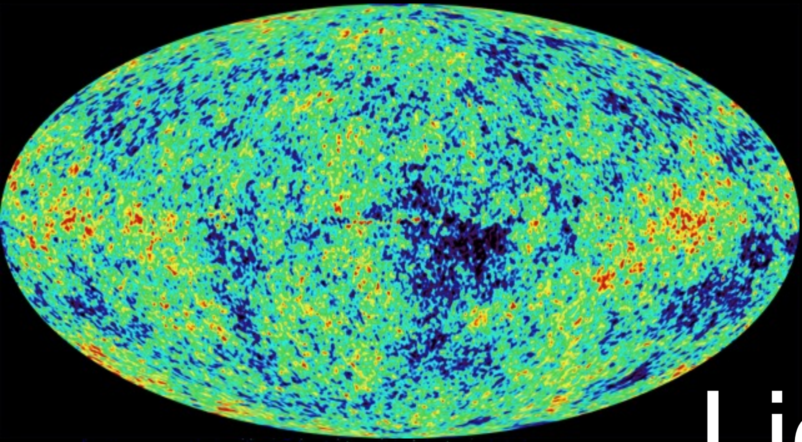
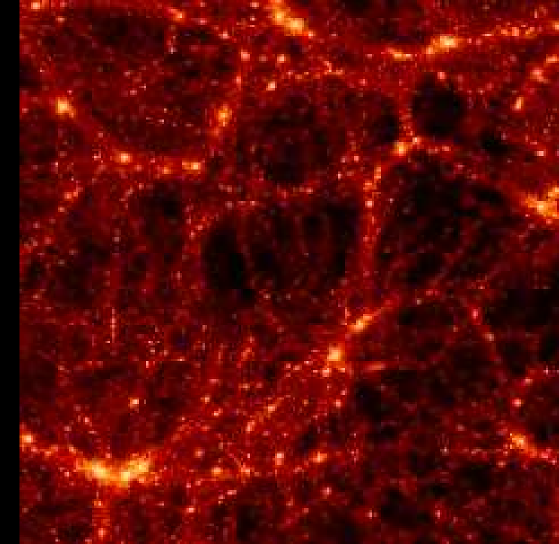
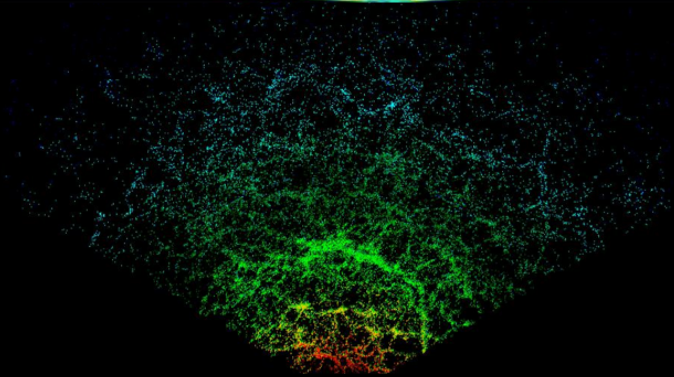


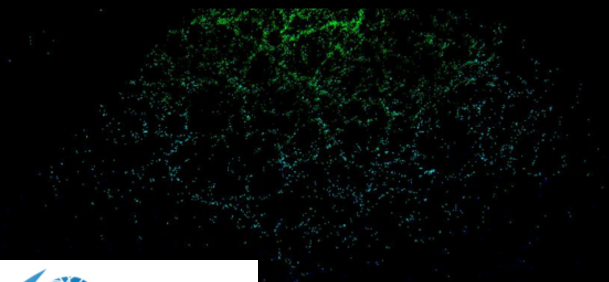


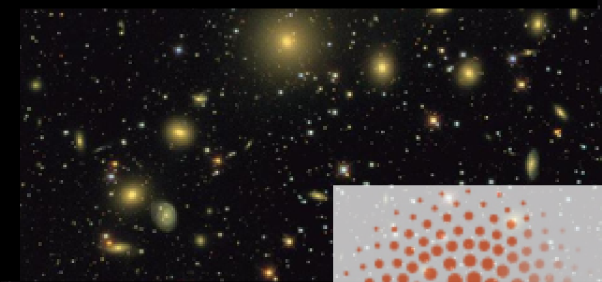
Licia Verde

ICREA & ICC-UB-IEEC
Barcelona, Spain



Neutrino properties from cosmology





icc.ub.edu.liciaverde

A possible reference point

Particle data group, Neutrinos in Cosmology, Lesgourgues & Verde Chapter 26

https://pdg.lbl.gov/2022/reviews/astro-cosmo.html

(fully updated every 2 years, revised every year*)

What is a neutrino? (for cosmology)

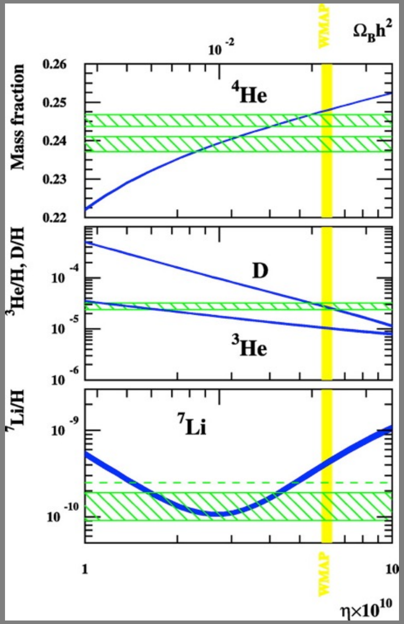
- Behaves like radiation at T~ eV (recombination/decoupling)
- Eventually (possibly) becomes non-relativistic, behaves like matter
- Small interactions (not perfect fluid)
- Has a high velocity dispersion (is “HOT”)

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.

Relict neutrinos influence in cosmology

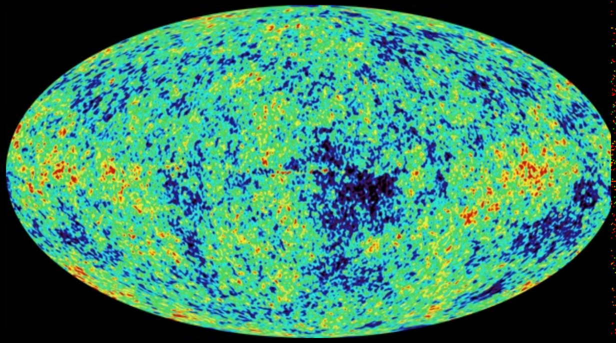
Primordial nucleosynthesis



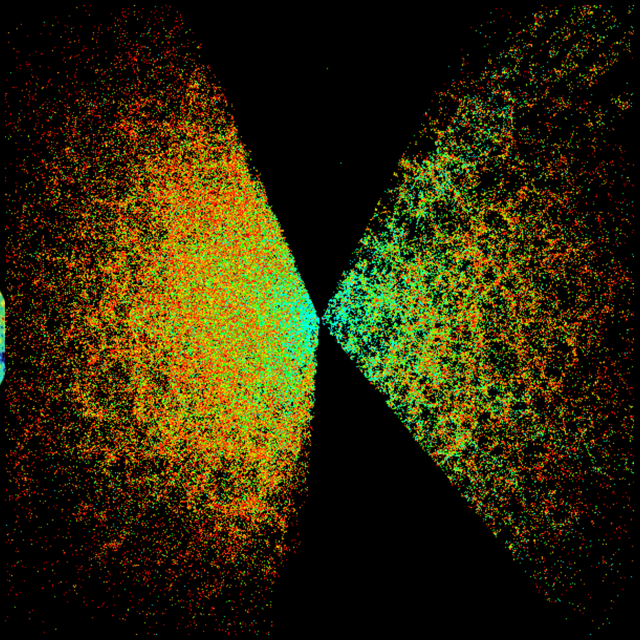
T~ MeV

N_{eff} *changes neutron freezeout and hence Y_{He} & Y_D*

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)

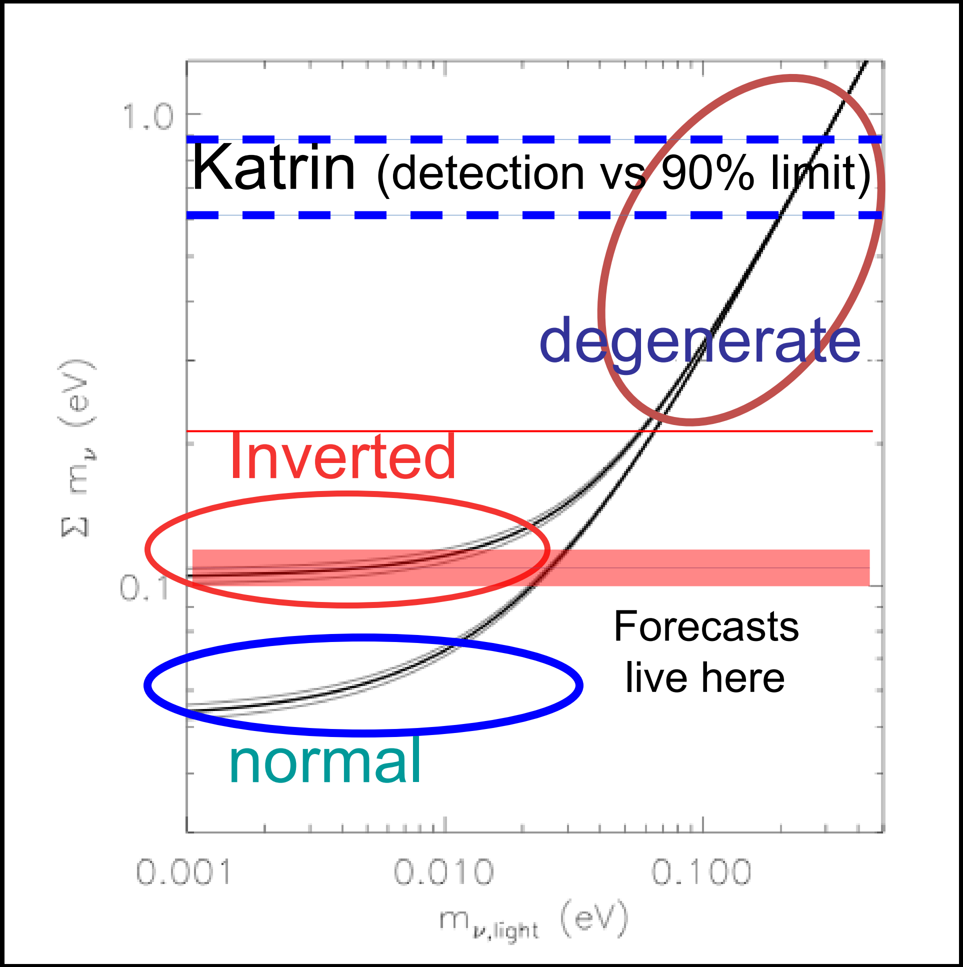
Mostly model-dependent statements: measuring cosmological parameters values**

Implications: tldnr

Cosmology is key to determine neutrino masses

!

Neutrino mass limits



CMB(Planck) +BAO

+LSS

5% or less effects on P(k)

recap

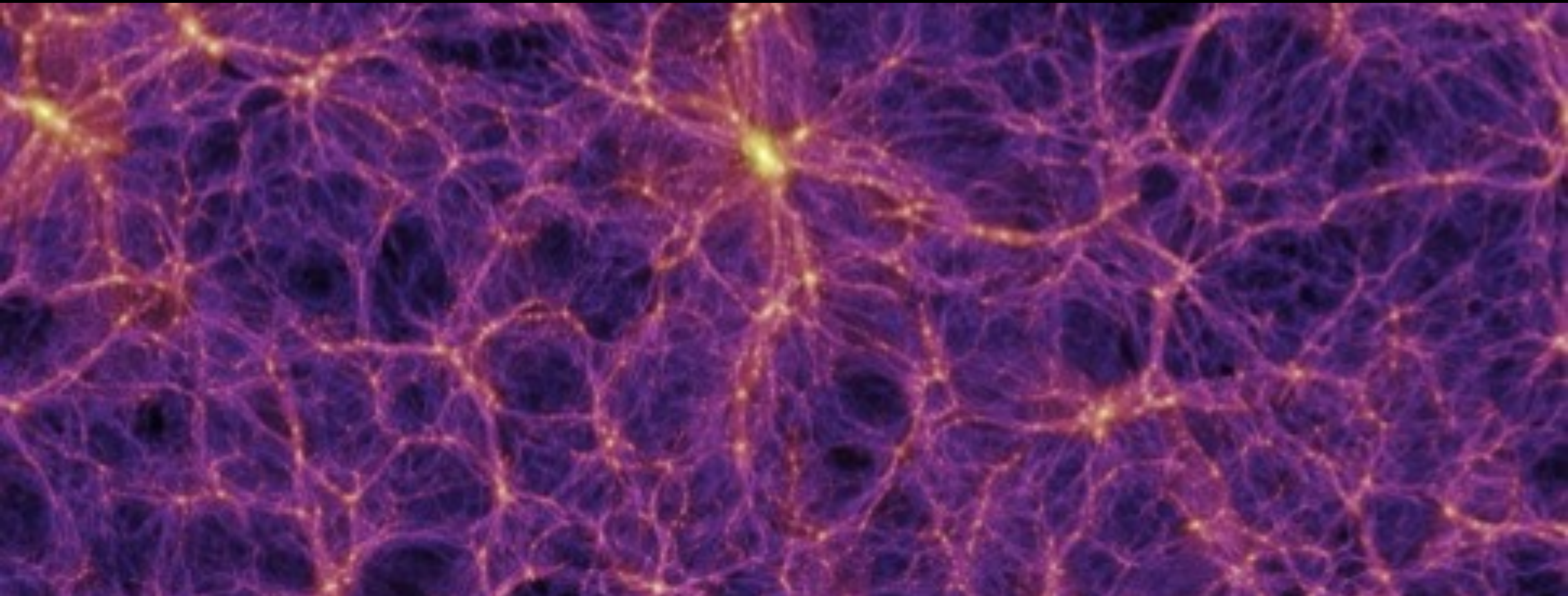
- There is a CνB
- Cosmology places stringent limits on Σm_ν
- If IH then a measurement is around the corner
- However, IH is under pressure from a Bayesian perspective
- This has important implications
- What if KATRIN measures something?

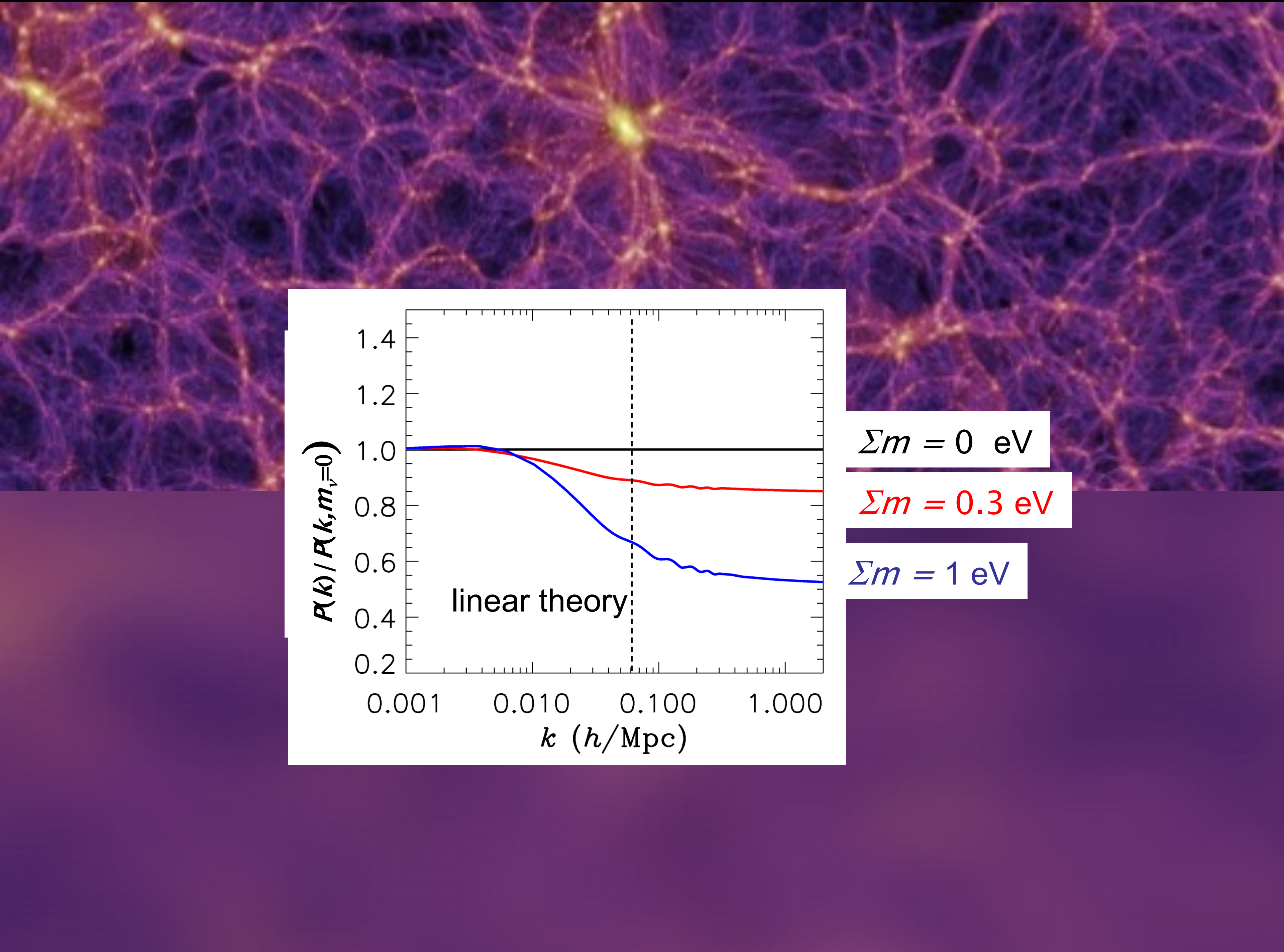
Boltzmann codes....

- Like CLASS or CAMB have all this (and more in)
- Mostly linear predictions
- They are also shipped with MCMC's "engines"
- And a suite of data with errors and covariances
- And appropriate likelihoods..... (and non-linear corrections)
- ....to do parameter constraints

What about non-linearities?

!





1.4
1.2
1.0
0.8
0.6
0.4
0.2
P(k) / P(k,m_ν=0)
linear theory
0.001
0.010
0.100
1.000
k (h/Mpc)
Σm = 0 eV
Σm = 0.3 eV
Σm = 1 eV

What about non-linearities?

Approaches: Analytic i.e. Perturbation theory

N-body Simulations

Intermediate:

Emulators

Simulate just neutrino masses

Use particles

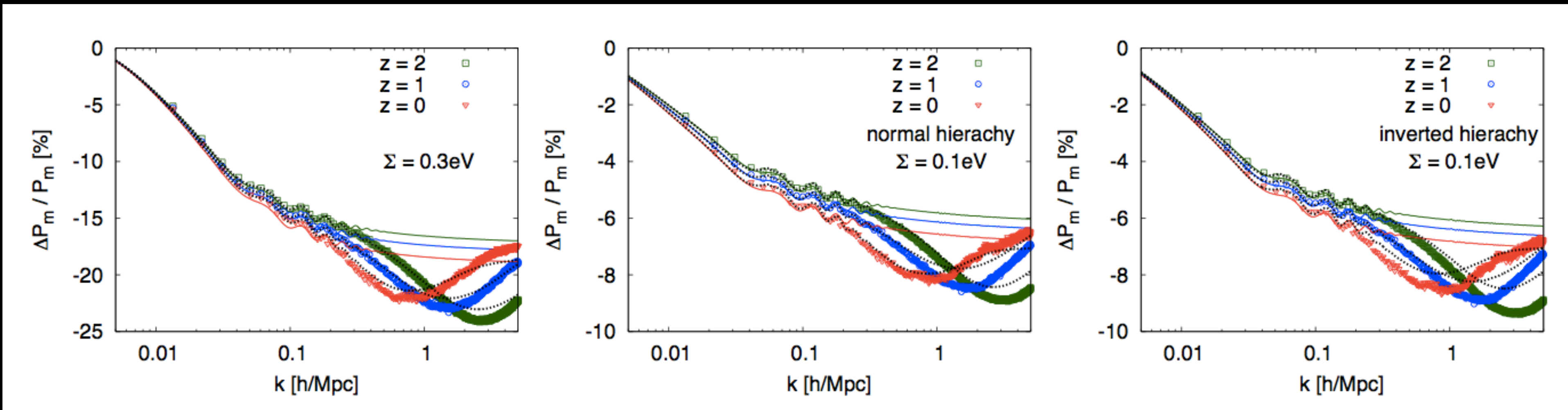
Use grids

Use hybrid

Simulate also hierarchy

Neutrinos effect on the matter P(k)

Σ (total mass)

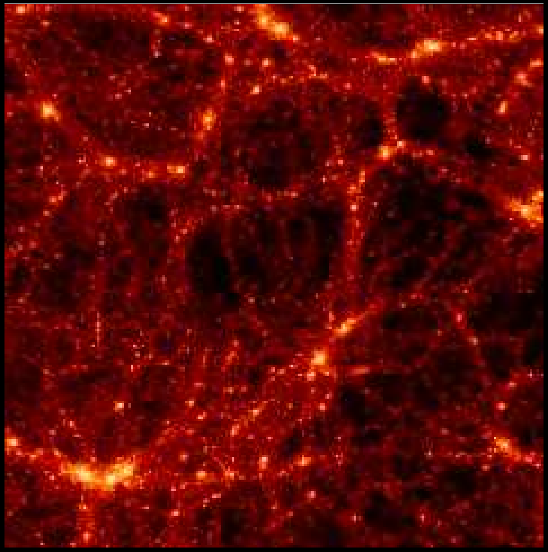


Note that non-linearities enhance the signal

This is for MATTER in real space

What about real world effects?

- Baryonic physics (lensing and galaxy surveys)
- Bias (galaxy surveys)
- redshift space (galaxy surveys)



Redundancy is the key

Neff

- Cosmic Microwave Background experiments have detected a “dark radiation” (relativistic species which are not photons) with the right abundance to be neutrinos decoupled from the early Universe.
- We want to test if other properties of that fluid are also consistent with neutrinos.
- We want to test that the consistency is robust e.g., against changes in the cosmological parameters.

How many neutrinos?

- Cosmology is sensitive to Neff primarily because energy density in relativistic particles affects directly the universe's expansion rate during the radiation domination era
- True for any thermal background of light particles such as axions and axion-like particles, hidden sector photons, majorons, or even gravitons
- Likewise, any process that alters the thermal abundance of neutrinos (e.g., a low reheating temperature) or affects directly the expansion rate itself (e.g., a time-dependent G) can mimic a non-standard Neff.

Degeneracy may not be perfect : effective parameter

$N_{eff:}$ number of effective species

$$H^2(t) \simeq \frac{8\pi G}{3}(\rho_\gamma + \rho_\nu)$$

$$\rho_\nu \propto T^4 N_{\rm eff}$$

Standard: N_{eff}=3.045

Extra radiation, boosted expansion rate

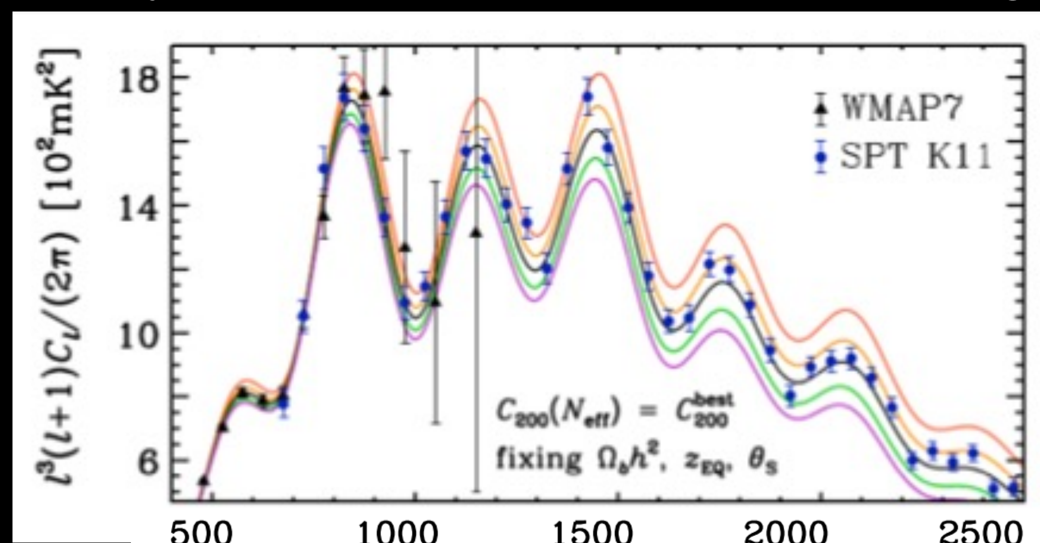
Any thermal background of light particles, anything affecting expansion rate

Look at BBN N_{eff} around 3 to 4

Look at CMB: effects matter-radn equality and so sound horizon at decoupling -> degeneracy with ω_m and H

Anisotropic stress,
z_{eq} on diffusion damping

Main effect: increasing N_{eff} increases Silk Damping scale (for fixed θs), small phase shifts too



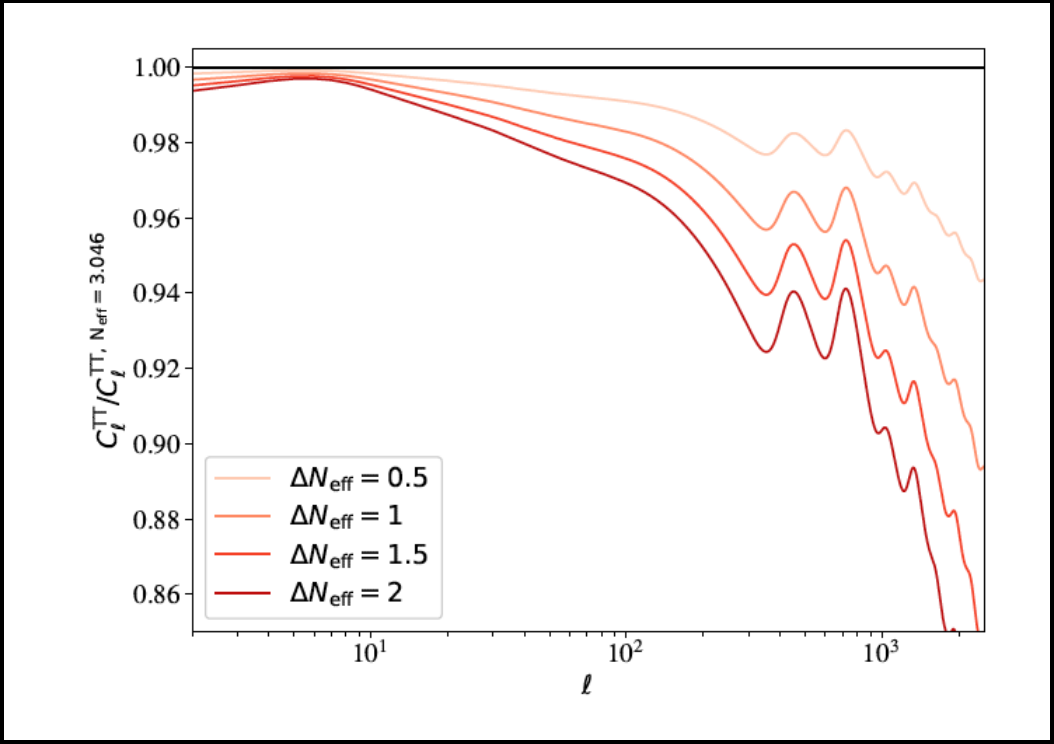
Hou et al 2011

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

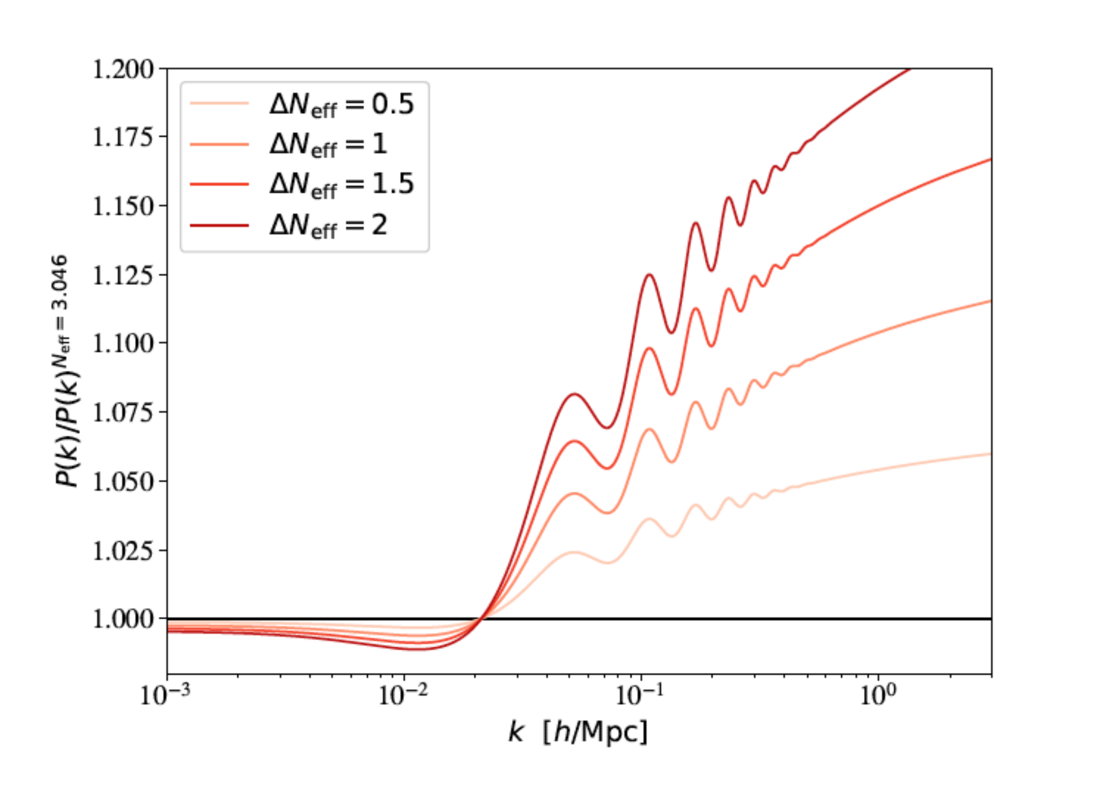


Increase Silk damping

Neutrinos, Neff: Physical effects

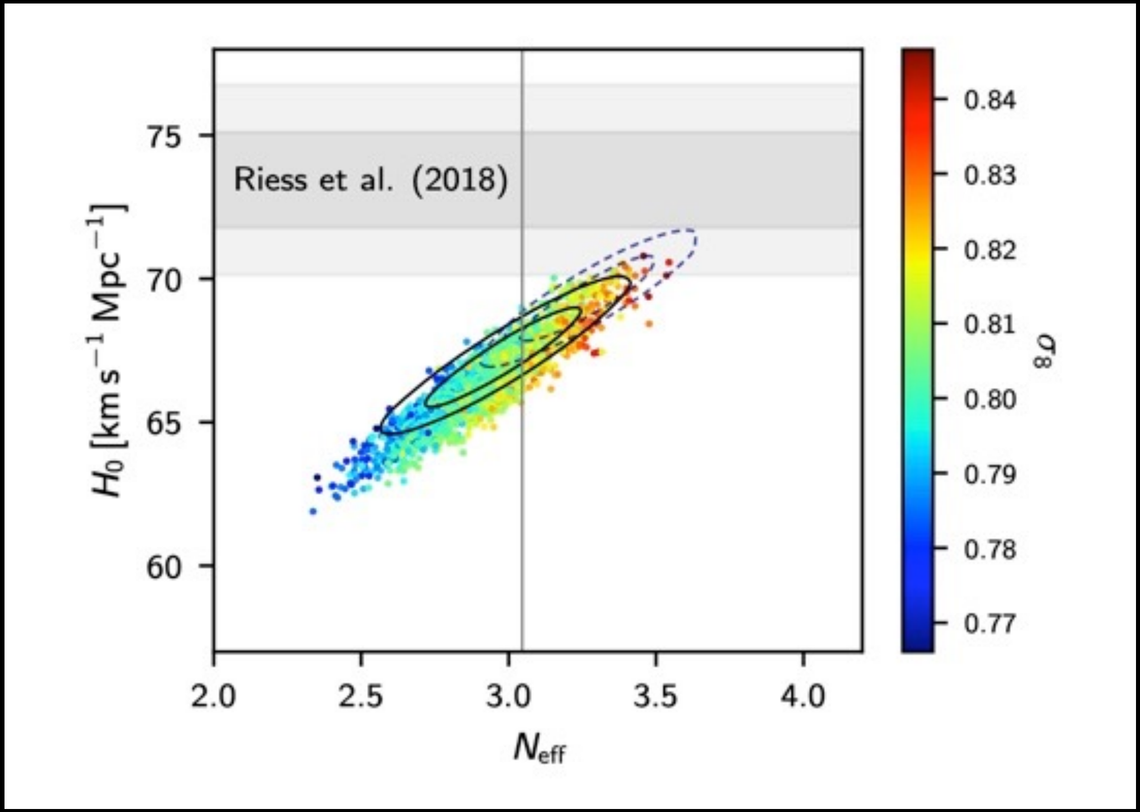
Keep zeq fixed (and matter to Λ fixed, and wb) so play with Neff and H0

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



Parameter constraints: Neutrino species

Planck collaboration, 2018 paper VI



$$N_{\mathrm{eff}} = 3.11^{+0.44}_{-0.43} \quad (95\,\%,\ \mathrm{TT{+}lowE{+}lensing{+}BAO});$$

$$N_{\mathrm{eff}} = 2.99^{+0.34}_{-0.33} \quad (95\,\%,\ \mathrm{TT,TE,EE{+}lowE{+}lensing{+}BAO}).$$

Summary N_{eff} constraints

	Model	95%CL	
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+$N_{\rm eff}$	$2.92^{+0.36}_{-0.37}$	P18
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$2.99^{+0.34}_{-0.33}$	P18
" + BAO + R21	ΛCDM+$N_{\rm eff}$	3.34 ± 0.14 (68%CL)	
"	" +5-params.	2.85 ± 0.23 (68%CL)	

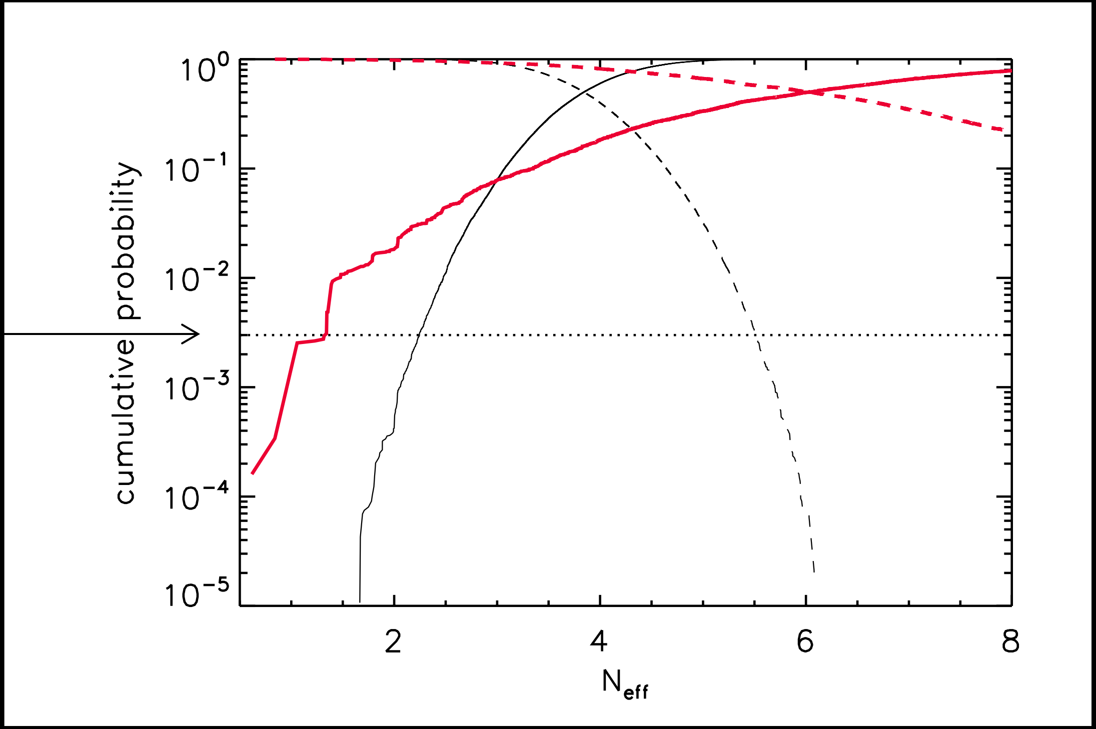
diValentino

Back a decade

On the other hand…

the cosmic neutrino background has been detected at $>> 4\ \sigma$

99.7%
or 0.003

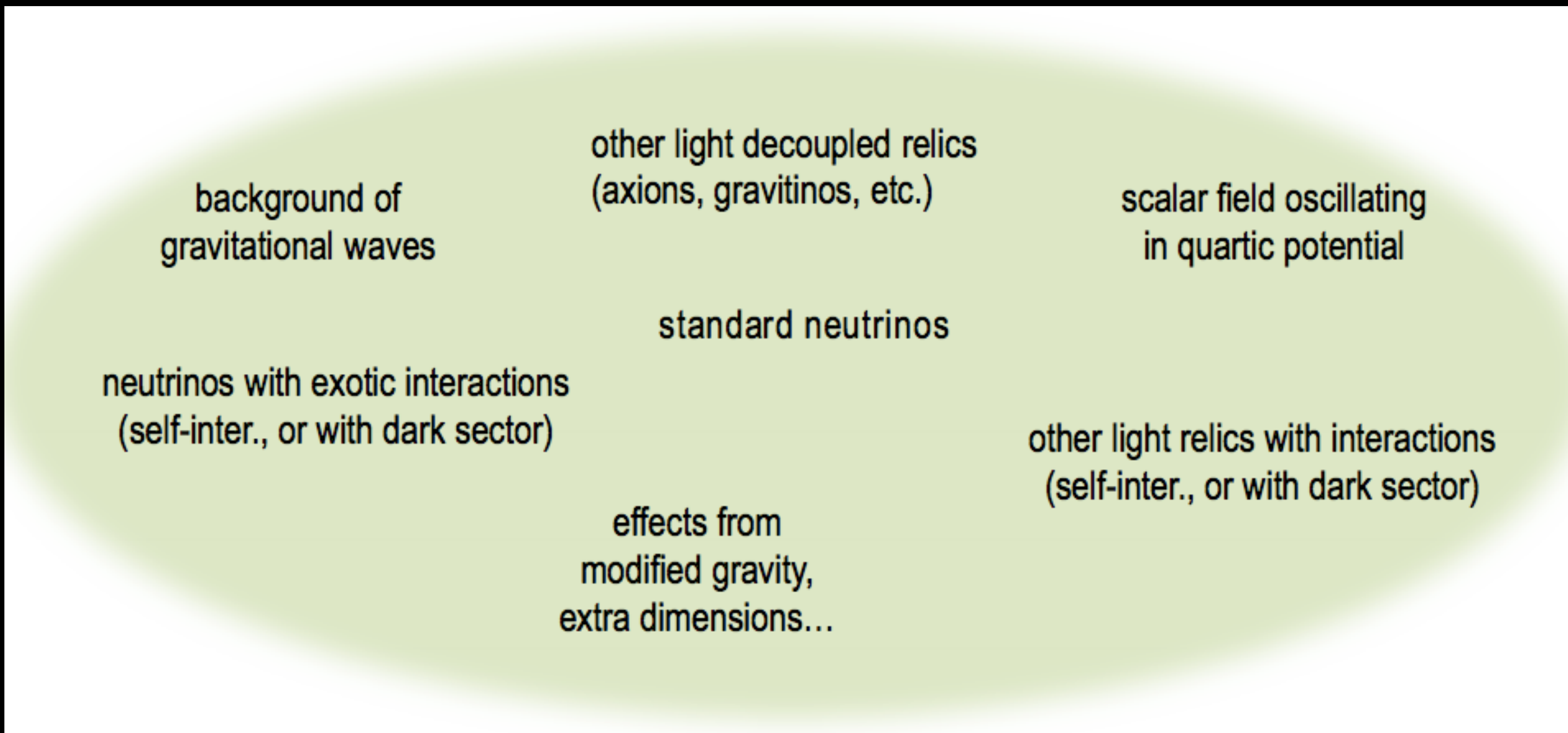


WMAP

SPT

How do you know it’s neutrinos?

“Dark radiation” candidates



ALL of these scale like radiation!

need EXTRA evidence

Let’s look at the ***perturbations***

The $\{c^2_{vis}, c^2_{eff}\}$ parametrization

Background (no anisotropies)

Equation of state $\bar{p} = w_{dr}\bar{\rho}$ $\qquad \frac{\dot{\rho}}{\rho} = -3(1+w_{dr})\frac{\dot{a}}{a}$

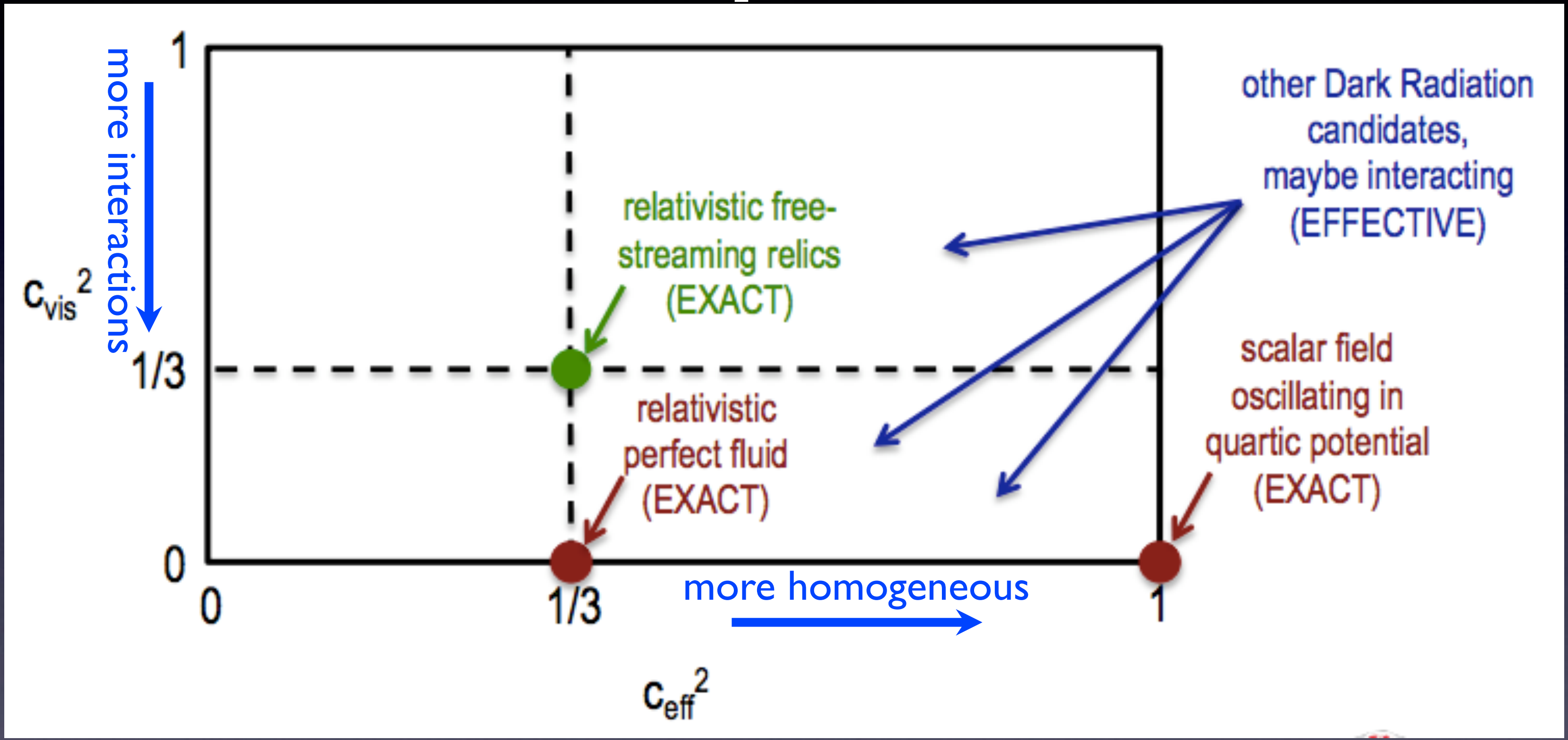
Sound speed $\dot{\bar{p}} = c_a^2\dot{\bar{\rho}}$ $\qquad c_a^2 = w_{dr} - \frac{1}{3}\frac{\dot{w}_{dr}}{1+w+_{dr}}\left(\frac{\dot{a}}{a}\right)^{-1}$

First-order Perturbations

Isotropic pressure $\delta p = c_{eff}^2 \delta\rho$

Anisotropic pressure $\dot{\sigma} = f\left(c_{vis}^2\right)$

The $\{c^2_{vis}, c^2_{eff}\}$ parametrization



If we can get strong constraints around $c^2_{vis}=c^2_{eff}=1/3$ that makes further evidence for neutrino background!

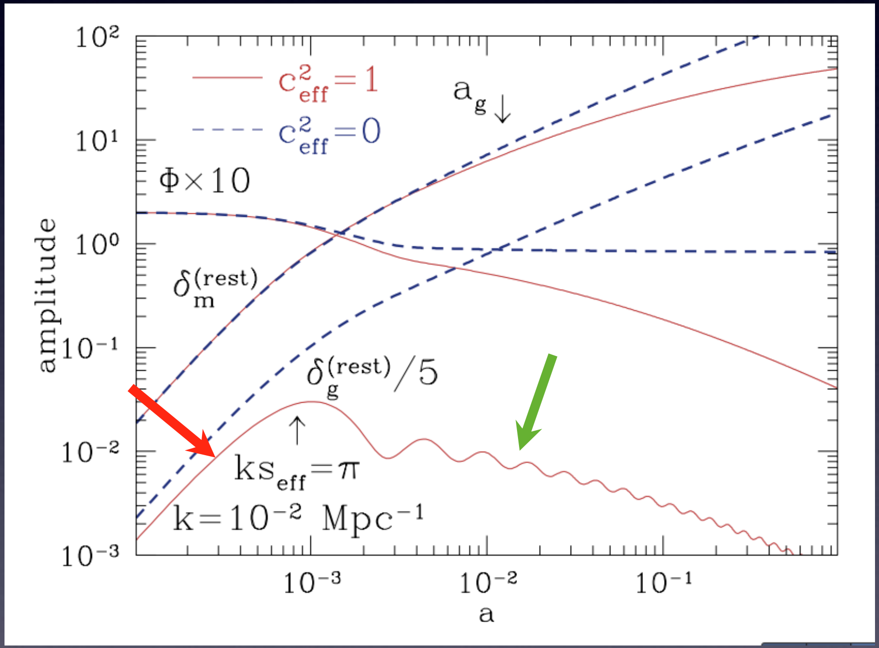
Otherwise, alternative dark radiation would be favored

Effects of c^2_{eff} on the ν density perturbations

Perturbations grow as power-law above the sound horizon

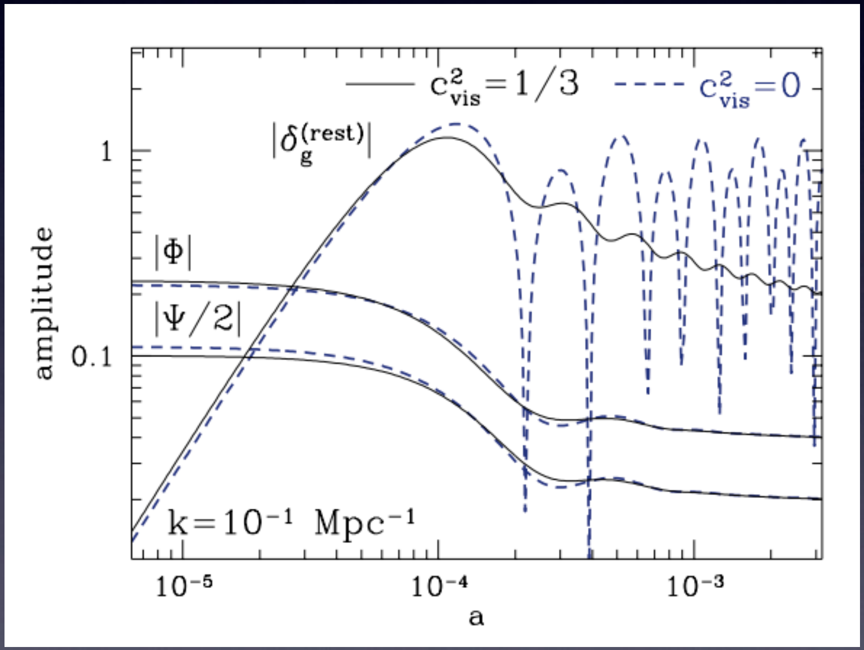
and begin to oscillate with decaying amplitude below the sound horizon

Depending on the value of c^2_{eff} the perturbations will stop growing earlier/later



Wayne Hu (1998)

Effects of c^2_{vis} on the ν density perturbations

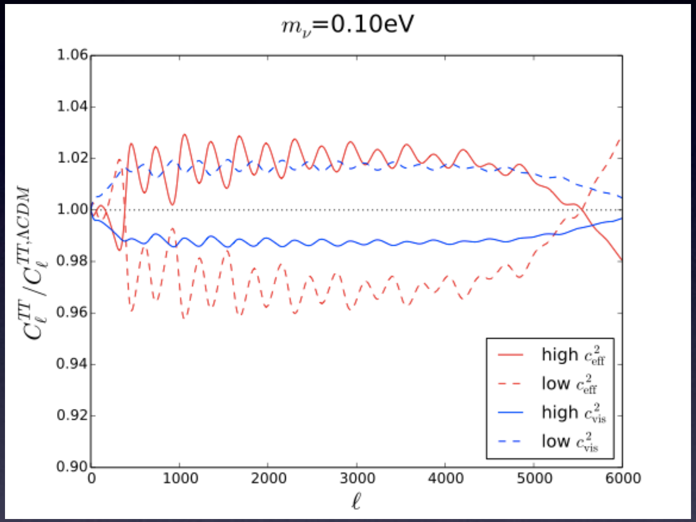


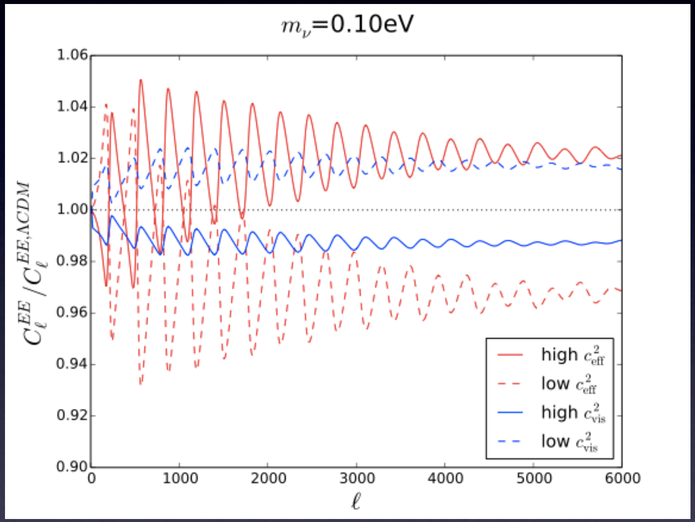
Wayne Hu (1998)

c^2_{vis} mimics the effect of the mean free path of particles in an imperfect fluid with interactions

The limit $c^2_{vis} = 0$ corresponds to a negligible mean free path, i.e., to the strongly interacting regime where the pressure remains isotropic.

Effects of c^2_{vis},c^2_{eff} on the T&E Power spectrum of the CMB



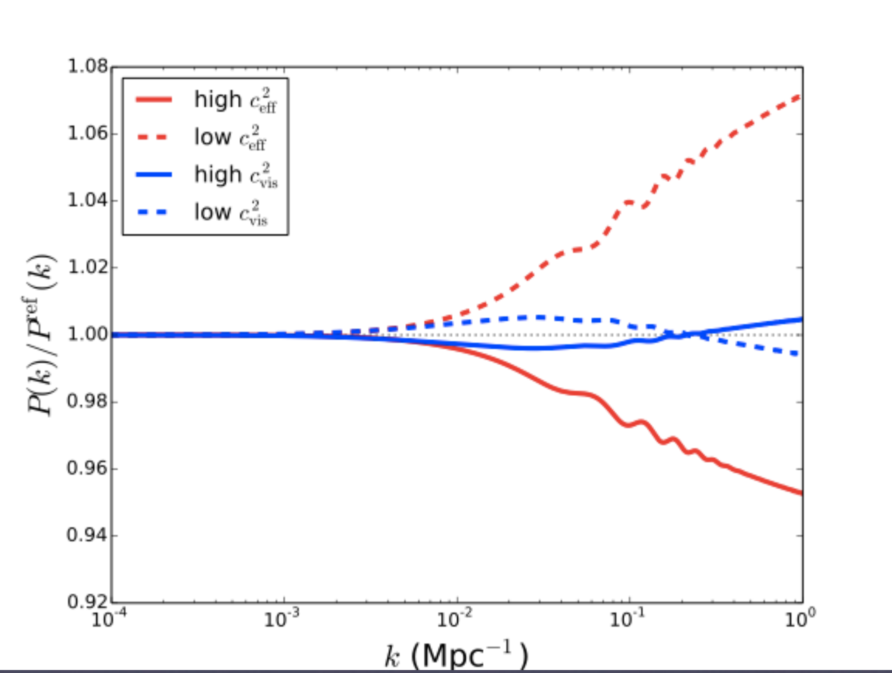


c^2_{vis} and c^2_{eff} change the **amplitude** (and shape) of the temperature and polarization power spectra

c^2_{vis} and c^2_{eff} change the **phase** of the acoustic oscillations, especially in the polarization spectra

The relative effect of c^2_{vis} and c^2_{eff} does **not** depend on neutrino mass, at least in the range $\Sigma m_\nu < 0.3$eV

Effects of {c^2_{vis},c^2_{eff}} on the matter power spectrum



c^2_{eff} modifies power at small scales at the level of several percent
Lyman-alpha forest data should be able to help here!!

These P(k) ratios are again independent of m_ν

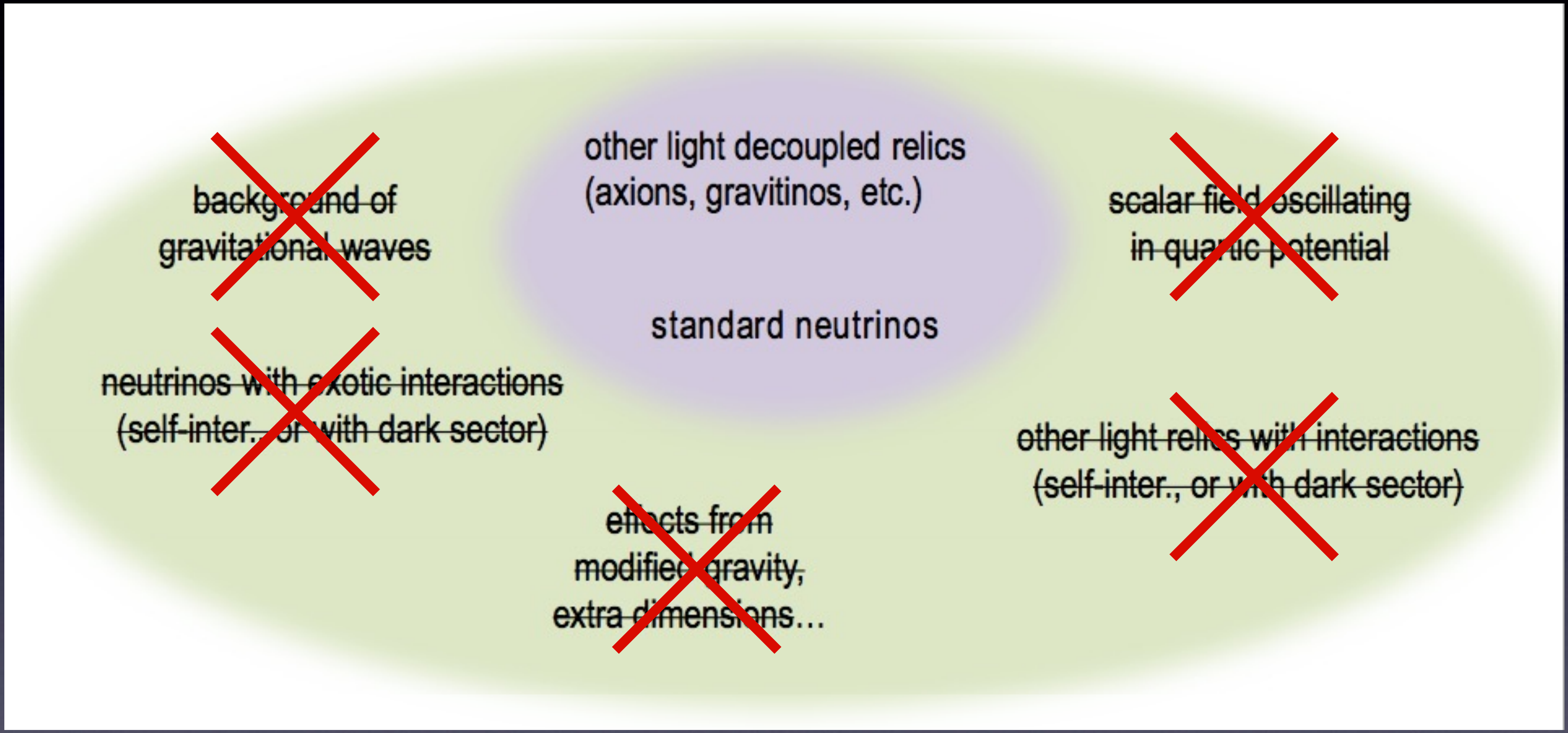
Cosmological constraints CMB + CMB lensing

CMB + lensing						
Parameter	ΛCDM$+c^2_{\rm eff}+c^2_{\rm vis}$	$+N_{\rm eff}$	$+m_\nu$	$+w$	$+\alpha_s$	$+N_{\rm eff}+m_\nu$
$100\,\omega_b$	$2.162^{+0.047}_{-0.052}$	$2.174^{+0.057}_{-0.055}$	$2.124^{+0.048}_{-0.056}$	$2.179^{+0.052}_{-0.056}$	$2.180^{+0.050}_{-0.056}$	$2.136^{+0.060}_{-0.068}$
ω_{cdm}	$0.1163^{+0.0037}_{-0.0034}$	$0.1181^{+0.0054}_{-0.0051}$	$0.1186^{+0.0037}_{-0.0036}$	$0.1164^{+0.0037}_{-0.0035}$	0.1163 ± 0.0035	0.1184 ± 0.0055
H_0	68.3 ± 1.1	69.6 ± 2.9	$63.7^{+4.1}_{-2.6}$	$85.5^{+14.0}_{-4.5}$	$68.3^{+1.1}_{-1.2}$	$65.4^{+4.0}_{-4.2}$
$10^{+9}A_s$	$2.31^{+0.12}_{-0.15}$	$2.34^{+0.12}_{-0.16}$	2.36 ± 0.13	$2.27^{+0.12}_{-0.15}$	$2.35^{+0.13}_{-0.15}$	2.39 ± 0.14
n_s	$0.984^{+0.021}_{-0.020}$	$0.991^{+0.024}_{-0.025}$	$0.981^{+0.020}_{-0.018}$	$0.979^{+0.022}_{-0.021}$	$0.980^{+0.022}_{-0.019}$	$0.987^{+0.025}_{-0.022}$
τ_{reio}	$0.090^{+0.012}_{-0.014}$	$0.093^{+0.013}_{-0.015}$	$0.093^{+0.013}_{-0.014}$	$0.088^{+0.012}_{-0.014}$	$0.095^{+0.013}_{-0.016}$	$0.094^{+0.013}_{-0.016}$
$c^2_{\rm eff}$	0.314 ± 0.013	0.314 ± 0.013	$0.309^{+0.013}_{-0.014}$	$0.318^{+0.013}_{-0.014}$	$0.320^{+0.014}_{-0.016}$	$0.312^{+0.014}_{-0.013}$
$c^2_{\rm vis}$	$0.49^{+0.12}_{-0.22}$	$0.49^{+0.11}_{-0.21}$	$0.51^{+0.14}_{-0.19}$	$0.46^{+0.11}_{-0.23}$	$0.50^{+0.13}_{-0.22}$	$0.56^{+0.14}_{-0.24}$
$N_{\rm eff}$	–	$3.22^{+0.32}_{-0.37}$	–	–	–	$3.17^{+0.34}_{-0.37}$
M_ν [eV]	–	–	< 1.03	–	–	< 1.05
w	–	–	–	$-1.49^{+0.18}_{-0.38}$	–	–
α_s	–	–	–	–	-0.010 ± 0.010	–

All cases remain consistent with neutrinos, although in some cases the claim $c^2_{\rm vis}\neq 0$ **weakens**

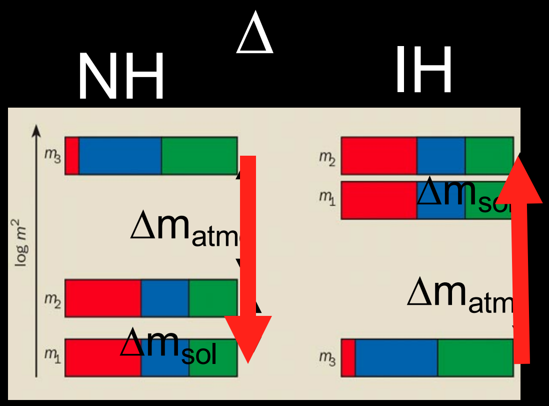
Audren et al. JCAP arXiv:1412.5948

Killing dark radiation candidates



courtesy of Julien Lesgourgues

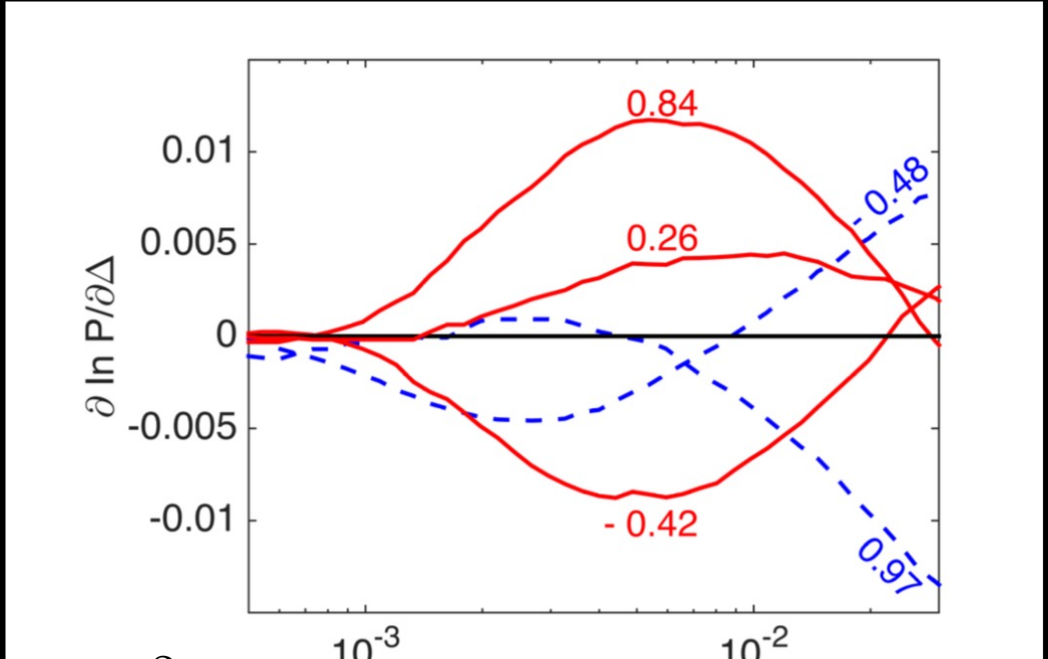
Hierarchy effect on the shape of the linear matter power spectrum



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

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



$\Omega_c h^2$ fixed

$\Sigma = 0.1 eV$

$\Sigma = 0.06 eV$

How about hierarchy?

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

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

Combine with constraints from oscillations

’Later or another time

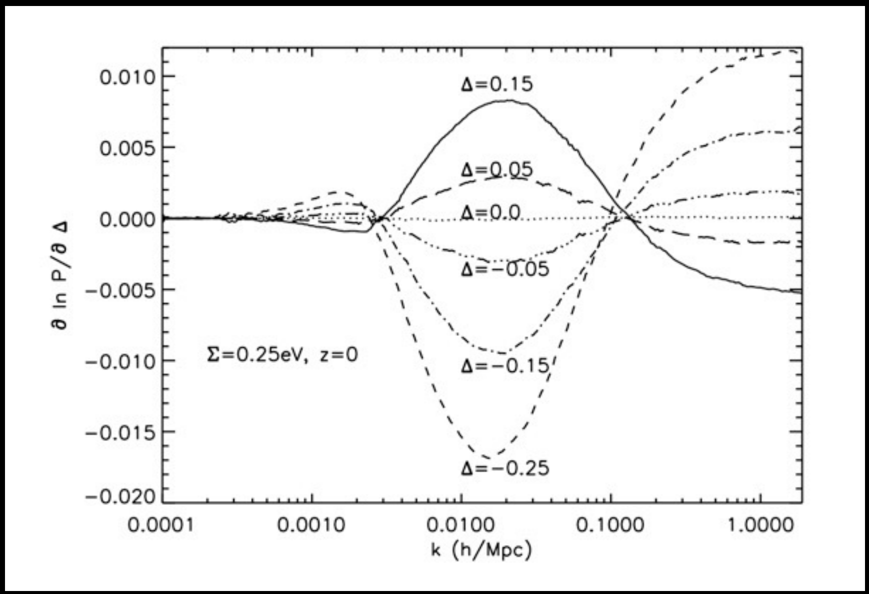
What is hierarchy?

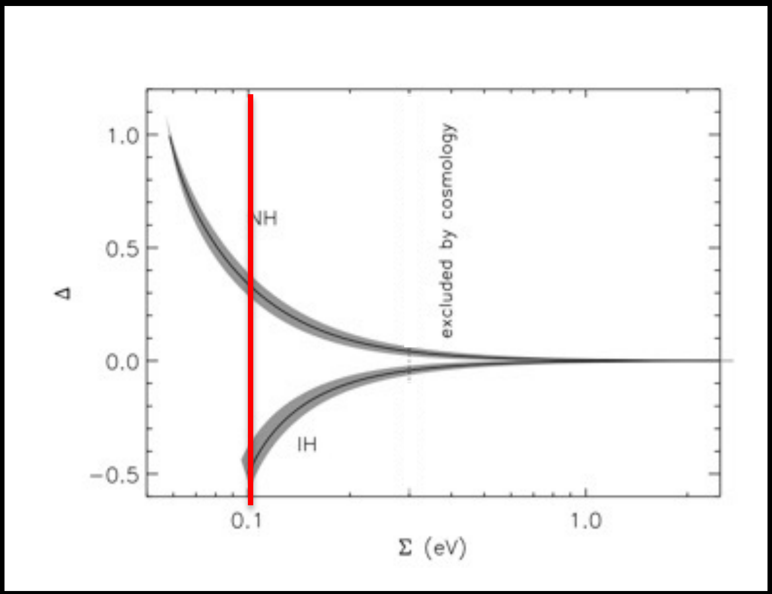
- There are three masses m1, m2, m3 and therefore only two square mass splitting (measurable quantity). One will be smaller than the other one.
- m1,m2 refer to the smaller splitting
- m3 can be above (NH) or below (IH) this pair.
- Hierarchy is given by the ***sign*** of the larger mass splitting.

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

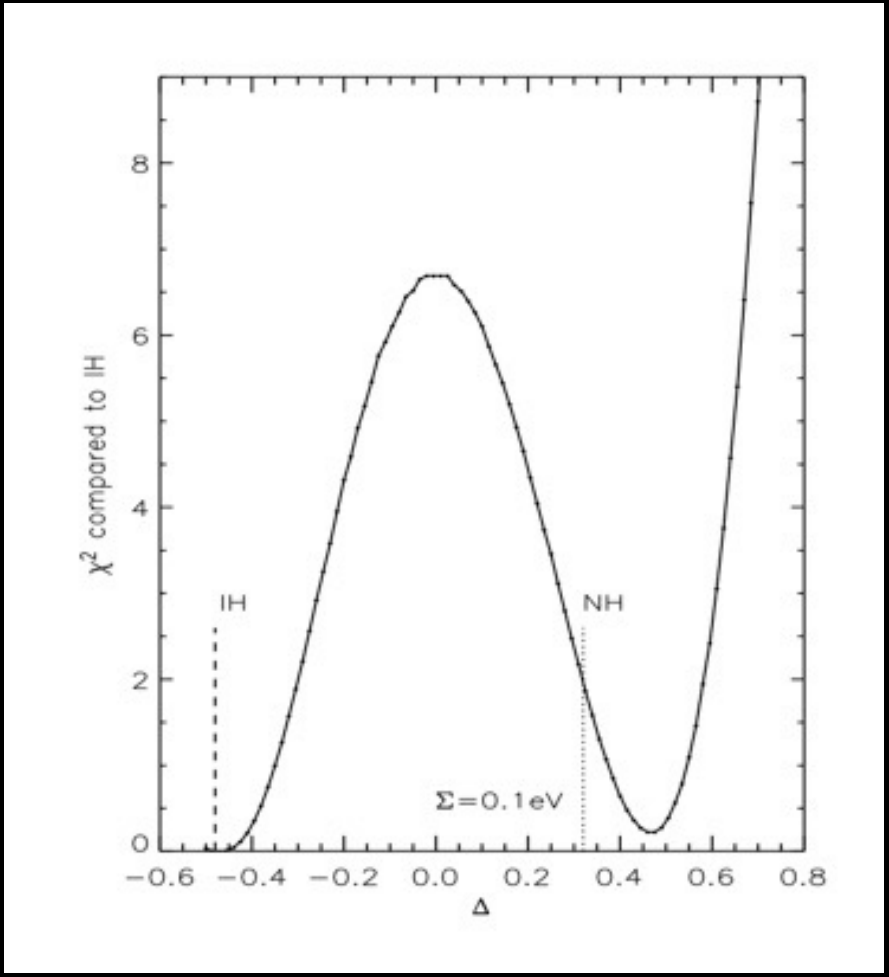
Bayesian statistics





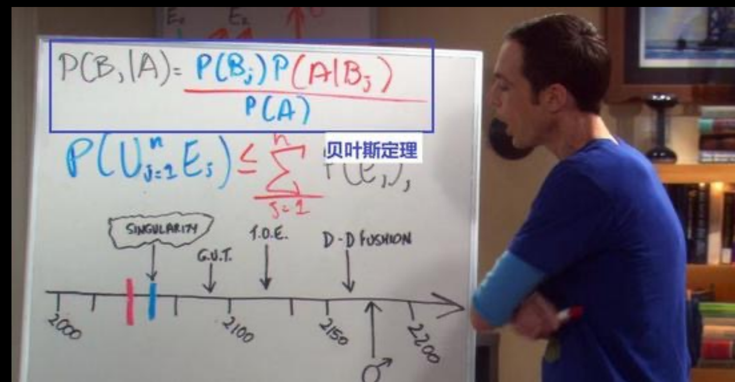
The upper limit. $\Sigma m\nu/eV <\sim 0.1$ indicate that not all Δ are possible if neutrinos….
Consistency check!

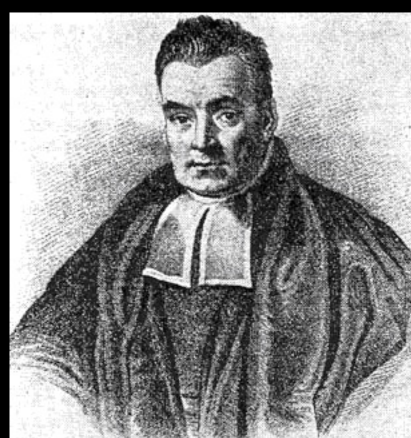
About the LHS

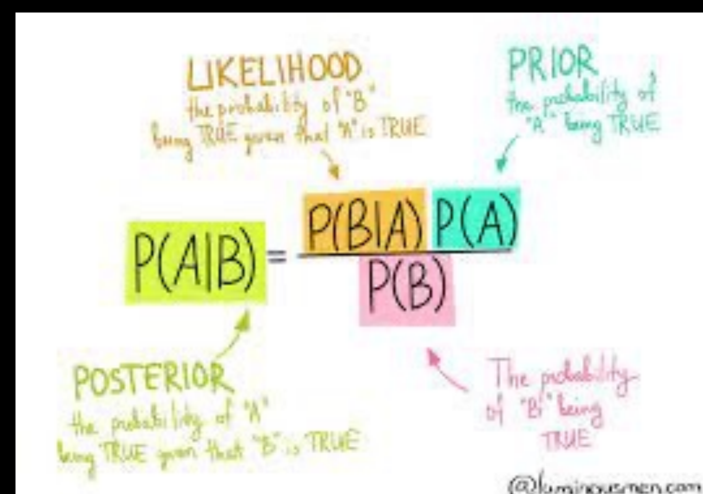


Let's dream…..

Bayes


$P(B_j|A) = \frac{P(B_j)P(A|B_j)}{P(A)}$
贝叶斯定理
SINGULARITY
G.U.T.
T.O.E.
D-D FUSION
2000
2100
2150
2200




LIKELIHOOD
the probability of "B" being TRUE given that "A" is TRUE
PRIOR
the probability of "A" being TRUE
$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}$
POSTERIOR
the probability of "A" being TRUE given that "B" is TRUE
The probability of "B" being TRUE
@luminousmen.com

Compute the Bayesian evidence

$$P(\alpha|D,M) = \frac{P(D|\alpha,M)P(\alpha|M)}{P(D|M)},$$

$$P(D|M) = \int P(D|\alpha,M)P(\alpha|M)d\alpha\,.$$

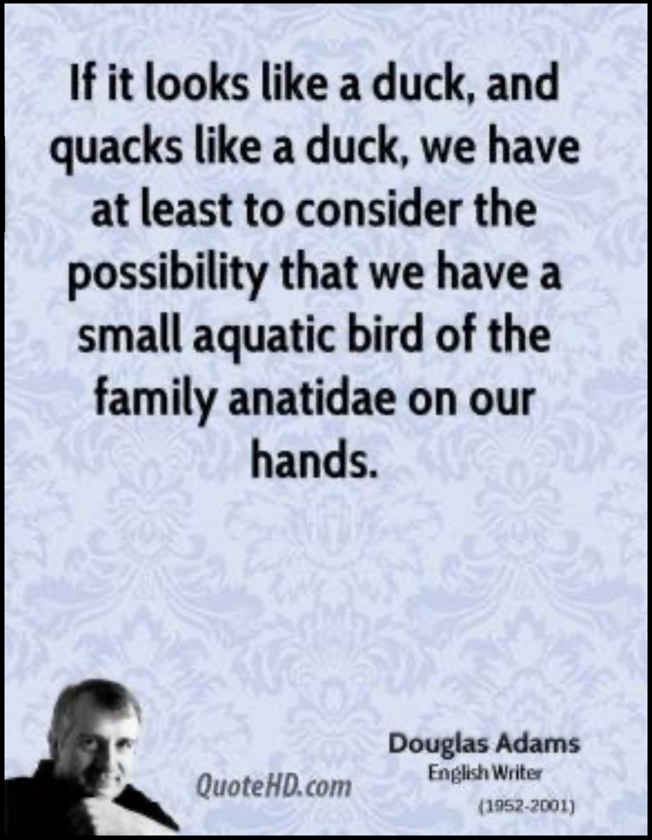
$$P(M|D) \;=\; P(D|M)P(M)/P(D);$$

Then take ratios

IT WILL ALWAYS DEPEND ON THE PRIOR

Use oscillations measurements + cosmological limits (assume Gaussian likelihood)

Neutrinos propreties from the sky



Recap

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

CMB+LSS limit $M\nu < 0.1$ 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.

Conclusions

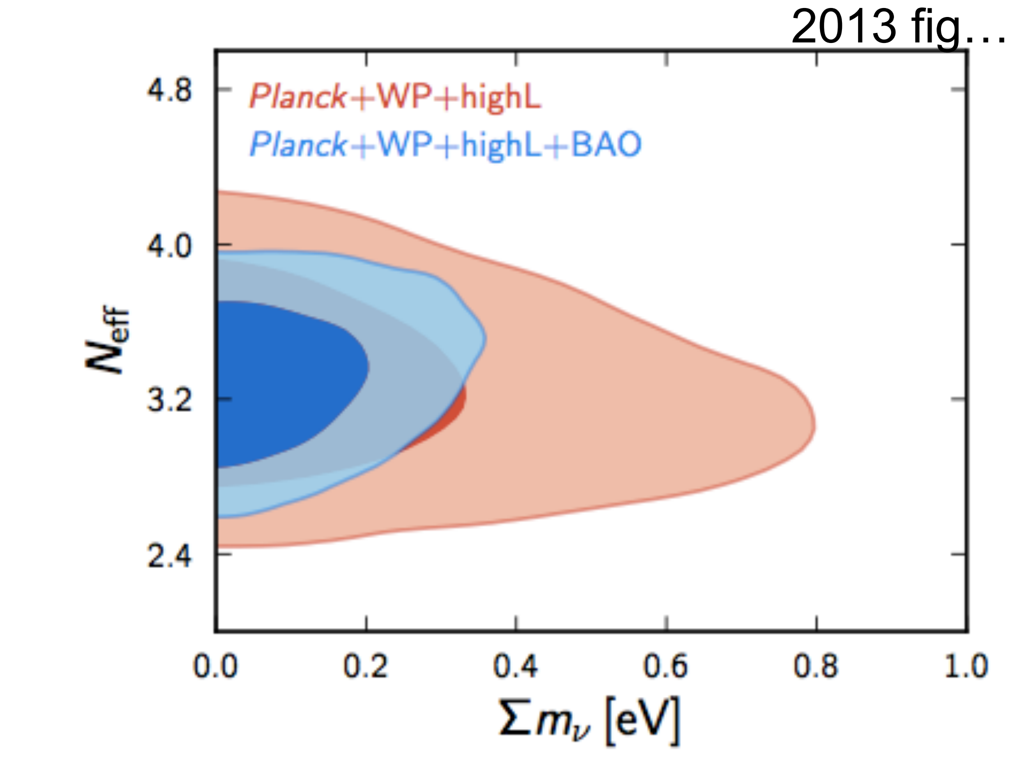
- Precision cosmology means that we can start (or prepare for) constraining interesting physical quantities
- Neutrino properties: absolute mass scale, number of families, possibly hierarchy
- My "bet": $0.06 < \Sigma m\nu/\mathrm{eV} <\sim 0.1$ (95%) Large future surveys means that sub % effects become detectable, which brings in a whole new set of challenges and opportunities (e.g., mass, hierarchy)
- The (indirect) detection of neutrino masses is within the reach of forthcoming experiments (even for the minimum mass allowed by oscillations)
- Systematic and real-world effects are the challenge, need for in-build consistency checks!
- COMPLEMENTARITY is key

END

In summary:

- N_{eff} consistent with 3

- These are "light" neutrinos (<0.1* eV at 95%CL)



- more wiggle room: go beyond the minimal LCDM (errors gets slightly larger, but… epicycles)
- Avoid thermalization (some v. radical options)

Implications

Strong Bayesian Evidence for NH, when using the stated priors

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 be very convincing

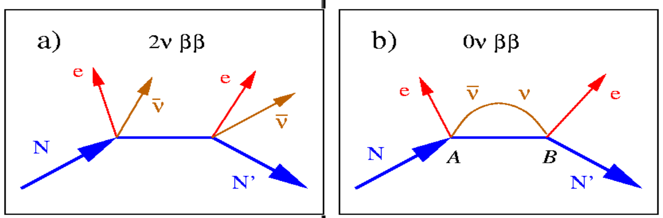
Or by measuring $0\nu\beta\beta$ decay.

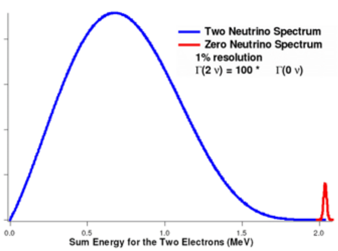
Dirac or Majorana? ⟺ hierarchy

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)?