Neutrino cosmology

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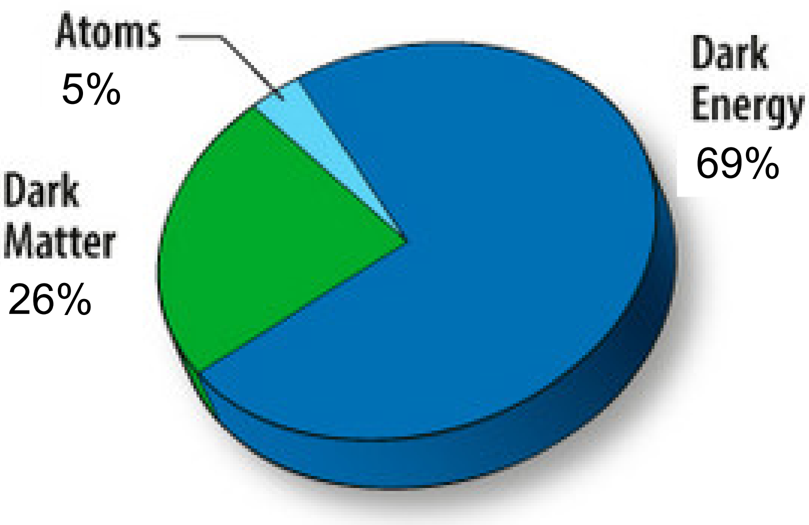
The concordance flat ΛCDM model...

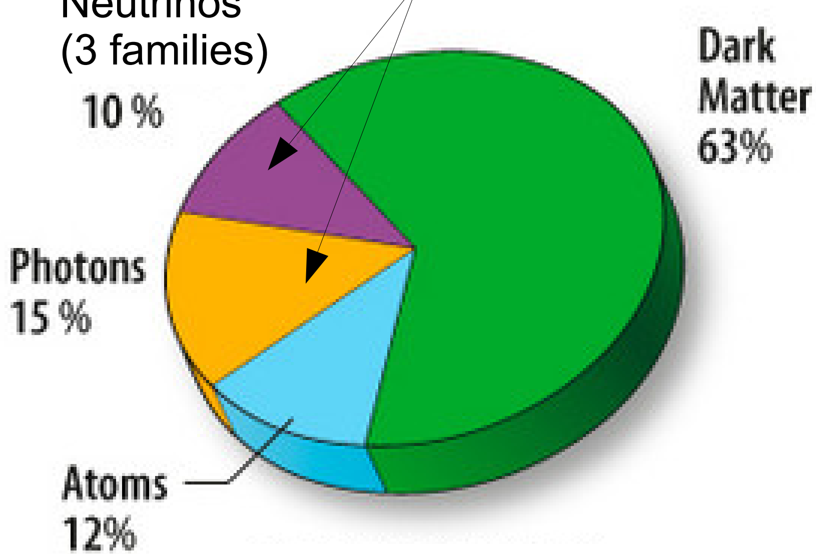
The simplest model consistent with **present observations**.

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

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



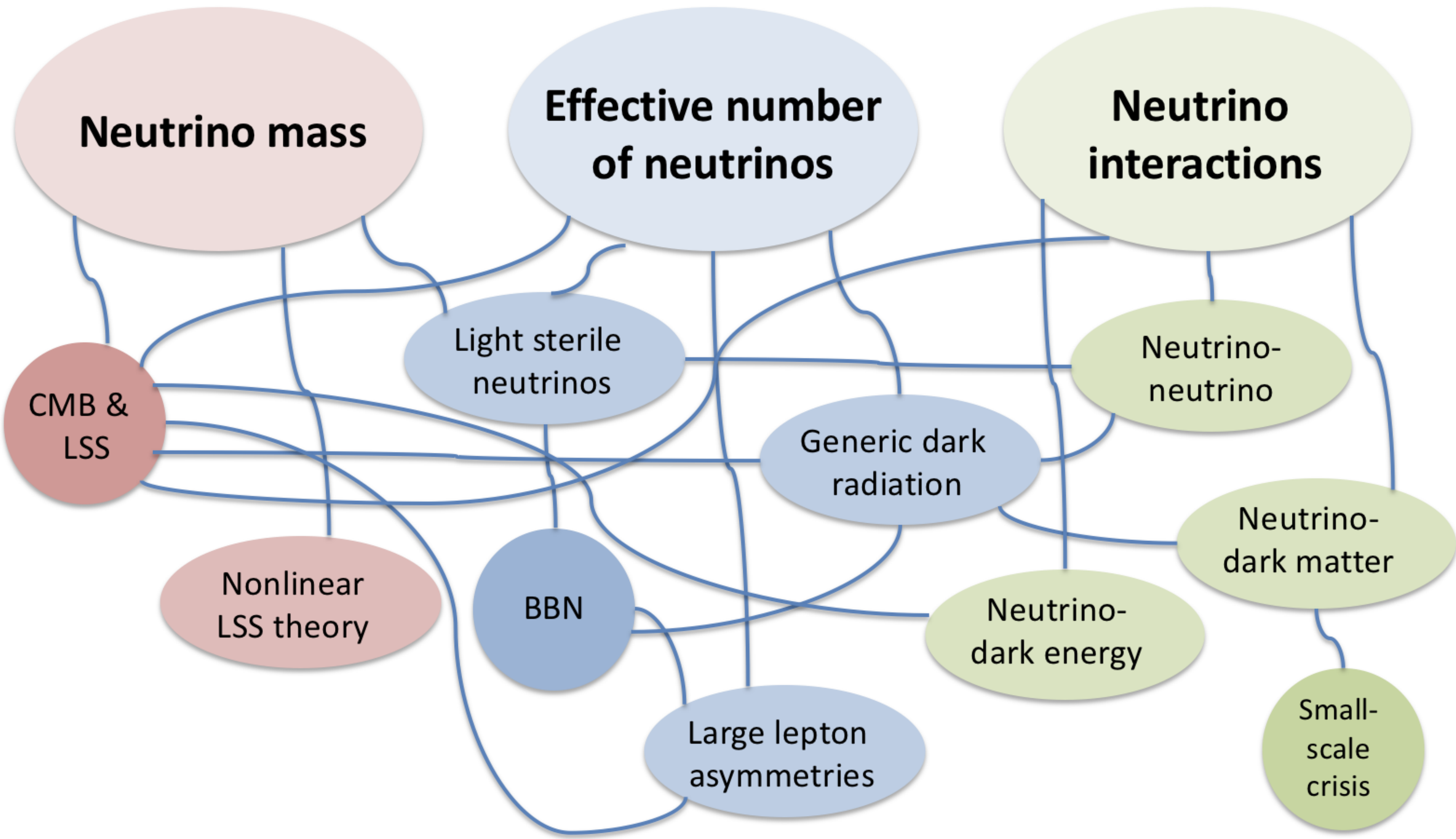
Composition today



13.4 billion years ago
(at photon decoupling)

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

The neutrino sector beyond ΛCDM...



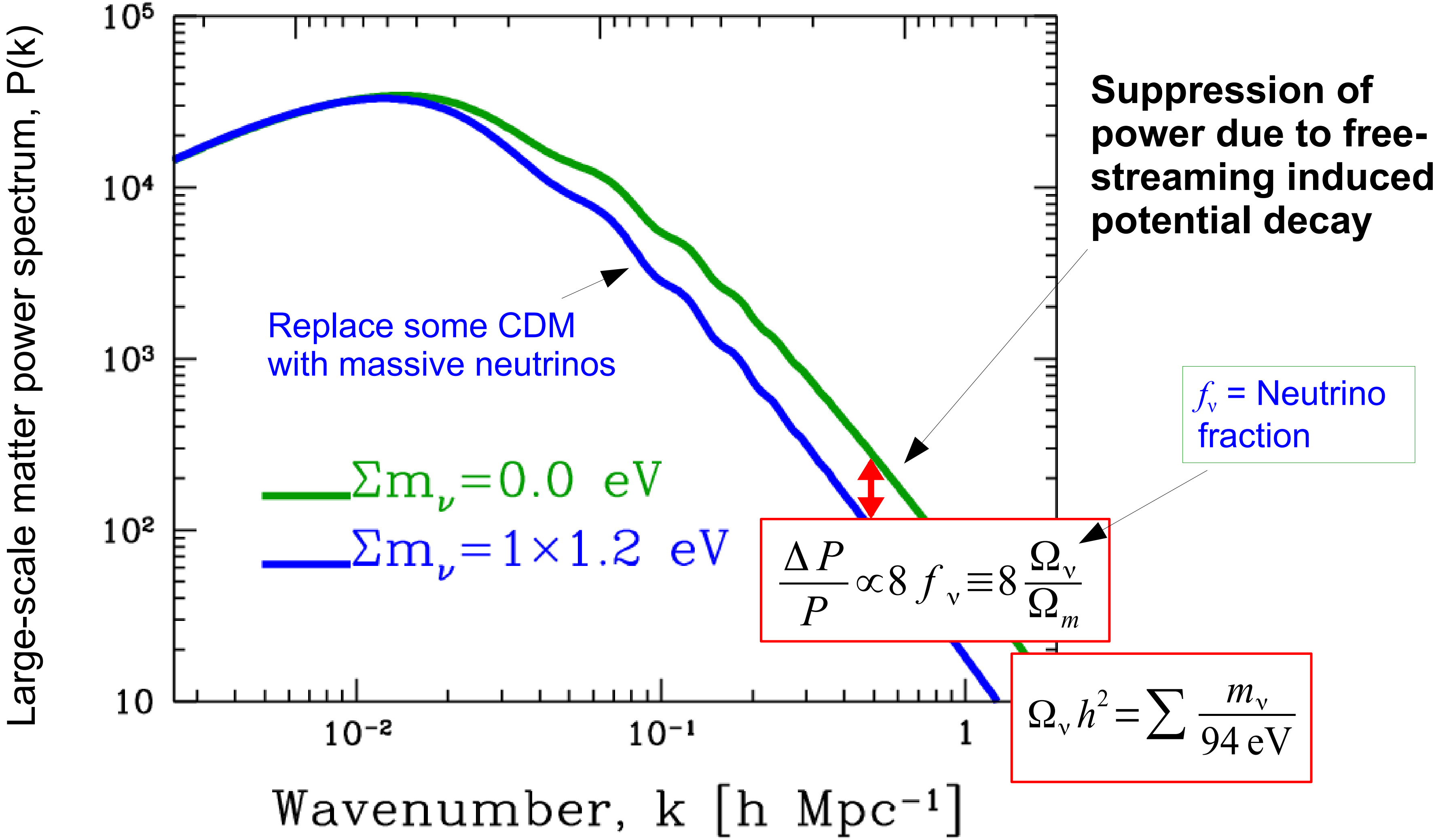
This talk...

Mainly an update on cosmological constraints on neutrino physics based on the final data release of the Planck CMB mission in July 2018 (official + independent analyses).

- Neutrino mass sum
- Effective number of neutrinos
- Tension with other astrophysical data sets (of potential interest to neutrino physics)

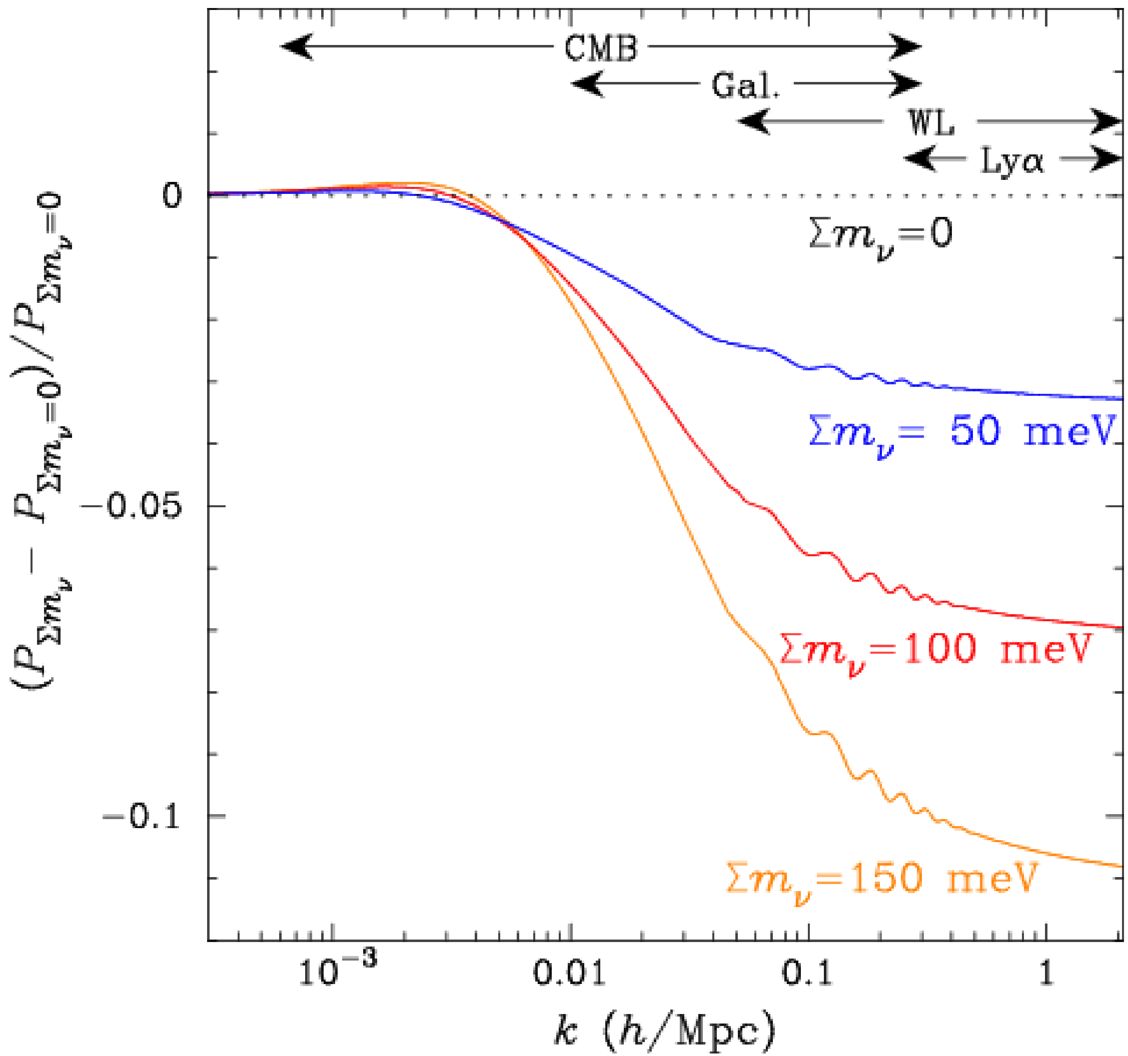
1. Neutrino masses and cosmology...

Neutrino masses in cosmology...



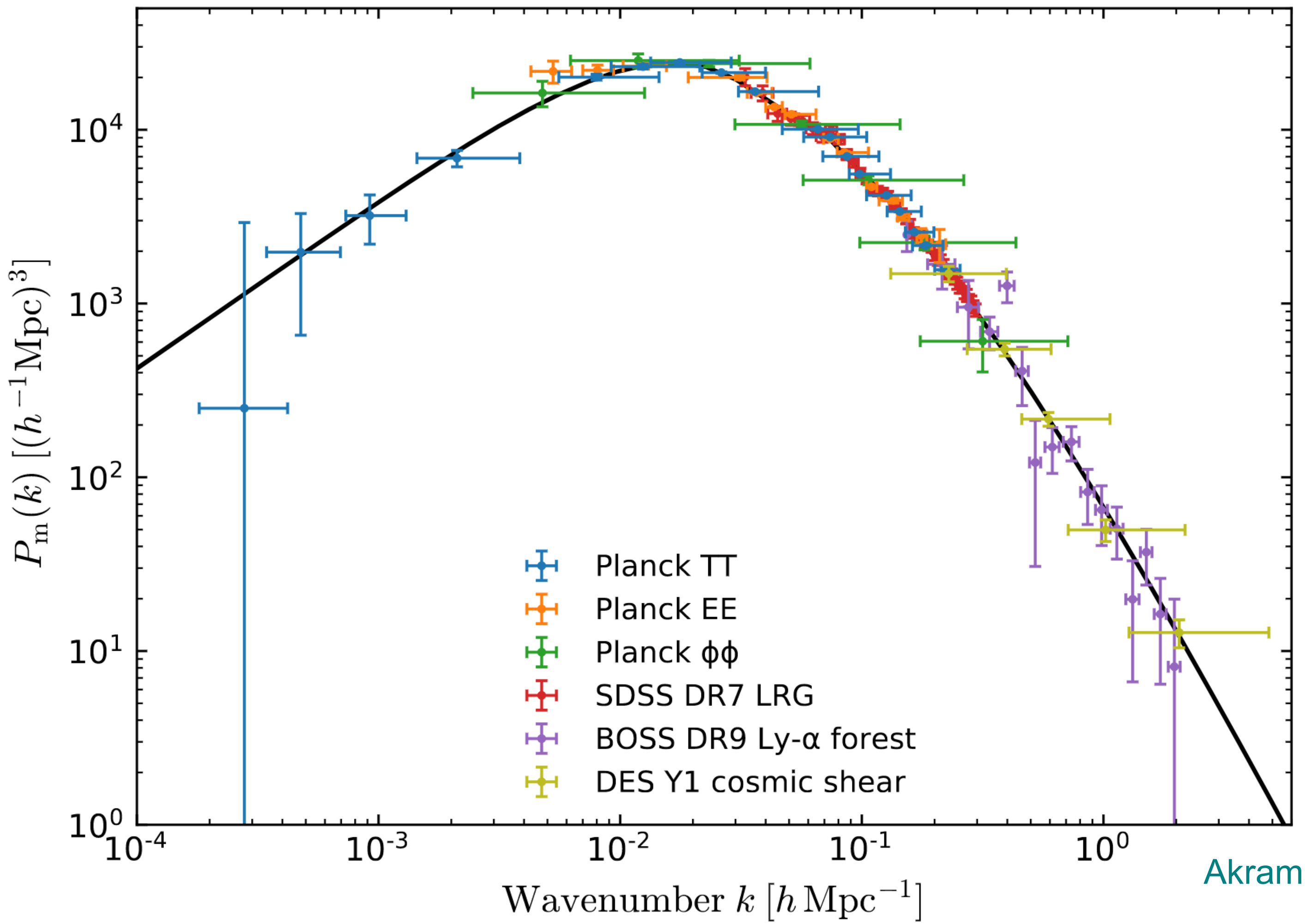
Neutrino masses in cosmology...

Relative power spectrum



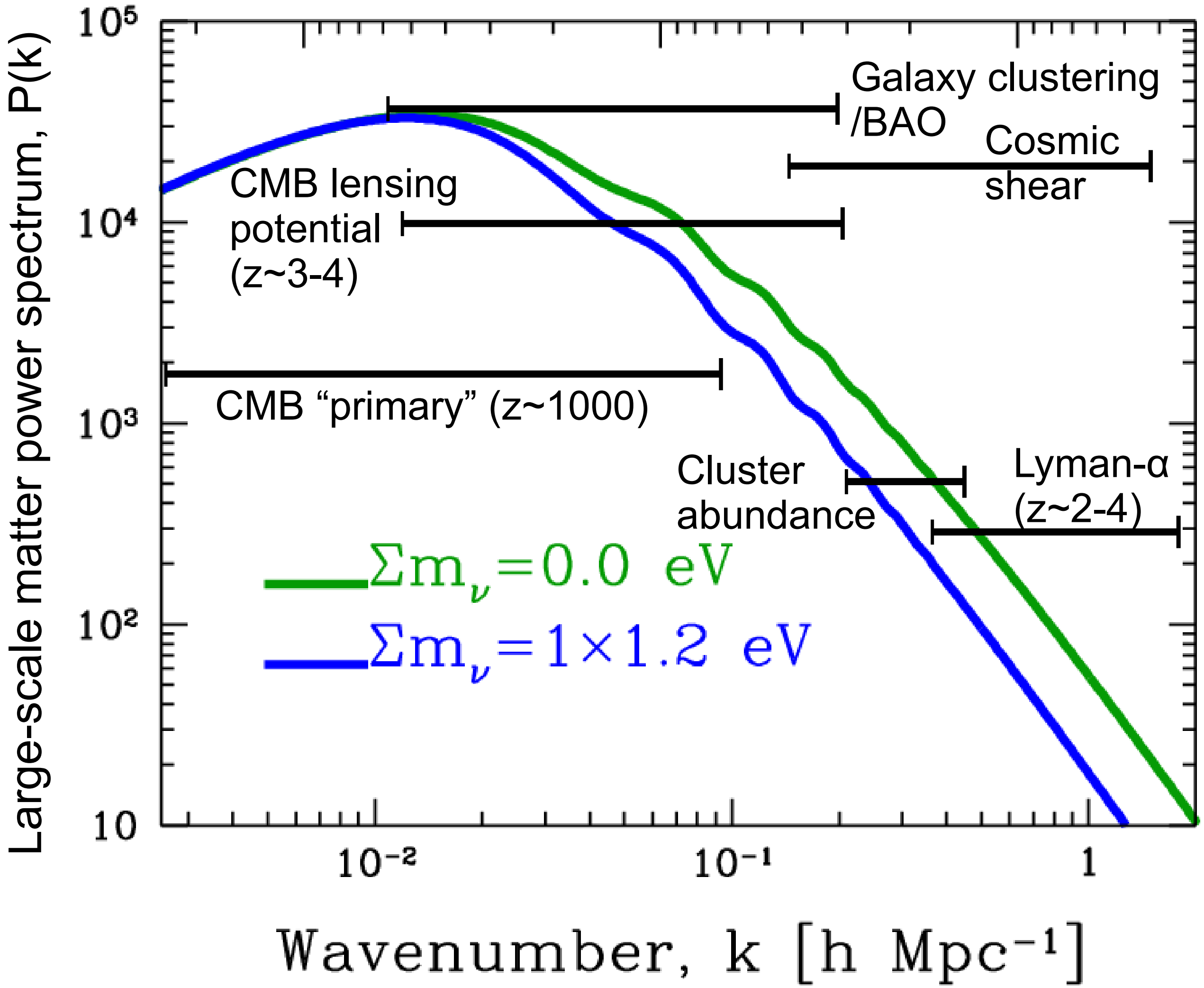
Who can measure it?

Large-scale power spectrum measurements circa 2018



Akrami et al. 2018

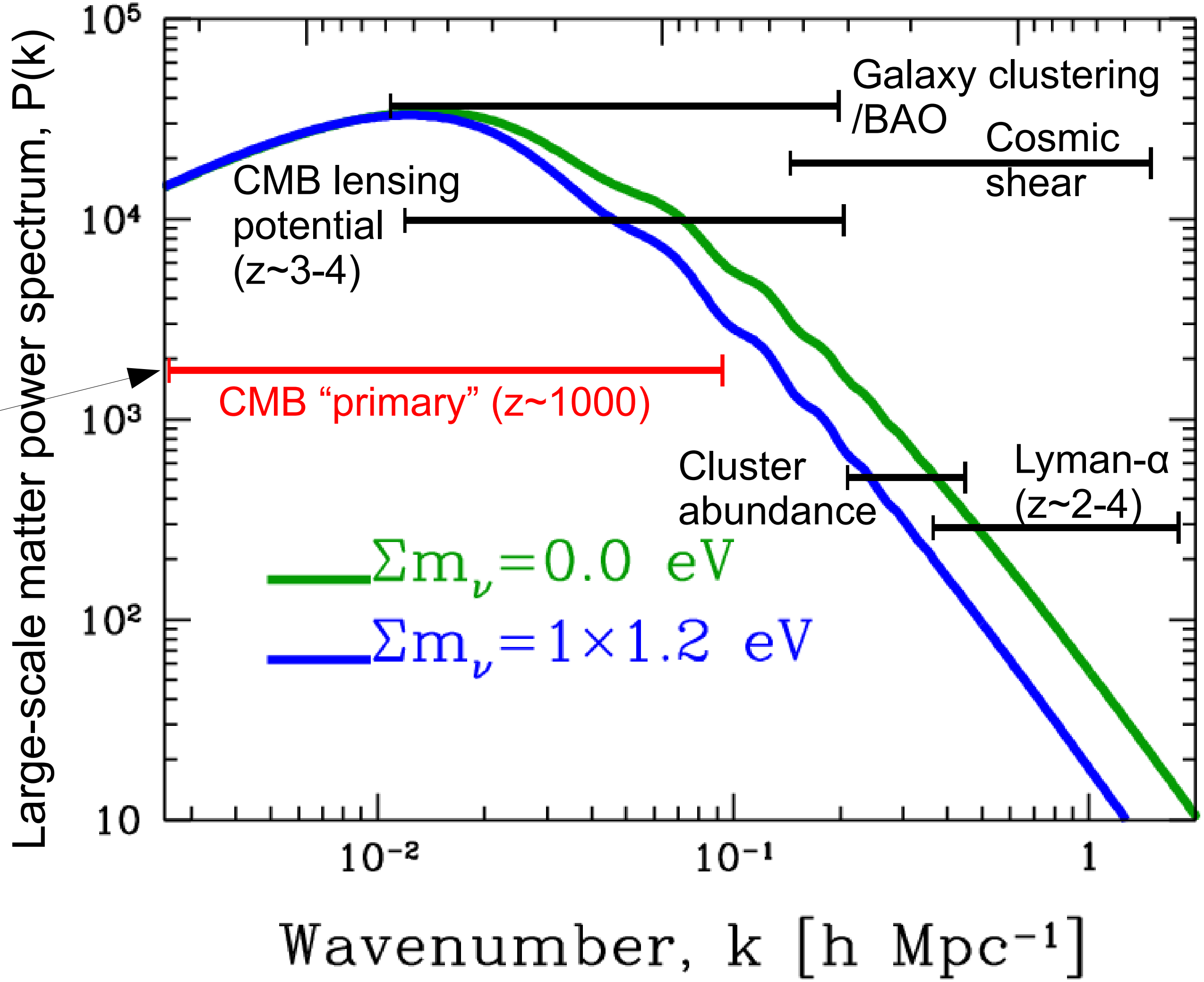
Who can measure it?



Who can measure it?

"Anchor"
ΛCDM model
parameters

$\omega_m, \omega_b, n_s,$
A_s, τ, h



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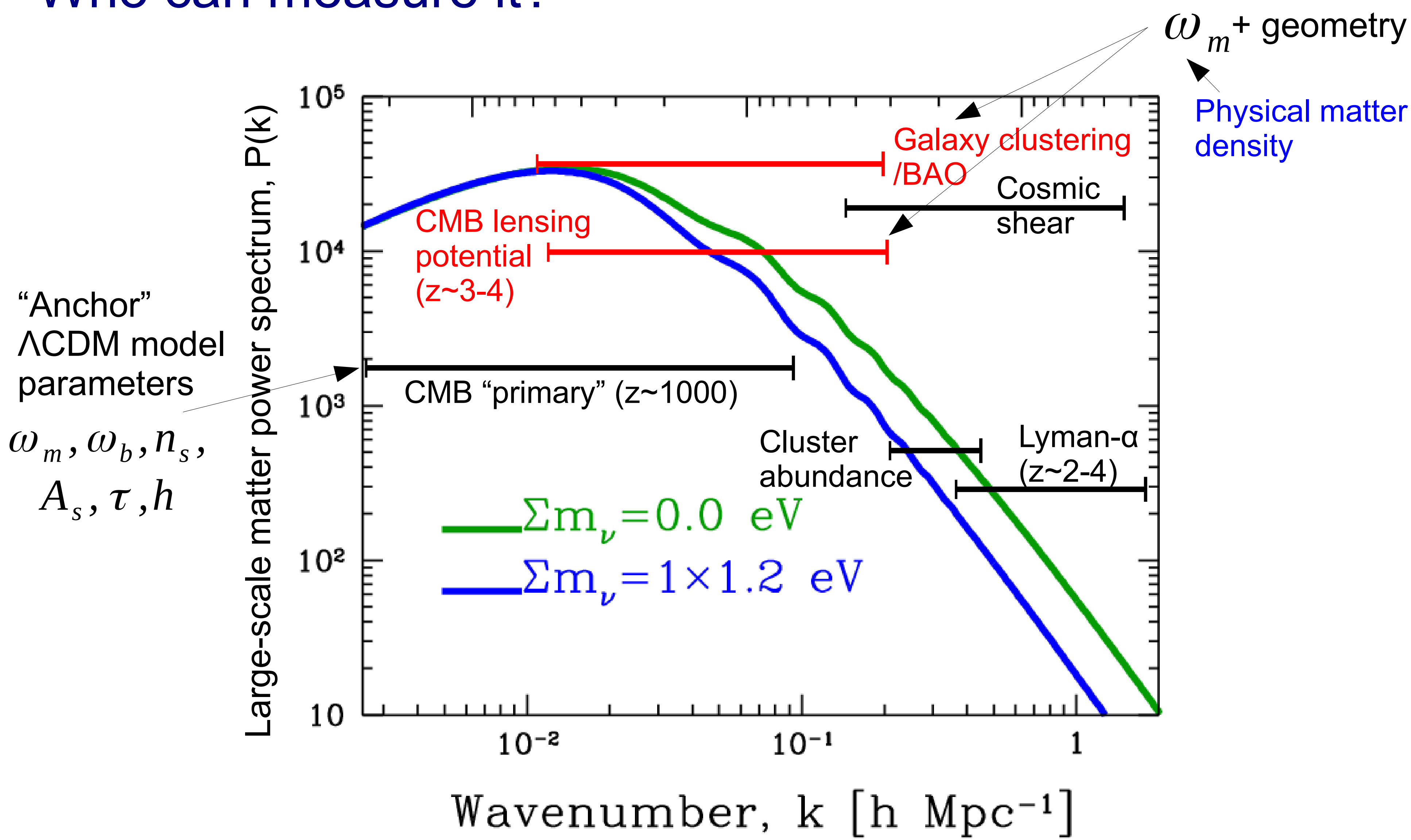

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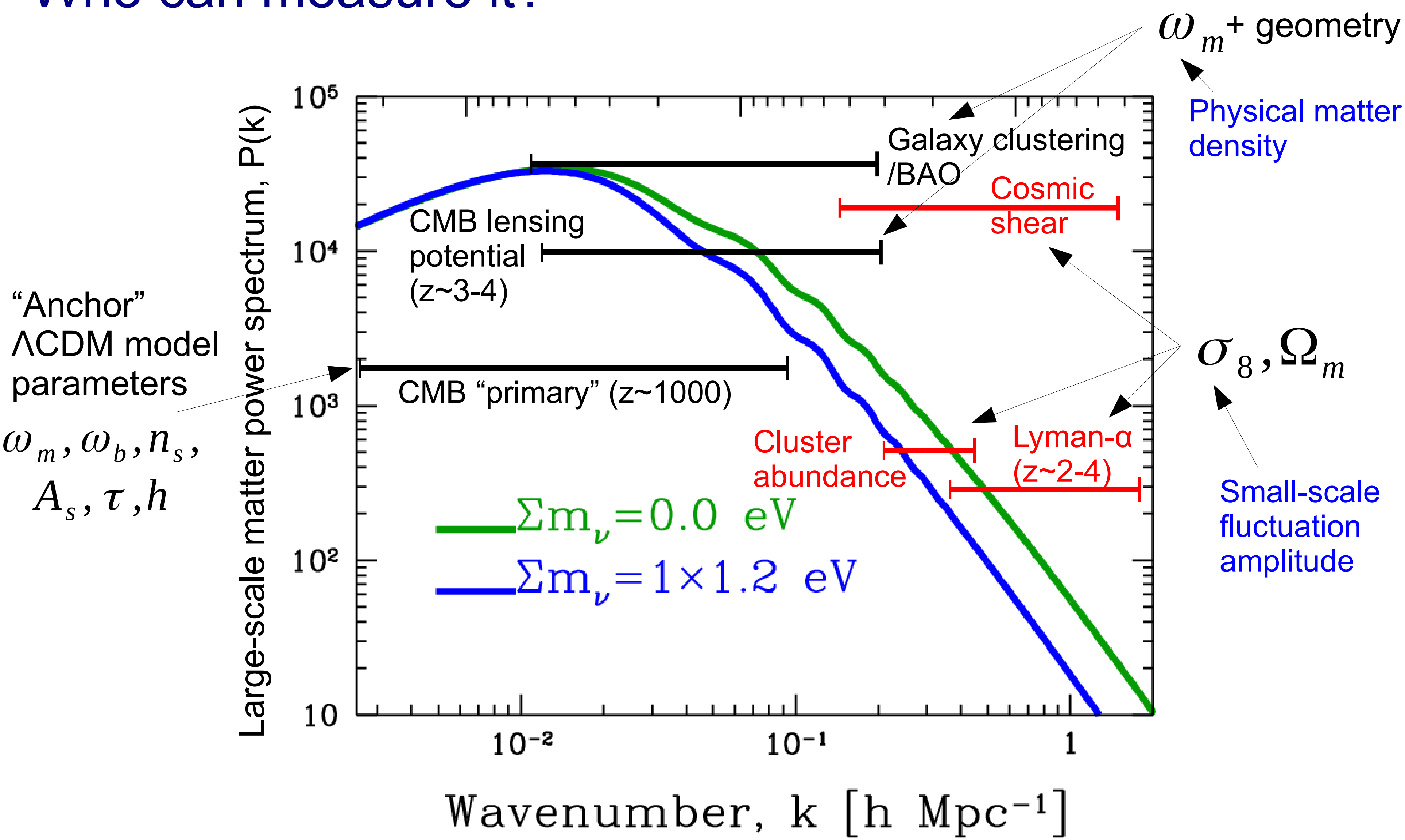
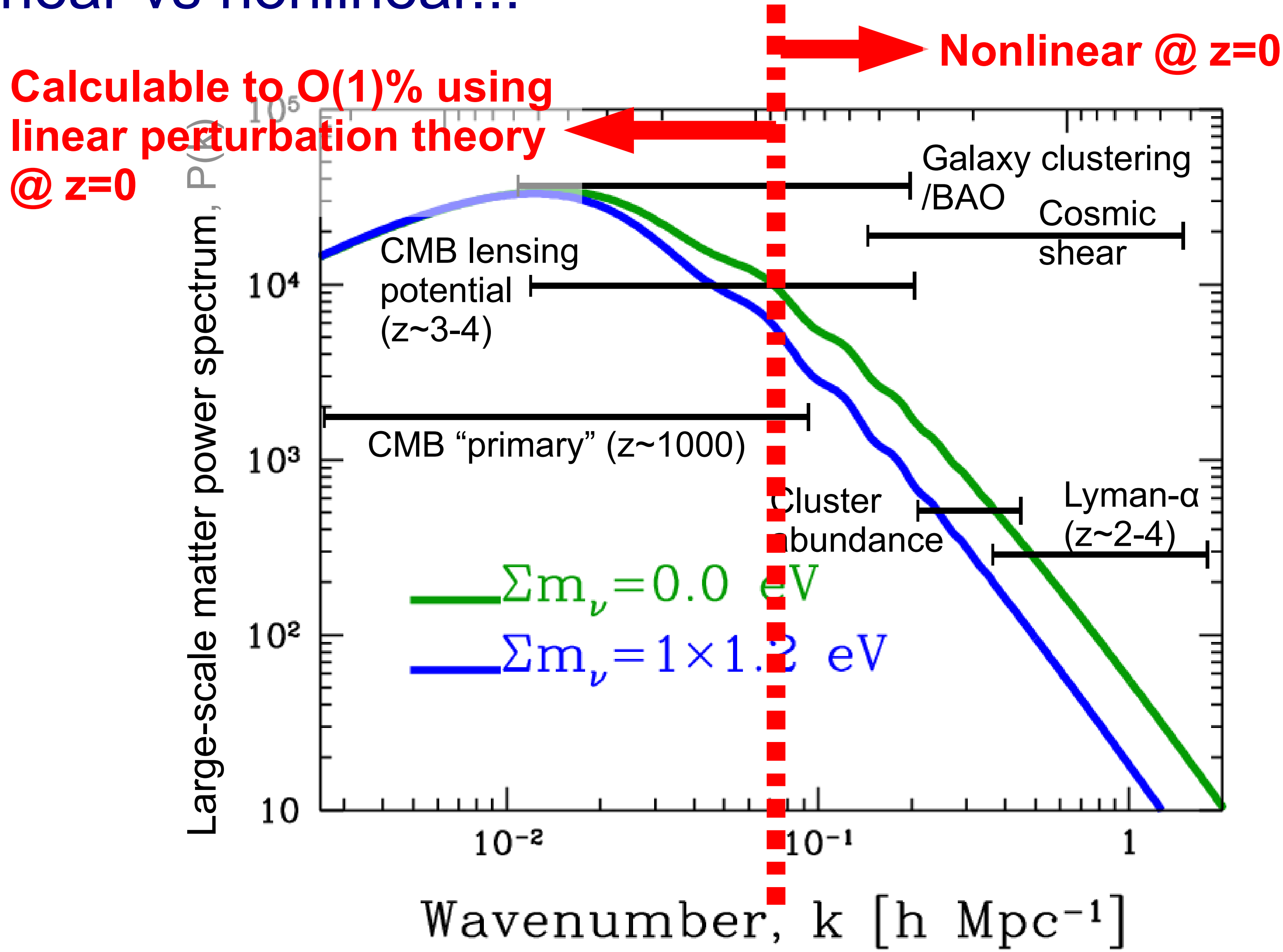


See also talk of C. Carbone

Linear vs nonlinear...



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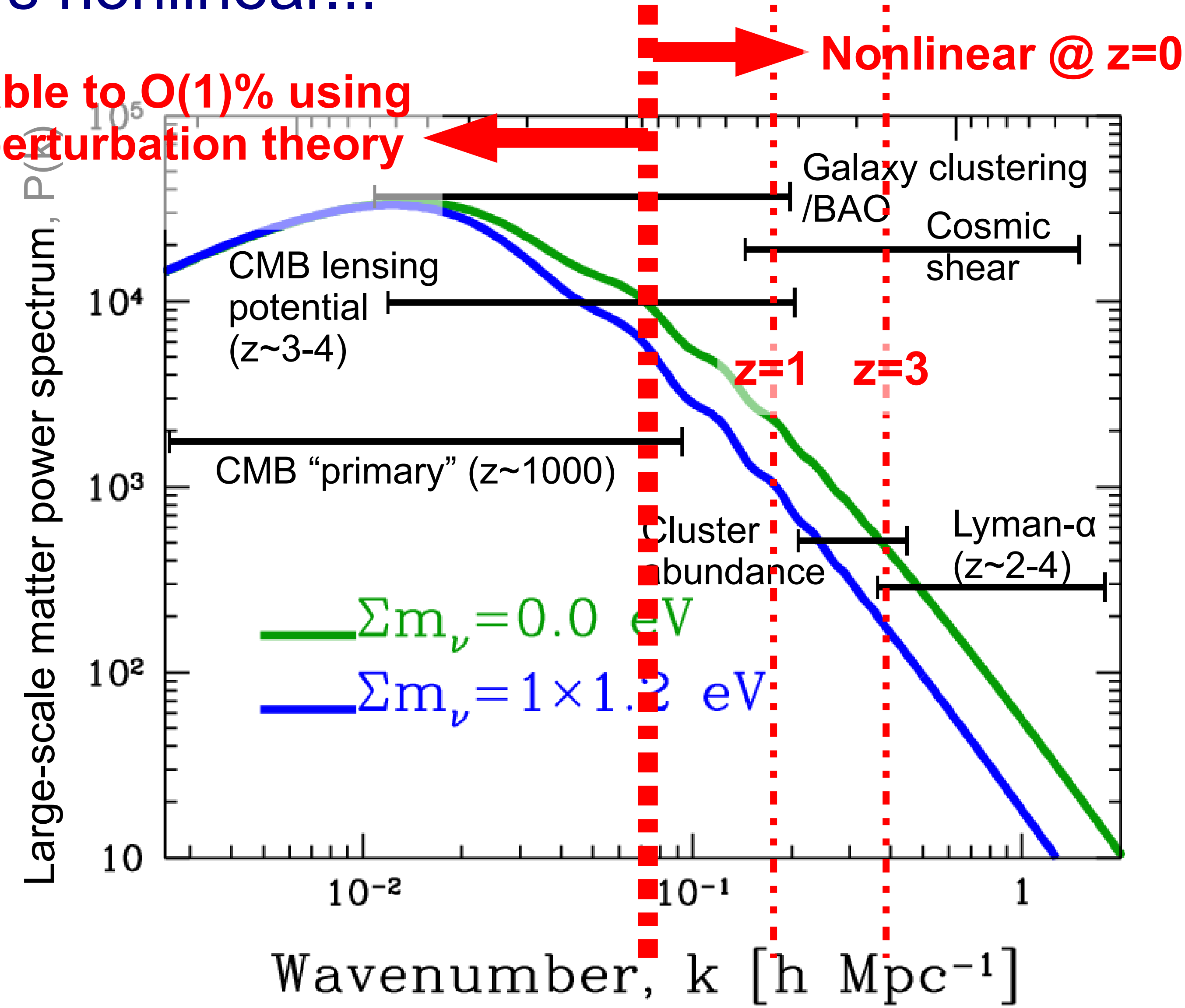
Linear vs nonlinear...

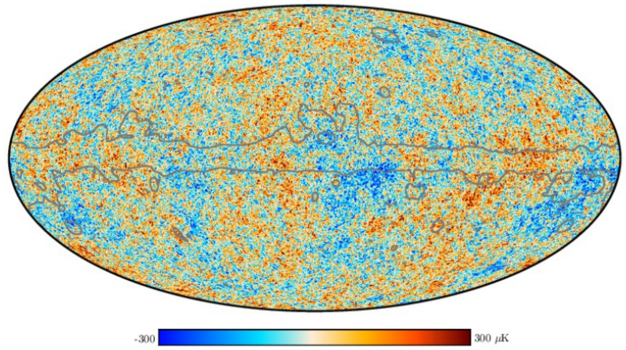


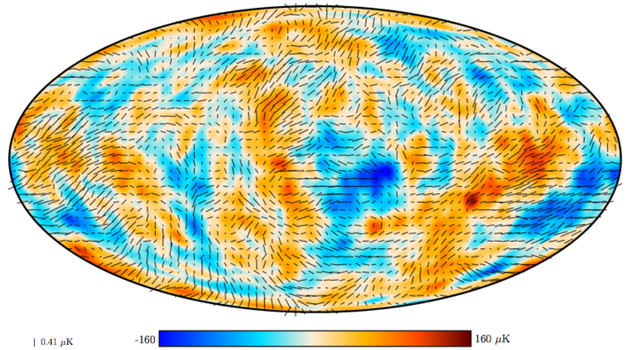
Types and degrees of nonlinearity...

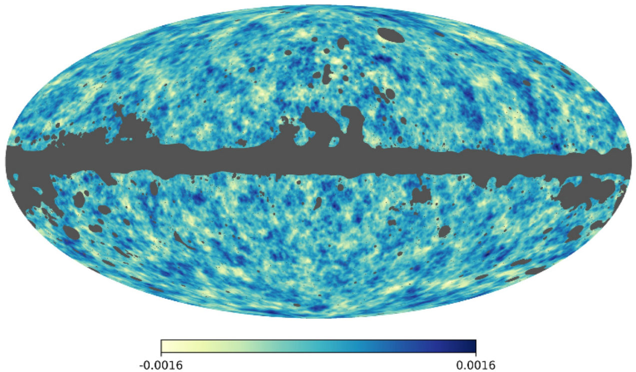
	Nonlinear DM (collisionless)	**Baryons @ k < O(1) Mpc^{-1}**	**Nonlinear tracer bias**	**Empirical proxy**
BAO	Mild	No	Mild	No
Cosmic shear	Yes	No	No	No
Galaxy power spectrum	Yes	No	Yes	No
Cluster abundance	Yes	No	No	Cluster mass vs X-ray temp or richness
Lyman alpha	Yes	Yes	No	No
Calculable from 1st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

1a. Neutrino masses and Planck 2018

Three CMB observables...







Temperature:

- Neutrino mass signatures.
- Cosmic-variance-limited to ℓ ~ 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.

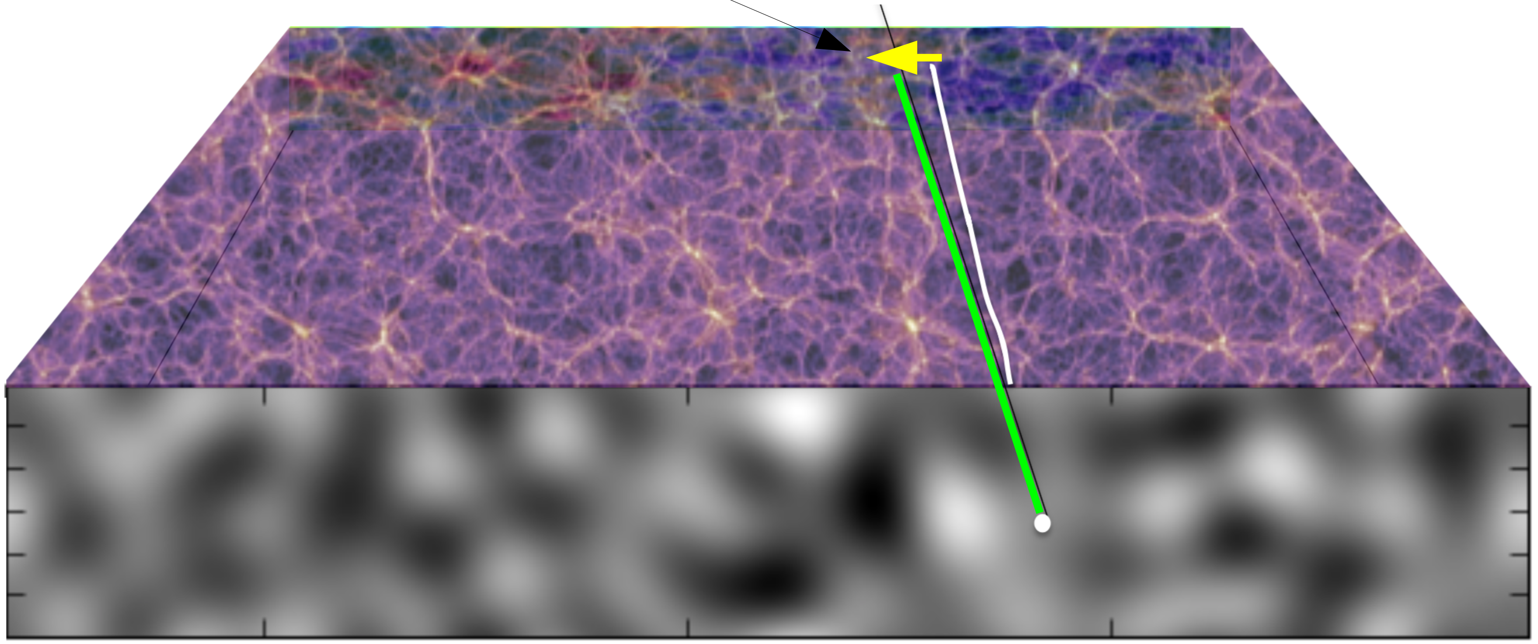
Lensing potential:

- 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.

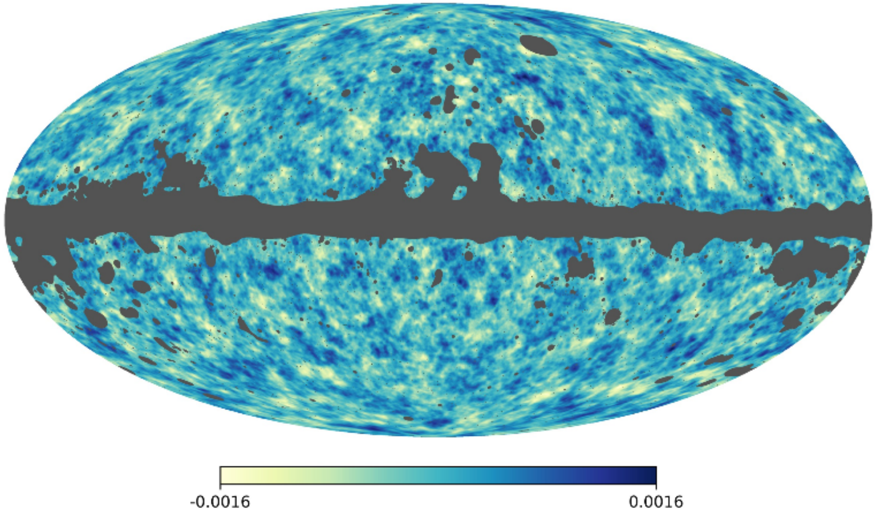
Projected matter density ~ $\nabla \cdot d(\hat{\mathbf{n}}) = \int_0^{r_{\rm CMB}} dr W(r) \delta(\hat{\mathbf{n}}, r)$



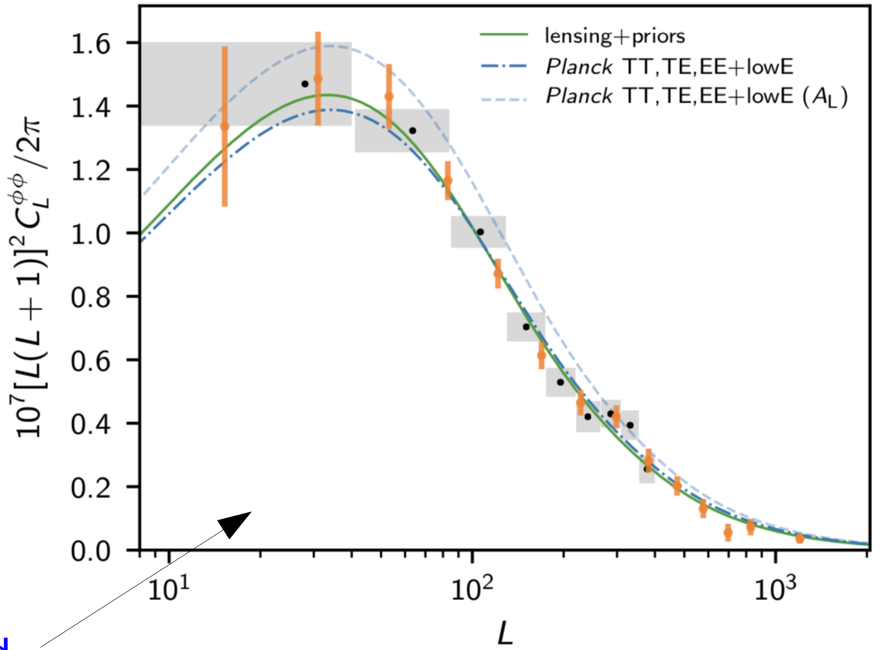
From Blake Sherwin

Weak lensing of the CMB: Lensing potential...

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



Lensing potential power spectrum



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

Akrami et al. [Planck] 2018

Constraints on the neutrino mass sum…

ΛCDM+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

Two different high-ℓ likelihood functions

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

Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13 \text{ eV}$

Palanque-Delabrouille et al. 2015

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

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 ~40%.
- ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV]:

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

$\sum m_\nu < 0.121\ \text{eV}$	Degenerate
$\sum m_\nu < 0.146\ \text{eV}$	Normal hierarchy
$\sum m_\nu < 0.172\ \text{eV}$	Inverted hierarchy

Roy Choudhury & Hannestad 2019

Caveat 2 of 2: model dependence...

All bounds so far have been derived from a ΛCDM+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**
+ r	0.115	0.142	0.167
+ w	0.186	0.215	0.230
+ $w_0 w_a$	0.249	0.256	0.276
+ $w_0 w_a$, $w(z) > -1$	0.096	0.129	0.157
+ Ω_k	0.150	0.173	0.198

Primordial tensors

Dynamical dark energy

Spatial curvature

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...

It doesn't even have to be a real neutrino...

Smallest relevant scale enters the horizon

Any particle species 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.

Neutrino temperature per definition

$$\sum_i \rho_{\nu,i} + \rho_X = N_{\rm eff} \left(\frac{7}{8} \frac{\pi^2}{15} T_\nu^4 \right)$$

$$= (3.044 + \Delta N_{\rm eff}) \rho_\nu^{(0)}$$

Three SM neutrinos

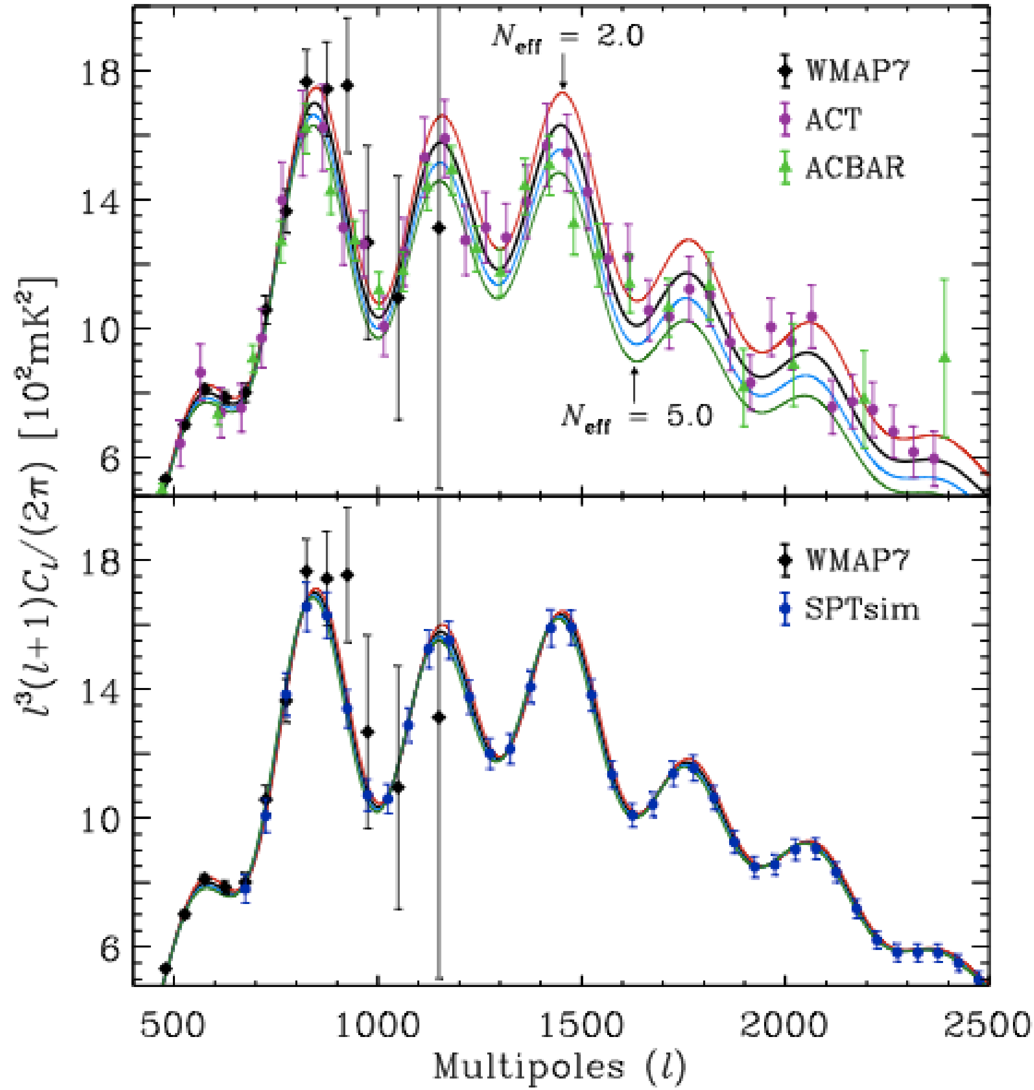
Other non-interacting relativistic energy densities, e.g., light sterile neutrinos, axions, hidden photons, etc.

Corrections due to non-instantaneous decoupling, finite-temperature QED, and flavour oscillations

See also talk of P. de Salas

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.



Hou, Keisler, Knox et al. 2011

Constraints on N_{eff} ...

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

Planck-inferred $N_{\rm eff}$ compatible with 3.044 at better than 2σ.

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

ΛCDM+Neff+neutrino mass 8-parameter fit

$$N_{\rm eff} = 2.96^{+0.34}_{-0.33}$$
$$\sum m_\nu < 0.12 \ \ \mathrm{eV}$$

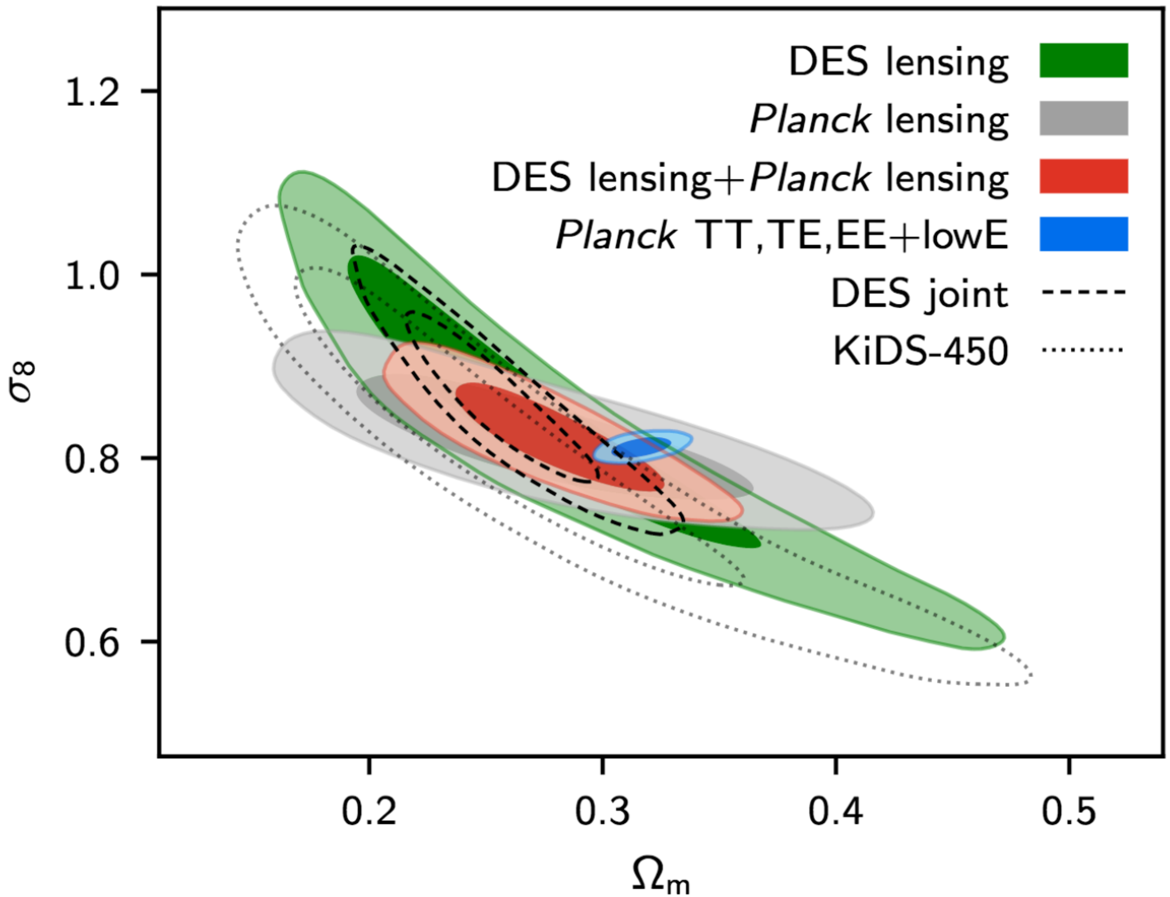
95% C. L.
Planck TT+TE+EE+lowE +lensing+BAO

3. Flies in the ointment...

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...

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

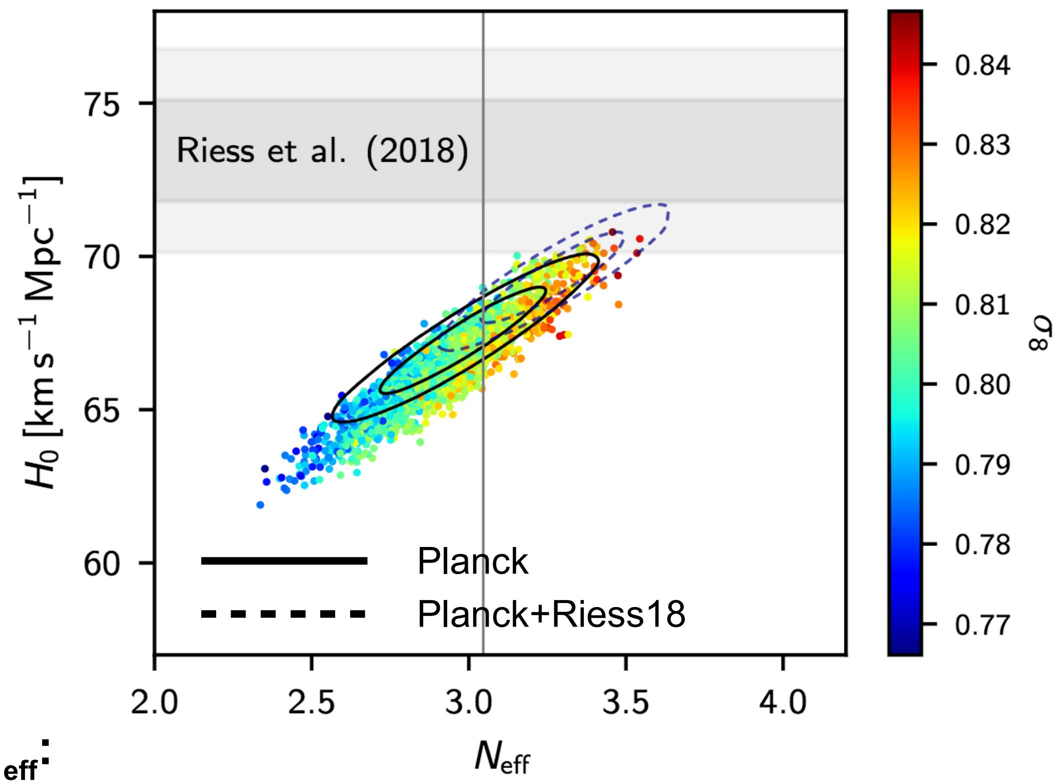
- **TT+TE+EE+lowE+lensing**

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

- **Local measurement**:

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

Riess et al. 2019



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

$$N_{\rm eff} = 3.27 \pm 0.15$$
$$H_0 = 69.32 \pm 0.97\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

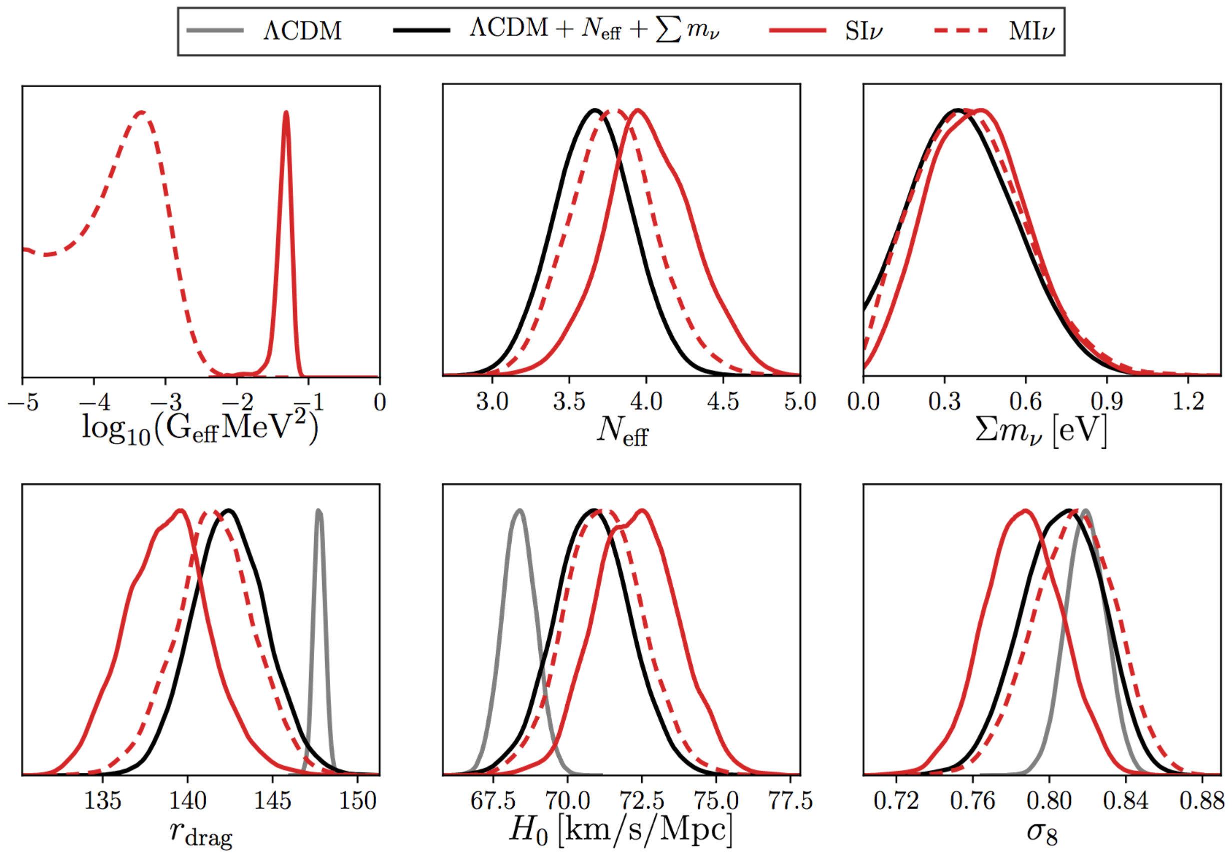
68% C. L.
Planck TT+TE+EE+lowE
+lensing+BAO+Riess

Neutrino self-interaction as a solution?

See also talk of I. Oldengott

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

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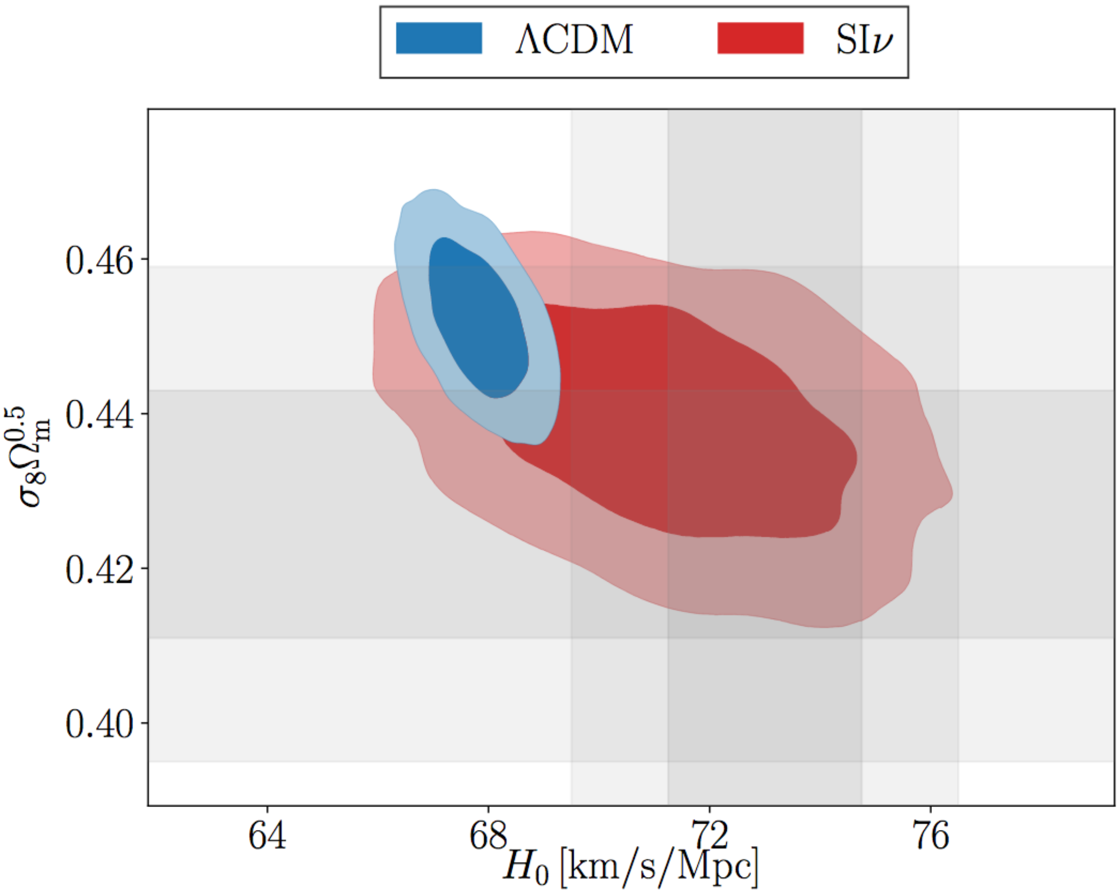

Kreisch, Cyr-Racine & Dore 2019

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 4.4σ discrepancy between Planck and local measurements of H_0 remains in ΛCDM, which cannot be resolved with $N_{eff}>3$ alone.
- **Strongly-interacting neutrinos** as a solution to the H_0 tension?