Cosmology and neutrinos

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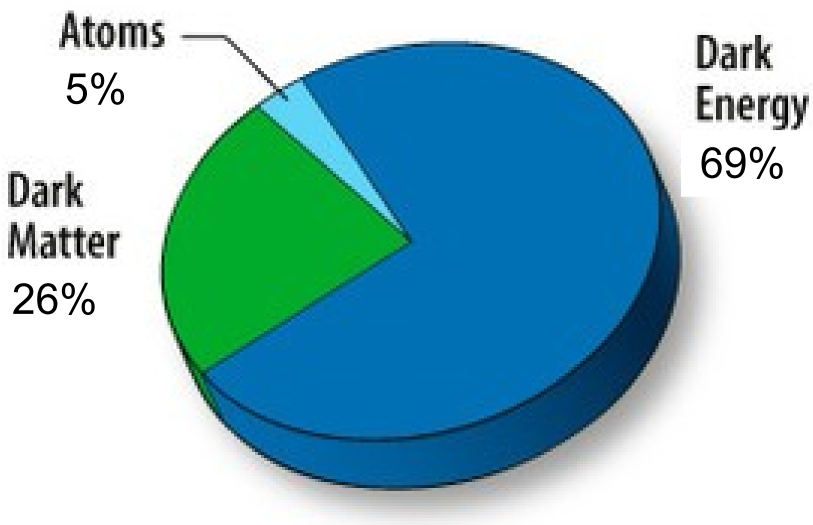
Dark Side of the Universe, Annecy, 2018

The concordance flat ΛCDM model...

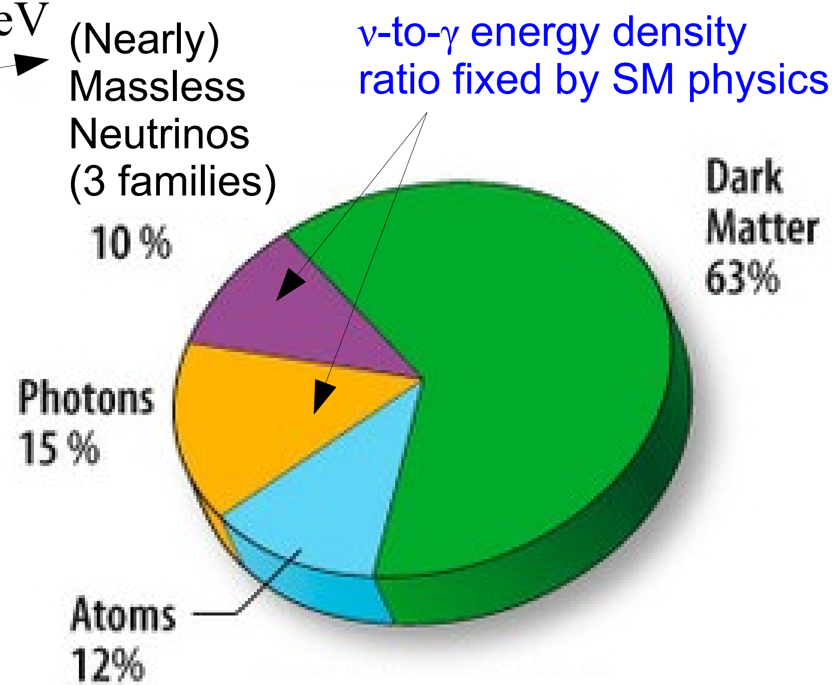
The simplest model consistent with **present observations**.

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...

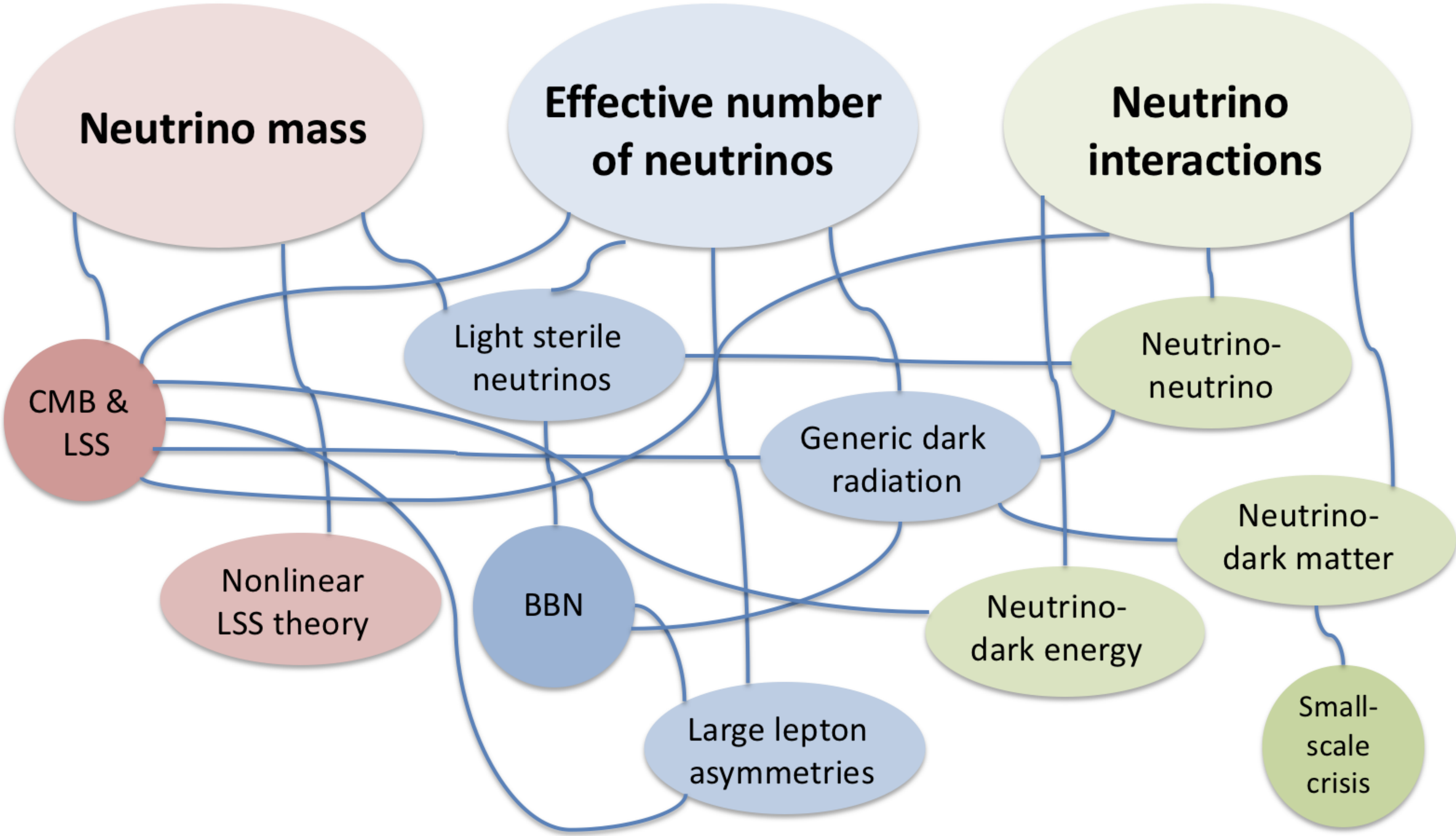
There are many ways in which the neutrino sector might be more complex than is implied by the standard picture.

Neutrino dark matter

$$\Omega_{\nu,0} h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}} = ??$$

- **Masses** larger than 0.06 eV.
  - No reason to fix at the minimum mass.
  - Laboratory upper limit $\Sigma m_\nu < 7$ eV from β-decay endpoint.
- **More than three flavours**. $N_{\mathrm{eff}} \neq 3\,??$
  - Light sterile neutrinos and other light states, "dark radiation".
- **Free-streaming or not?**
  - Possible new neutrino interactions.

The neutrino sector beyond ΛCDM...

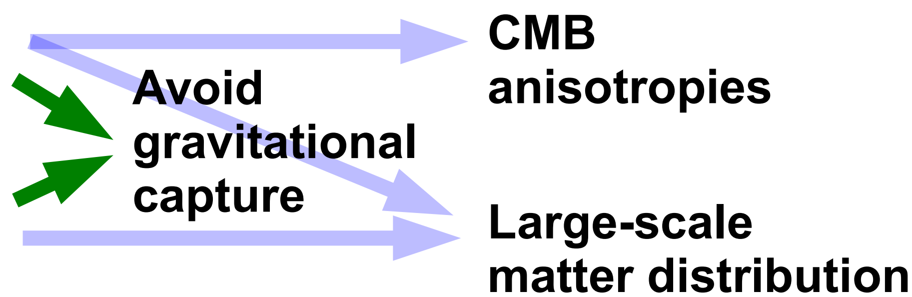


1. Neutrino masses and cosmology...

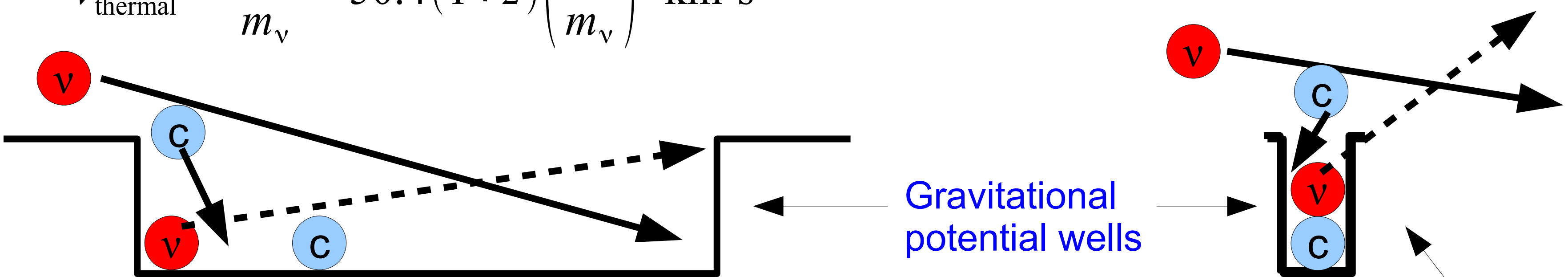
Free-streaming neutrinos...

For most of the observable history of the universe neutrinos have significant speeds.

- eV-mass neutrinos become nonrelativistic near γ decoupling.
- Even when nonrelativistic, neutrinos have large thermal motion.



$$v_{\mathrm{thermal}} = \frac{T_\nu}{m_\nu} \simeq 50.4(1+z)\left(\frac{\mathrm{eV}}{m_\nu}\right)\ \mathrm{km\ s^{-1}}$$



Non-clustering

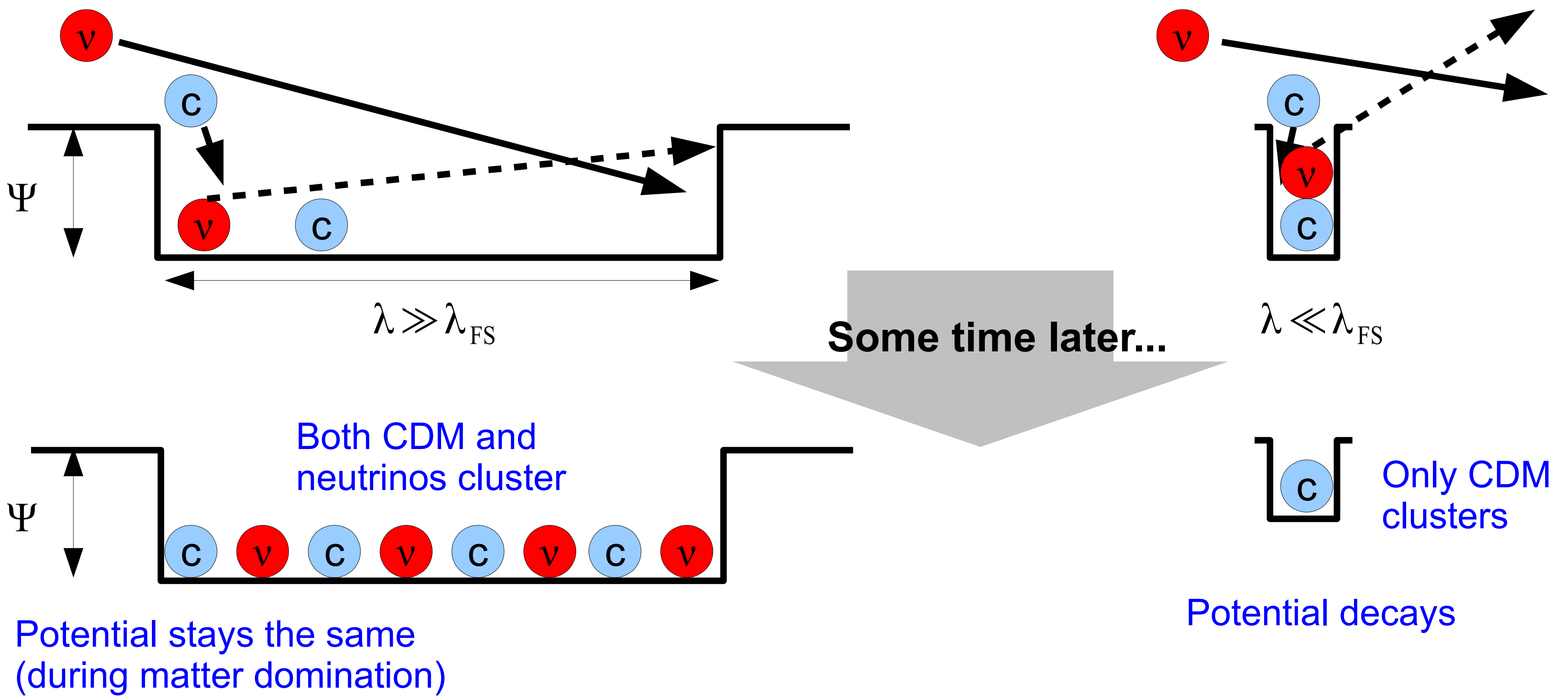
$\lambda \ll \lambda_{\mathrm{FS}}$

$k \gg k_{\mathrm{FS}}$

Free-streaming scale:

$$\lambda_{\mathrm{FS}} \equiv \sqrt{\frac{8\pi^2 v_{\mathrm{thermal}}^2}{3\Omega_m H^2}} \simeq 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{\mathrm{eV}}{m_\nu}\right)\ h^{-1}\ \mathrm{Mpc}\,; \quad k_{\mathrm{FS}} \equiv \frac{2\pi}{\lambda_{\mathrm{FS}}}$$

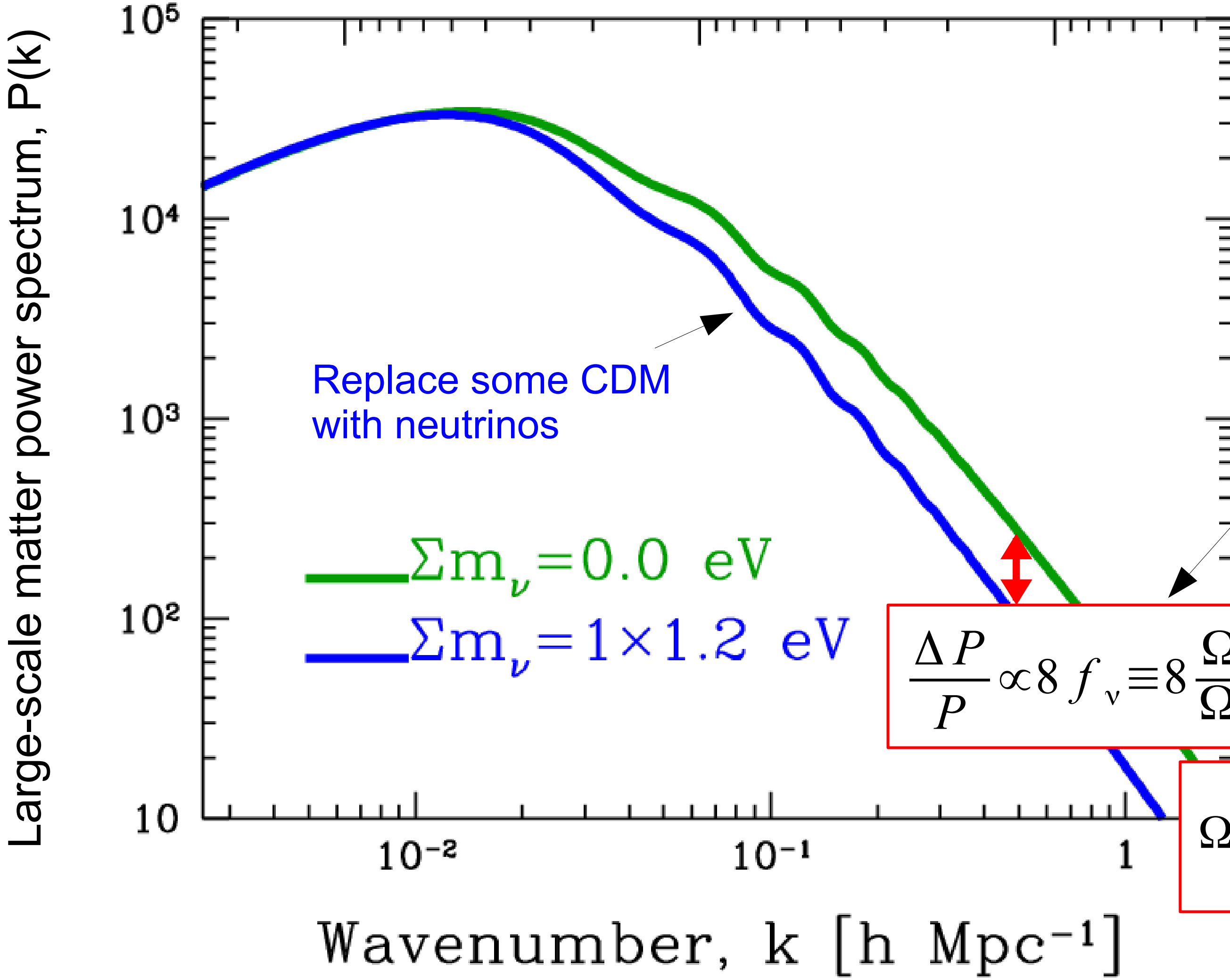
Consider a neutrino and a cold dark matter particle encountering two gravitational potential wells of different sizes in an expanding universe:



→ **Cosmological neutrino mass measurement** is based on observing this free-streaming induced potential decay at $\lambda << \lambda_{FS}$.

Large-scale matter power spectrum...

$$P(k) = \langle |\delta(k)|^2 \rangle$$



Small-scale suppression due to potential decay

f_ν = Neutrino fraction

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

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

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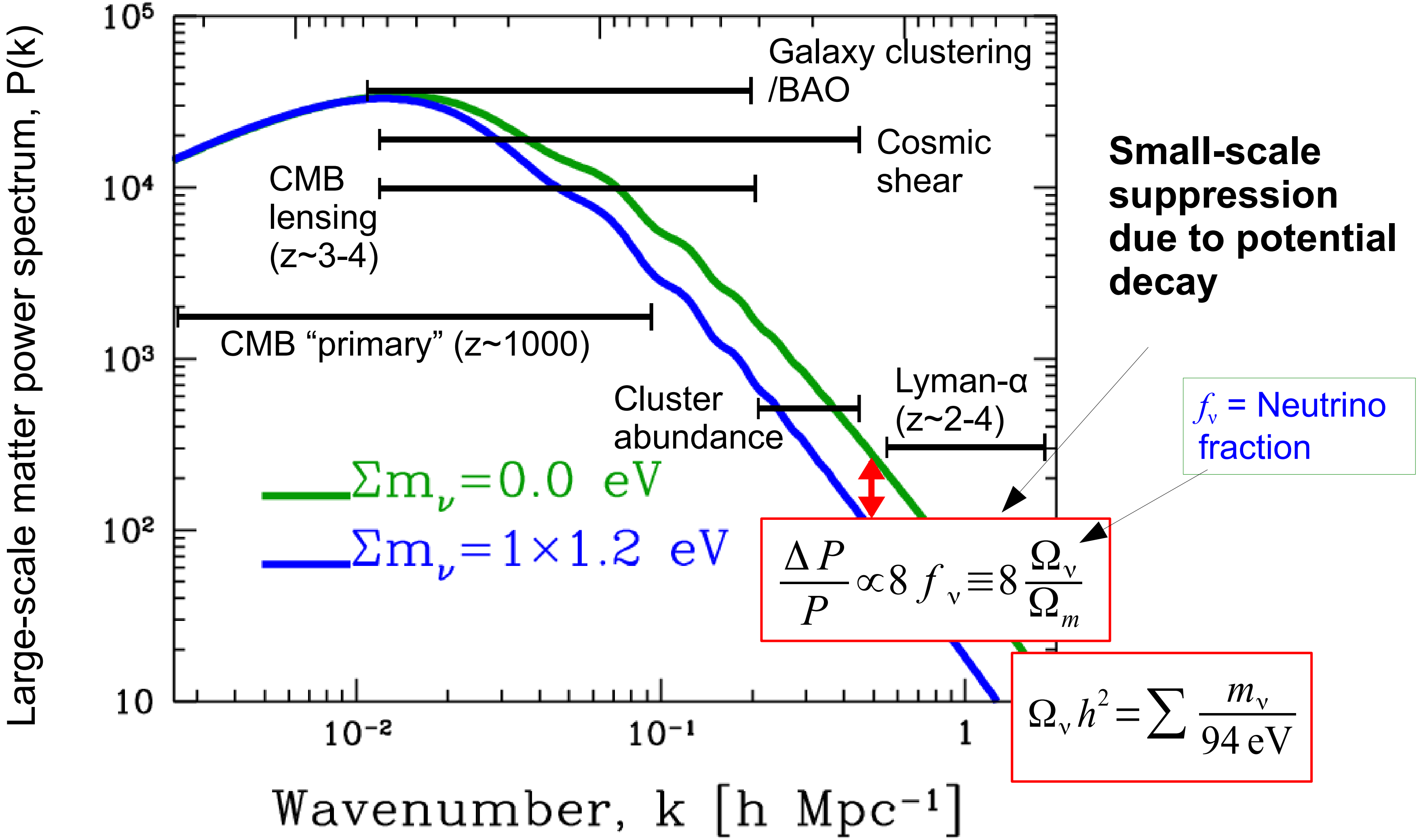

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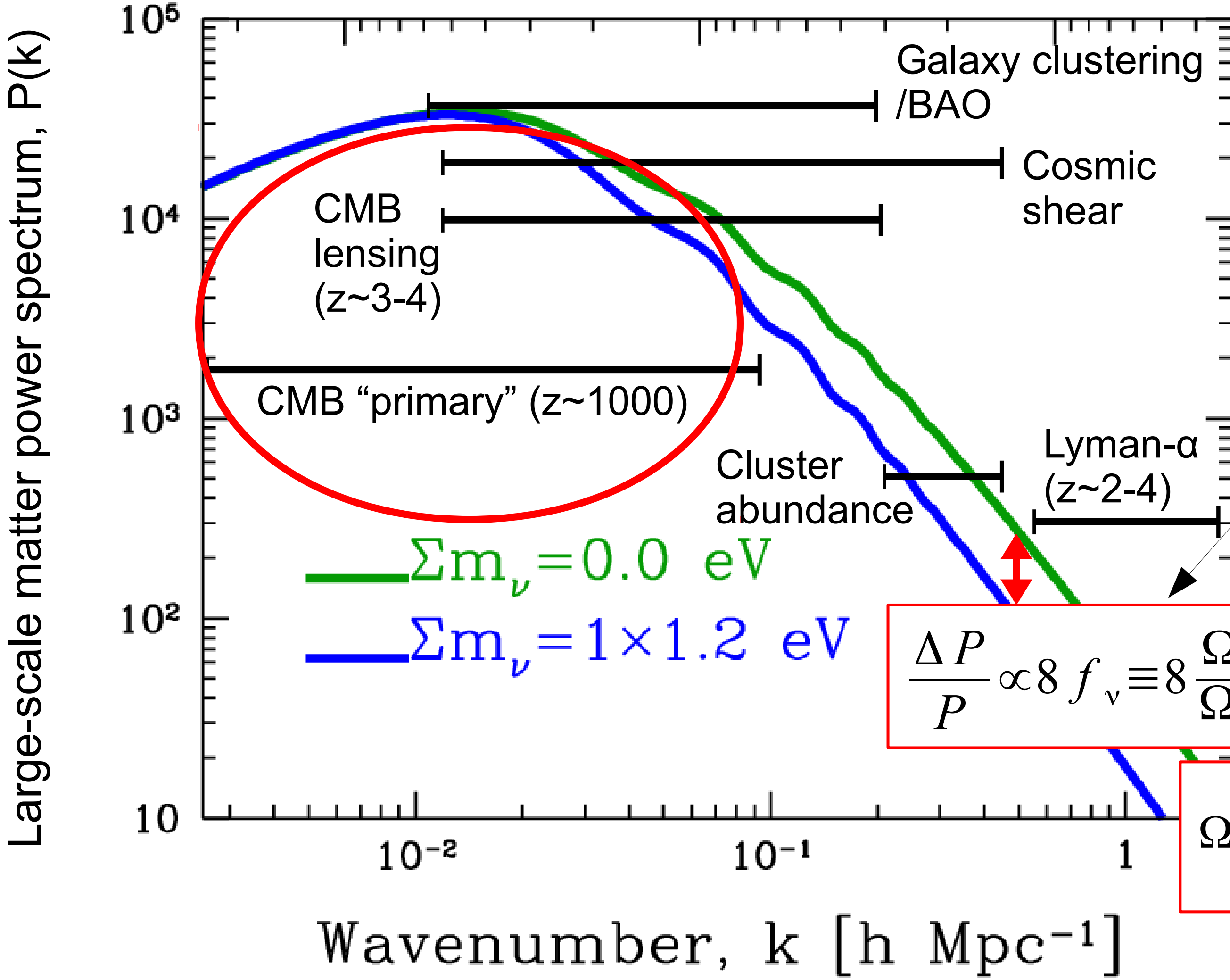

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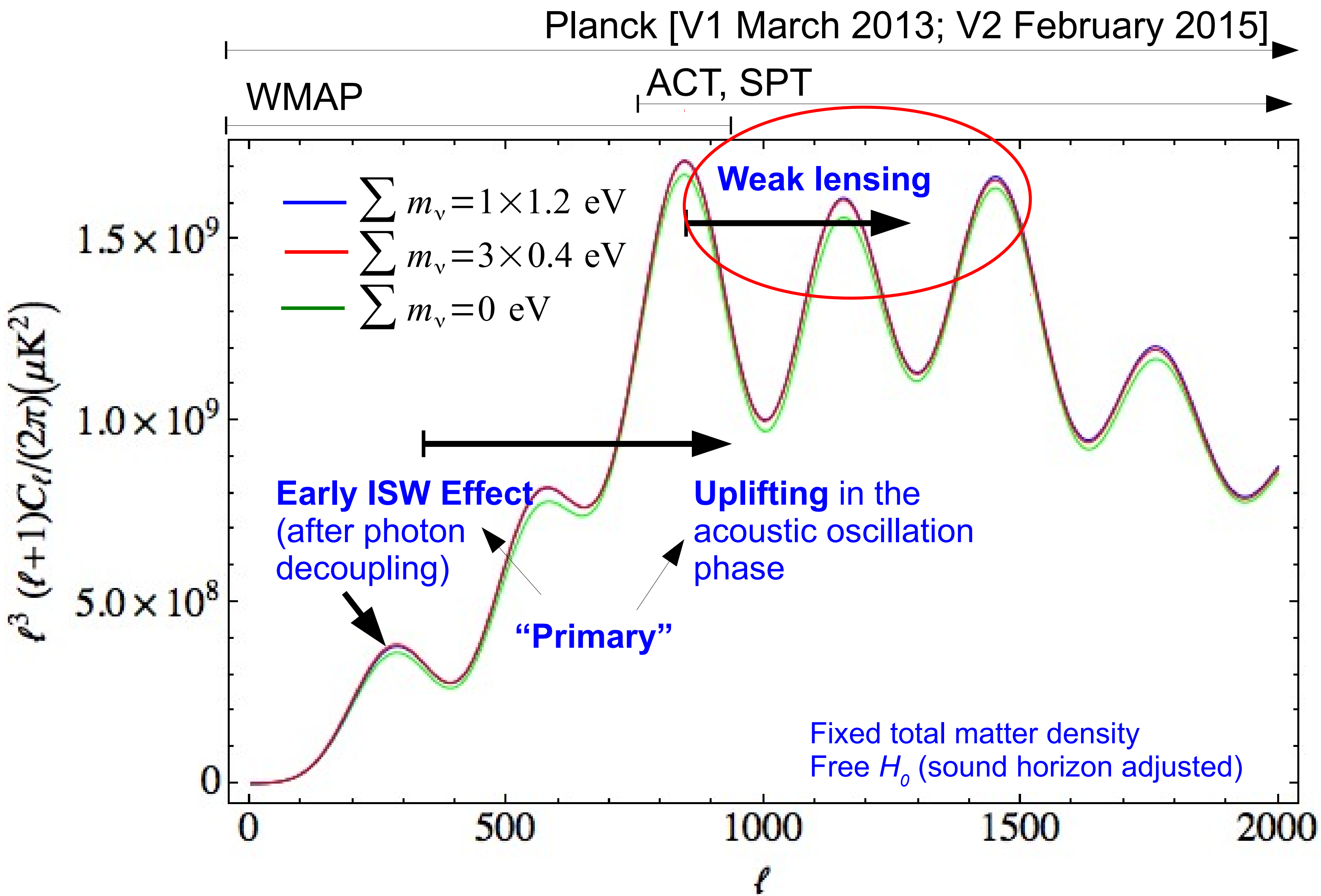
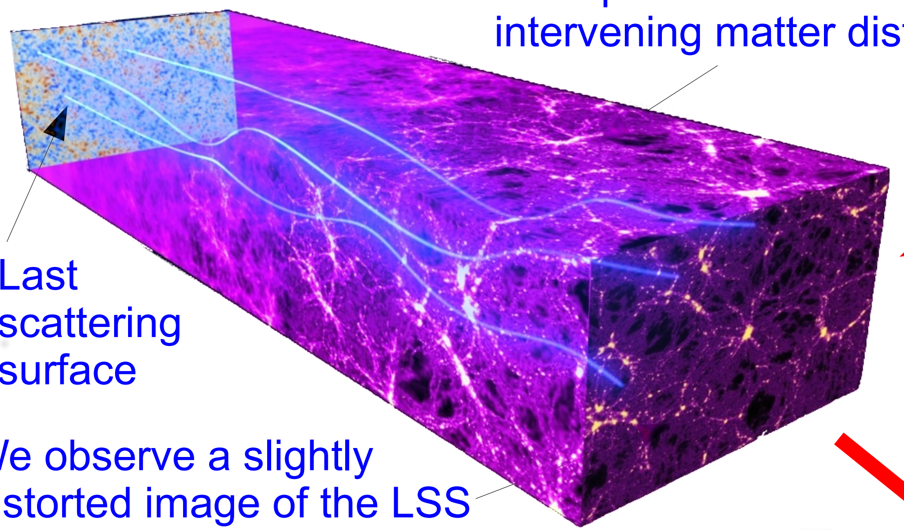
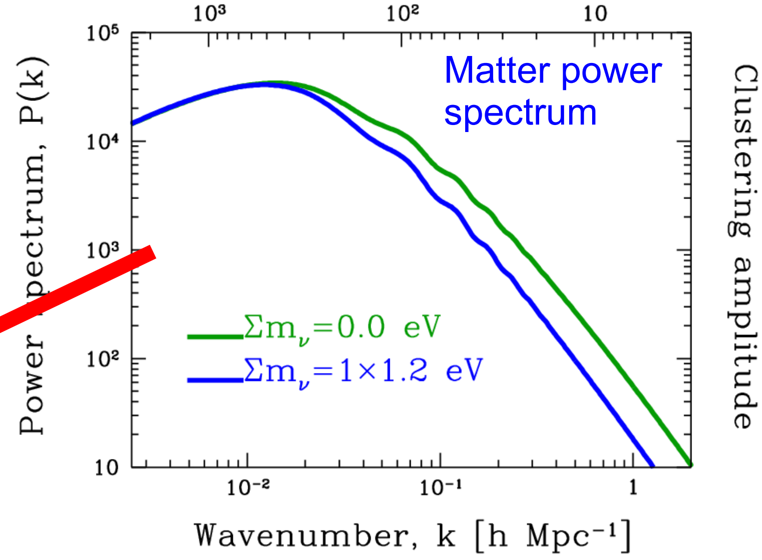
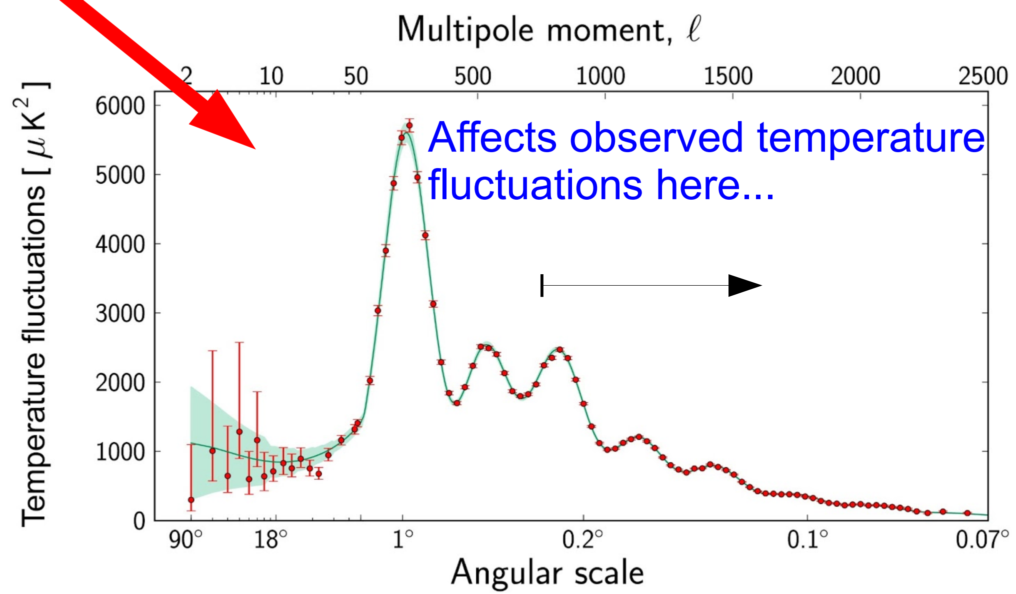
Neutrino mass signatures in the CMB TT spectrum...



Weak lensing of the CMB...







Planck TT+TE+EE+lowP

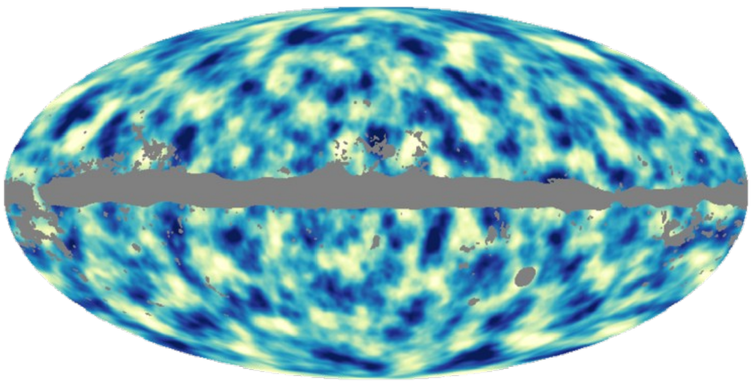
$$\sum m_\nu < 0.49 \text{ eV} \quad (95\% \text{C.L.})$$

... largely because of this lensed TT signal.

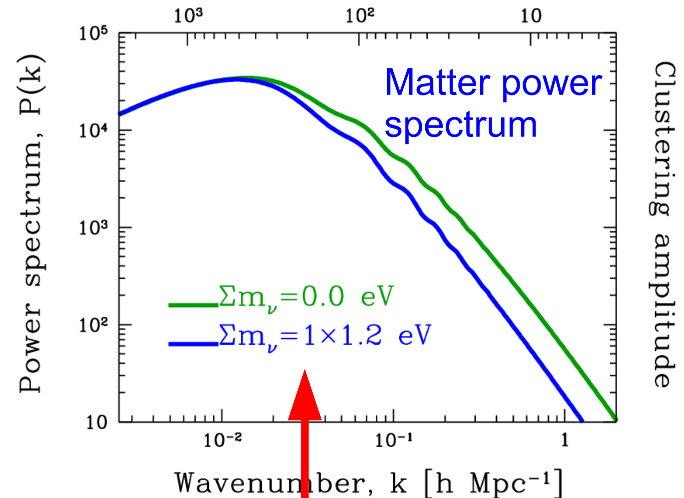
Ade et al. [Planck] 2016

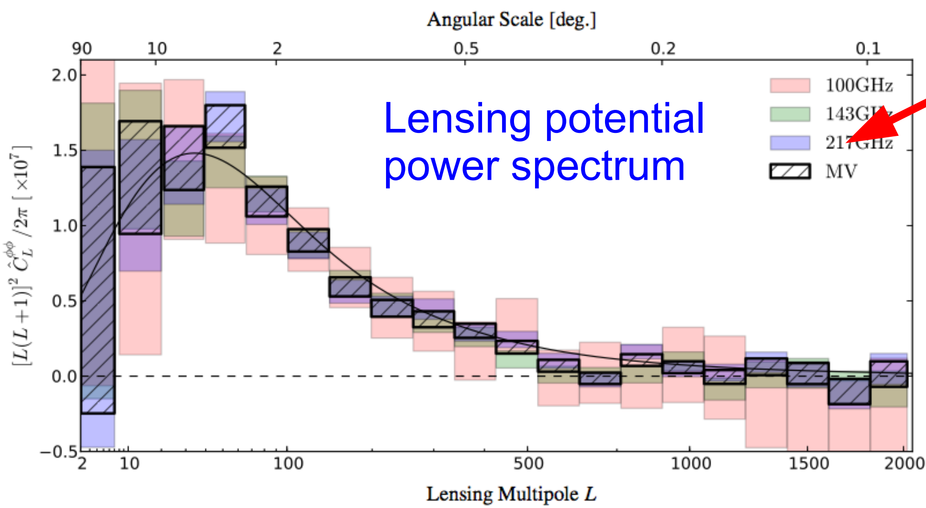
Weak lensing: lensing potential power spectrum...

Reconstructing the intervening matter distribution from higher-order correlations.



Lensing potential map





This is essentially this integrated along the line-of-sight (with some geometric factors folded in).

Ade et al. [Planck] 2016

Planck TT+TE+EE+lowP+lensing

$$\sum m_\nu < 0.59\ \text{eV} \quad (95\%\ \text{C.L.})$$

Current 95% C.L. constraints...

Lattanzi & Gerbino, arXiv:1712.07109

7-parameter fits

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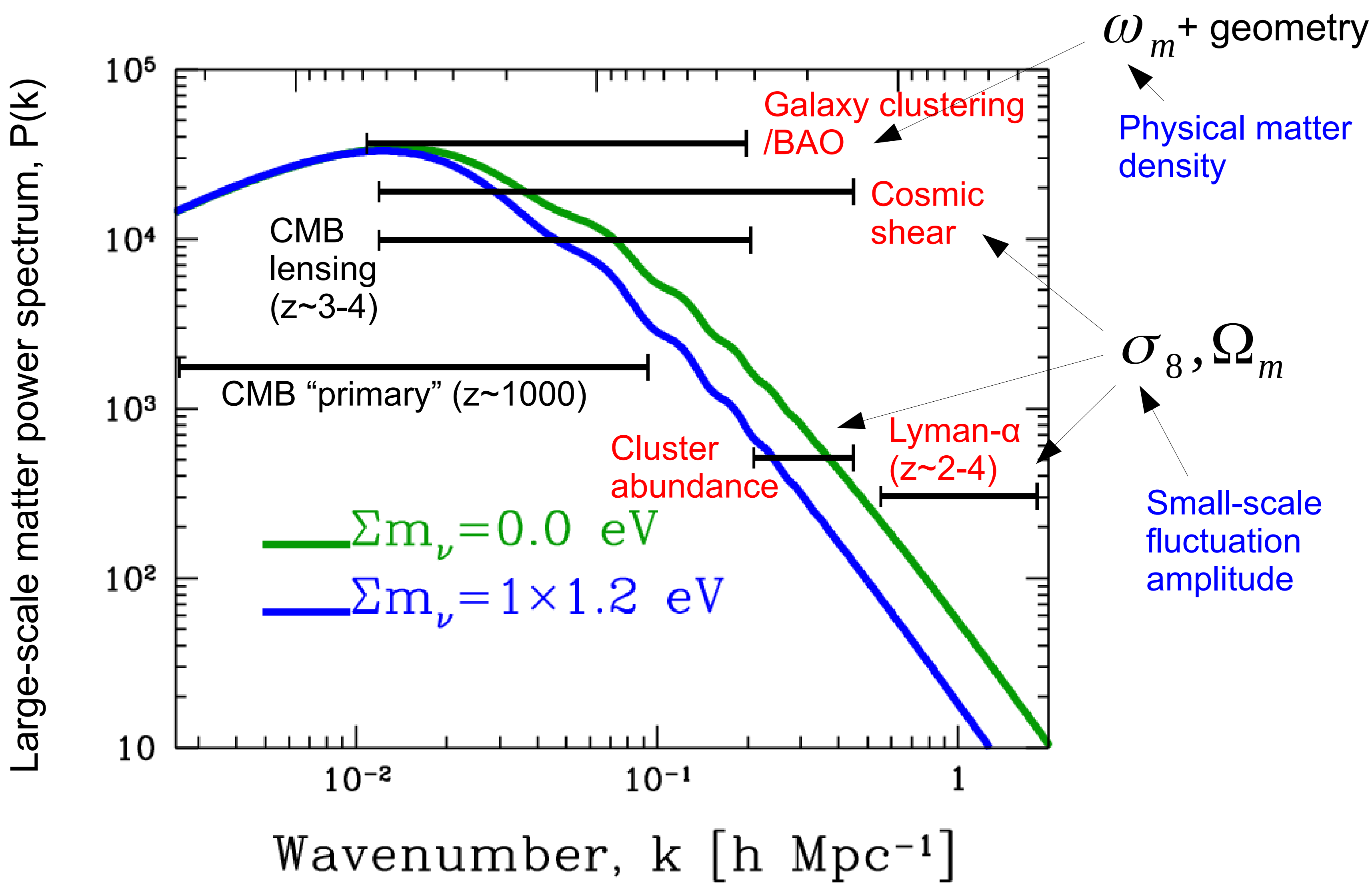
Info from large-scale structure probes...



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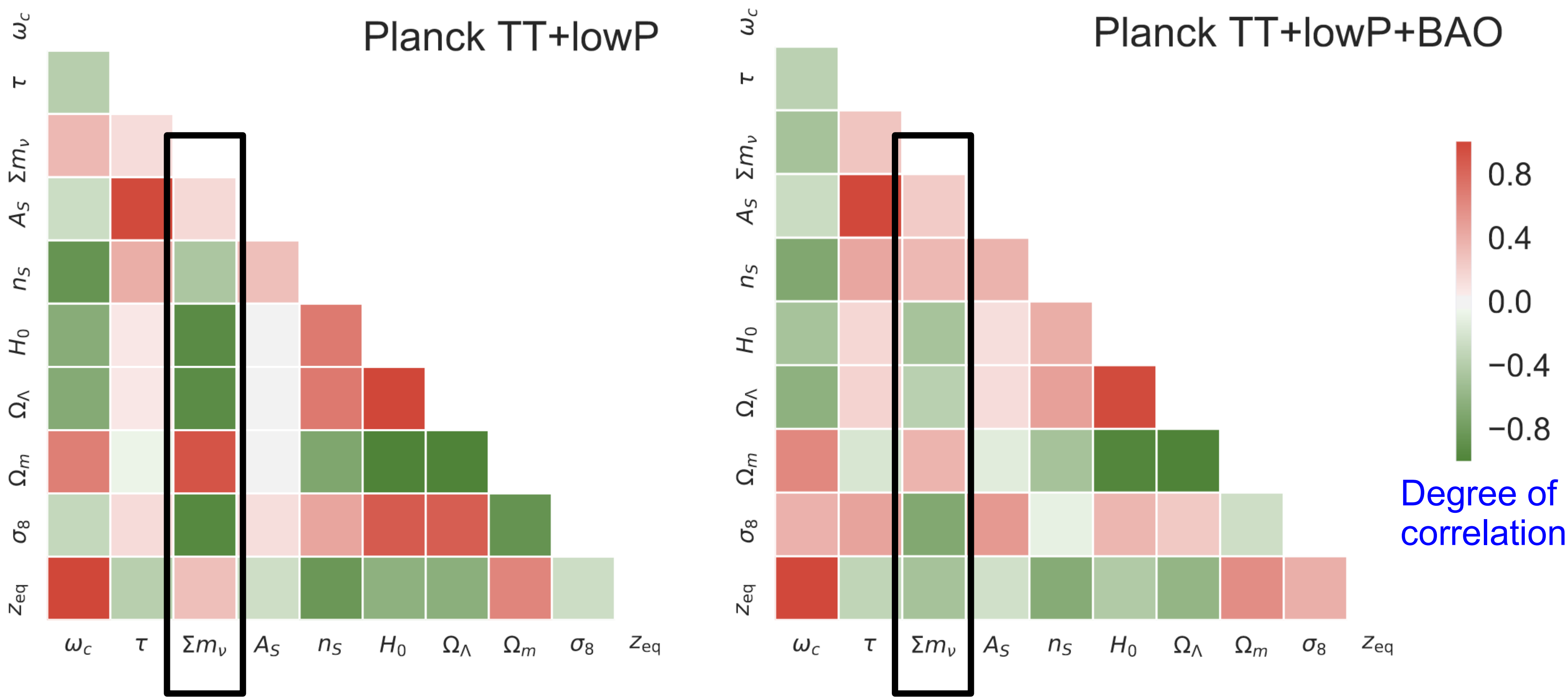
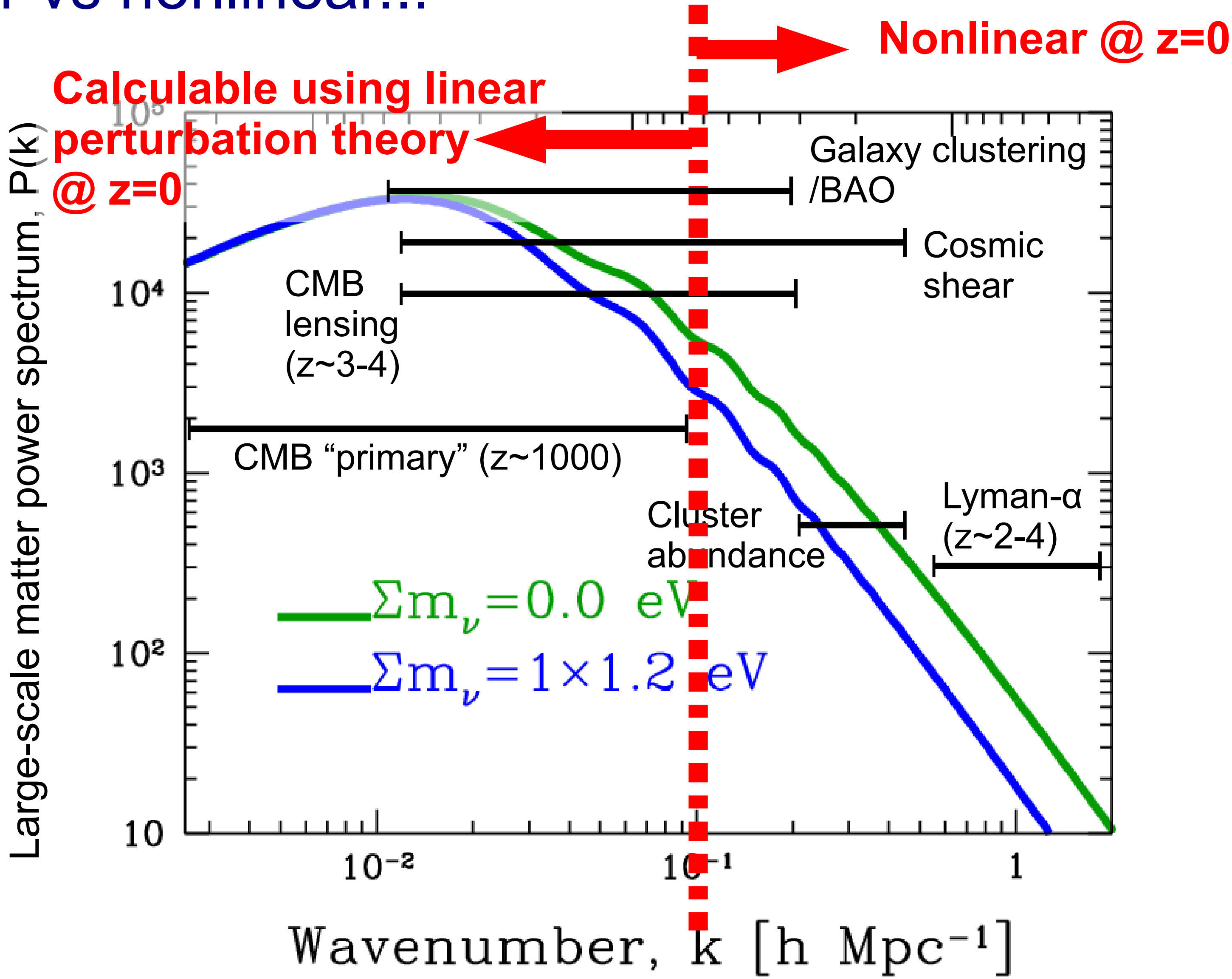


Lattanzi & Gerbino, arXiv:1712.07109

Linear vs nonlinear...

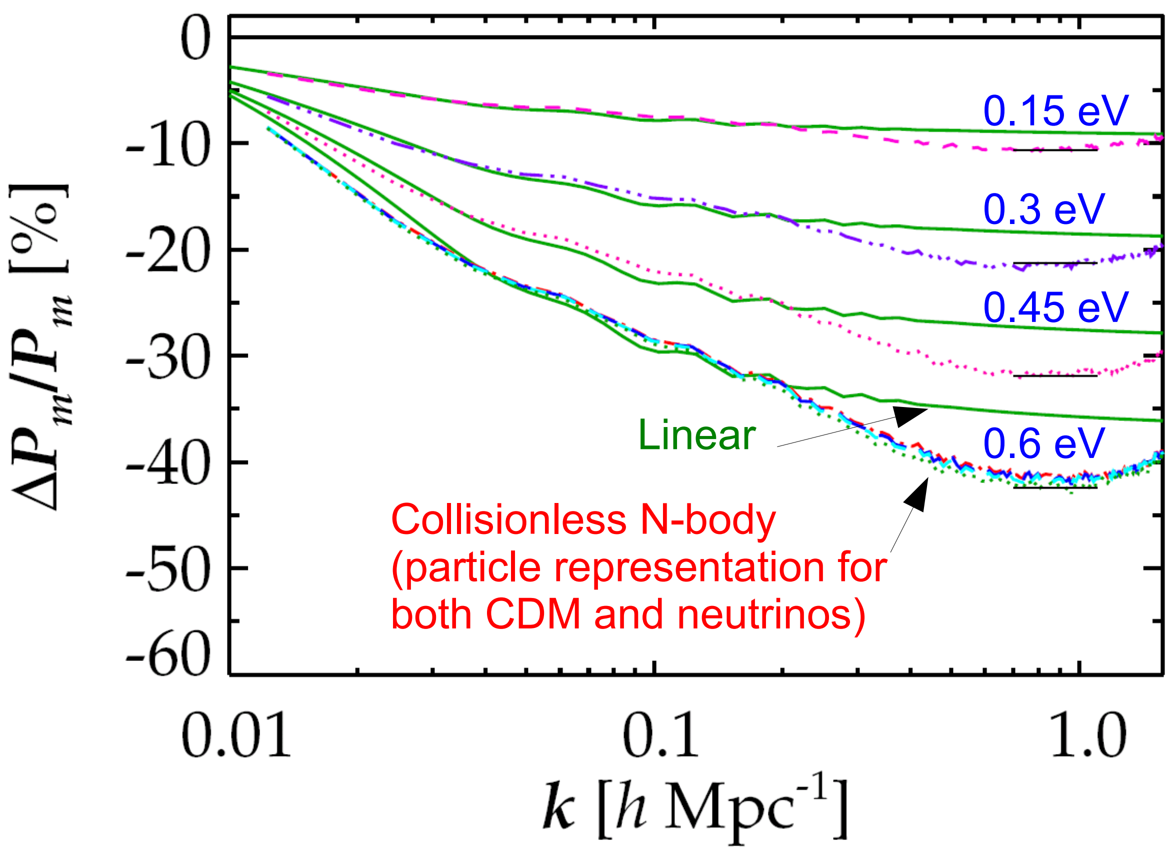


Degrees of nonlinearity...

Baryonic physics affects
all probes at k > O(1) Mpc^{-1}
@ > %-level

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

Collisionless nonlinearities only...



Change in the total matter power spectrum relative to the massless case:

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, Haugbolle & Thomsen 2008;Viel, Haehnelt & Springel 2010; Bird, Viel & Haehnelt 2012
Brandbyge & Hannestad 2009, 2010; Brandbyge, Hannestad, Haugbolle & Y[3]W 2010; Ali-Haimoud & Bird 2012; and many more...

Which bound should I use?

Lattanzi & Gerbino, arXiv:1712.07109

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Y³W's rule of thumb:

Look beyond the number and ask, is the tight constraint obtained at another parameter's expense?

Which bound should I use?

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Lattanzi & Gerbino, arXiv:1712.07109

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Caution: Spectral index!
2.3σ discrepancy between Lya and Planck:

$n_s = 0.939 \pm 0.010$ Lya

$n_s = 0.9645 \pm 0.0049$ Planck

Which bound should I use?

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+ Local Hubble rate $H_0 = 73.02 \pm 1.79$

Riess et al. 2016

$$\sum m_\nu < 0.113 \text{ eV}$$

(Planck only $H_0 = 67.5 \pm 0.64$; 3σ discrepancy)

Moral of the story here...

- Treat aggressive cosmological neutrino mass bounds from **combining multiple data sets** with extreme caution.

  - Significant discrepancies in the estimates of **other cosmological parameters** likely mean that the analysis (theory, data, etc.) is not as well understood as the proponents would like to think.

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 ~ 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

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

Three SM neutrinos

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...

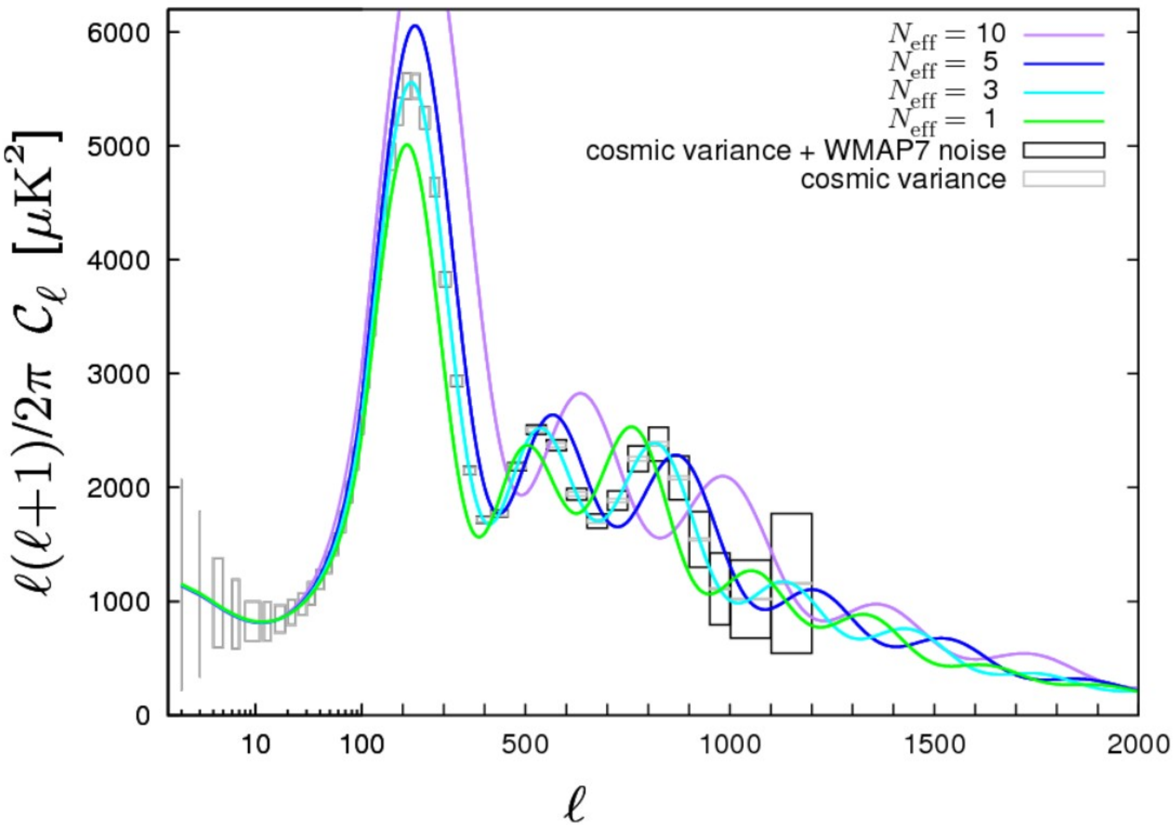


Figure courtesy of J. Hamann

- Looks easy... But we also use the **same data** to measure at least 6 other cosmological parameters:

Hubble parameter

baryon density

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

matter density

optical depth to reionisation

primordial fluctuation amplitude & spectral index (inflation parameters)

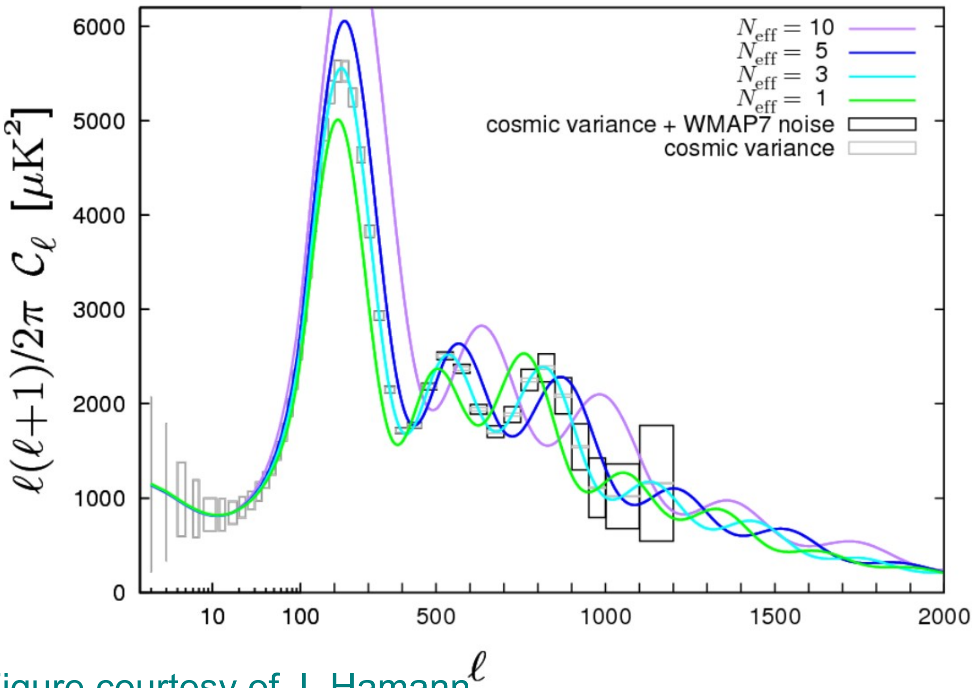
- Plenty of parameter degeneracies!

What the CMB really probes: equality redshift...

Exact degeneracy between the physical matter density ω_m and N_{eff}.

$$1 + z_{eq} = \frac{\omega_m}{\omega_r} \simeq \frac{\omega_m}{\omega_\gamma} \frac{1}{1 + 0.2271 N_{eff}}$$

Ratio of 3rd and 1st peaks sensitive to the redshift of matter-radiation equality via the early ISW and other time-dependent effects.



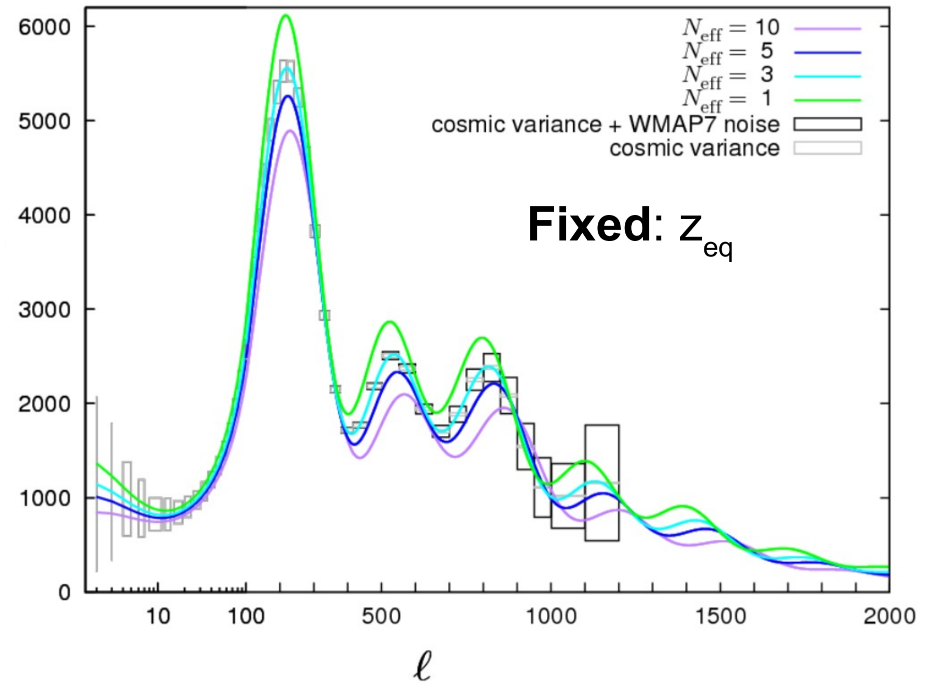


Figure courtesy of J. Hamann

What the CMB really probes: angular sound horizon...

Exact degeneracy between ω_m and the Hubble parameter h.

Peak positions depend on:

$$\theta_s = \frac{r_s}{D_A}$$

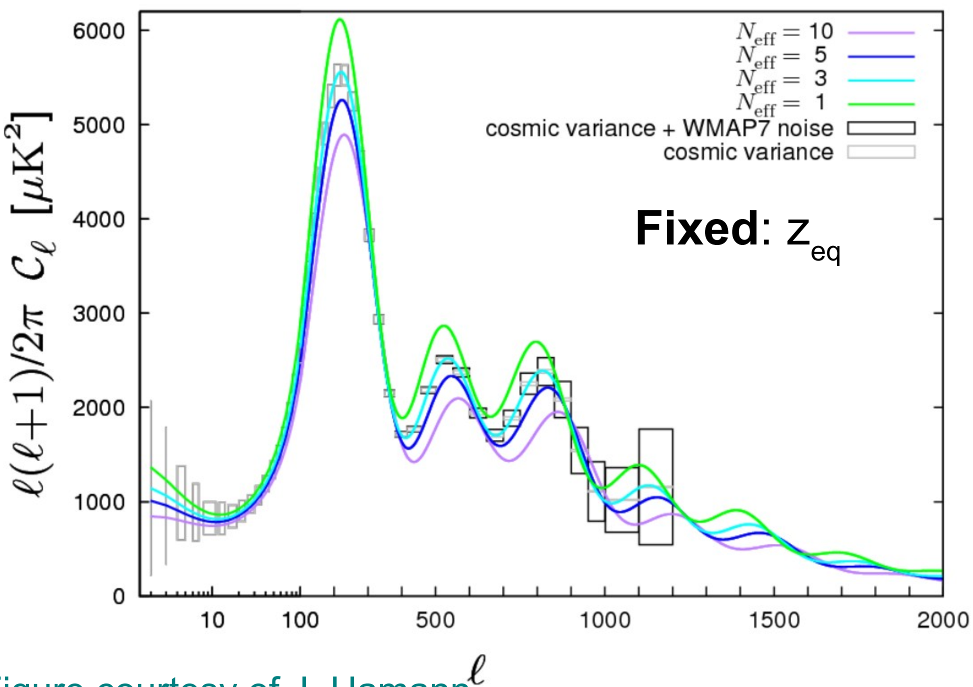
Sound horizon at decoupling (r_s)

Angular distance to the last scattering surface (D_A)

Flat ΛCDM →

$$\theta_s \propto \frac{\left(\omega_m h^{-2}\right)^{-1/2}}{\int_{a_*}^{1} \frac{da}{\sqrt{\omega_m h^{-2} a^{-3} + \left(1-\omega_m h^{-2}\right)}}}$$

Fixed z_{eq}, ω_b



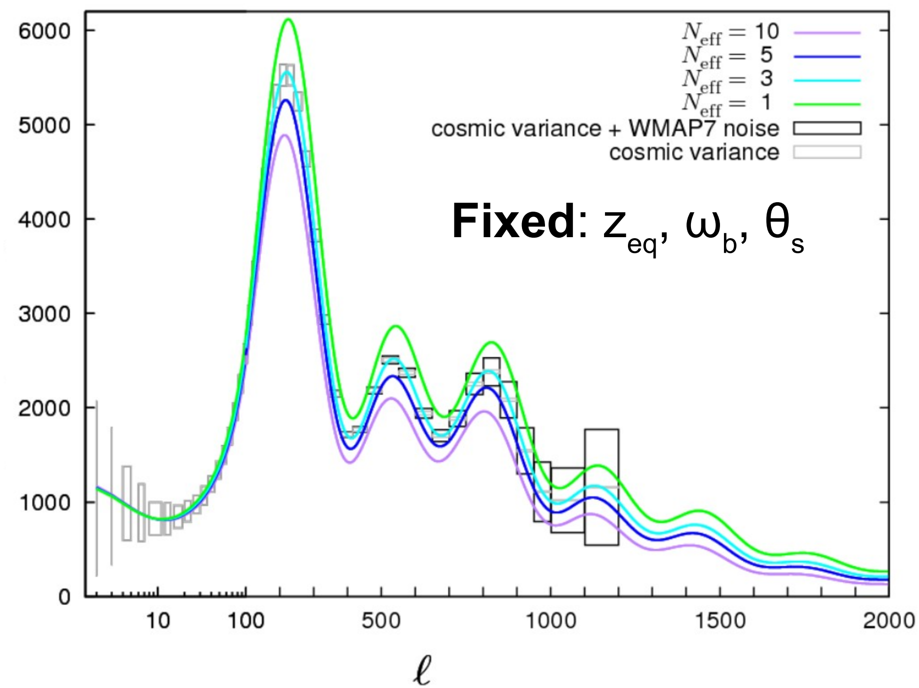
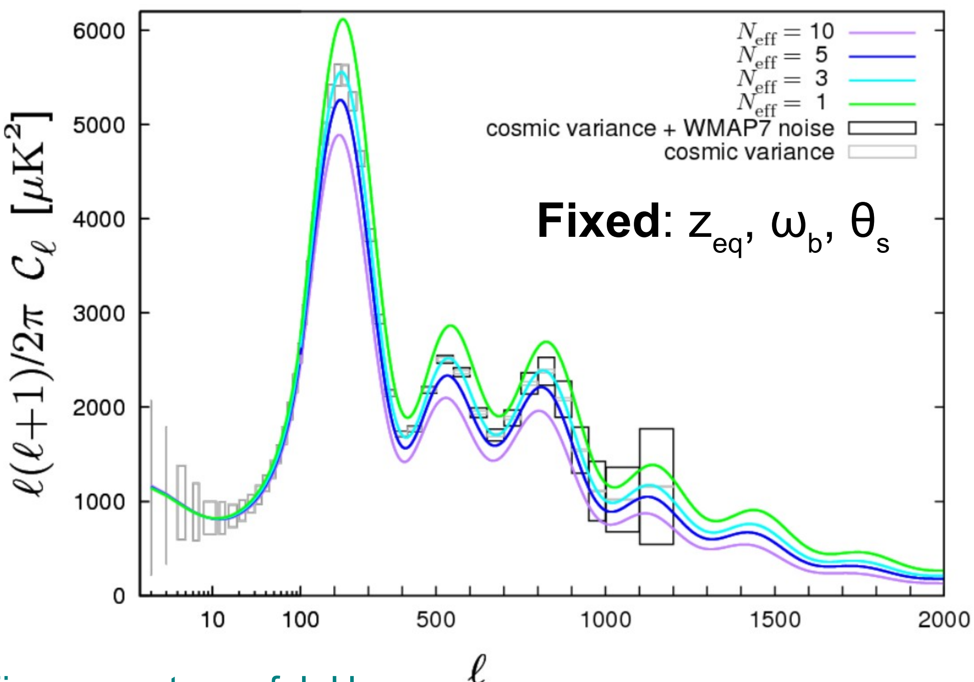


Figure courtesy of J. Hamann

What the CMB really probes: anisotropic stress...

Apparent (i.e., not physical) partial degeneracies with inflationary parameters: primordial fluctuation amplitude A_s and spectral index n_s.

- However, free-streaming (non-interacting relativistic) particles have **anisotropic stress**.
- First real signature of N_{eff} in the 3rd peak!



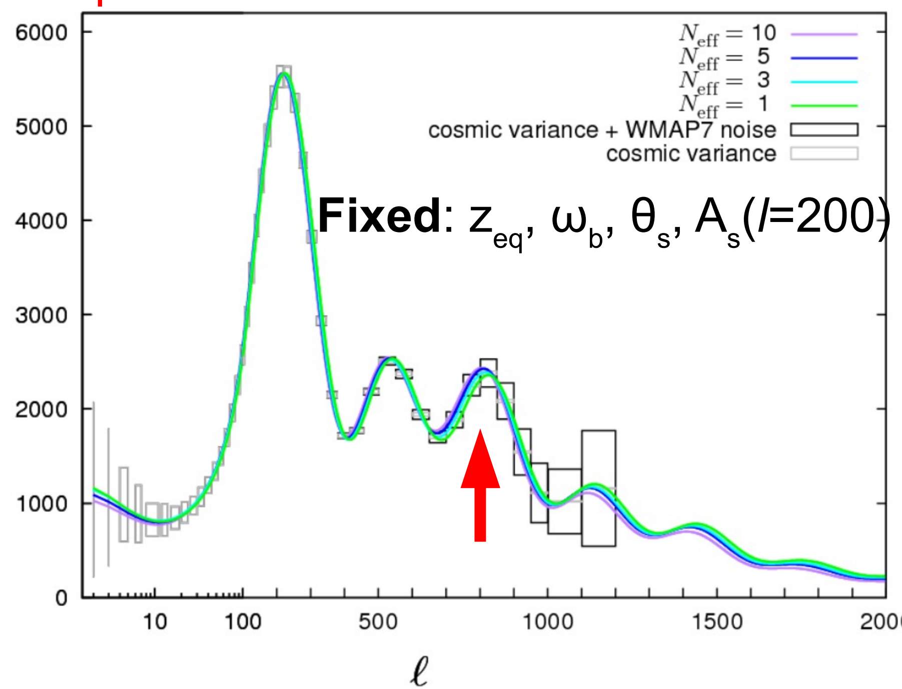
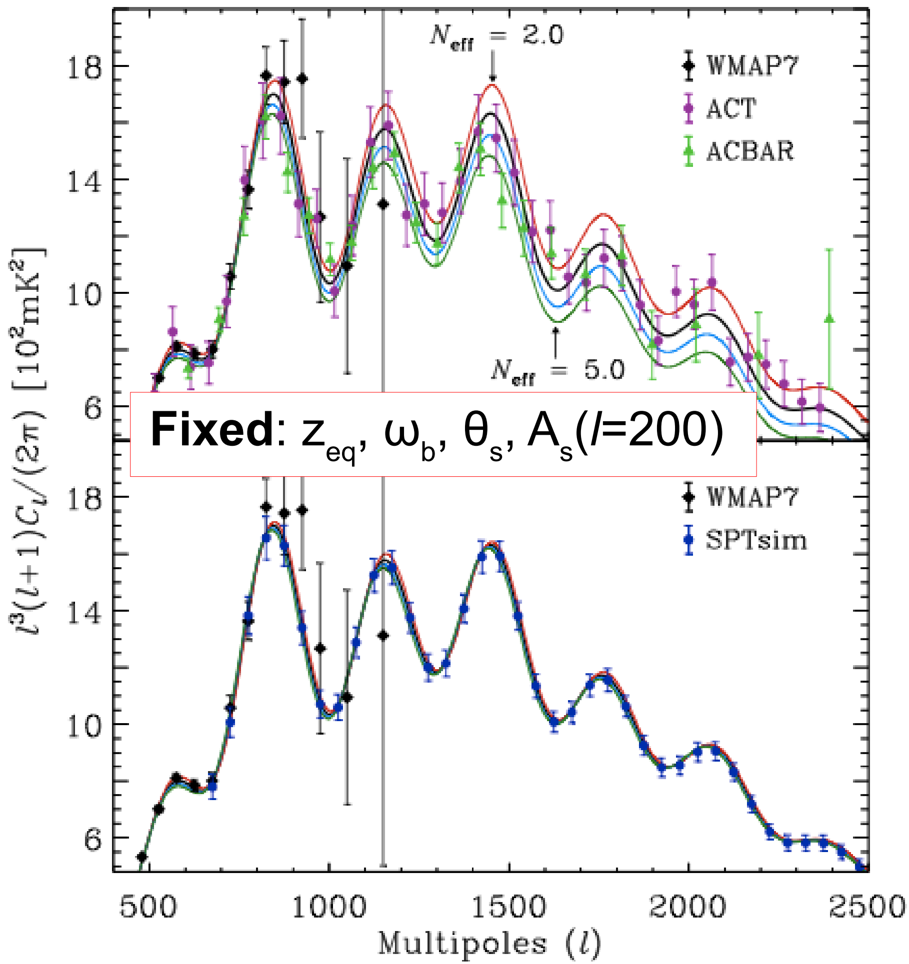


Figure courtesy of J. Hamann

The damping tail...



Fixed: z_{eq}, ω_b, θ_s, $A_s(l=200)$

Hou, Keisler, Knox et al. 2011

The main signature of N_{eff} lies in the CMB damping tail:

- Measured by **ACT** data since 2010; **SPT** since 2011; **Planck** since 2013.
- Probe **angular photon diffusion scale**:

$$\theta_d = \frac{r_d}{D_A}$$

← Diffusion scale at decoupling

- + sound horizon measurement:

$$\frac{\theta_d}{\theta_s} = \frac{r_d}{r_s} \propto \omega_m^{1/4}$$

Fixed z_{eq}, ω_b

Breaks N_{eff}-h-ω_m-degeneracy

Current constraints on N_{eff} ...

Ade et al. [Planck] 2016

Planck-inferred $N_{\rm eff}$ compatible with 3.046 at better than 2σ.

ΛCDM+N_{eff} (7 parameters)

$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP}\,;$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO}\,;$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \text{TT, TE, EE+lowP}\,;$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \text{TT, TE, EE+lowP+BAO}\,.$$

68% C.I.

ΛCDM+neutrino mass+N_{eff} (8 parameters)

$$\left. \begin{array}{r} N_{\rm eff} = 3.2 \pm 0.5 \\ \sum m_\nu < 0.32\ \text{eV} \end{array} \right\} \text{95\%, } \textit{Planck}\ \text{TT+lowP+lensing+BAO.}$$

Varying Y_p too...

The CMB damping tail is also sensitive to the **Helium-4 mass fraction**.

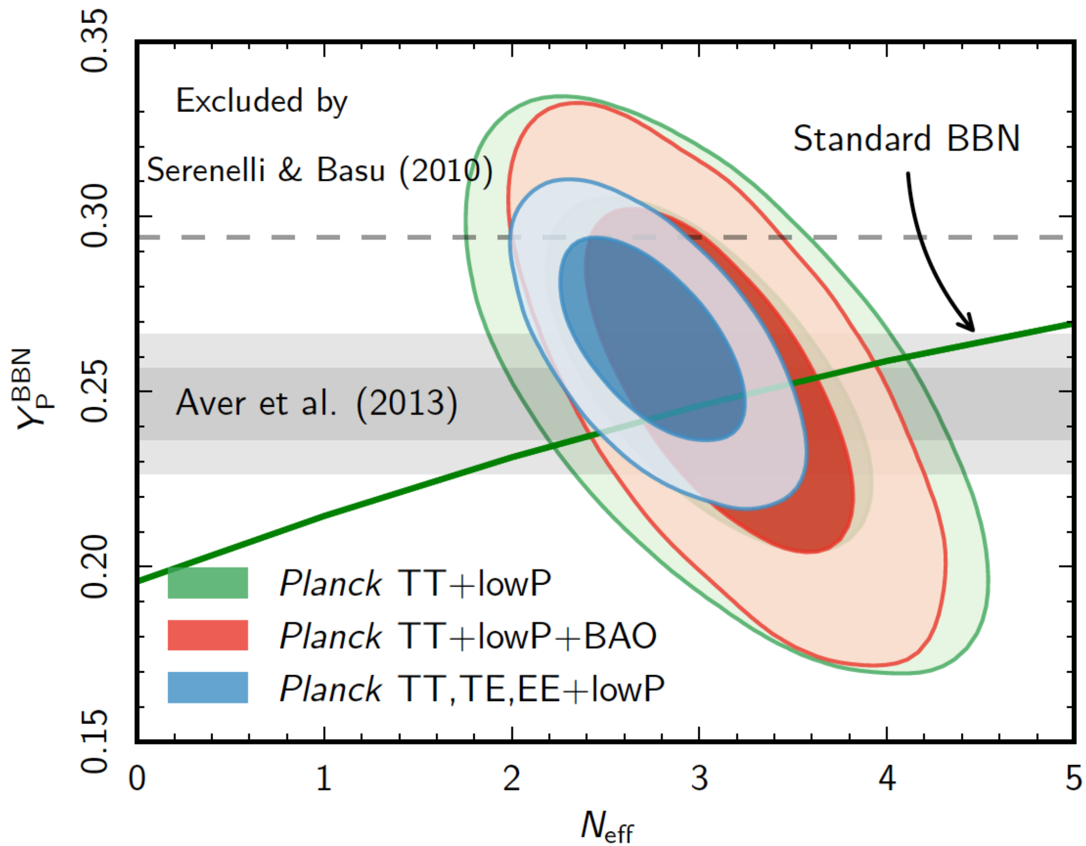
- Photon diffusion scale:

$$r_d^2 \simeq \frac{16}{15}\frac{\pi^2}{6}\int_0^{a_*}\frac{da}{a^3\sigma_T n_e H}$$

Free electron number density (dependent on recombination history)

→ **N_{eff}-Y_p degeneracy**

- Planck-inferred (N_{eff}, Y_p) values are consistent with standard BBN predictions.



Ade et al. [Planck] 2016

The N_{eff}-H_0 degeneracy...

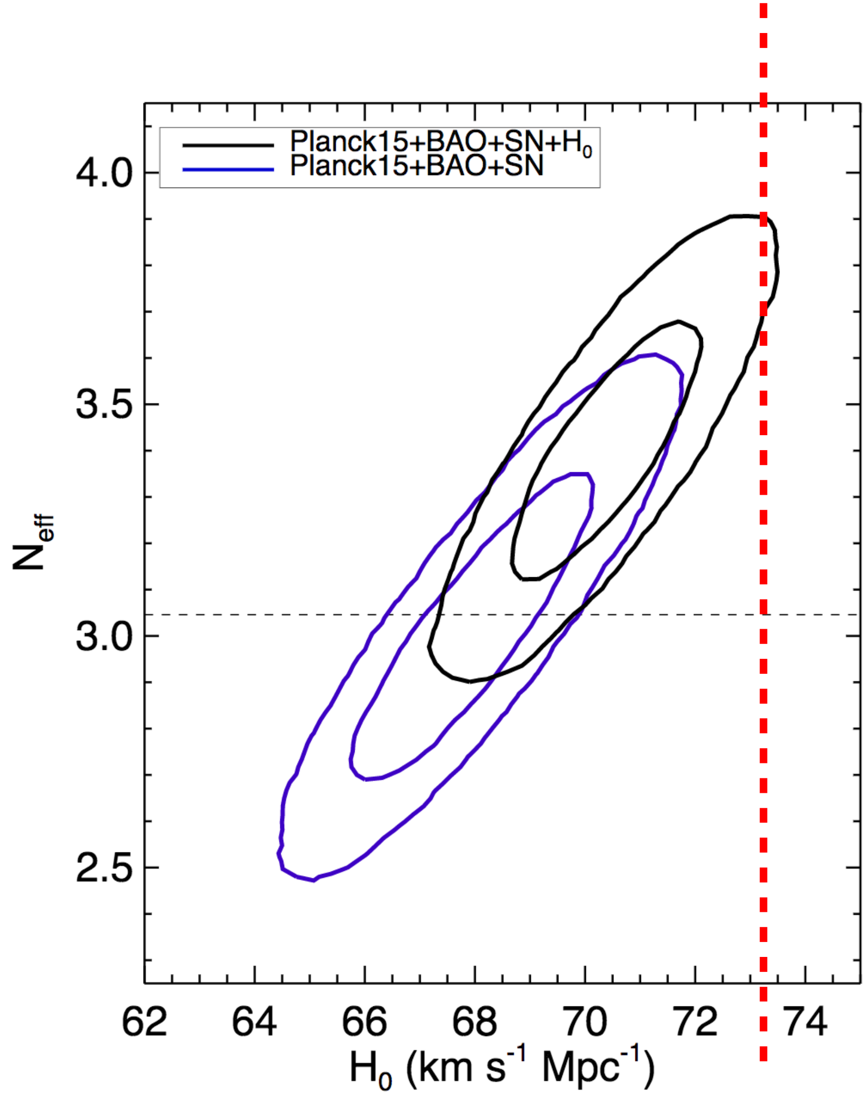
A larger $N_{\rm eff}$ does bring the Planck-inferred H_0 into better agreement with local measurements.

- **Combined Planck+HST fit**:

$$N_{\rm eff} = 3.41 \pm 0.22$$
$$H_0 = 70.4 \pm 1.2\,{\rm km\,s^{-1}\,Mpc^{-1}}$$

Riess et al. 2016

$$H_0 = 73.24 \pm 1.74\,{\rm km\,s^{-1}\,Mpc^{-1}}$$



Summary...

- **Precision cosmological data** provide strong constraints on the neutrino mass sum.
  - Quasi-linear bounds hover around 0.15-0.3 eV.
  - Use aggressive bounds (combining multiple nonlinear and possibly discrepant data sets) with extreme caution.

- A **fourth neutrino**??
  - No evidence at all.
  - But a 3.4σ discrepancy between Planck and local measurements of H_0 remains, which when analysed in combination tends to drive up the preferred value of N_{eff}.