

Neutrino cosmology

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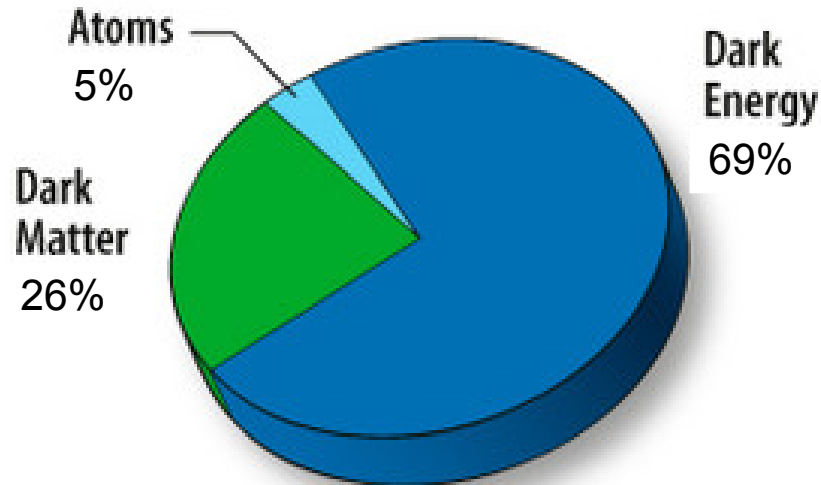
The concordance flat Λ CDM model...

The **simplest** model consistent with **present observations**.

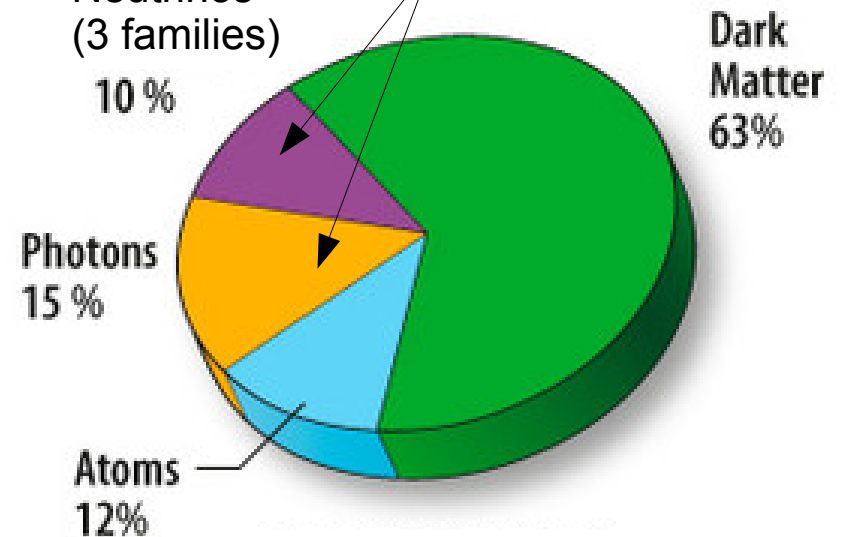
Min. value from $\sum m_\nu = 0.06 \text{ eV}$
oscillations experiments

(Nearly)
Massless
Neutrinos
(3 families)

ν -to- γ energy density
ratio fixed by SM physics



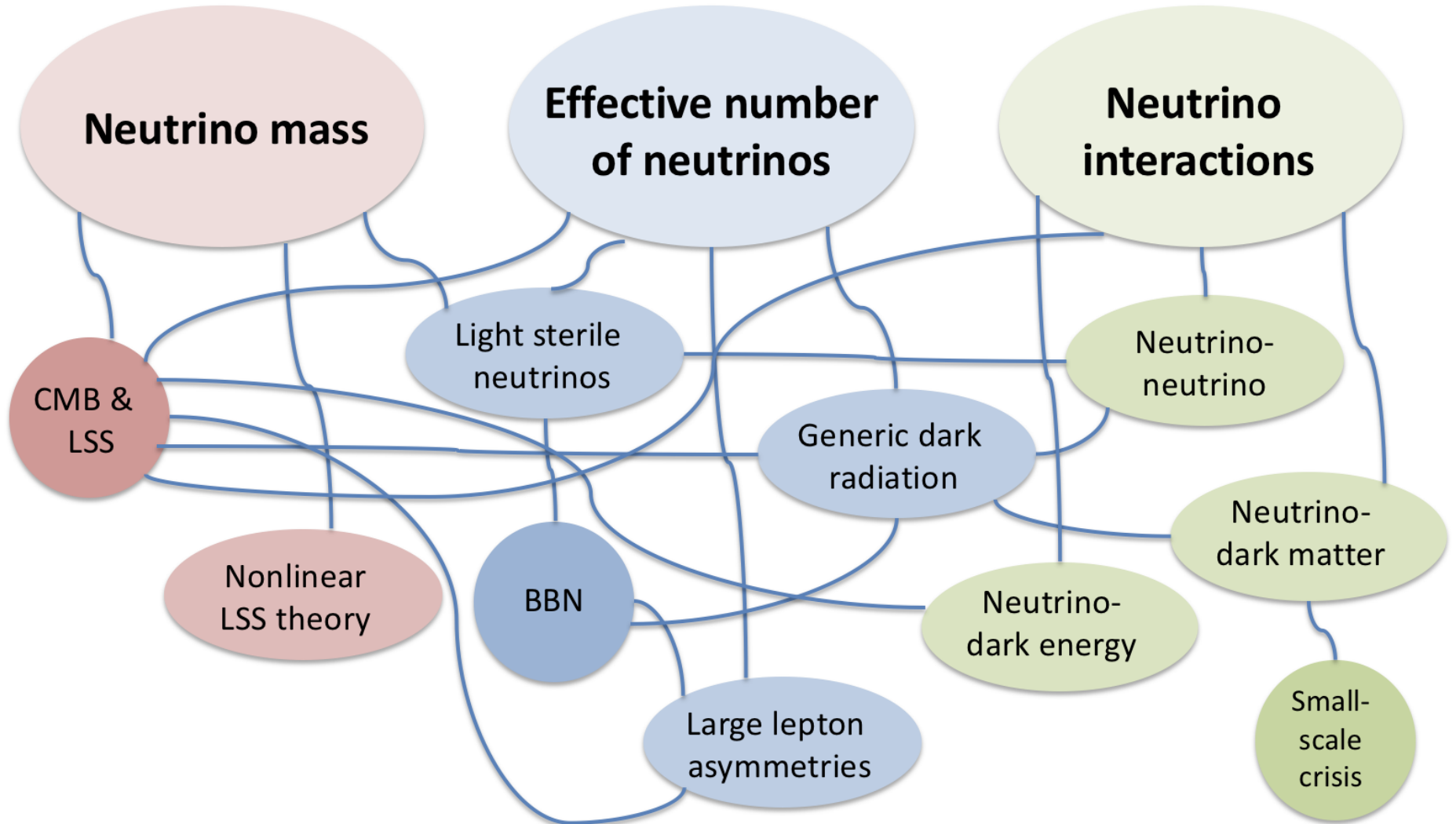
Composition today



13.4 billion years ago
(at photon decoupling)

Plus flat spatial geometry+initial conditions
from single-field inflation

The neutrino sector beyond Λ CDM...



Why should anyone care?

Complementarity to terrestrial particle physics experiments.

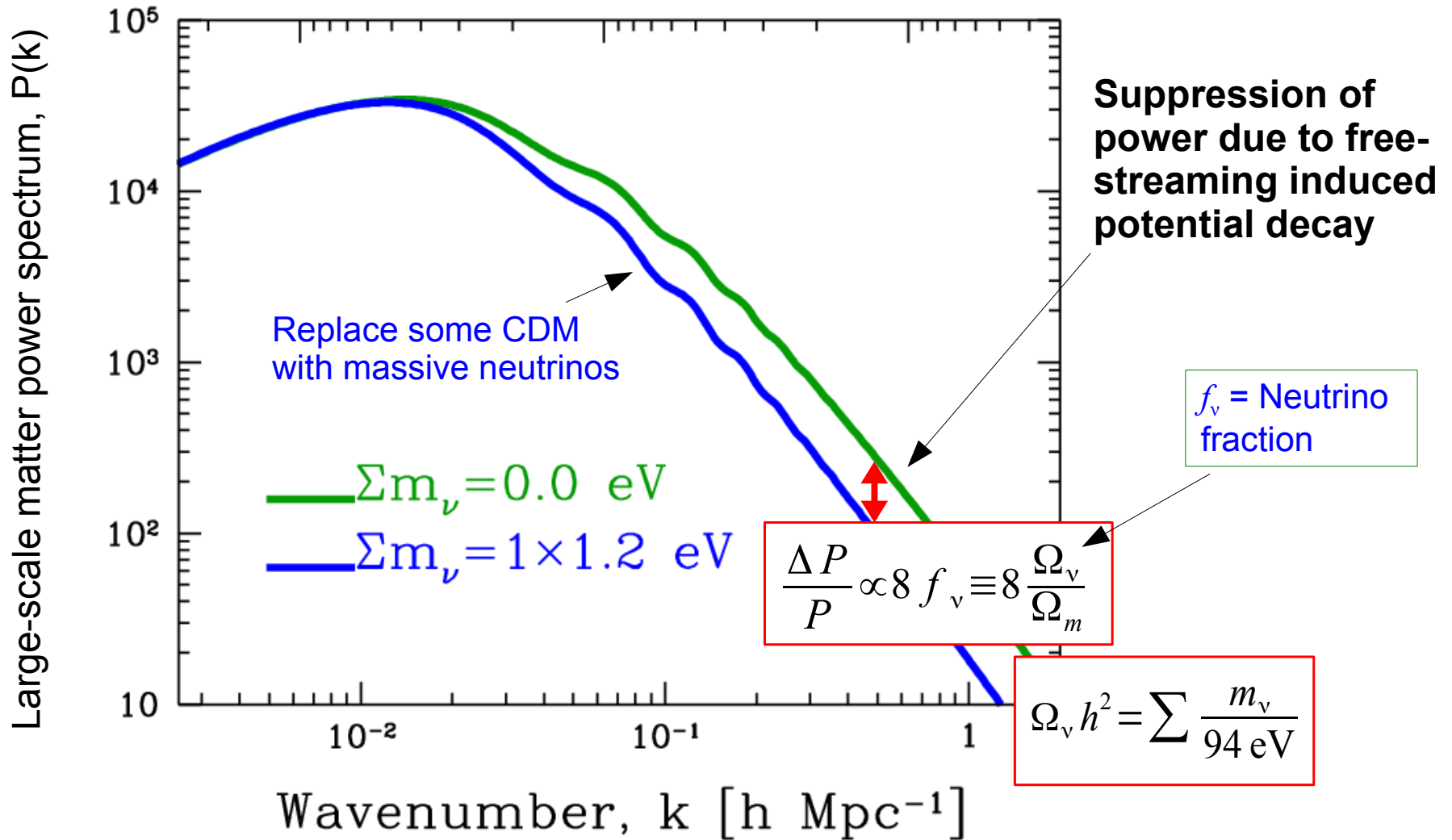
- **Massive neutrino cosmology = Measurement of the absolute neutrino mass scale**
 - Best precision cosmological constraint is about **a factor of 15 better** than current laboratory constraints
- **Effective number of neutrinos = Search for light BSM relics**
 - The LSND/MiniBooNE/reactor light sterile neutrino [See plenary talk of S. Goswami on Thursday](#)
 - Other light BSM relics

Tension between CMB and other astrophysical data sets.

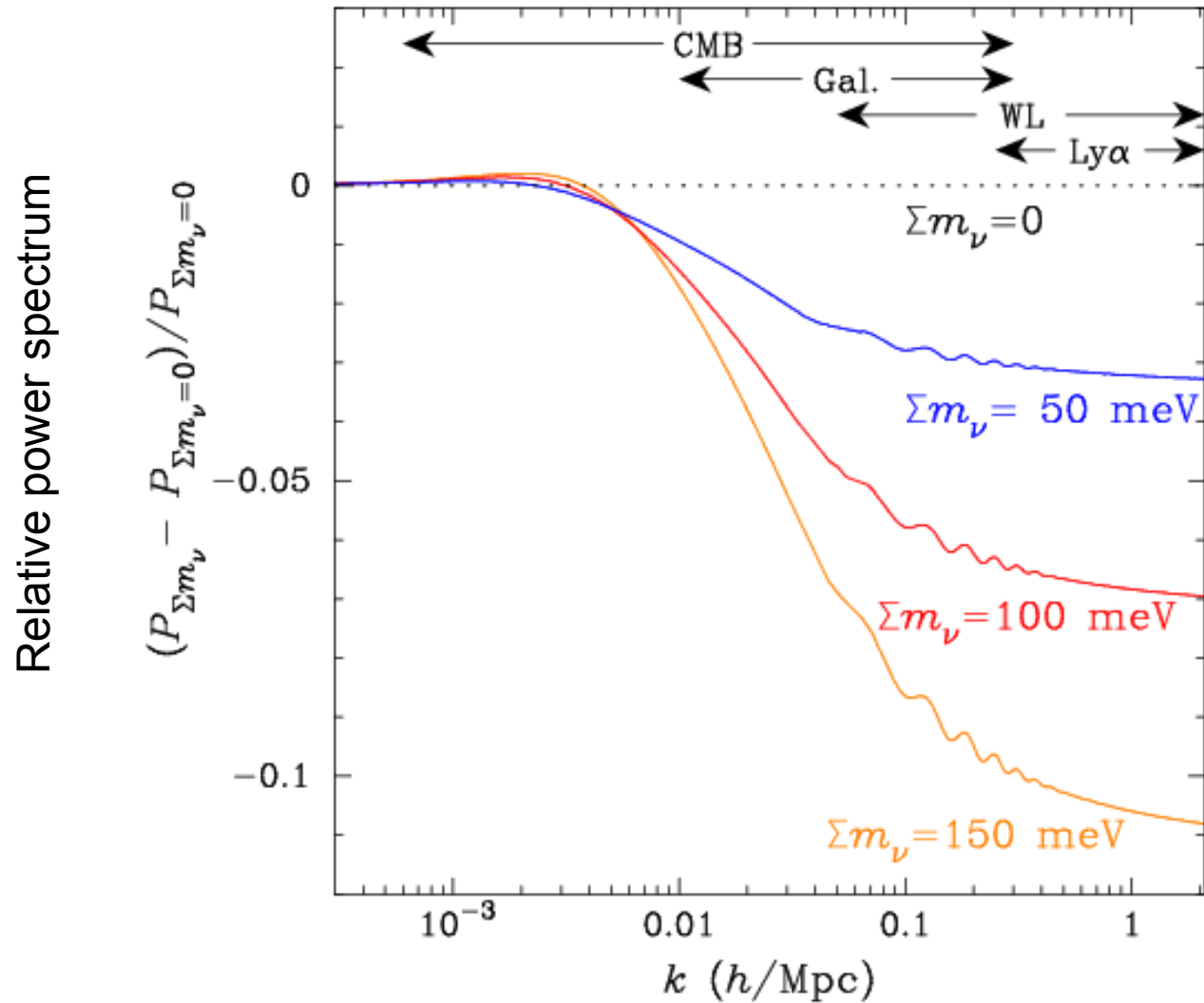
- Can neutrino physics save the day?

1. Massive neutrino cosmology
=
Measurement of the absolute
neutrino mass scale

Neutrino masses in cosmology...

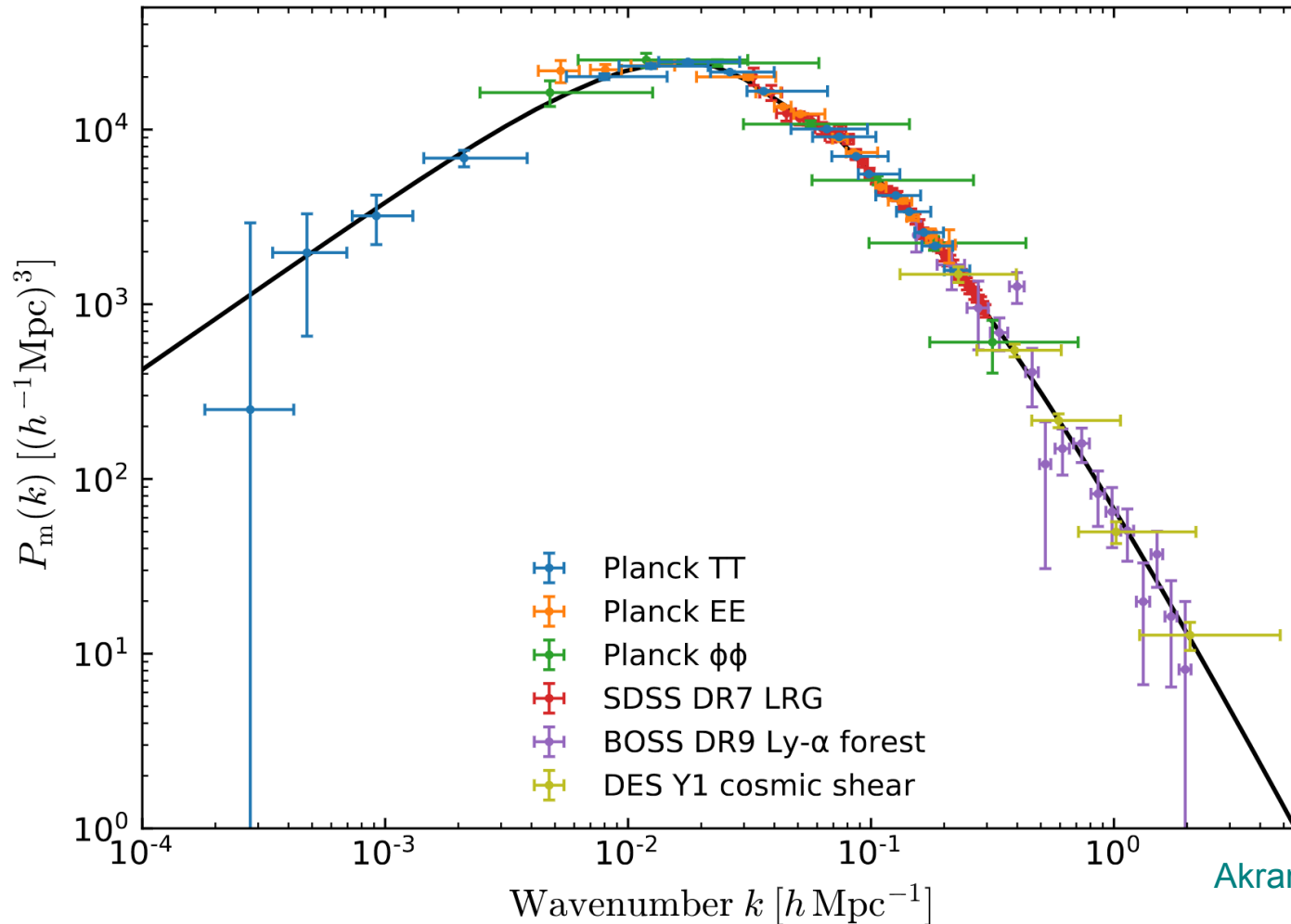


Neutrino masses in cosmology...



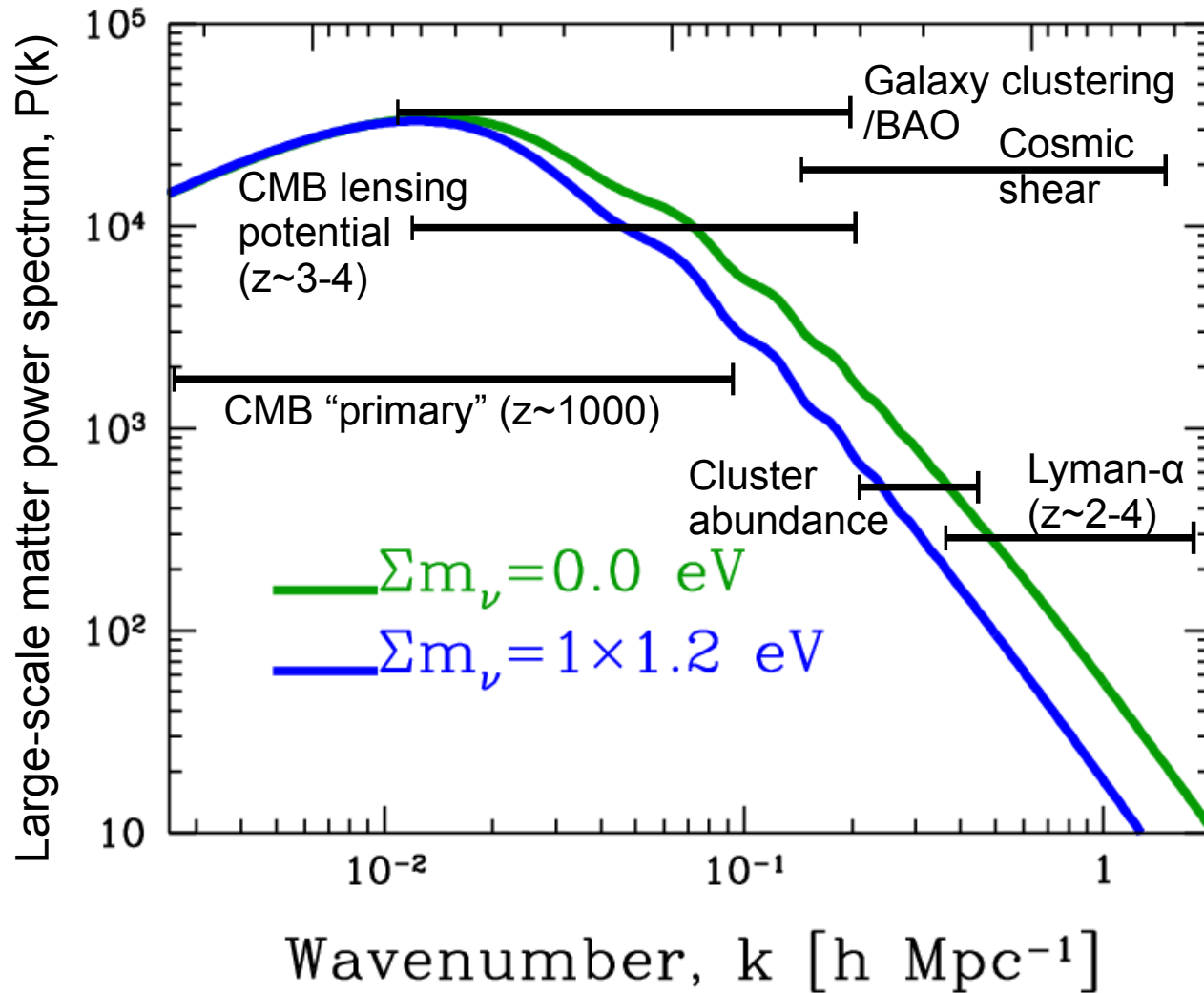
Who can measure it?

Large-scale power spectrum measurements circa 2018

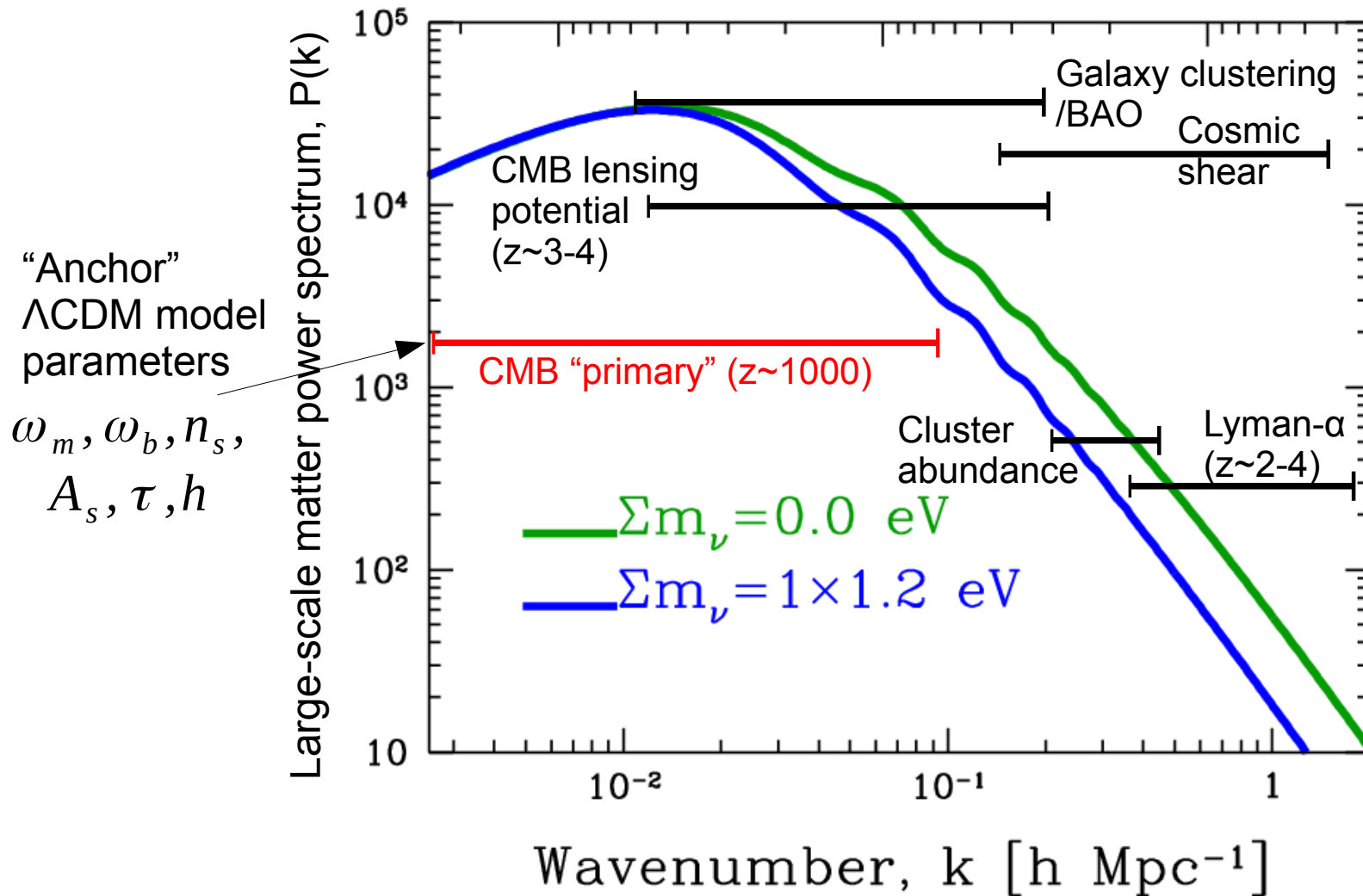


Akrami et al. 2018

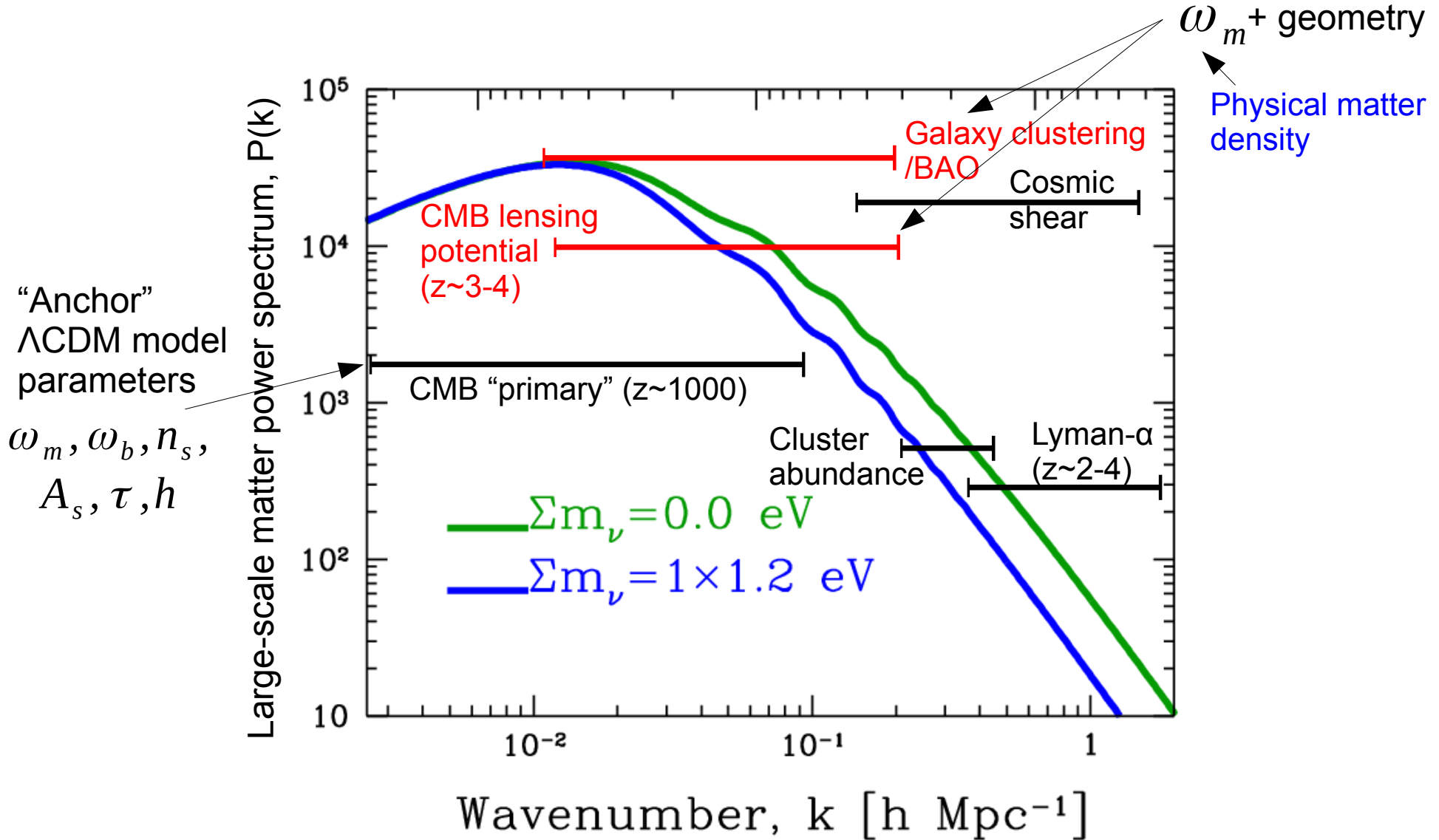
Who can measure it?



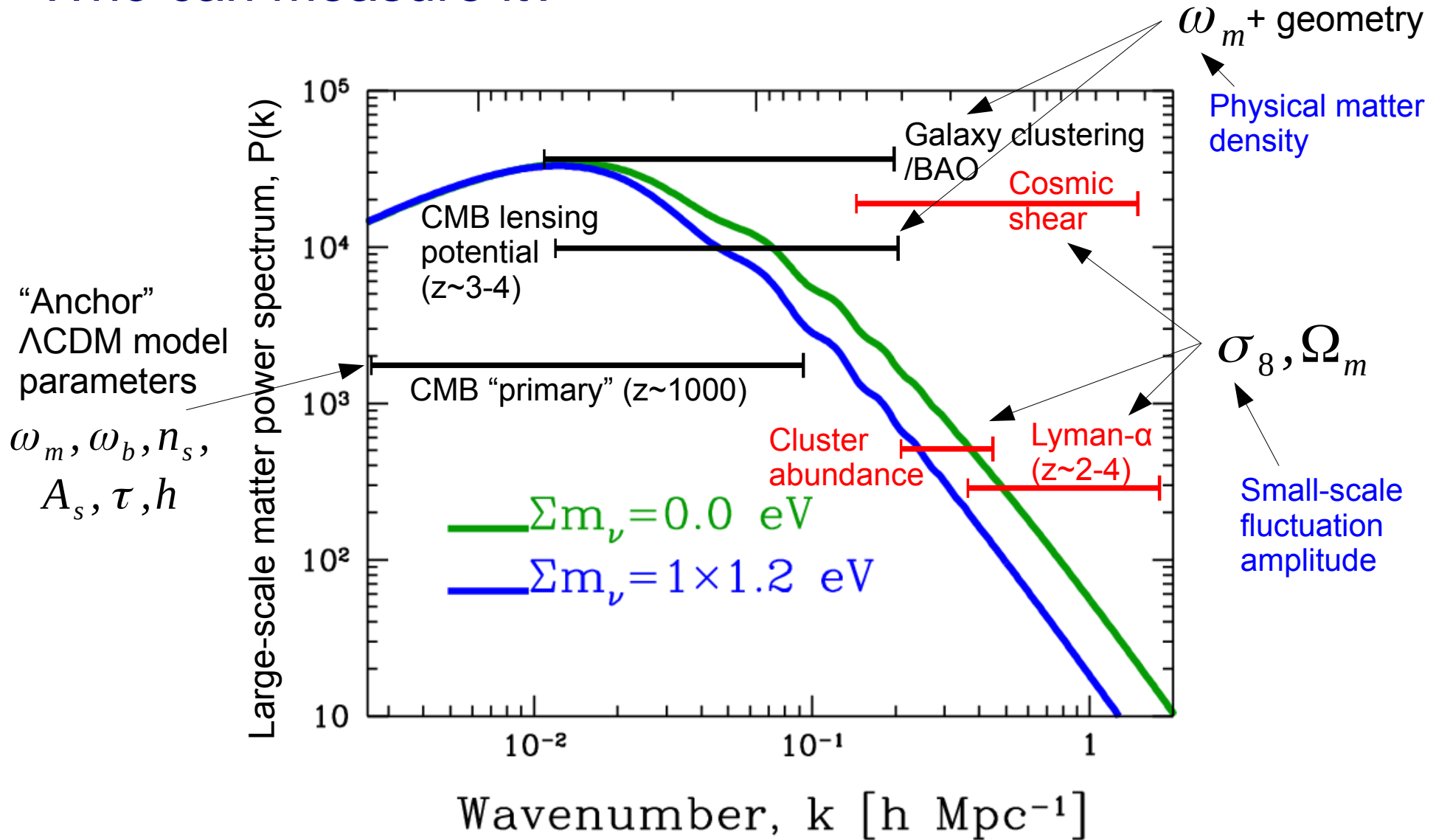
Who can measure it?



Who can measure it?

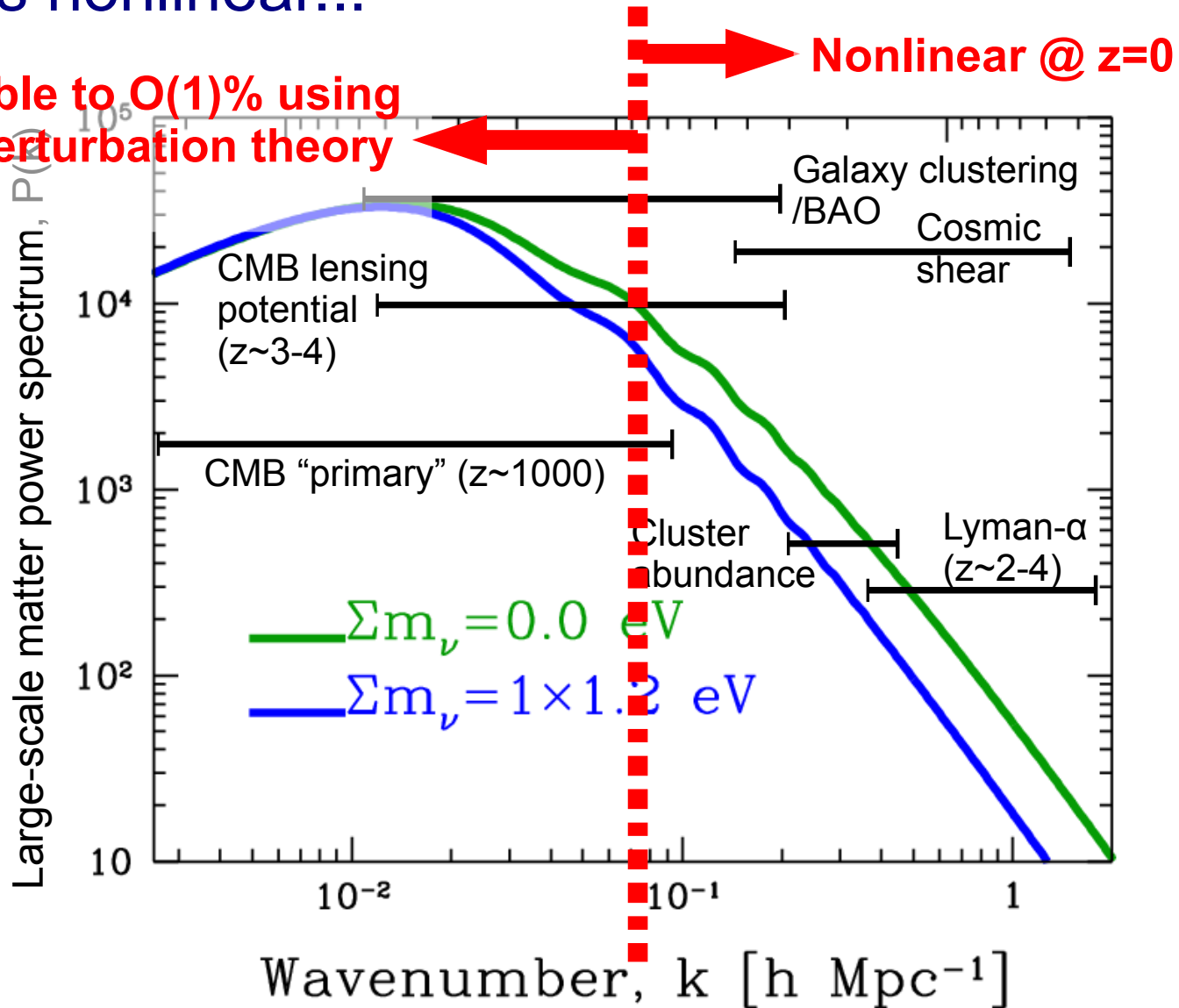


Who can measure it?



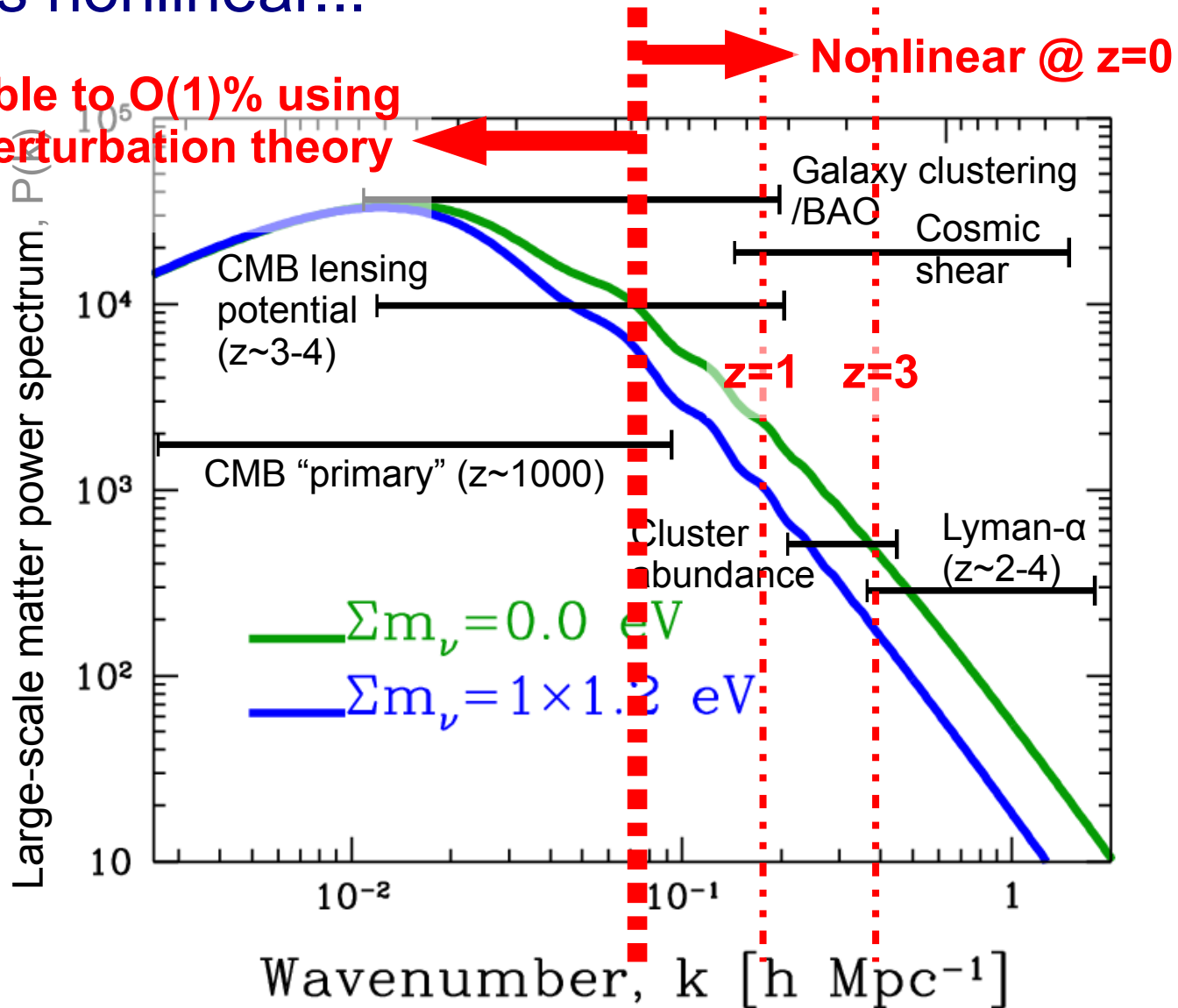
Linear vs nonlinear...

Calculable to O(1)% using
linear perturbation theory
@ z=0



Linear vs nonlinear...

Calculable to O(1)% using
linear perturbation theory
@ z=0



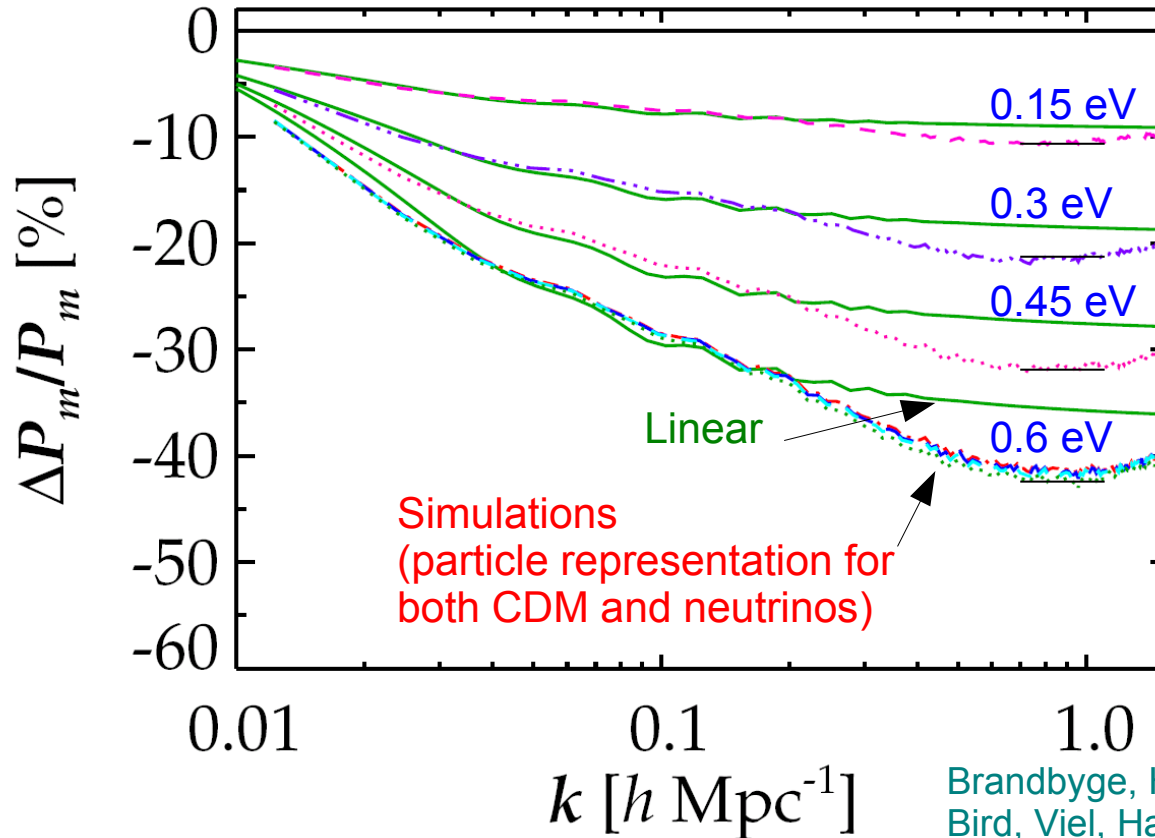
There are nonlinearities and nonlinearities...

	Nonlinear DM (collisionless)	Baryons @ $k < O(1) \text{ Mpc}^{-1}$	Nonlinear tracer bias	Empirical proxy
BAO	Mild	No	Mild	No
Cosmic shear	Yes	No	No	No
Galaxy power spectrum	Yes	No	Yes	No
Cluster abundance	Yes	No	No	Cluster mass vs X-ray temp or richness
Lyman alpha	Yes	Yes	No	No
Calculable from 1 st principles?	Fairly easy	No	No	No

“Fairly easily” calculable nonlinearities...

See talk of A. Upadhye this afternoon

Collisionless DM (gravity-only) nonlinearities



Linear perturbation theory:

$$\frac{\Delta P_m}{P_m} \sim 8 \frac{\Omega_\nu}{\Omega_m}$$

With **nonlinear** corrections:

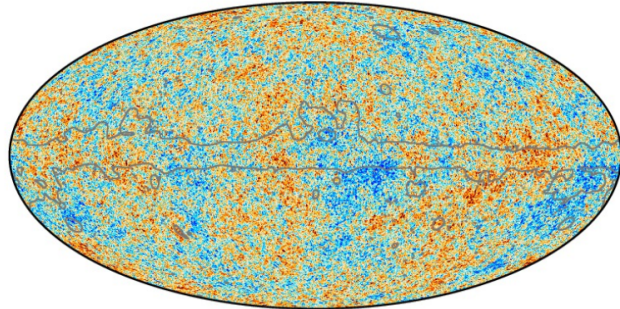
$$\frac{\Delta P_m}{P_m} \sim \underline{9.8} \frac{\Omega_\nu}{\Omega_m}$$

Brandbyge, Hannestad, Haugballe & Thomsen 2008;
Bird, Viel, Haehnelt 2012; etc.

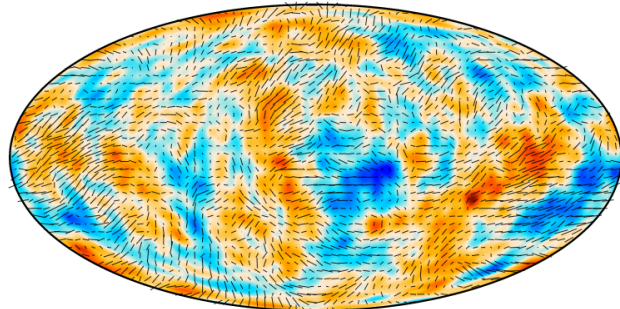
- **Not a closed topic!** A lot of ongoing research on how to account for massive neutrinos on nonlinear scales.

1a. Neutrino masses and Planck 2018

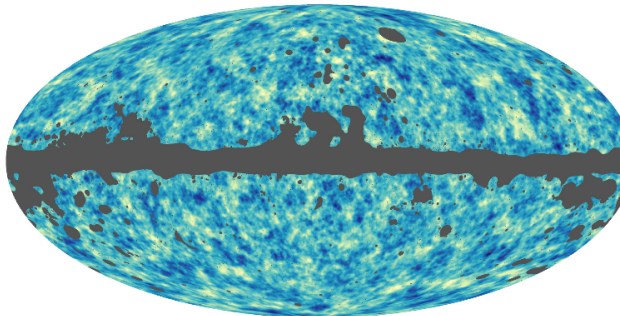
Three CMB observables...



-300 300 μK



160 μK



-0.0016 0.0016

Temperature:

- Neutrino mass signatures.
- Cosmic-variance-limited to $\ell \sim 2000$ since 2013 (i.e., nothing more to be done here)

Polarisation:

- **No independent neutrino mass signature.**
- Low multipoles lifts A_s - τ degeneracy, which helps to tighten other parameter constraints.

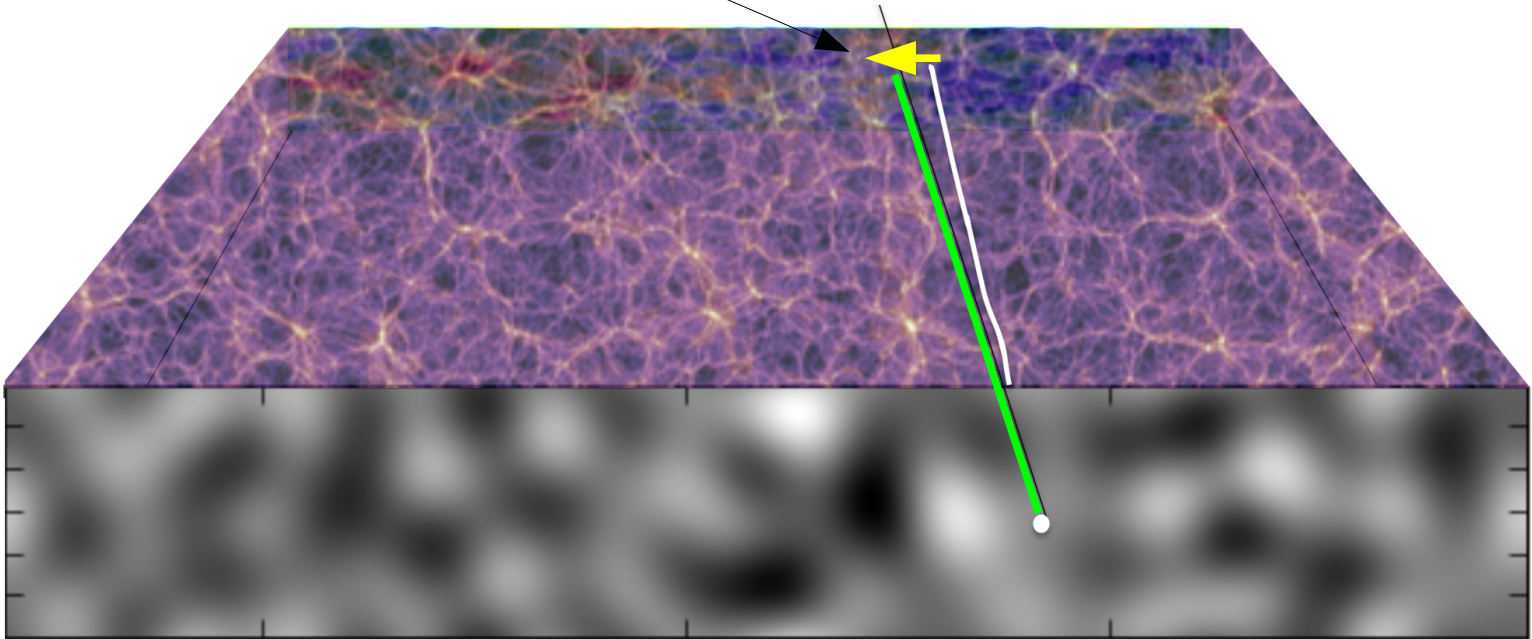
Lensing potential:

- Secondary observable reconstructed from temperature (present) and/or polarisation (future) maps.
- Contains **independent neutrino mass signatures.**

Weak lensing of the CMB: Lensing potential...

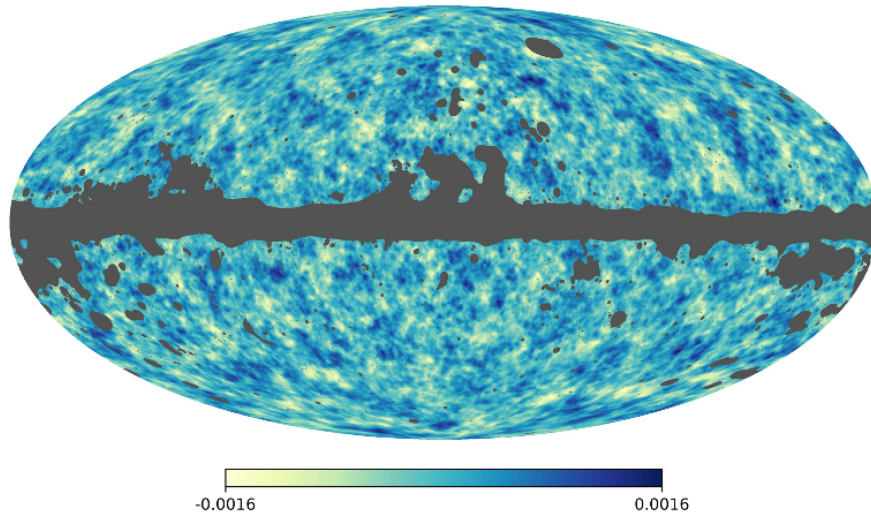
CMB photons are deflected by the intervening matter distribution, by an amount proportional to the **projected matter density** in a direction.

$$\text{Projected matter density} \sim \nabla \cdot d(\hat{\mathbf{n}})_{\text{lensing}} = \int_0^{r^{\text{CMB}}} dr \overline{W}(r)_{\text{geometry}} \delta(\hat{\mathbf{n}}, r)_{\text{density}}$$



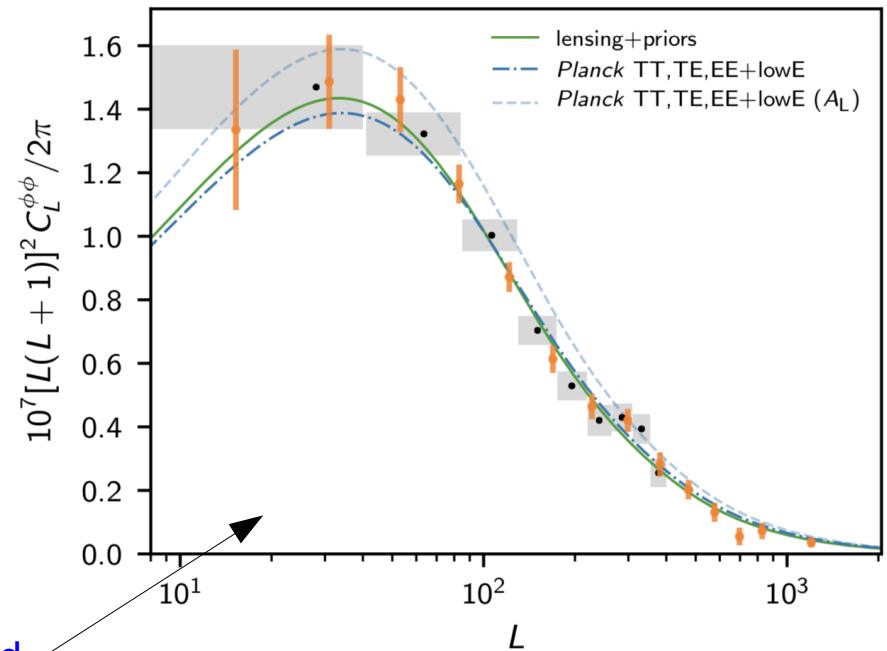
Weak lensing of the CMB: Lensing potential...

Projected matter density (or, equivalently, the lensing potential) reconstructed from the CMB temperature 4-point correlation function.



Line-of-sight integral of the 3D matter power spectrum weighted by geometric factors; dominated by contributions at $z \sim 3-4$

Lensing potential power spectrum



Akrami et al. [Planck] 2018

Constraints on the neutrino mass sum...

Λ CDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

Low- ℓ polarisation only

		+Lensing	+BAO (non-CMB)	+Lensing+BAO
Planck2018 TT+lowE	0.54	0.44	0.16	0.13
2015 numbers	0.72	0.68	0.21	n/a

Plus high- ℓ polarisation

Planck2018 TT +lowE+TE+EE	0.26	0.24	0.13	0.12
Planck2018 TT +lowE+TE+EE [CamSpec]	0.38	0.27	n/a	0.13
2015 numbers	0.49	0.59	0.17	n/a

Two different high- ℓ
likelihood functions

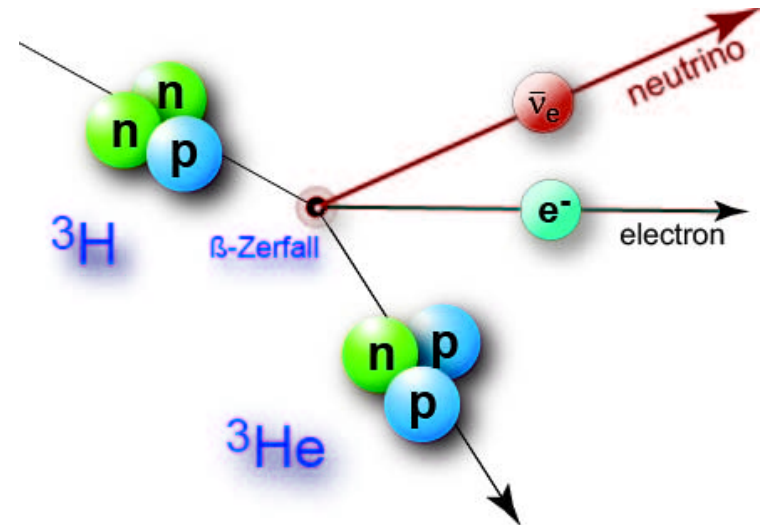
Planck2015 TT+lowP+Lya $\sum m_\nu < 0.13$ eV

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Palanque-Delabrouille et al. 2015

Cf upper limit from tritium β -decay endpoint spectrum...

Current cosmological constraints on the neutrino mass sum is about **a factor of 15 better** than laboratory constraints.



$$m_e \equiv \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2} < 1.1 \text{ eV}$$

Aker et al. [KATRIN] 2019

Equivalent constraint on the neutrino mass sum:

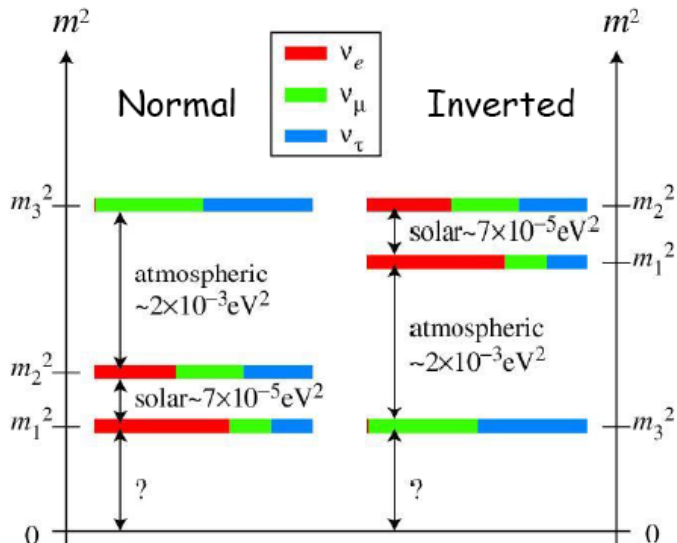
$$\sum m_\nu < 3 \text{ eV}$$



Caveat 1 of 2 : which mass hierarchy...

Bounds on the mass sum **do depend to an extent on the neutrino mass hierarchy** assumed in the fit.

- Using **different mass orderings** in the fit actually changes the bounds by up to $\sim 40\%$.
- Λ CDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV]:



$$\sum m_\nu < 0.121 \text{ eV} \quad \text{Degenerate}$$

$$\sum m_\nu < 0.146 \text{ eV} \quad \text{Normal hierarchy}$$

$$\sum m_\nu < 0.172 \text{ eV} \quad \text{Inverted hierarchy}$$

Planck 2018 TT+TE+EE+
lowE+lensing + BAO

Roy Choudhury & Hannestad 2019

Caveat 2 of 2: model dependence...

All bounds so far have been derived from a Λ CDM+neutrino mass 7 parameter fits.

- Can make the fit model more complicated in order to “relax” the bounds.

	Model	Degenerate	Normal	Inverted
	Baseline ΛCDM+Σm_ν	0.121	0.146	0.172
Primordial tensors	+ r	0.115	0.142	0.167
Dynamical dark energy	+ w	0.186	0.215	0.230
	+ $w_0 w_a$	0.249	0.256	0.276
Spatial curvature	+ $w_0 w_a, w(z) > -1$	0.096	0.129	0.157
	+ Ω_k	0.150	0.173	0.198

Roy Choudhury
& Hannestad 2019

- However, this sort of game doesn't gain you that much. (Some relaxation, but it's not like you can squeeze in a 1 eV neutrino.)
- It doesn't always work in the desired direction.

Take home message...

- The tightest post-Planck 2018 cosmological bound on the neutrino mass sum from a 7-parameter fit **remains at around 0.13-0.17 eV** (95% C.L.), depending on the **mass ordering** used in the fit.
- It is however arguably **far more robust** than the existing Lyman-alpha bound formally of the same value.
 - Quasi-linear observables calculable from linear theory.

2. Effective number of neutrinos

=

Search for light BSM relics

Energy density in light relics...

Any light (sub eV-mass) thermal relic that

- decouples while ultra-relativistic and before $z \sim 10^6$
- does **not** interact with itself or anything else after decoupling

will behave (more or less) like a neutrino as far as the CMB and LSS are concerned.

Smallest relevant scale enters the horizon

$$\begin{aligned}
 \sum_i \rho_{\nu, i} + \rho_X &= N_{\text{eff}} \left(\frac{7}{8} \frac{\pi^2}{15} T_{\nu}^4 \right) \\
 &= (3.043 + \Delta N_{\text{eff}}) \rho_{\nu}^{(0)}
 \end{aligned}$$

Three SM neutrinos

Other light BSM relics, e.g., light sterile, neutrinos, axions, hidden photons, etc.

Neutrino temperature per definition

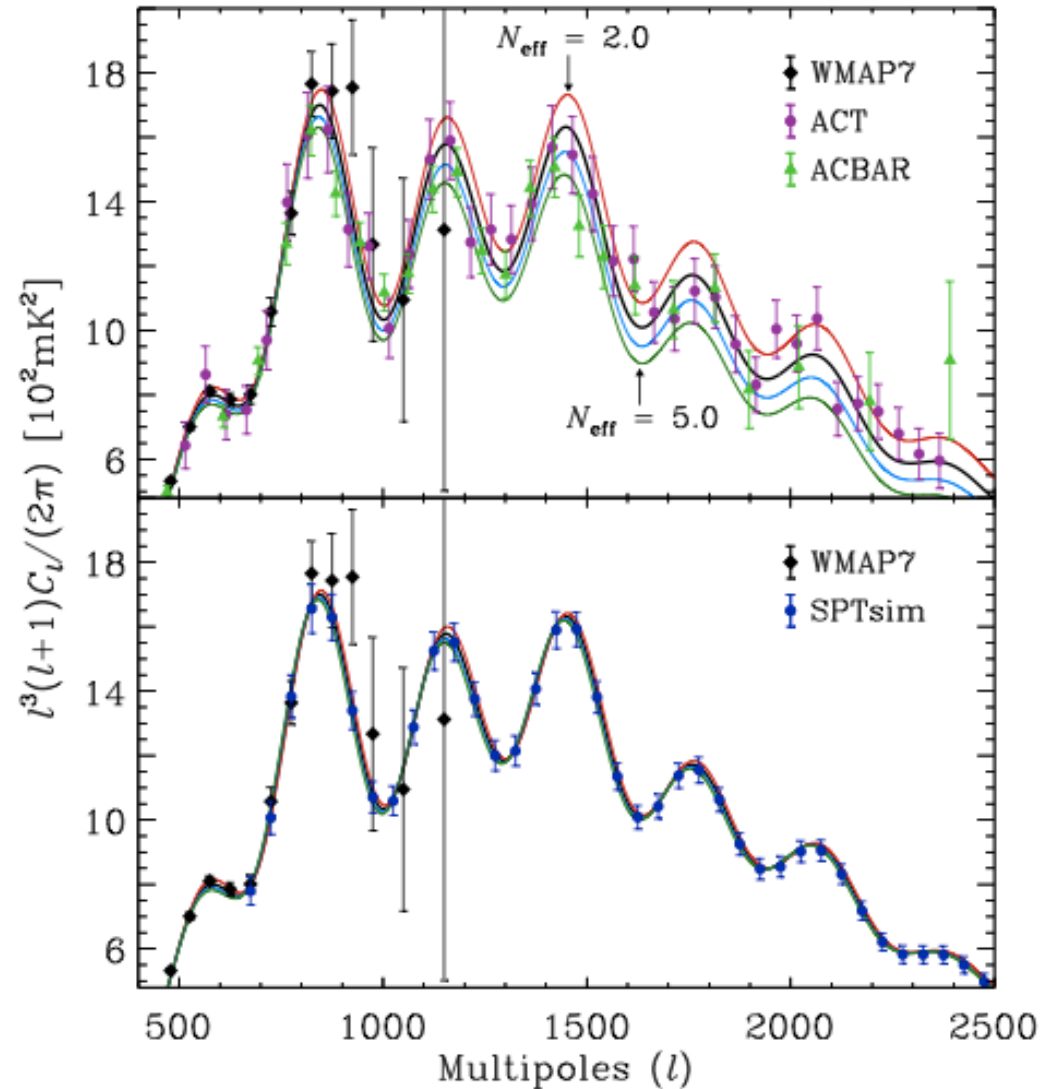
SM corrections from non-instantaneous decoupling, finite-temperature QED, and flavour oscillations

See talk of J. Bennett this afternoon

Bennett, Buldgen, Drewes & Y³W 2019
Bennett et al. in prep

N_{eff} signatures in the CMB...

- **Matter-radiation equality** (odd peak height ratios)
- **Angular acoustic scale** (acoustic peak locations)
- **Anisotropic stress** (3rd peak shift)
- **Angular diffusion scale** (damping tail)
 - Measured by ACT since 2010; SPT since 2011; Planck since 2013
 - **Primary signature** in the Planck era.



Constraints on N_{eff} ...

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Planck-inferred N_{eff} **compatible with the standard value of 3.043** at better than 2σ .

Λ CDM+Neff 7-parameter fit	Planck 2018 (95%)	Planck2015 (95%)
TT+lowE	3.00 ^{+0.57} _{-0.53}	3.13±0.64
+lensing+BAO	3.11 ^{+0.44} _{-0.43}	n/a
TT+lowE+TE+EE	2.92 ^{+0.36} _{-0.37}	2.99±0.40
+lensing+BAO	2.99 ^{+0.34} _{-0.33}	n/a

Λ CDM+Neff+neutrino mass
8-parameter fit

$$N_{\text{eff}} = 2.96^{+0.34}_{-0.33}$$

$$\sum m_\nu < 0.12 \text{ eV}$$

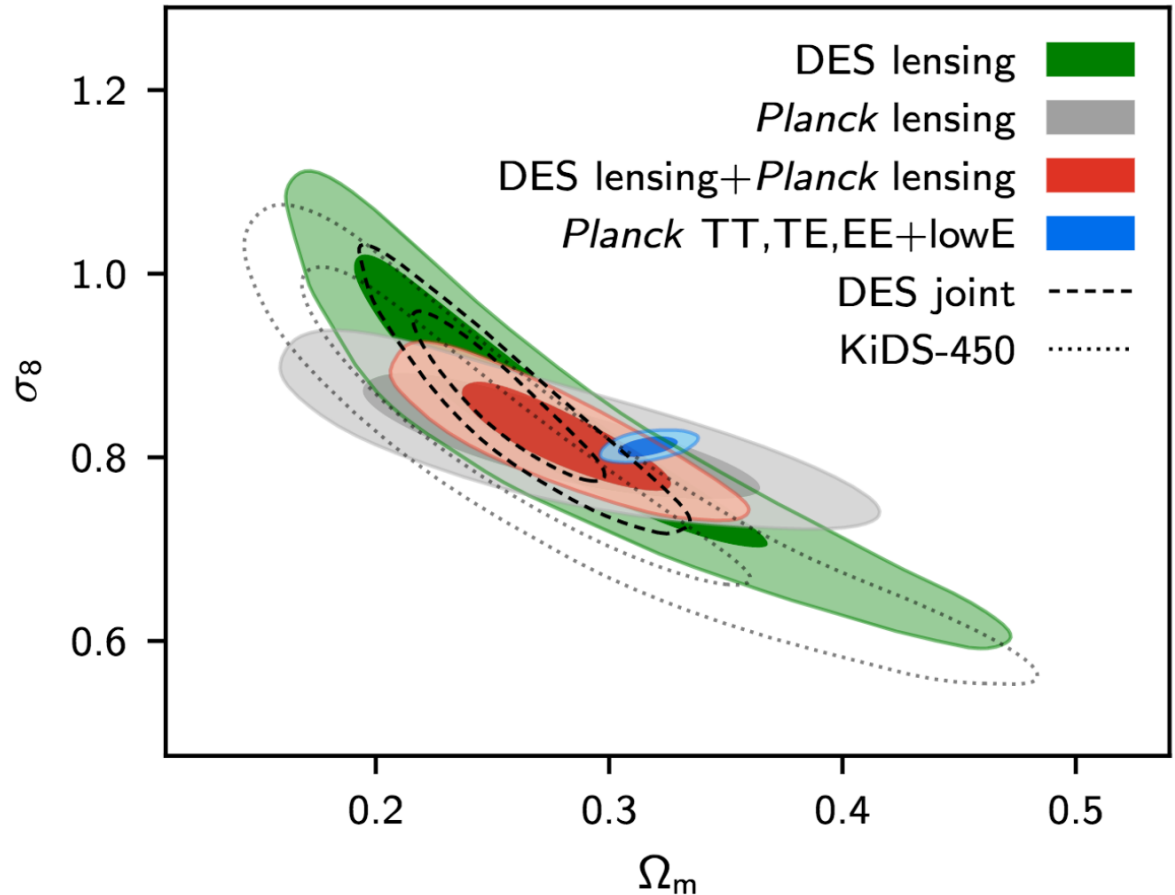
95% C. L.
Planck TT+TE+EE+lowE
+lensing+BAO

3. Flies in the ointment:
tension between CMB and other
astrophysical observations...

Small fly: the σ_8 - Ω_m discrepancy...

Cosmic shear measurements tend to prefer **lower values** of σ_8 or Ω_m than Planck.

- Mostly mild to modest discrepancy
- (One claim of 2.6σ discrepancy from KiDS [Joudaki et al. 2018](#))
- Appears amenable to improved treatment of lensing systematics.



Big fly: the H_0 discrepancy...

4.4 σ discrepancy between the Planck-inferred H_0 and local measurements:

- **TT+TE+EE+lowE+lensing**

$$H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

- **Local measurement:**

$$H_0 = 74.03 \pm 1.42 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

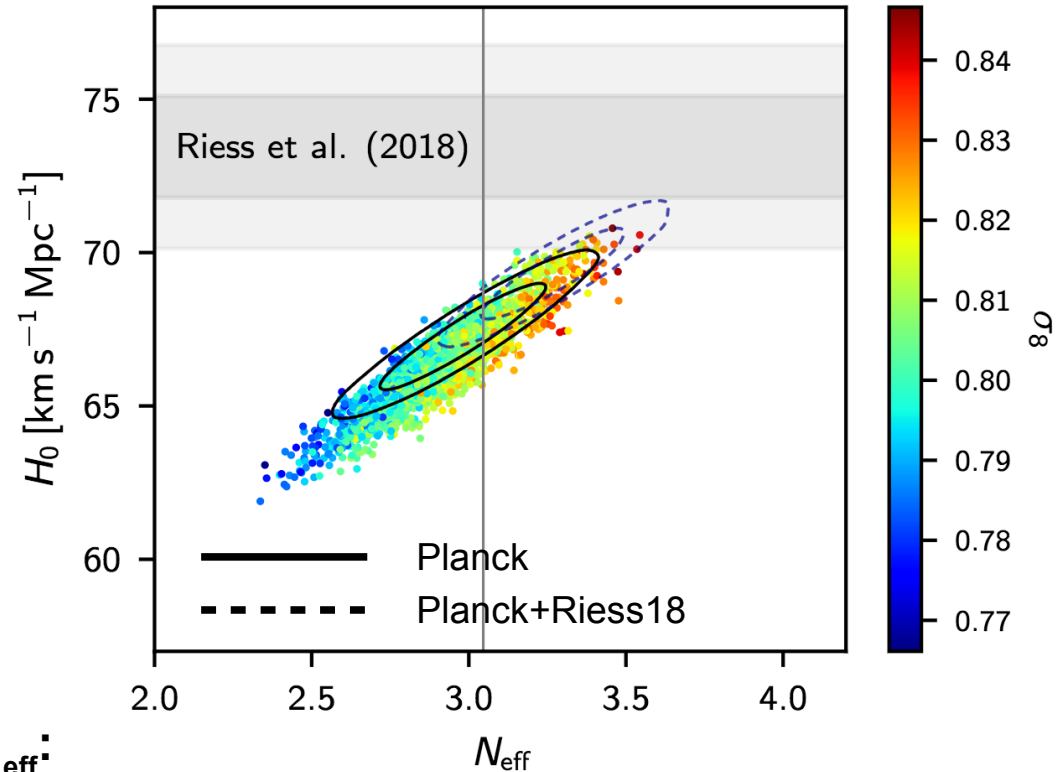
Riess et al. 2019

Joint Planck+Riess 2018 fit varying N_{eff} :

$$N_{\text{eff}} = 3.27 \pm 0.15$$

$$H_0 = 69.32 \pm 0.97 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

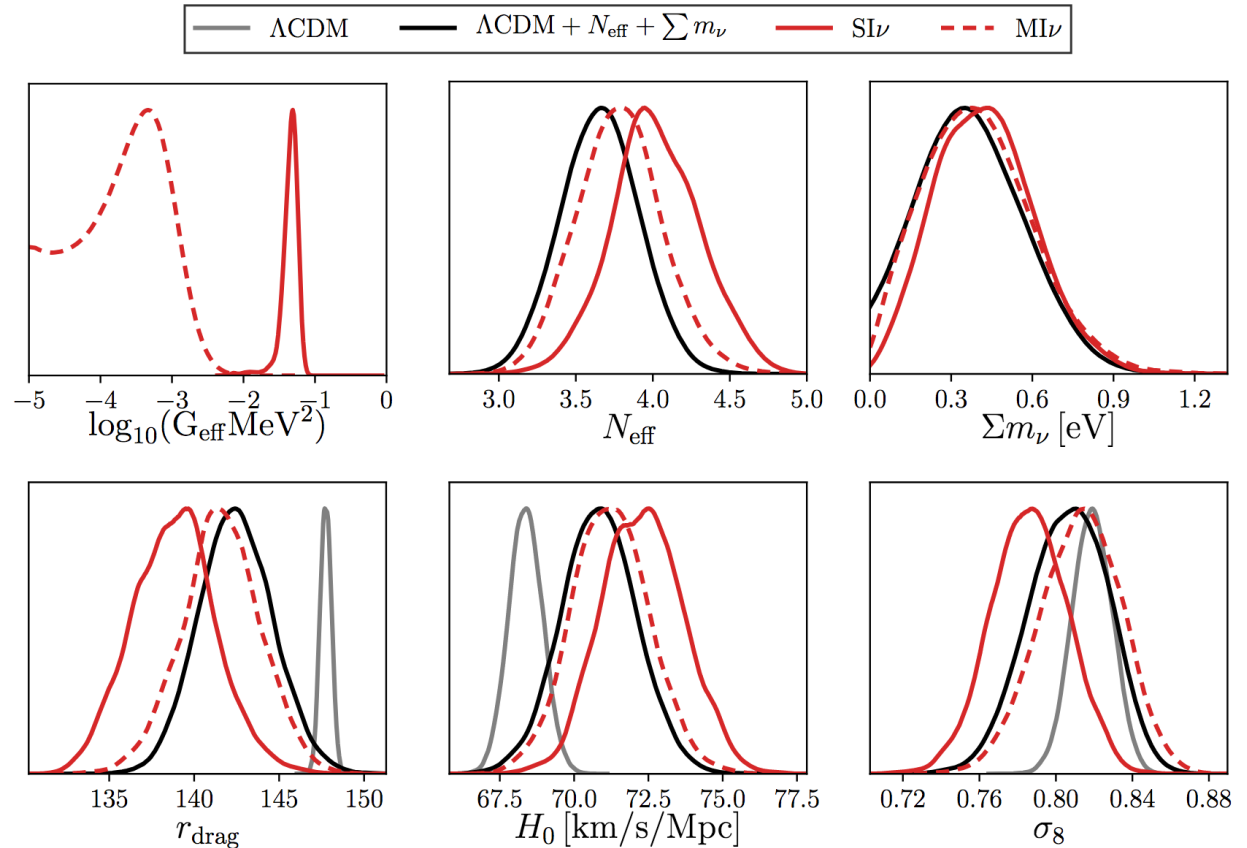
} 68% C. L.
Planck TT+TE+EE+lowE
+lensing+BAO+Riess



Neutrino self-interaction as a solution?

It has been claimed that cosmological data (TT+lens+BAO+HST) prefer a “strong” 4-fermion contact interaction amongst the neutrinos.

- **Strongly-interacting mode** appears to **alleviate both** the H_0 tension and the σ_8 - Ω_m discrepancy.



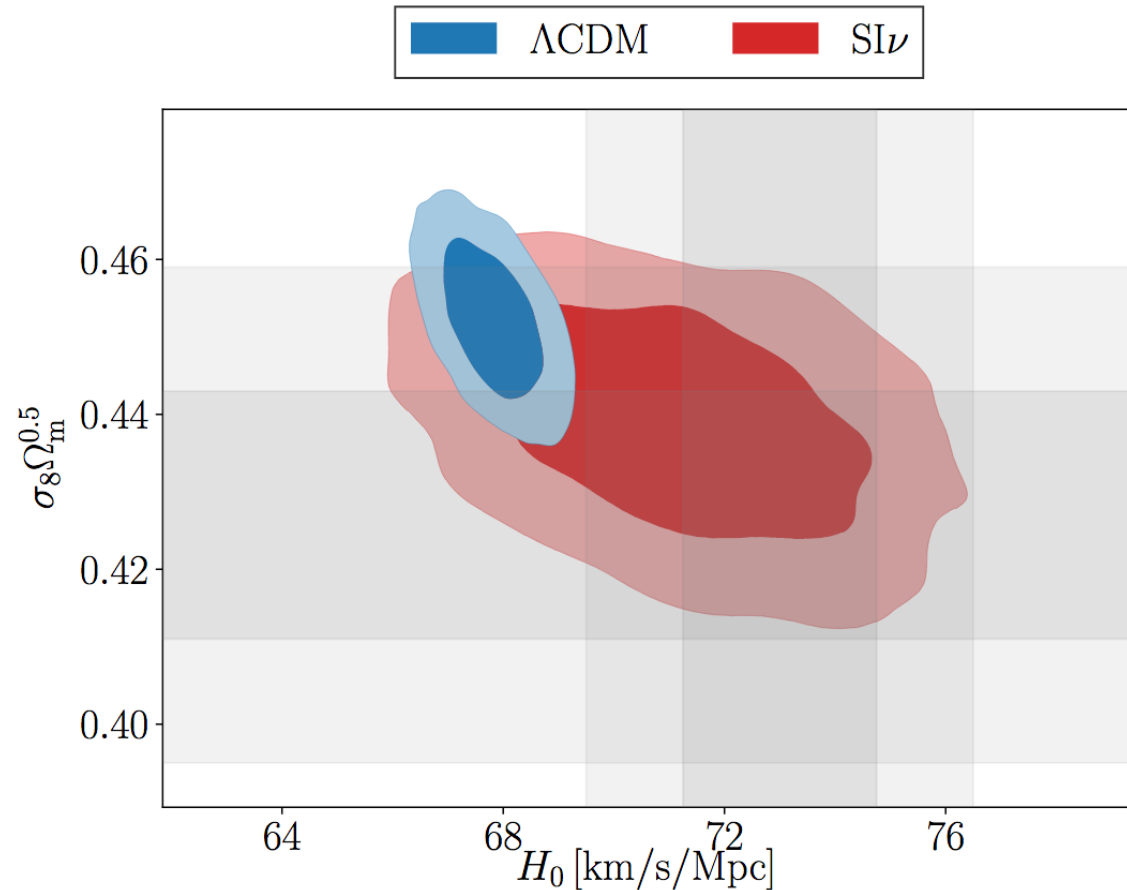
Kreisch, Cyr-Racine & Dore 2019

Also Oldengott, Tram, Rampf & Y³W 2017; Lancaster, Cyr-Racine, Knox & Pan 2017; Escudero & Witte 2019; Blinov, Kelly, Krnjaic & McDermott 2019

Neutrino self-interaction as a solution?

It has been claimed that cosmological data (TT+lens+BAO+HST) prefer a “strong” 4-fermion contact interaction amongst the neutrinos.

- **Strongly-interacting mode** appears to alleviate both the H_0 tension and the σ_8 - Ω_m discrepancy.



Summary...

- **Precision cosmological data** provide strong constraints on the neutrino mass sum.
 - The tightest post-Planck 2018 cosmological bound on the neutrino mass sum from a 7-parameter fit **remains at around 0.13-0.17 eV** (95% C.L.).
 - It is however far more robust than the existing Lyman-alpha bound (formally of the same value) because of issues of nonlinearity.
- **Extra neutrino species?**
 - No evidence at all.
 - But a **4.4 σ discrepancy** between Planck and local measurements of H_0 remains in Λ CDM, which cannot be resolved with $N_{\text{eff}} > 3$ alone.
- **Strongly-interacting neutrinos** as a solution to the H_0 tension?