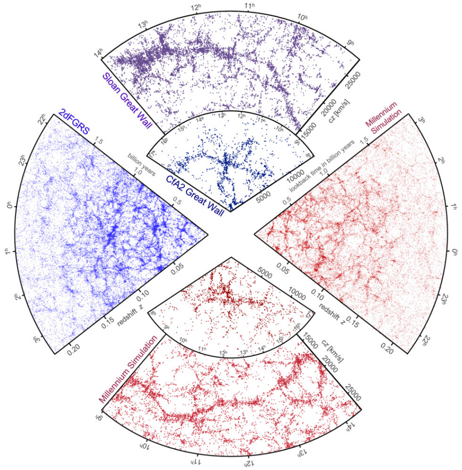
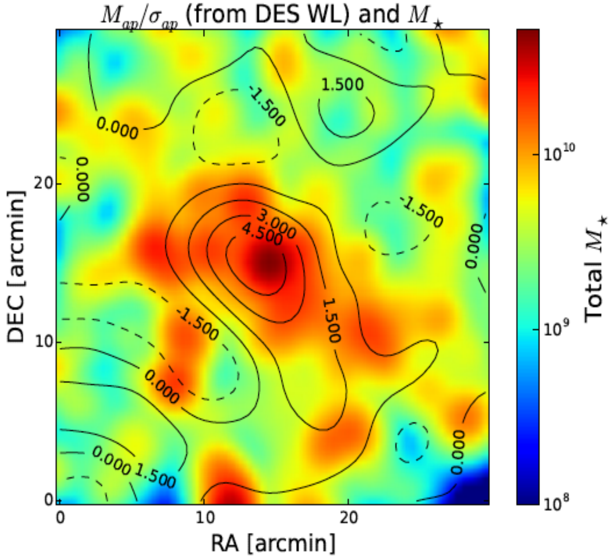
Neutrino mass from cosmological surveys





Ofer Lahav (UCL)

Outline

- Brief History of Hot Dark Matter
- The improvement on neutrino mass upper limit (factor 10 in 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
- Combining cosmological + terrestrial experiments
- What's next?

The Big Neutrino Questions

- What is the absolute neutrino mass?

  (in the range [0.06, 0.2] eV)
- What is the hierarchy – Normal or Inverted?
- Is $N_{eff} = 3.046$, or larger (Sterile/'dark radiation')?
- Is the neutrino its anti-particle?

Brief History of 'Hot Dark Matter'

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

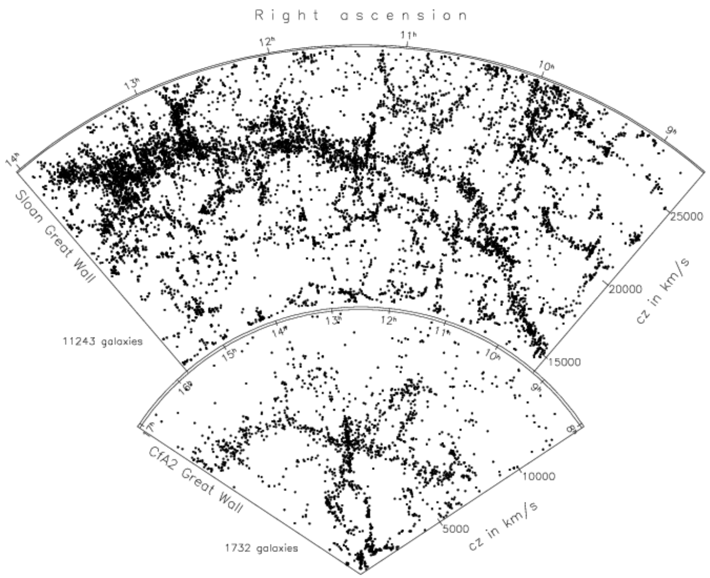
* 1980s: HDM - Problems with structure formation

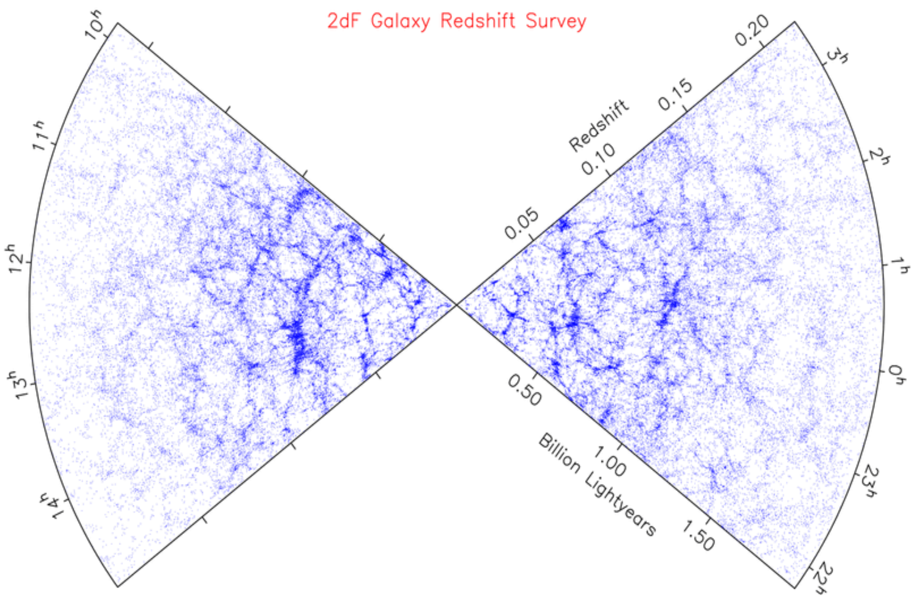
* 1990s: Mixed CDM (80%) + HDM (20%)

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

  But now we know HDM exists!
  How much?

Tiny Neutrino Masses from Great Walls



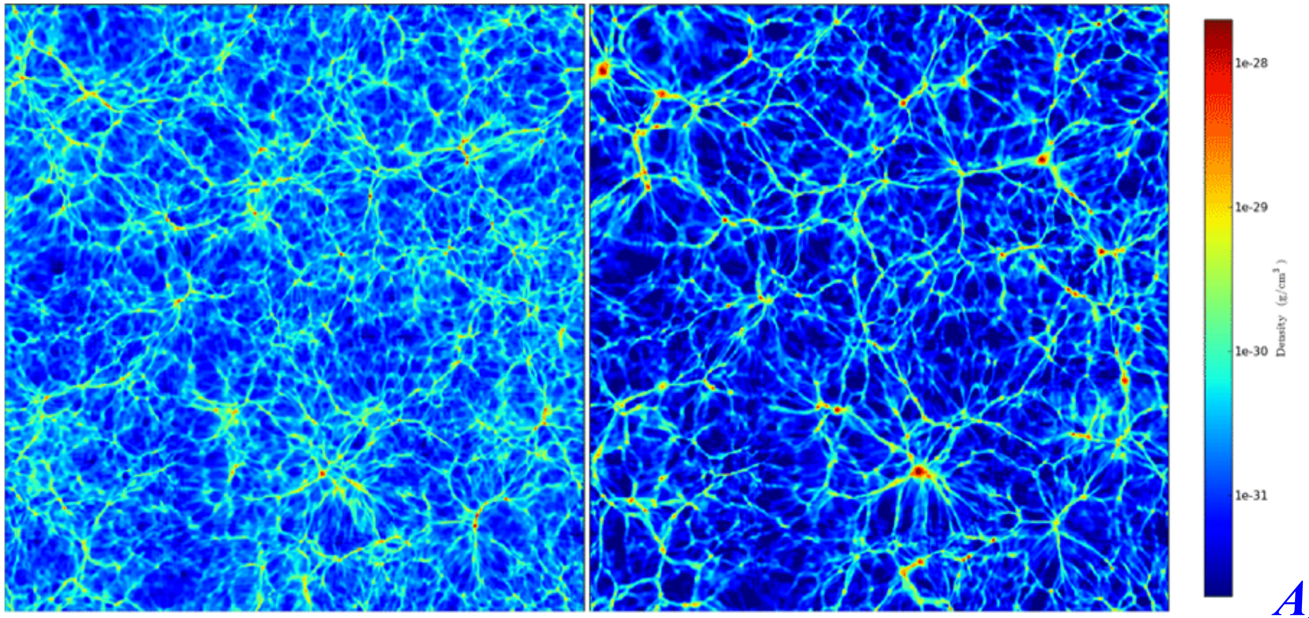


Neutrino Mass from Cosmology

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

$k > k_{nr} = 0.026\ (m_\nu/1\ eV)^{1/2}\ \Omega_m^{1/2}\ h/Mpc$

$\Omega_\nu h^2 = M_\nu/(94\ eV)$

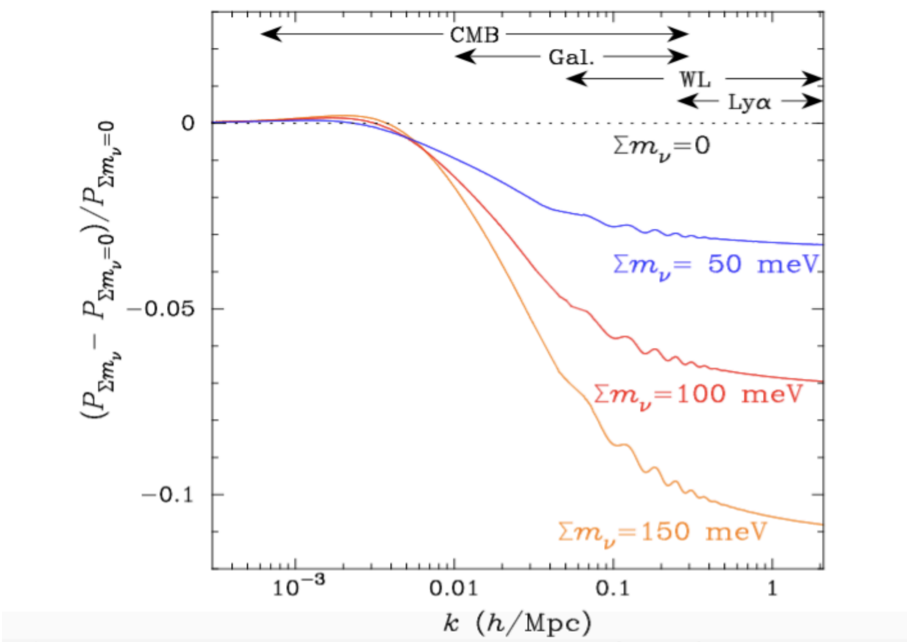


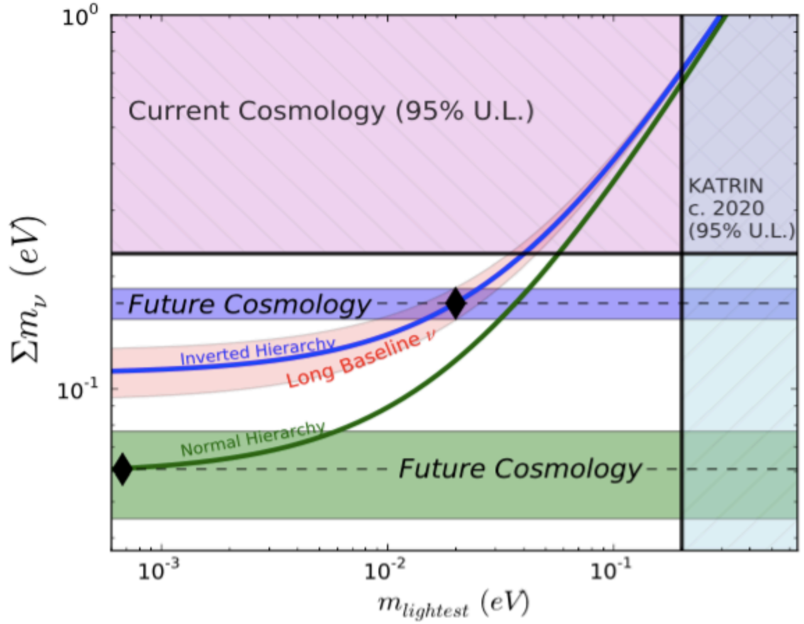
Agarwal & Feldman 2010

CDM+ 1.9 eV neutrinos

CDM

The sub-eV Neutrino Cosmology





Abazajian et al. 1309.5383

Why do we need bigger surveys?

- Error on power spectrum
- Suppression due to neutrino free streaming

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

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

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

e.g. 2dF : 0.2 (Gpc/h)^3
DES: 20 (Gpc/h)^3

Methodology: health warnings

- Some probes are sensitive to the neutrino mass directly (e.g. the shape of the power spectrum at k=…).
- 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 Physica”.

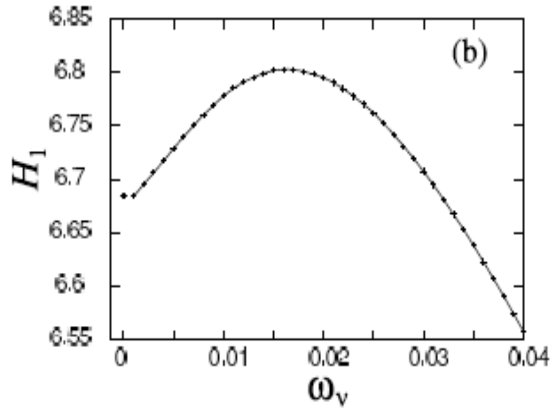
Neutrinos masses and the CMB

If $z_{nr} > z_{rec}$ →

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

Then neutrinos behave like matter -

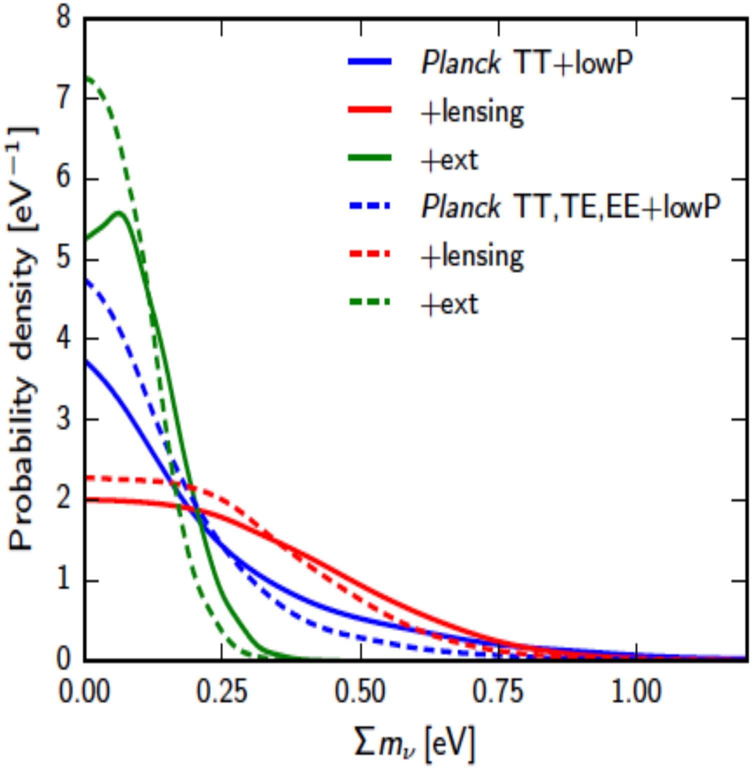
this defines a critical value in CMB features



* Ichikawa et al. (2004) , Fukugita et al. (2006)

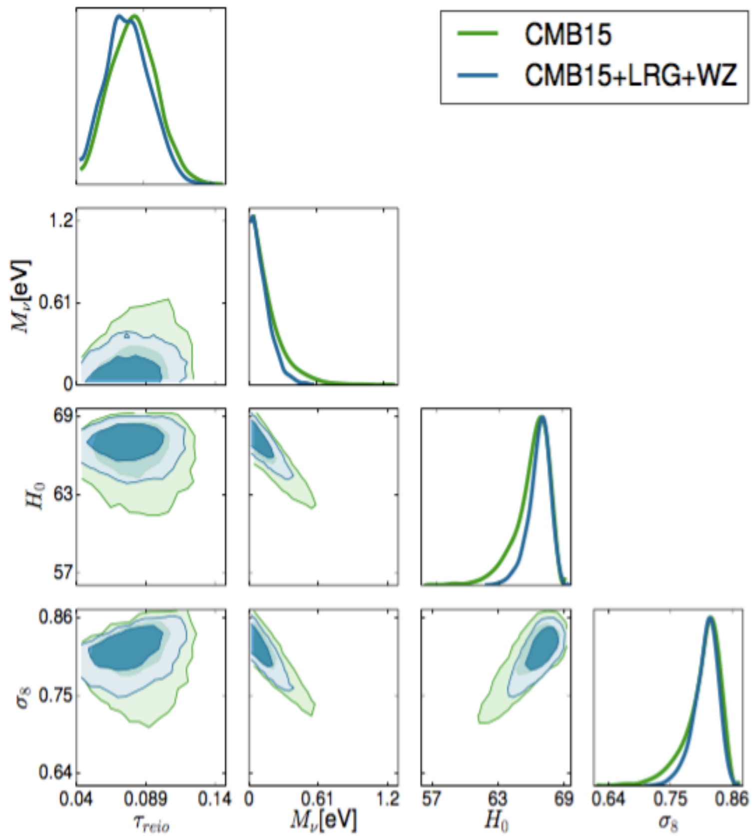
Lensing of the CMB could help!

Planck 2015 ++



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

CMB + LSS



Data sets	M_ν at 95% CL
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

Cuesta, Niro & Verde 1511.05983

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	< 0.23 eV
BOSS Ly-alpha + Planck15	Palanque-Delabrouille etal. 2015	< 0.12 eV

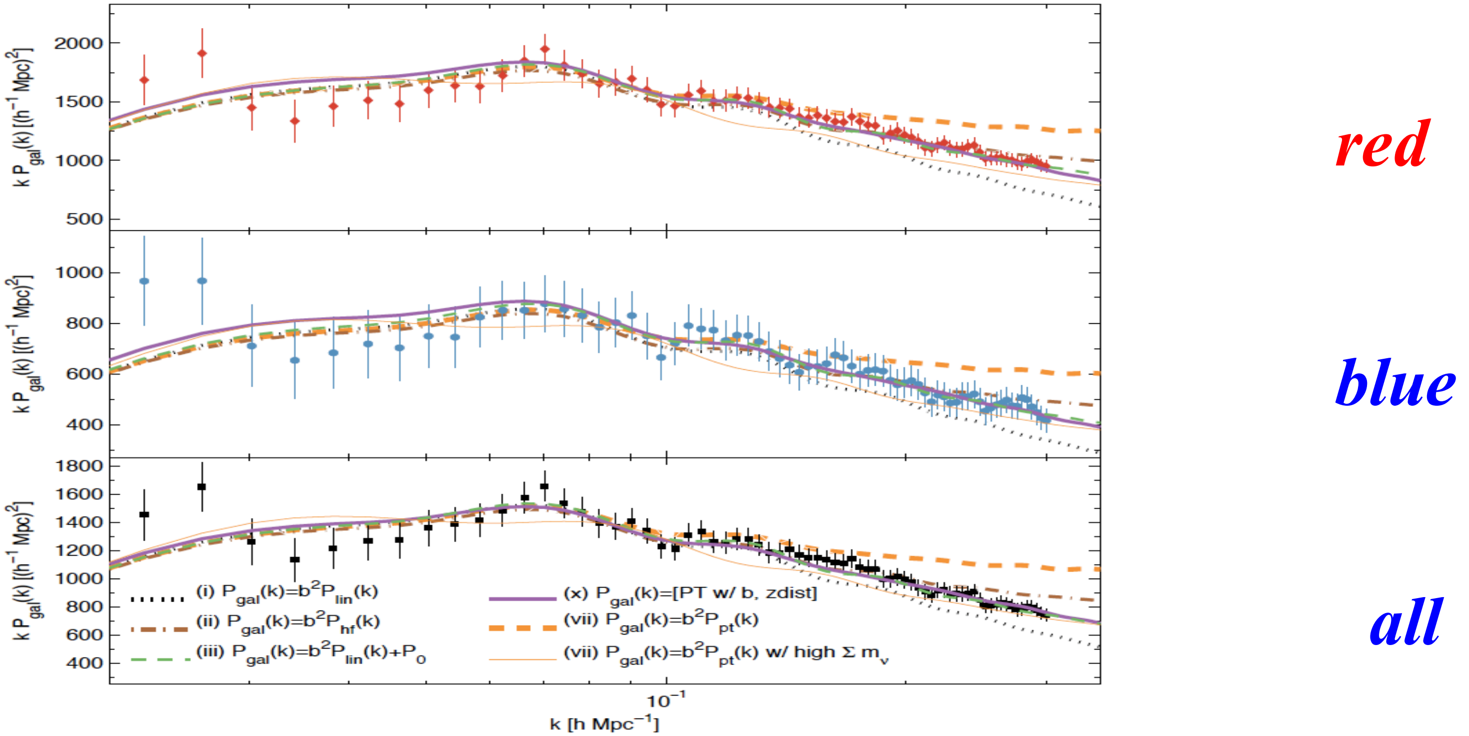
All upper limits 95% CL, but different assumed priors !

2-sigma Neutrino mass – forecast for future surveys

Data	Authors	Error (Σ)
DES (LSS) + P DES (LSS+WL) + P	OL et al. 2010 Font-Ribera et al 2014	0.1 eV 0.08 eV
Euclid +Planck (LSS/WL)	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	0.05 eV

Errors 95% CL, but different assumed priors !

Controlling systematics Neutrino mass from red vs blue SDSS galaxies



upper limit in the range 0.5-1.1 eV

red and blue within 1–sigma

Swanson, Percival & Lahav (MN, 2010)

The 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 + …

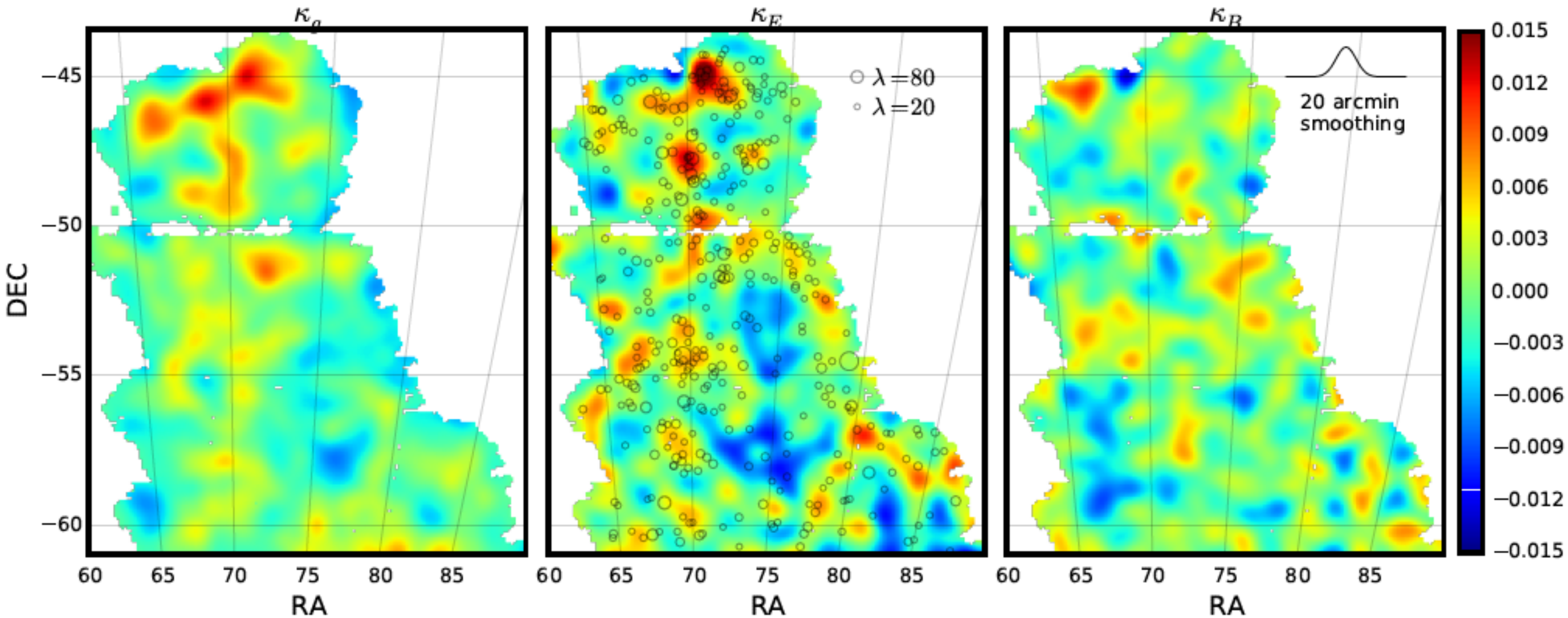
- Science Verification (SV): 250 sq deg to full depth
- Y1: approx 2000 sq deg 40% of depth.
  Median seeing FWHM approx 0.9”
  (as required for WL in riz)
- Y2: approx remaining 3000 sq deg same depth
- Y3: ended

- So far about 50% of the data observed,
- 68 DES papers on the arXiv

Objects	As of Dec 2015	Expected from full 5yr DES
Galaxies with photo-z (> 10 sigma)	7M (SV), 100M (Y1+Y2),	300M
Galaxies with shapes	3M (SV), 80M (Y1+Y2)	200M
Galaxy clusters (lambda>5)	150K (Y1+Y2)	380K
SN Ia SLSN	1000 2 + confirmed + candidates	Thousands 15-20
New Milky Way companions	17	25
QSO's at z> 6 Lensed QSO's	1 + confirmed + candidates 2 + candidates	375 100 (i<21)
Stars (> 10 sigma)	2M (SV), 30M (Y1+Y2)	100M
Solar System: Trans Neptunian Objects Jupiter Trojans Main Belt asteroids Kuiper Belt Objects	32 in SN fields + 2 in the WF 19 300K (Y1+Y2)	50 + many more in the wide field 500-1000

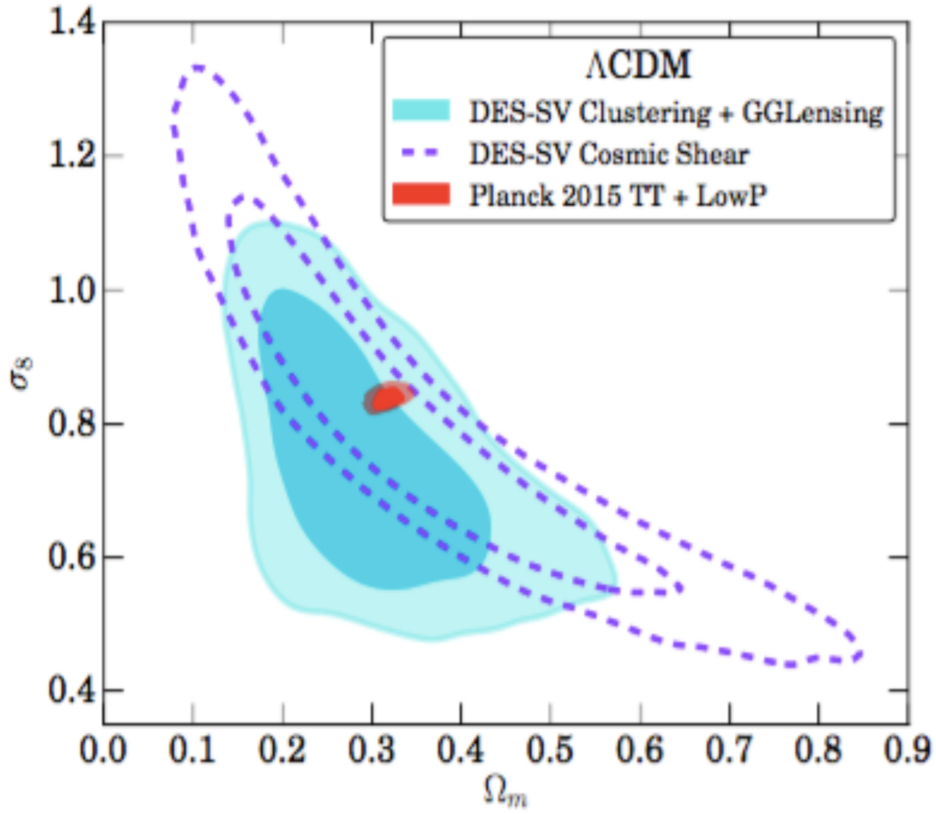
Dark Matter map from Weak Lensing

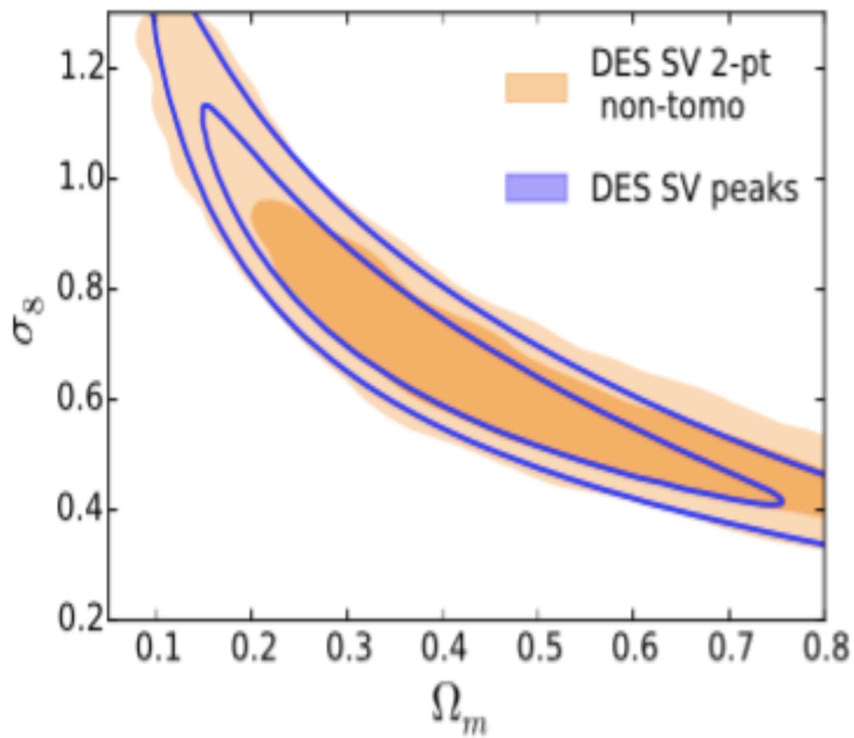
SV area 139 sq deg (only 3% of final DES)
Cross correlation signal: 5-7 sigma



Chang, Vikram, Jain et al. (PRL) 1M Background sources @ z ~0.8
Vikram, Chang, Jain et al. (PRD) 1M Foreground lenses @ z ~ 0.3

Is DES consistent with LCDM?

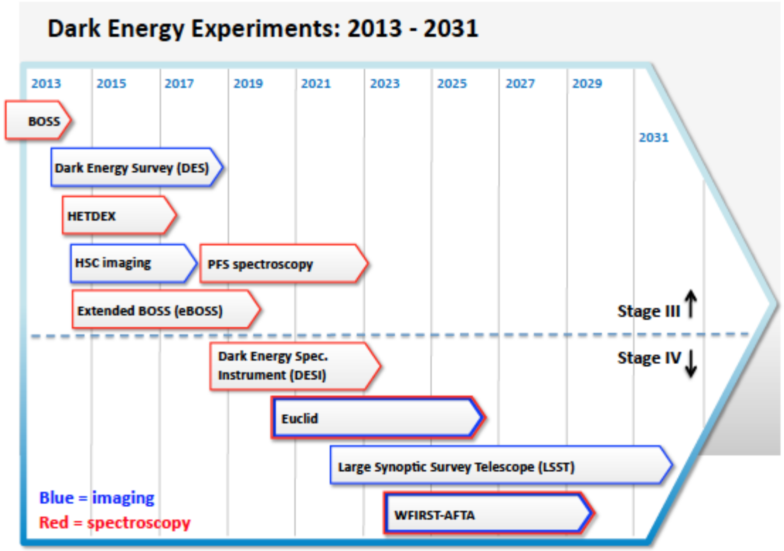


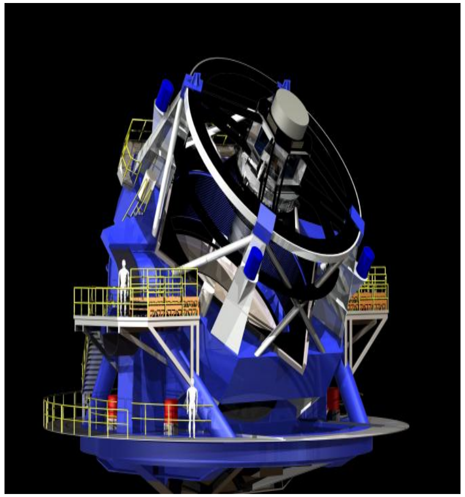


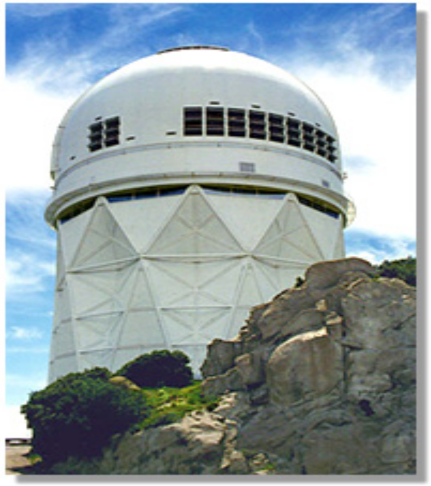
Kwan et al. 1604.07871
(dashed line DES Collaboraton

Kacprzak et al. 1603.05040

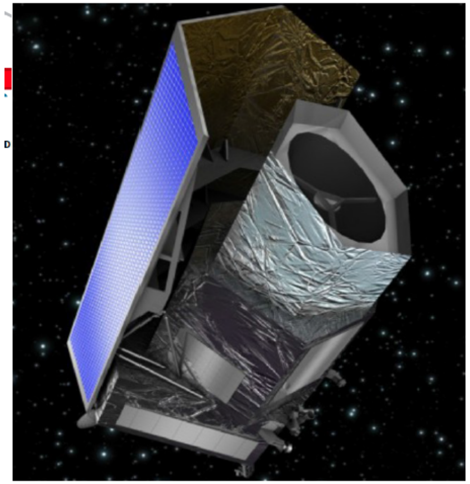
The era of DESI, Euclid, LSST,…



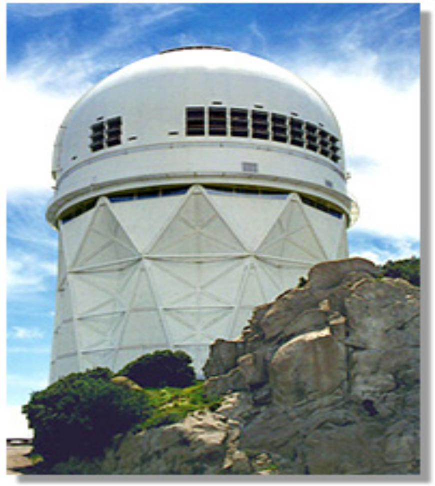




Mayall 4-Meter Telescope



Dark Energy Spectroscopic Instrument (DESI) – 10 times BOSS



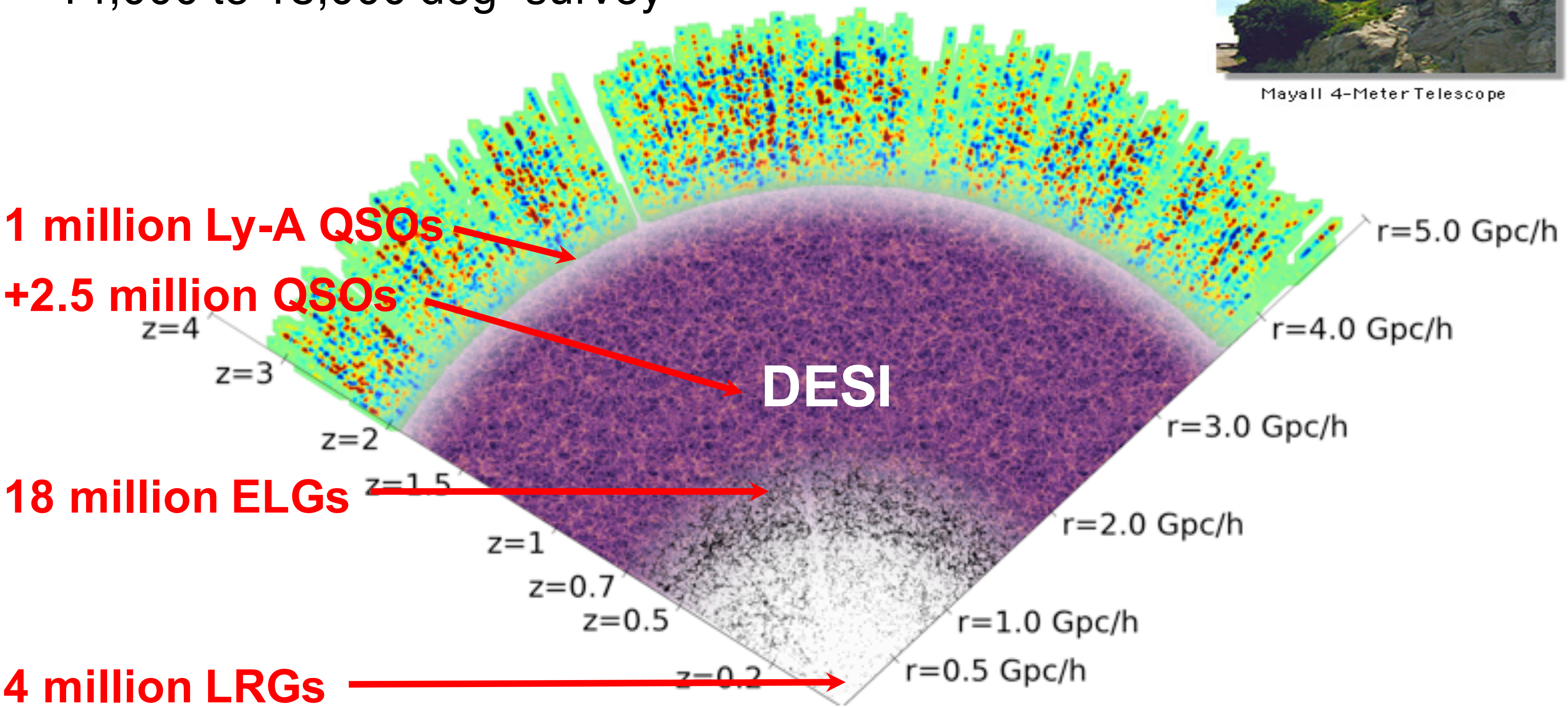
Mayall 4-Meter Telescope

Mayall telescope available up to 100% of dark time,

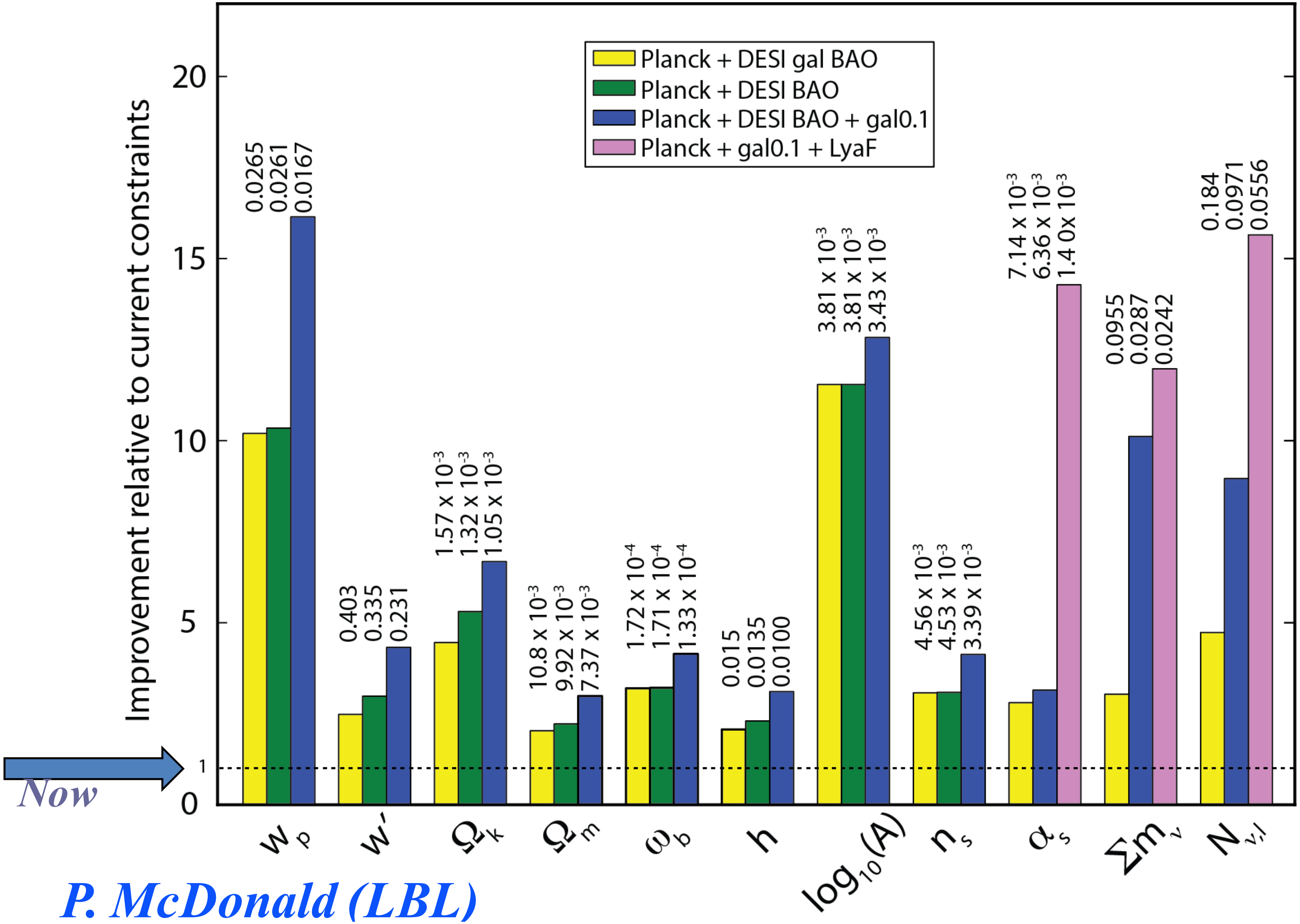
5000 fibres, 20min base integration time

> 20 million targets

14,000 to 18,000 deg^2 survey

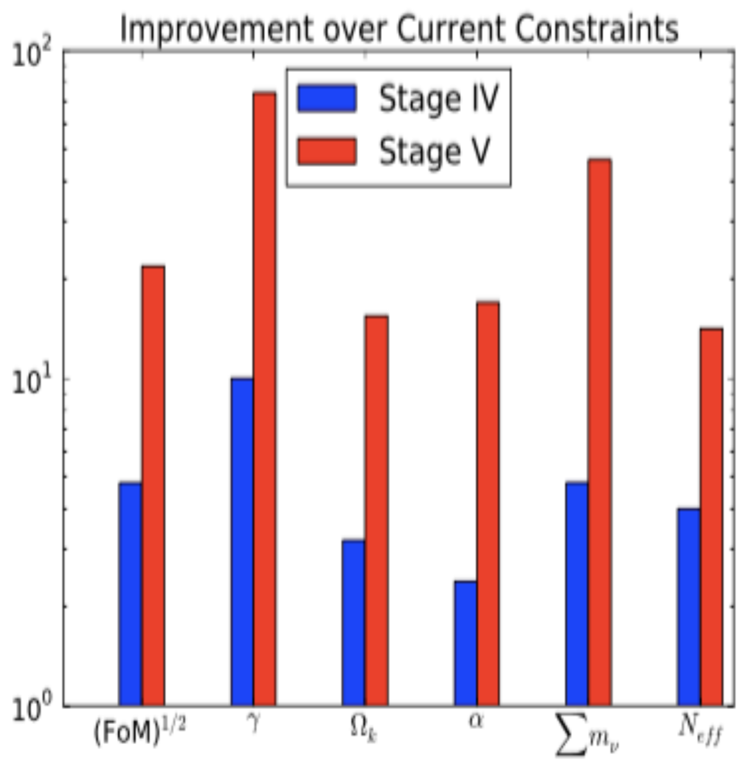


DESI - forecast



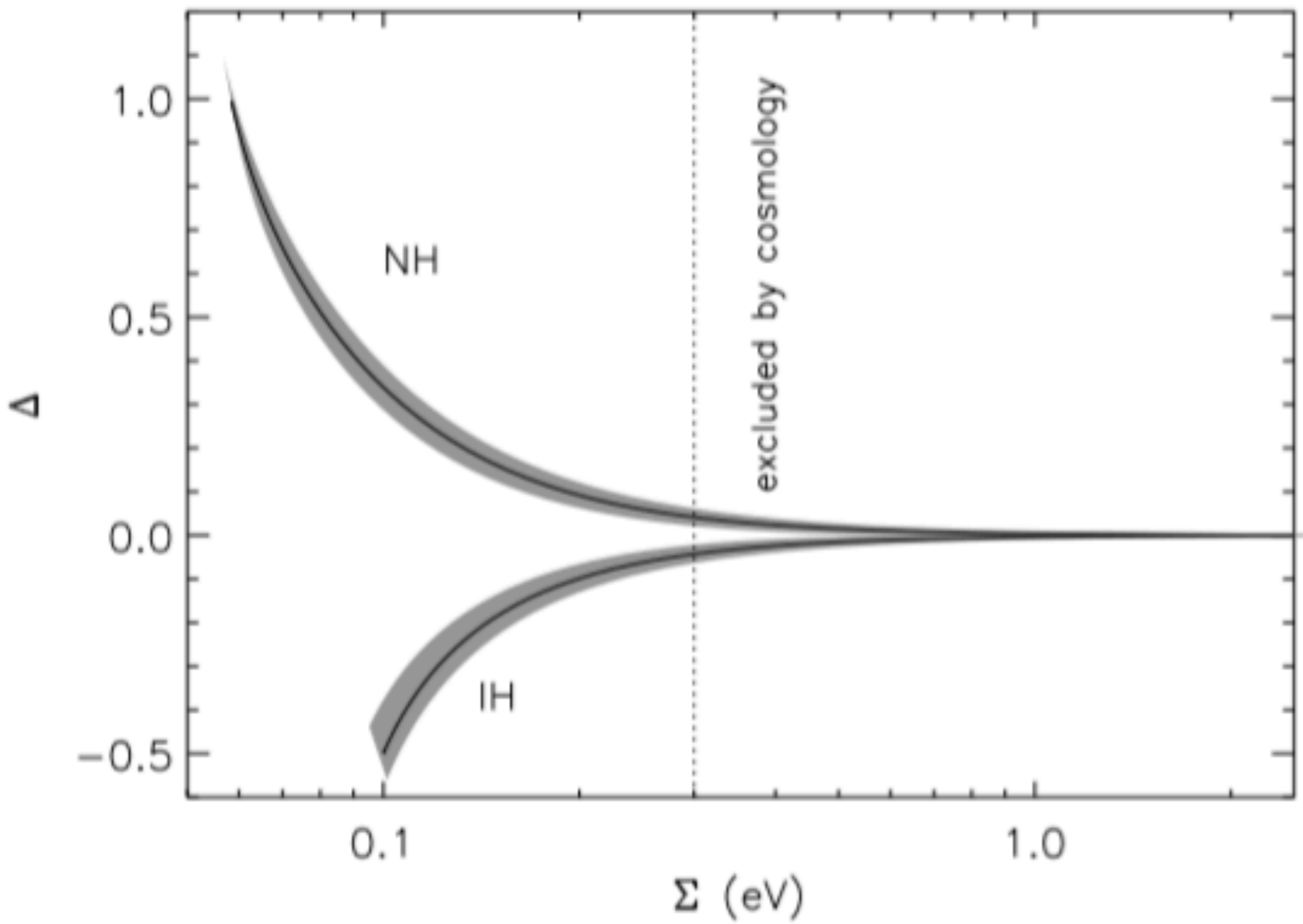
P. McDonald (LBL)

Forecast for stages IV and V



Cosmic Vision 1604.07626

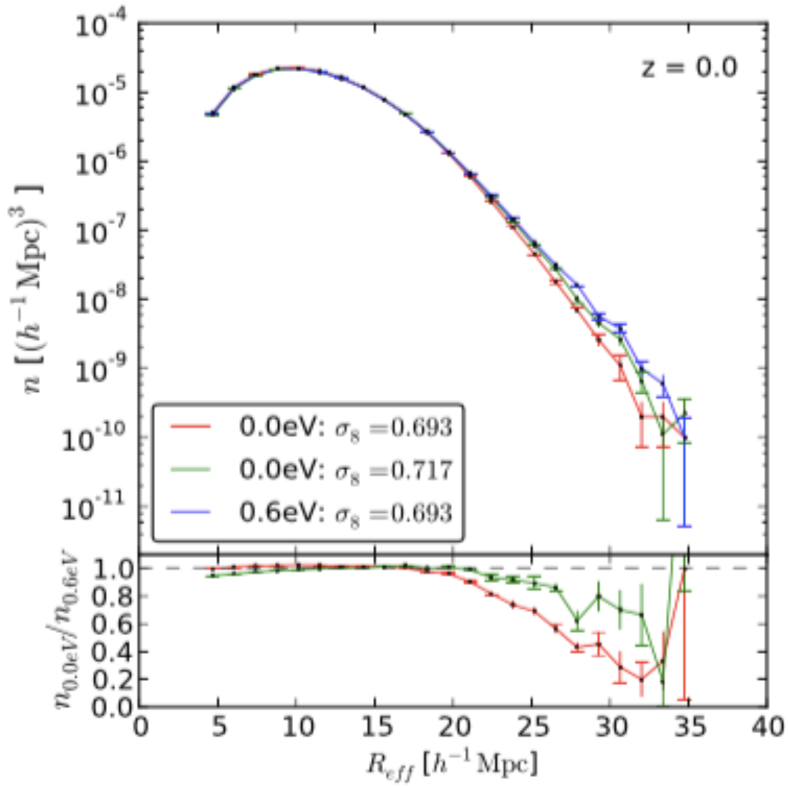
Could Cosmology tell the Hierarchy?



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

Jimenez et al. 2010

Neutrino mass from the Cosmic Web
Void abundance



Massara et al. (2015)

Combine Cosmology & terrestrial experiments:

DES+Planck vs. KATRIN

$M_\nu < 0.1$ eV $M_\nu < 0.6$ eV

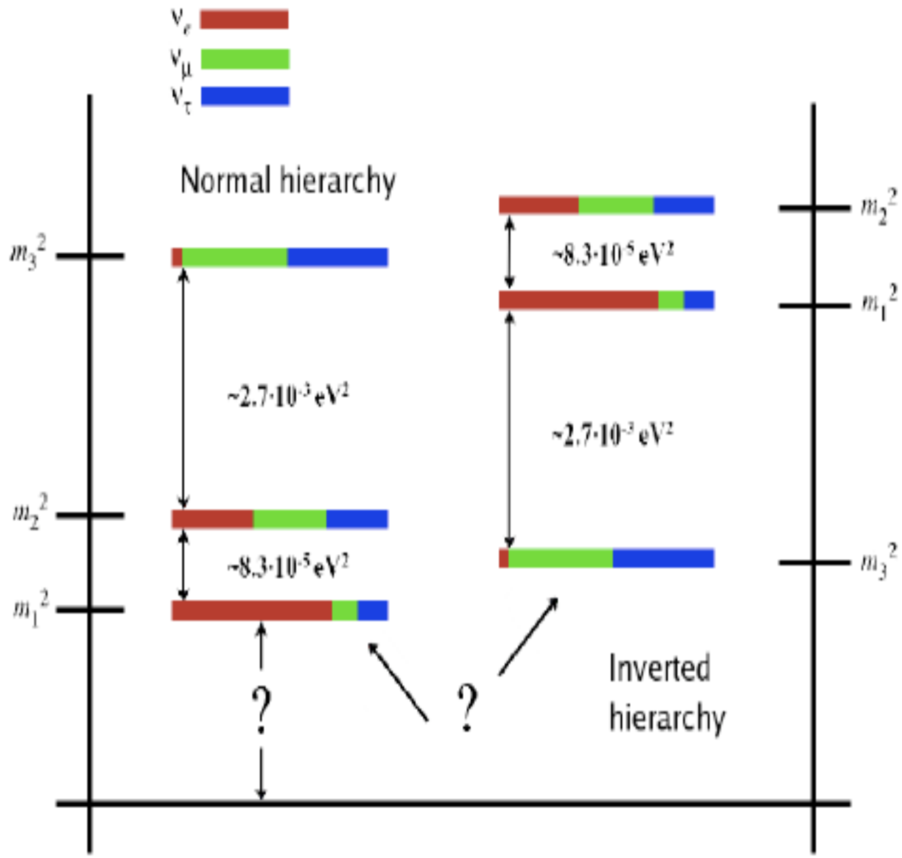
OL , Kiakotou, Abdalla and Blake (2010) 0910.4714
Host et al.

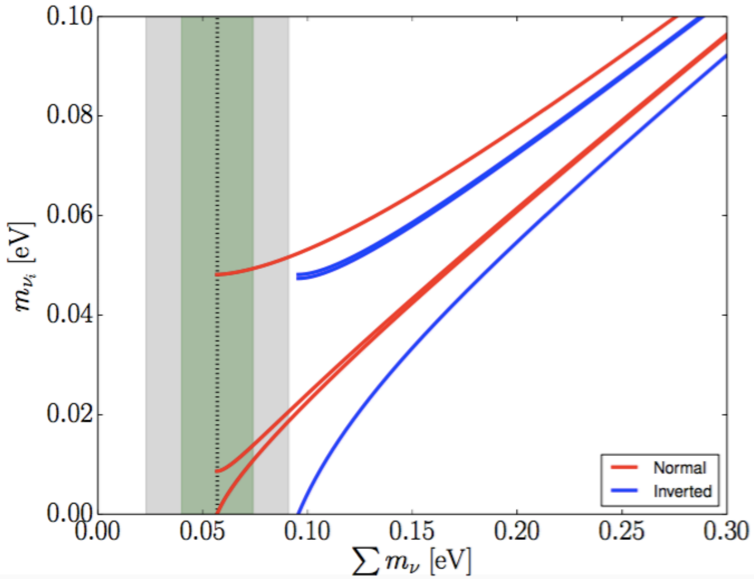
Summary

- Current upper limits on sum neutrino mass
- <0.2 eV (10 times better that 15 years ago)
- Future surveys will improve it by factor 5-10, towards to lower limit of 0.06 eV.
- So far no tension between cosmology and terrestrial experiments
- Hopefully a measurement soon!
- Controlling systematics is crucial
- Great prospects for new surveys coming decade

Extra slides

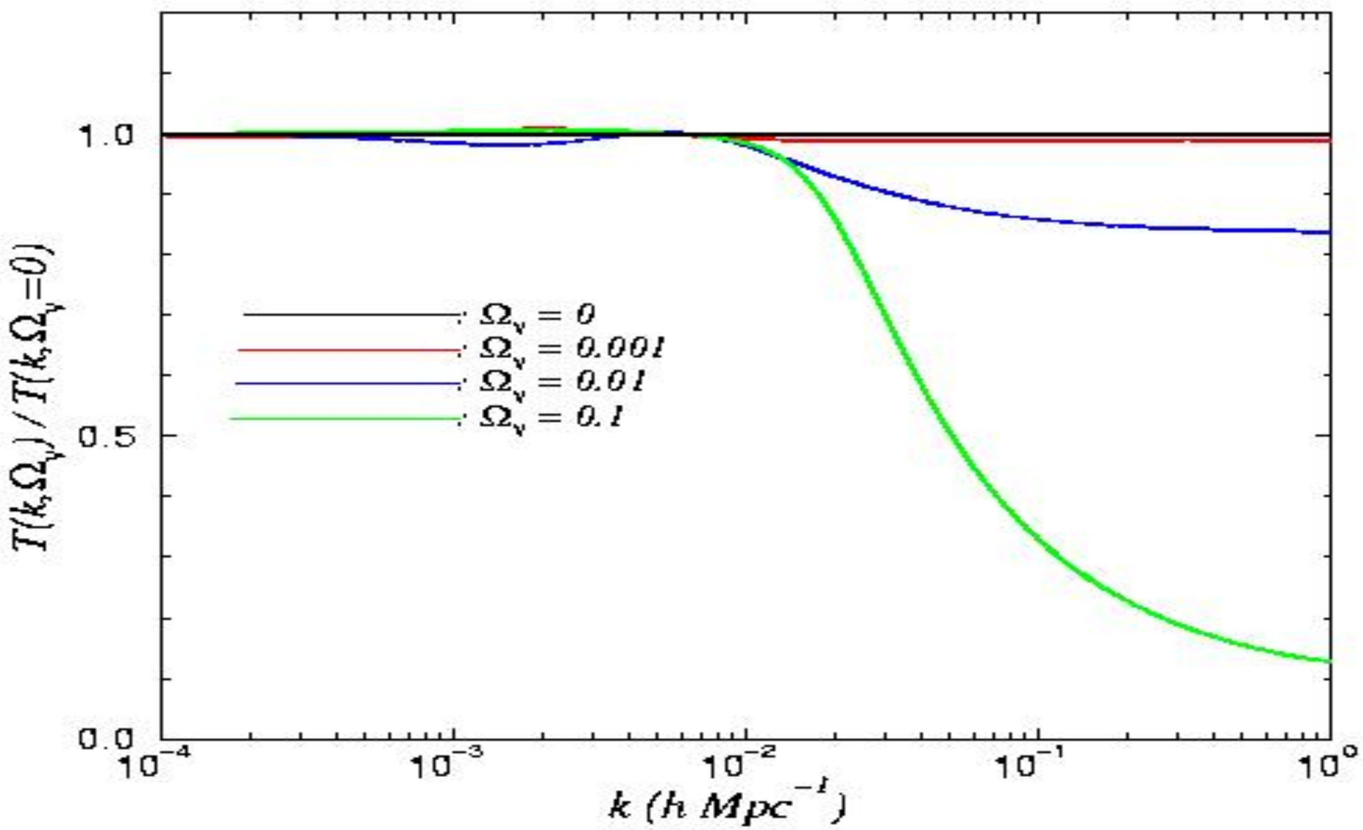
Neutrino Mass Hierarchy





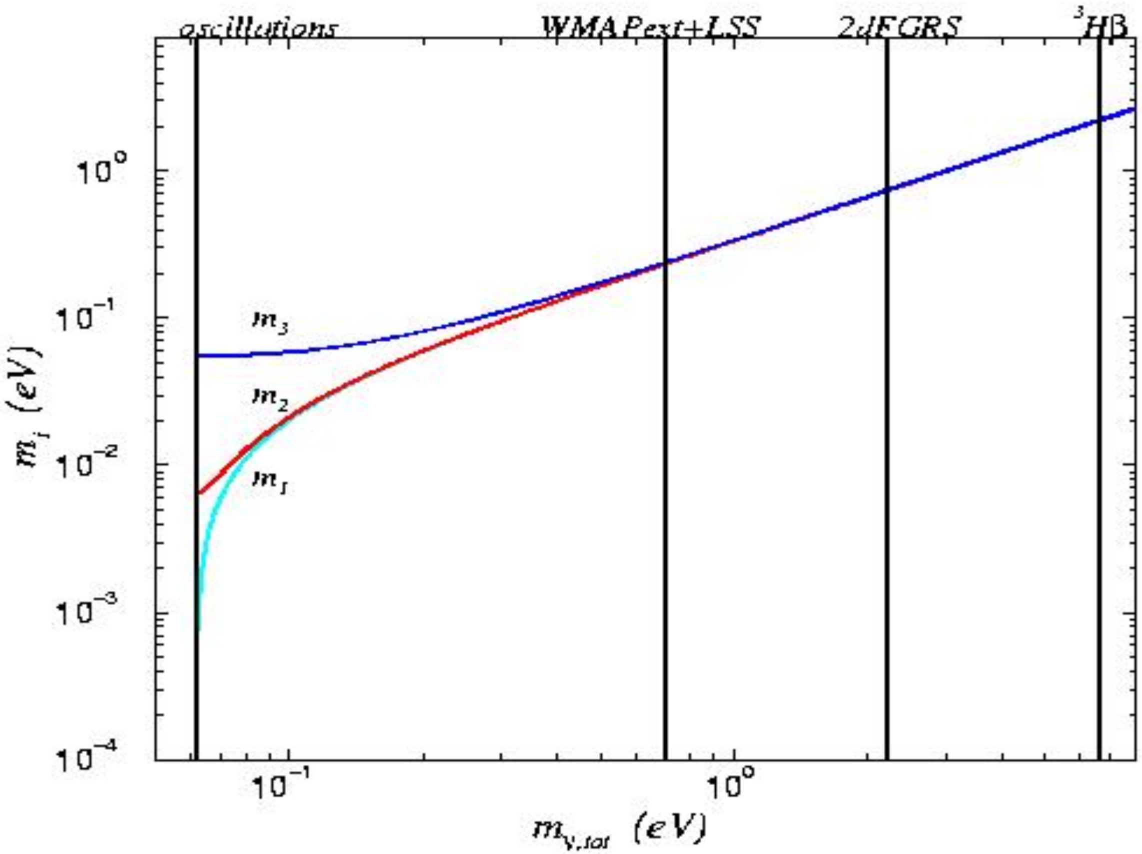
Font et al. 1308.4164

$P(k)=A\ k^n\ T^2(k)$



1.0
0.5
0.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$k\ (h\ Mpc^{-1})$
$T(k,\Omega_\nu)\ /\ T(k,\Omega_\nu=0)$
$\Omega_\nu = 0$
$\Omega_\nu = 0.001$
$\Omega_\nu = 0.01$
$\Omega_\nu = 0.1$

Absolute Masses of Neutrinos

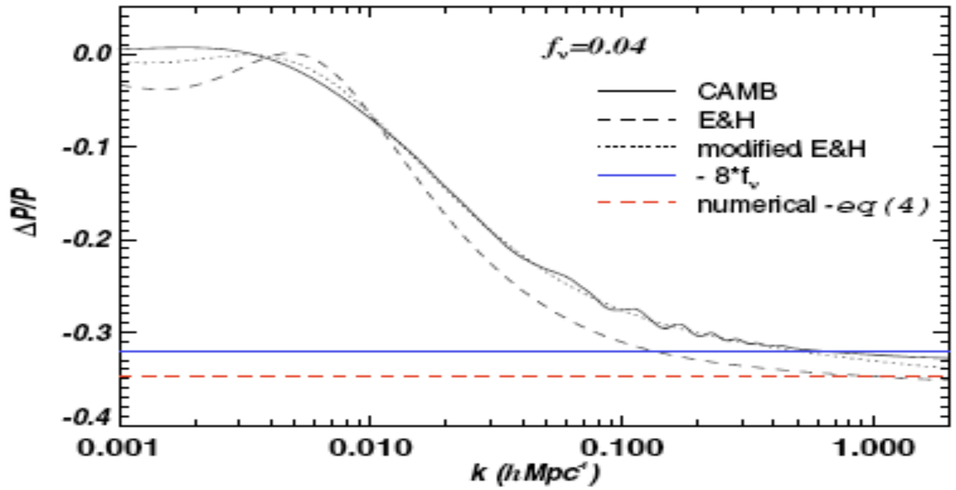


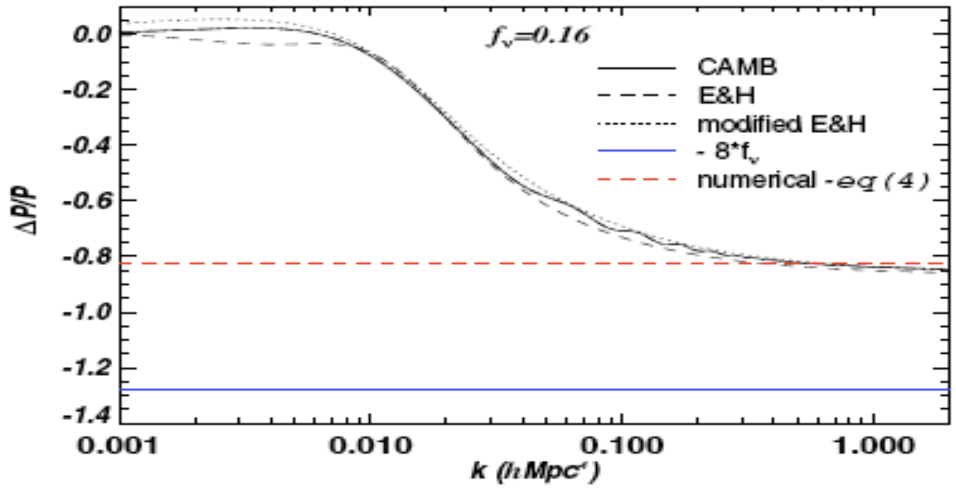
Based on measured squared mass differences from solar and atmospheric oscillations

Assuming $m_1 < m_2 < m_3$

Elgaroy & OL, NJP 05

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





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

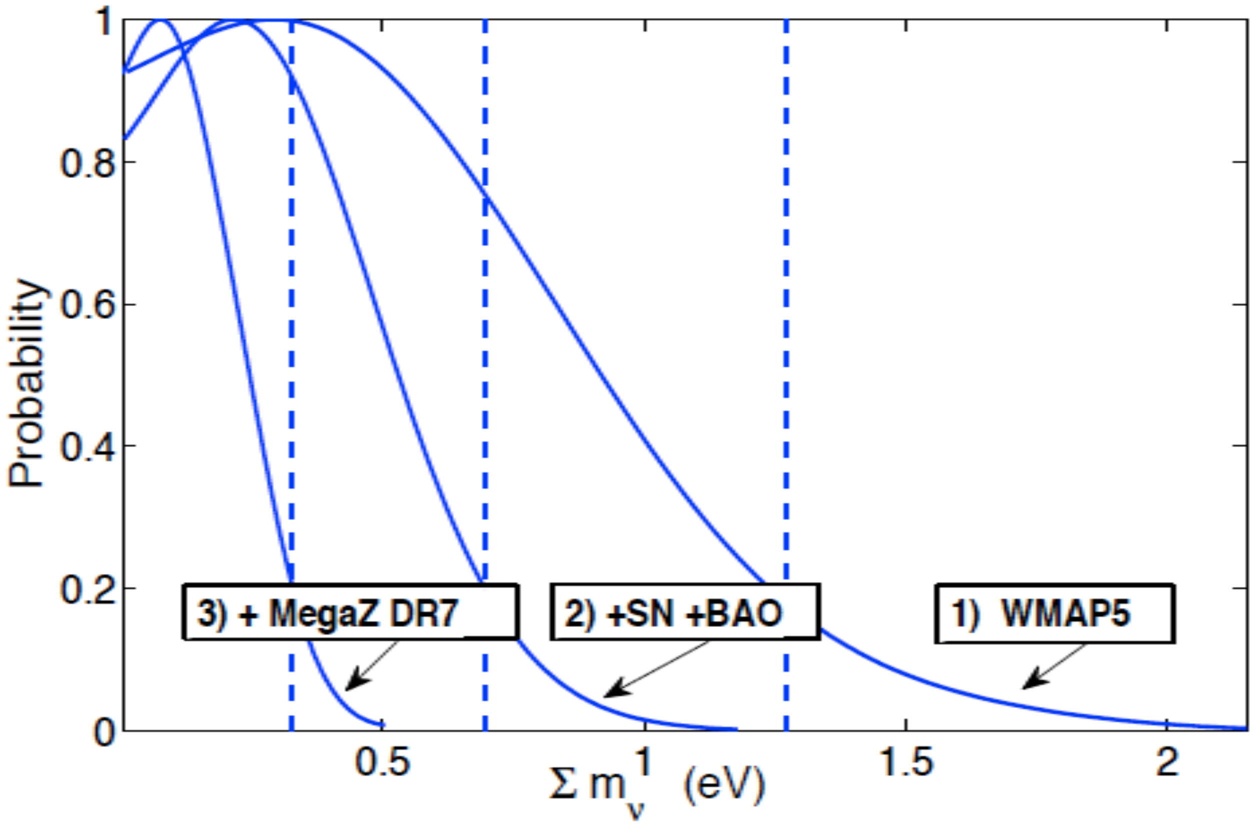
(although not valid on useful scales)

Kiakotou, Elgaroy, OL
astro-ph 0709.0253, PRD

Neutrino mass from MegaZ-LRG

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

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



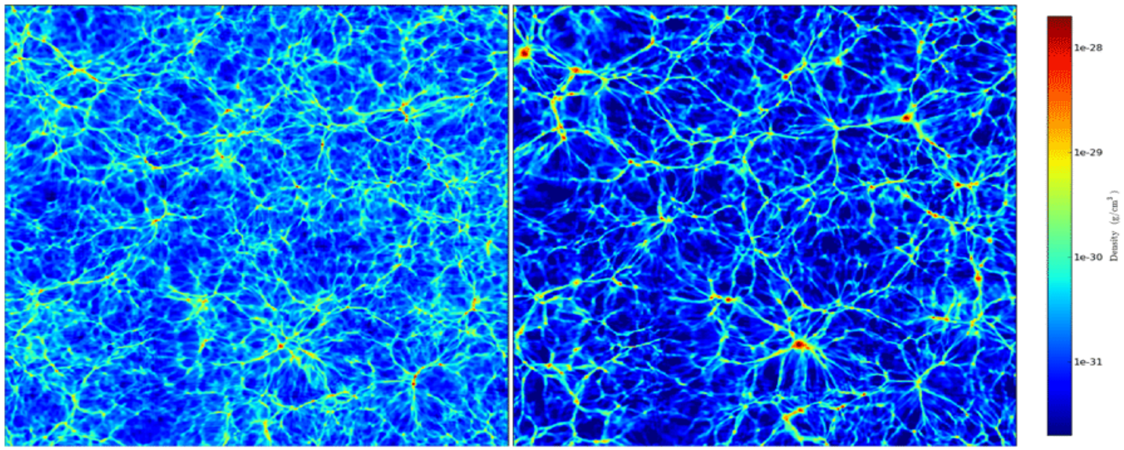
Thomas, Abdalla & Lahav (PRL, 2010)

cf. Reid et al. (2010) ; Planck + BAO (2013) give < 0.23 eV

Neutrino mass from galaxy surveys

700,000 galaxies with ANNz photo-z within 3.3 (Gpc/h)^3

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



BBC News

Neutrino 'ghost particle' sized up by astronomers

11:48 GMT, Tuesday, 22 June 2010 12:48 UK

Thomas, Abdalla & Lahav, PRL (2010)

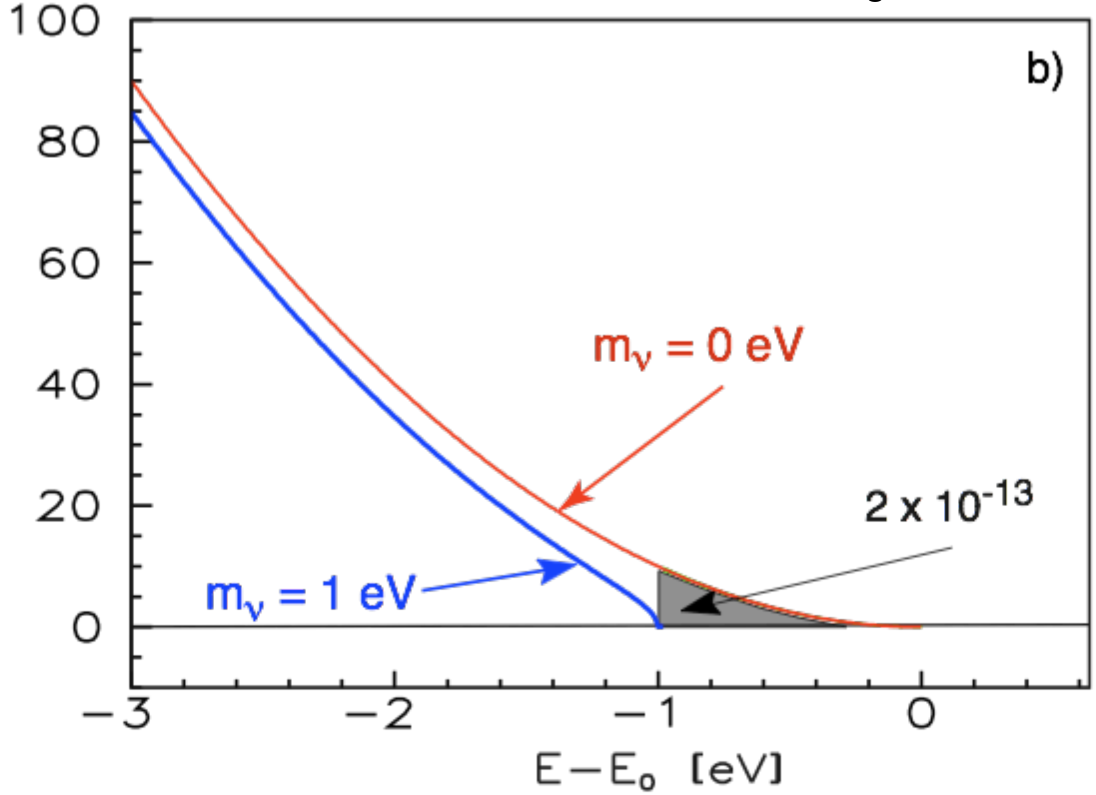
Tritium beta decay

- 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



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

More points

* within the Λ-CDM scenarios, subject to priors.
* weak gravitational lensing of background galaxies and of the CMB.