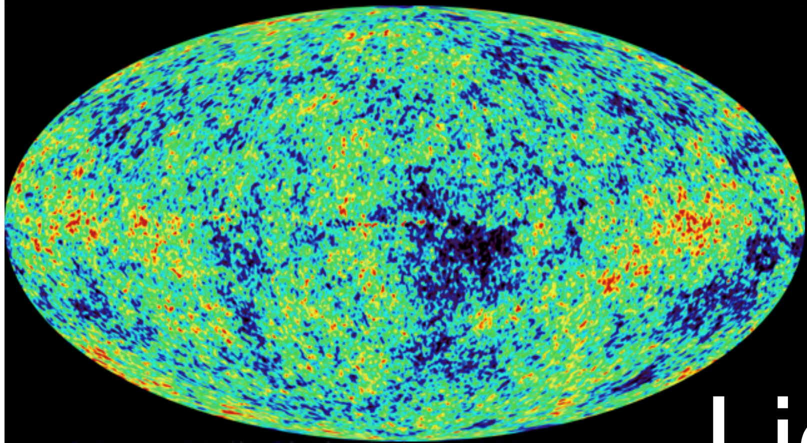
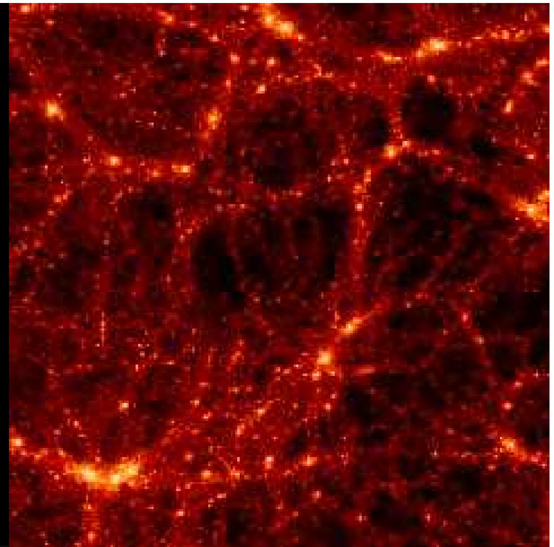
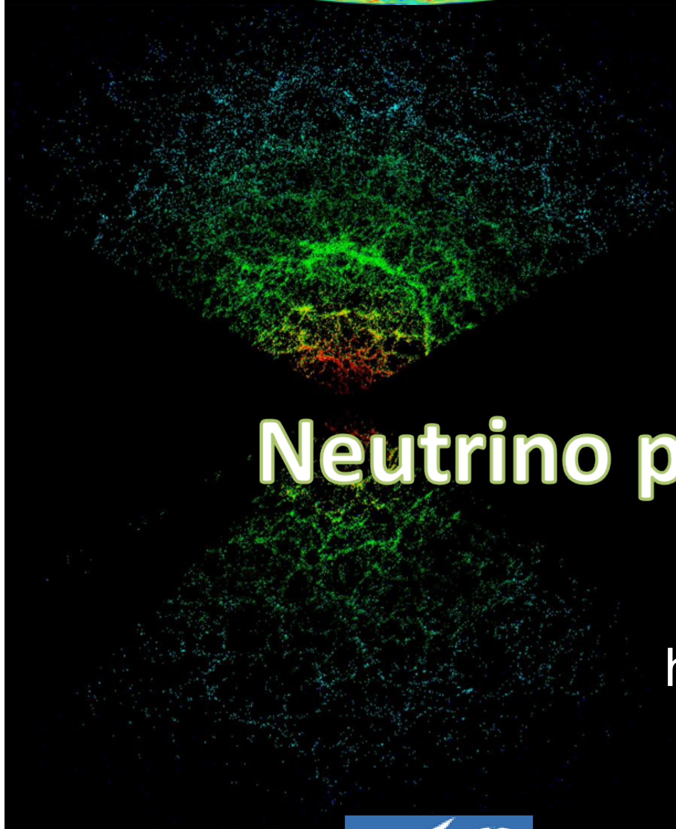
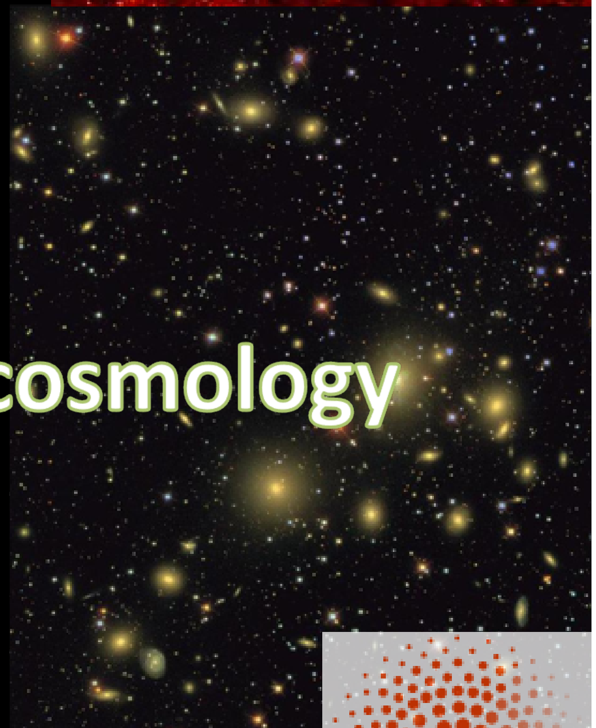




Licia Verde

ICREA & ICC-UB-IEEC
Barcelona, Spain





Neutrino properties from cosmology

http://icc.ub.edu/~liciaverde

Institut de Ciències del Cosmos

outline

- Background and mass limits
- Lesgourgues and Verde, *Neutrinos in cosmology* new section in Review of Particle physics out in early 2018

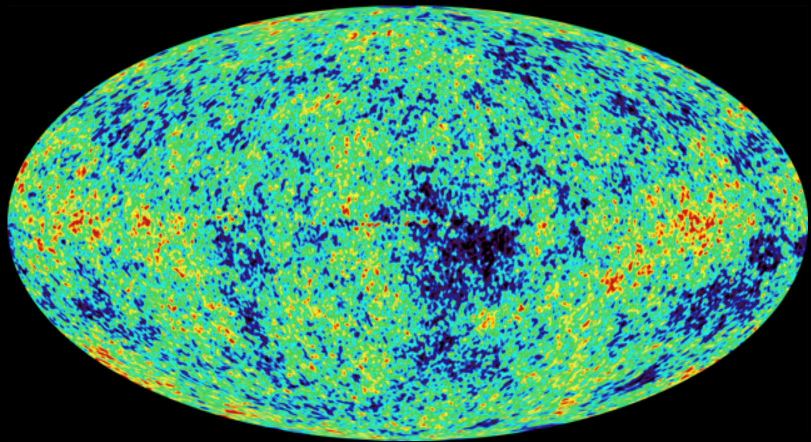
- *Neutrino mass limits: robust information from the power spectrum of galaxy surveys;* Cuesta, Niro, Verde, 2016

- *Neutrino footprint in Large Scale Structure;* Jimenez, Penya-Garay, Verde**, 2016**

- *Strong Bayesian Evidence for the Normal Neutrino Hierarchy;* Simpson, Jimenez, Penya-Garay, Verde, arXiv:1703.03425

- *Biases from neutrino bias: to worry or not to worry?*; Raccanelli, Verde, Villaescusa-Navarro, arXiv:1704.07837

Cosmic Neutrino Background



A relict of the big bang, similar to the CMB except that the CvB decouples from matter after 2s (~ MeV) not 380,000 years

At decoupling they are still relativistic ($m\nu << T\nu$) ➔ large velocity dispersions (1eV ~ 100 Km/s)

Recall:
T~1eV Matter-radiation equality,
T=0.26eV Recombination

60Billion nu/s/cm^2 from the sun
~100nu/cm^3 from CvB

What is a neutrino? (for cosmology)

- Behaves like radiation at T~ eV (recombination/decoupling)
- Eventually (possibly) becomes non-relativistic, behaves like matter
- Small interactions (not perfect fluid)
- Has a high velocity dispersion (is “HOT”)

For aficionados

- Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature 1MeV
- We then have today a Cosmological Neutrino Background at a temperature

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4}\, eV$$

at least two neutrino mass eigenstates are non-relativistic today

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

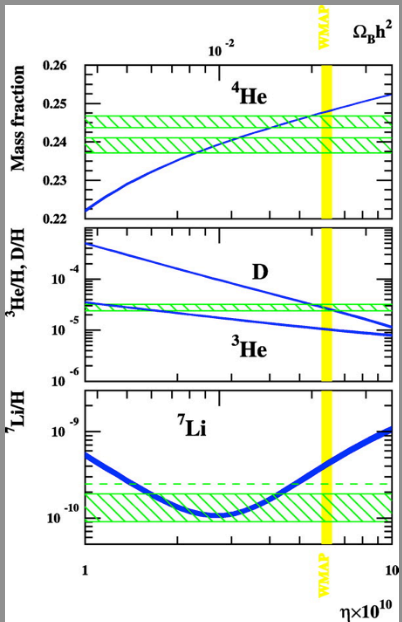
That, for a massive neutrino translates in:

$$\Omega_\nu h^2 = \frac{\sum_\nu m_\nu}{93.14 eV}$$

Neutrinos affect the growth of cosmic clustering so they can leave key imprints on the cosmological observables

Relict neutrinos influence in cosmology

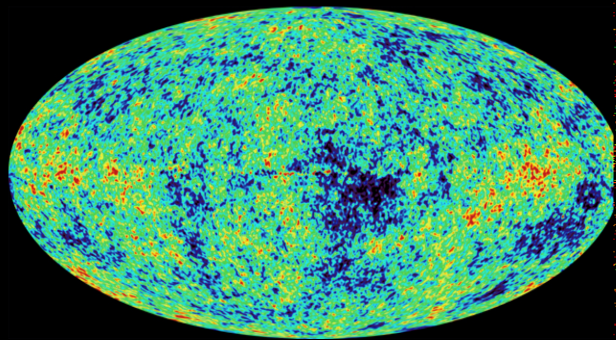
Primordial nucleosynthesis



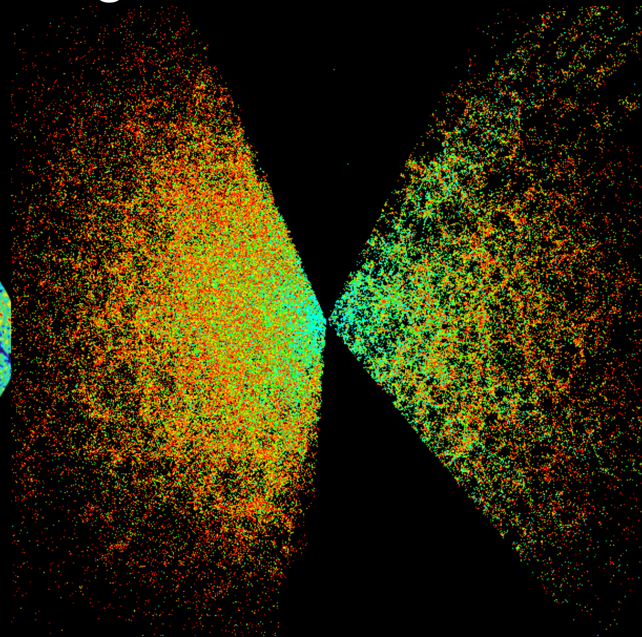
T~ MeV

N_{eff}

CMB



Large-scale structure



T<eV

N_{eff} mass

What do we know and what would we like to know?

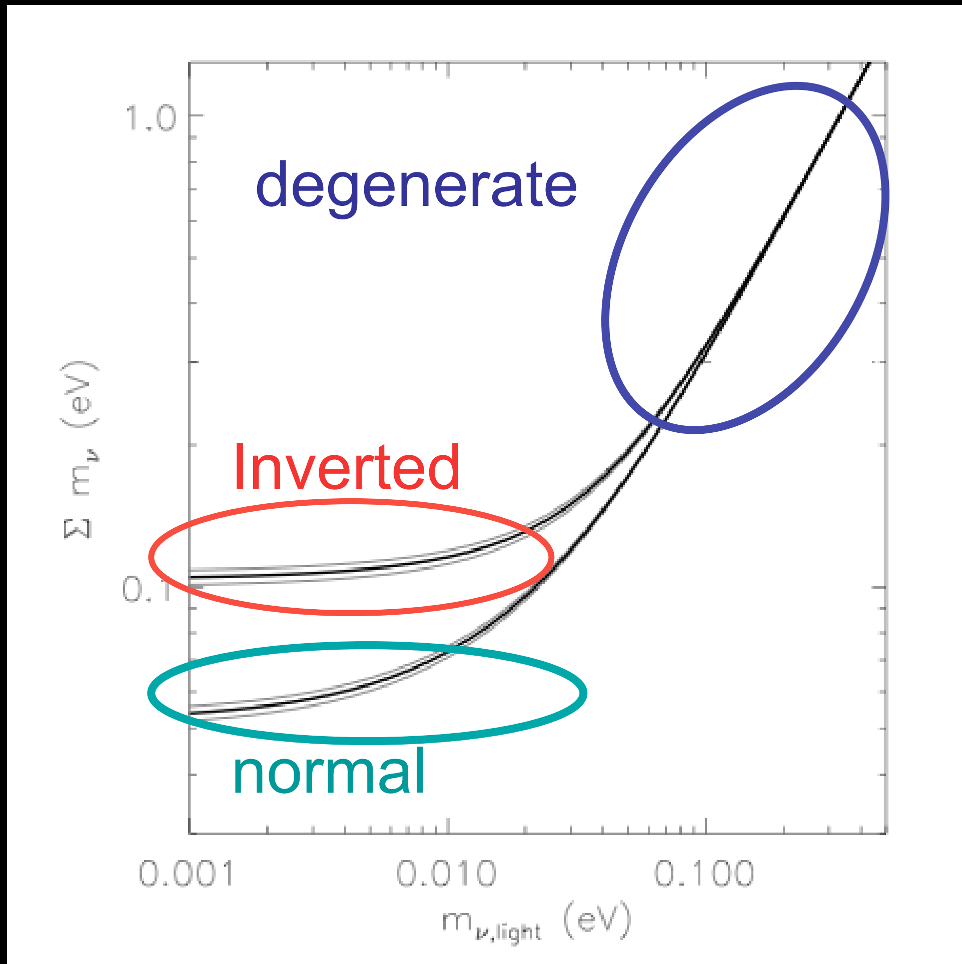
How many “neutrinos”?

Have we really seen the cosmic neutrino background?
(i.e. Are we really sure it’s neutrinos?)

Their total mass $M\nu$ or Σ
(and are we really sure??)

The individual masses (hierarchy)

Cosmology is key in determining the absolute mass scale



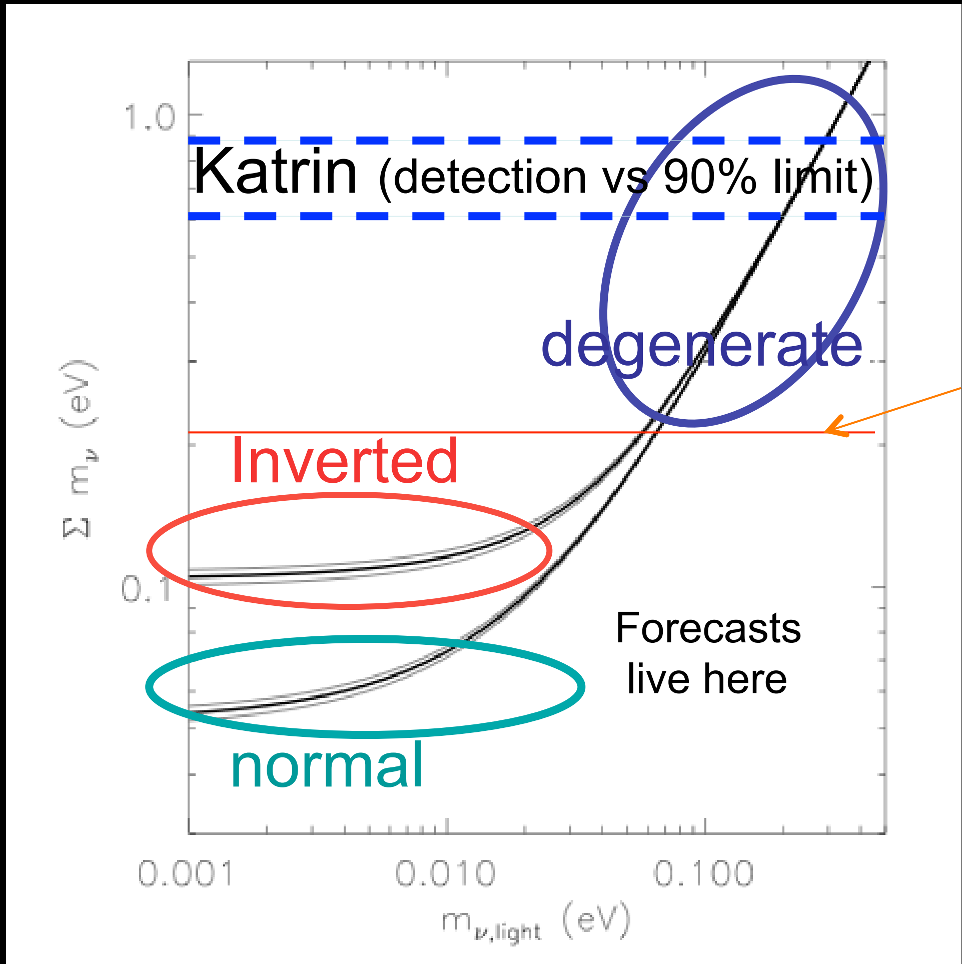
In principle measurable
The problem is systematic errors

This means that neutrinos contribute at least to ~0.5% of the total matter density

The KATRIN Experiment

Ambitious terrestrial experiment

Cosmology is key in determining the absolute mass scale



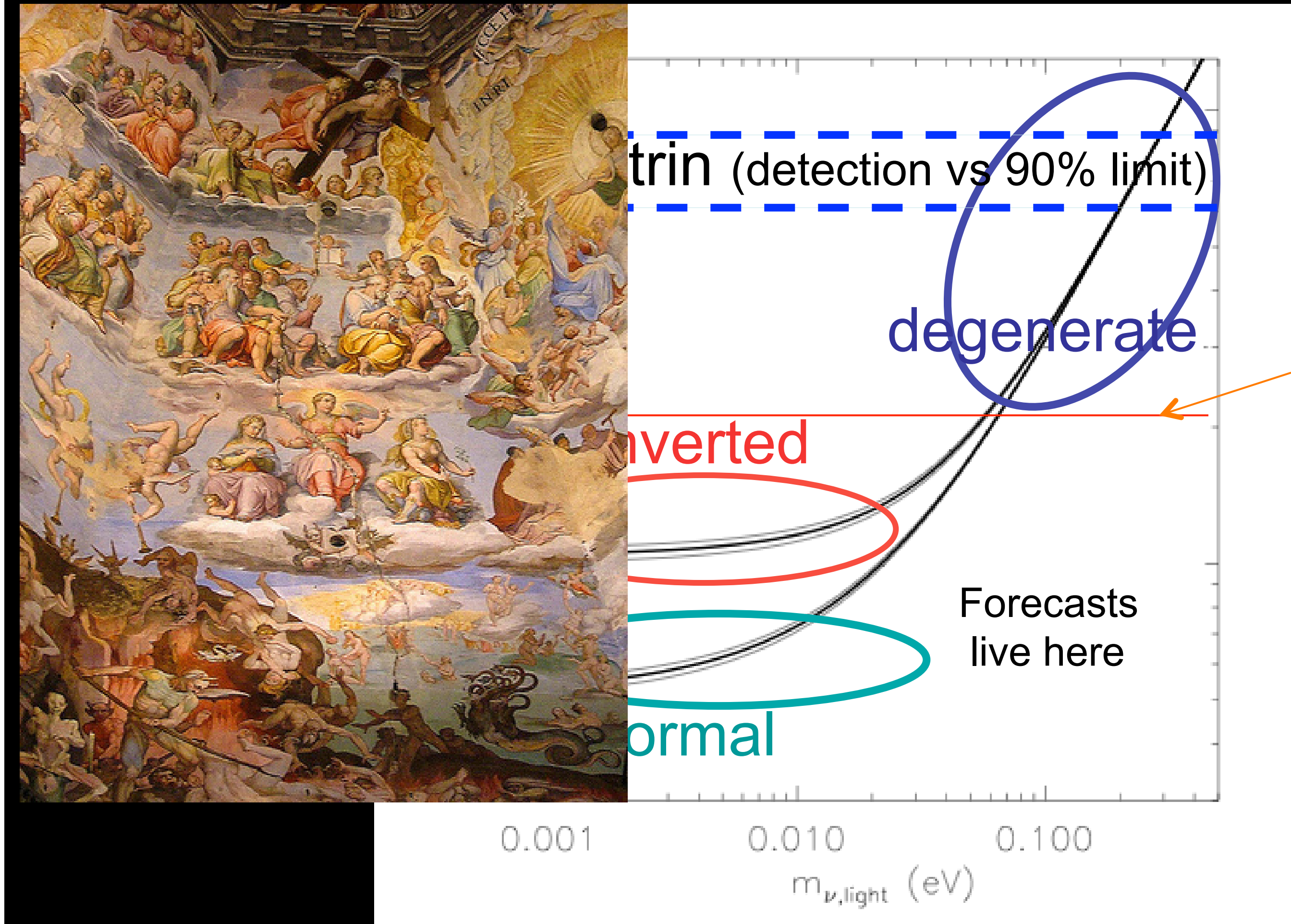
forecasted

CMB(Planck) +BAO
95% limit

The problem is systematic errors

This means that neutrinos contribute at least to ~0.5% of the total matter density

Cosmology is key in determining the absolute mass scale



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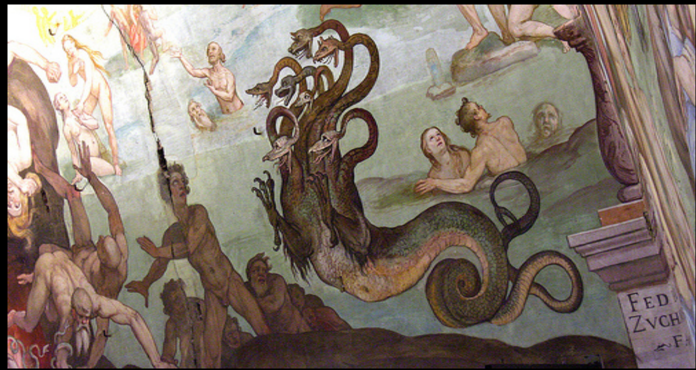


Beware of systematics!!!!!

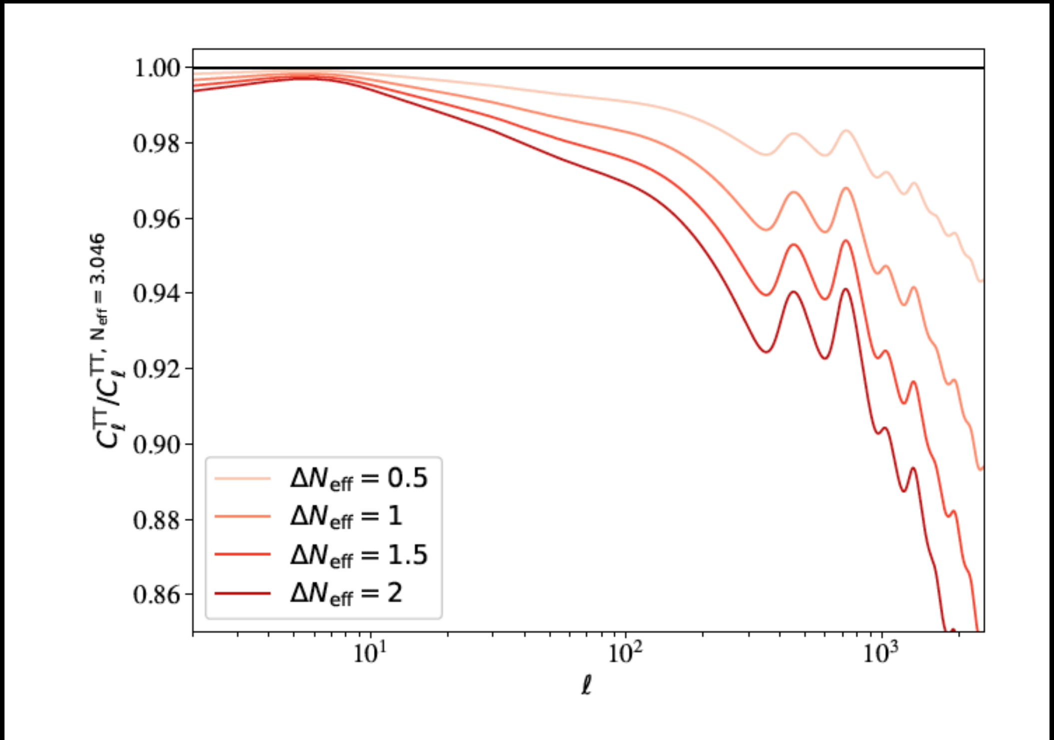
It would be of great value to have internal consistency check(s)
(more later)

Neutrino mass: Physical effects

Neff and the CMB

Naively: changes matter radiation equality but other physics can do that

Keep zeq fixed (and matter to Λ fixed, and wb) so play with Neff and H_0

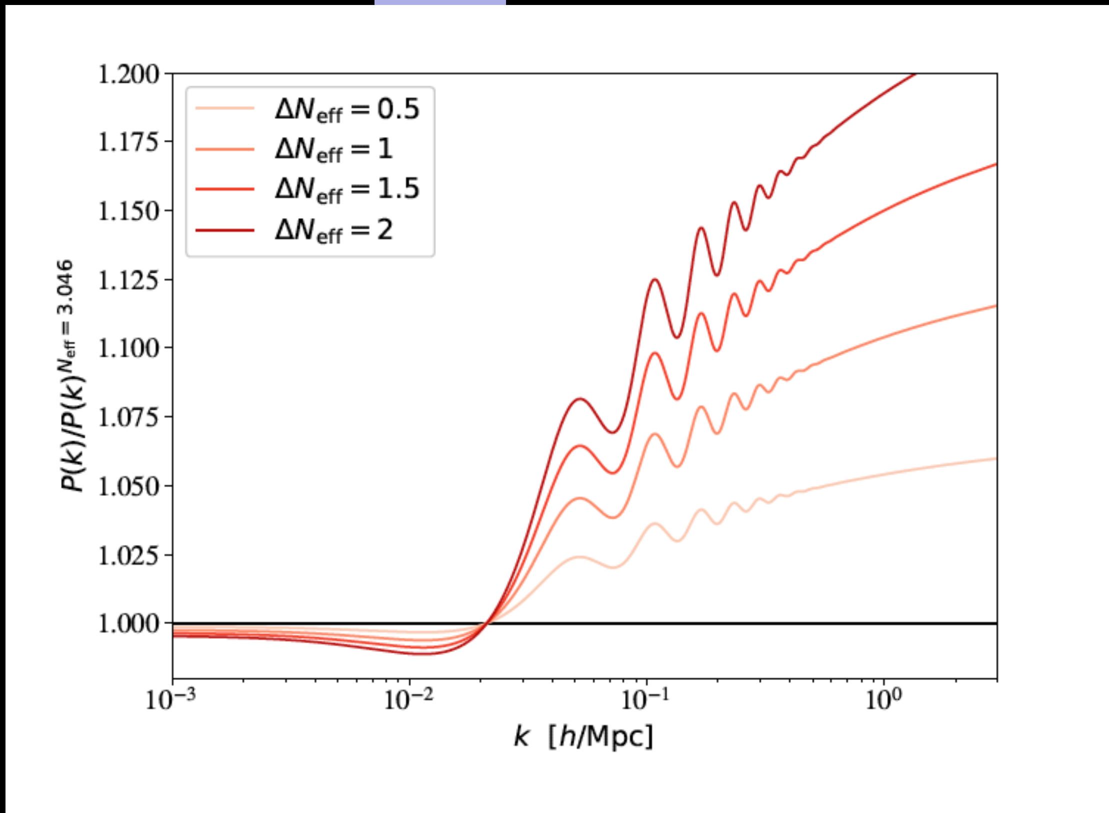


Increase Silk damping

Neutrino mass: Physical effects

Keep zeq fixed (and matter to Λ fixed, and wb) so play with Neff and H0

But then you've changed $\dfrac{\Omega_b}{\Omega_c}$

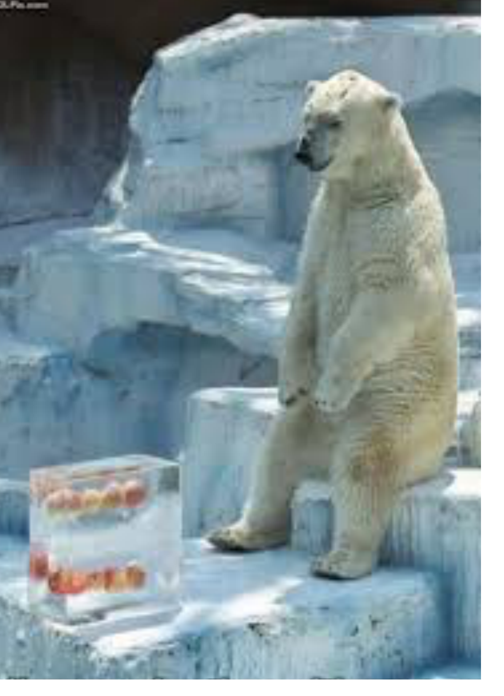


N_{eff} status in a nutshell

$$N_{\rm eff} \ \text{is} \ 3 \pm 0.3$$ (for otherwhise standard LCDM)

Degeneracy with h

CMB polarization really helps reducing the error-bars



Planck people, we are eagerly waiting…

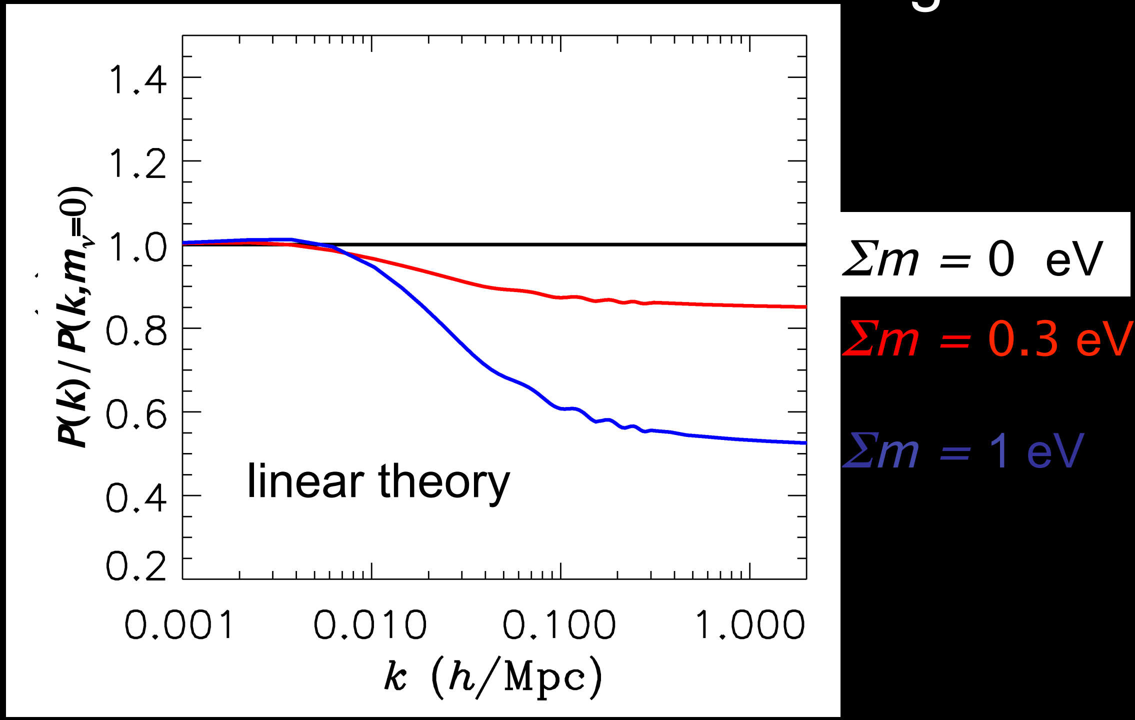
Neutrino mass: Physical effects

Total mass >~1 eV become non relativistic before recombination CMB

Total mass <~1 eV become non relativistic after recombination:
alters matter-radn equality, da, but effect can be "cancelled" by other parameters CMB Degeneracy

After recombination

FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



Different masses become non-relativistic a slightly different times
Cosmology can yield information about neutrino mass hierarchy

Neutrino mass: Physical effects

Total mass >~1 eV become non relativistic before recombination CMB

Total mass <~1 eV become non relativistic after recombination: alters matter-radn equality, da, but effect can be "cancelled" by other parameters CMB Degeneracy

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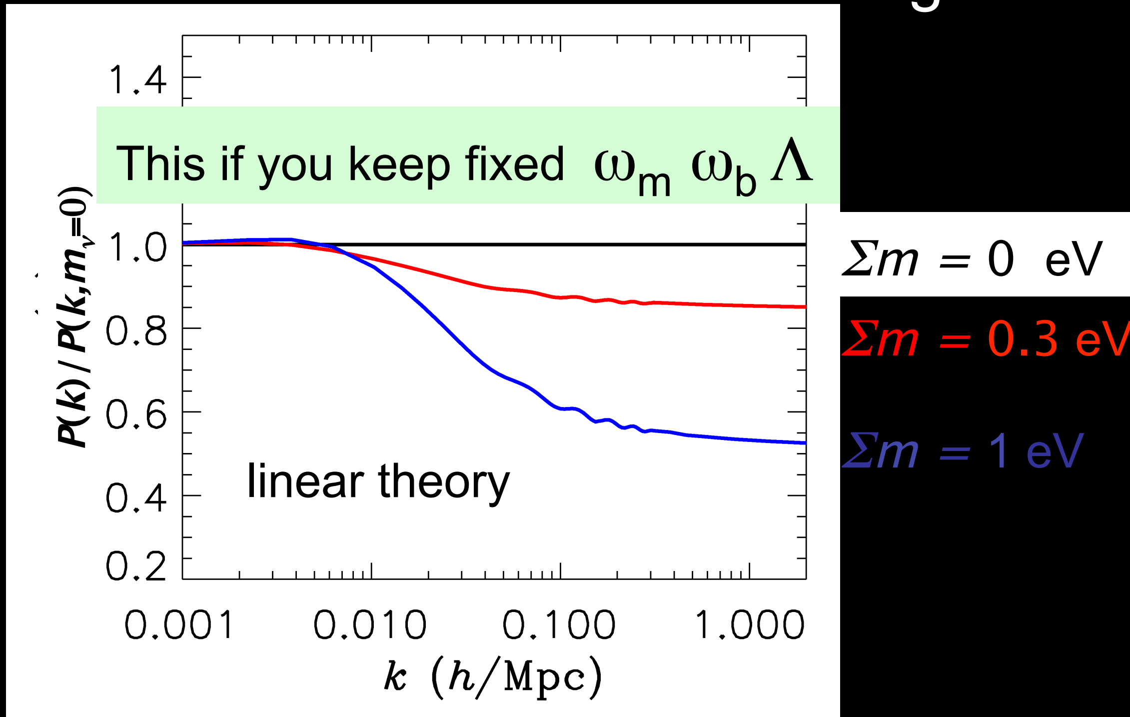
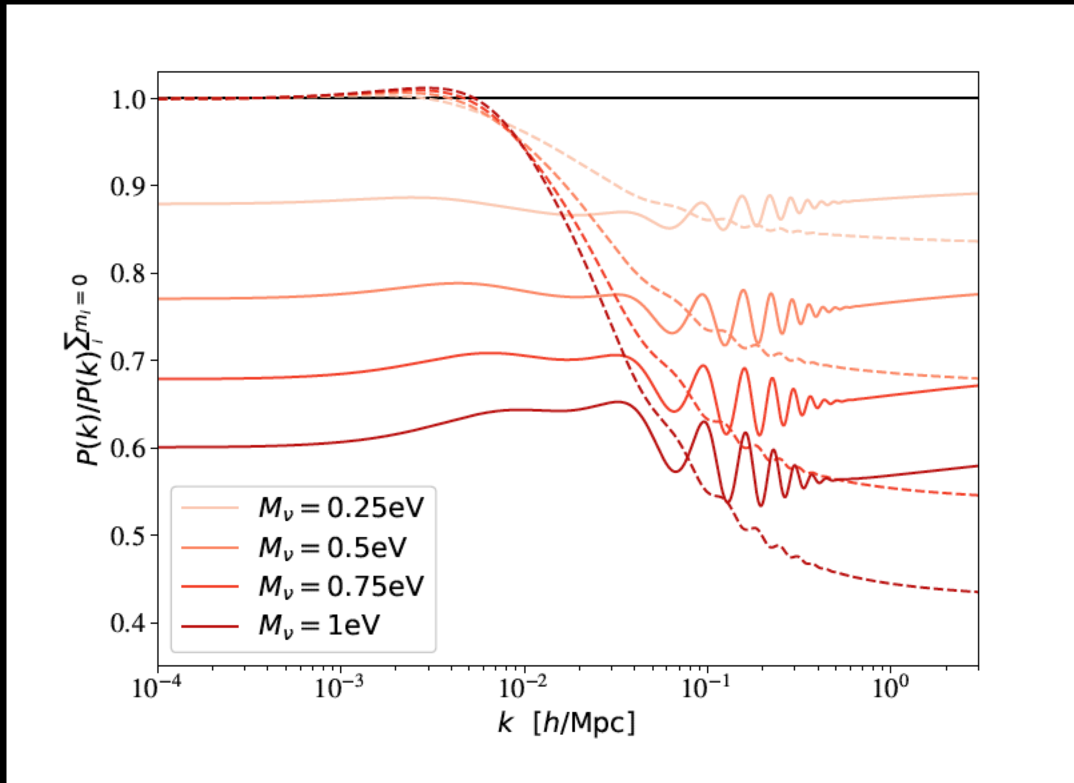


Different masses become non-relativistic a slightly different times
Cosmology can yield information about neutrino mass hierarchy

Neutrino mass: Physical effects

Move along CMB parameters degeneracy

keep fixed ω_c $\omega_{b,}$ θ_s i.e. play with h again…



Suppression
BAO

Different masses become non-relativistic a slightly different times
Cosmology can yield information about neutrino mass hierarchy

Including large-scale structure clustering

Pros: see the "signature" scale-dependent clustering suppression

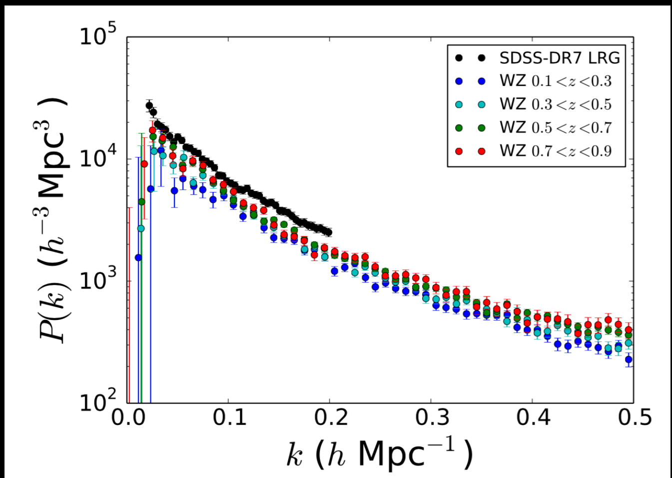
Cons: astrophysics, bias,non-linearities

Possible approach & useful exercise : use completely different tracers and see if there is agreement

Cuesta, Niro, LV, 2016

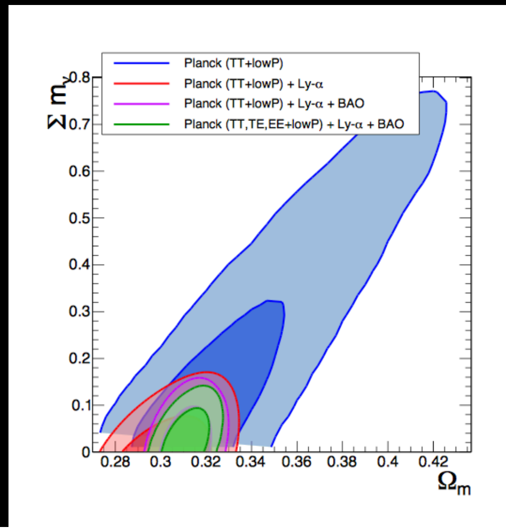
Neutrino mass limits: robust information from the power spectrum of galaxy surveys

Use galaxy clustering (red and blue galaxies)



Ly α from BOSS survey

Palanque-Delabrouille et al. 2015



Limits on the sum of the masses

$$M_\nu < 0.14\, eV\ (95\%\text{C.L.})$$

Robust to choice of galaxies

CMB+BAO+LRG limit

$$M_\nu < 0.13\, eV\ (95\%\text{C.L.})$$

Competitive with CMB+BAO+Lyman alpha

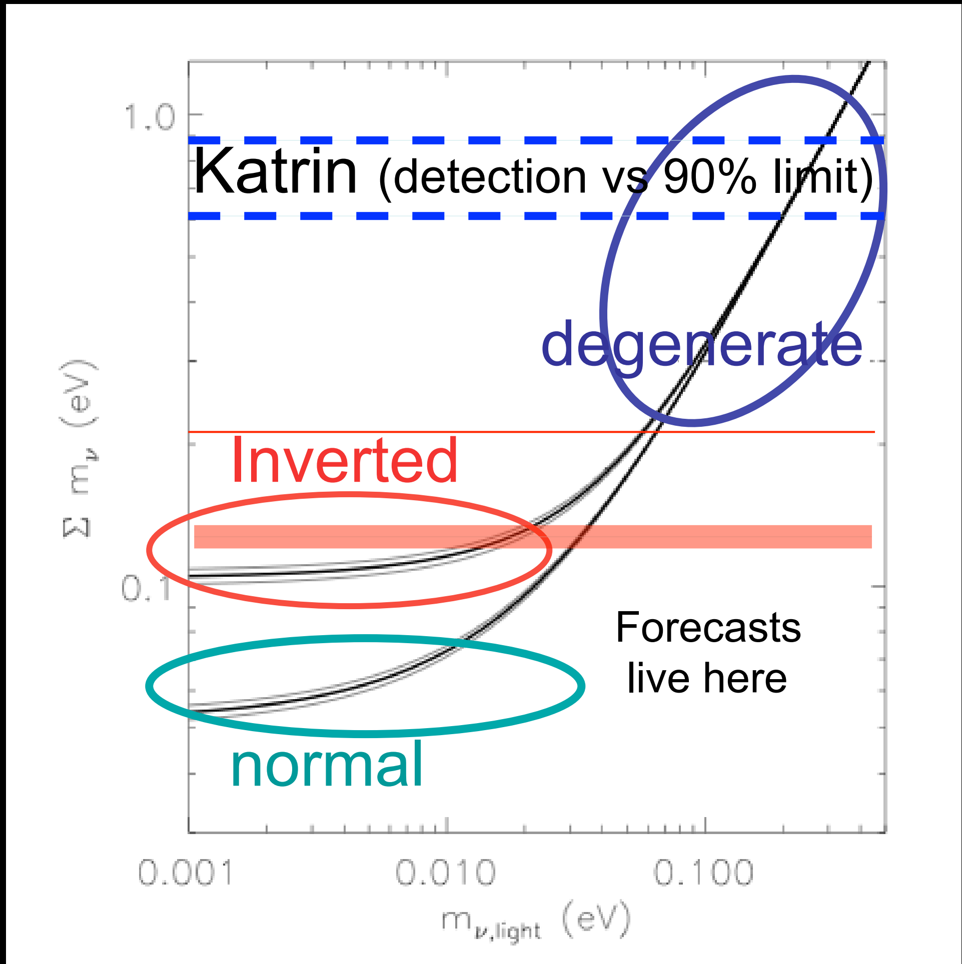
$$M_\nu < 0.12\ \text{eV}(95\%\text{C.L.})$$

Completelty different tracers

Confirmed see also other works: e.g., Giusarma et al 2016, Vagnozzi et al 2017

NB in the past: various claims of detection 0.3-0.4eV mass….not with solely AAA ratings data sets

The Cosmology limits

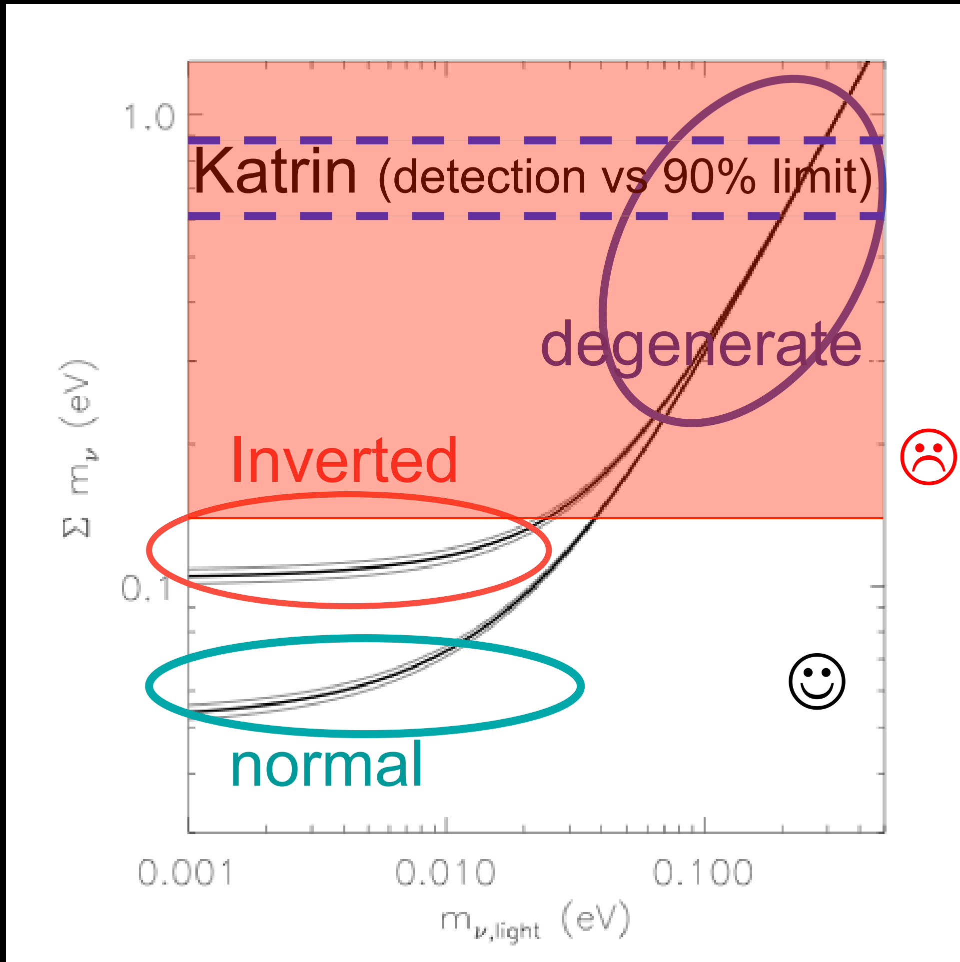


CMB(Planck) +BAO

+LSS

+H0?

Implications I



If we add H0 then HI ☹

Σ<0.11eV @95%

This means that neutrinos contribute at least to ~0.5% of the total matter density

Implications II

CMB+BAO+LRG limit $M_\nu < 0.13\, eV$ (95%C.L.)

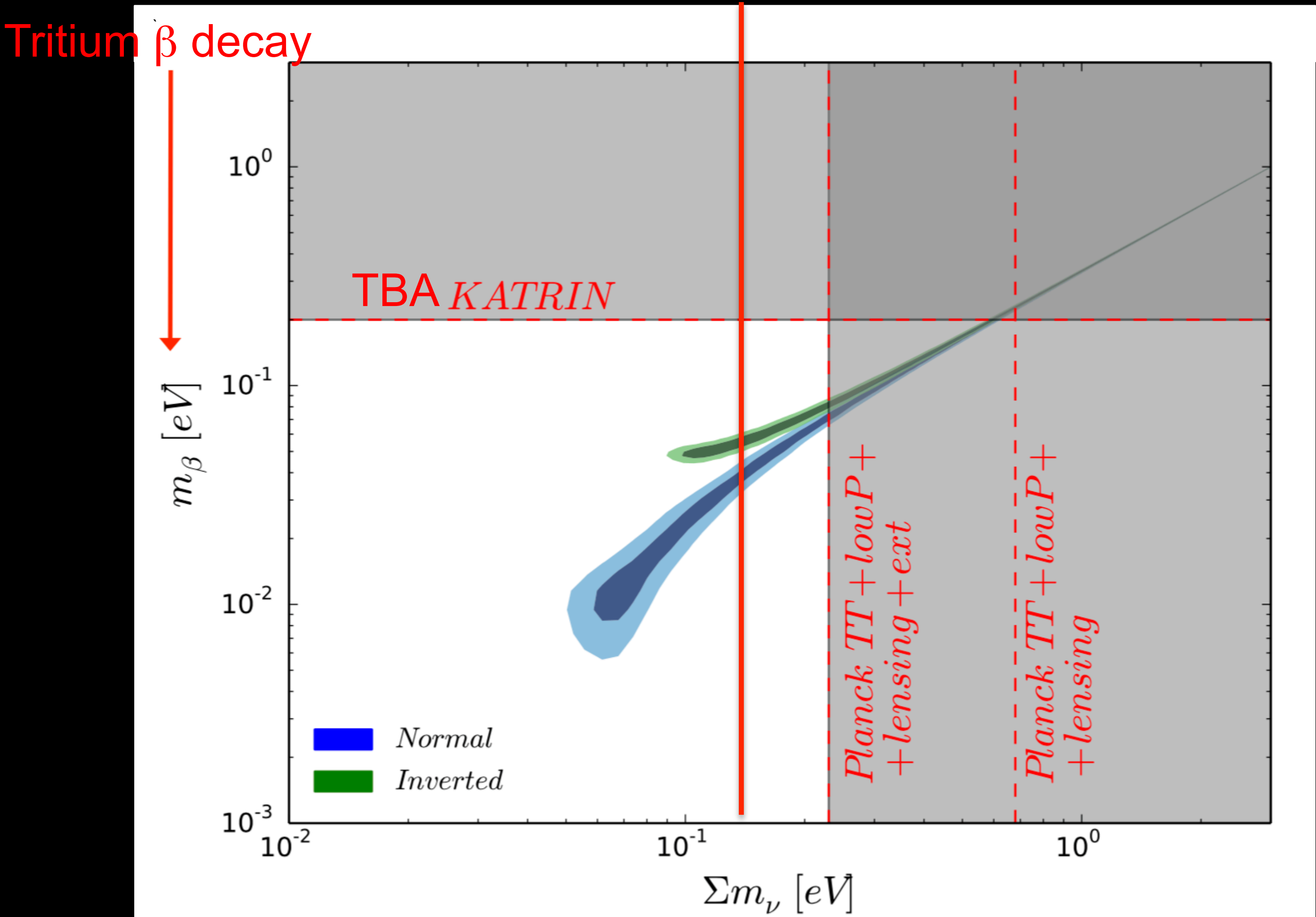
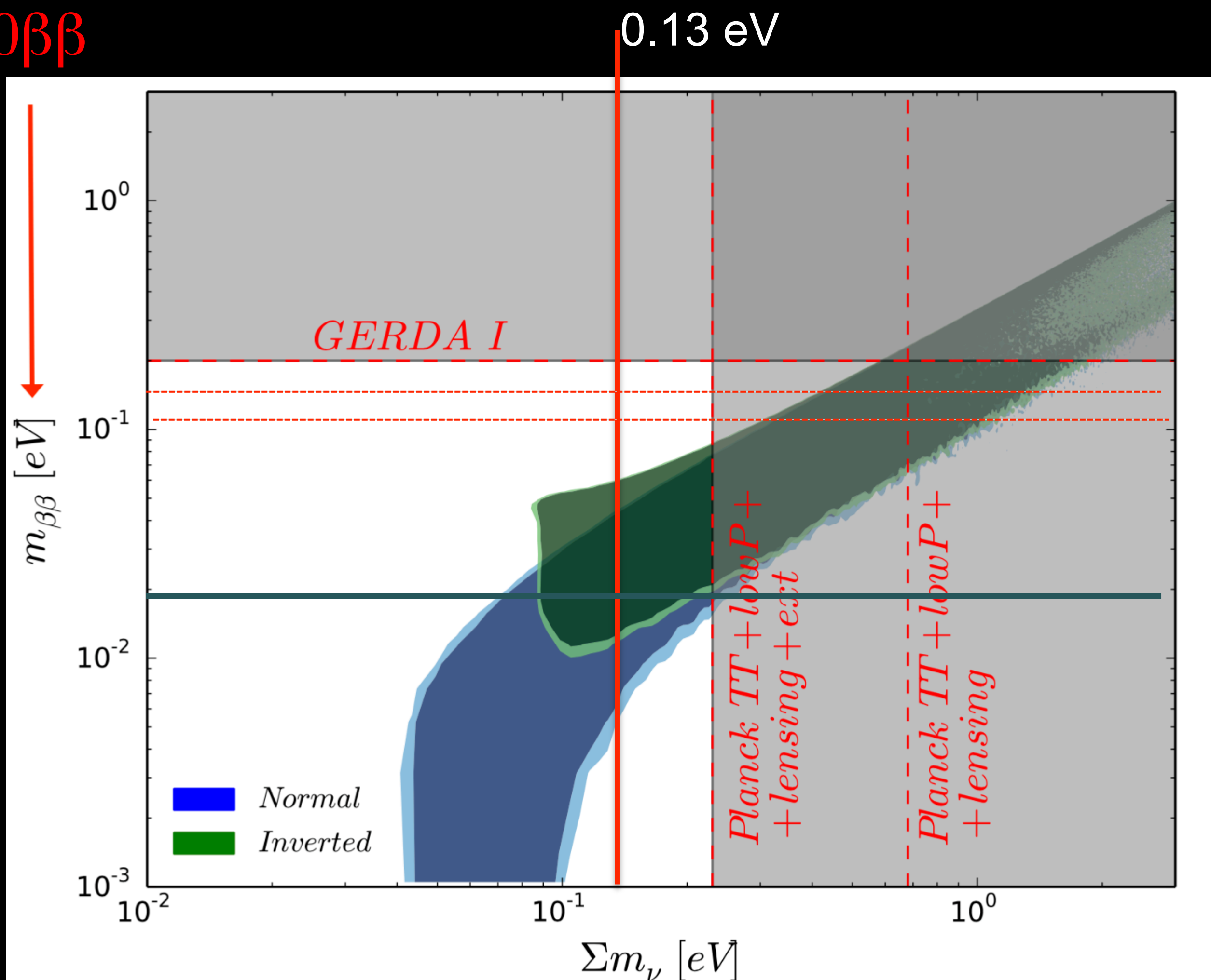


Fig. adapted*
from M. Lattanzi

* Taken from google

Implications III

$\nu 0\beta\beta$



GERDAII

Kamland-Zen

Ton-scale experiment

Fig. adapted* from M. Lattanzi

Of course <T $\nu 0\beta\beta$ experiments could see something, that would be interesting

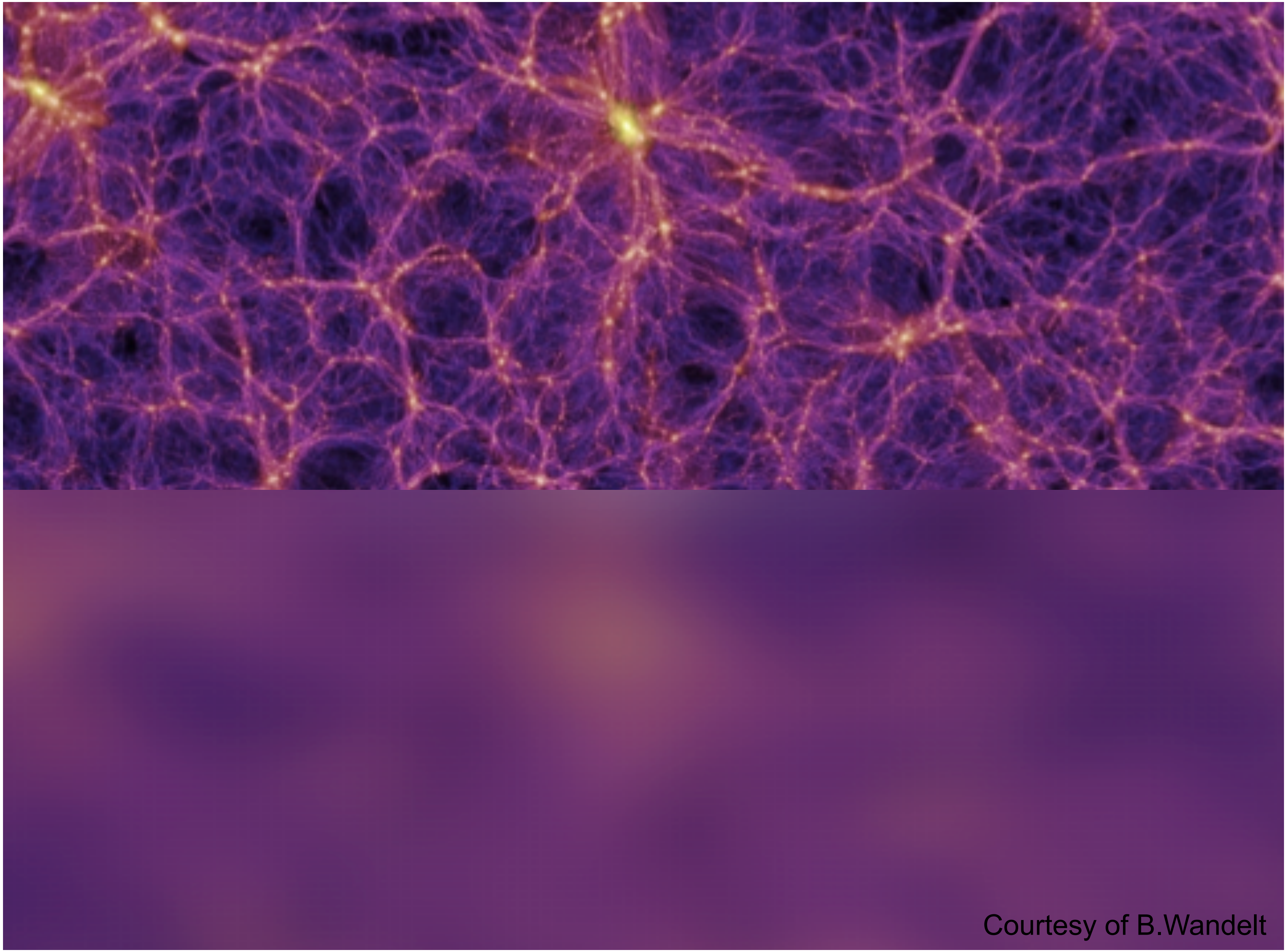
Implications II

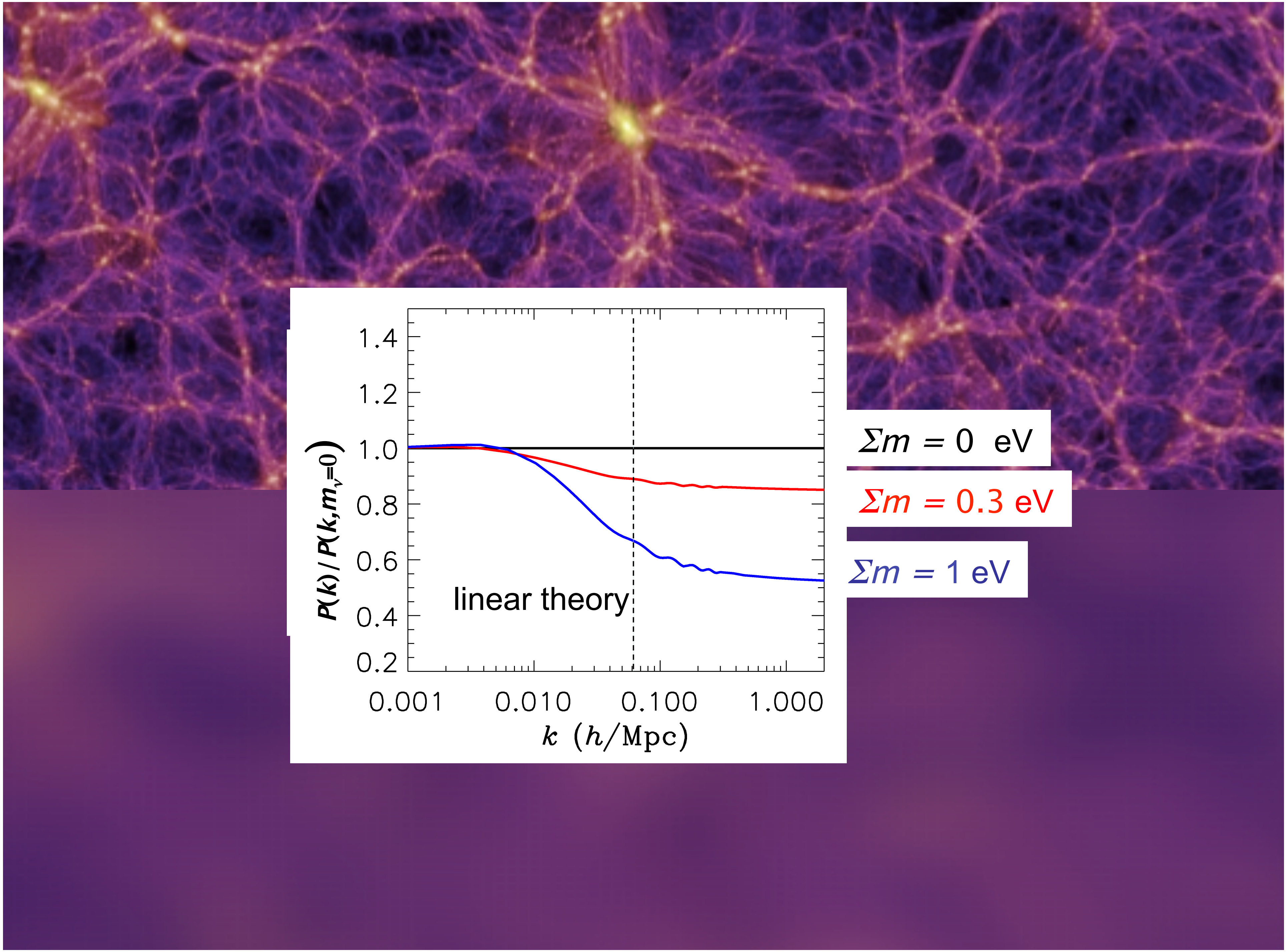
CMB+BAO+LRG limit $M_\nu < 0.13\,eV\ (95\%\mathrm{C.L.})$

The pessimist: The inverted hierarchy is under pressure

The optimist: If IH then a measurement of Mv is just around the corner!

Back to this later


Courtesy of B.Wandelt



1.4
1.2
1.0
0.8
0.6
0.4
0.2
$P(k)/P(k,m_\nu=0)$
linear theory
0.001
0.010
0.100
1.000
$k\ (h/\mathrm{Mpc})$
$\Sigma m = 0$ eV
$\Sigma m = 0.3$ eV
$\Sigma m = 1$ eV

Imagine we measure a non zero Mv

Beware of systematics!!!!!

It would be of great value to have an internal consistency check

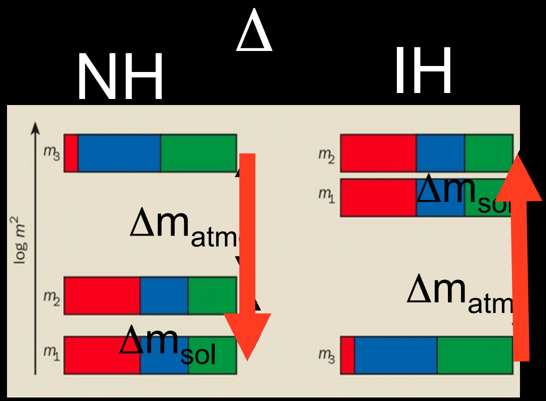
What is hierarchy?

- There are three masses m1, m2, m3 and therefore only two square mass splitting (measurable quantity). One will be smaller than the other one.
- m1,m2 refer to the smaller splitting
- m3 can be above (NH) or below (IH) this pair.
- Hierarchy is given by the ***sign*** of the larger mass splitting.

Only **after the oscillations measurements are in** and we find that one mass splitting is much smaller than the other one we can say

One large two small is NH two large one small is IH

Hierarchy effect on the shape of the linear matter power spectrum



Neutrinos of different masses have different transition redshifts from relativistic to non-relativistic behavior, and their individual masses and their mass splitting change the details of the radiation-domination to matter- domination regime.

approx

$$\mathrm{NH:}\quad \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma$$
$$\mathrm{IH:}\quad \Sigma = m + 2M \quad \Delta = (m - M)/\Sigma$$

Jimenez, Kitching, Penya-Garay, Verde, JACP2010

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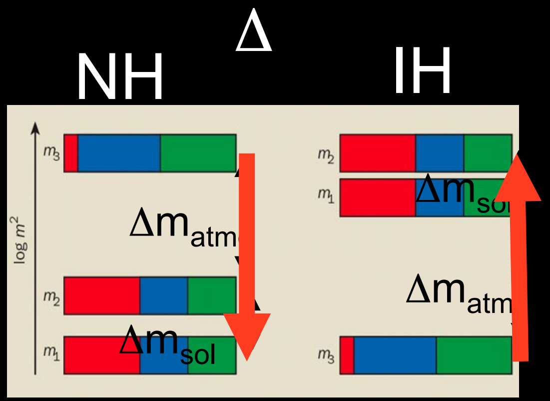

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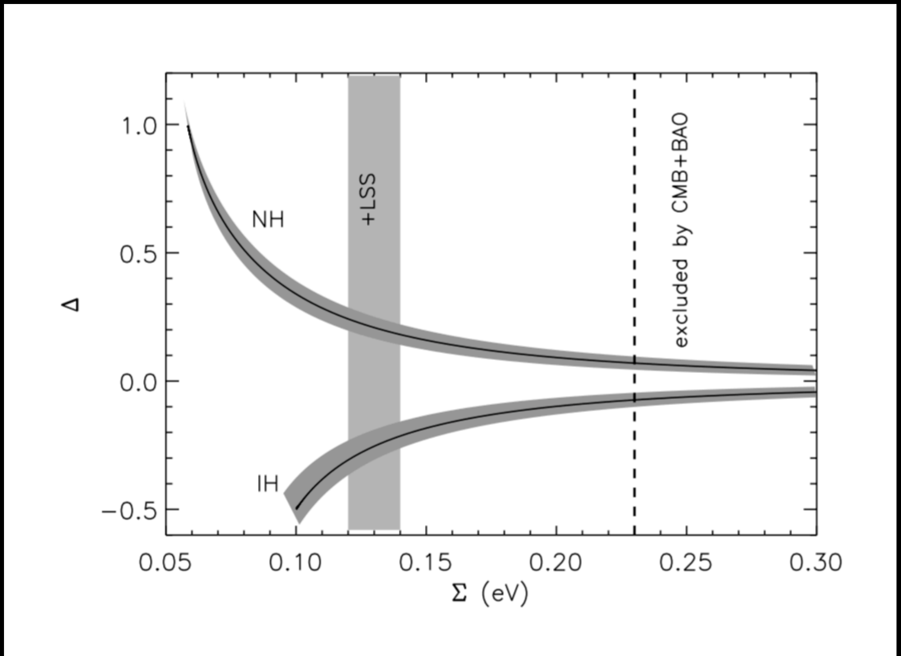

Jimenez, Penya-Garay, Verde, 2016

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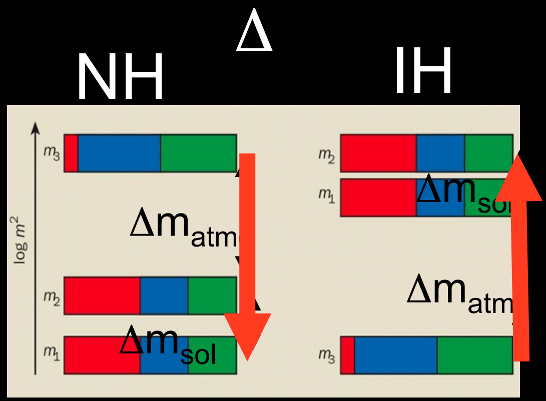

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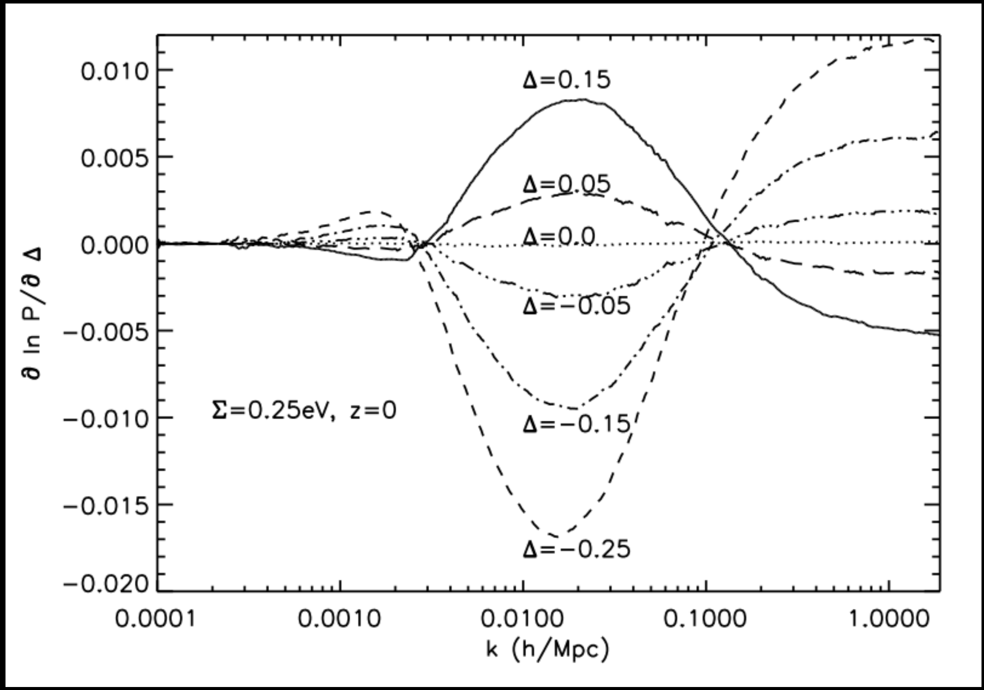
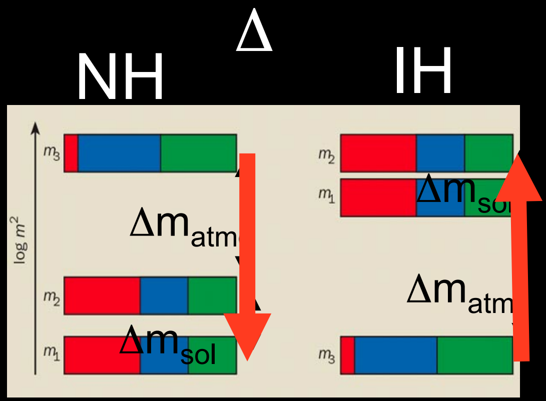


Jimenez, Kitching, Penya-Garay, Verde, JACP2010

Hierarchy effect on the shape of the linear matter power spectrum



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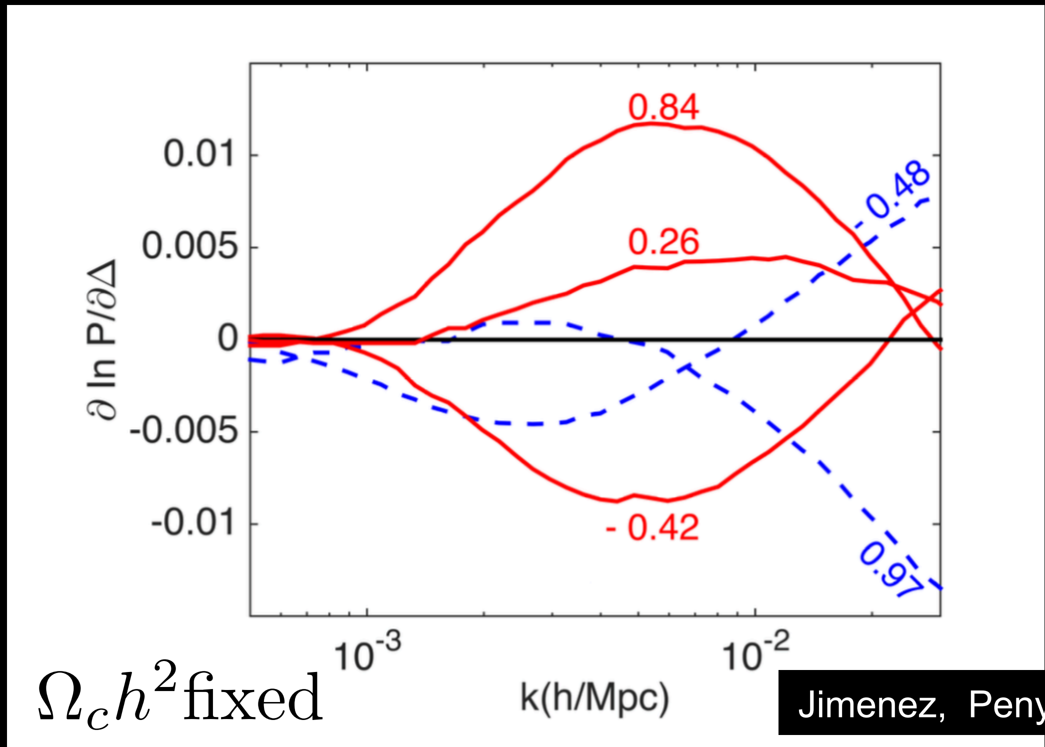
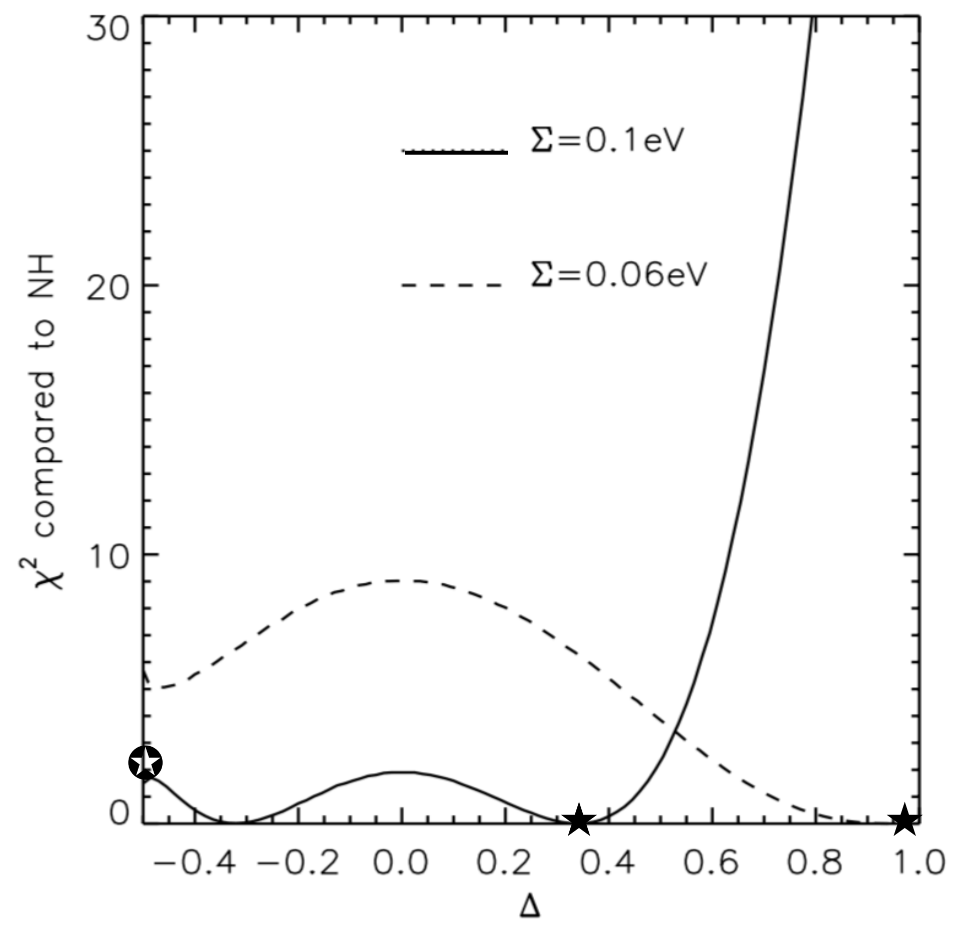


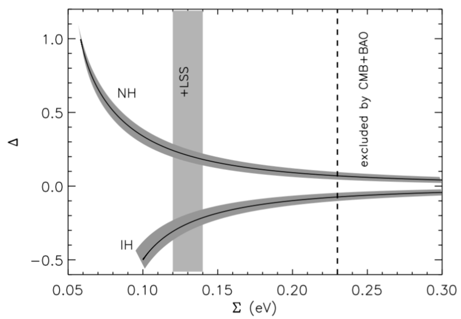
$\Sigma = 0.1eV$

$\Sigma = 0.06eV$

Jimenez, Penya-Garay, Verde, 2016

When Fisher fails





Still a powerful consistency check

Cosmology is (mostly) sensitive to $|\Delta|$

Still offers a powerful consistency check

What would it take to measure Δ?

Basically: the ultimate experiment

In combination with $v0\beta\beta$ experiements can help answering:
Are neutrinos Dirac or Majorana?

Dirac or Majorana? ⟺ hierarchy

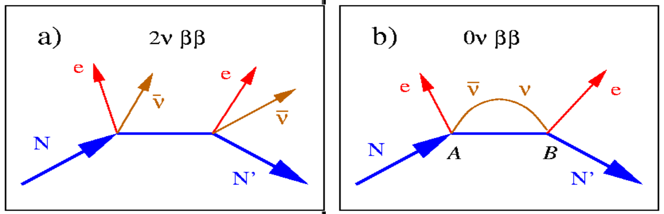
Are neutrinos their own anti-particle?(are they Majorana or Dirac?)

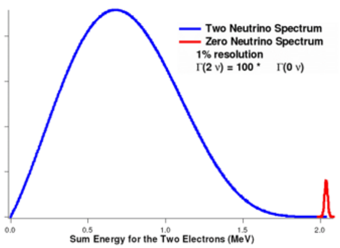
$0\nu\beta\beta$ (next generation)

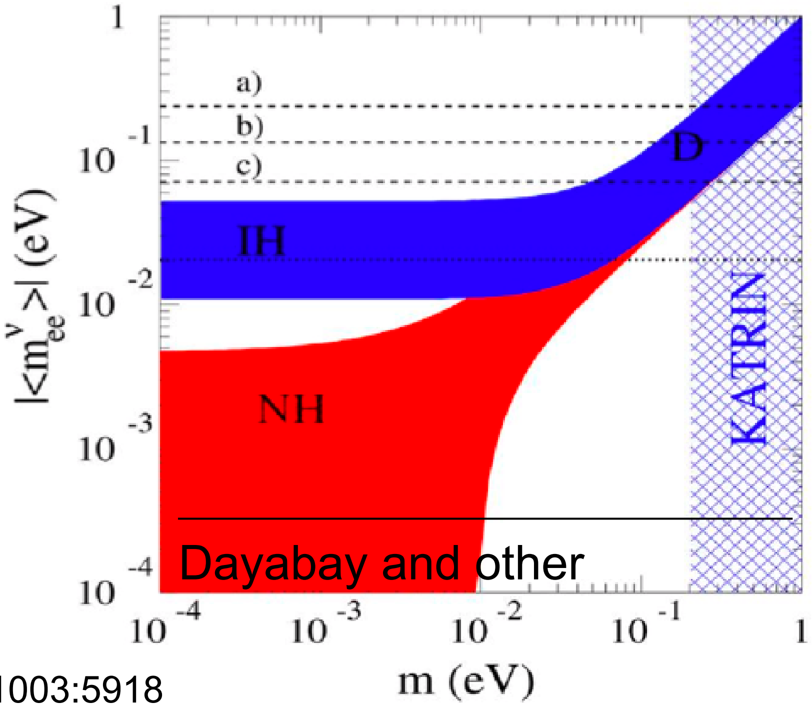
Yes

No

Because Dirac OR
because below threshold (still unknown)?







Majorana

Jimenez, Kitching, Penya-Garay, Verde, arXiv:1003:5918

What Bayes has to say about mass hierarchy

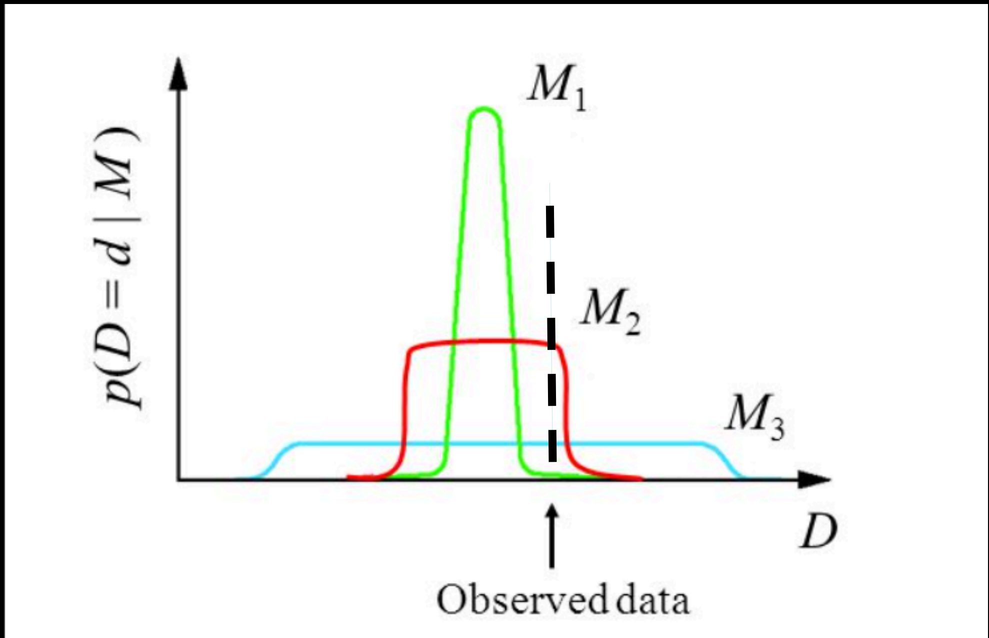
Simpson et al '17

1.
When comparing two models or hypotheses use the Bayesian evidence and the Bayes factor

$$p(D|\mathcal{H}) = \int p(D|\alpha, \mathcal{H}) p(\alpha|\mathcal{H}) d\alpha$$

Evidence Likelihood prior

Exp(accuracy-complexity)



Goldilocks 1 D example

M1: too simple,
unlikely to generate the data

M3: too complex,
can generate many other cases,
why this one?

M2: just right

What Bayes has to say about mass hierarchy

2.
When you have a physical quantity which value may span many orders of magnitude (and especially if unbounded) the least informative prior you can use is a log prior (Jeffrey's prior) shown by e.g., Clarke and Barron 94, see also MacKay 2003.

In the case of ν's masses:

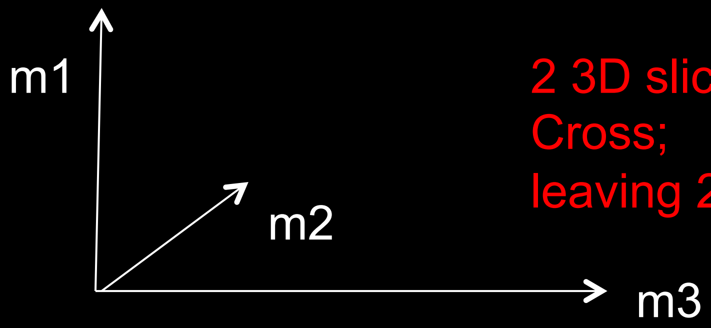
Uncertainty spans several orders of magnitude, at least one is unbounded from below

Should one's prior belief of the neutrino mass depend on the units which one uses to measure it? Whether we use eV or kg? we ought to assign equivalent probabililties to each.

The three masses share a common origin (mechanism to give massto ν's) so they should have the same prior (exchangeability)

The solar mass splitting is small but non-zero. Have to do a 3D analysis.

Simple example

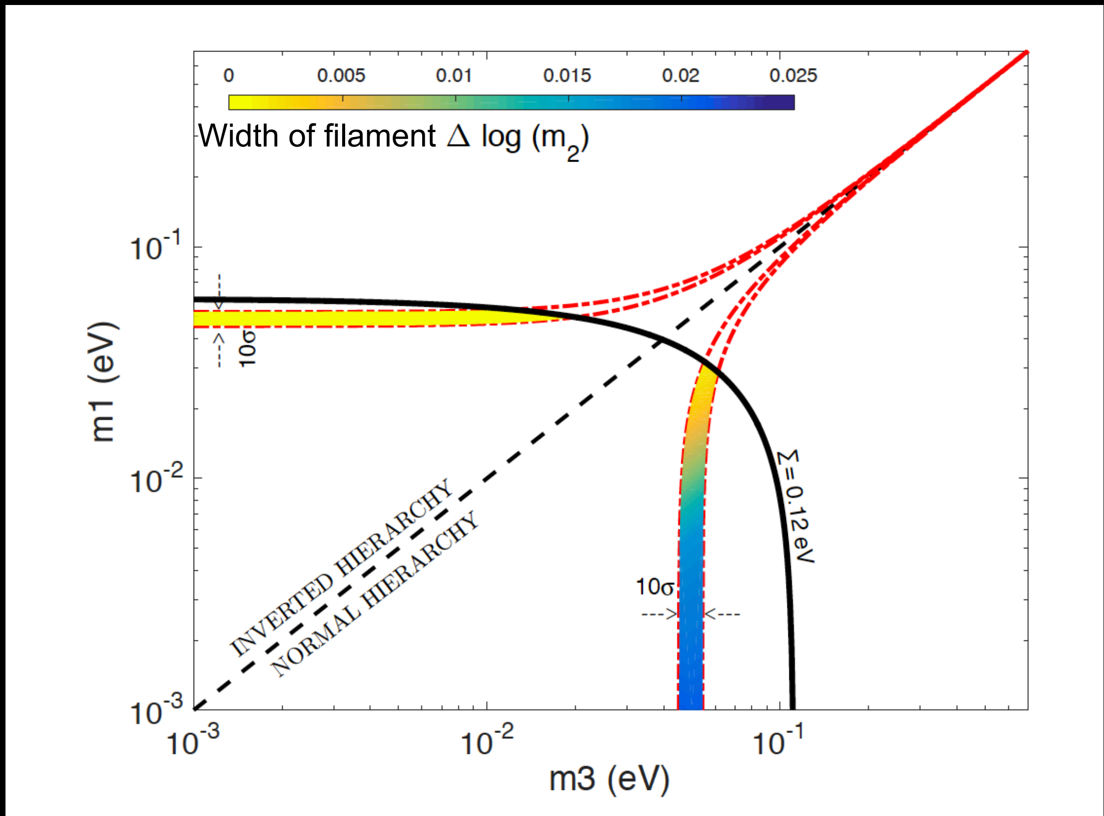


2 3D slices that Cross;
leaving 2 filaments

$$m_2^2 - m_1^2 = 7.50\,(\pm 0.18) \times 10^{-5}\mathrm{eV}^2\,,$$

$$m_3^2 - m_\ell^2 = \begin{cases} 2.524\,(\pm 0.040) \times 10^{-3}\mathrm{eV}^2, & \text{(NH)} \\ -2.514\,(\pm 0.040) \times 10^{-3}\mathrm{eV}^2, & \text{(IH)} \end{cases}$$

m2 in projection

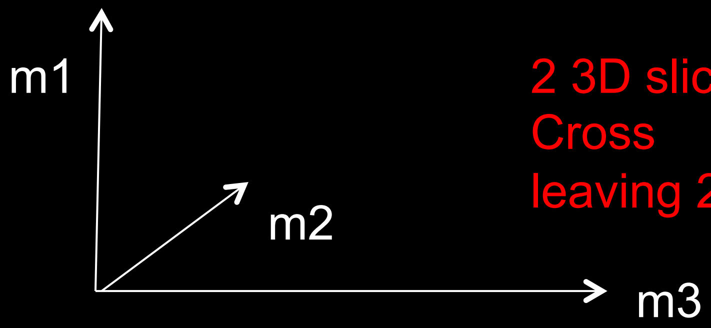


@ very large masses, the uncertainty in Δm_{12}^2 corresponds to a vanishingly small interval in log m

Posterior penalized for large Σ

Σ is not uniquely defined in the m1 m3 plane

Simple example

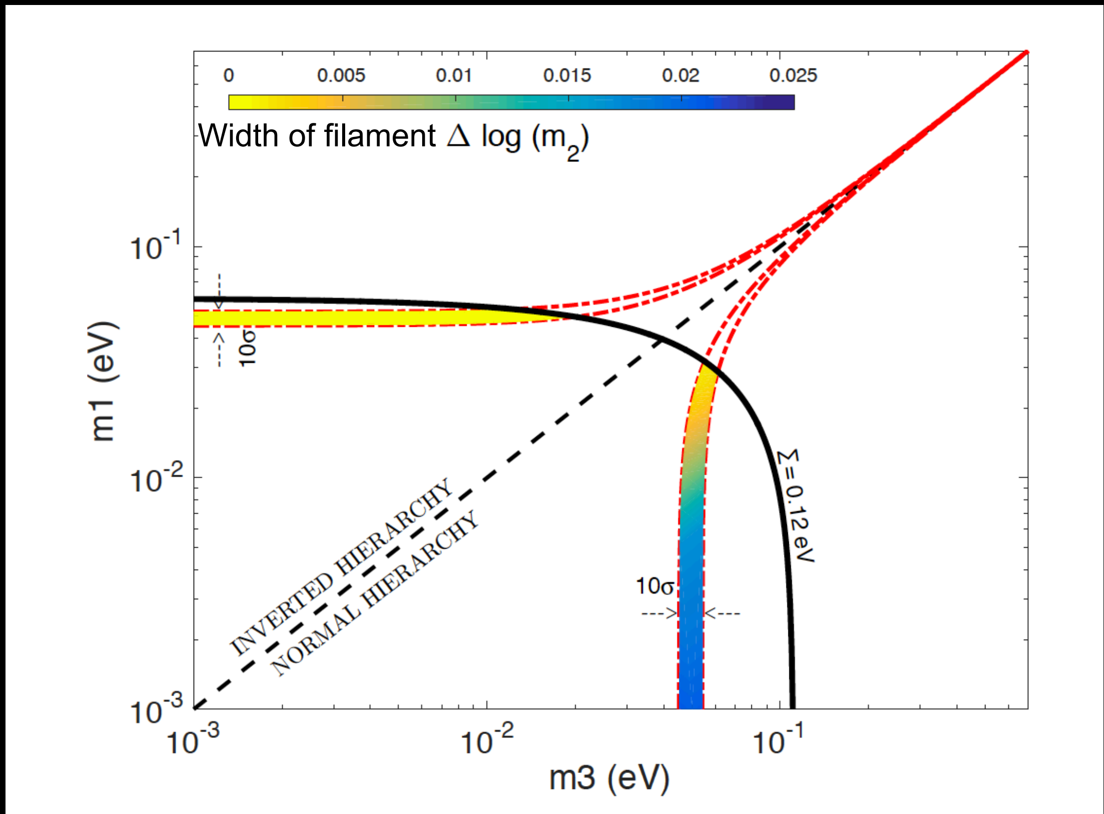


2 3D slices that
Cross
leaving 2 filaments

$$m_2^2 - m_1^2 = 7.50\,(\pm 0.18) \times 10^{-5}\text{eV}^2\,,$$

$$m_3^2 - m_\ell^2 = \begin{cases} 2.524\,(\pm 0.040) \times 10^{-3}\text{eV}^2, & \text{(NH)} \\ -2.514\,(\pm 0.040) \times 10^{-3}\text{eV}^2, & \text{(IH)} \end{cases}$$

m2 in projection



Evidence ratio heavily favors NH
Stronger with cosmological data

But if $\Delta m_{12}^2 = 0$ then NH = IH
With cosmological data NH
very slightly favoured

Better calculation: Hierarchical Model

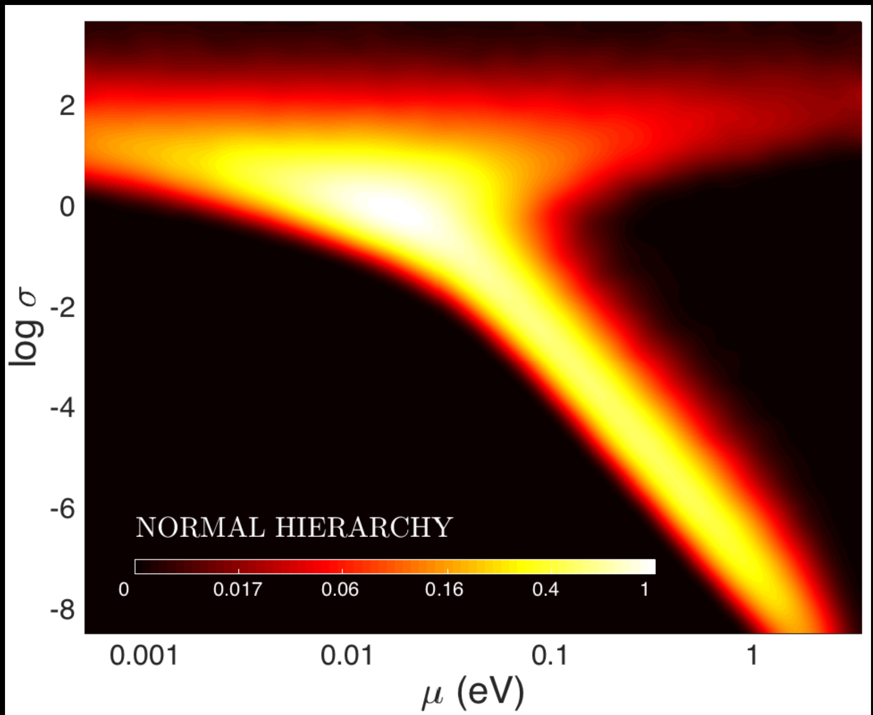
Hyperprior: a family of priors and marginalize over them.
Normal distribution for each of the (log)masses with μ, mean and σ , width

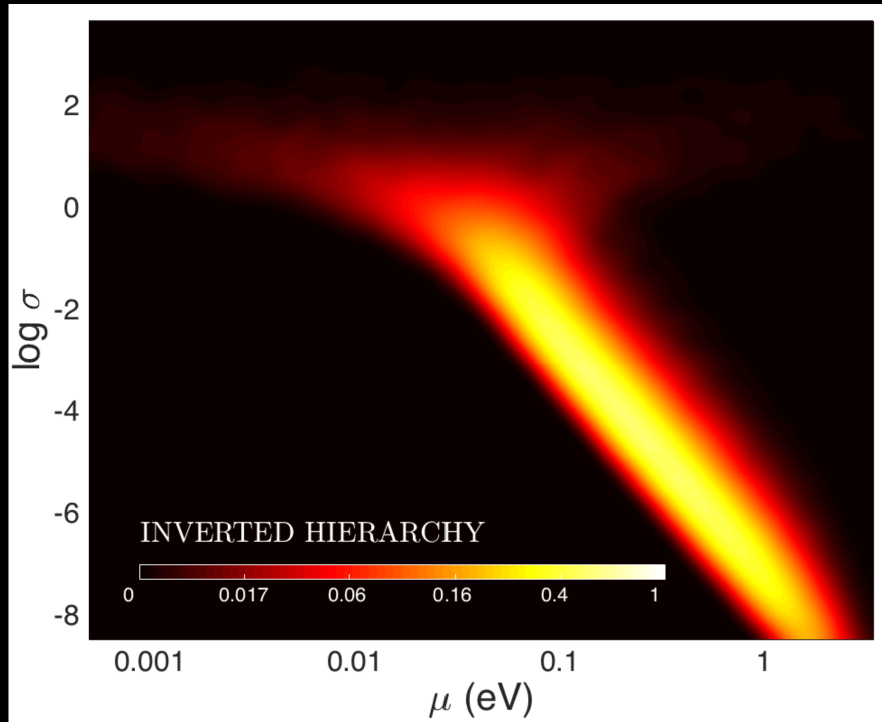
Use oscillations measurements + cosmological limits (assume Gaussian likelihood)

Then marginalize over μ, σ

Compute Evidence

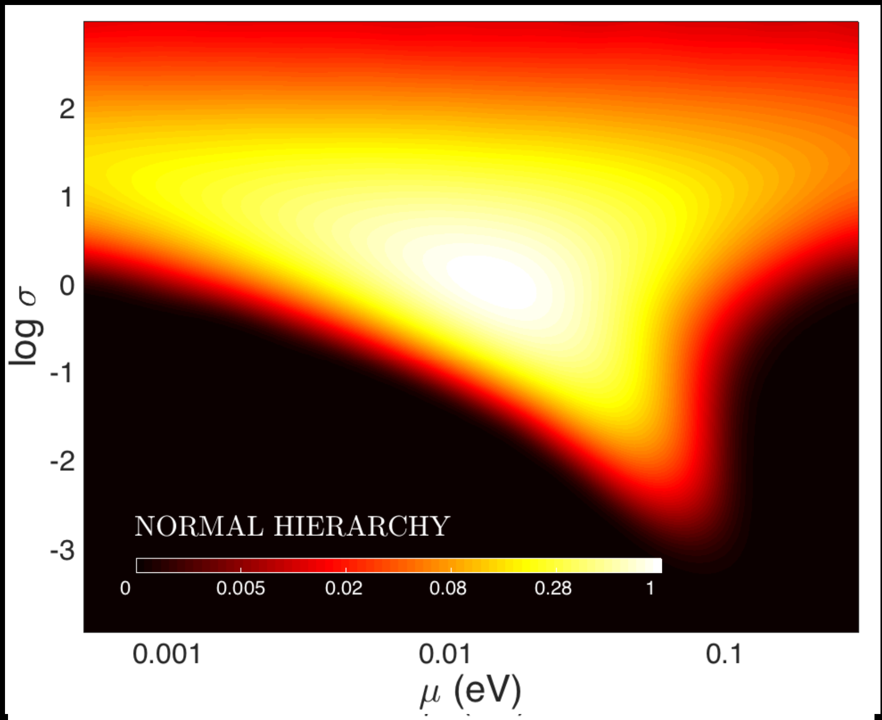
Hyperpriors

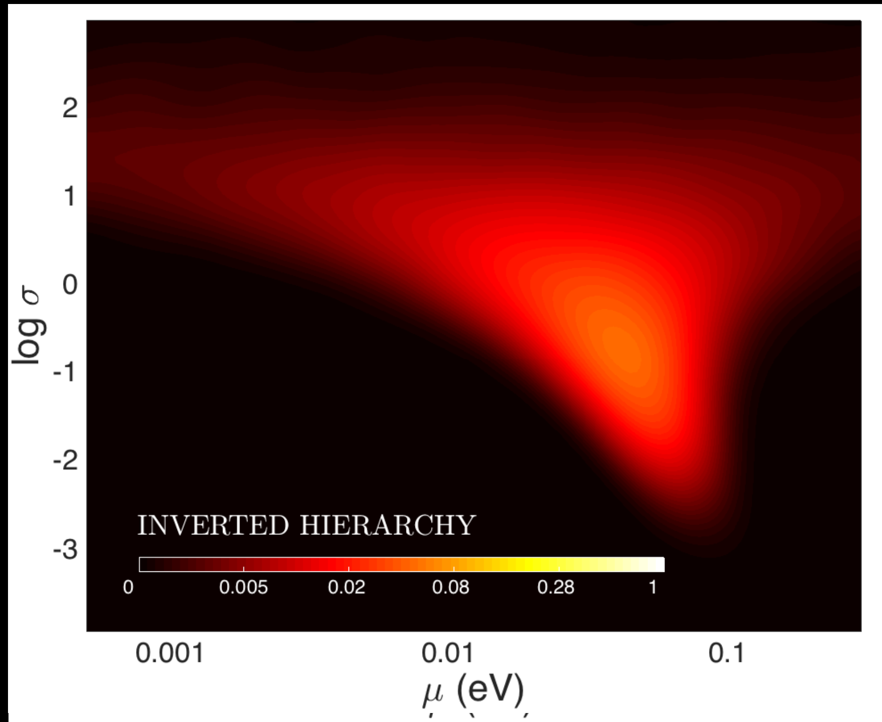




No cosmological bound on Σ, $\Sigma<6.9$ eV

Hyperpriors





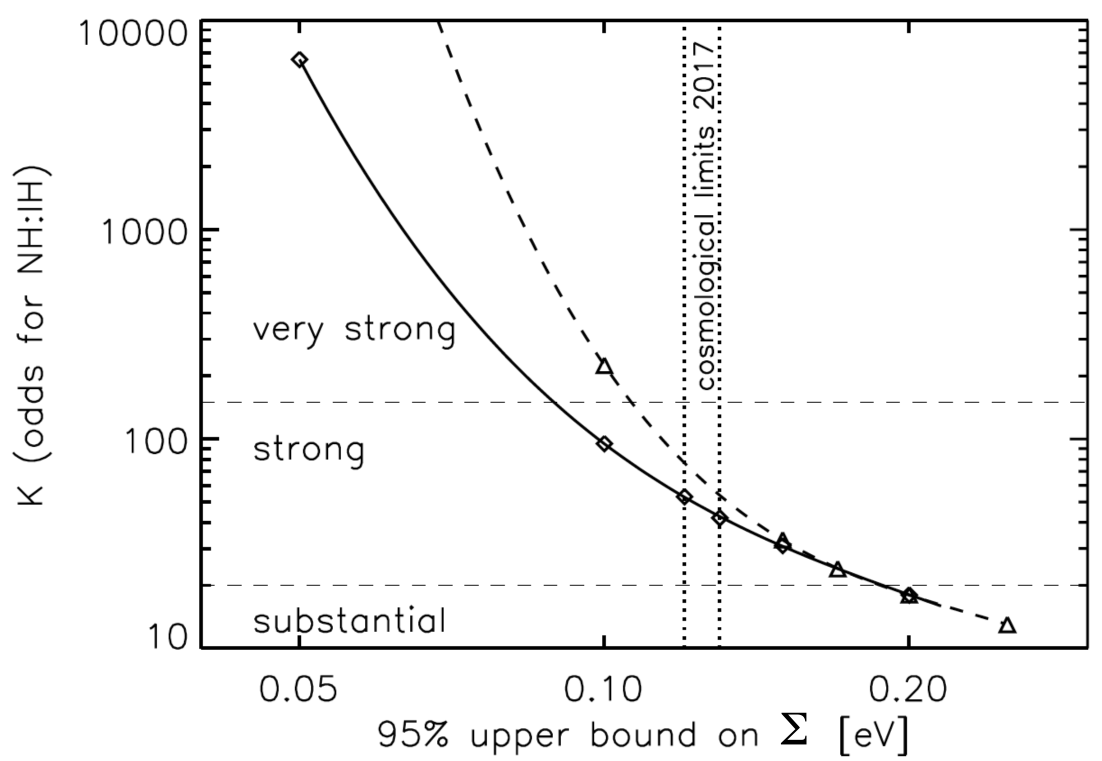
With a cosmological bound, $\Sigma < 0.15$ eV

Note the different scale

Evidence (Jeffrey's scale modified)

@0

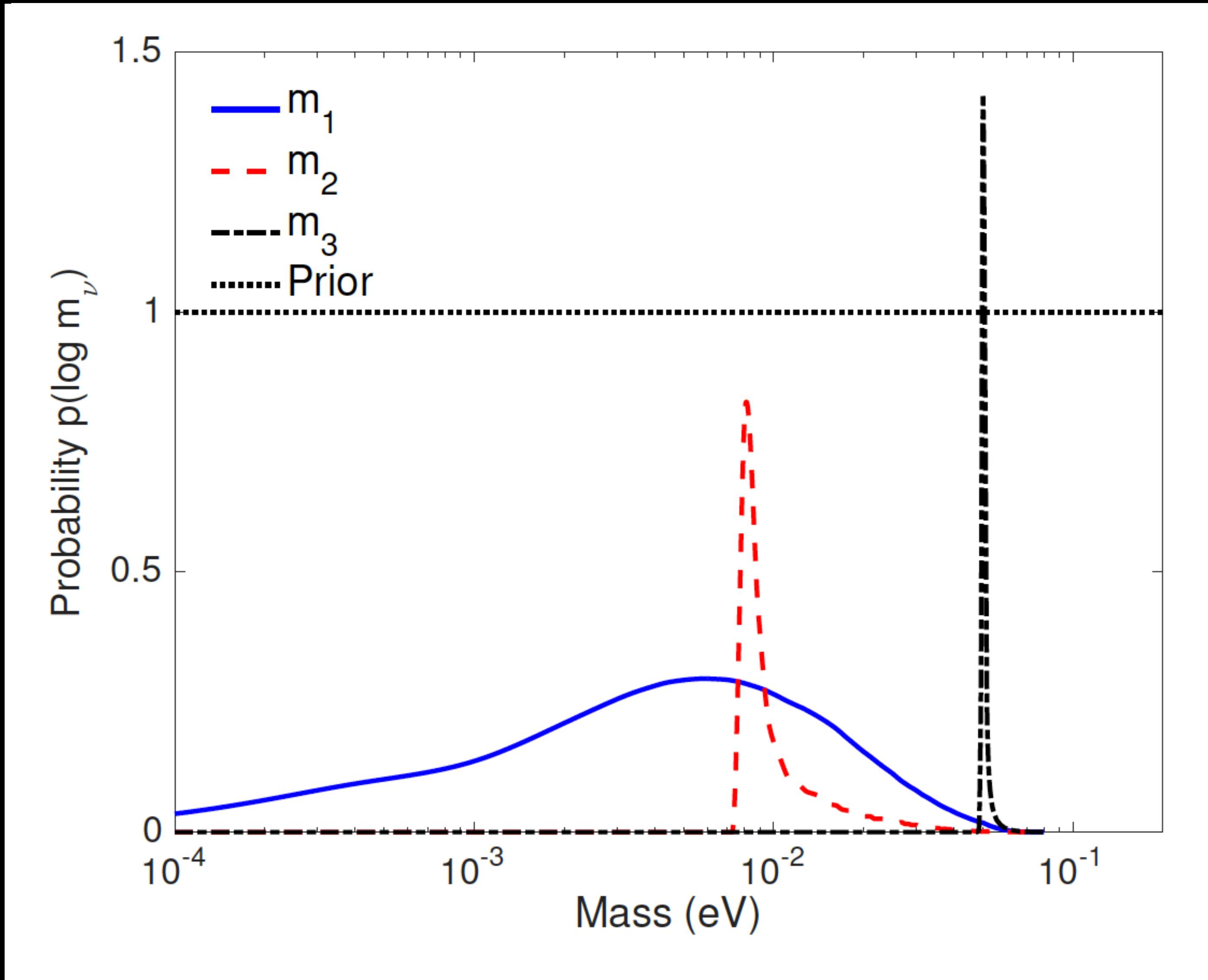
Σ (eV) 95%	< 0.05	< 0.1	< 0.12	< 0.13	< 0.15	< 0.2	< 0.5	< 6.9
Odds (NH/IH)	6500:1	95:1	53:1	42:1	31:1	18:1	7:1	2.6:1
$\log K$	9	4.5	4.0	3.7	3.4	2.9	1.9	1.0
Classification	Very Strong	Strong	Strong	Strong	Strong	Positive	Positive	Weak



@0.05eV

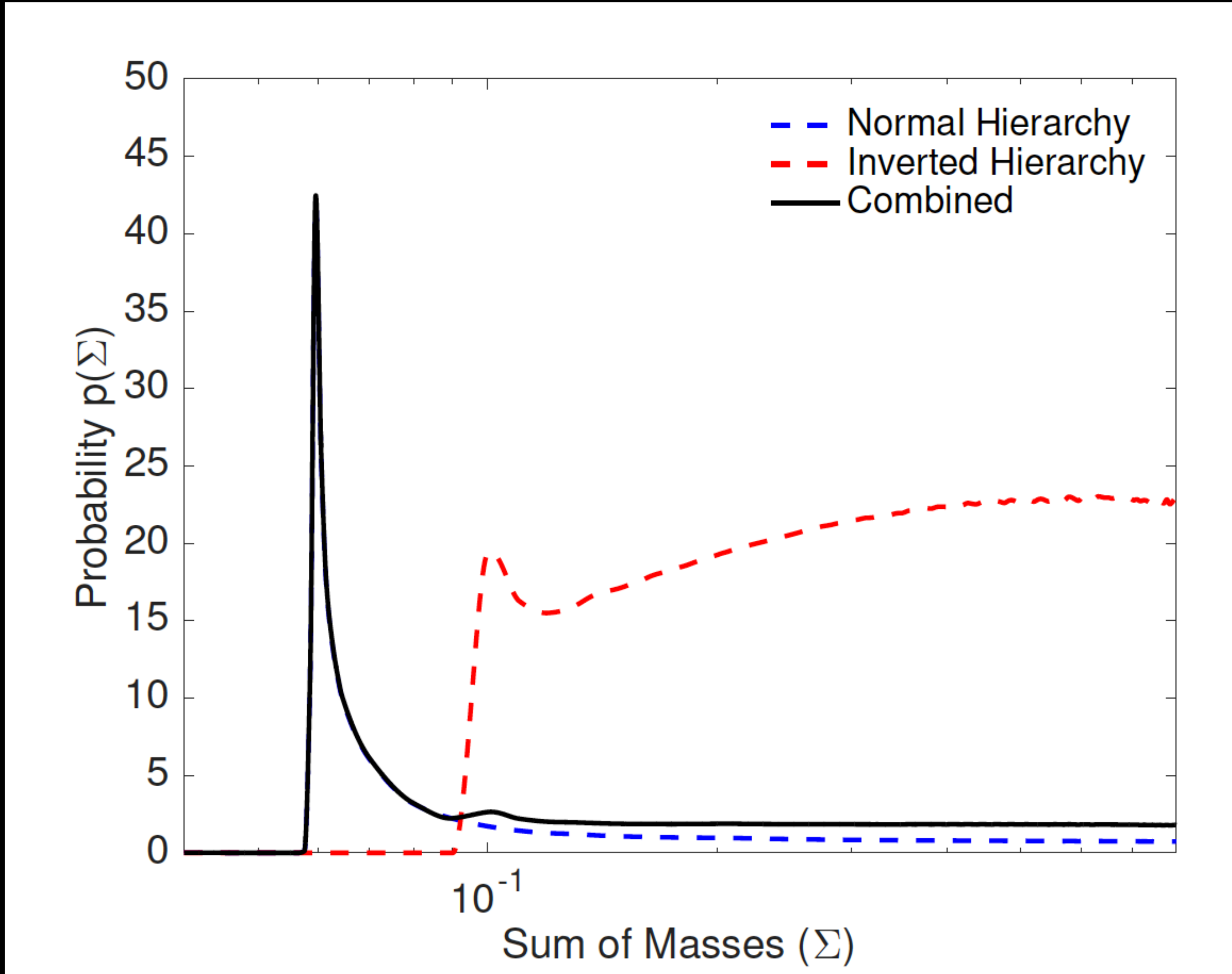
Σ (eV) 95%	< 0.1	< 0.15	< 0.17	< 0.2	< 0.25	< 0.5	< 6.9
Odds (NH/IH)	225:1	33:1	24:1	18:1	13:1	6.3:1	2.6:1
$\log K$	5.4	3.5	3.2	2.9	2.5	1.8	1.0
Classification	Very Strong	Strong	Strong	Positive	Positive	Positive	Weak

Posteriors for the masses, NH



Σ<0.12eV

Posterior for the sum of the masses…



Normalization rescaled for clarity

Without cosmological information

Implications

Strong Bayesian Evidence for NH, when using the stated priors
(Normal family in log m AND cosmological bounds*)

Double beta decay experiments: favours experimental techniques reaching multi-ton active mass detectors and very low background

Experiments more sensitive to normal mass hierarchy are much more likely to be successful

Conclusions could be evaded by drastically changing the prior,
but you will have to convince me (and Jeffreys and Clarke and Barron…)

Or by measuring $0\nu\beta\beta$ decay.

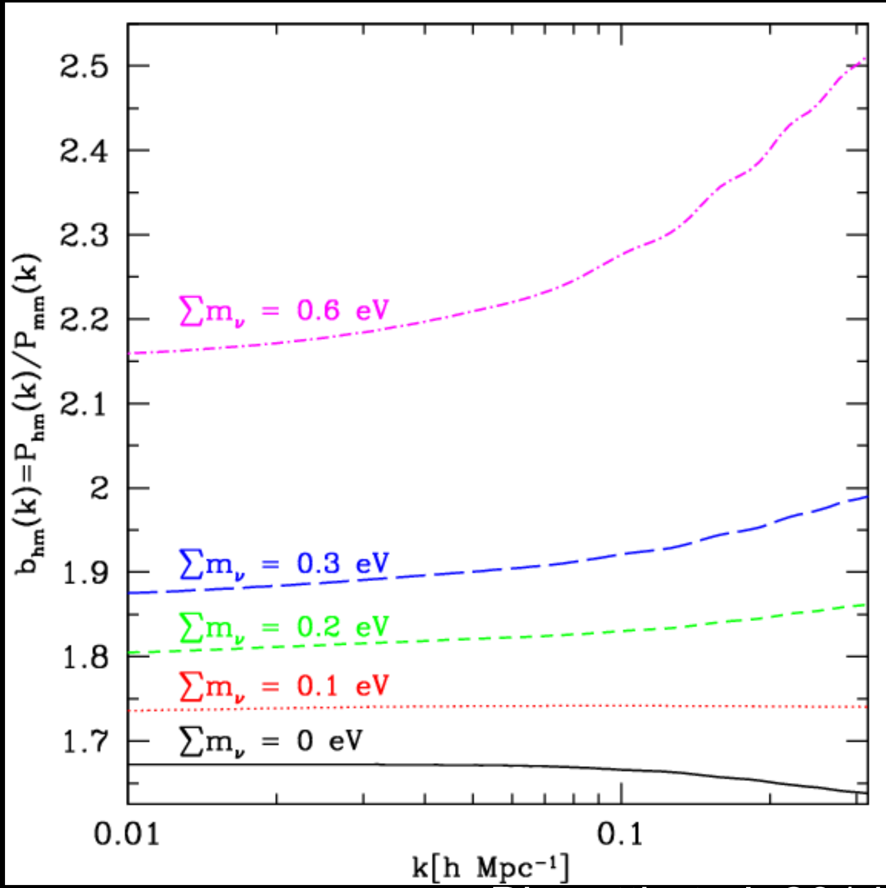
Biases from neutrino bias

Raccanelli et al '17

Here, <u>halo bias</u>

Neutrinos' thermal velocities avoid their clustering in DM halos

The bias defined with respect to the total matter,m, (Cold+baryons+neutrinos) has <u>a scale-dependence that depends on neutrino masses</u>.



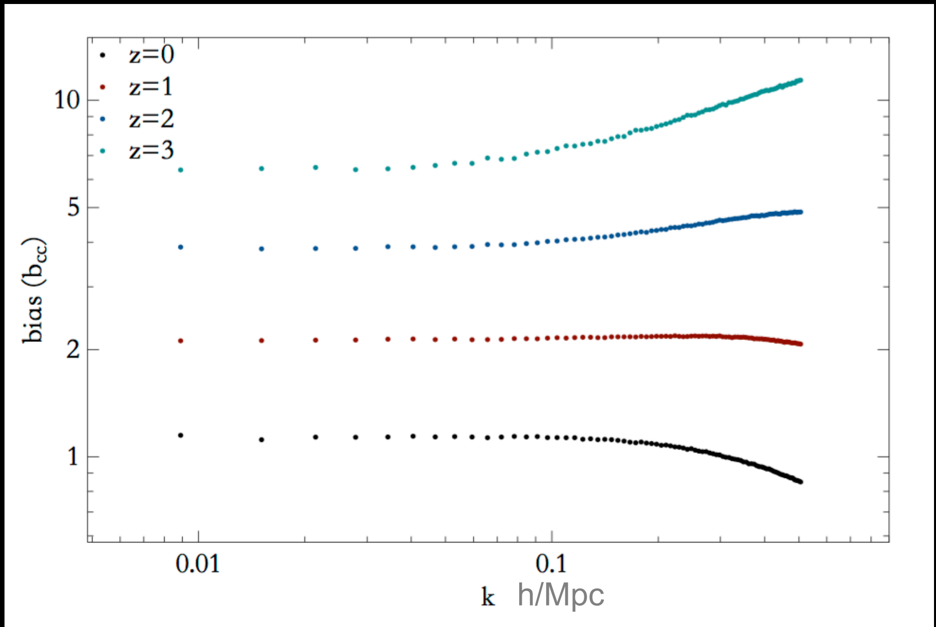
Biagetti et al. 2014

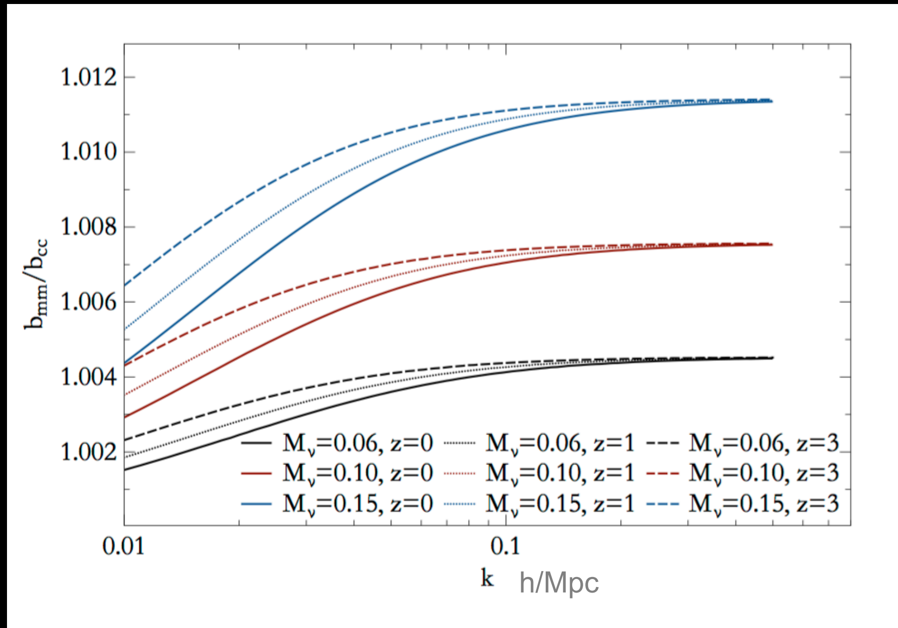
See e.g., LoVerde 2014, Castorina et al 2015, 2014, Villaescusa-Navarro 2014, Biagetti 2014 etc.

Is this a problem if ignored?

First: note that the bias defined with respect to Cold+Baryons, b_{cc}, does not have this issue.

Overall amplitude depends on Σ, but not its scale-dependence

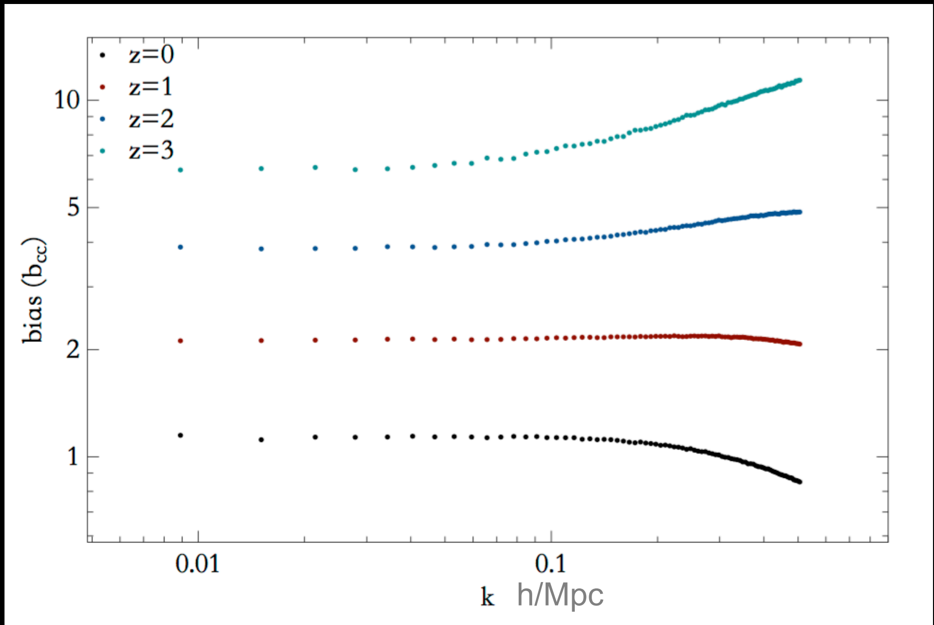


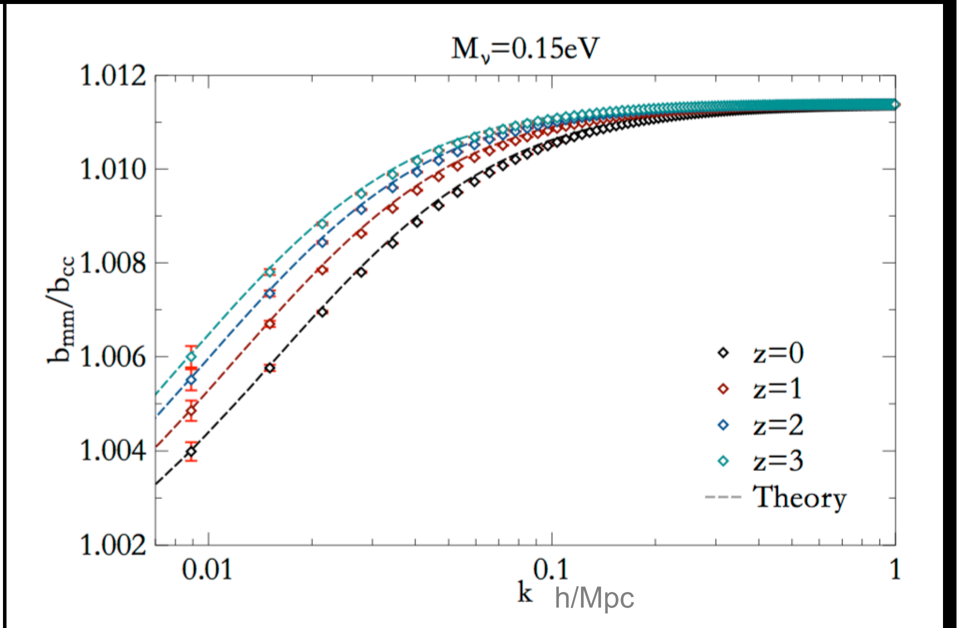


Is this a problem if ignored?

First: note that the bias defined with respect to Cold+Baryons, $b_{cc,}$ does not have this issue.

Overall amplitude depends on Σ, but not its scale-dependence





We offer useful fitting formulae and a prescription to compute $b_{mm}(k,\Sigma,z)$

Should you worry?

Why worry if you can correct for it at very little extra cost?

Get fits for b_{cc} numerically (no need to explore different Σ)

Get b_{mm} analytically from that.

Calibration on N-body simulations done for you.
Formulae in the paper .

Conclusions

$0.058 \text{ eV} < \Sigma < 0.13 \text{ eV}$

Cuesta, Niro, Verde, 2016

For discussion:
how can upper bound be evaded?
At what cost? E.g. Bellomo et al 2017

Measuring Δ offer a crucial consistency check

Jimenez, Penya-Garay,Verde, 2016

If you are a betting person you should bet for NH.
(and Σ~0.06eV)

Simpson, Jimenez, Penya-Garay, Verde, ‘17

Do correct for scale dependence neutrino bias, it’s easy and can save you from troubles!

Raccanelli, Verde, Villaescusa-Navarro, ‘17

END

NB there will be positions available in the group, announced soon.
If interested contact me.