Neutrino Masses from Cosmological Probes

- Background
- Neutrino masses from LSS and the CMB
- Joint teresstrial & Cosmology

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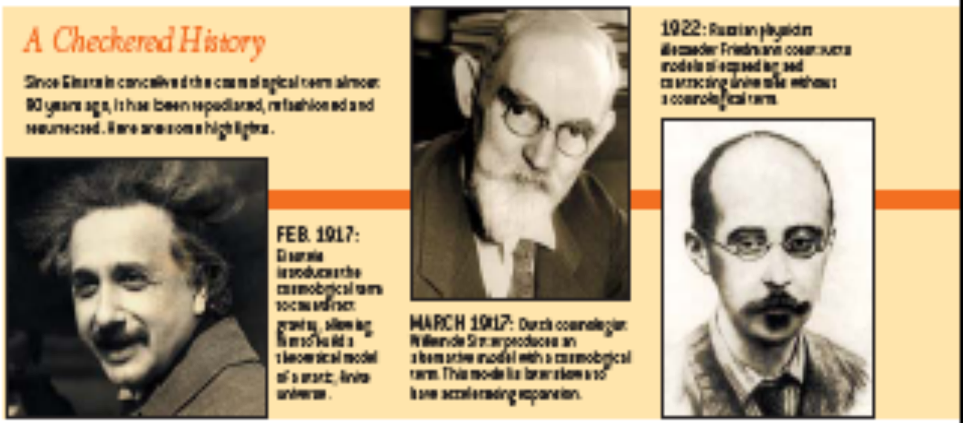
The Chequered History of the Cosmological Constant Λ



The old problem:

Theory exceeds observational limits on Λ by 10^{120} !

New problems:

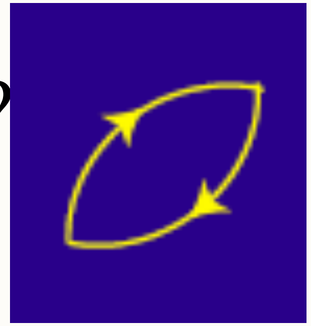
- Is Λ on the LHS or RHS?

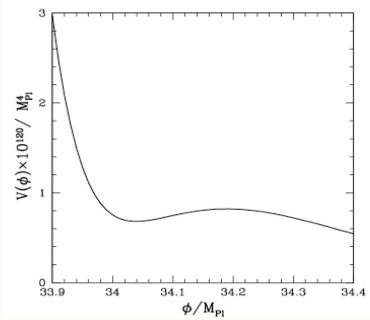
- Why are the amounts of Dark Matter and Λ so similar?

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

But what is “Dark Energy”?

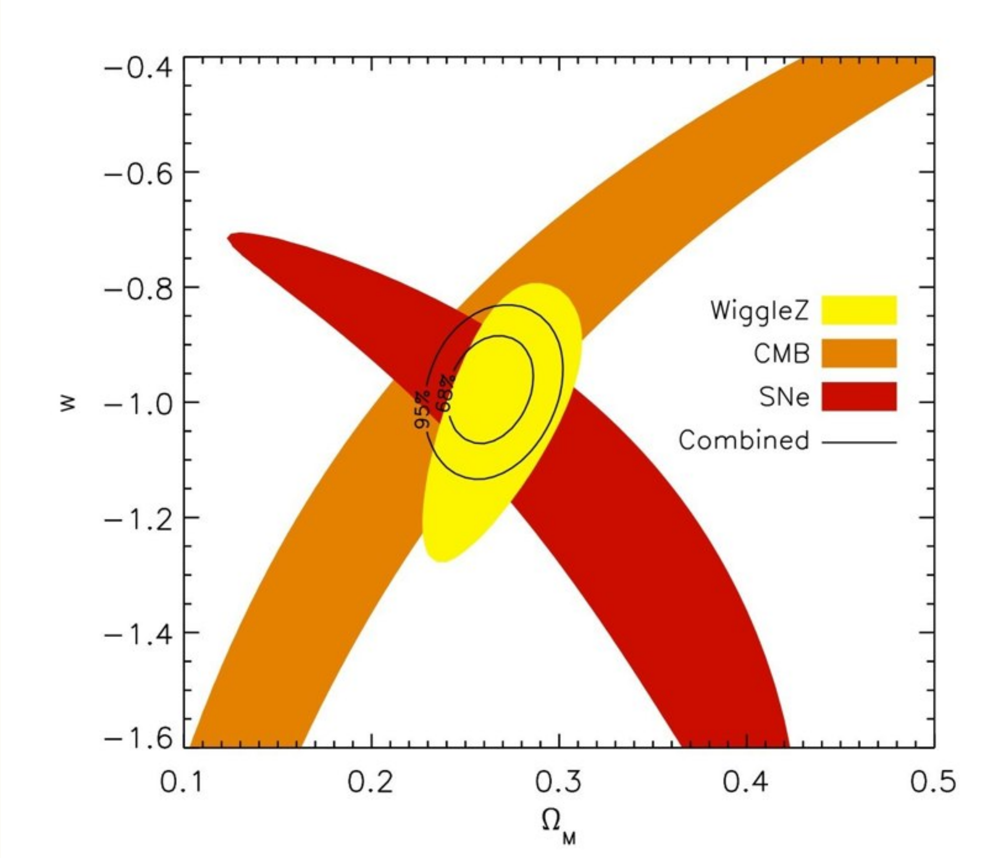
- Vacuum energy (cosmological constant)?
- Dynamical scalar field?
  - $w=p/\rho$
  - for cosmological constant: $w = -1$
- Manifestation of modified gravity?
- Inhomogeneous Universe?





- What if cosmological constant after al
- Multiverse - Landscape?
- The Anthropic Principle?

WiggleZ + CMB + SN Ia



w = -1.03 +- 0.08

Blake et al. 2011

The Landscape of Large Surveys 2011-2020

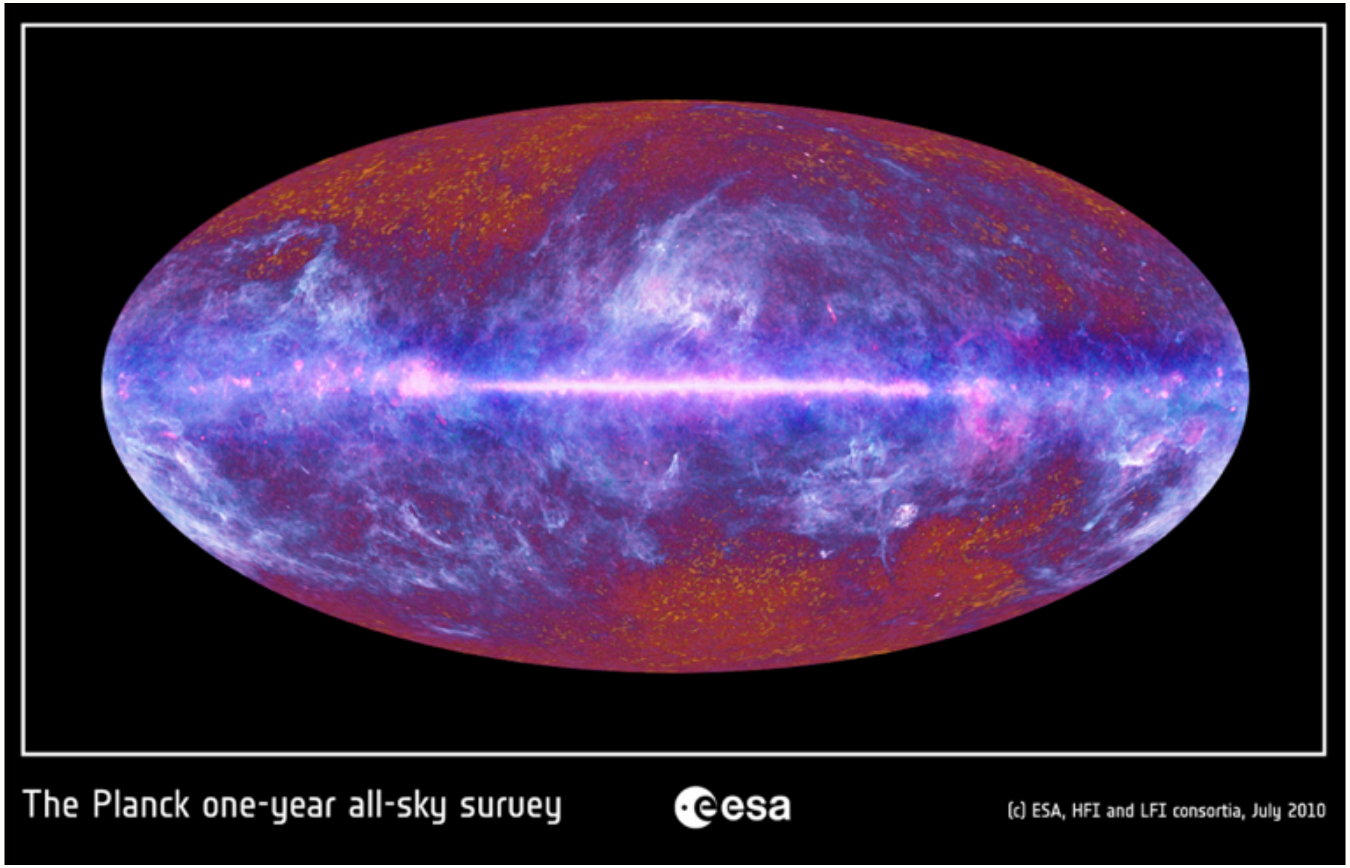
(some exit, some under construction, some proposed)

Photometric surveys: ***DES, VISTA, Pan-STARRS, HSC, Skymapper, PAU, LSST, …***

Spetroscopic surveys: ***WiggleZ, BOSS, e-BOSS, BigBOSS, DESpec, HETDEX, Subaru/Sumire , VISTA/spec, SKA, …***

Space Missions: ***Euclid, WFIRST***

Planck's whole sky
Cosmic Microwave Background



First Cosmology results & data release expected in Jan 2013

The Dark Energy Survey

- 4 complementary techniques

  Cluster Counts

  Weak Lensing

  Large Scale Structure

  Supernovae Ia

- 8-band survey

  5000 deg^2 *grizY* + *JHK from VHS*

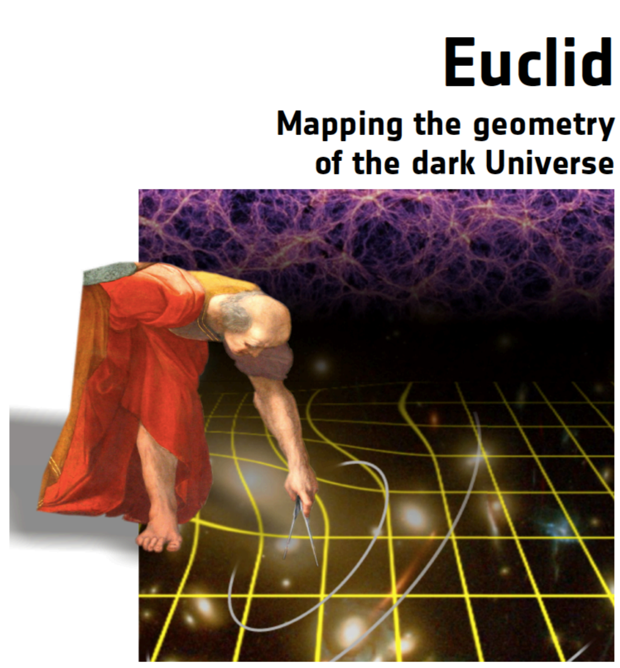
  300 million photometric redshifts +SPT SZ clusters

  Survey 2012-2017

Blanco 4-meter at CTIO

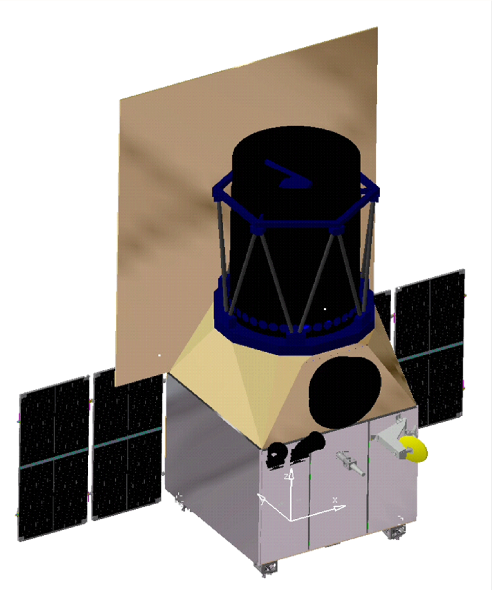
EUCLID

ESA Cosmic Vision
planned launch 2019



The key original ideas:
weak lensing from space
and photo-z from the ground
(DUNE) + spectroscopy (SPACE)

The new Euclid:
1B galaxy images + 50M spectra
(+ground based projects,
e.g. PS, DES, LSST,…)



Massive Neutrinos and Cosmology

- Why bother? – neutrino mass itself, effect on other parameters
- Limits on the total Neutrino mass from cosmology within ΛCDM
- Mixed Dark Matter?
- Non-linear power spectrum and biasing – halo model and simulations
- Combined cosmological observations and laboratory experiments

Brief History of ‘Hot Dark Matter’

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

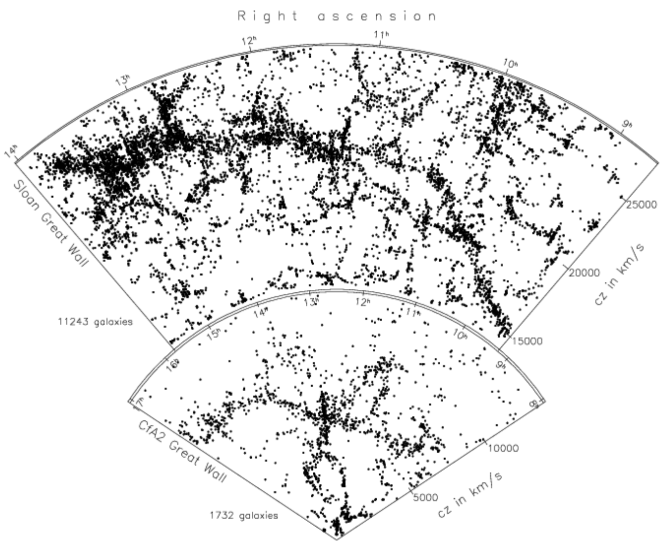
* 1980s: HDM - Problems with structure formation

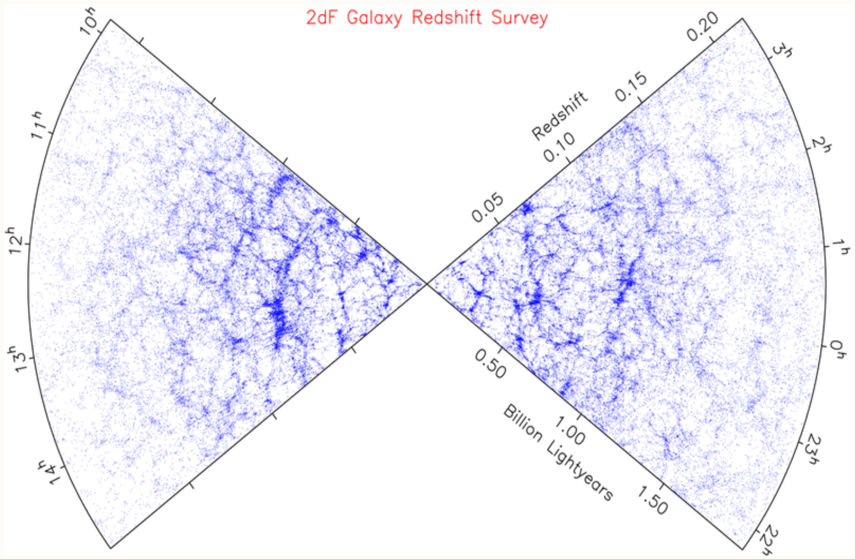
* 1990s: Mixed CDM (80%) + HDM (20%)

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

But now we know HDM exists!
How much?

Neutrino Masses from Great Walls

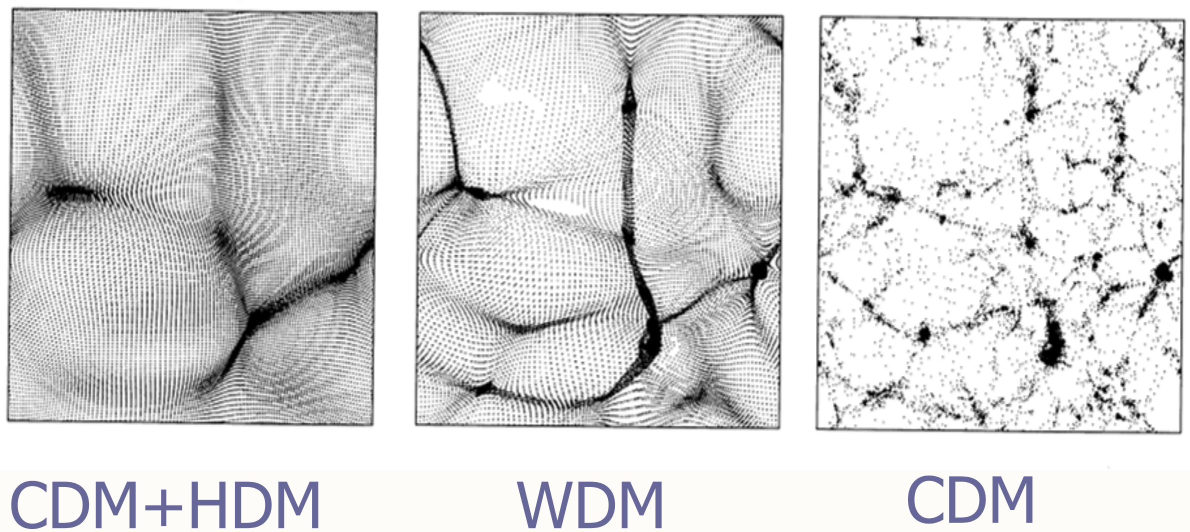




Neutrinos decoupled when they were still relativistic, hence they wiped out structure on small scales

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

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



Colombi, Dodelson, & Widrow 1995

Massive neutrinos mimic a smaller source term

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

Neutrino properties

The number of neutrino species N_ν affects the expansion rate of the universe, hence BBN.
BBN constraints N_ν between 1.7 and 3 (95% CL)
(e.g. Barger et al. 2003).

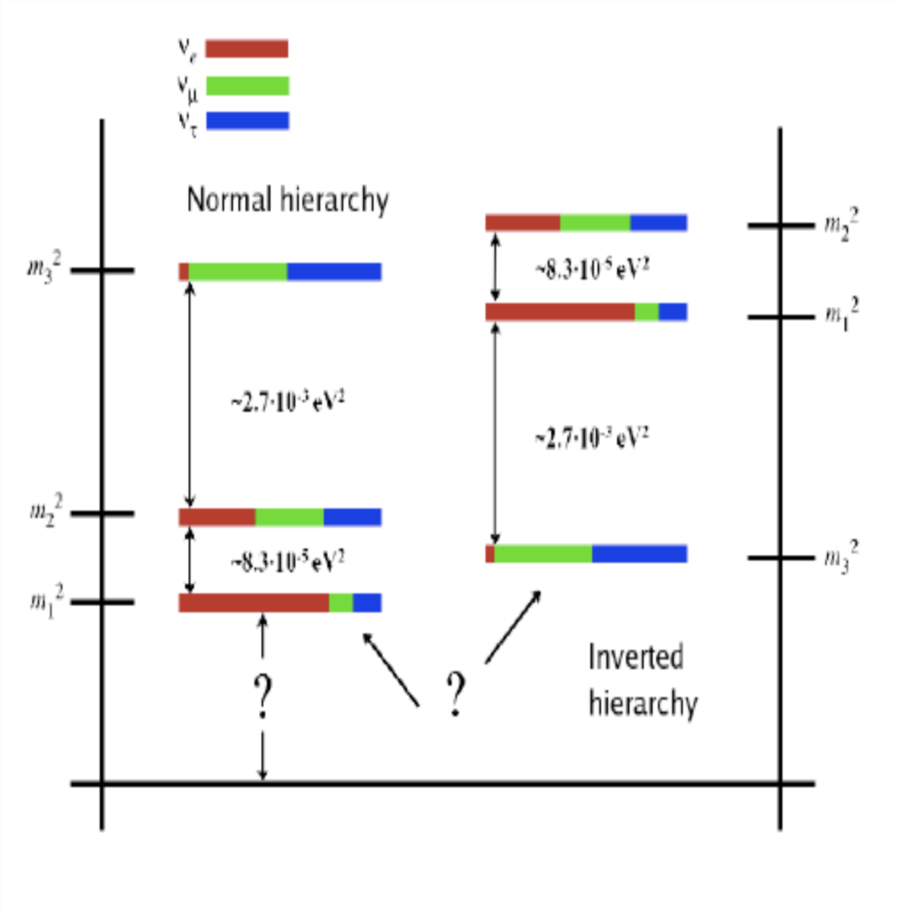
From CMB+LSS+SN Ia, $N_\nu = 4.2^{+1.2}_{-1.7}$ (95% CL)
(Hannestad 2005)

We shall assume $N_\nu = 3$

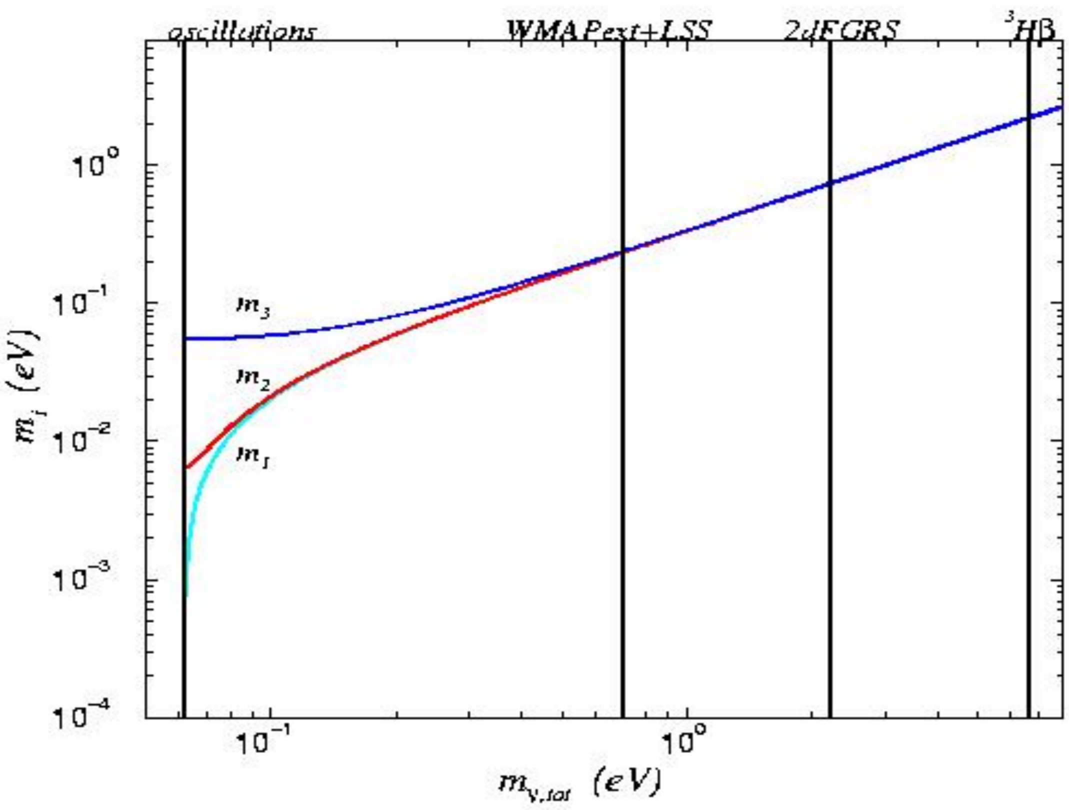
Electron, muon and tau neutrinos
Eigen states m_1, m_2, m_3
112 neutrinos per cm^3

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

Neutrino Mass Hierarchy



Absolute Masses of Neutrinos

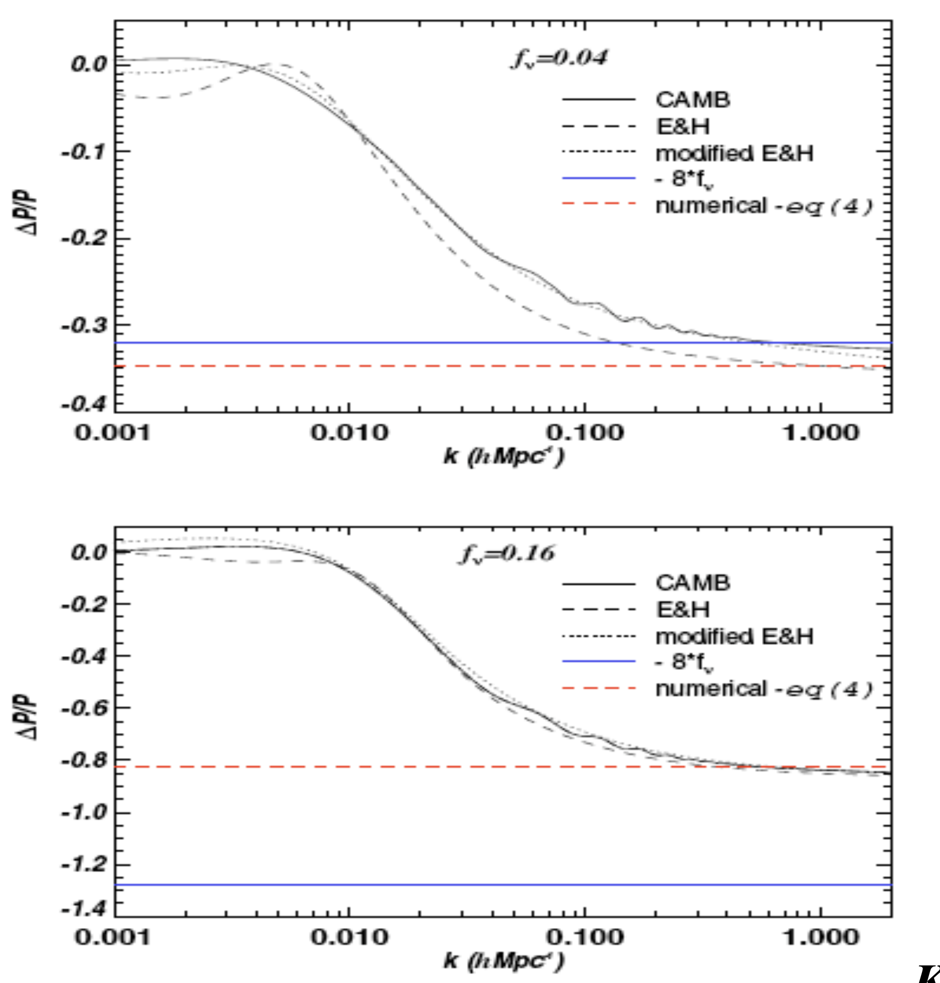


Based on measured squared mass differences from solar and atmospheric oscillations

Assuming $m_1 < m_2 < m_3$

Elgaroy & OL, NJP 05

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



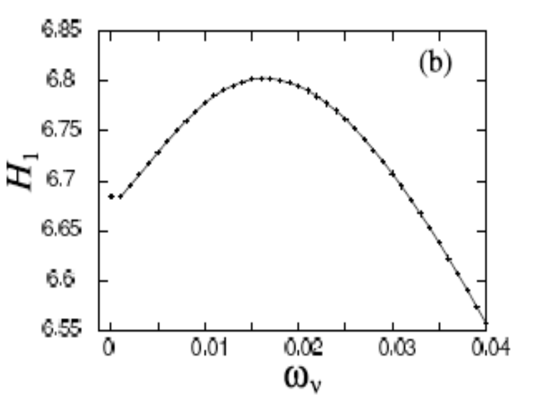
$\Delta P(k)/P(k)$
$= -8\ \Omega_\nu / \Omega_m$

Not valid on
useful scales!

Kiakotou, Elgaroy, OL
astro-ph 0709.0253, PRD

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)
  from WMAP1 alone → $M_\nu < 2.0$ eV

* Fukugita et al. (2006)
  from WMAP3 alone → $M_\nu < 2.0$ eV

Lensing of the CMB could help!

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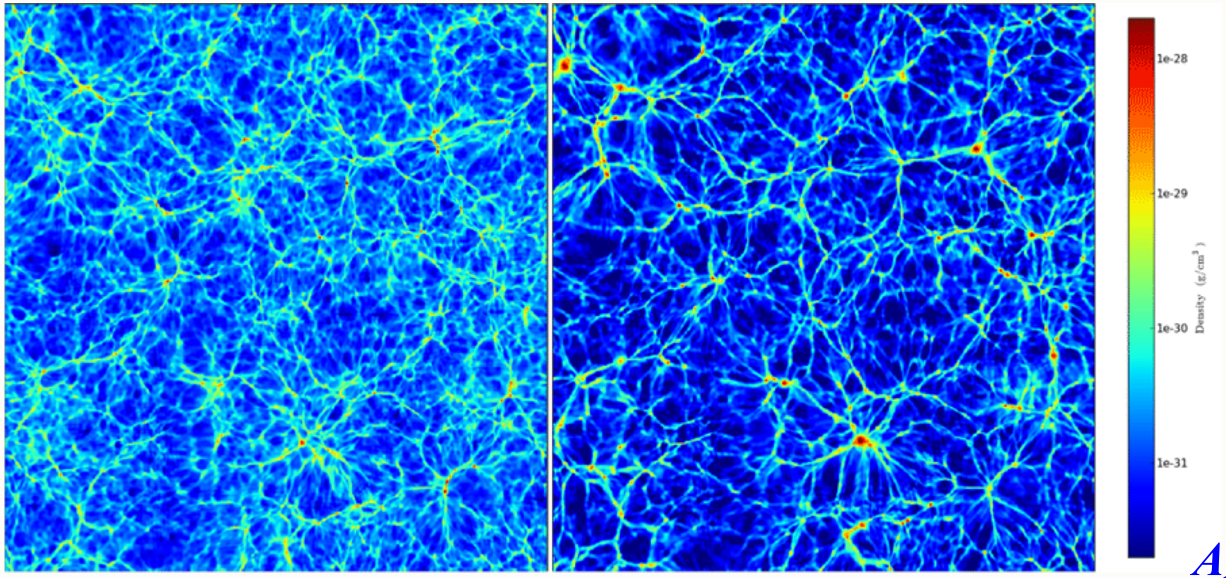
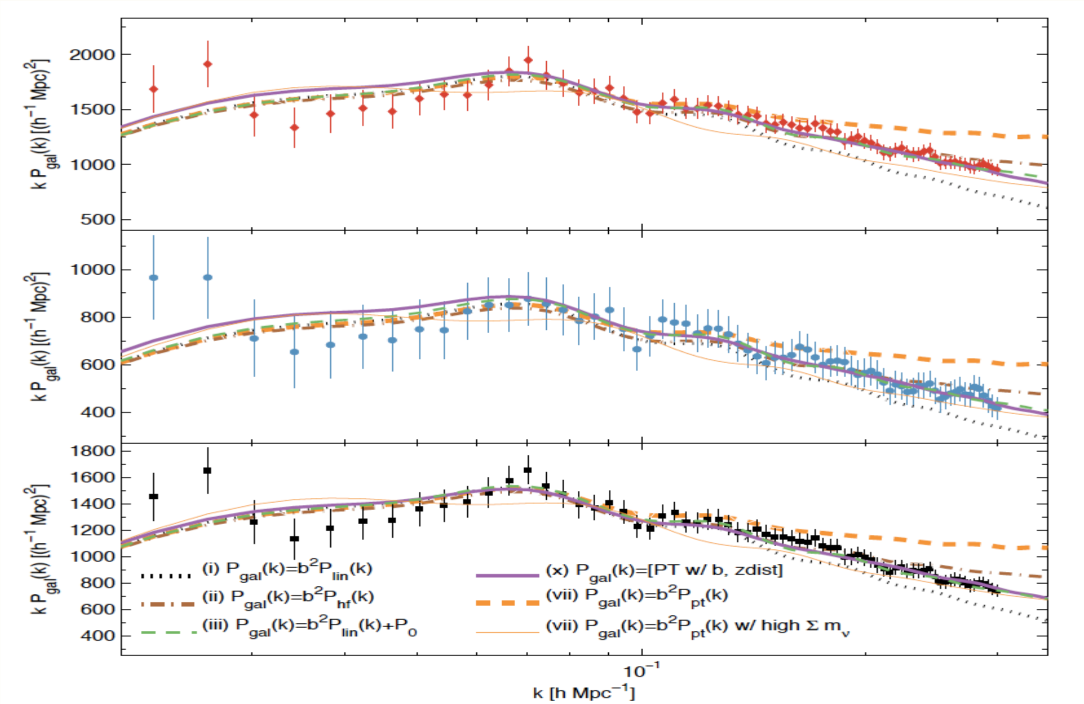


CDM+ 1.9 eV neutrinos **CDM**

Agarwal & Feldman 2010

Neutrino mass from red vs blue SDSS galaxies



red

blue

all

upper limit in the range 0.5-1.1 eV

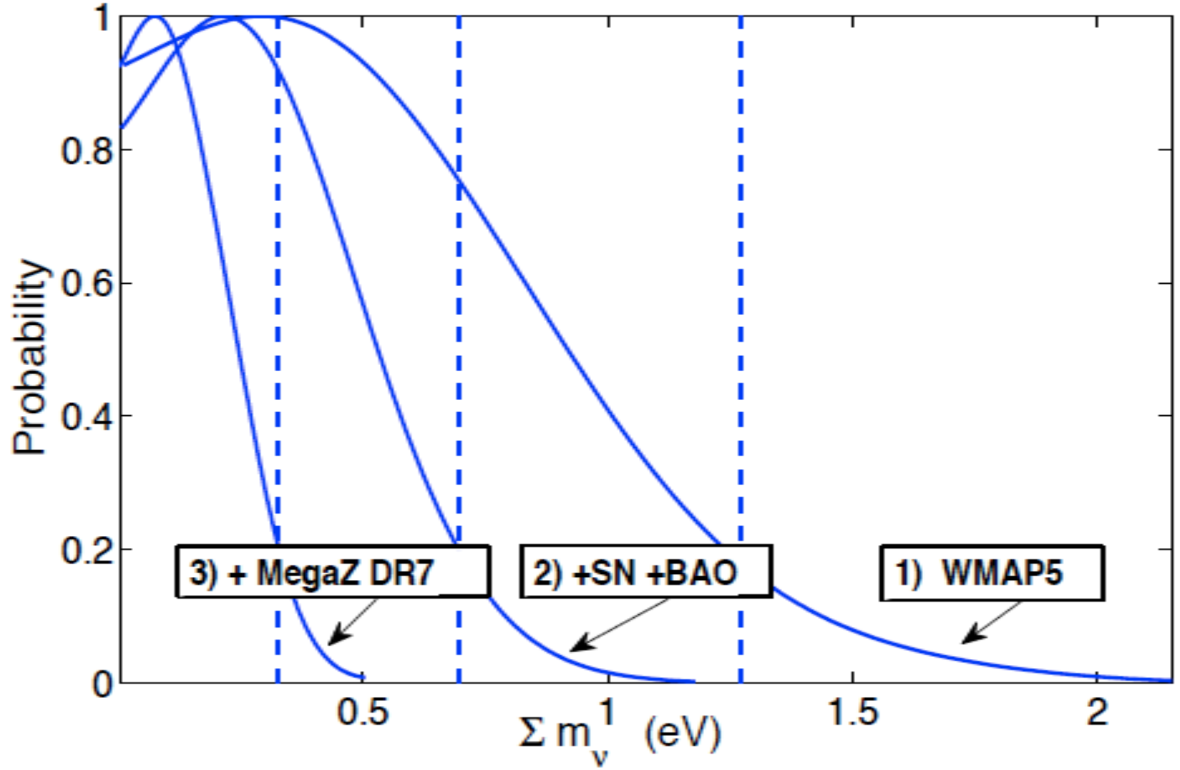
red and blue within 1–sigma

Swanson, Percival & Lahav (MN, 2010)

Neutrino mass from MegaZ-LRG

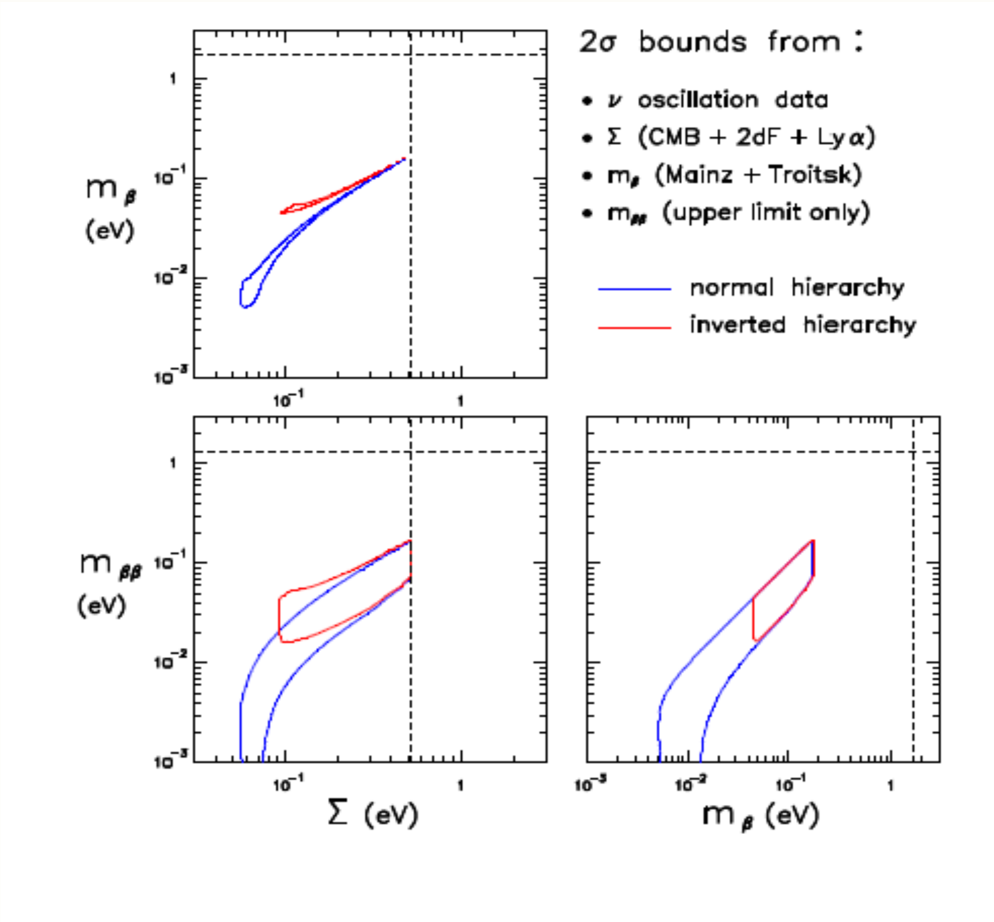
700,000 galaxies within 3.3 (Gpc/h)^3

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



Thomas, Abdalla & Lahav (PRL, 2010)
cf. Reid et al. (2010)

Combined Cosmology & Terrestrial Experiments



Fogli et al. Hep-ph/0408045

see also Hannestad 2007

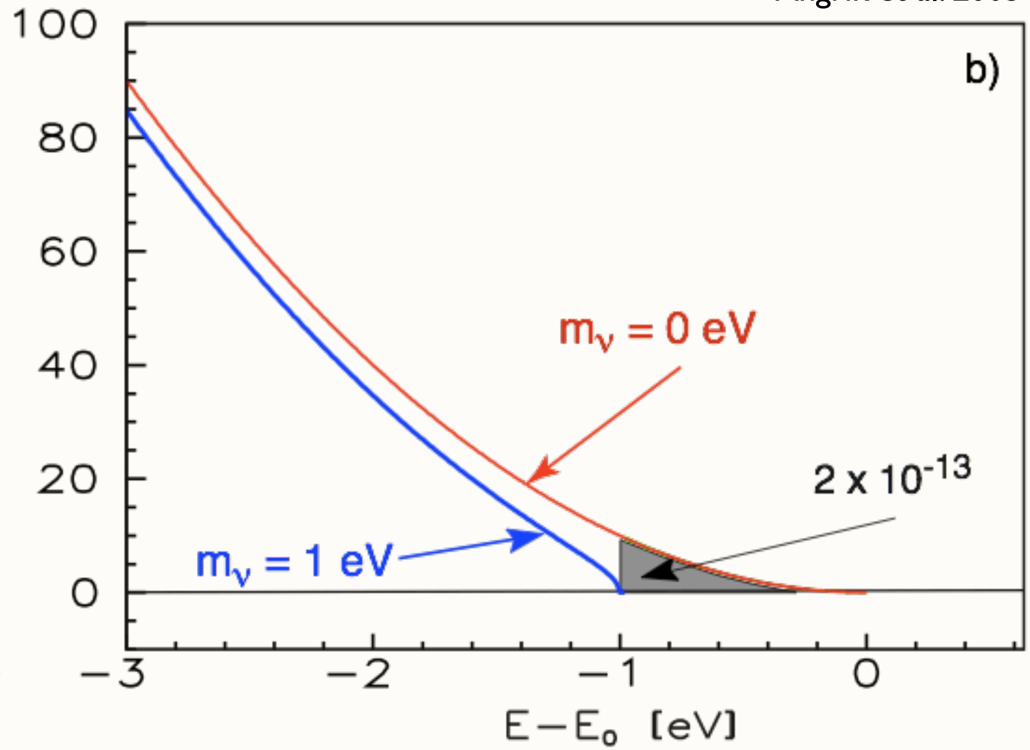
Tritium beta decay

- 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



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

Total Neutrino Mass

DES+Planck vs. KATRIN

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

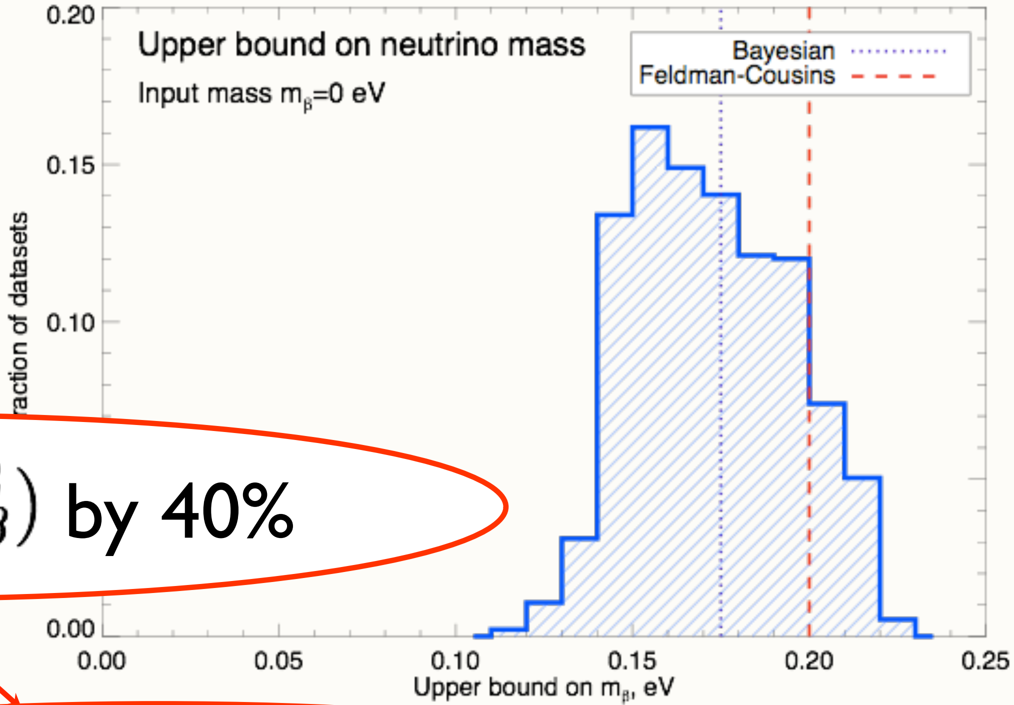
Lahav, Kiakotou, Abdalla and Blake (2010)

0910.4714

Host, OL, Abdalla & Eitel 2007, PRD

1) Null result

- **Assume zero mass**
- Frequentist reference: $m_\beta < 0.20$ eV, 90%C.L.
- Find upper limit in each

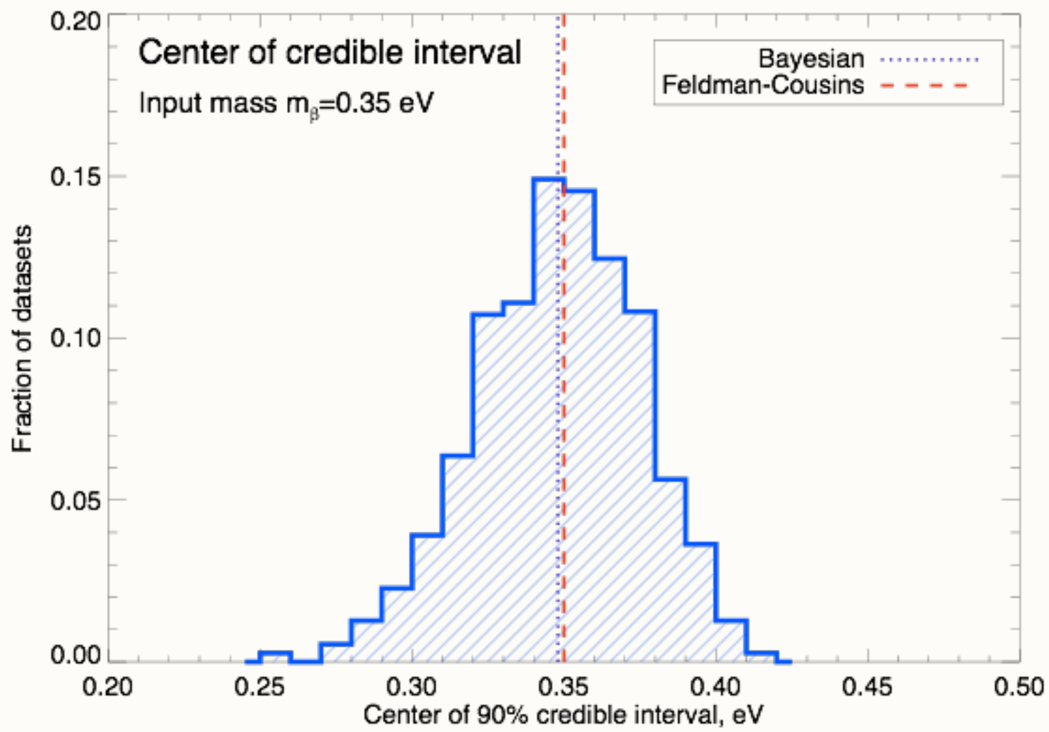


Reducing $\sigma(m_\beta^2)$ by 40%

$$\rightarrow m_\beta < 0.17 \text{ eV}, \ 90\%\text{C.L.}$$

2) Discovery potential

- Assume m_β = 0.35 eV
- 1000 posteriors
- Recover input regardless of analysis



Neutrinos - Summary

- Redshift surveys (+ CMB+…) $M_\nu < 0.3$ eV
- Within the Λ-CDM scenarios, subject to priors.

* Alternatives: MDM ruled out.

* Future: sensitivity down to 0.05 eV
using galaxy surveys+Planck,
and weak gravitational lensing of background galaxies and of the CMB.

* Combine with Lab experiments
Resolve the three neutrino masses!