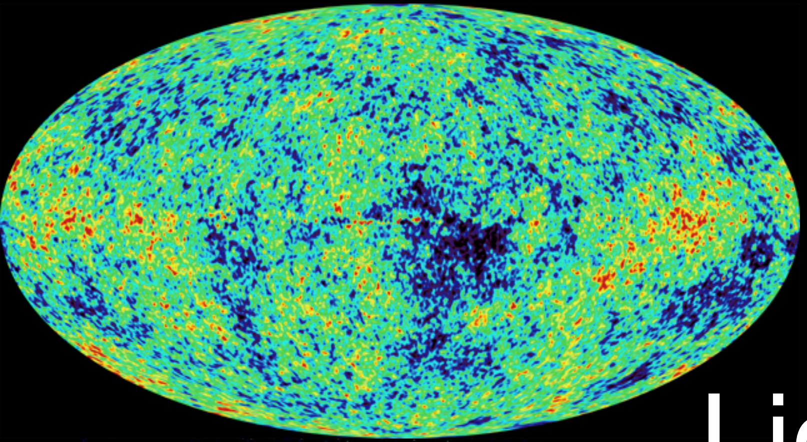
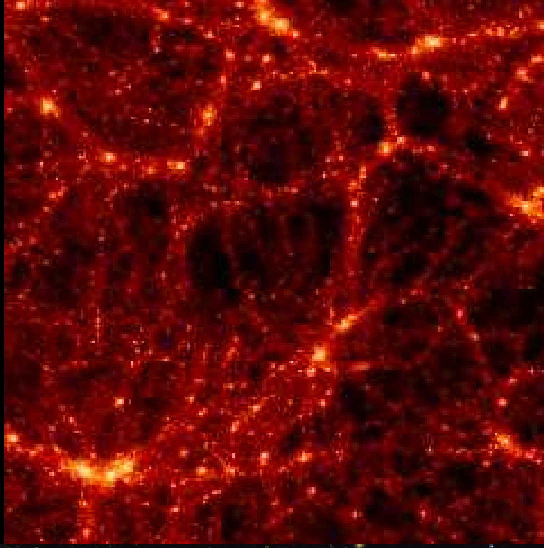
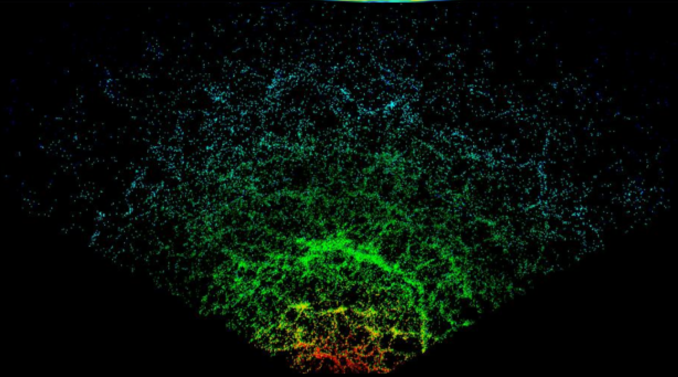


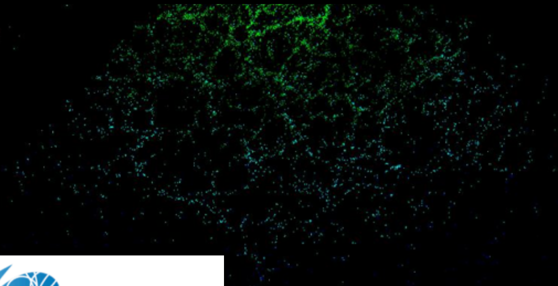


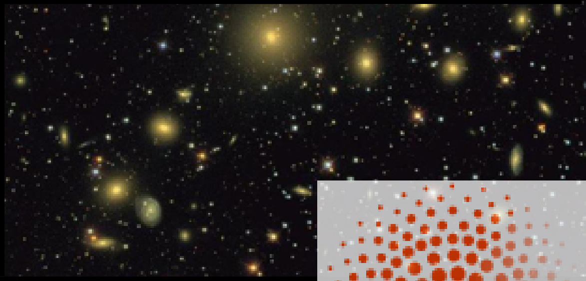
Licia Verde

ICREA & ICC-UB-IEEC
Barcelona, Spain



Neutrino properties from cosmology





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

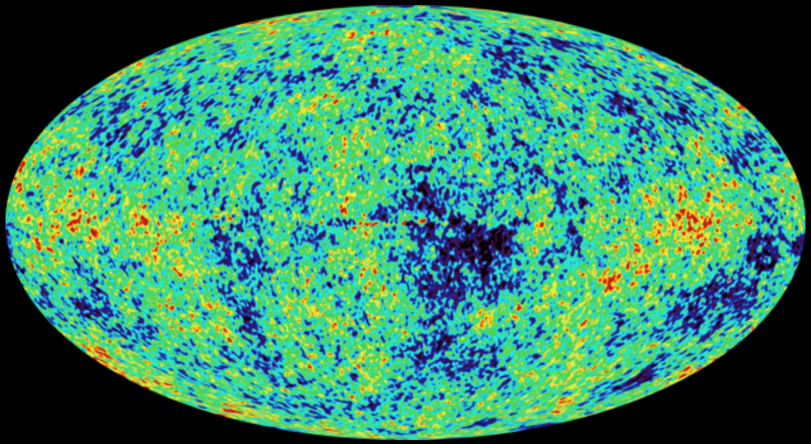
Institute of Cosmos Sciences · Excelencia María de Maeztu · ICREA · Universitat de Barcelona · Gobierno de España · Ministerio de Economía, Industria y Competitividad · erc

In case one gets zoomed out

Particle data group, Neutrinos in Cosmology, Lesgourgues & Verde
https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrinos-in-cosmology.pdf
(fully updated every 2 years, revised every year)

Cosmic Neutrino Background

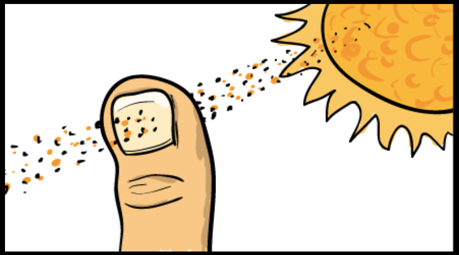
A relict of the big bang, similar to the CMB except that the CvB decouples from matter after 2s (~ MeV) not 380,000 years



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



*

Cosmic Neutrino Background

60Billion nu/s/cm^2 from the sun
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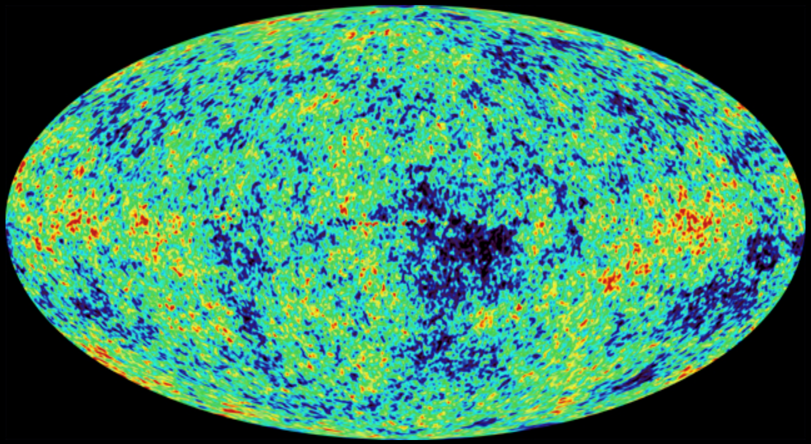


Compare that with 1.d-7 baryons

A relict neutrino background pervading the Universe is a **generic prediction** of the standard hot big bang model. While it has not yet been detected directly, it has been indirectly confirmed by the accurate **agreement of predictions and observations** of
a) the primordial abundance of light elements
b) the power spectrum of CMB anisotropies
c) the large scale clustering of cosmological structures.
Within the hot big bang model such good agreement would fail dramatically without a CvB with properties matching closely those predicted by the standard neutrino decoupling model.

*

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”)

Neutrinos

The only known particle behaving
as radiation at early time (during the CMB acoustic oscillations)
and as dark matter (not cold) at late time (during structure formation)
This has consequences for the background evolution and the structure growth.

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:

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

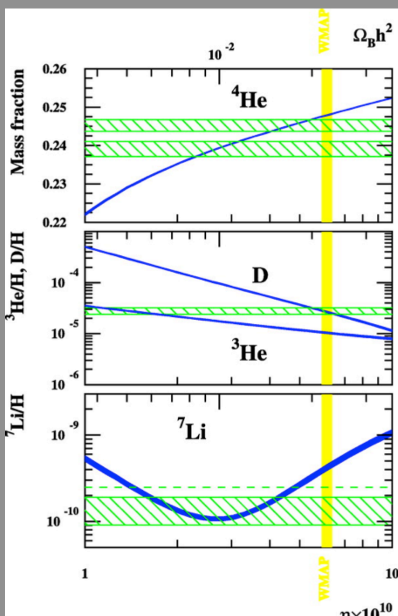
That, for a massive neutrino translates in:

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

Neutrinos affect the growth of cosmic clustering and (indirectly) the expansion history so they can leave key imprints on the cosmological observables

Relict neutrinos influence in cosmology

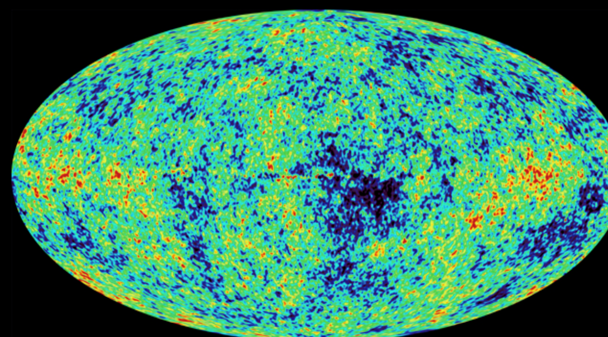
Primordial nucleosynthesis



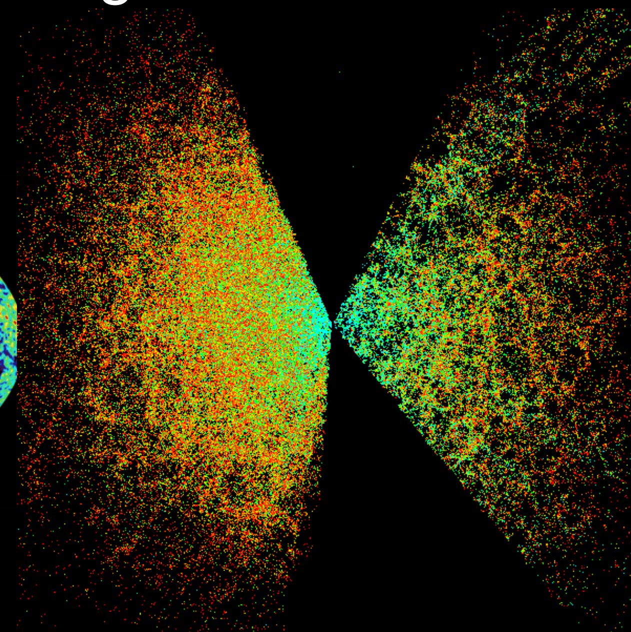
T~ MeV

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"? (dark radiation)

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)

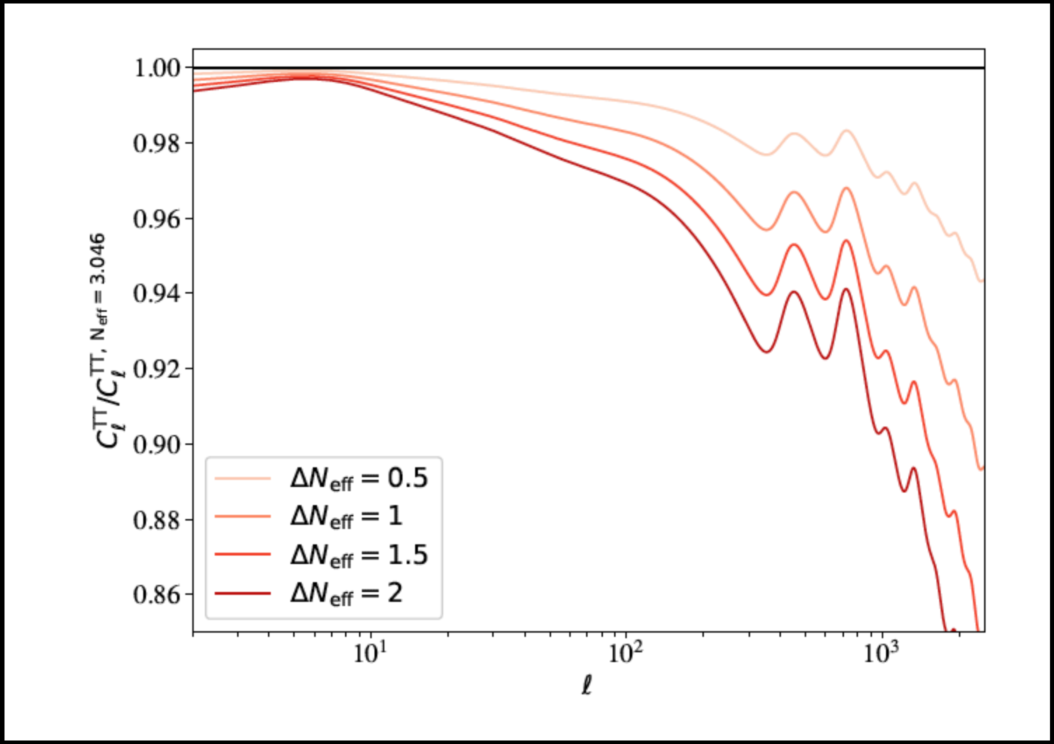
Mostly model-dependent statements: measuring cosmological parameters values**

Neutrinos Neff: 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

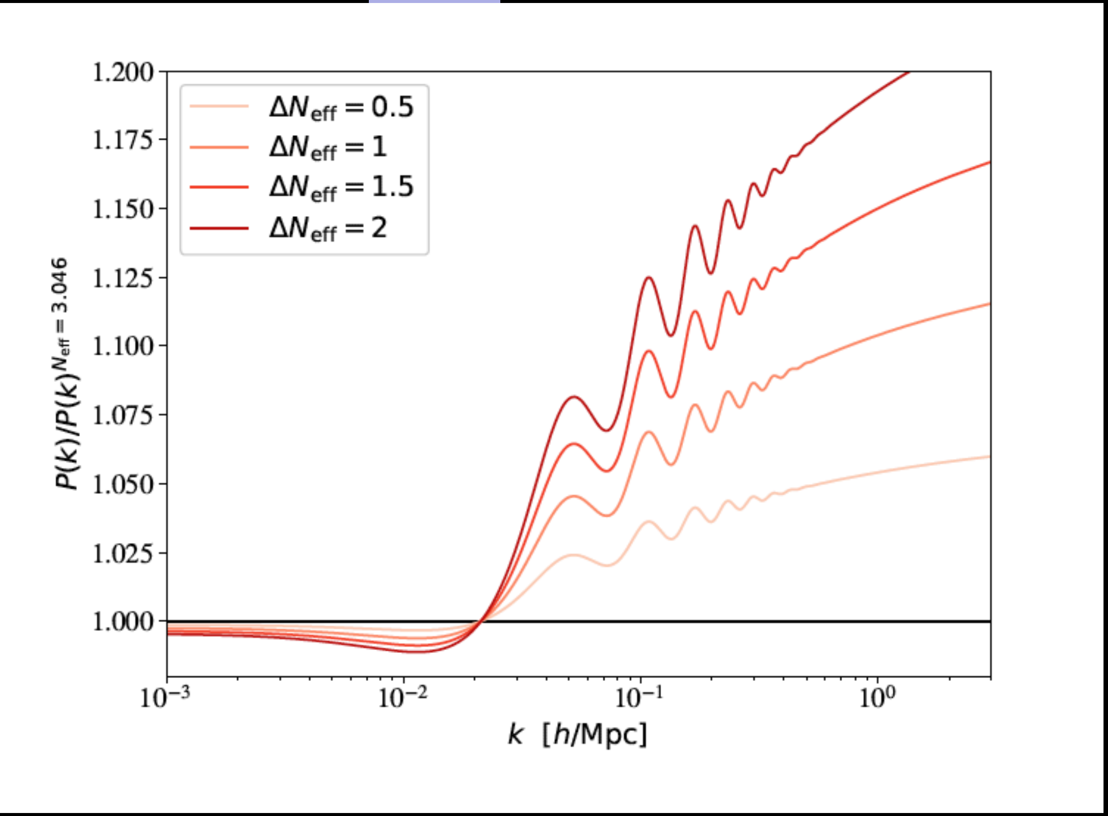


Increase Silk damping

Neutrinos, Neff: Physical effects

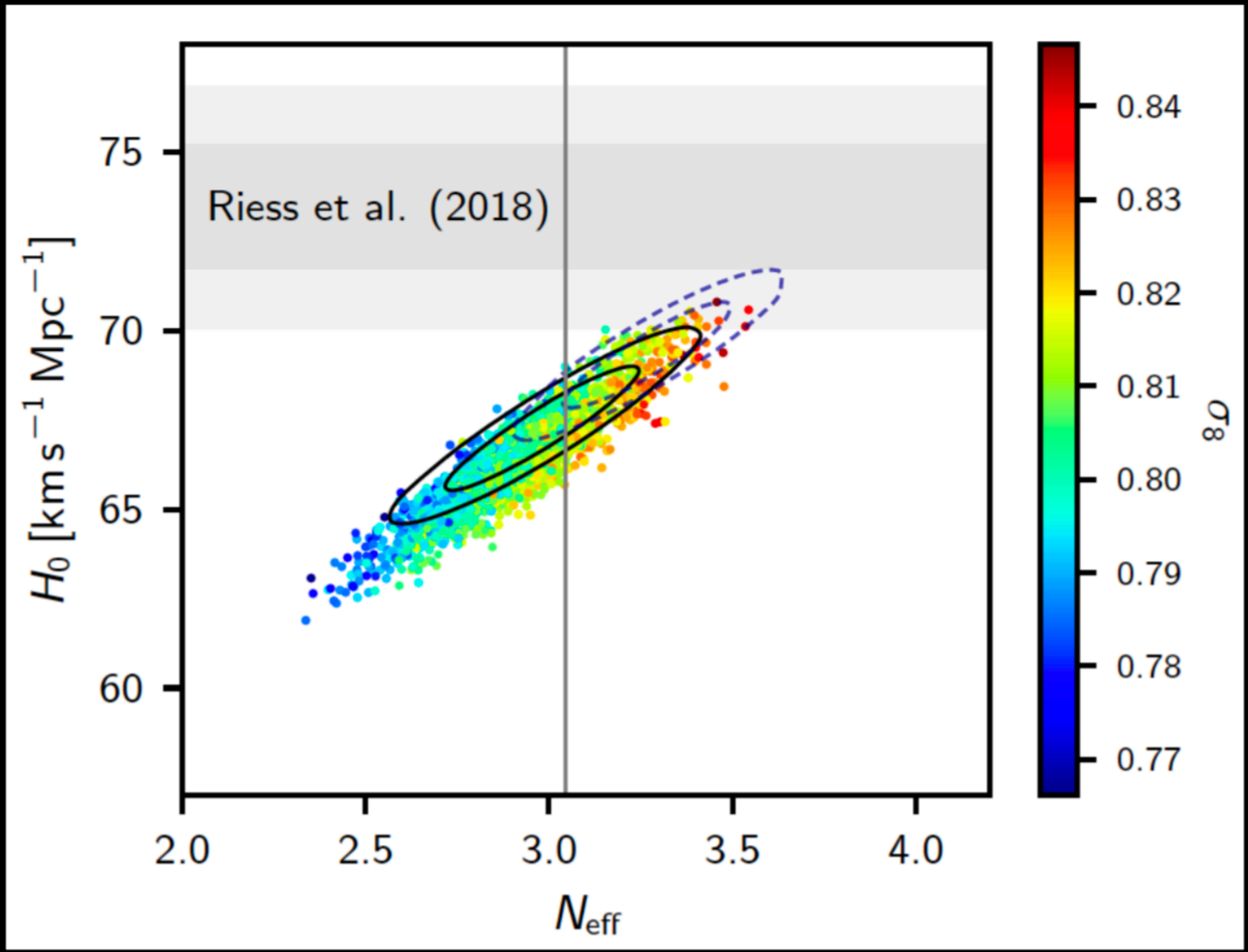
Keep zeq fixed (and matter to Λ fixed, and wb) so play with Neff and H0

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



Neutrinos, Neff: Physical effects

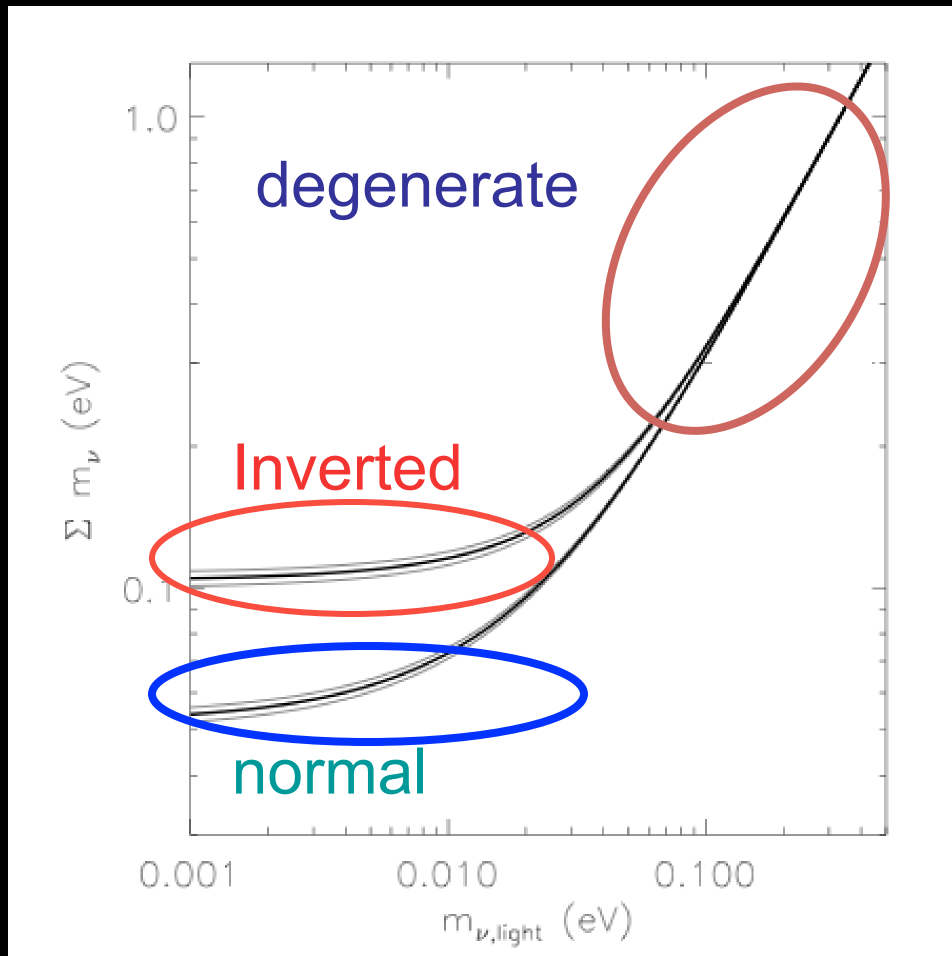
Planck 2018 has spoken



$$N_{\rm eff} = 2.92^{+0.36}_{-0.37} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

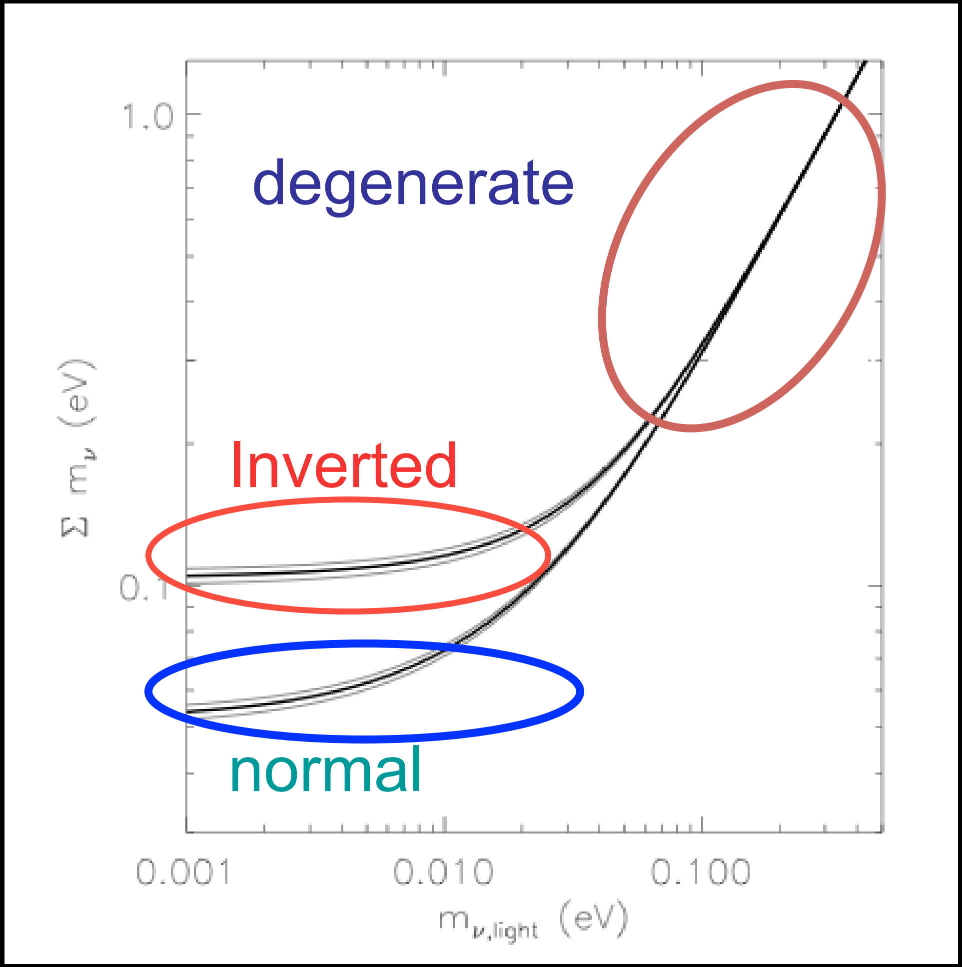
*

Cosmology is key in determining the absolute mass scale



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

Cosmology is key in determining the absolute mass scale



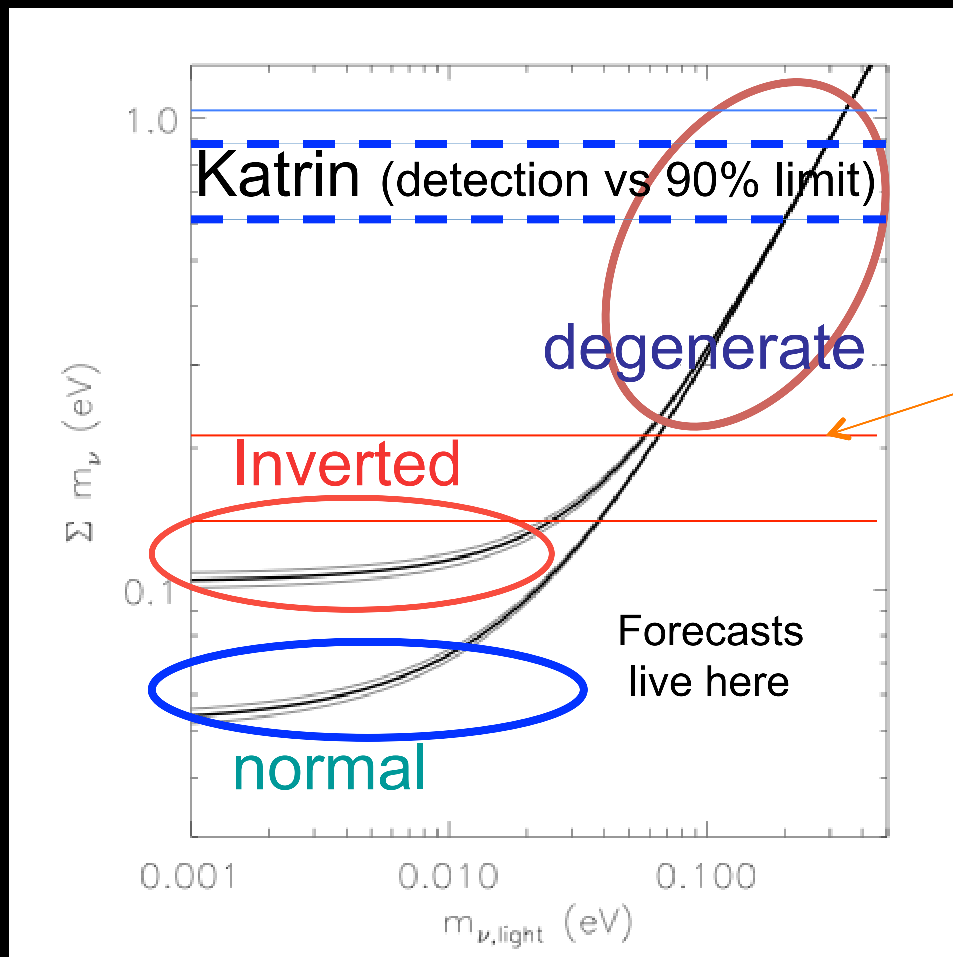
The challenge is systematic errors

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



Katrin limit (Aker et al Sept '19)

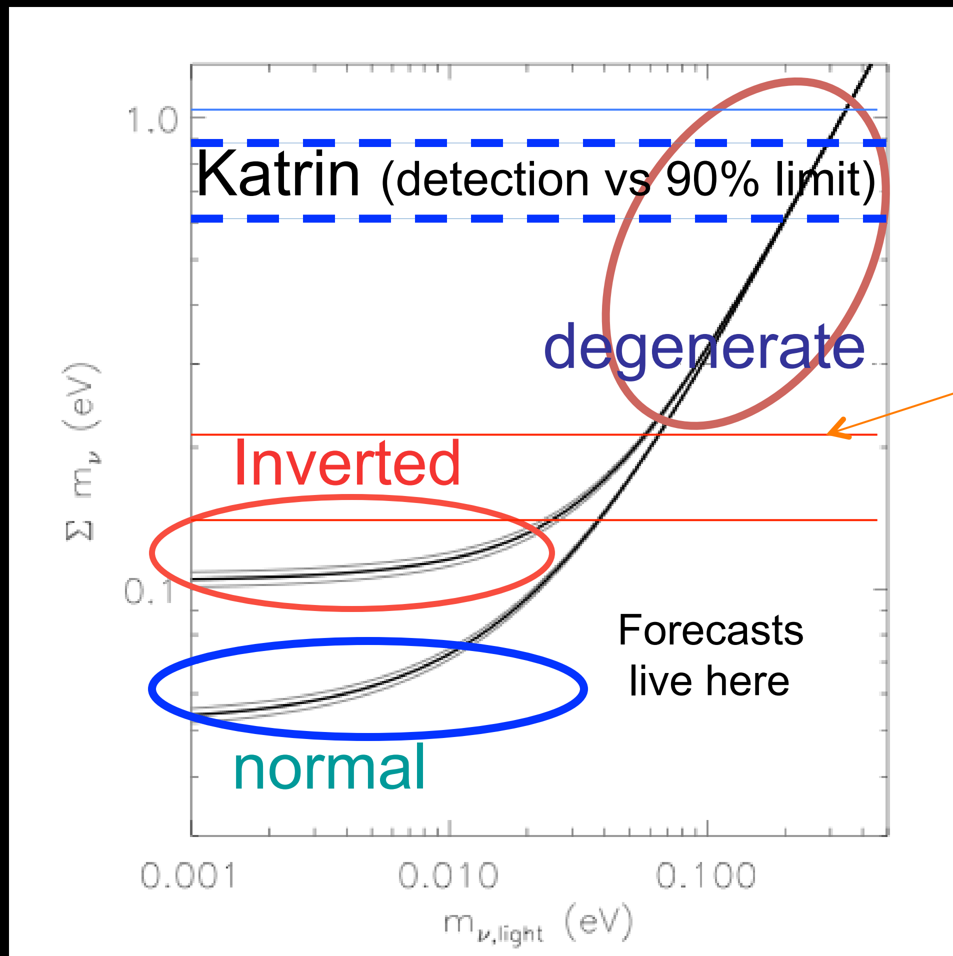
forecasted

CMB(Planck) +BAO
95% limit

2018+ lensing +BAO+pol

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

Cosmology is key in determining the absolute mass scale



Katrin limit (Aker et al Sept ‘19)

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CMB(Planck) +BAO
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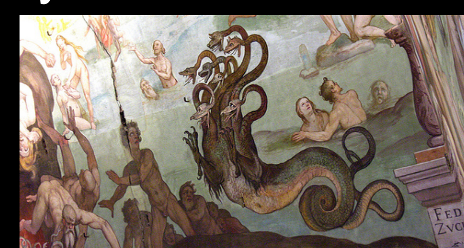
The problem is
systematic errors



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

Beware of systematics!!!!!

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

Neutrino mass: Physical effects

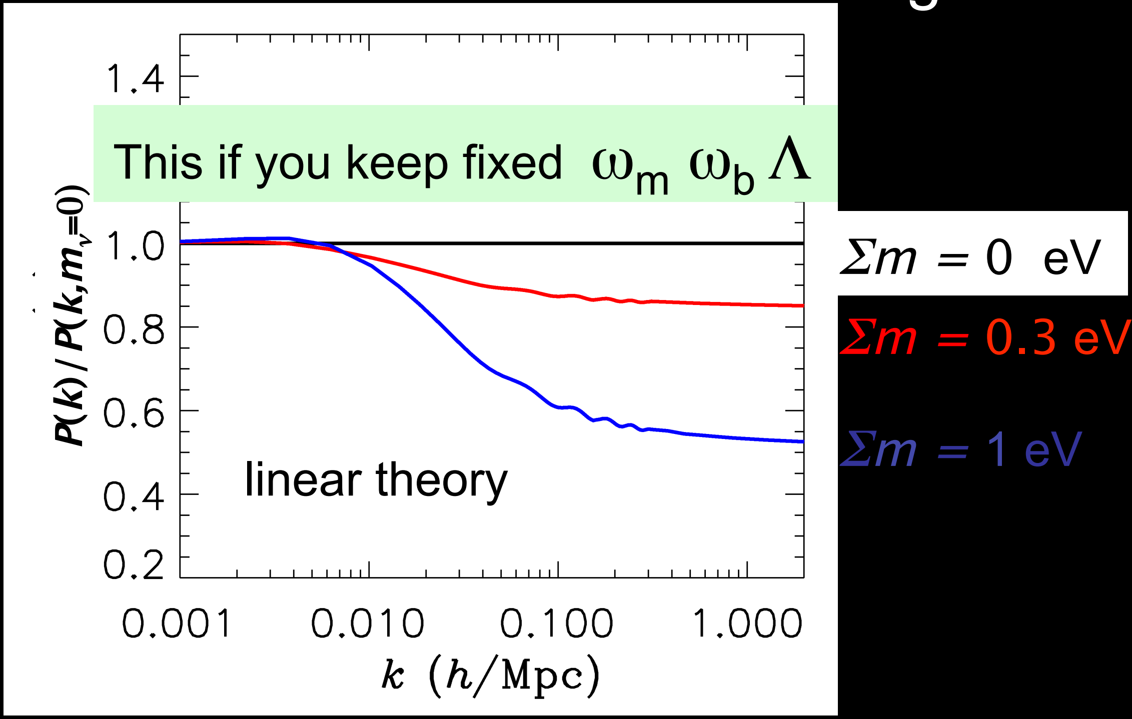
Total mass >~1 eV become non relativistic before recombination CMB

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**

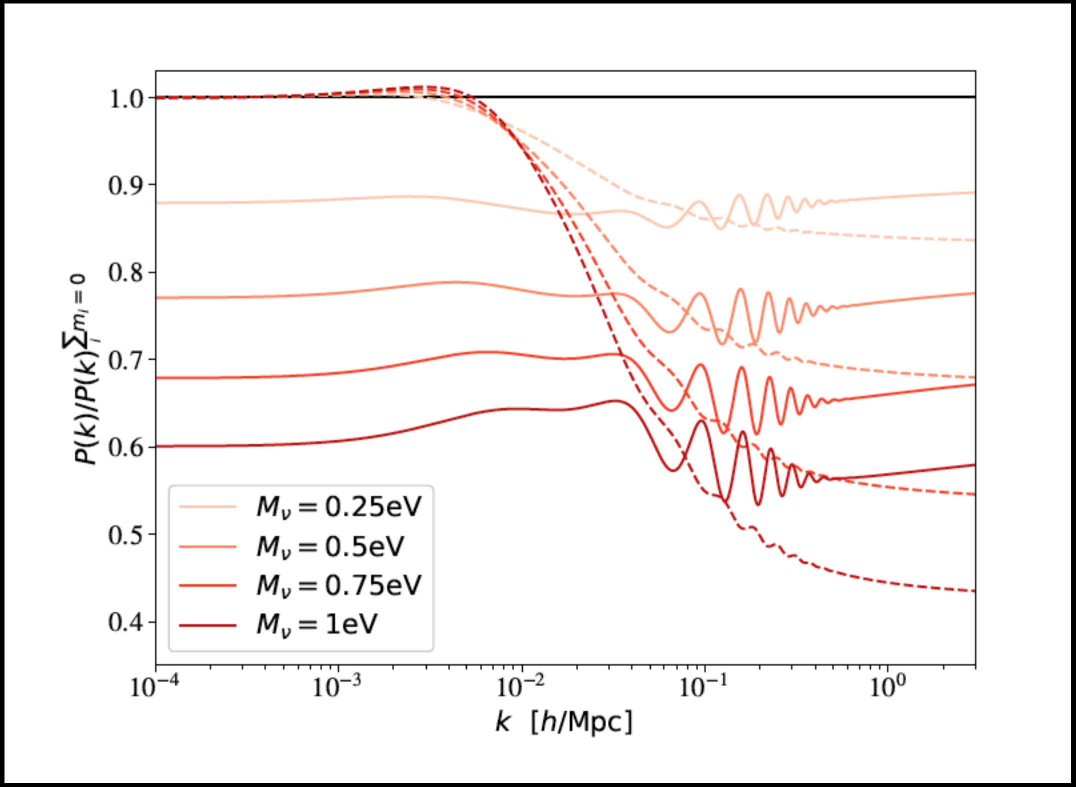
Neutrino mass: Physical effects

Move along CMB parameters degeneracy

H0 is everywhere!

keep fixed ω_c $\omega_{b,}$ θ_s

i.e. play with h …



Suppression

BAO

(exp.history)

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

Including large-scale structure clustering

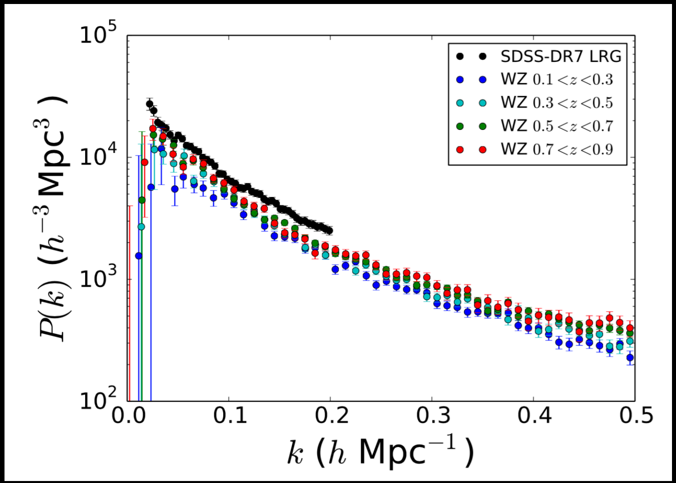
Pros: see the "signature" scale-dependent clustering suppression

Cons: astrophysics, bias,non-linearities

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

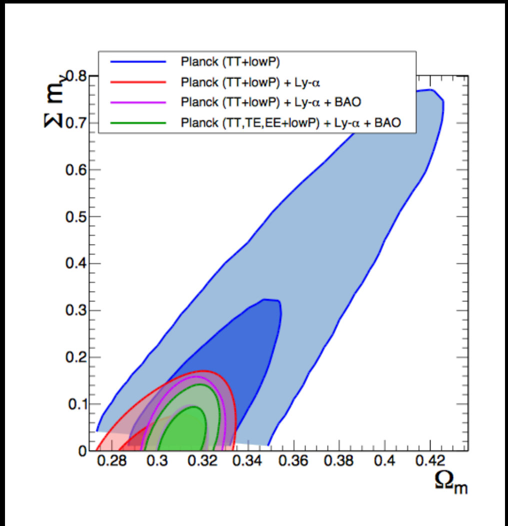
Cuesta, Niro, LV, 2016
Neutrino mass limits: robust information from the power spectrum of galaxy surveys

Use galaxy clustering (red and blue galaxies)



Ly α from BOSS survey

Palanque-Delabrouille et al. 2015



Limits on the sum of the masses

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

Robust to choice of galaxies

0.11 eV (eBOSS hot off the press)

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

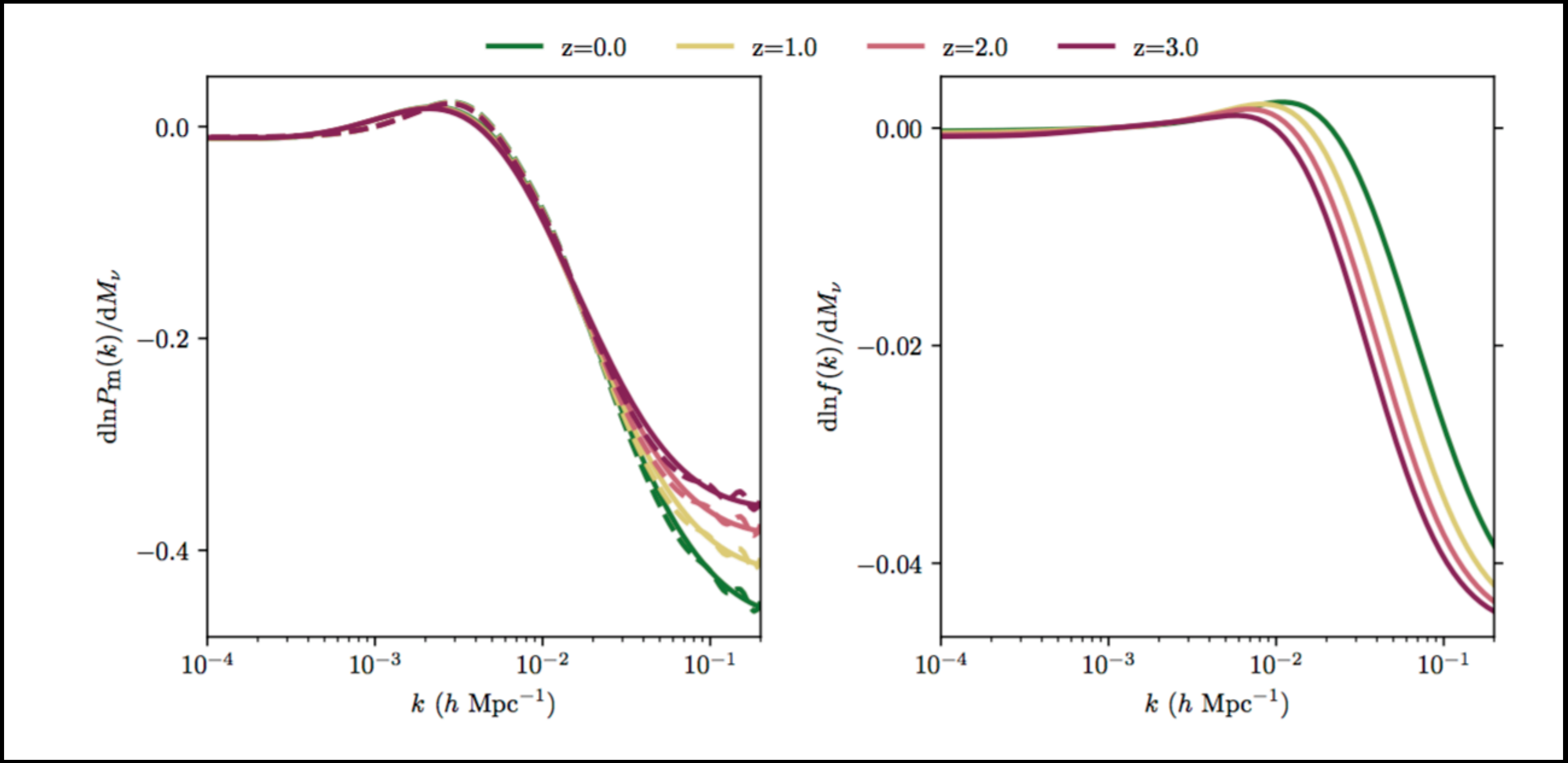
Competitive with CMB+BAO+Lyman alpha $$M_\nu < 0.12 \ \mathrm{eV} (95\%\mathrm{C.L.})$$

Planck 2018 full incl. Lensing and BAO $$M_\nu < 0.12 \ \mathrm{eV} (95\%\mathrm{C.L.})$$

Completely different tracers

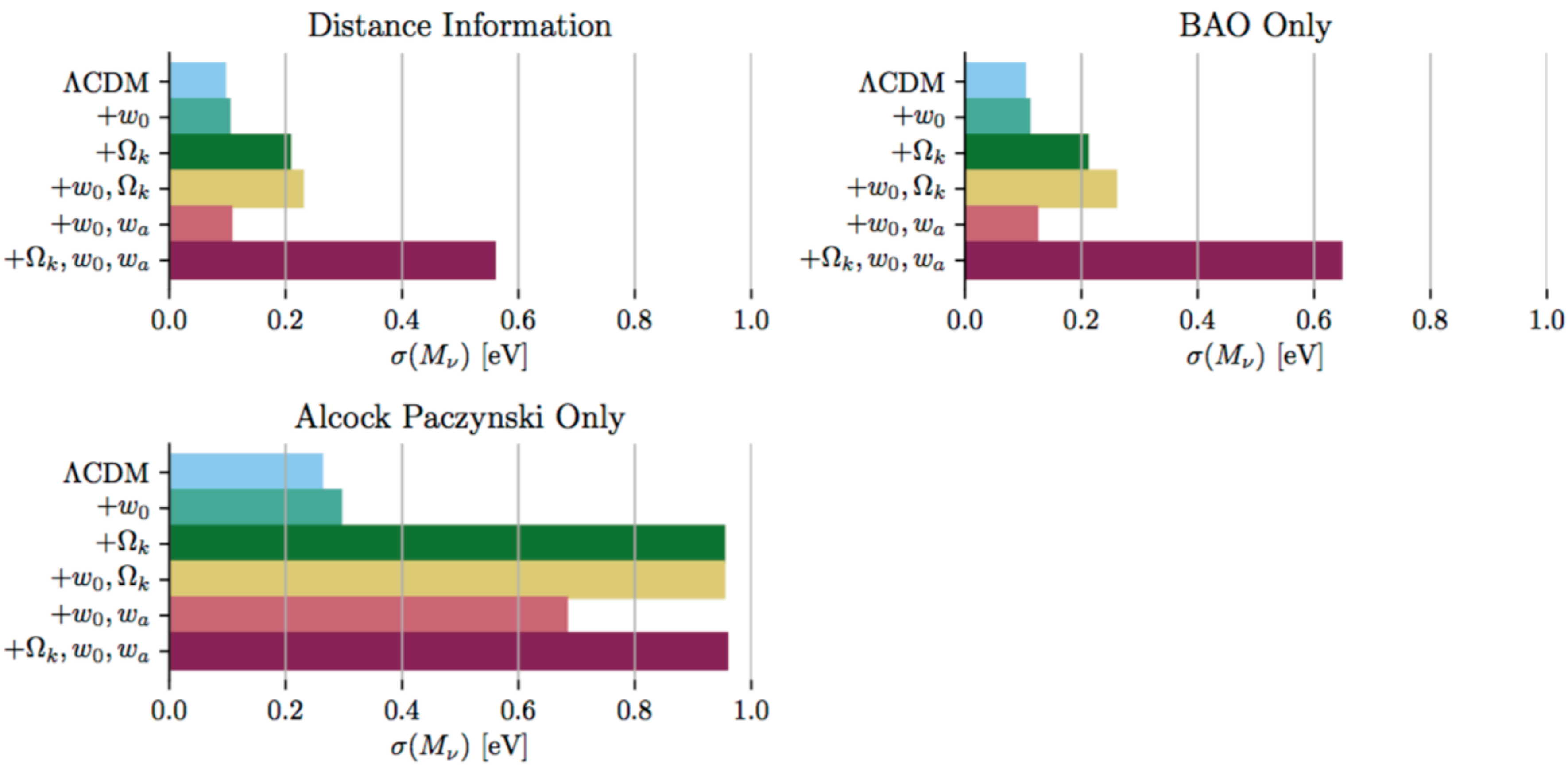
Confirmed see also other works: e.g., Giusarma et al 2016, Vagnozzi et al 2017

Expansion history vs growth



Boyle & Komatsu 2019

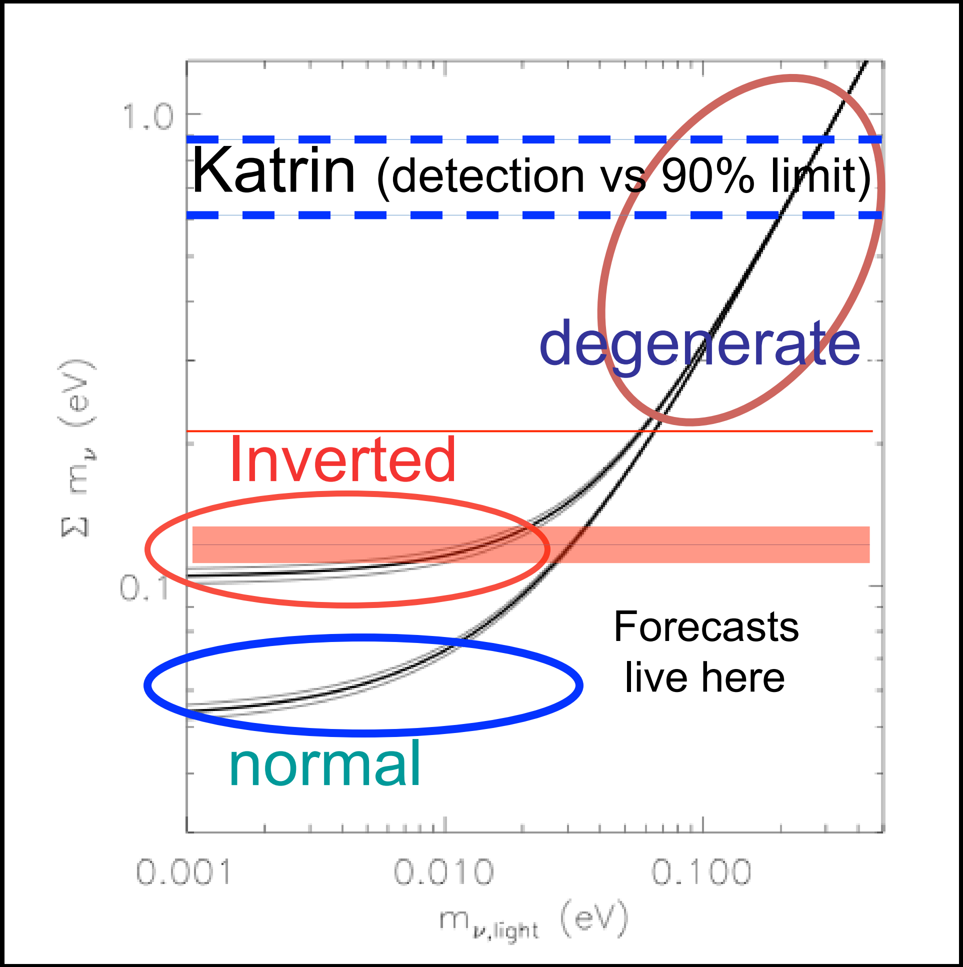
Expansion history vs growth



Forecast for Euclid

Boyle & Komatsu 2019

Neutrino mass limits

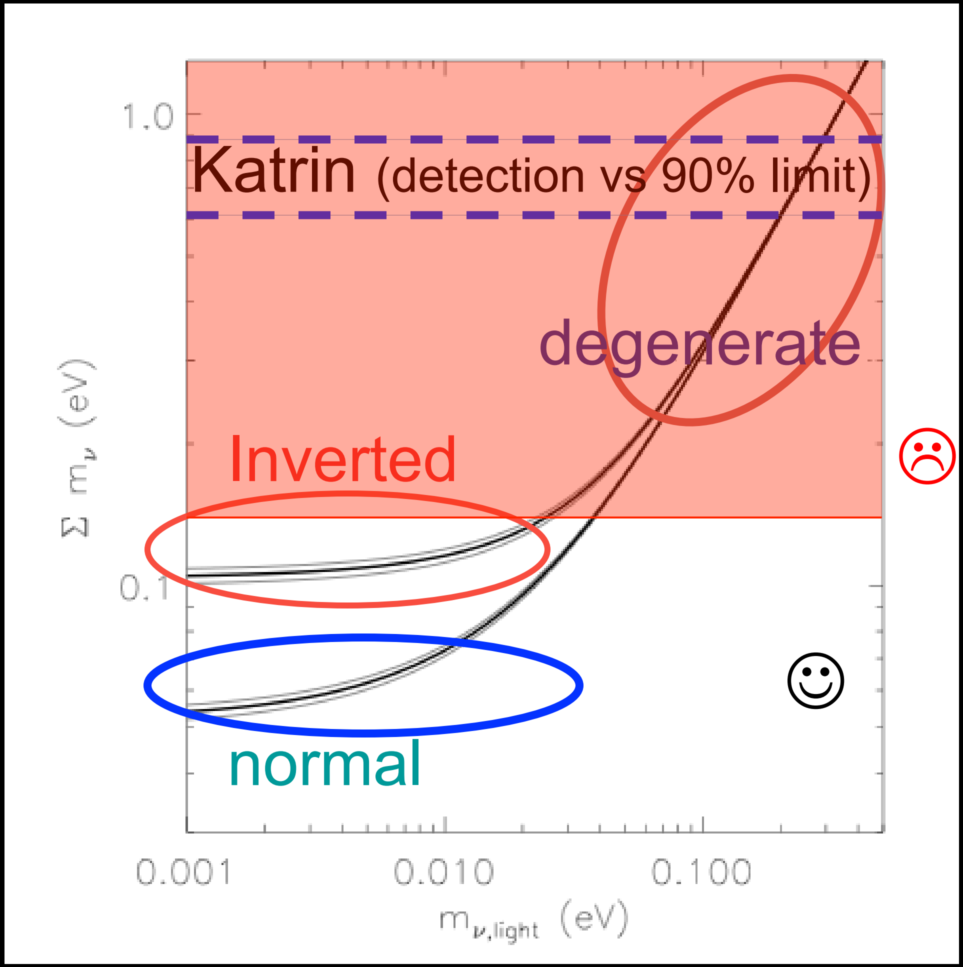


CMB(Planck) +BAO

+LSS

5% or less effects on P(k)

Implications I



If we add H0 or eBOSS 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+LSS limit 0.11 eV

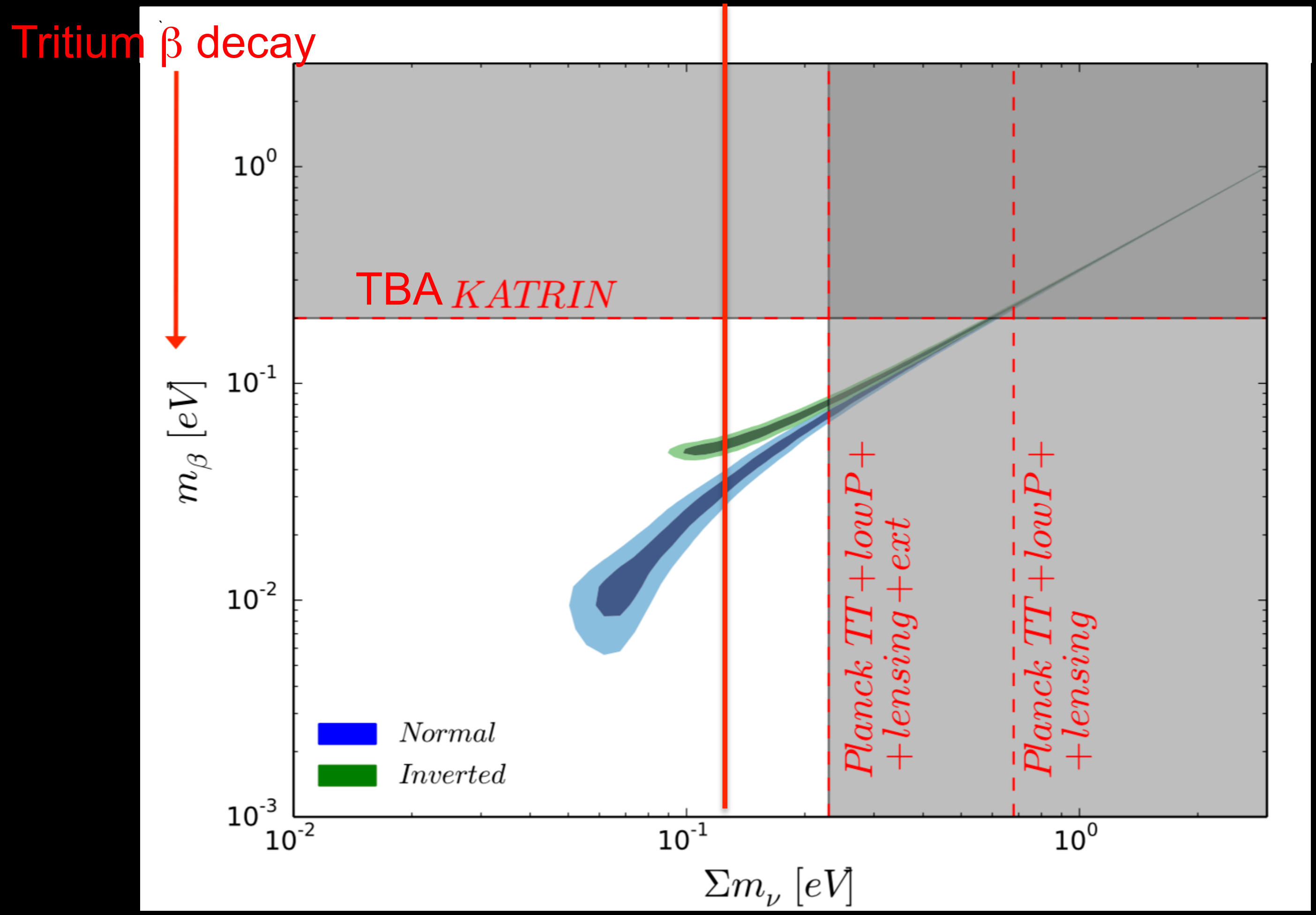


Fig. adapted*
from M. Lattanzi

* Taken from google

Implications III

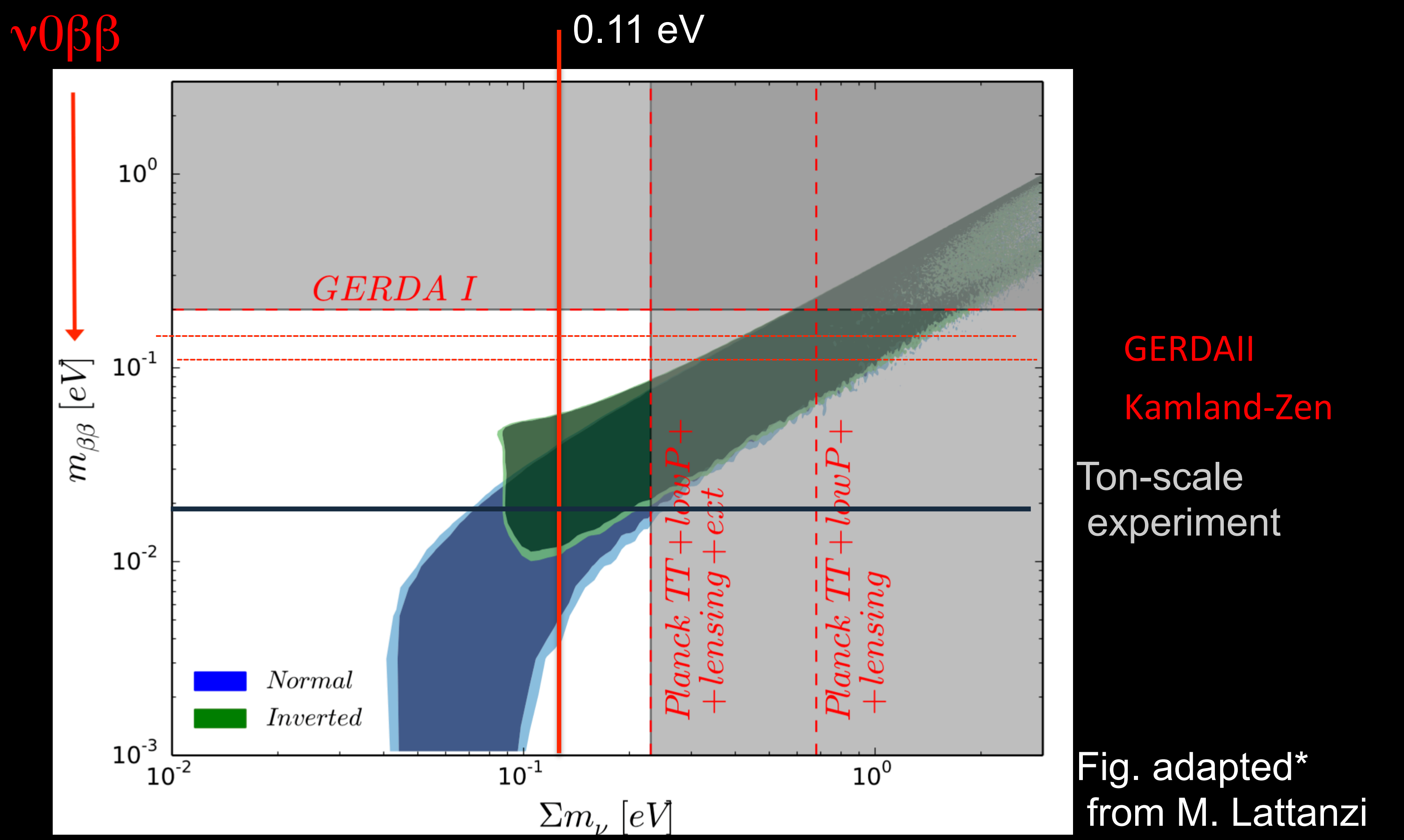


Fig. adapted* from M. Lattanzi

Of course <T ν0ββ experiments could see something, that would be interesting

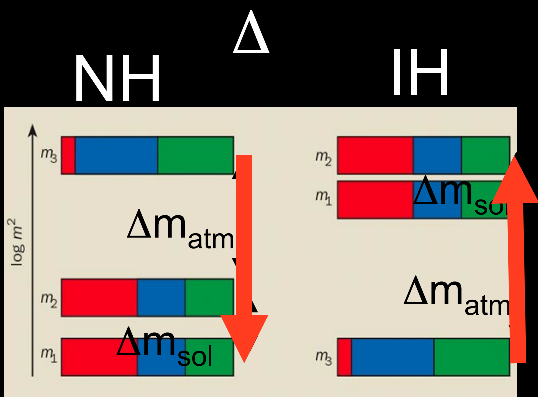
Implications: tldnr

Cosmology is key to determine neutrino masses

The pessimist: The inverted hierarchy is under pressure

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

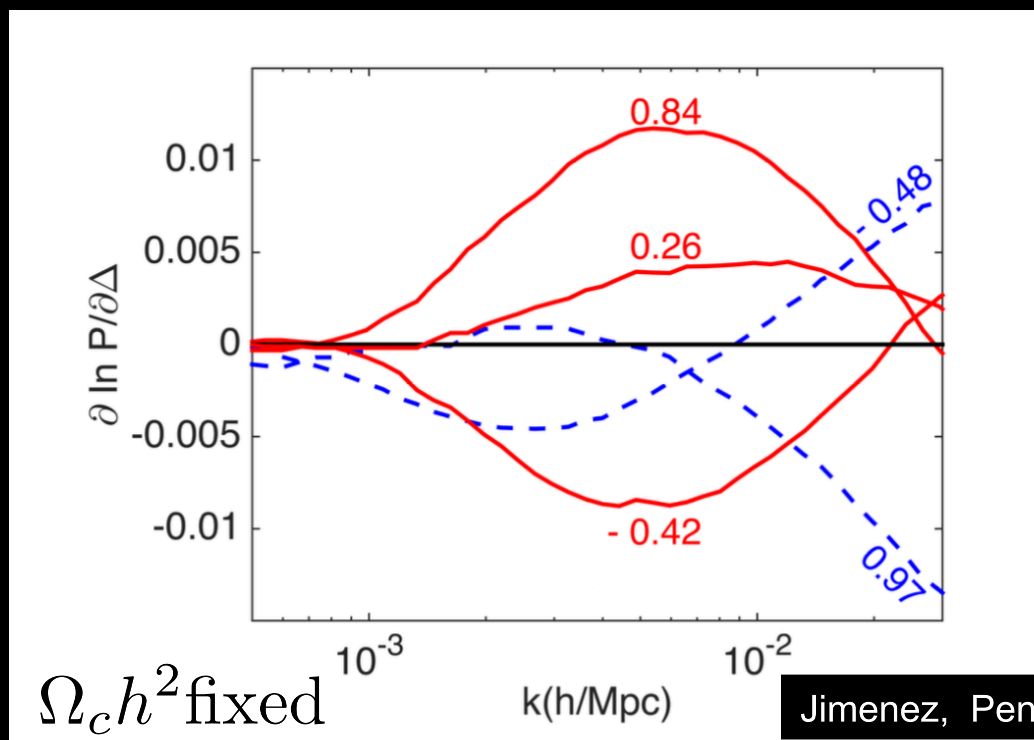
Hierarchy effect on the shape of the linear matter power spectrum



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

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



$\Sigma = 0.1eV$

$\Sigma = 0.06eV$

Jimenez, Penya-Garay, Verde, 2016

How about hierarchy?

In principle there is a signal in LSS, but it is small and at large scales

see also Archidiacomo et al 2020

Use model-selection techniques
(cosmologists do inference so tend to be Bayesian)

Simpson et al. 2017 (advocates log priors, controversial, but , I think, right)

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.

Conclusions

Cosmic neutrino background, wonderful end-to-end test (indirect)

CMB+BAO+LRG limit $M\nu < 0.11$ eV

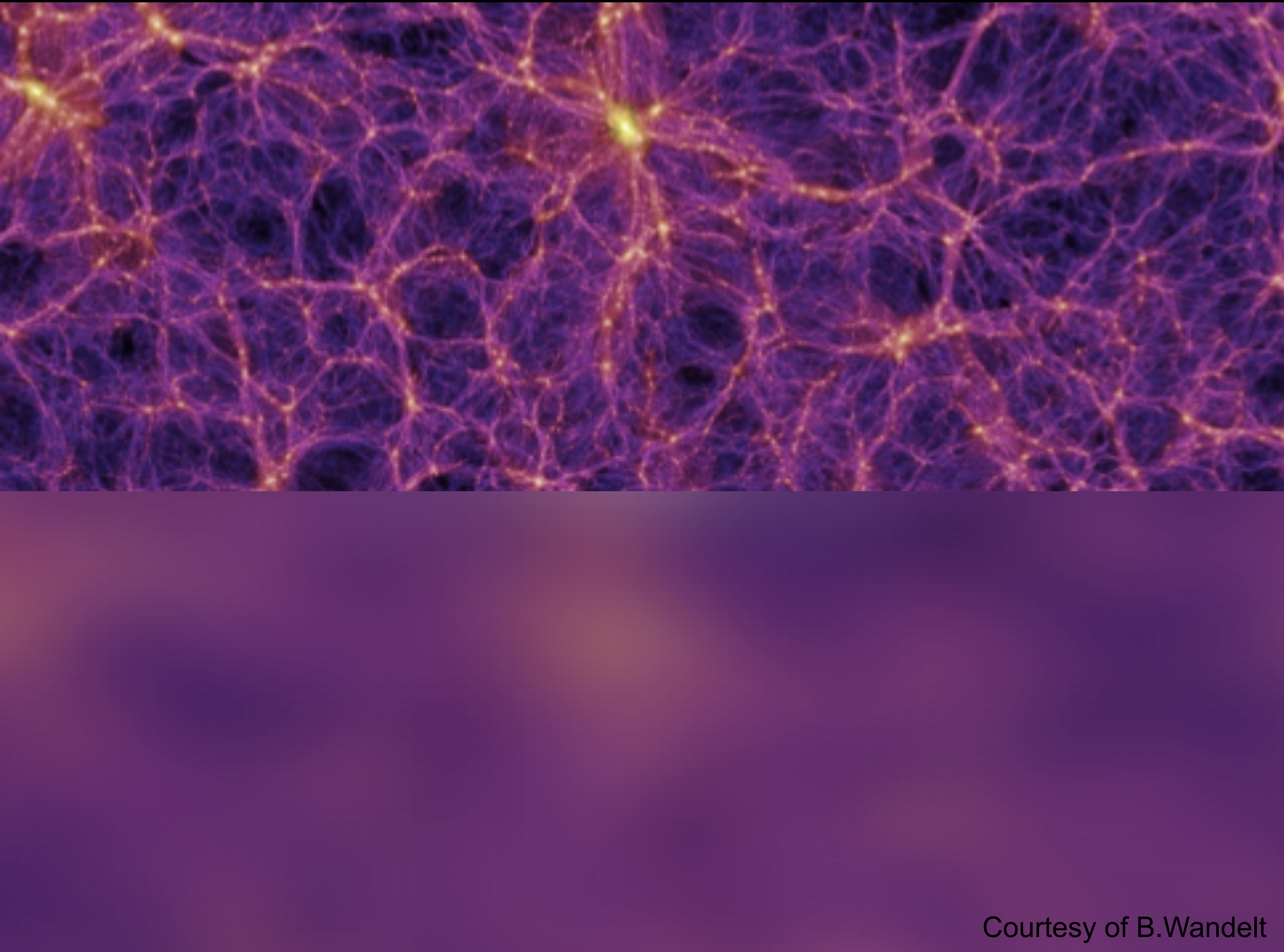
The pessimist: The inverted hierarchy is under pressure

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

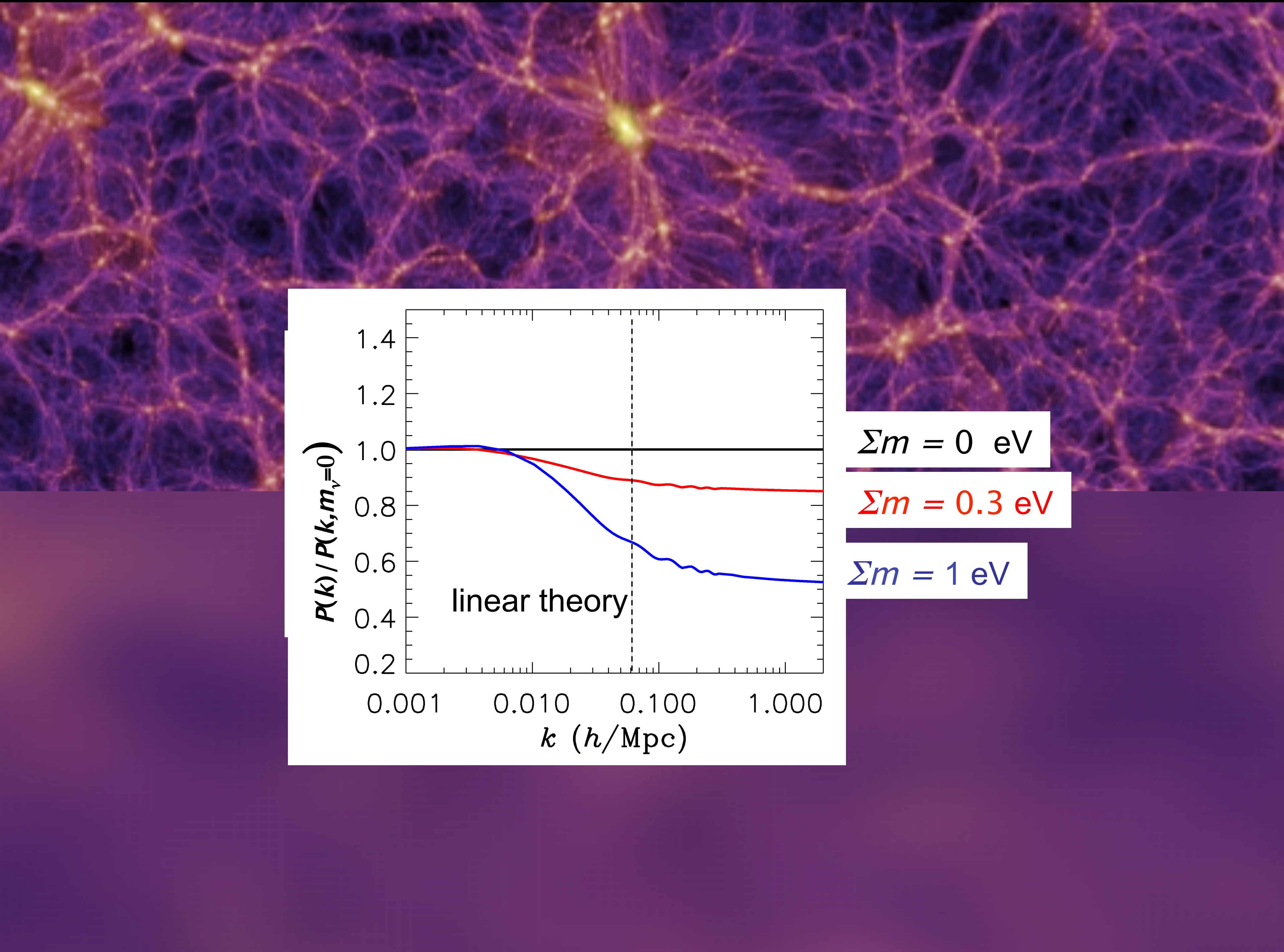
IH under pressure, but how much depends on choice of priors

Cosmology is the key to determine neutrino mass scale
It's challenging: galaxies can be messy, but it's what we've got.
Model dependent statement.
However, a wonderful end-to-end test.

Back up slides



Courtesy of B.Wandelt

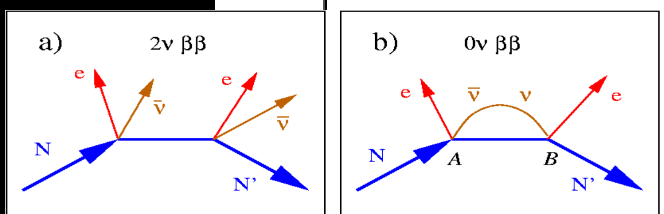


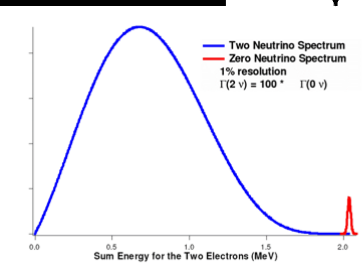
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$P(k)/P(k,m_\nu=0)$
linear theory
0.001
0.010
0.100
1.000
$k\ (h/\mathrm{Mpc})$
$\Sigma m = 0$ eV
$\Sigma m = 0.3$ eV
$\Sigma m = 1$ eV

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

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

Yes

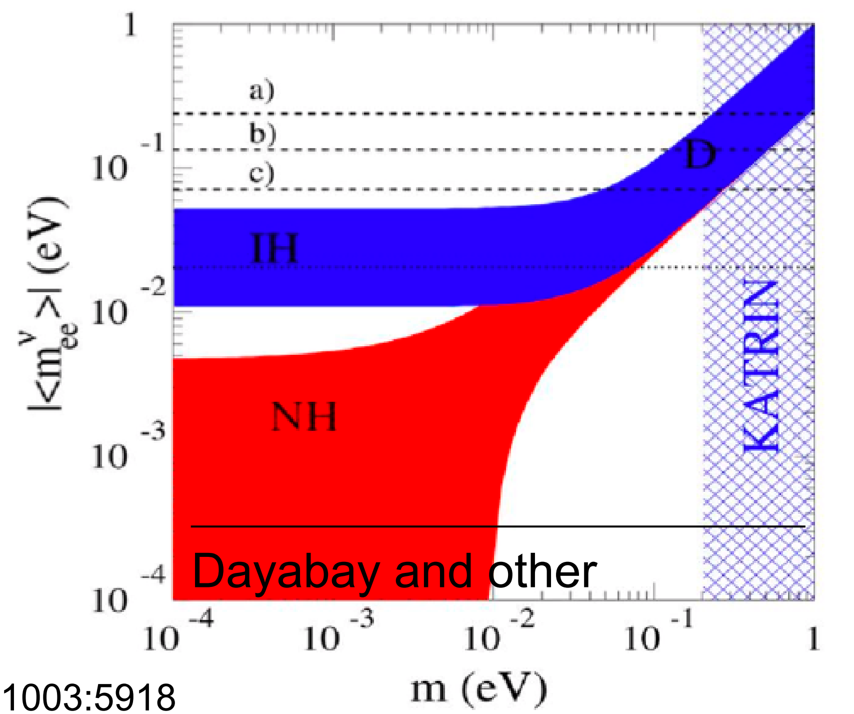




Majorana

No

Because Dirac OR
because below threshold (still unknown)?



[redacted]ay, Verde, arXiv:1003:5918

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

Better calculation: Hierarchical Model

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

Use oscillations measurements + cosmological limits (assume Gaussian likelihood)

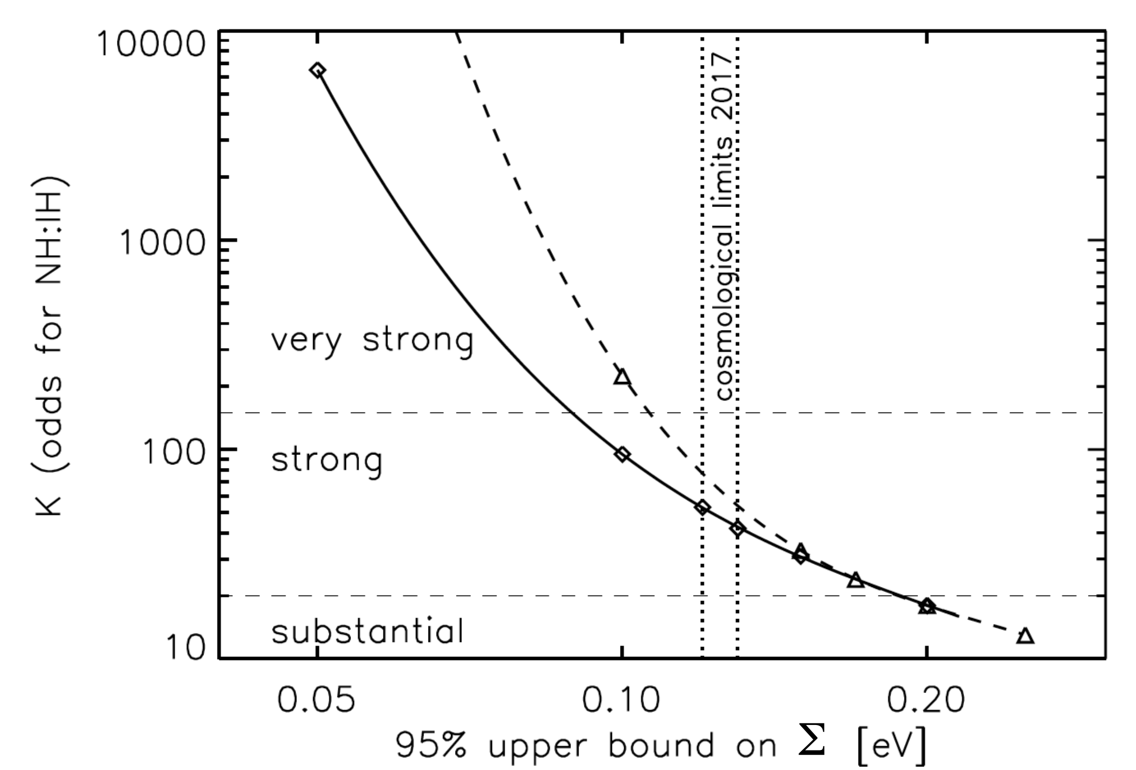
Then marginalize over μ, σ

Compute Evidence

Evidence (Jeffrey's scale modified)

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

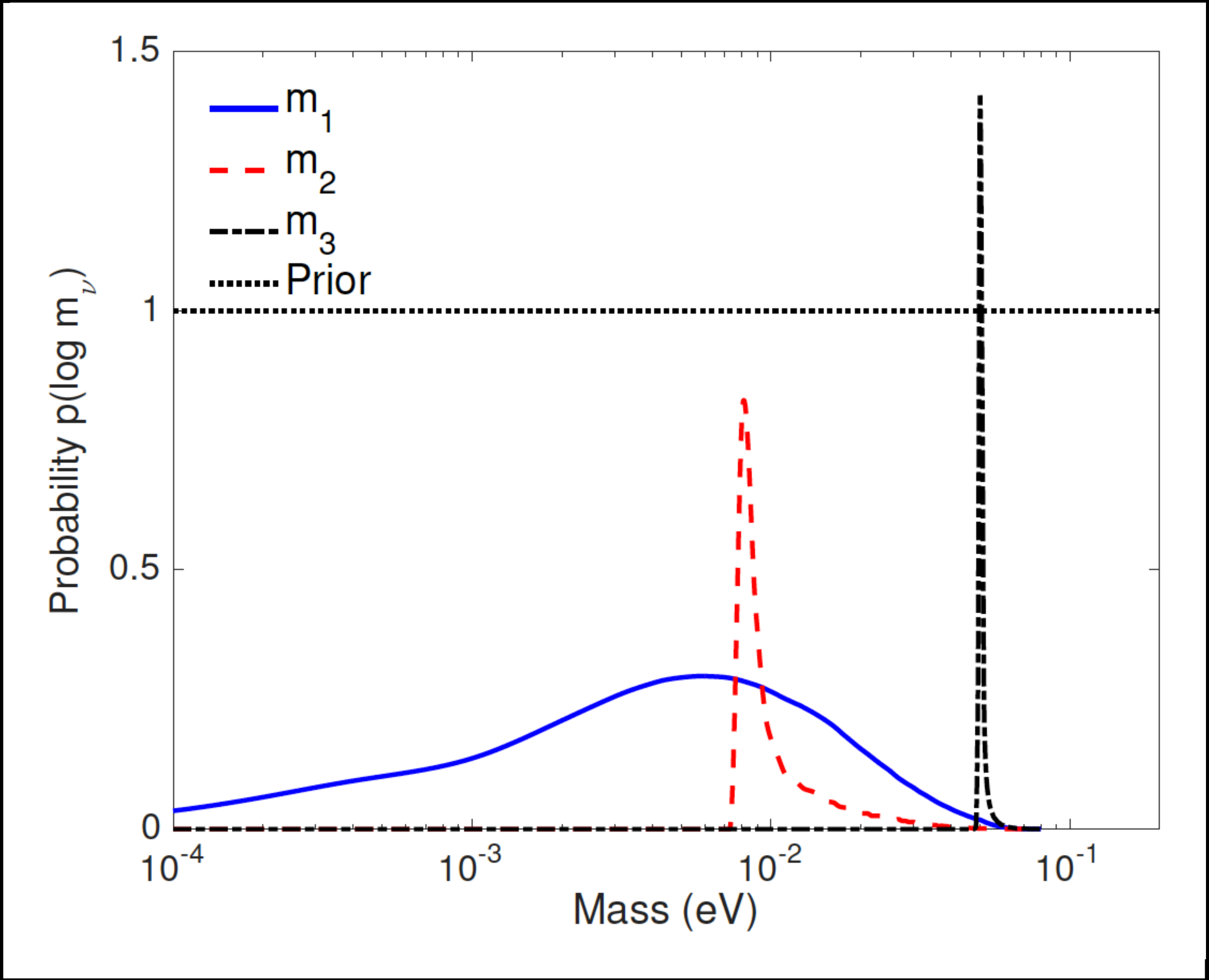
@0



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

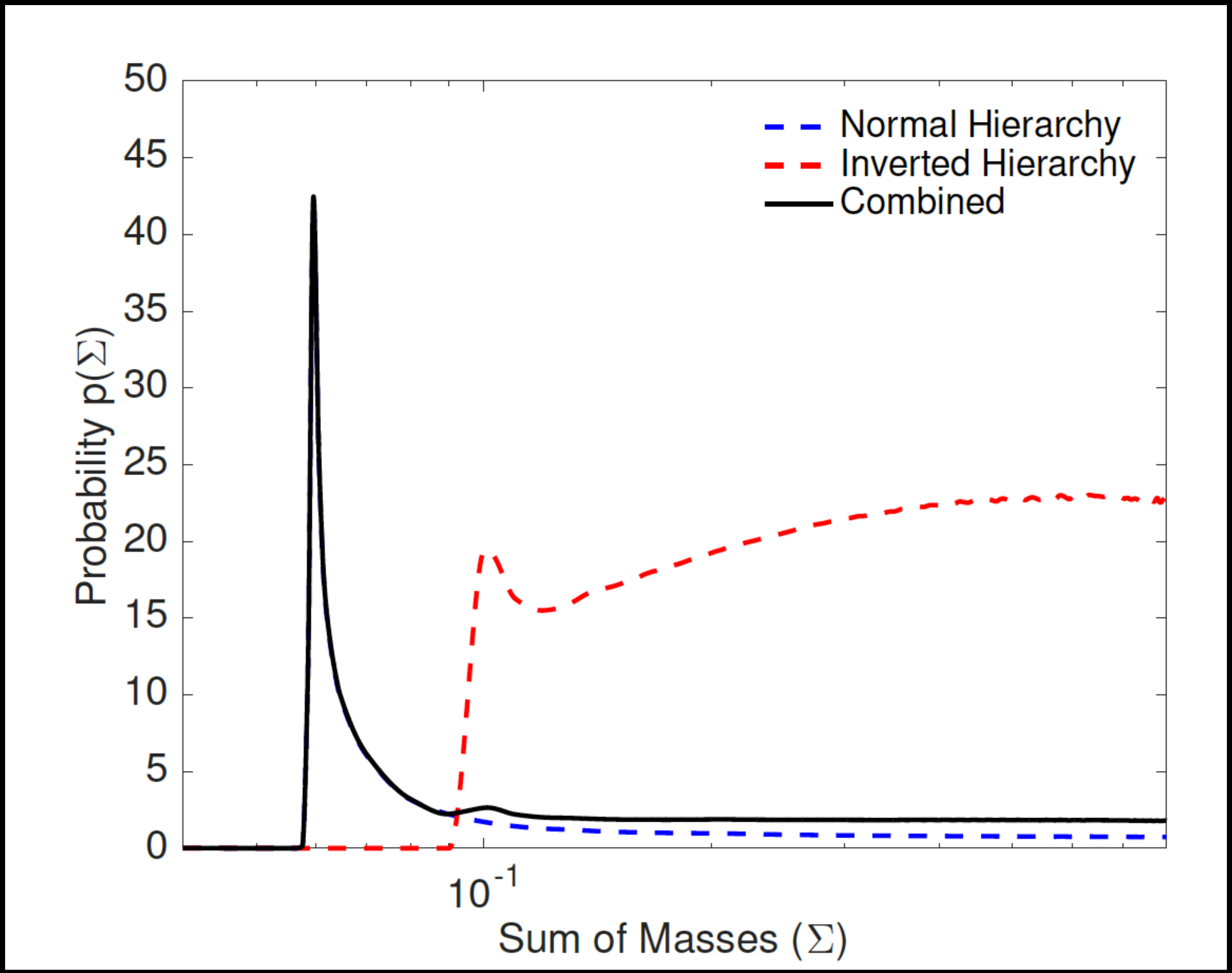
@0.05eV

Posteriors for the masses, NH



Σ<0.12eV

Posterior for the sum of the masses…



Without cosmological information

Normalization rescaled for clarity