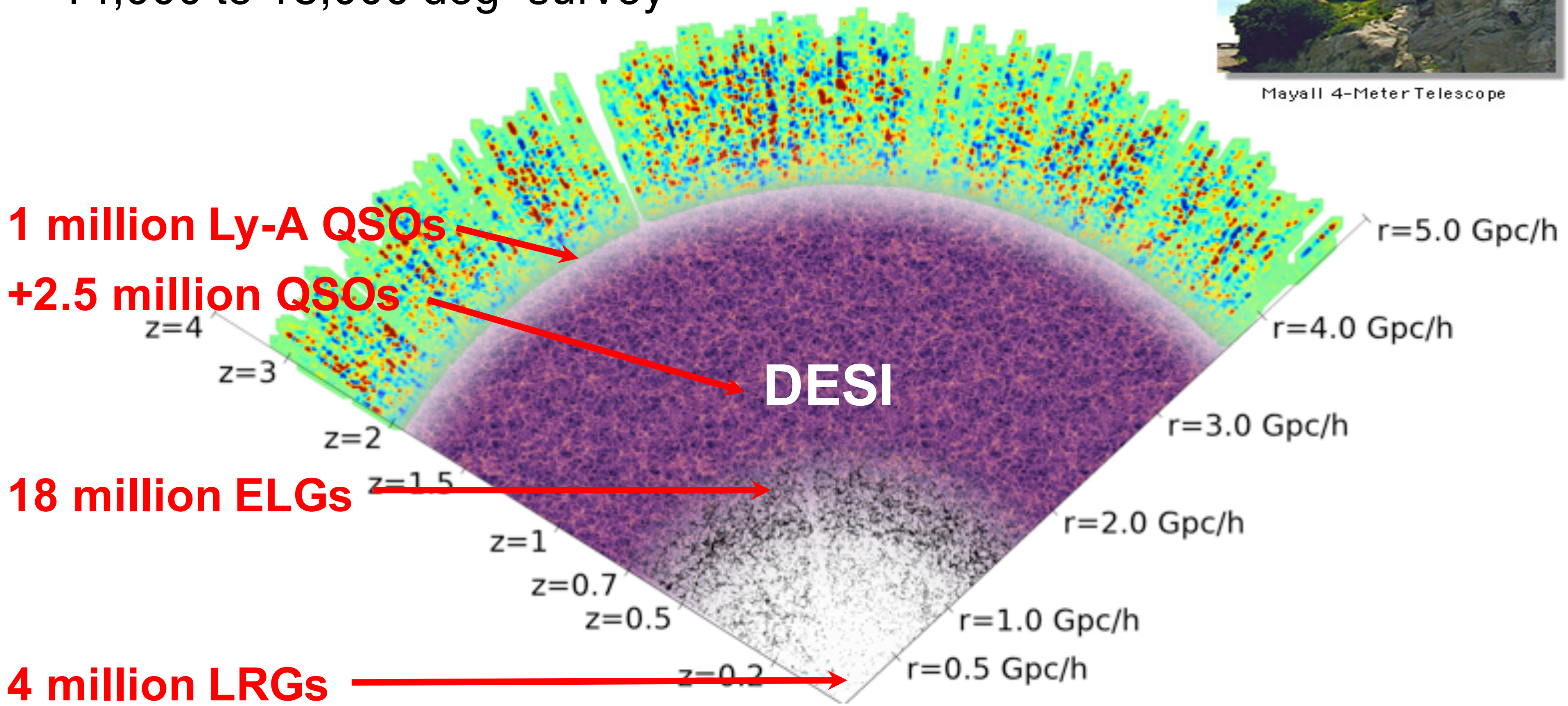
Dark Energy Spectroscopic Instrument (DESI) – 10 times BOSS

Mayall telescope available up to 100% of dark time,
- 5000 fibres, 20min base integration time
- > 20 million targets

14,000 to 18,000 deg^2 survey



Mayall 4-Meter Telescope

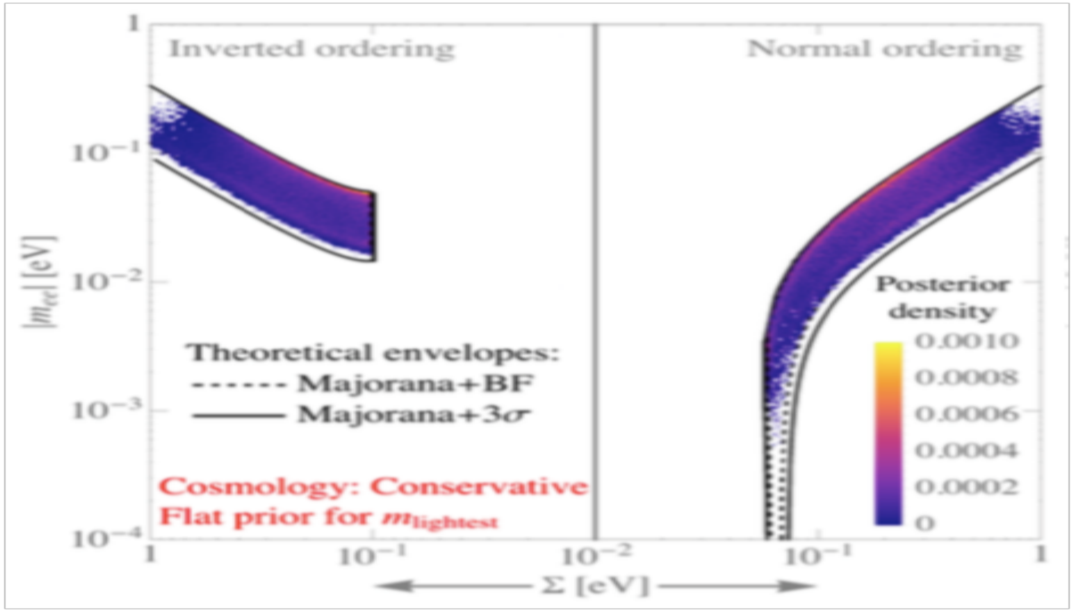


Combine Cosmology & terrestrial experiments:

DES+ Planck + KATRIN

e.g. Host, OL et al. (2007)

A global Bayesian analysis of neutrino mass from Double Beta Decay, Oscillations & Cosmology



Caldwell et al., arXiv:1705.01945

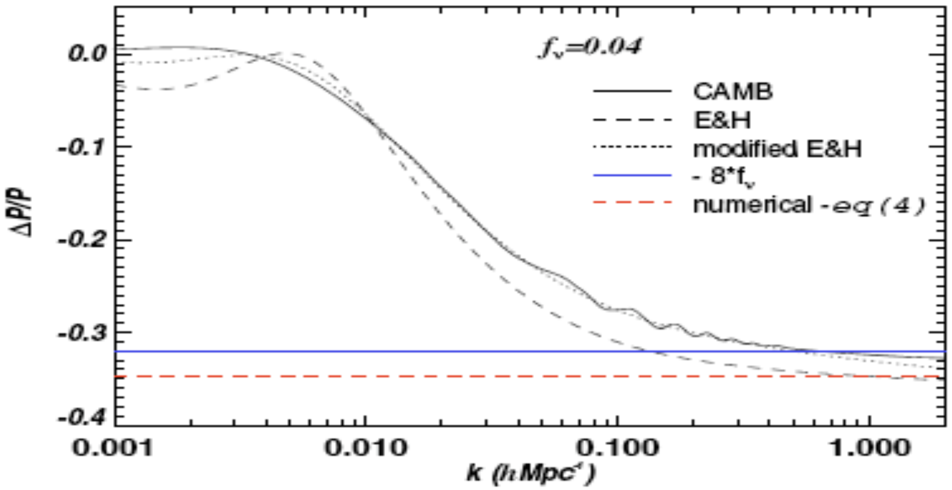
Cf. Agostini et al. arXiv:1705.02996

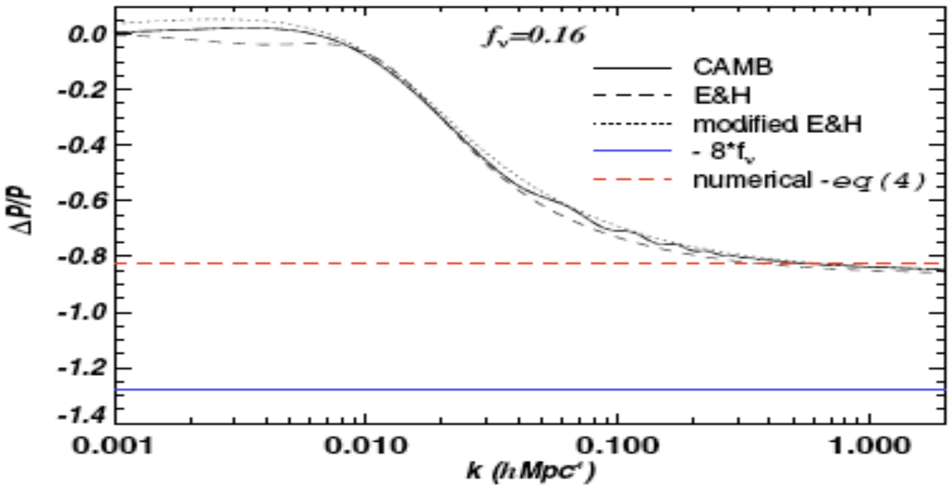
Summary

- Current upper limits on sum neutrino mass
  < 0.2 eV (2-sigma)
- Future surveys will improve it by factor 5, reaching the lower limit of 0.06 eV from oscillations
- So far no tension in neutrino mass between cosmology and terrestrial experiments: to meet soon!
- Hopefully a reliable neutrino mass measurement coming years!
- Controlling systematics is crucial
- Great prospects from new surveys for neutrino cosmology

Extra slides

$$\frac{\Delta P(k)}{P(k)} = \frac{P(k; f_\nu) - P(k; f_\nu = 0)}{P(k; f_\nu = 0)}.$$



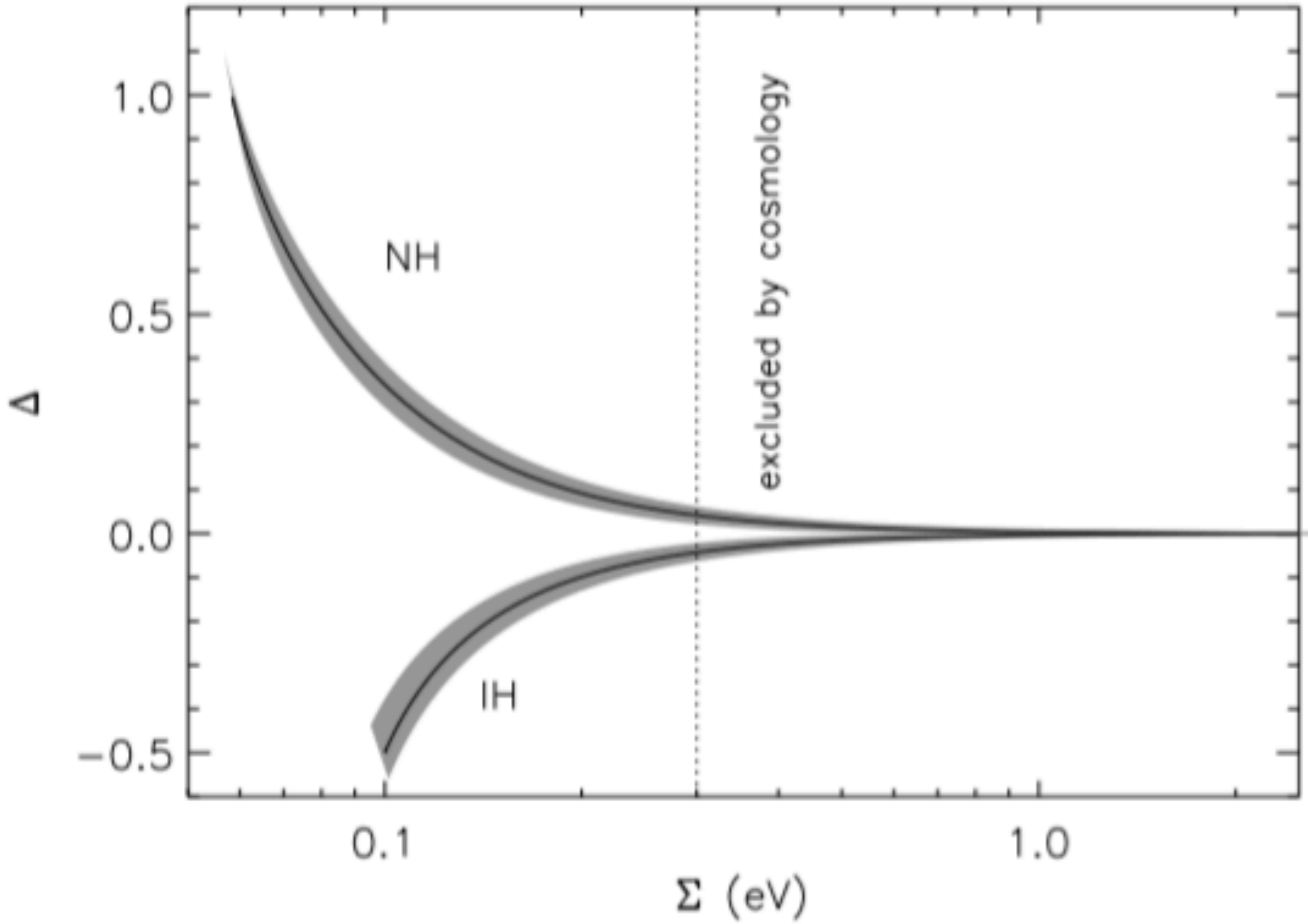


$\Delta P(k)/P(k) = -8\ \Omega_\nu/\Omega_m$

(although not valid on useful scales)

Kiakotou, Elgaroy, OL astro-ph 0709.0253, PRD

Could Cosmology tell the Hierarchy?



$\Delta = (M - m)/\Sigma$ for normal hierarchy

Jimenez et al. 2010

Why do we need bigger surveys?

- Error on power spectrum of density fluctuations
- Suppression due to neutrino free streaming

$$\Delta P(k)/P(k) \propto 1/\sqrt{V_{\rm eff}}.$$

$$\Delta P(k)/P(k) = -8\ \Omega_\nu/\Omega_m$$

- So measurement of neutrino mass improves as inverse $\sqrt{V_{\rm eff}}.$

e.g. 2dF : 0.2 (Gpc/h)^3
DES: 20 (Gpc/h)^3
So a factor 10 improvement on neutrino mass

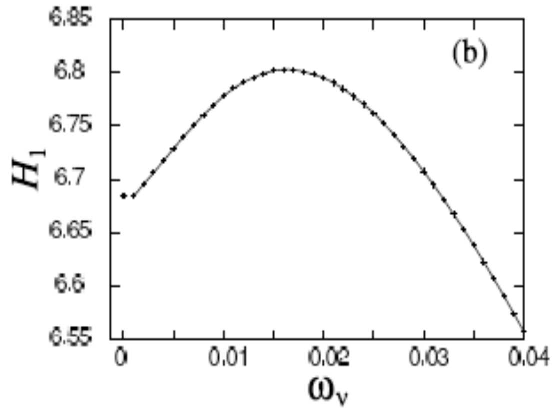
Neutrinos masses and the CMB

If $z_{nr} > z_{rec}$ →

$\Omega_\nu h^2 > 0.017$ (i.e. $M_\nu > 1.6$ eV)

Then neutrinos behave like matter -

this defines a critical value in CMB features



Ichikawa et al. (2004), Fukugita et al. (2006), Lesgourgues & Pastor (2006)

Another probe of neutrino mass:
Density fluctuations from lensing reconstruction of the CMB

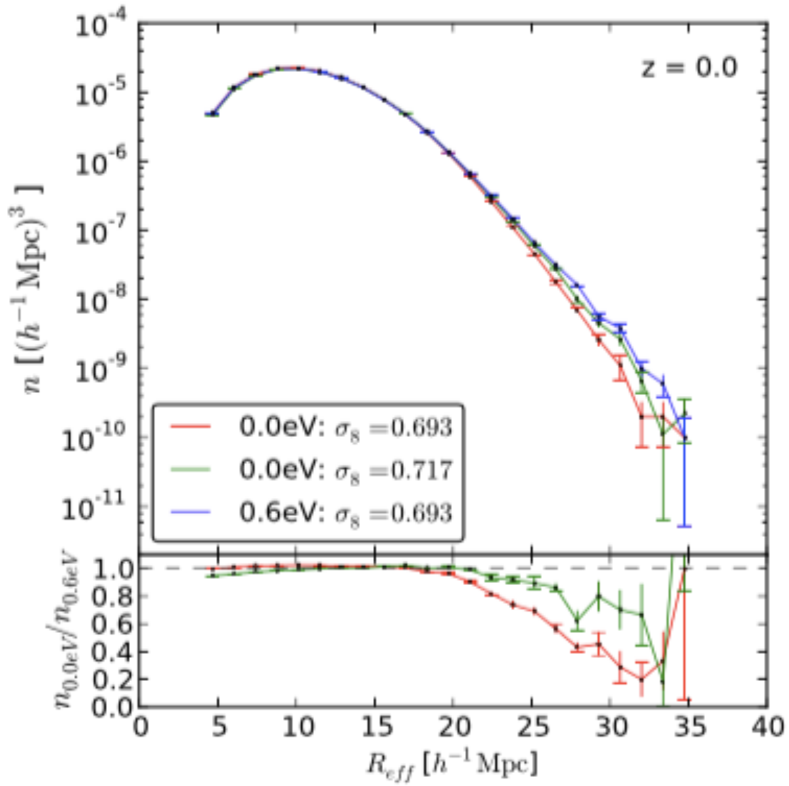
$M_{nu} = m_1 + m_2 + m_3$ from Planck++

Table 1.2: Summary of $\sum m_\nu$ constraints.

	Model	95%CL	Ref.
CMB alone			
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$	< 0.72 eV	[23]
Pl15[TT,TE,EE+lowP]	ΛCDM+$\sum m_\nu$	< 0.49 eV	[23]
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.73 eV	[24]
Pl16[TT+SimLow]	ΛCDM+$\sum m_\nu$	< 0.59 eV	[26]
Pl16[TT,TE,EE+SimLow]	ΛCDM+$\sum m_\nu$	< 0.34 eV	[26]
CMB + probes of background evolution			
Pl15[TT+lowP] + BAO	ΛCDM+$\sum m_\nu$	< 0.21 eV	[23]
Pl15[TT,TE,EE+lowP] + BAO	ΛCDM+$\sum m_\nu$	< 0.17 eV	[23]
Pl15[TT+lowP] + JLA	ΛCDM+$\sum m_\nu$	< 0.33 eV	[24]
Pl15[TT+lowP] + BAO	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.27 eV	[24]
CMB + probes of background evolution + LSS			
Pl15[TT+lowP+lensing]	ΛCDM+$\sum m_\nu$	< 0.68 eV	[23]
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.25 eV	[24]
Pl15[TT+lowP+lensing] + P(k)$_{\rm DR12}$	ΛCDM+$\sum m_\nu$	< 0.30 eV	[28]
Pl15[TT+lowP+lensing] + P(k)$_{\rm DR12}$ + HST	ΛCDM+$\sum m_\nu$	< 0.16 eV	[28]
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$\sum m_\nu$	< 0.59 eV	[23]
Pl15[TT,TE,EE+lowP] + BAO+ P(k)$_{\rm WZ}$	ΛCDM+$\sum m_\nu$	< 0.14 eV	[31]
Pl15[TT,TE,EE+lowP] + BAO+ P(k)$_{\rm DR7}$	ΛCDM+$\sum m_\nu$	< 0.13 eV	[31]
Pl15[TT,TE,EE+lowP] + BAO+ P(k)$_{\rm DR12}$	ΛCDM+$\sum m_\nu$	< 0.16 eV	[30]
Pl15[TT+lowP+lensing] + Lyα	ΛCDM+$\sum m_\nu$	< 0.12 eV	[29]
Pl16[TT+SimLow+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.17 eV	[26]
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+Ω_k	< 0.37 eV	[24]
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+w	< 0.37 eV	[24]
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.32 eV	[23]
Pl15[TT,TE,EE+lowP]+BAO+P(k)$_{\rm DR12}$+JLA	ΛCDM+$\sum m_\nu$+Ω_k+w	< 0.31 eV	[30]
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$\sum m_\nu$+5-params.	< 0.66 eV	[32]

RPP 2017
Lesgourgues & Verde

Beyond 2pt statistic: Neutrino mass from the Cosmic Web
Void abundance



Massara et al. (2015)

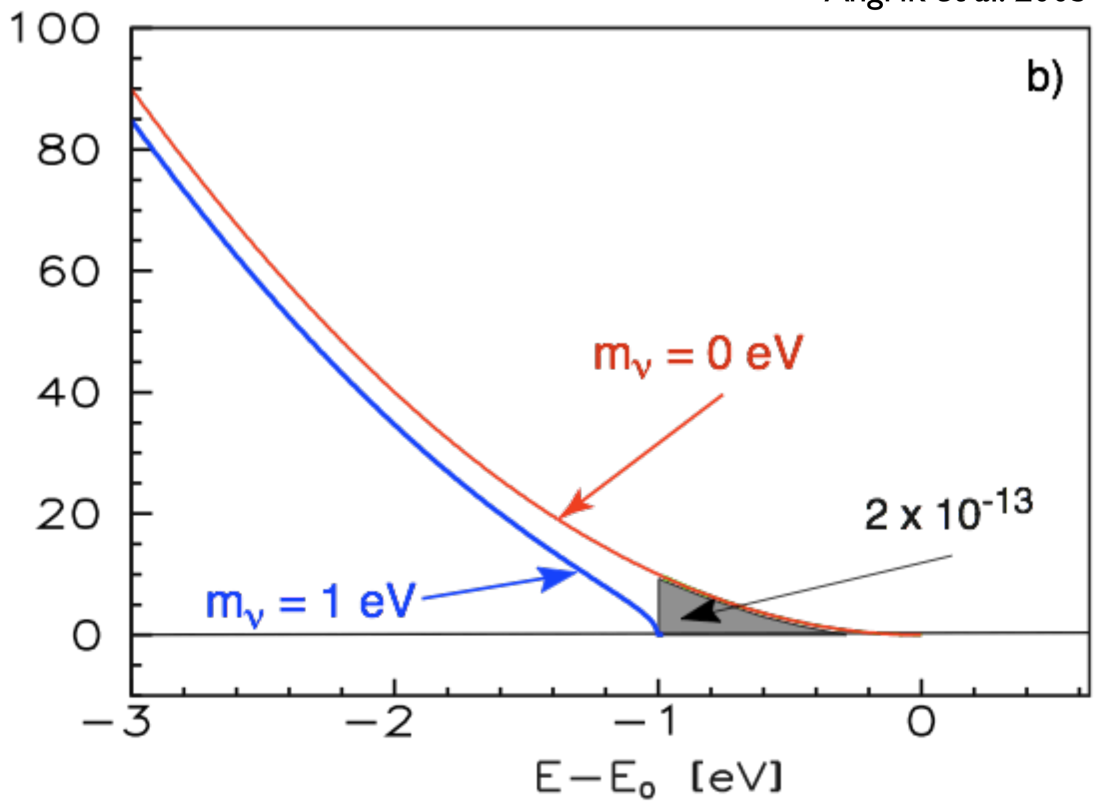
Tritium beta decay

- Nuclear recoil

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

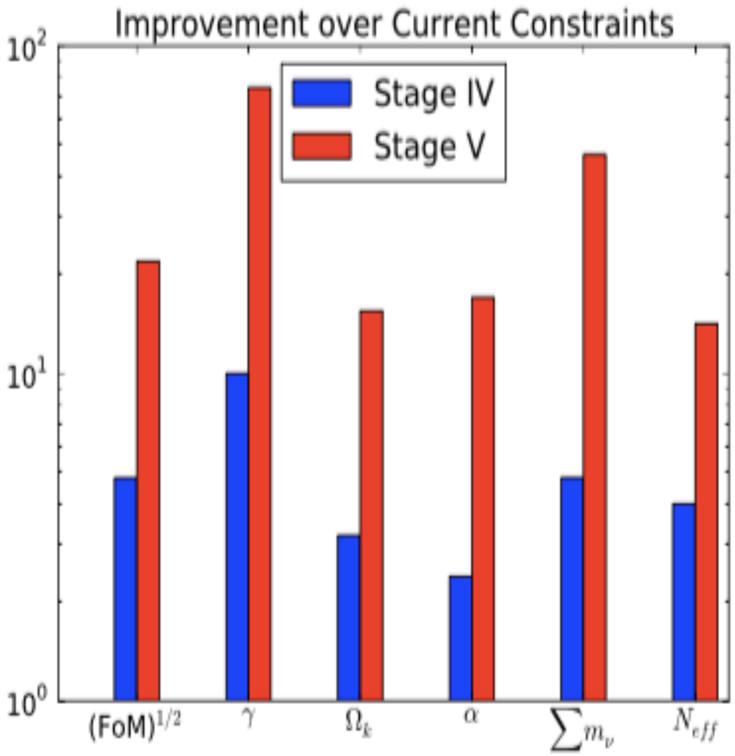
- The observable is the square of the effective electron neutrino mass

Angrik et al. 2005



$$\frac{\mathrm{d}N}{\mathrm{d}E} \simeq C\,(E_0 - E)\sqrt{(E_0 - E)^2 - m_\beta^2}$$

Forecast for stages IV and V



Cosmic Vision 1604.07626