Neutrinos in cosmology

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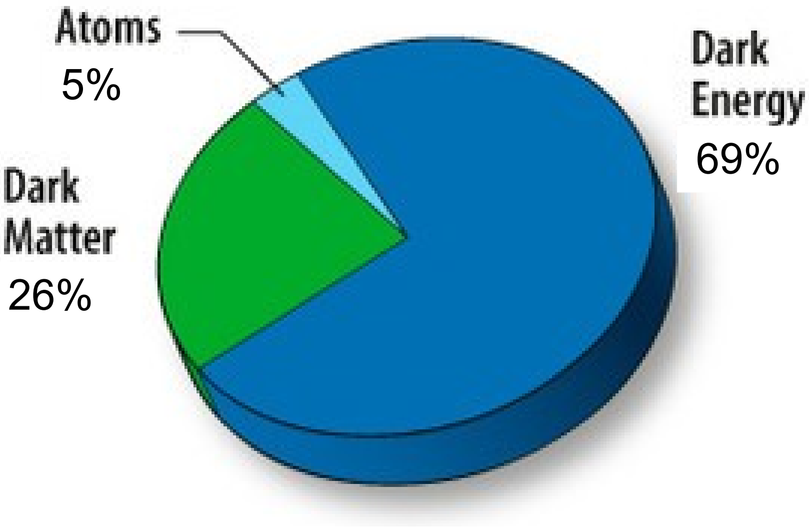
The concordance flat ΛCDM model...

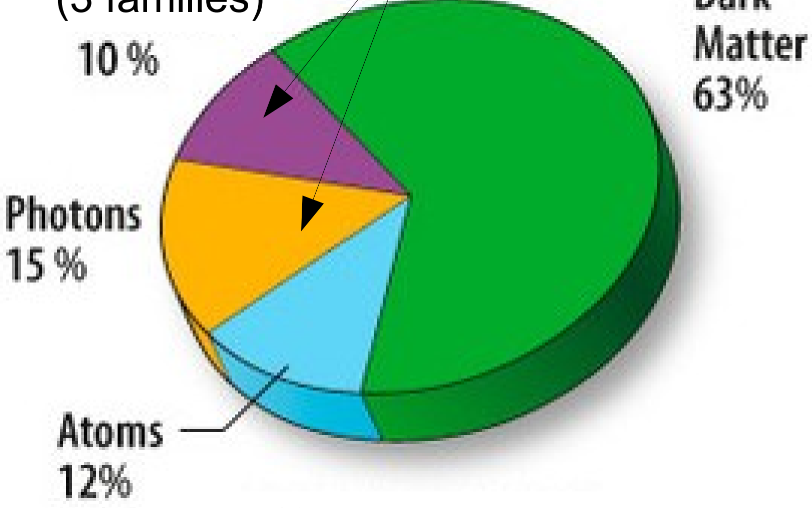
The simplest model consistent with **present observations**.

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

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



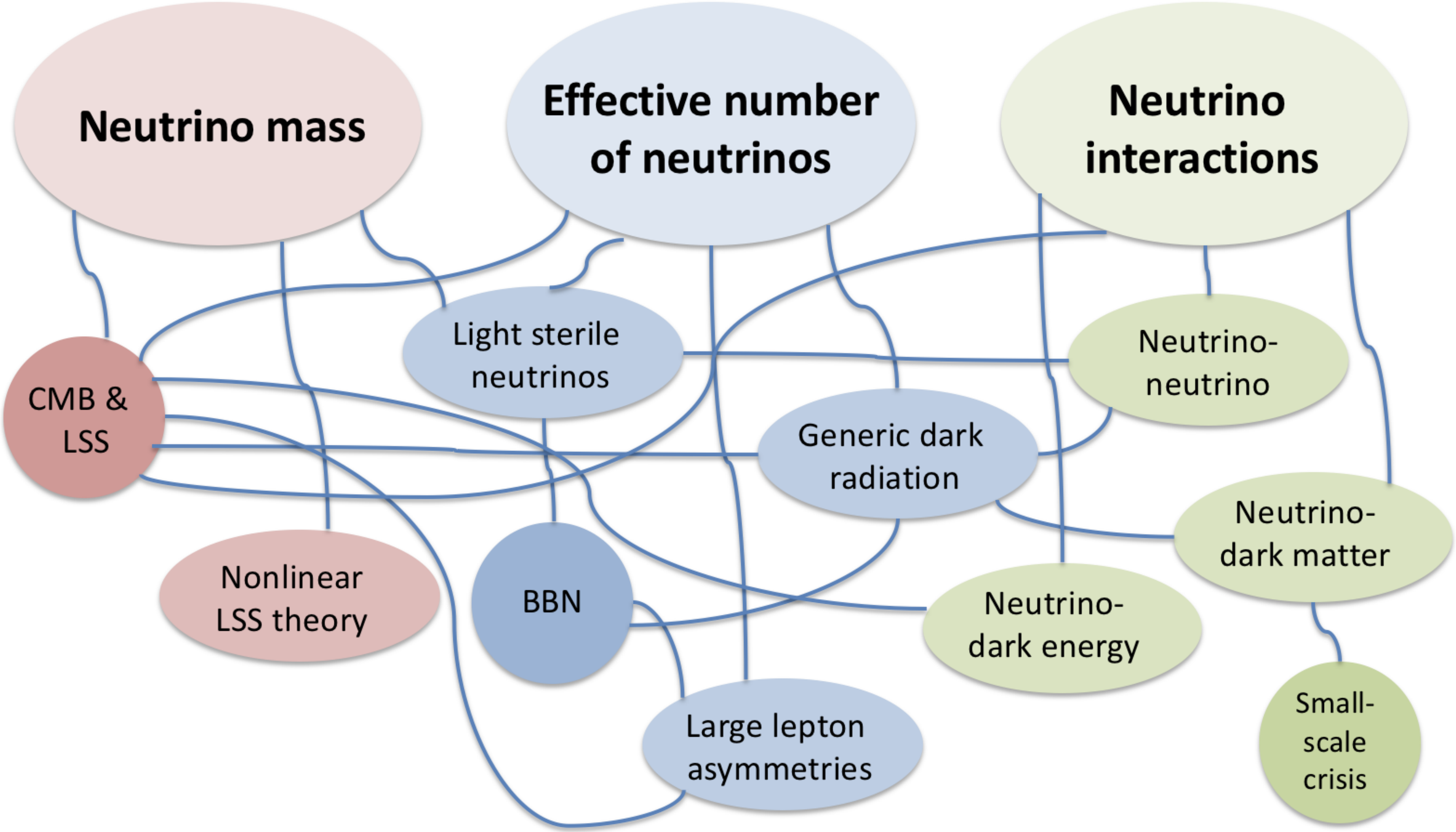
Composition today



13.4 billion years ago
(at photon decoupling)

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

The neutrino sector beyond ΛCDM...



Neutrino mass

Effective number of neutrinos

Neutrino interactions

CMB & LSS

Light sterile neutrinos

Neutrino-neutrino

Generic dark radiation

Neutrino-dark matter

Nonlinear LSS theory

BBN

Neutrino-dark energy

Small-scale crisis

Large lepton asymmetries

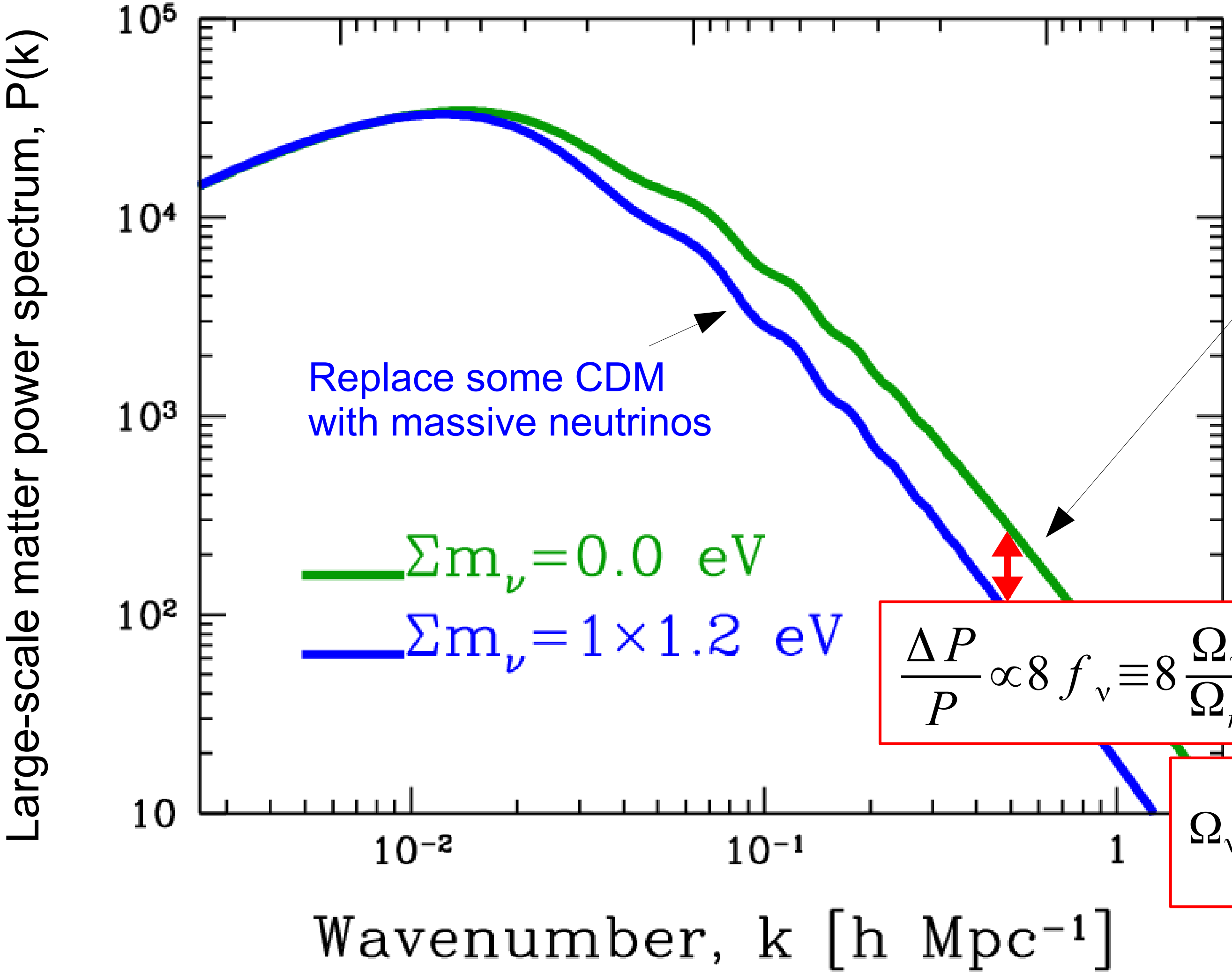
This talk...

Mainly an update on cosmological constraints on neutrino physics based on the final data release of the Planck CMB mission in July 2018.

- 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...



Replace some CDM with massive neutrinos

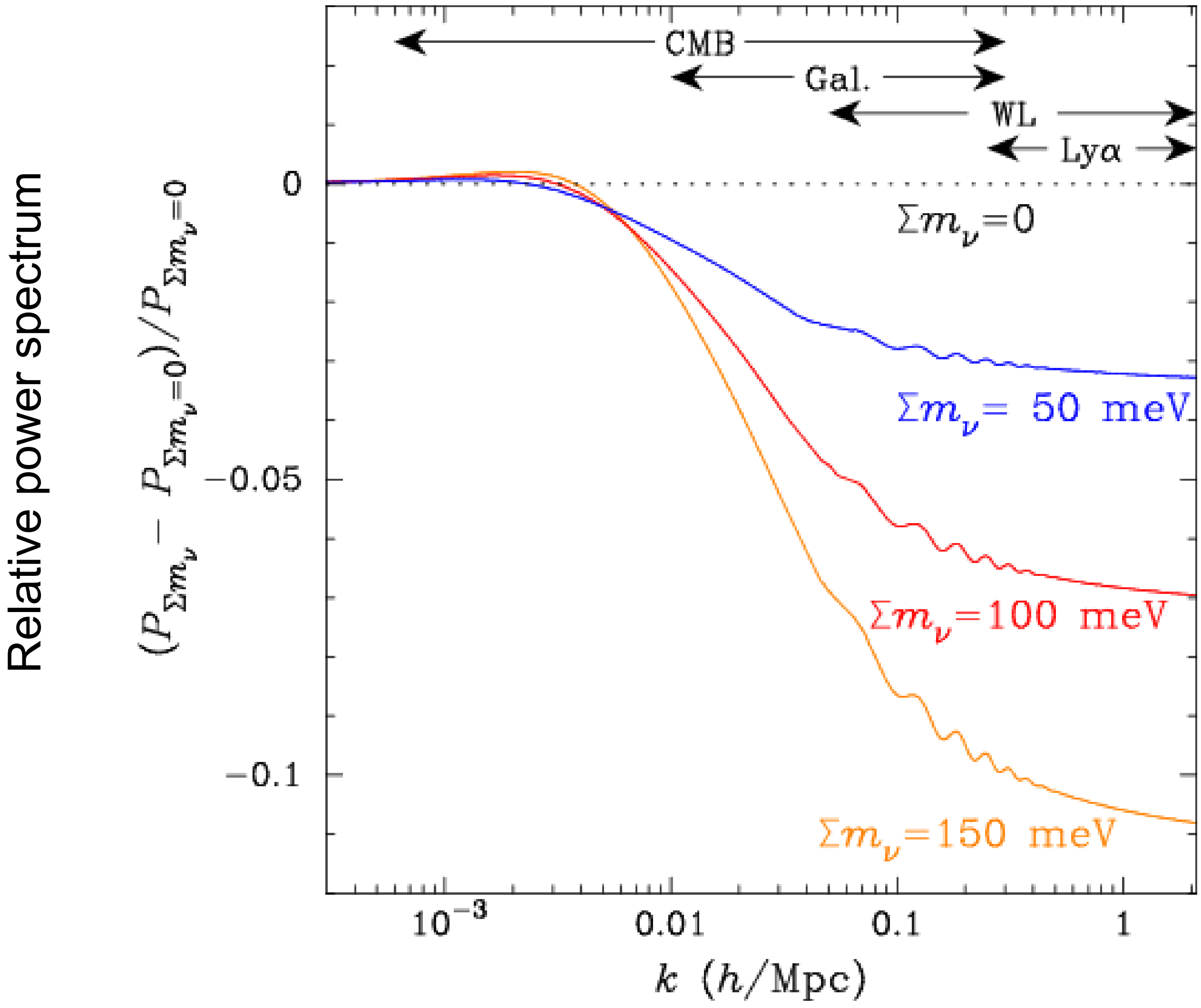
Suppression of power due to free-streaming induced potential decay

f_ν = Neutrino fraction

$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$$

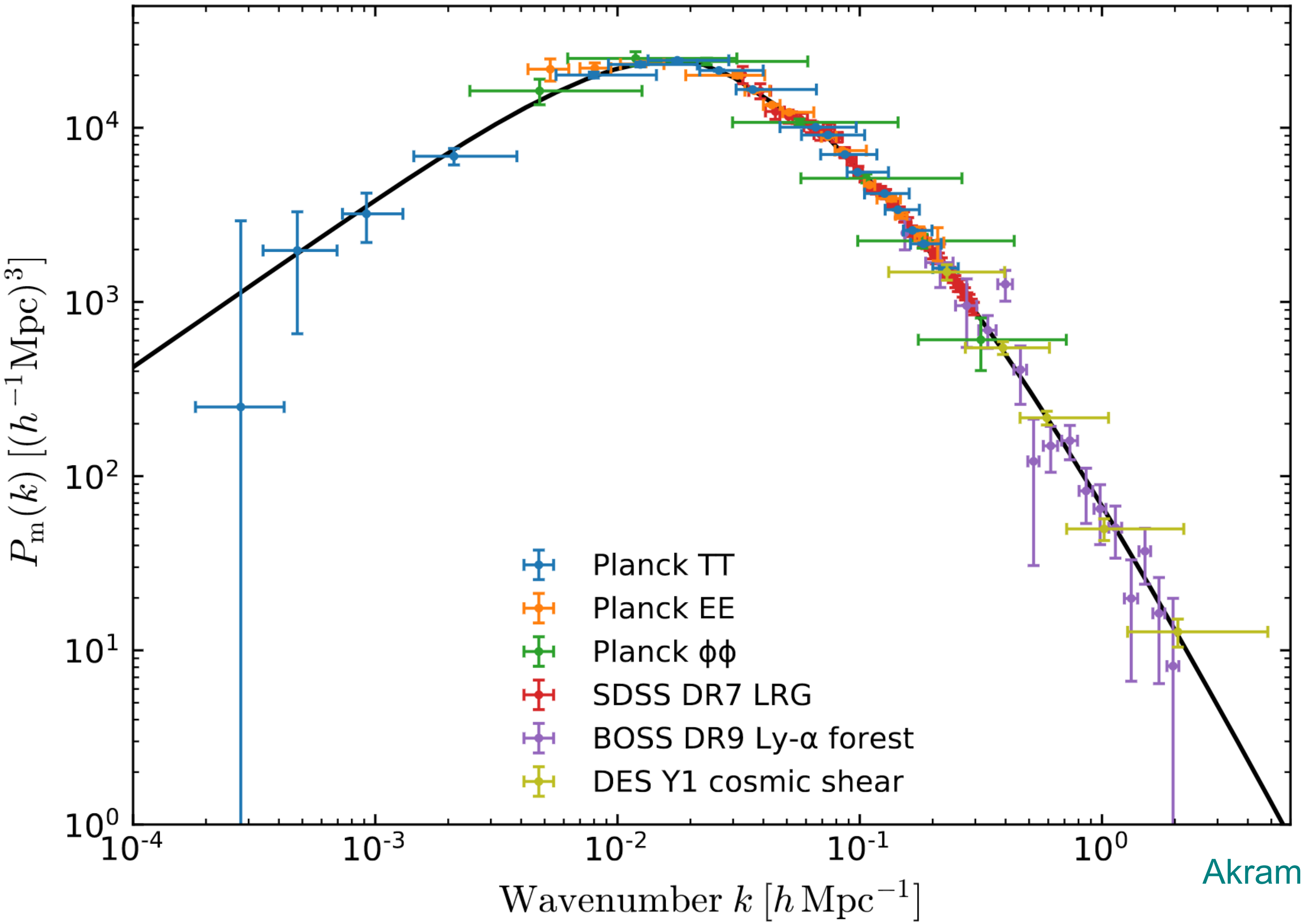
$$\Omega_\nu h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}}$$

Neutrino masses in cosmology...



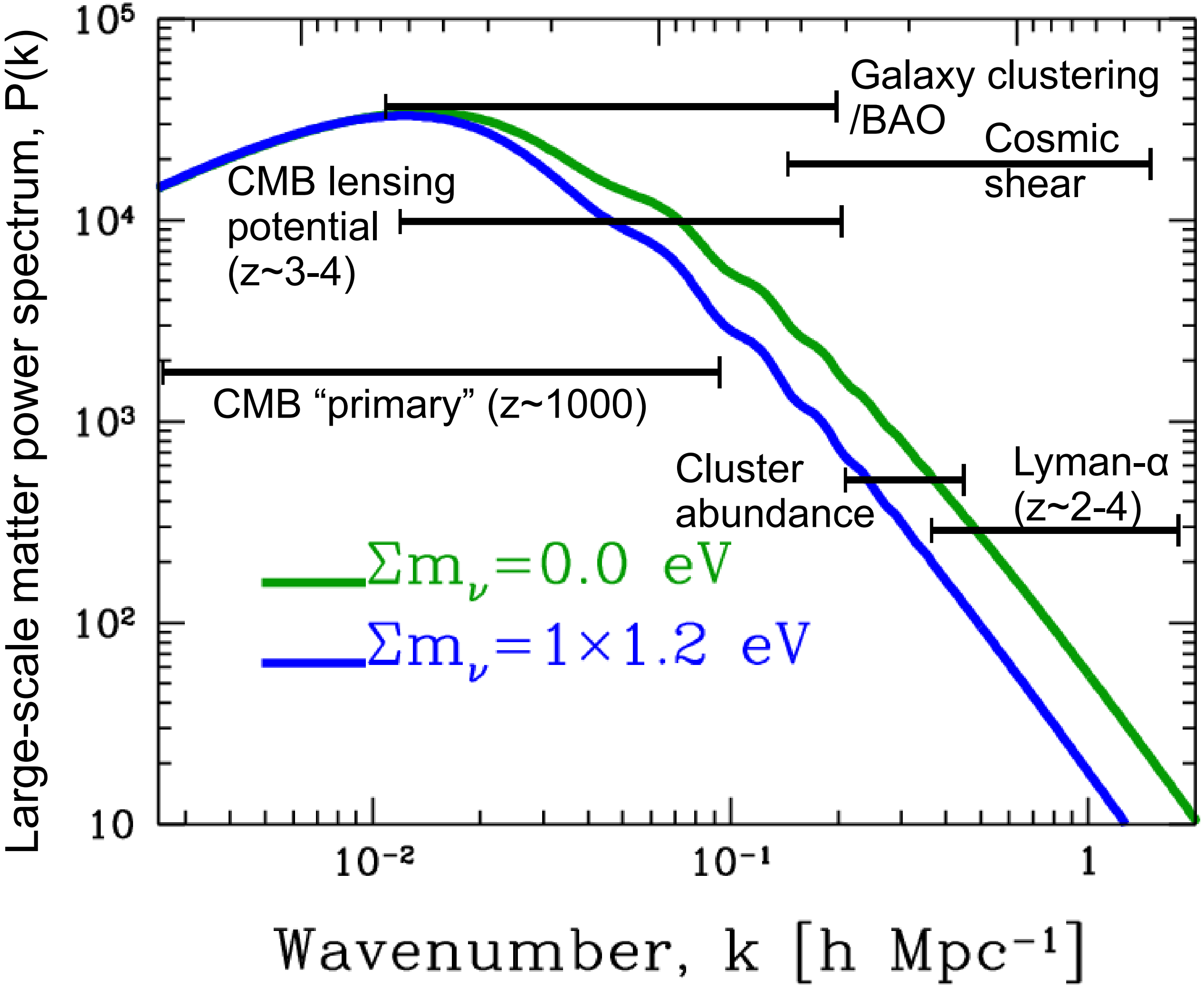
Who can measure it?

Large-scale power spectrum measurements circa 2018



Akrami et al. 2018

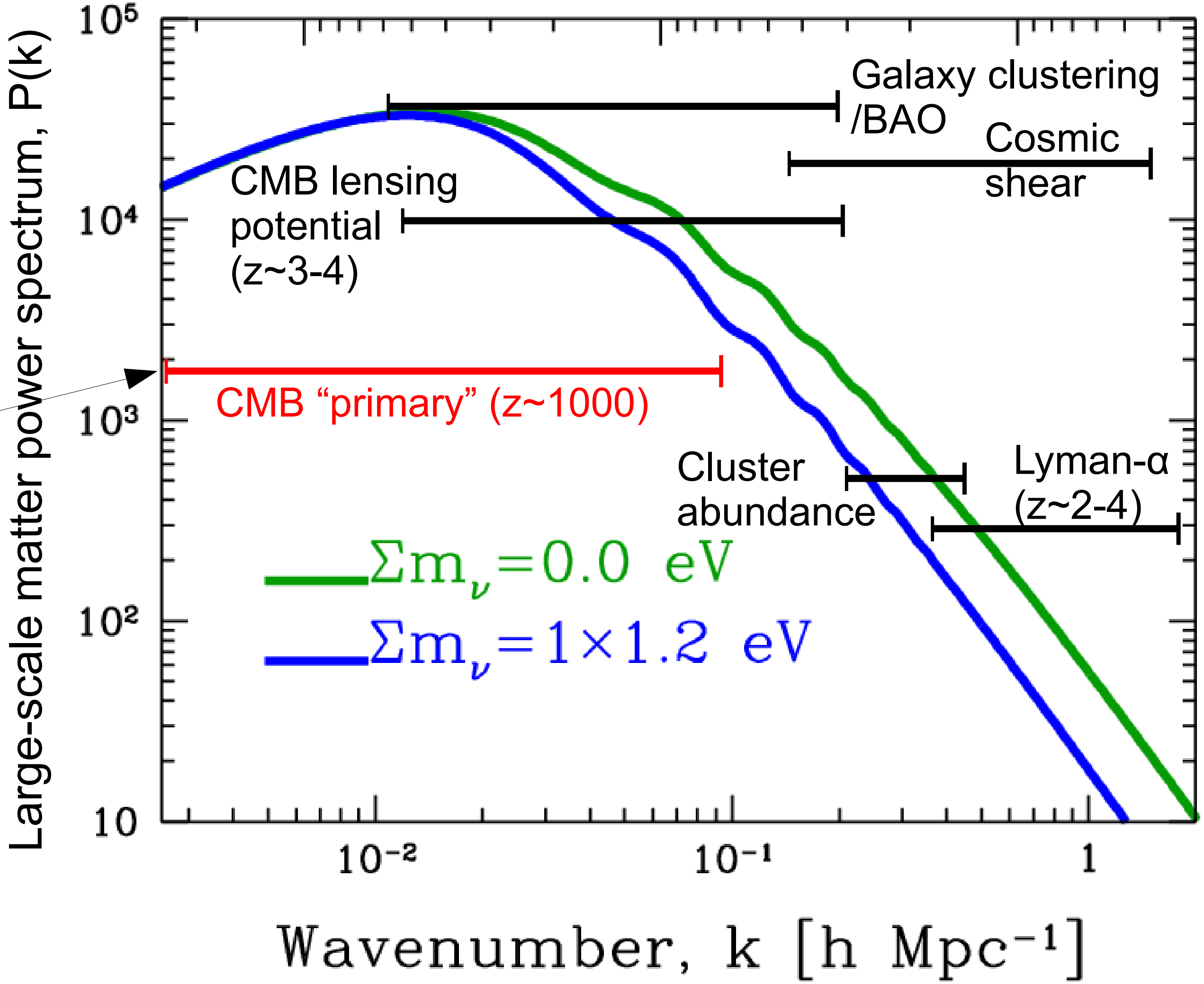
Who can measure it?



Who can measure it?

“Anchor”
ΛCDM model
parameters

$$\omega_m, \omega_b, n_s,$$
$$A_s, \tau, h$$



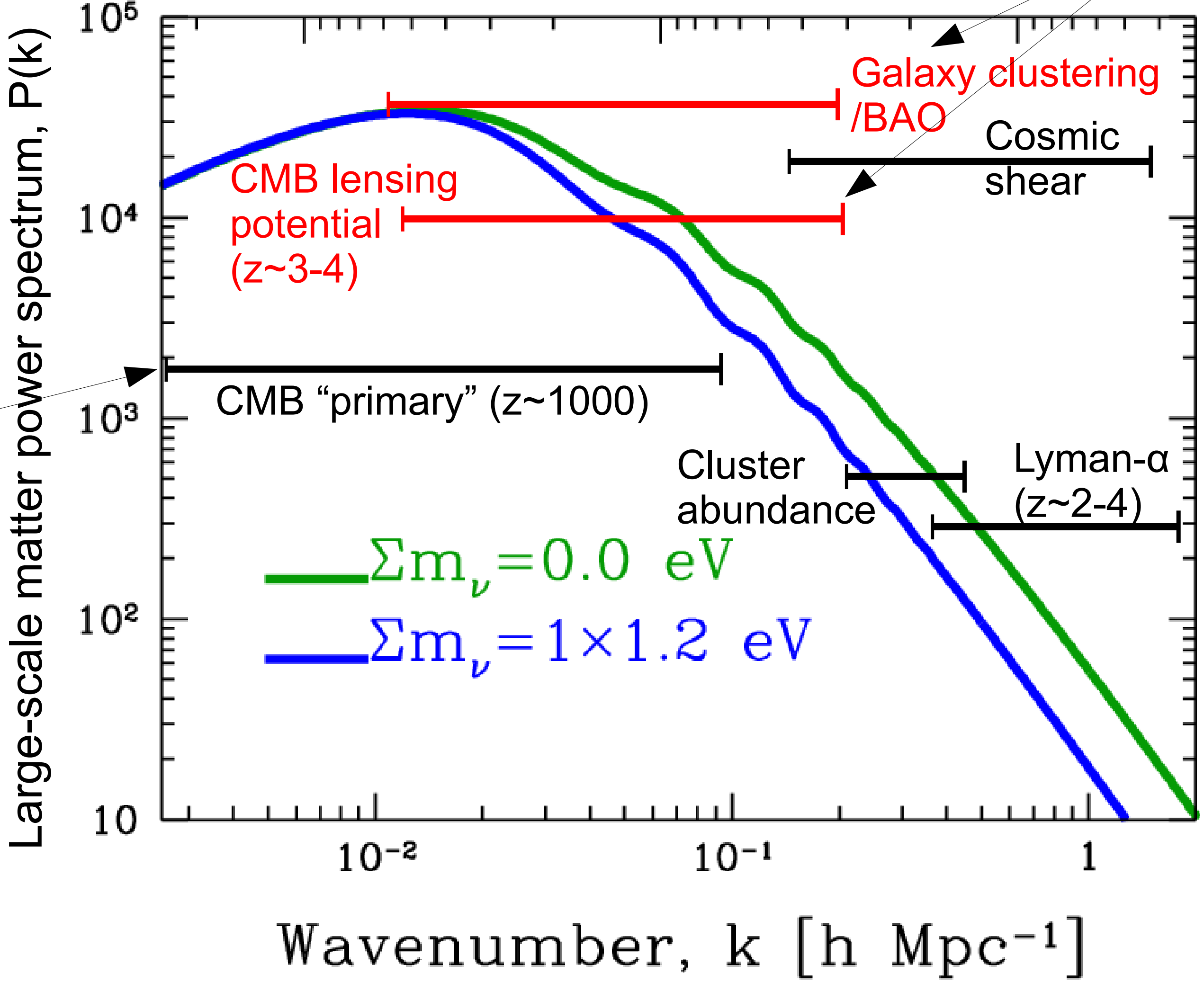
Who can measure it?

ω_m+ geometry

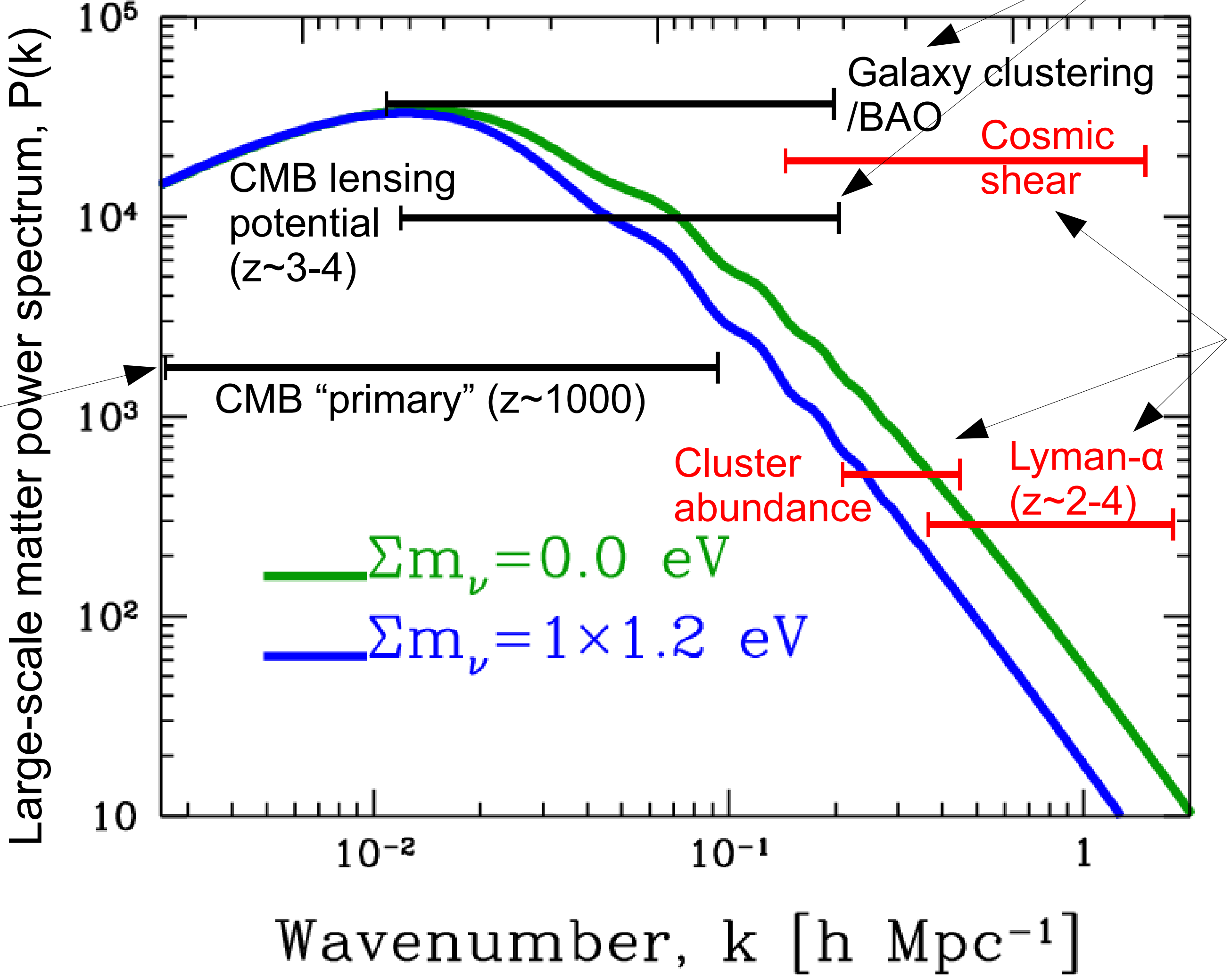
Physical matter density

“Anchor” ΛCDM model parameters

$\omega_m, \omega_b, n_s,$
A_s, τ, h



Who can measure it?



“Anchor”
ΛCDM model
parameters

$\omega_m, \omega_b, n_s,$
A_s, τ, h

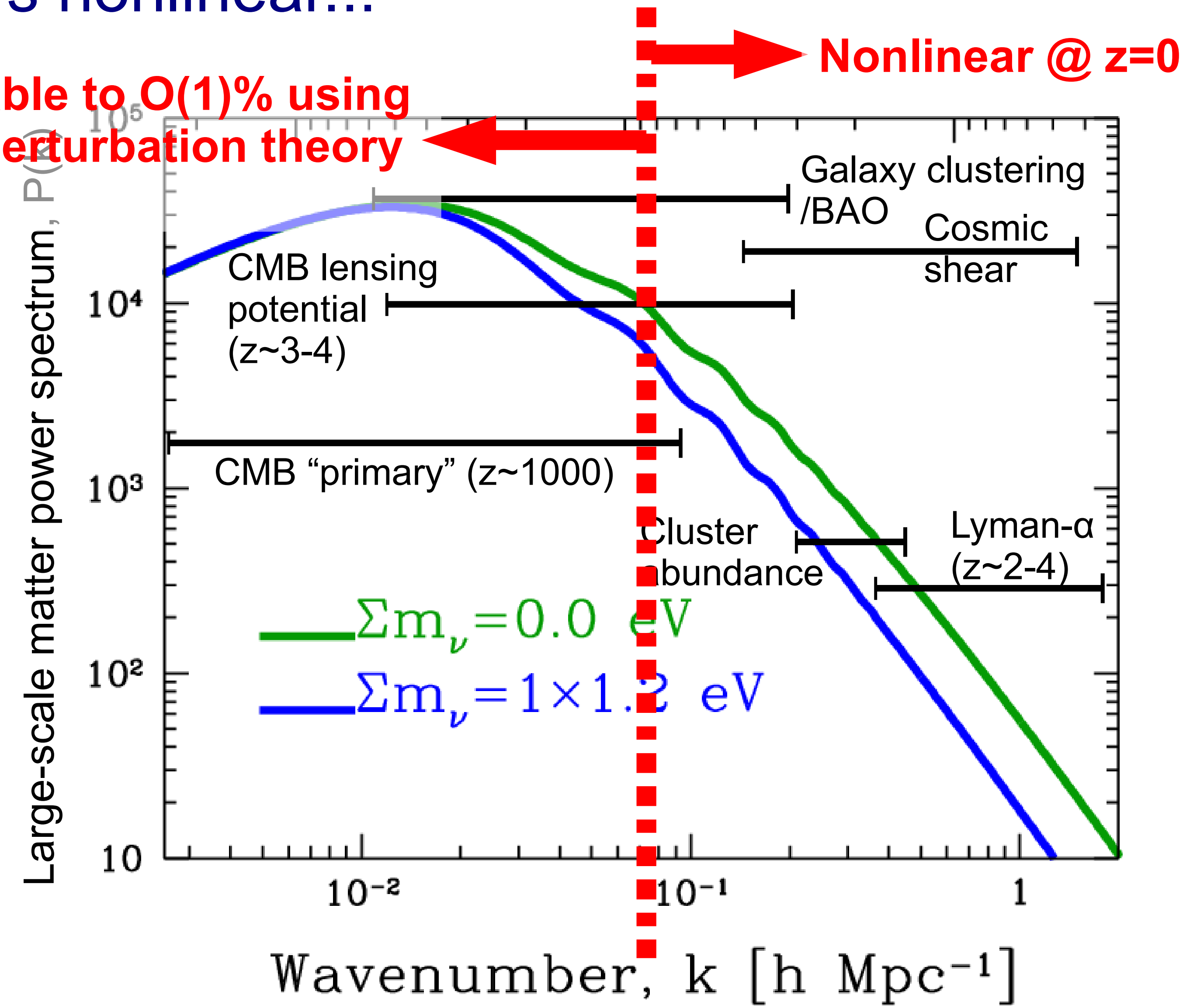
ω_m + geometry

Physical matter density

σ_8, Ω_m

Small-scale fluctuation amplitude

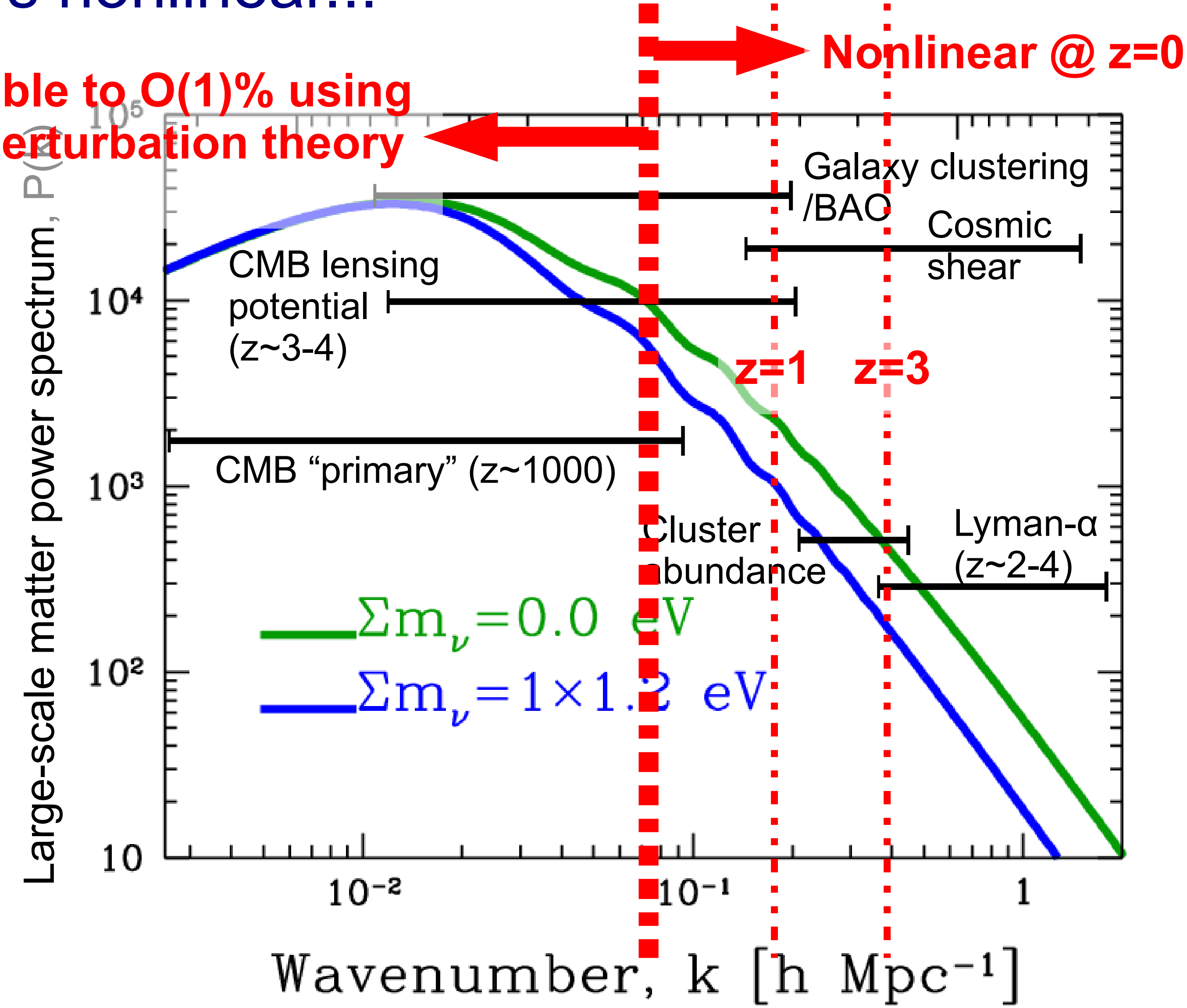
Linear vs nonlinear...



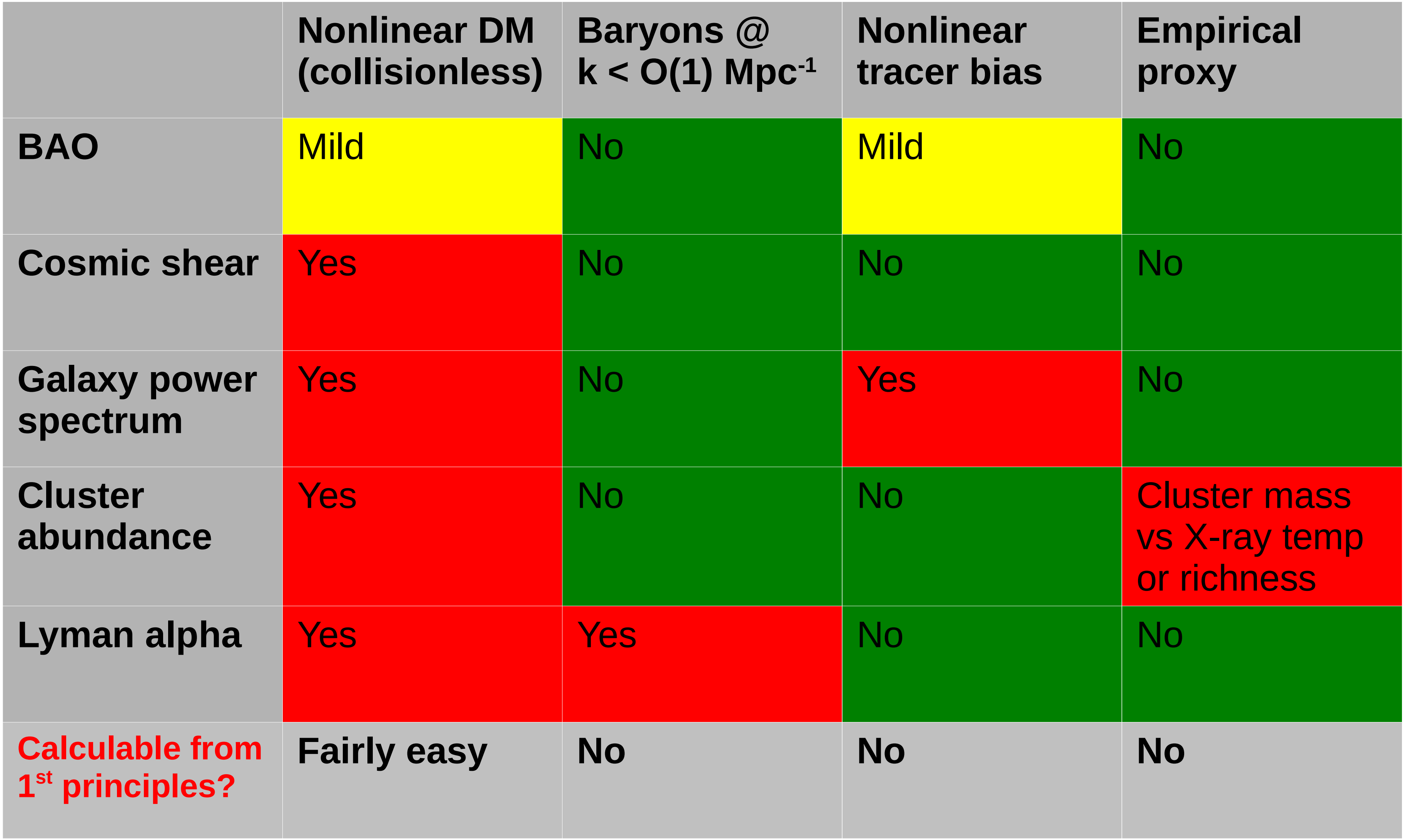
Calculable to O(1)% using linear perturbation theory @ z=0

Nonlinear @ z=0

Linear vs nonlinear...



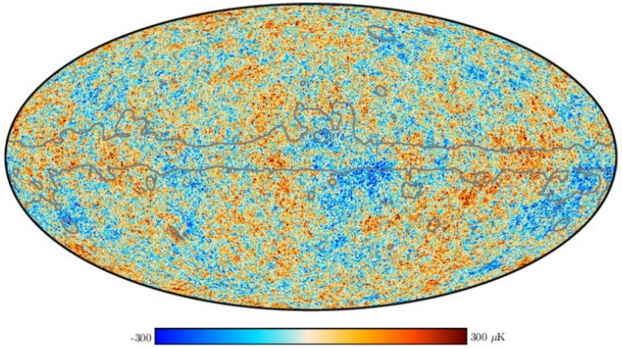
Types and degrees of nonlinearity...

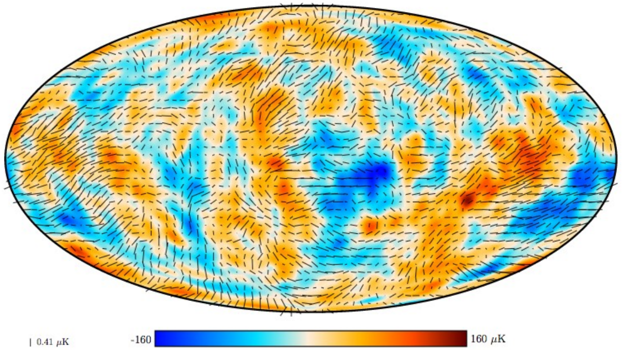


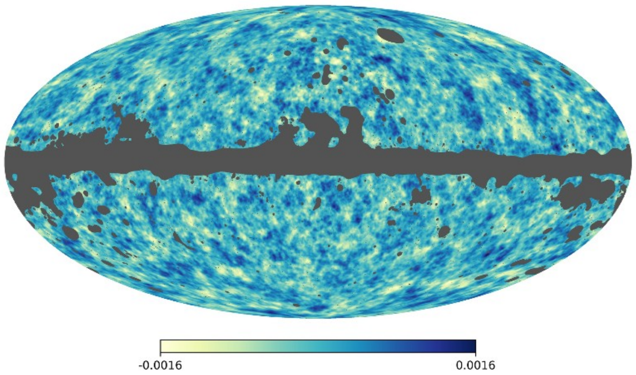
	Nonlinear DM (collisionless)	**Baryons @ k < O(1) Mpc^{-1}**	**Nonlinear tracer bias**	**Empirical proxy**
BAO	Mild	No	Mild	No
Cosmic shear	Yes	No	No	No
Galaxy power spectrum	Yes	No	Yes	No
Cluster abundance	Yes	No	No	Cluster mass vs X-ray temp or richness
Lyman alpha	Yes	Yes	No	No
Calculable from 1st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

1a. Neutrino masses and Planck 2018

Three CMB observables...



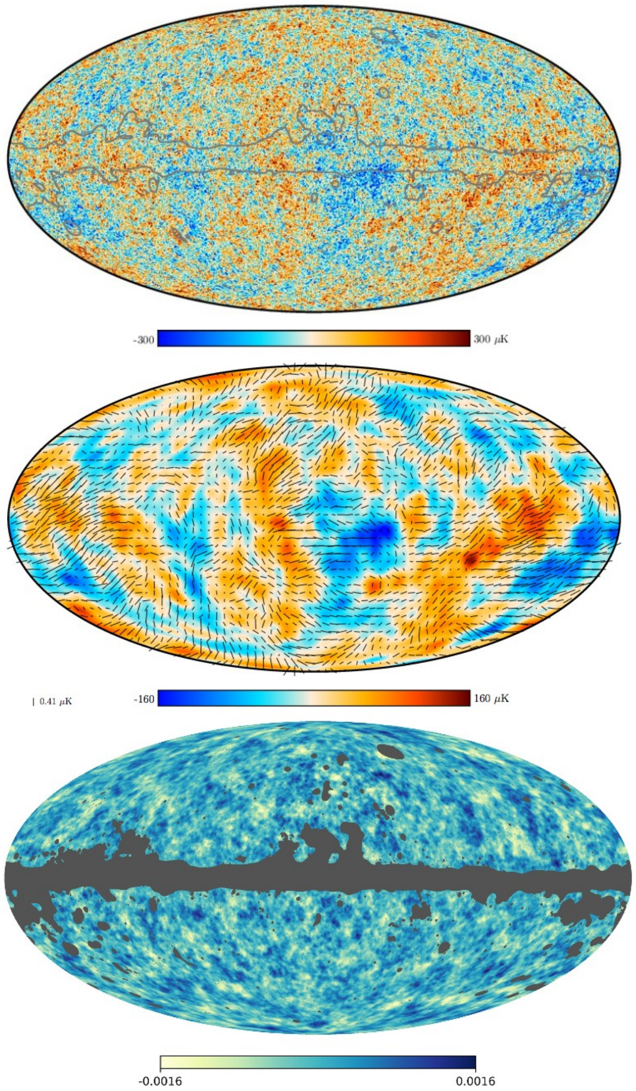




Temperature:

- Neutrino mass signatures.
- Cosmic-variance-limited to ℓ ~ 2000 since 2013 (i.e., nothing more to be done here)

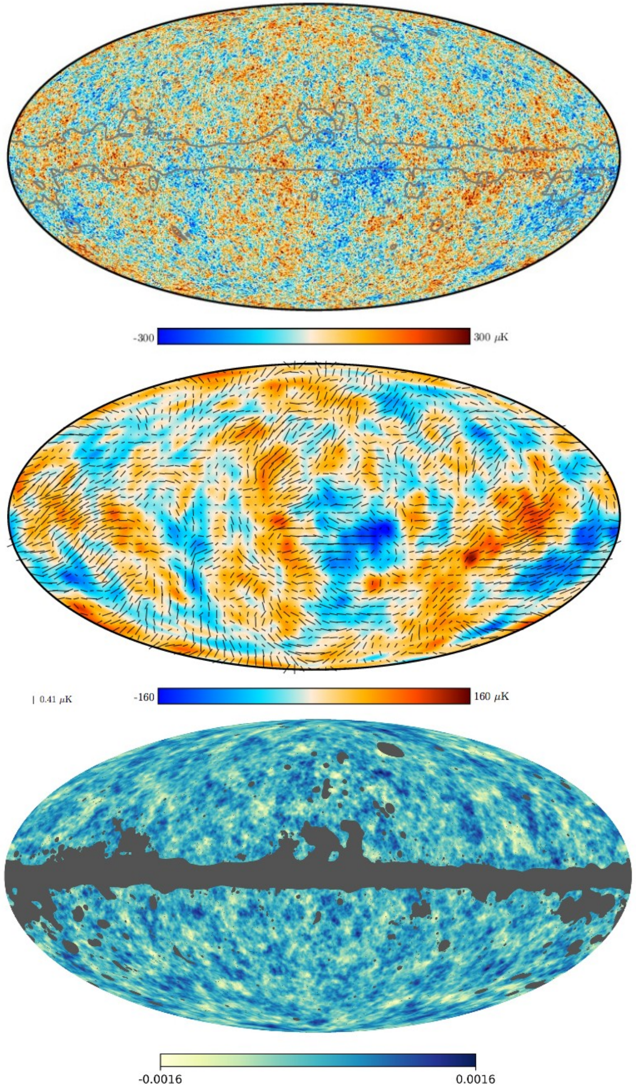
Three CMB observables...



Polarisation:

- No independent neutrino mass signature.
- Low multipoles lifts A_s-τ degeneracy, which helps to tighten other parameter constraints.
- **Planck 2018 vs 2015**: improved measurement and modelling of the likelihood functions.

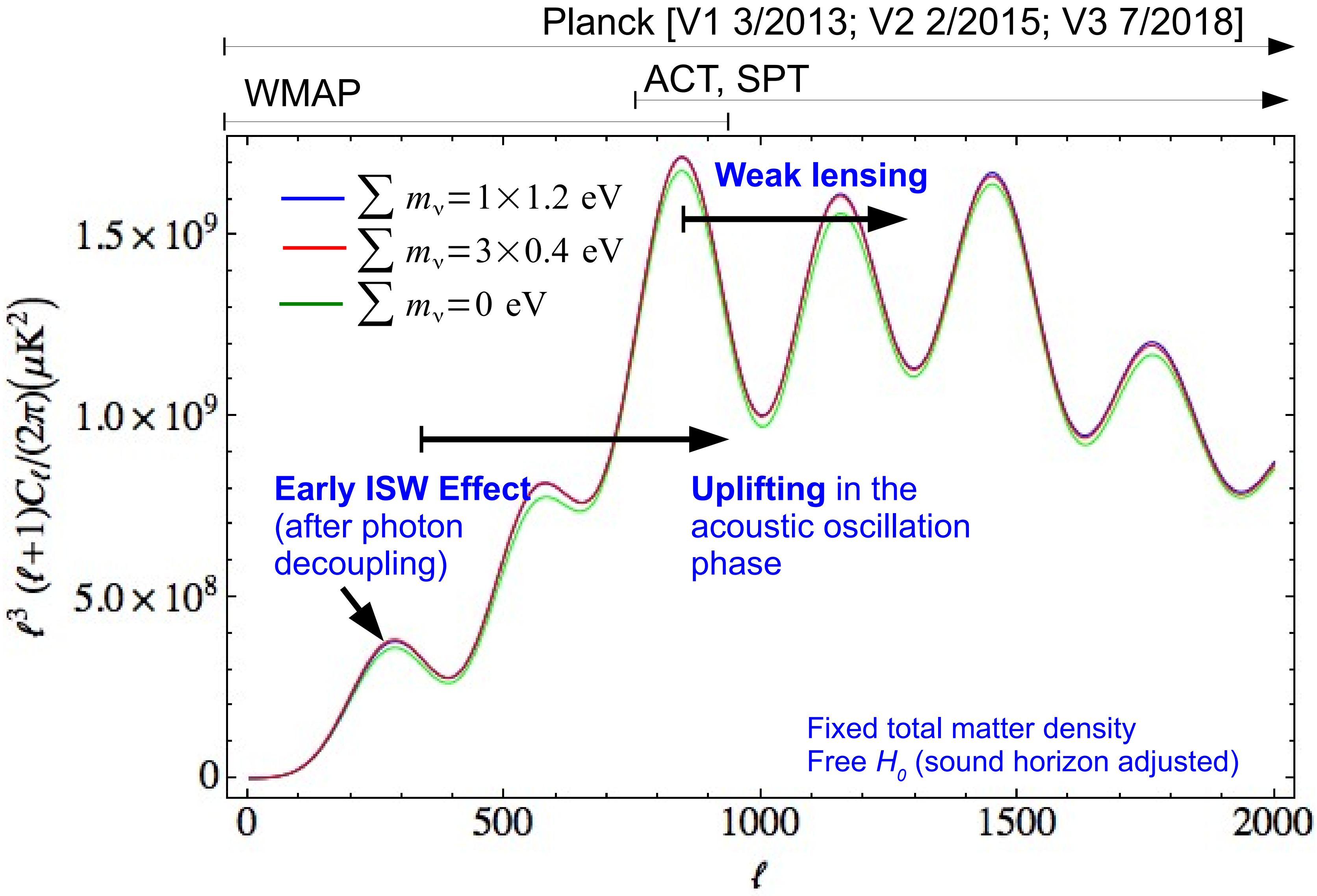
Three CMB observables...



Lensing potential:

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

Neutrino mass and the CMB temperature...



Planck [V1 3/2013; V2 2/2015; V3 7/2018]

WMAP

ACT, SPT

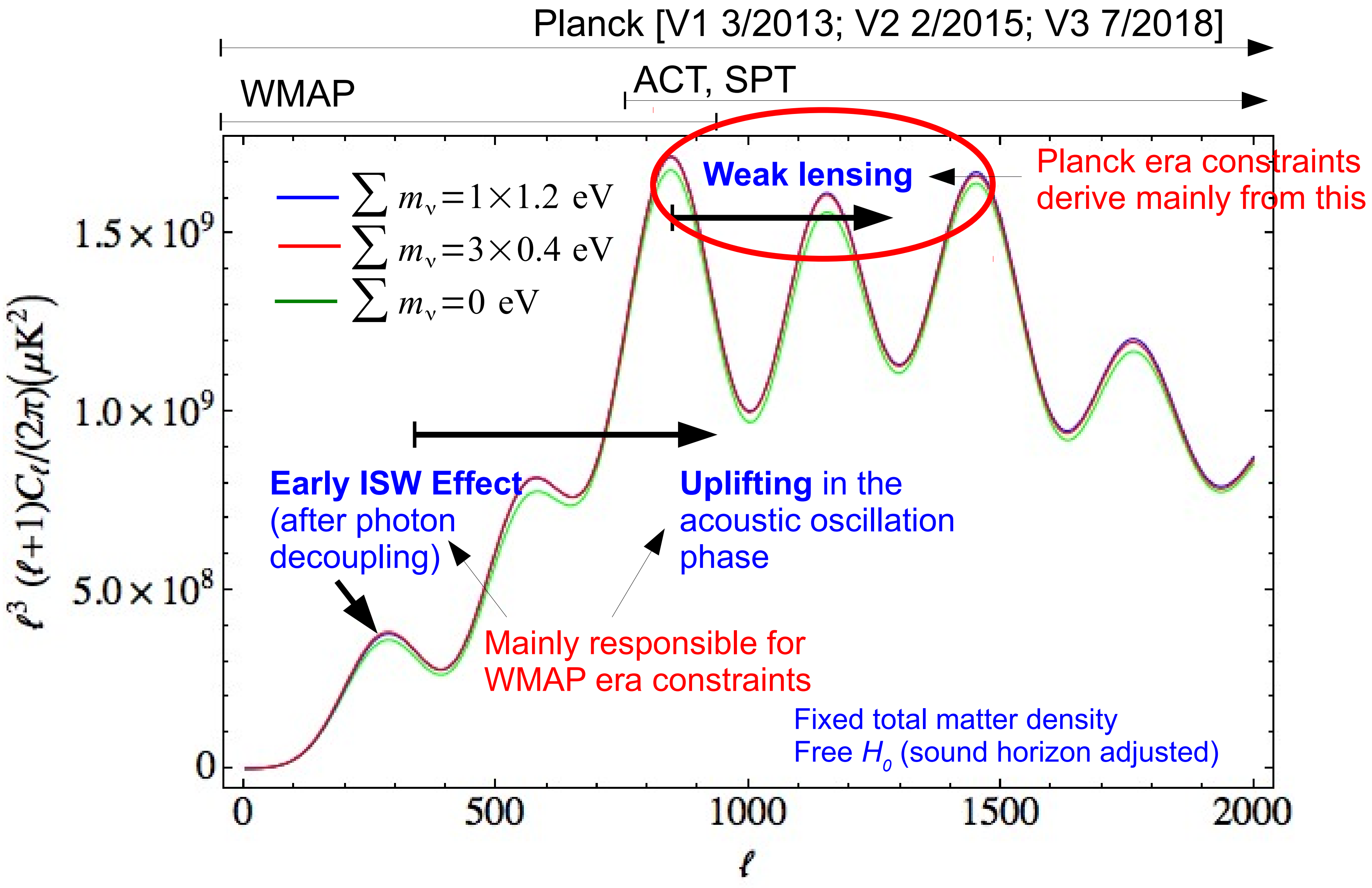
Weak lensing

Early ISW Effect (after photon decoupling)

Uplifting in the acoustic oscillation phase

Fixed total matter density
Free H_0 (sound horizon adjusted)

Neutrino mass and the CMB temperature...



Weak lensing

Planck era constraints derive mainly from this

Early ISW Effect (after photon decoupling)

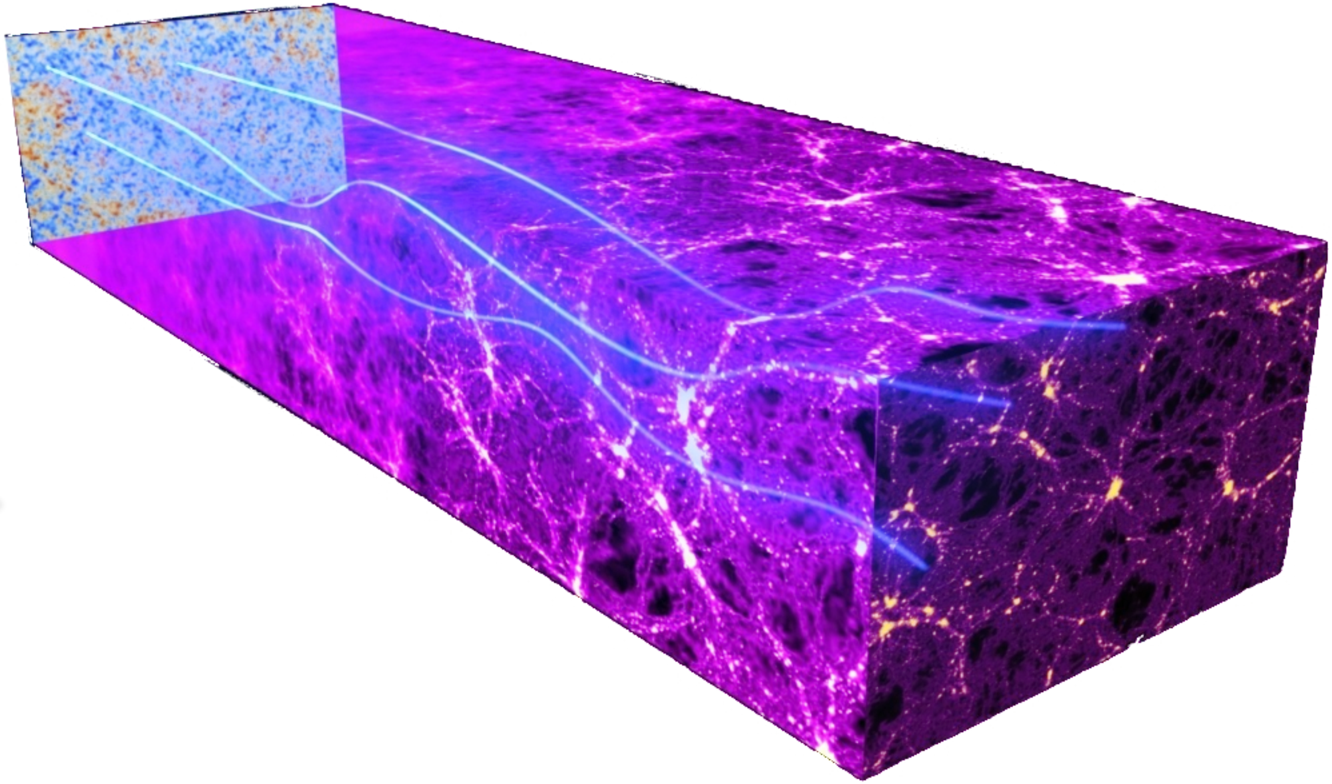
Uplifting in the acoustic oscillation phase

Mainly responsible for WMAP era constraints

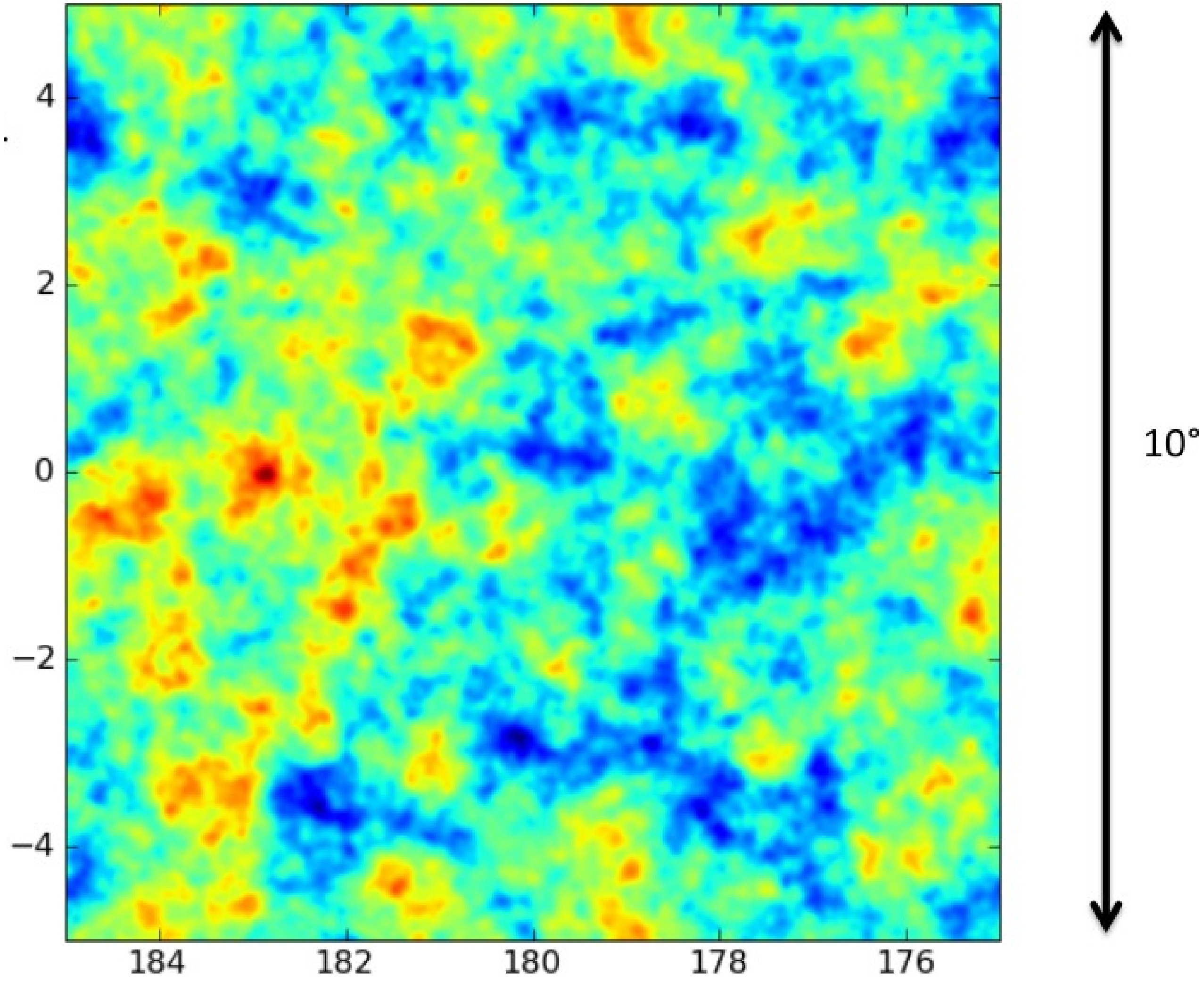
Fixed total matter density
Free H_0 (sound horizon adjusted)

Weak lensing of the CMB...

CMB photons are deflected by the intervening matter distribution, leading to a slightly **distorted image** of the large scattering surface.

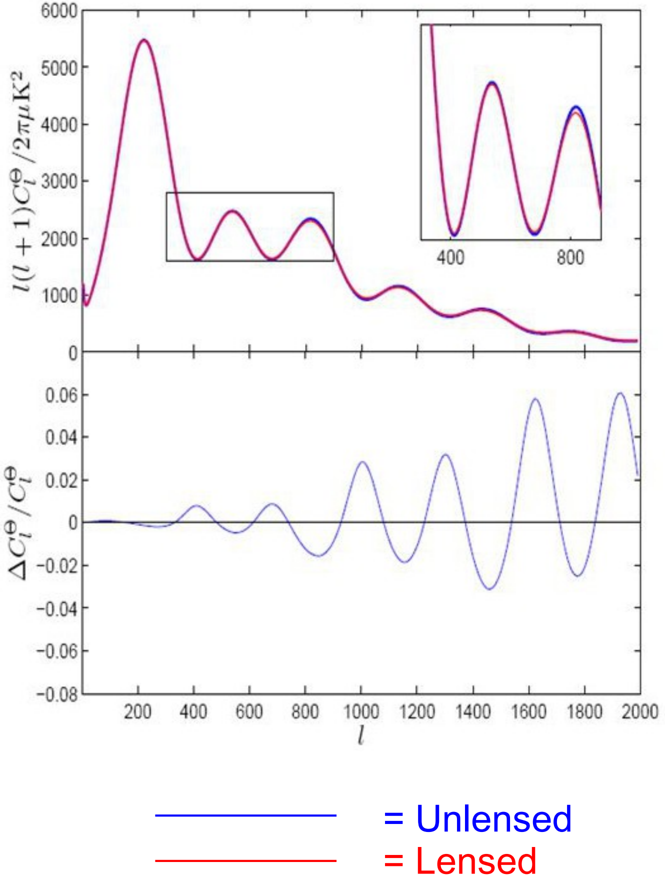


Unlensed CMB

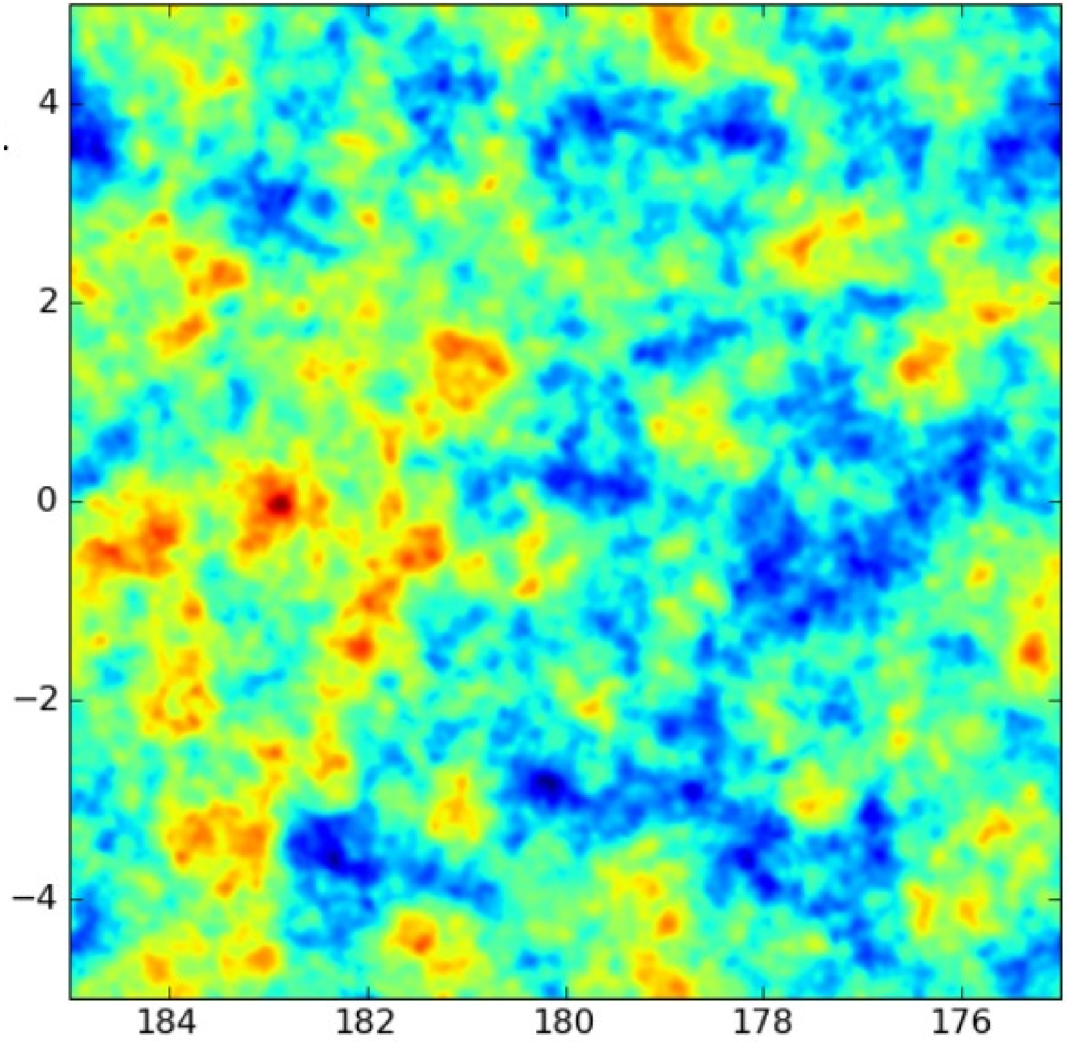


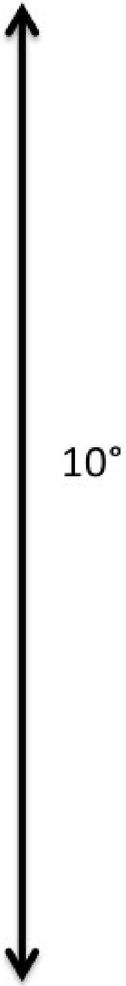
From Blake Sherwin

Smearing of the TT power spectrum at ℓ > 500

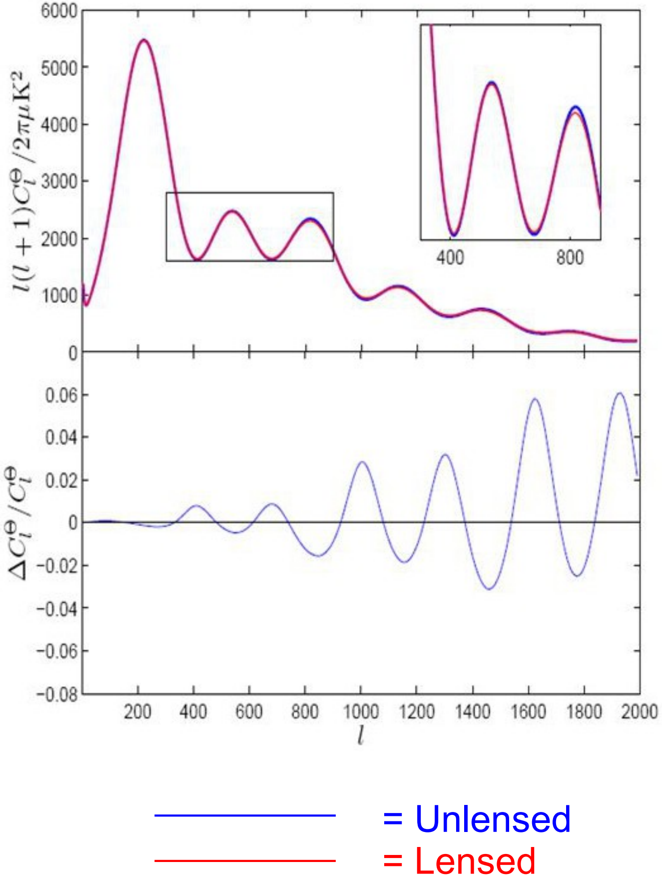


Lensed CMB





Smearing of the TT power spectrum at ℓ > 500



From Blake Sherwin

Constraints on the neutrino mass sum…

1 of 4

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

Low-ℓ polarisation only

Planck2018 TT+lowE	**0.54**
2015 numbers	0.72

Plus high-ℓ polarisation

Two different high-ℓ likelihood functions

Planck2018 TT +lowE+TE+EE	**0.26**
Planck2018 TT +lowE+TE+EE [CamSpec]	**0.38**
2015 numbers	0.49

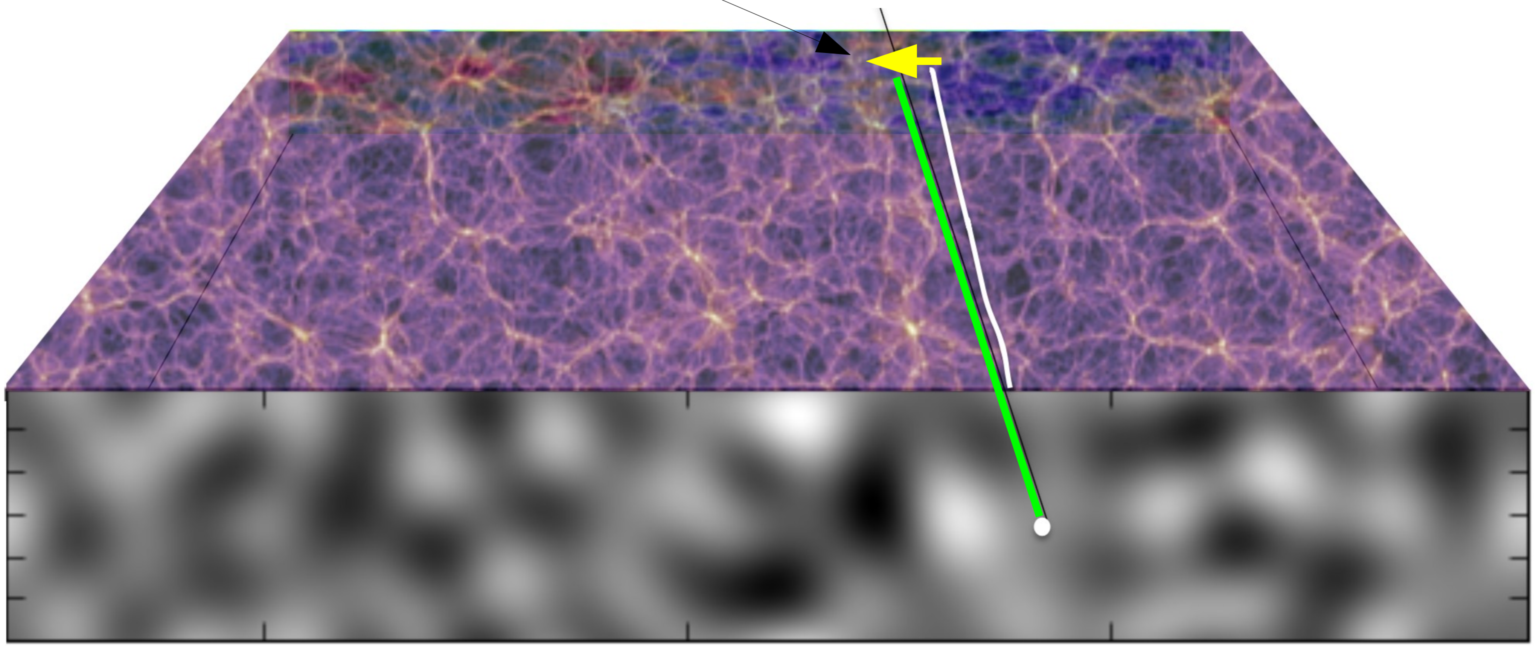
Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Weak lensing again: Lensing potential...

The amount of lensing deflection in any direction depends on the projected matter density in that direction.

Projected matter density ~

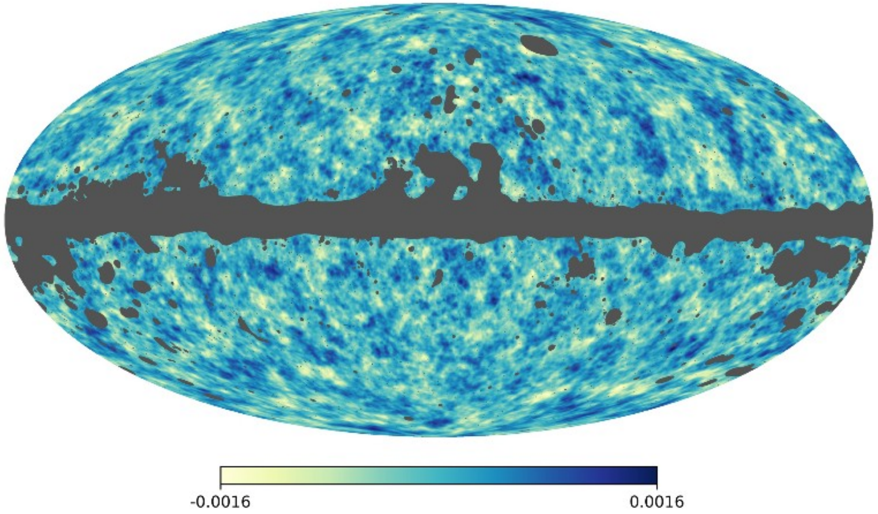
$$\nabla\cdot \underset{\text{lensing}}{d(\hat{\mathbf{n}})} = \int_0^{r_{\mathrm{CMB}}} dr\, \overset{\text{geometry}}{W(r)}\, \underset{\text{density}}{\delta(\hat{\mathbf{n}}, r)}$$



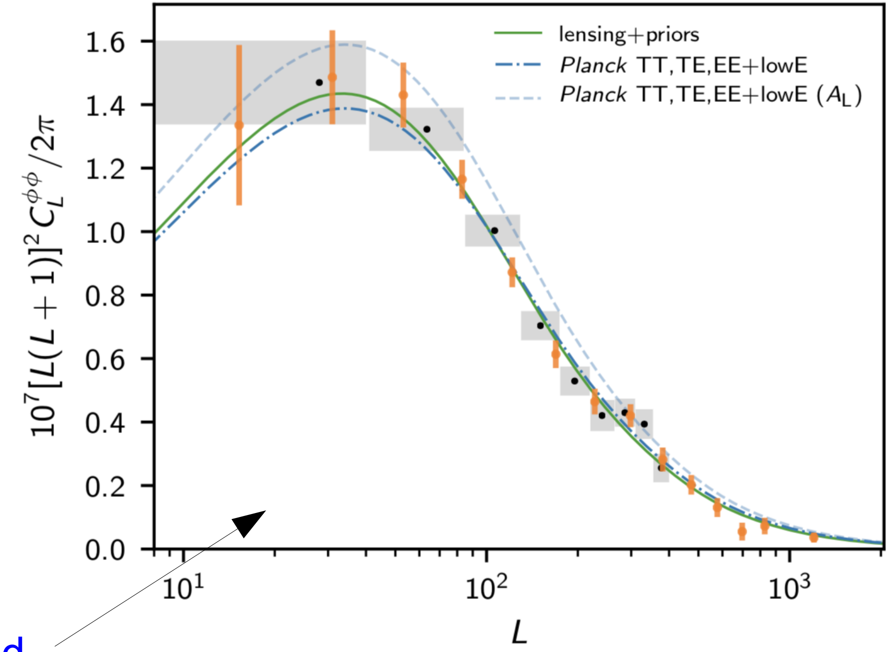
From Blake Sherwin

Weak lensing again: Lensing potential...

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



Lensing potential power spectrum



Akrami et al. [Planck] 2018

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

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
Planck2018 TT+lowE	**0.54**	**0.44**
2015 numbers	0.72	0.68

Plus high-ℓ polarisation

Planck2018 TT +lowE+TE+EE	**0.26**	**0.24**
Planck2018 TT +lowE+TE+EE [CamSpec]	**0.38**	**0.27**
2015 numbers	0.49	0.59

Two different high-ℓ likelihood functions

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

Constraints on the neutrino mass sum… 3 of 4

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

Low-ℓ polarisation only

		+Lensing	+BAO (non-CMB)
Planck2018 TT+lowE	**0.54**	**0.44**	**0.16**
2015 numbers	0.72	0.68	0.21

Plus high-ℓ polarisation

Two different high-ℓ likelihood functions

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

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

Constraints on the neutrino mass sum… 4 of 4

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

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 eV (95% C.L.).
- 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...

Any particle species that

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

Smallest relevant scale enters the horizon

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

Neutrino temperature per definition

Three SM neutrinos

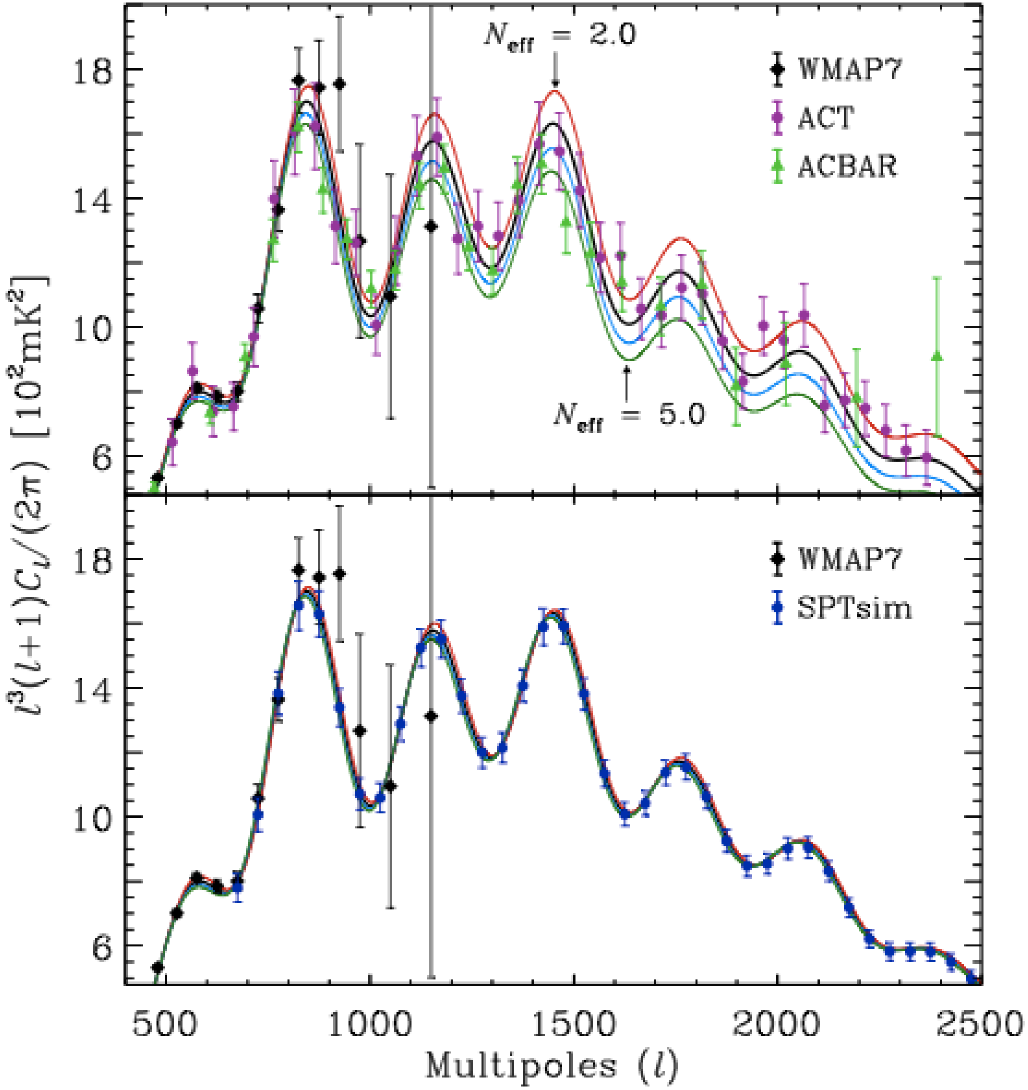
$$\sum_i \rho_{\nu,i} + \rho_X = N_{\mathrm{eff}}\left(\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right)$$
$$=(3.046+\Delta N_{\mathrm{eff}})\rho_\nu^{(0)}$$

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

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

N_{eff} signatures in the CMB...

- **Matter-radiation equality** (odd peak height ratios)
- **Angular acoustic scale** (acoustic peak locations)
- **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 3.046 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

Constraints on N_{eff} ...

Aghanim et al. [Planck] 2018
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+lensing+BAO	$\mathbf{2.99^{+0.34}_{-0.33}}$	n/a

ΛCDM+Neff+neutrino mass
8-parameter fit

$$\left.\begin{array}{l} N_{\mathrm{eff}} = 2.96^{+0.34}_{-0.33} \\ \sum m_\nu < 0.12 \ \ \mathrm{eV} \end{array}\right\}$$

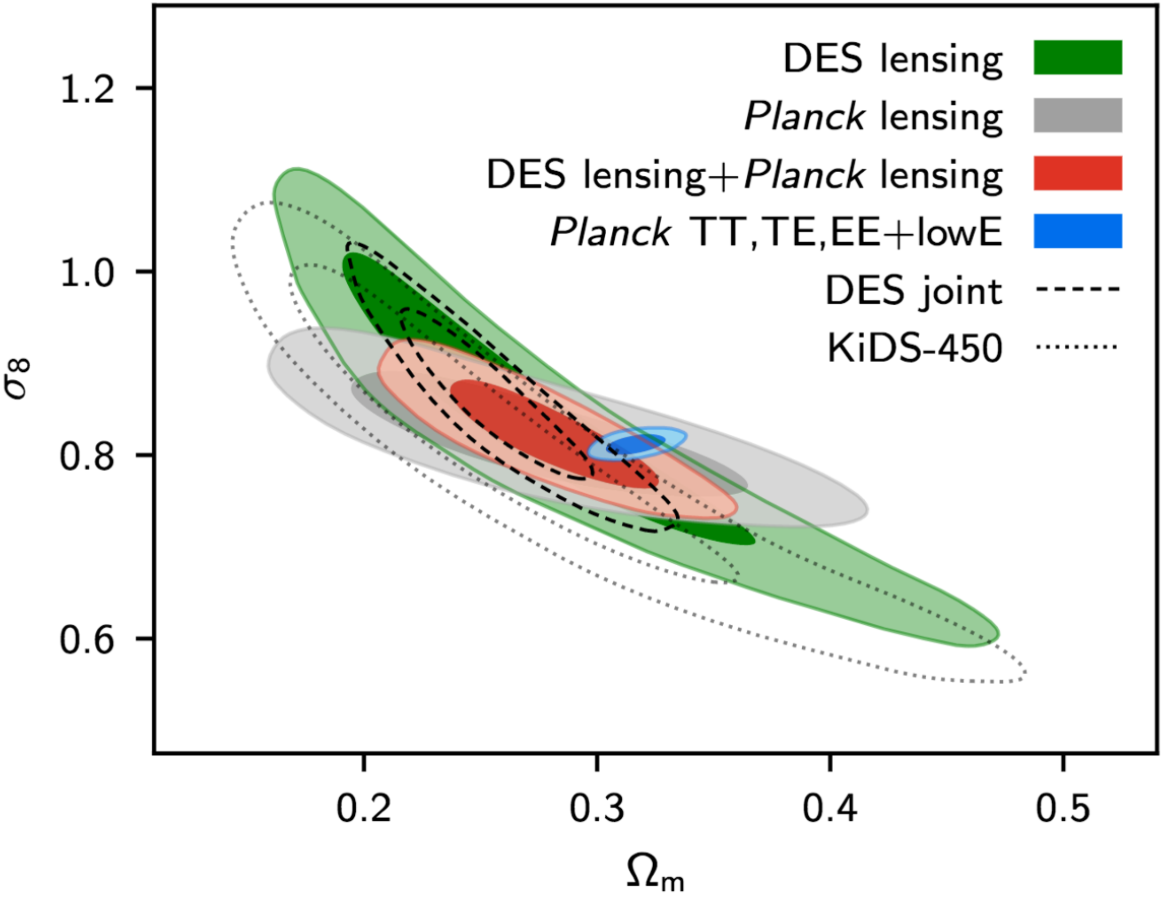
95% C. L.
Planck TT+TE+EE+lowE
+lensing+BAO

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...

3.6σ discrepancy between the Planck-inferred H_0 and local measurements:

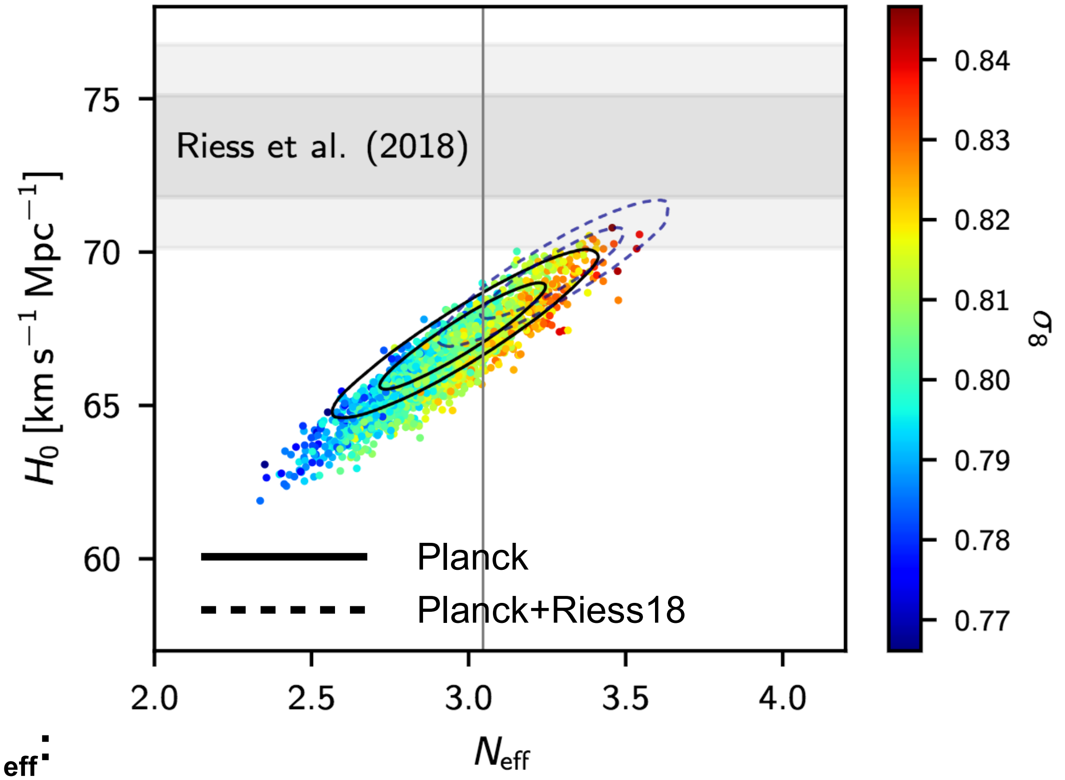
- **TT+TE+EE+lowE+lensing**

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

- **Local measurement**:

$$H_0 = 73.52 \pm 1.62\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Riess et al. 2018



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

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 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 3.6σ discrepancy between Planck and local measurements of H_0 remains in ΛCDM, which cannot be resolved with $N_{eff}>3$. The discrepancy does however drive up slightly the preferred value of N_{eff} in a combined analysis.