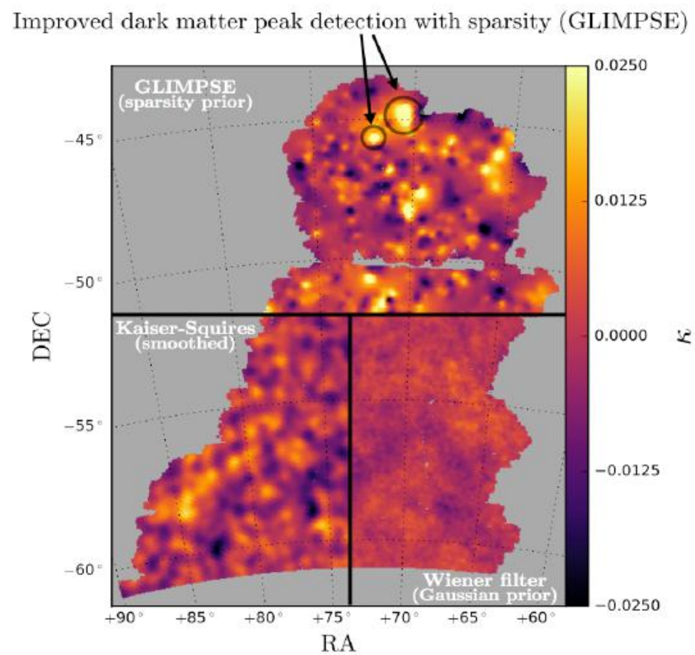
Neutrino mass from cosmological surveys



Dark Matter Map with 3 Methods

Jeffery et al. (2018)

Ofer Lahav (UCL)

The Big Neutrino Questions

- What is the absolute sum of neutrino mass?
  -upper limit of about 0.2 eV from Cosmology
  - 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)?
- Neutrino properties from Cosmology:
  a crucial test of our data and methodology

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%):

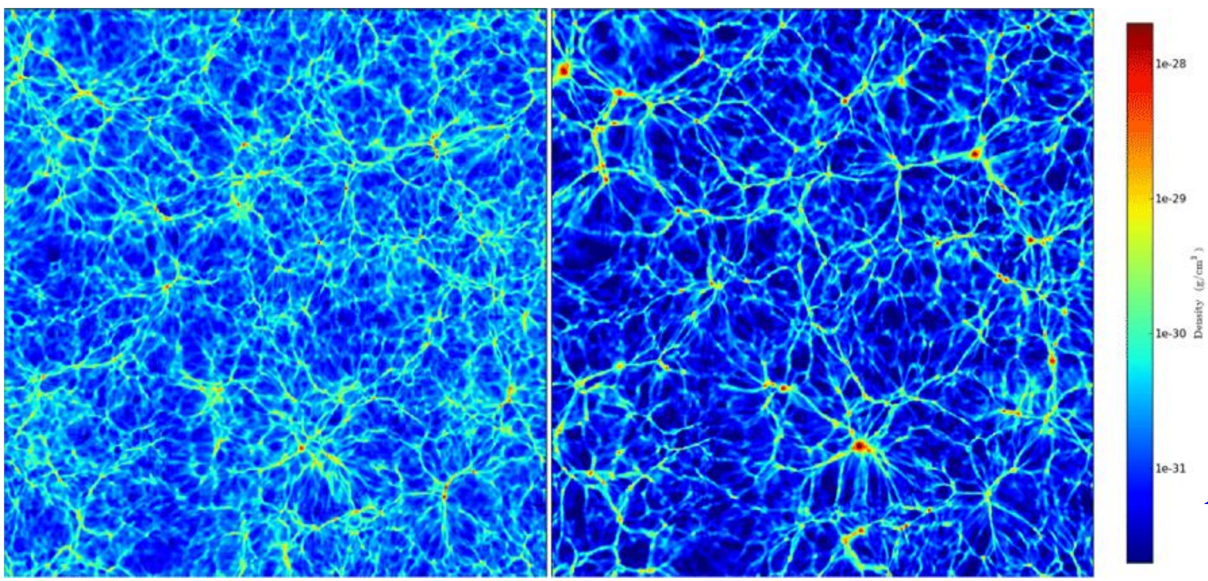
But now we know HDM exists!
How much?

Neutrino Mass from Cosmology

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

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

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



CDM+ 1.9 eV neutrinos. structure 'washed out'

CDM

Agarwal & Feldman 2010

Cf. Krishna Naidoo's talk

"Back of the envelope" (cf. Boltzmann solver CAMB)

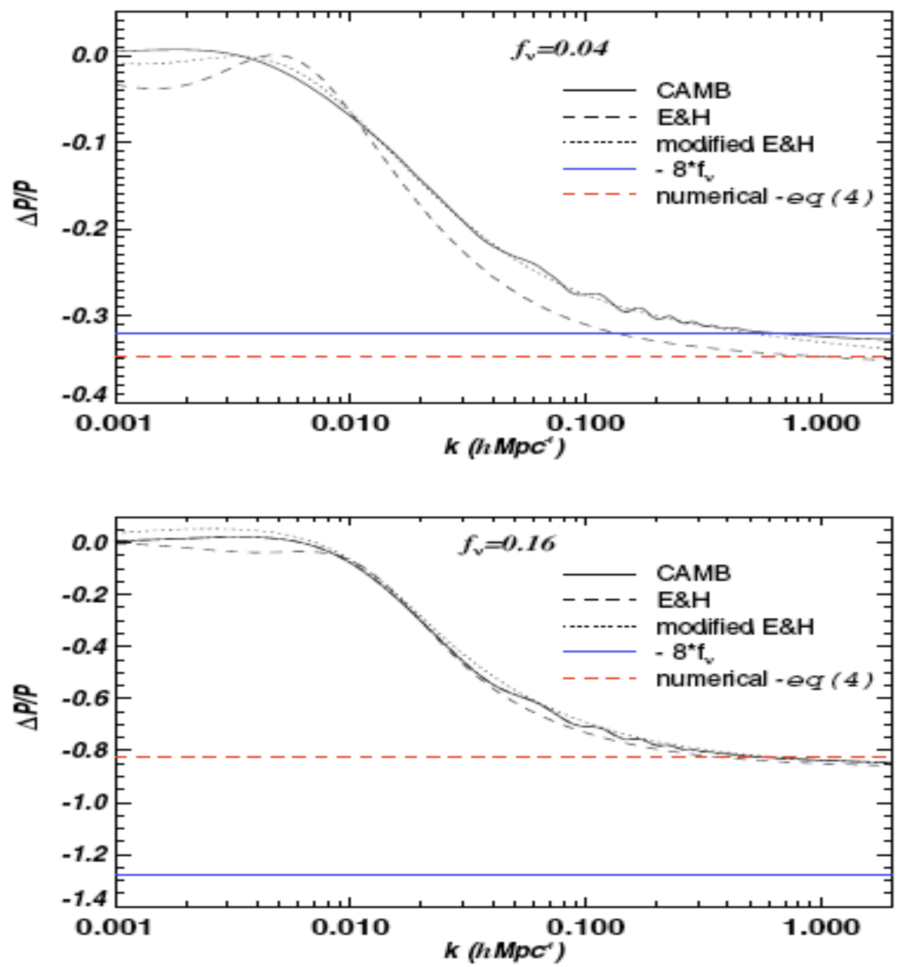
$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4\pi G\rho_0(1 - f_\nu)\delta.$$

$f_\nu = \Omega_\nu / \Omega_m$

$$\frac{P(k, f_\nu) - P(k, f_\nu = 0)}{P(k, f_\nu = 0)} \simeq -\frac{6}{5} f_\nu \ln(1 + z_{\rm eq}).$$

$= -8\ \Omega_\nu / \Omega_m$

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



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

(although not valid on useful scales)

Kiakotou, Elgaroy, OL
astro-ph 0709.0253, PRD

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

2-sigma Neutrino mass upper limits from existing data

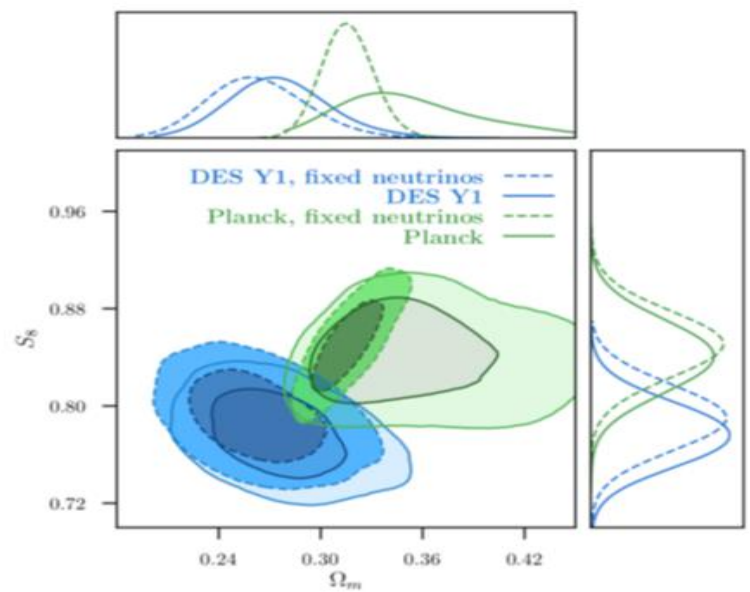
Data	Authors	$M_\nu = \Sigma m_i$
2dFGRS MegaZ-LRG + WMAP	Elgaroy, OL et al. (2002) Thomas et al. (2010)	< 1.8 eV < 0.28 eV
Planck13+robust surveys	Leistedt et al. (2014)	< 0.3 eV
Planck15++	Planck collaboration 2015	< 0.23 eV
BOSS Ly-alpha + Planck15	Palanque-Delabrouille etal. (2015)	< 0.12 eV
DES Y1 + Planck15+JLA+BAO	DES collaboration (2017)	< 0.26 eV

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

Neutrino mass from DES Y1 clustering+ weak lensing (3x2pt)

To fix or not to fix to minimal oscillations M_ν = 0.06 eV ?

from DES+Planck+BAO+SNIa
$w= -1.00_{-0.05}^{+0.04}$
Neutrino mass < 0.26 eV
(LCDM, 95% CL)



arXiv:1708.01530 (revised)

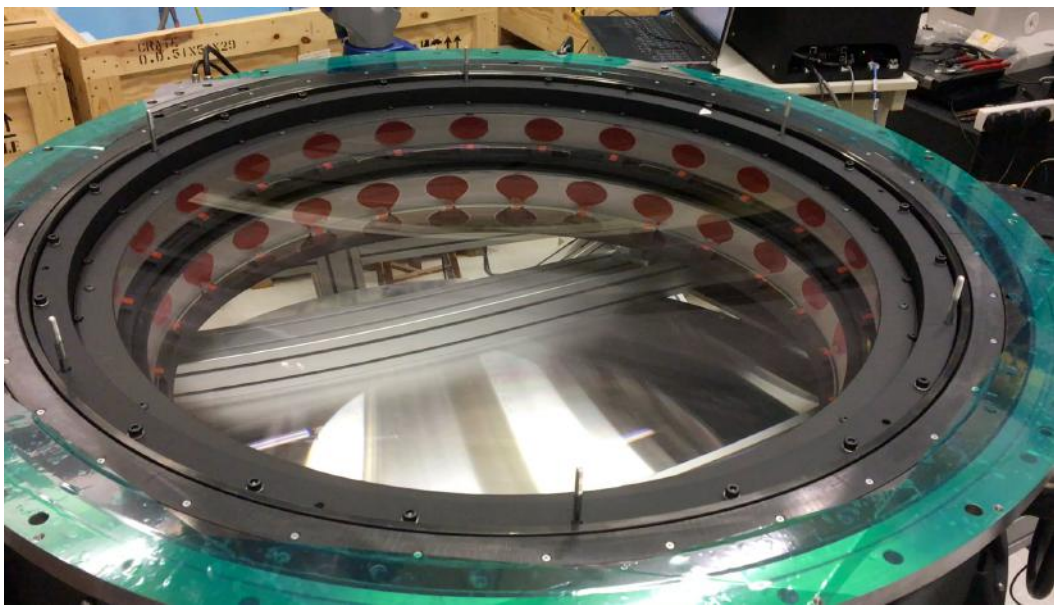
2-sigma errors on Neutrino mass – forecast for future surveys

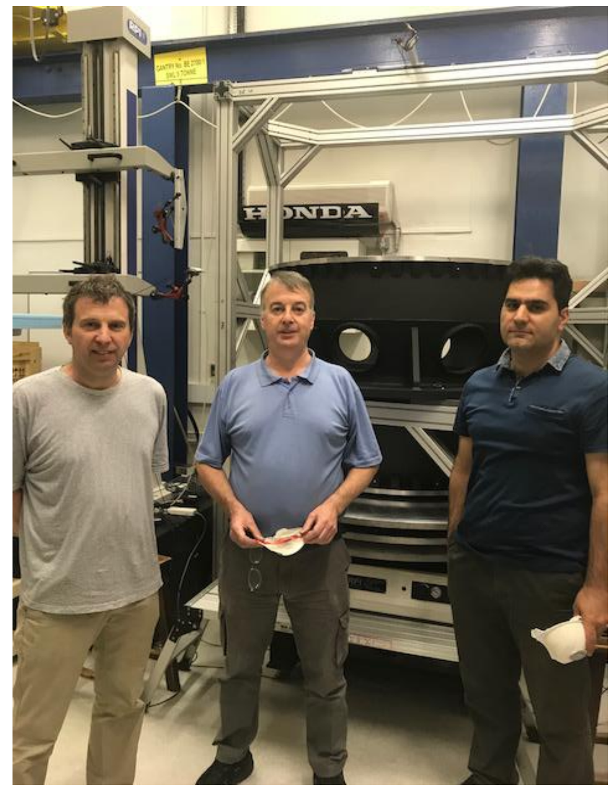
Data	Authors	Error (Σ)
DES (LSS) + Planck DES (LSS+WL) + Planck	OL et al. (2010) Font-Ribera et al. (2014)	0.1 eV 0.08 eV
Euclid (LSS/WL) + Planck	Amendola et al. 2016	0.04 eV 0.05 eV
LSST (WL) +Planck	Abazajian et al. 2014	0.04 eV
DESI++	Font-Ribera et al. 2014	0.04 eV
SKA++	Abdalla & Rawling 2007	0.05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

Errors 95% CL, but different assumed priors !

DESI Corrector Optical corrector just completed at UCL

- Six huge lenses (one-meter class) are required for the DESI corrector
- => Spectra of 35M galaxies & QSOs



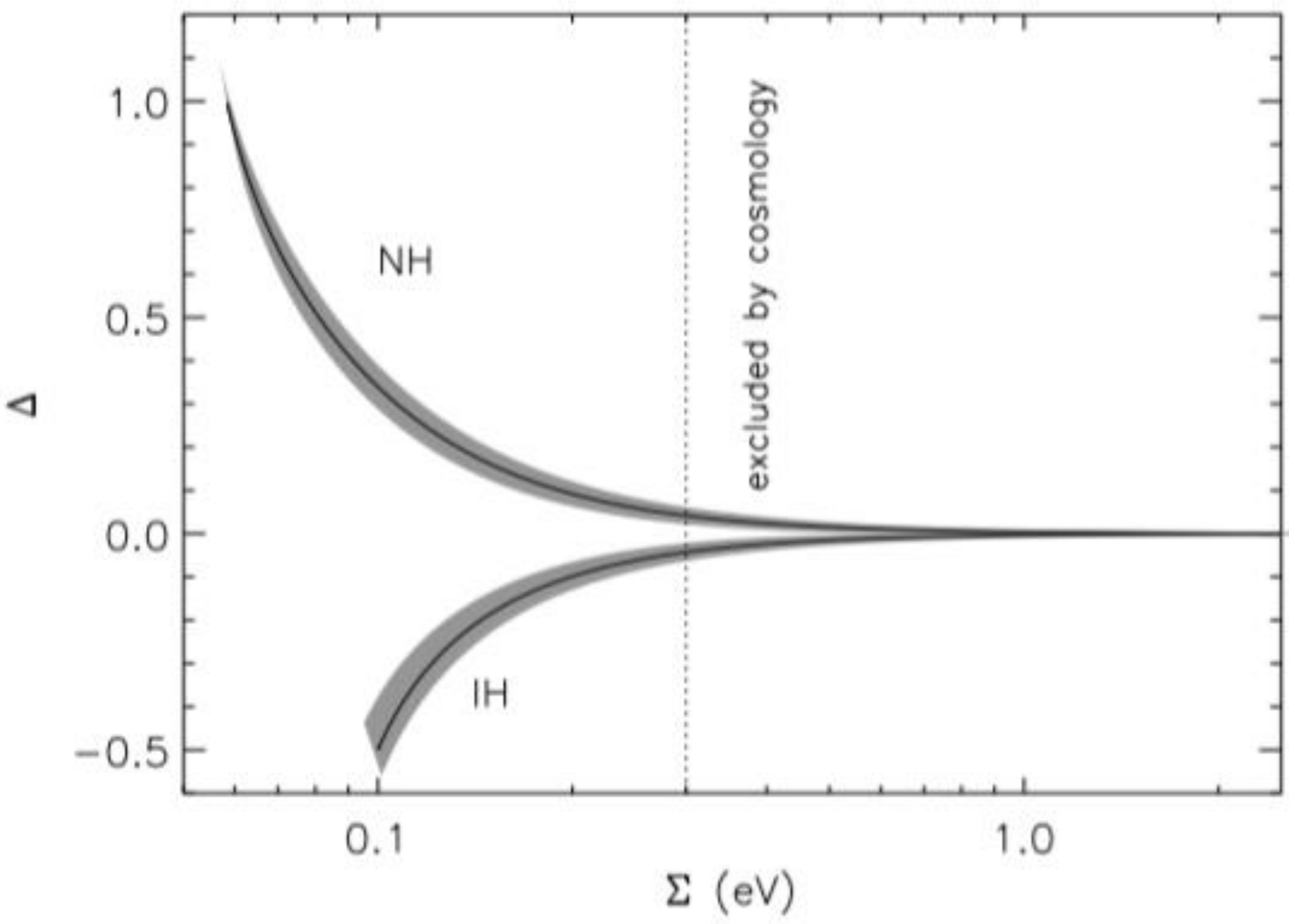


Rotation of ADC1 wrt ADC2

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".

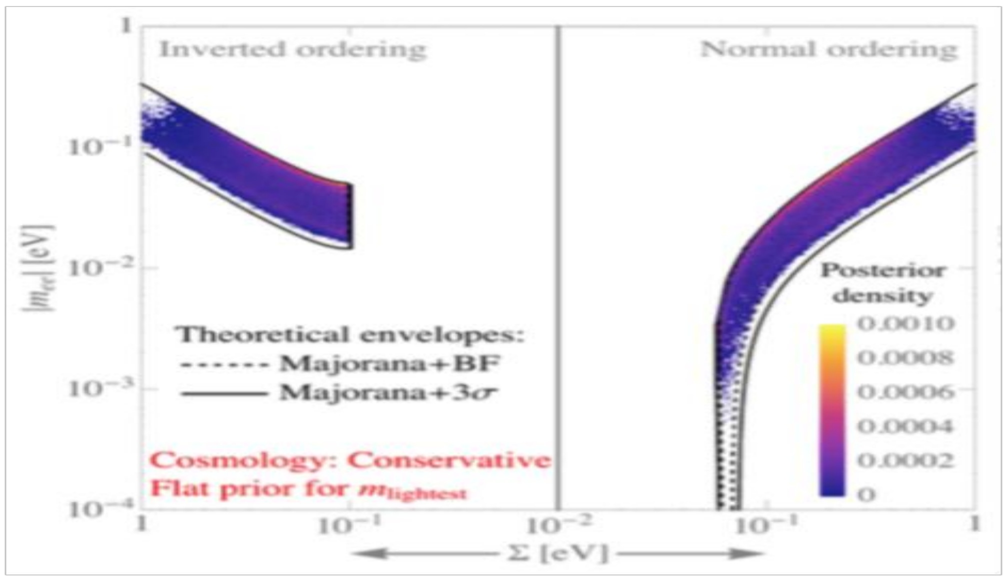
Could Cosmology tell the Hierarchy?



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

Jimenez et al. 2010

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



Cf. Host, OL et al (2007) on Planck+Katrin

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