Neutrino properties from cosmology

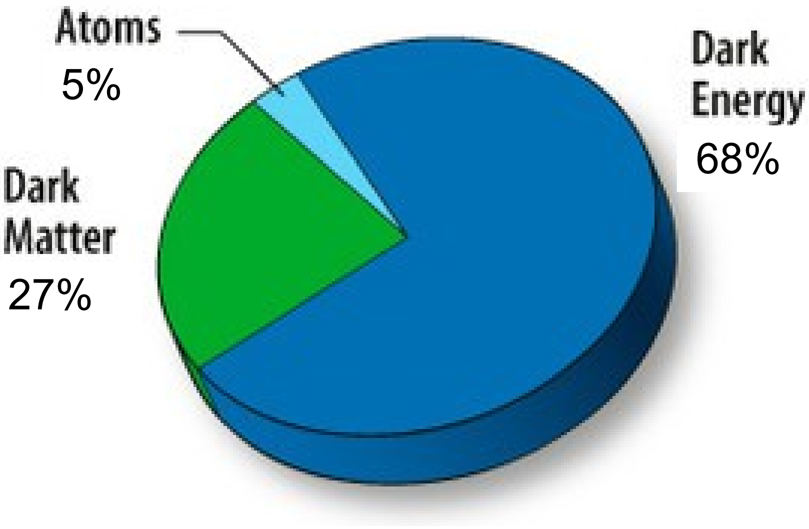
Yvonne Y. Y. Wong
The University of New South Wales
Sydney, Australia

Rencontres de Moriond EW 2014, La Thuile, March 15 – 22, 2014

The concordance flat ΛCDM model...

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

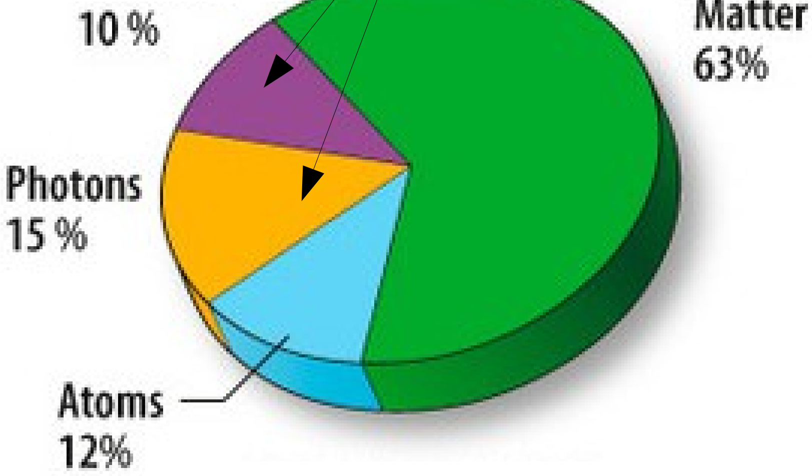
Min. value from $\sum m_\nu = 0.06\,\mathrm{eV}$ oscillations experiments



Composition today

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

(Nearly) Massless Neutrinos (3 families)



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 can be extended beyond the standard picture.

- **Masses** larger than 0.06 eV.
  - No reason to fix at the minimum mass.
  - Laboratory upper limit $\Sigma m_\nu < 7\ \mathrm{eV}$ from β-decay endpoint.

Neutrino dark matter

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

- **More than three flavours.** $N_{\mathrm{eff}} \neq 3\,??$
  - Sterile neutrinos and discrepancies potentially solved by them?

This talk

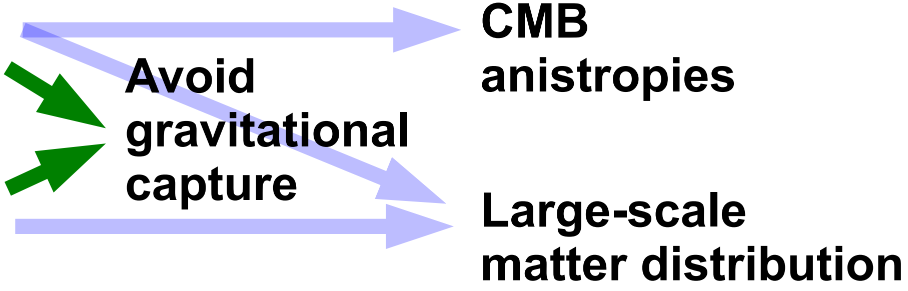
- **Hidden interactions**
  - Neutrino-neutrino, neutrino-dark matter, neutrino-dark energy.

Measuring neutrino masses with 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.

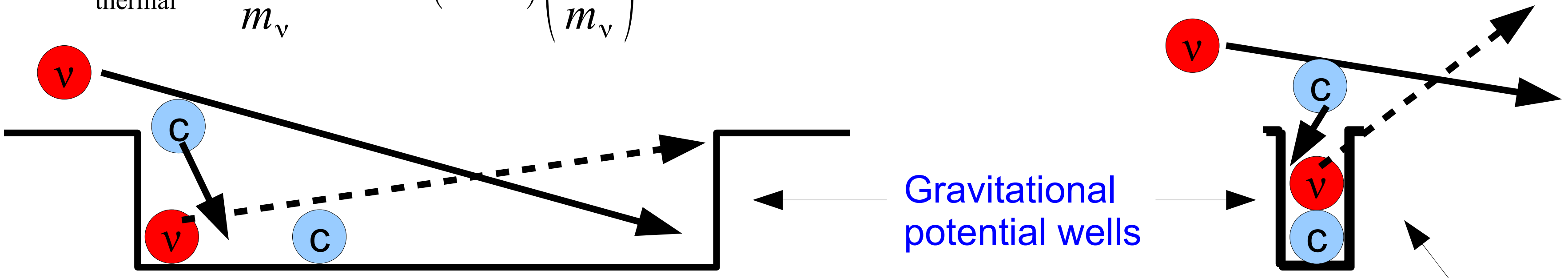


Avoid gravitational capture

CMB anistropies

Large-scale matter distribution

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



Gravitational potential wells

Non-clustering

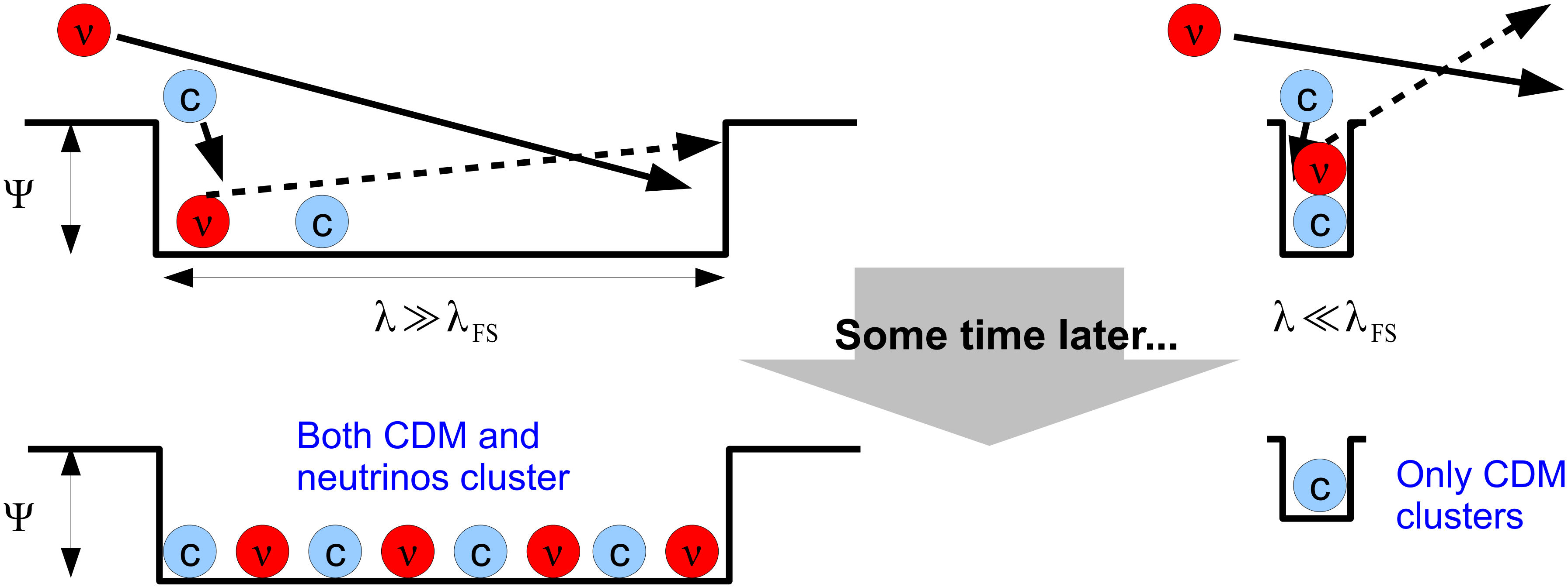
$$\lambda \ll \lambda_{\text{FS}}$$

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

Free-streaming scale:

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

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



Some time later...

Both CDM and neutrinos cluster

Only CDM clusters

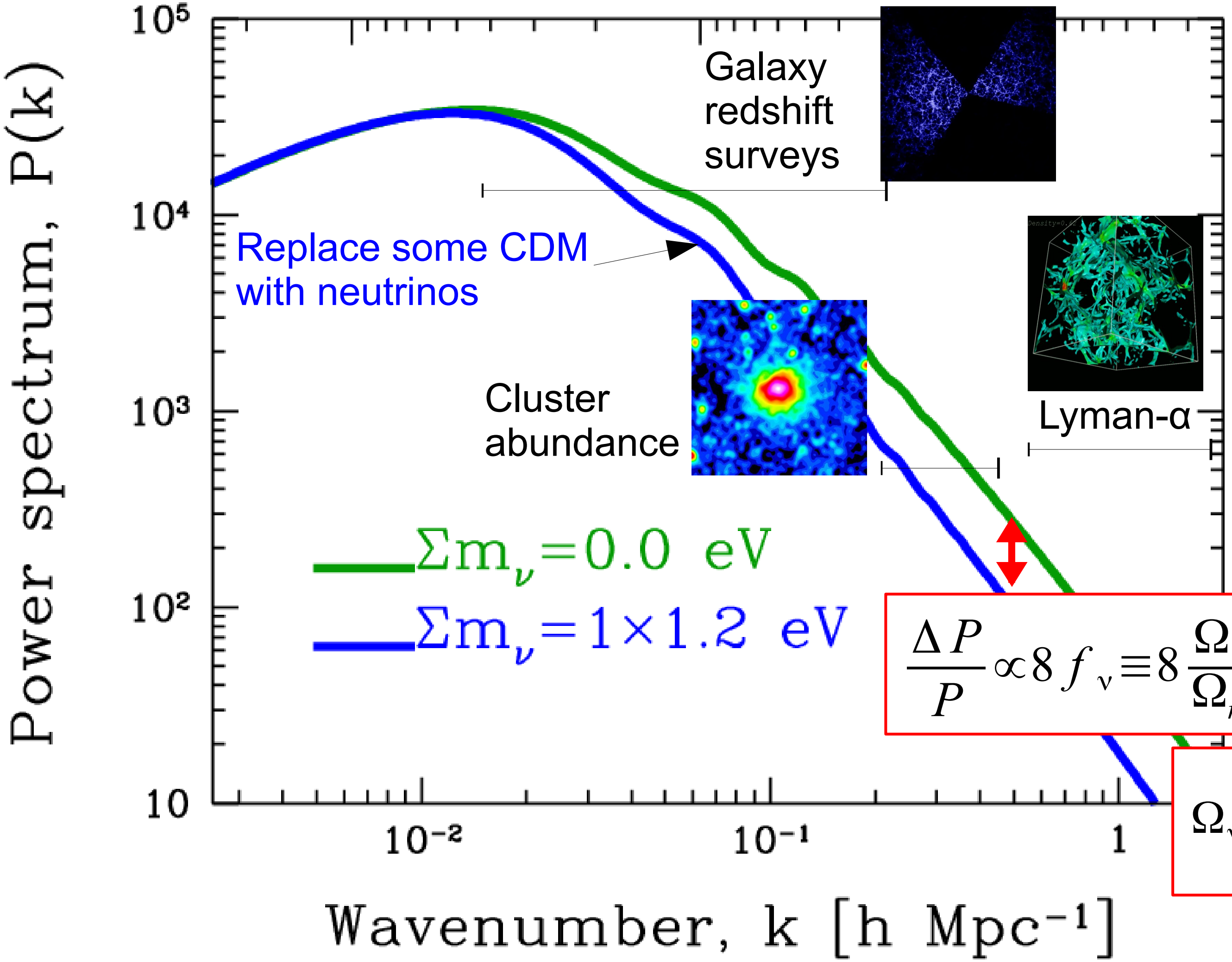
Potential stays the same (during matter domination)

Potential decays

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

Large-scale matter distribution...

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



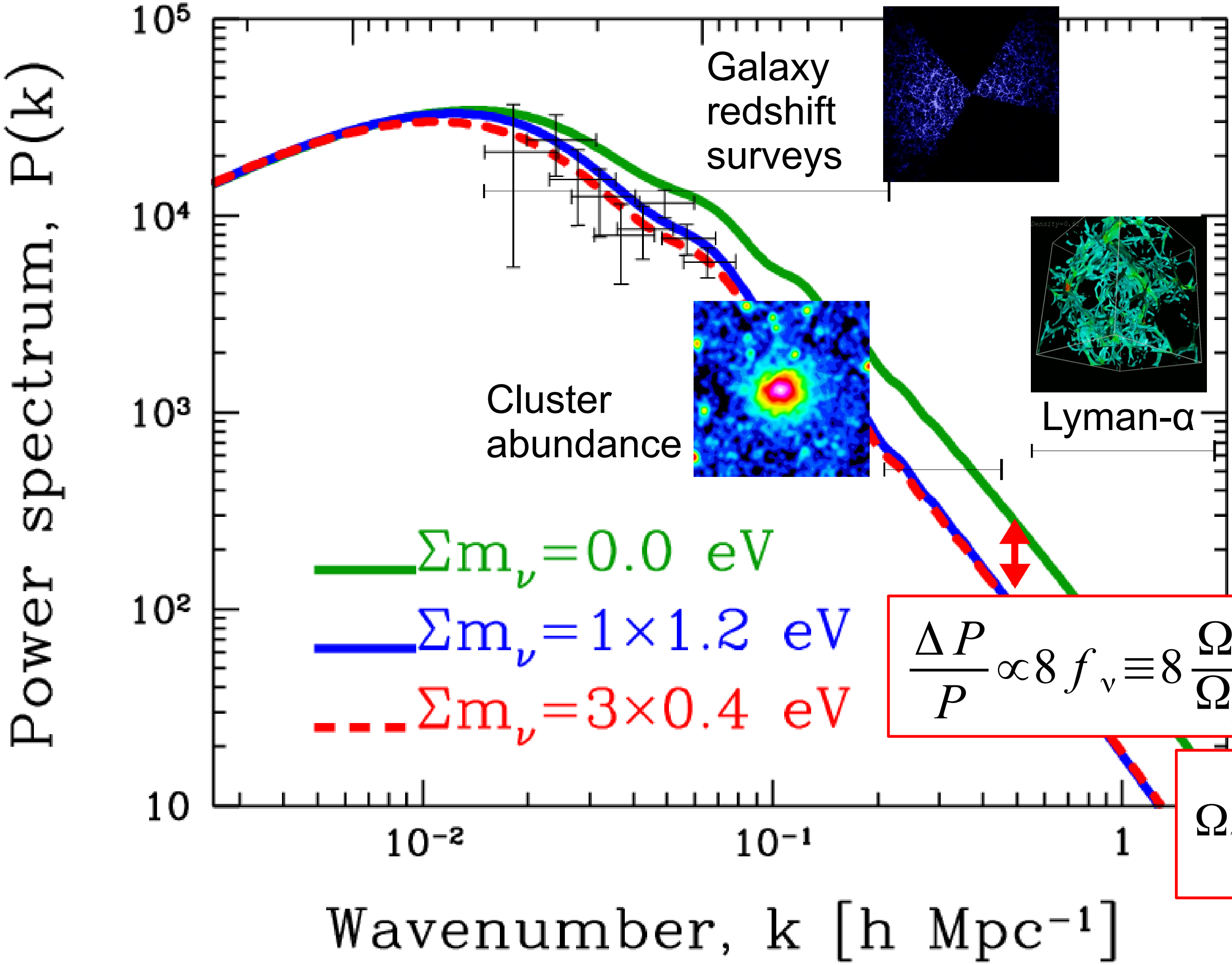
f_ν = Neutrino fraction

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

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

Large-scale matter distribution...

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

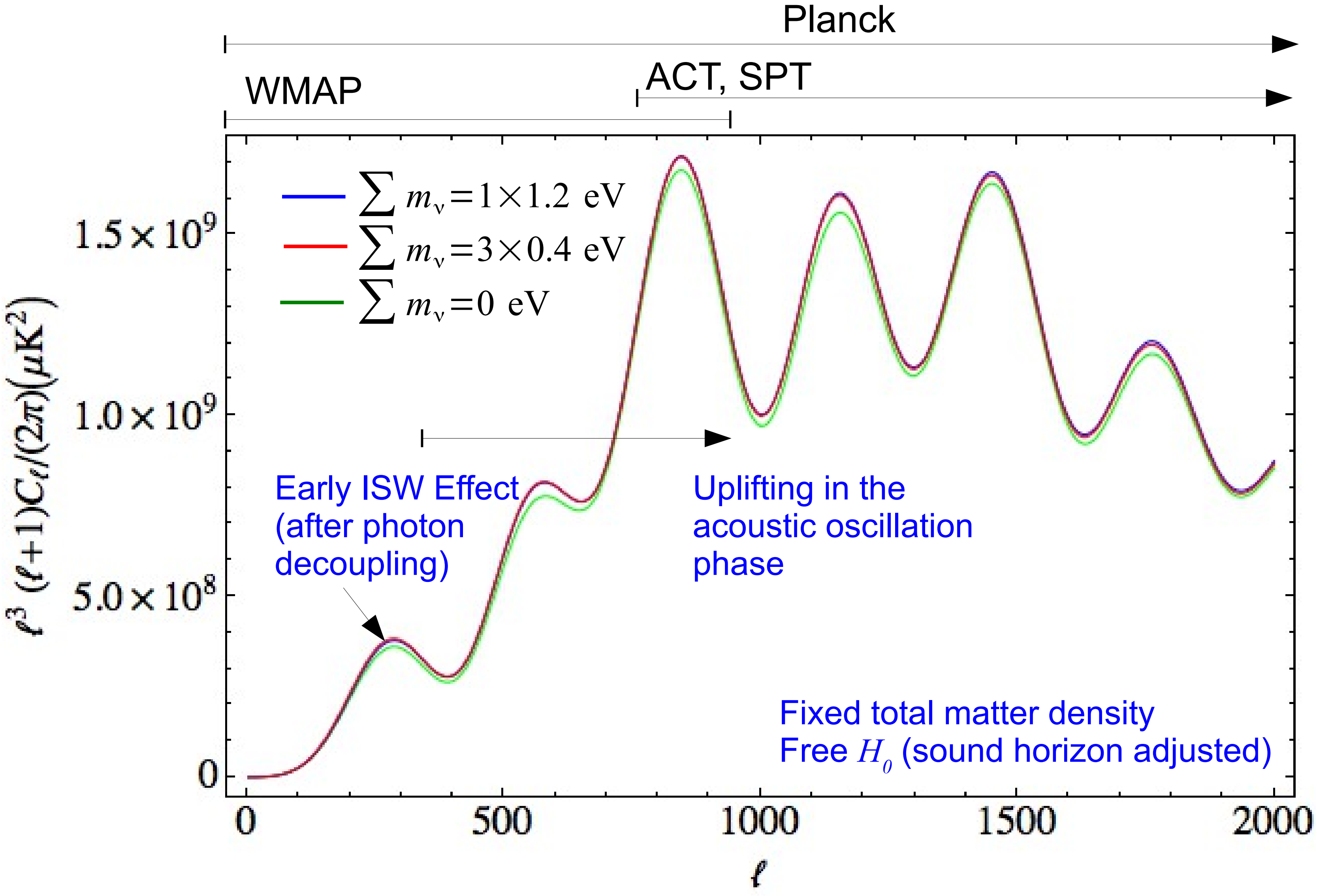


f_ν = Neutrino fraction

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

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

CMB anisotropies...



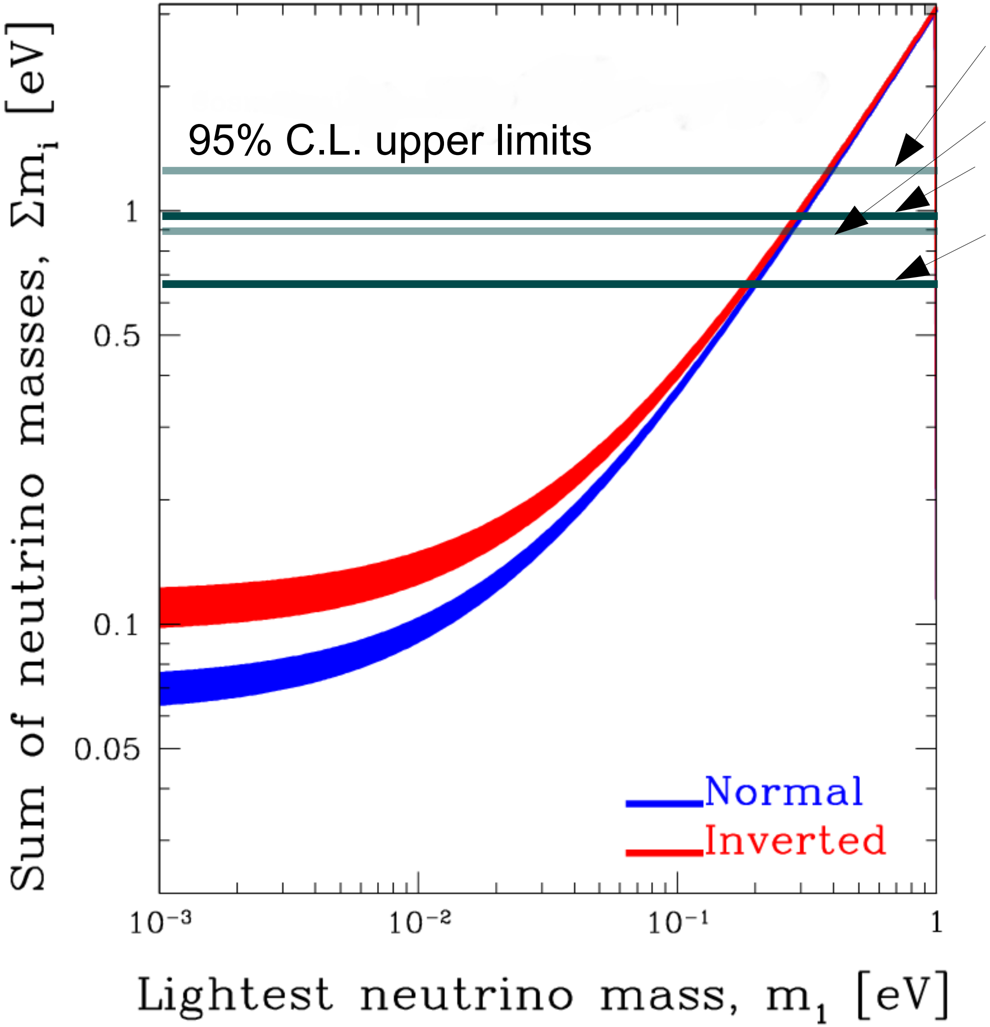
Early ISW Effect
(after photon
decoupling)

Uplifting in the
acoustic oscillation
phase

Fixed total matter density
Free H_0 (sound horizon adjusted)

Post-Planck constraints...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

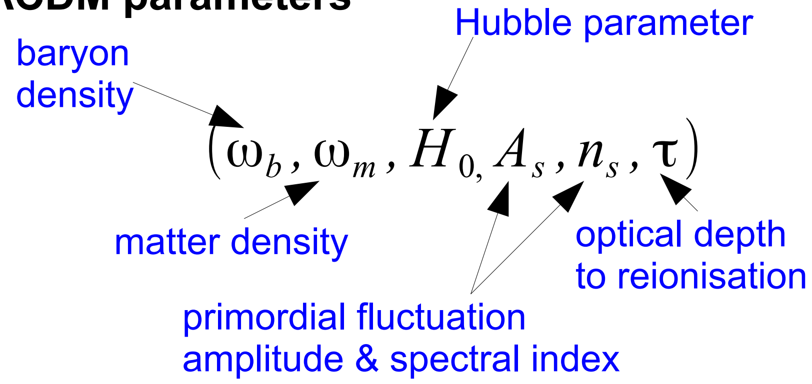
Planck + WMAP Polarisation

Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\% \text{C.L.})$$

Best CMB-only bound

ΛCDM parameters



Hubble parameter

baryon density

$$\left(\omega_b, \omega_m, H_{0,} A_s, n_s, \tau\right)$$

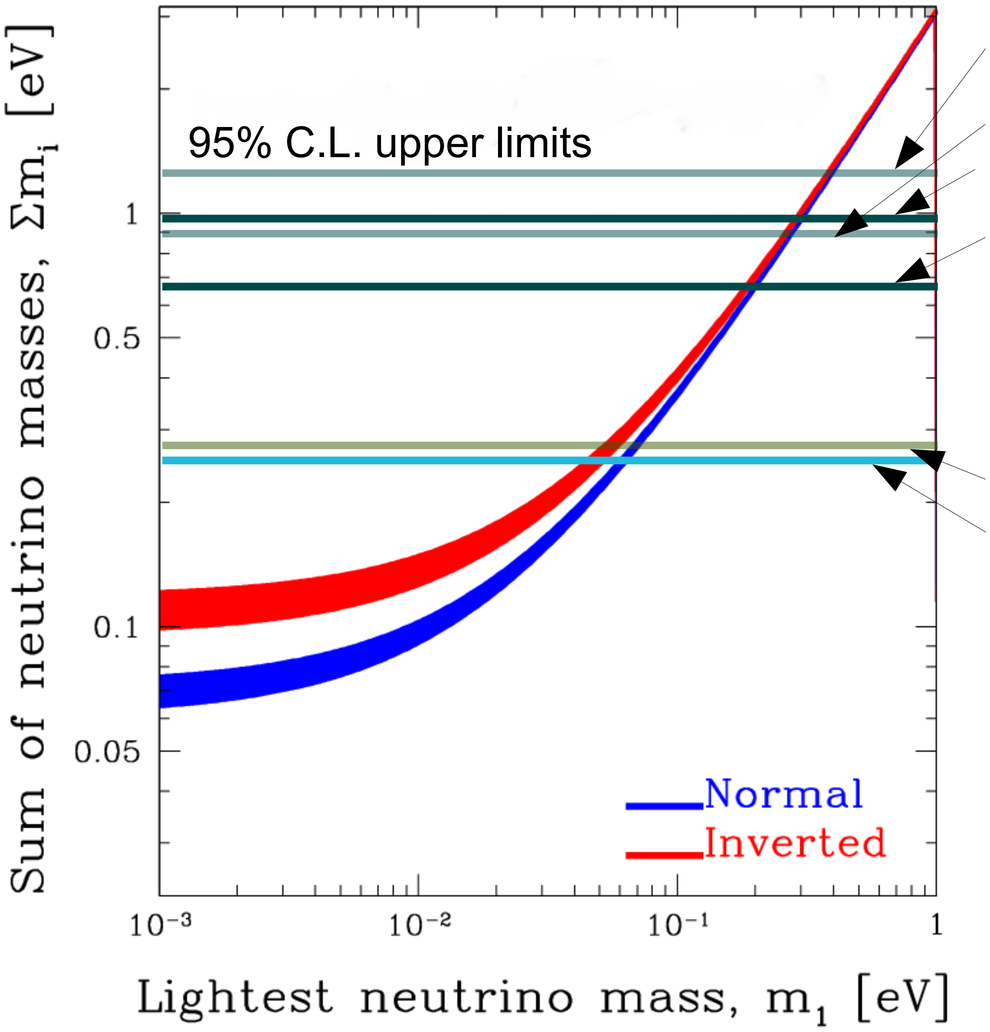
matter density

optical depth to reionisation

primordial fluctuation amplitude & spectral index

Post-Planck constraints...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\%\,\text{C.L.})$$

Best CMB-only bound

W7+ matter power spectrum + HST H_0

Planck + WP + (ACT ℓ > 1000 + SPT ℓ > 2000)
+ baryon acoustic oscillations

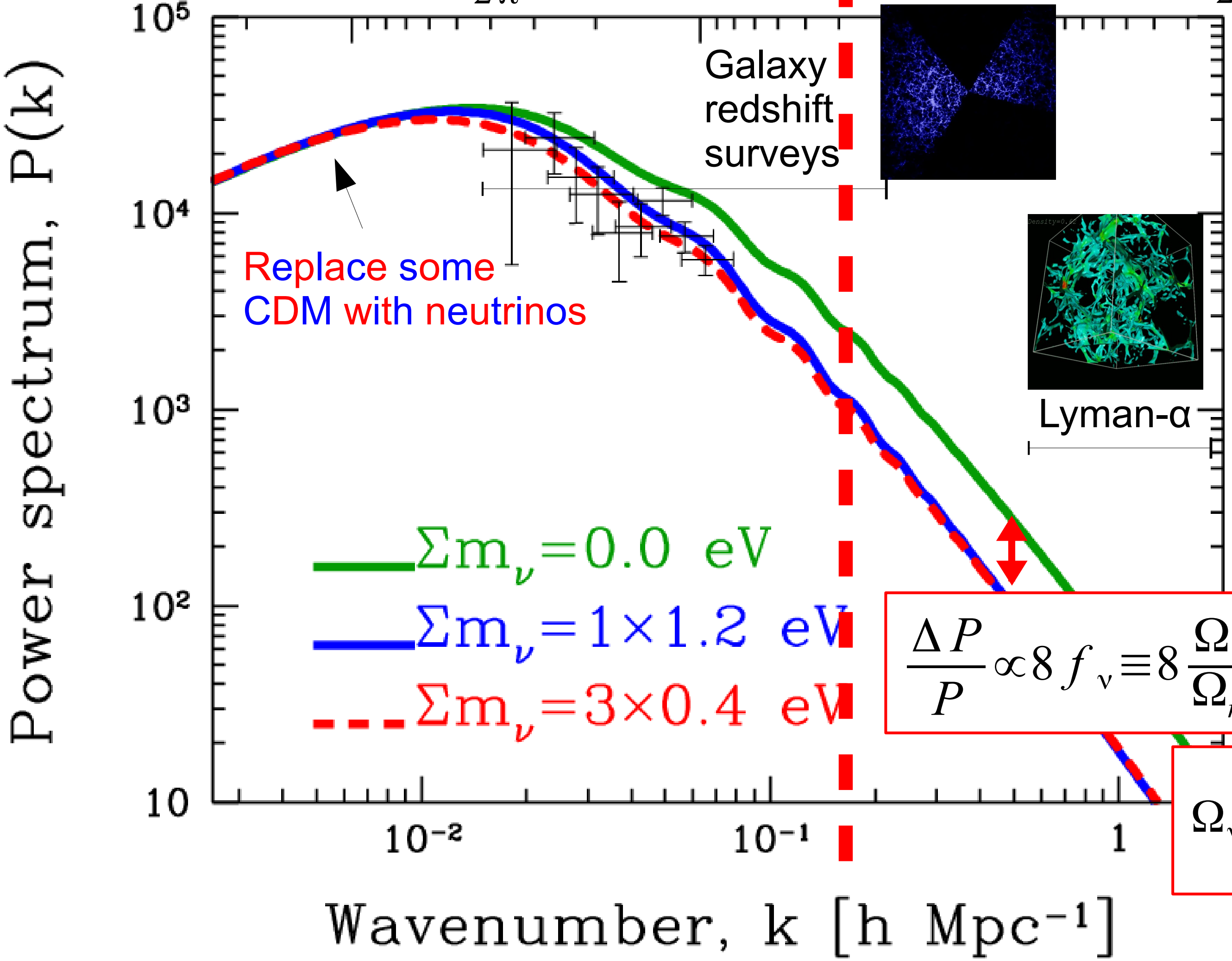
$$\sum m_\nu < 0.25 \text{ eV} \quad (95\%\,\text{C.L.})$$

Best minimal bound

Formally similar to the pre-Planck best minimal bound, but arguably less prone to issues of nonlinearities.

Matter power spectrum vs BAO...

$\frac{k^3 P(k)}{2\pi^2} < 1$ **Linear** ⟷ **Nonlinear** $\frac{k^3 P(k)}{2\pi^2} > 1$

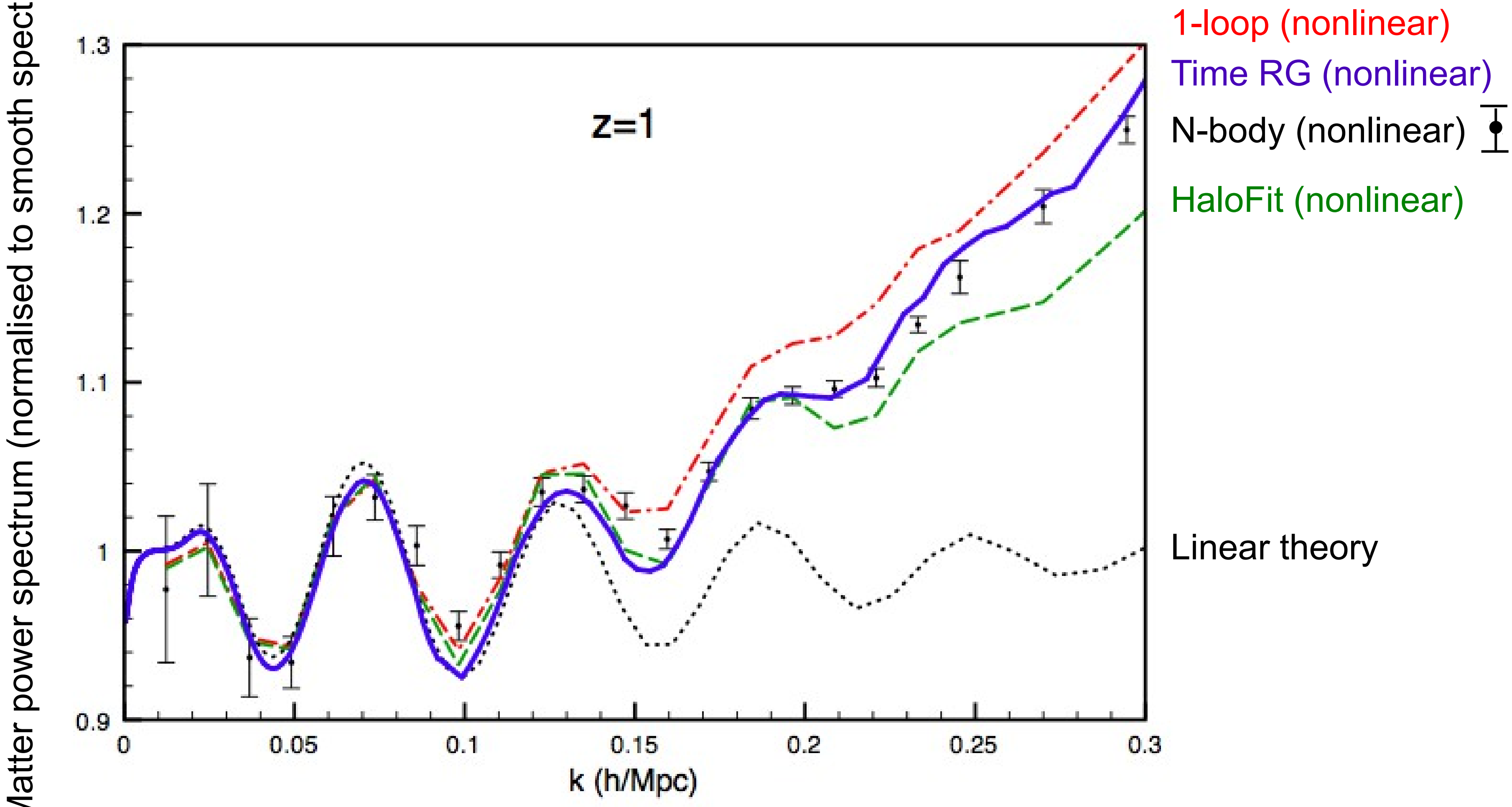


f_ν = Neutrino fraction

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

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

Matter power spectrum = Shape
Baryon acoustic oscillations = Location of oscillatory features



Pietroni 2008

The take-home message...

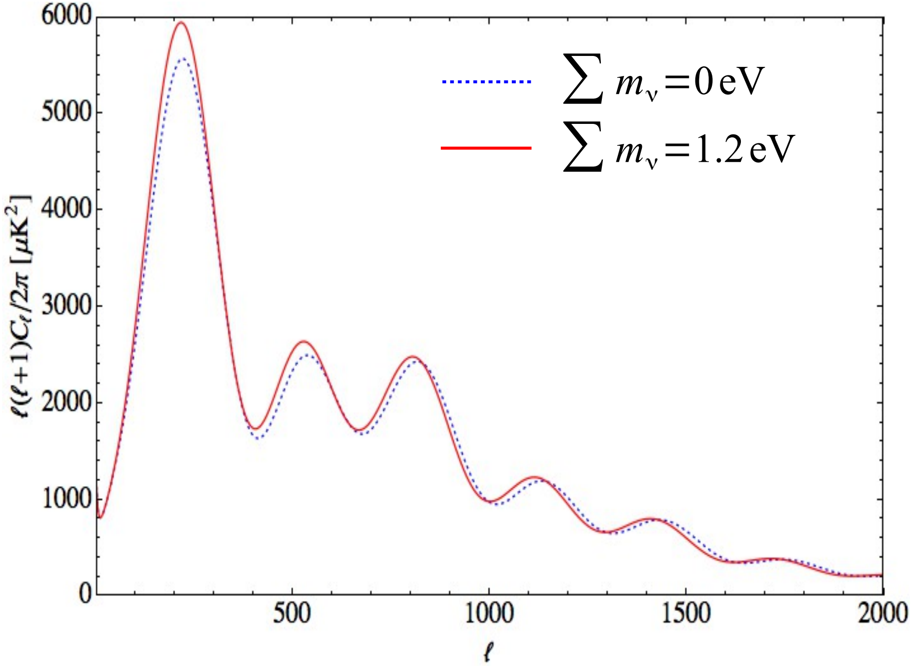
- Formally, the best minimal (7-parameter) upper bound on $\Sigma\, m_\nu$ is still hovering around 0.3 eV post-Planck.

- The bound has however become more robust against uncertainties:
  - Less nonlinearities in BAO than in the matter power spectrum.
  - Does not rely on local measurement of the Hubble parameter...
  - … or on the choice of lightcurve fitters for the Supernova Ia data.

- **Dependence on cosmological model** used for inference?

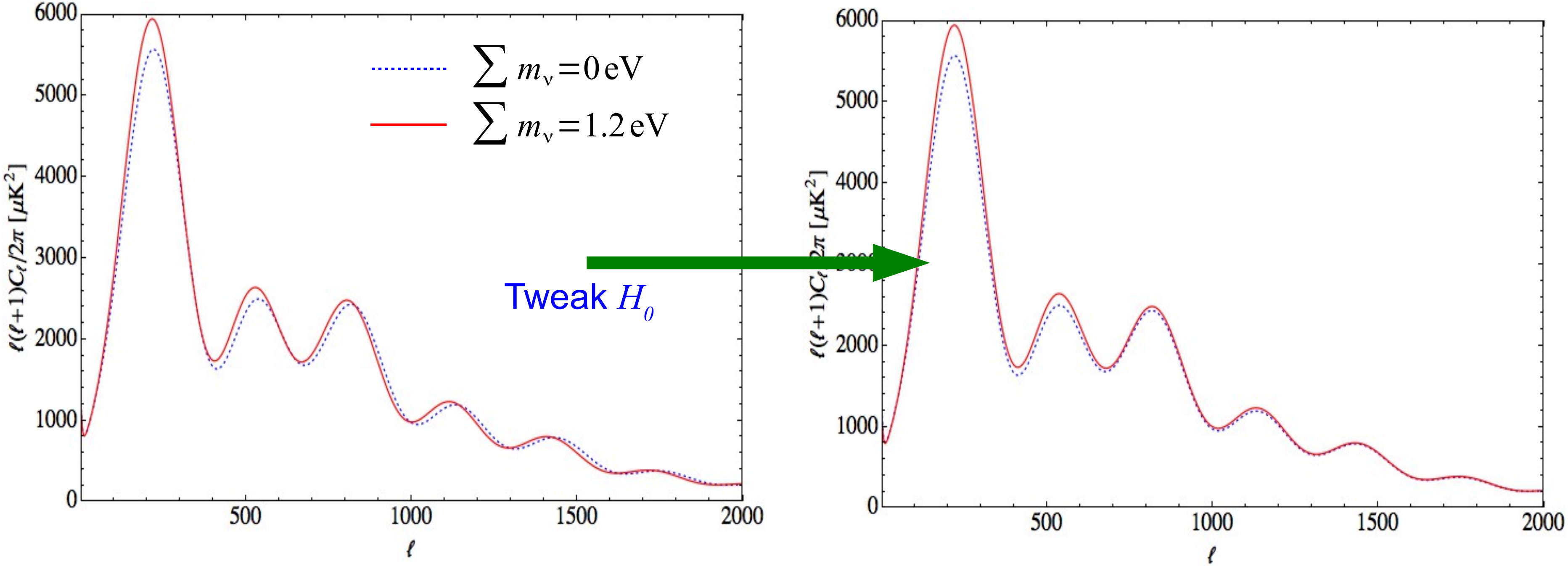
Model dependence: parameter degeneracies...

- We **do not** measure the neutrino mass *per se*, but rather its indirect effect on the clustering statistics of the CMB/large-scale structure.
  - It is **not impossible** that other cosmological parameters could give rise to similar effects (within measurement errors/cosmic variance).



Model dependence: parameter degeneracies...

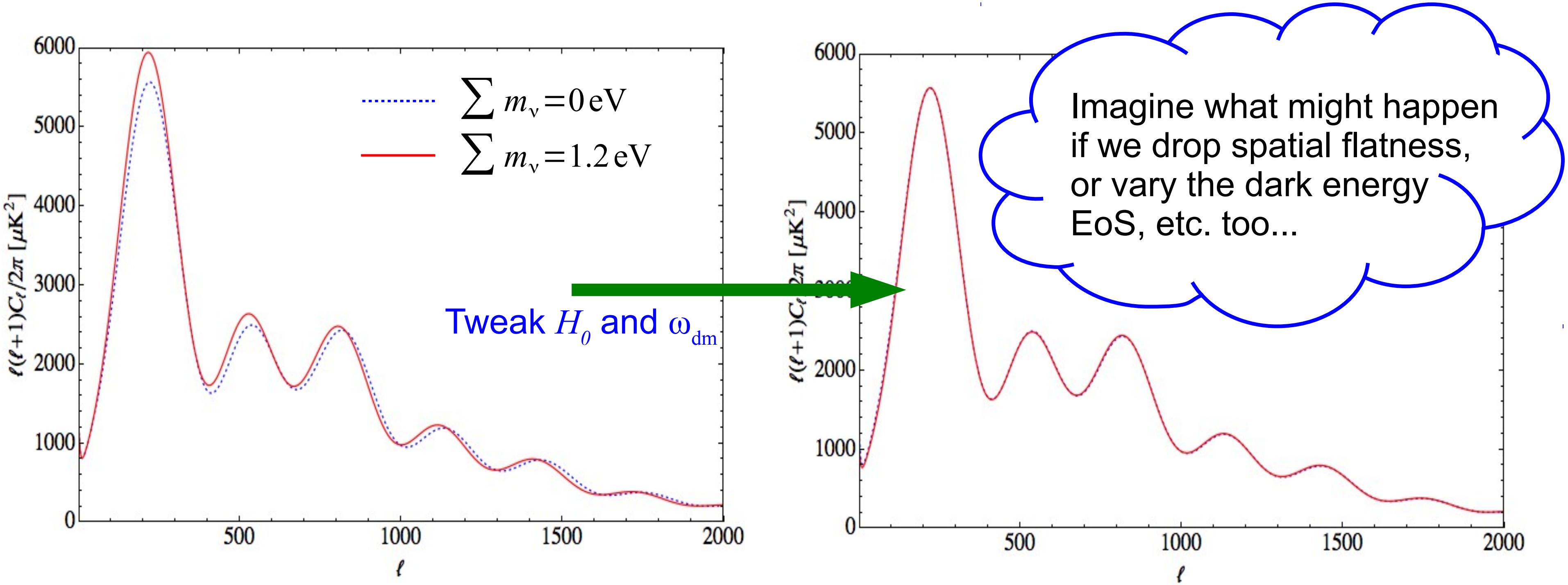
- We **do not** measure the neutrino mass *per se*, but rather its indirect effect on the clustering statistics of the CMB/large-scale structure.
  - It is **not impossible** that other cosmological parameters could give rise to similar effects (within measurement errors/cosmic variance).



Tweak H_0

Model dependence: parameter degeneracies...

- We **do not** measure the neutrino mass *per se*, but rather its indirect effect on the clustering statistics of the CMB/large-scale structure.
  - It is **not impossible** that other cosmological parameters could give rise to similar effects (within measurement errors/cosmic variance).

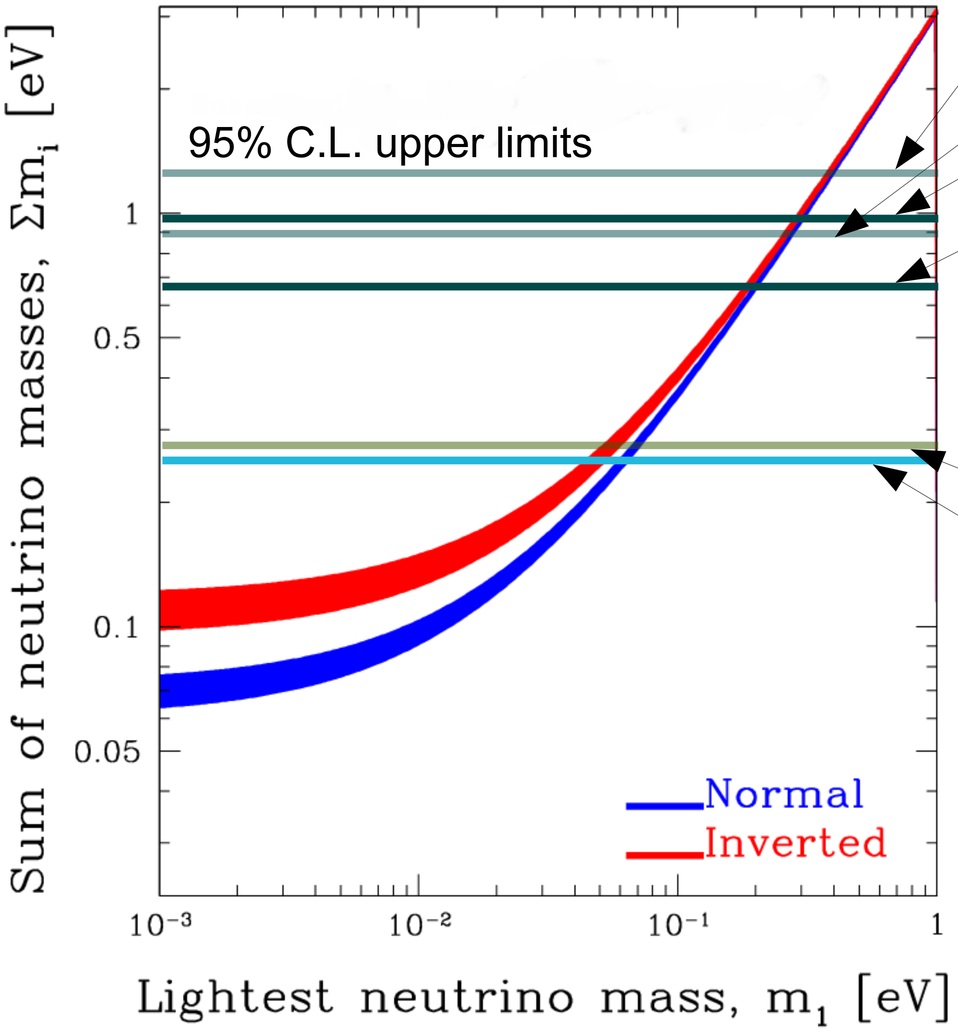


Tweak H_0 and ω_{dm}

Imagine what might happen if we drop spatial flatness, or vary the dark energy EoS, etc. too...

Post-Planck...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\,\%\,\text{C.L.})$$

Best CMB-only bound

W7+ matter power spectrum + HST H_0

Planck + WP + (ACT ℓ > 1000 + SPT ℓ > 2000)
+ baryon acoustic oscillations

$$\sum m_\nu < 0.25 \text{ eV} \quad (95\,\%\,\text{C.L.})$$

Best minimal bound

Dropping assumption of spatial flatness:

$$\sum m_\nu < 0.32 \text{ eV} \quad (95\,\%\,\text{C.L.})$$

Other extensions?? Still to be checked!

A fourth neutrino??

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 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.

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

$$= (3.046 + \Delta N_{\mathrm{eff}})\rho_\nu^{(0)}$$

Three SM neutrinos

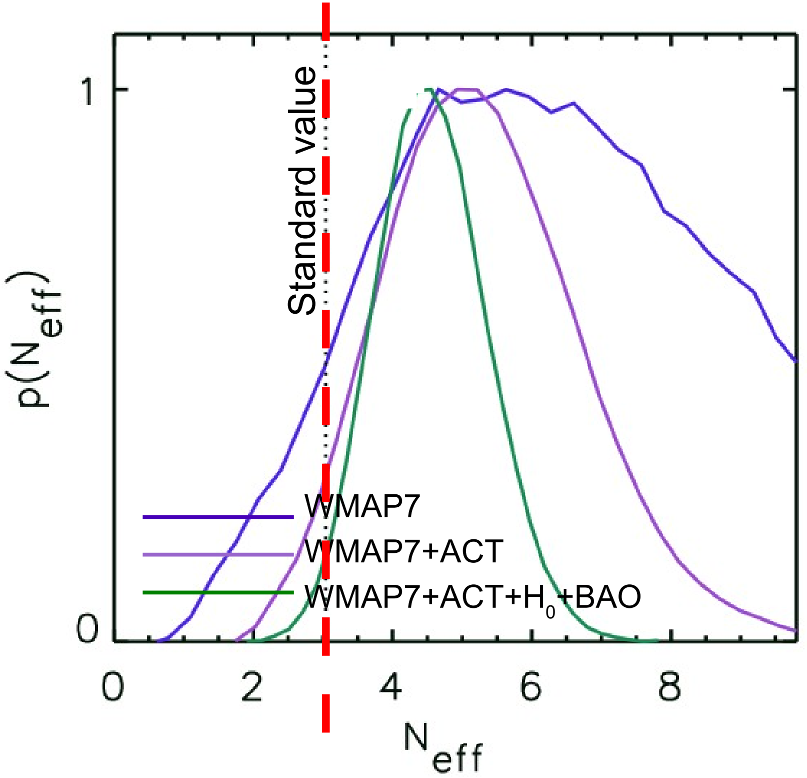
Neutrino temperature per definition

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

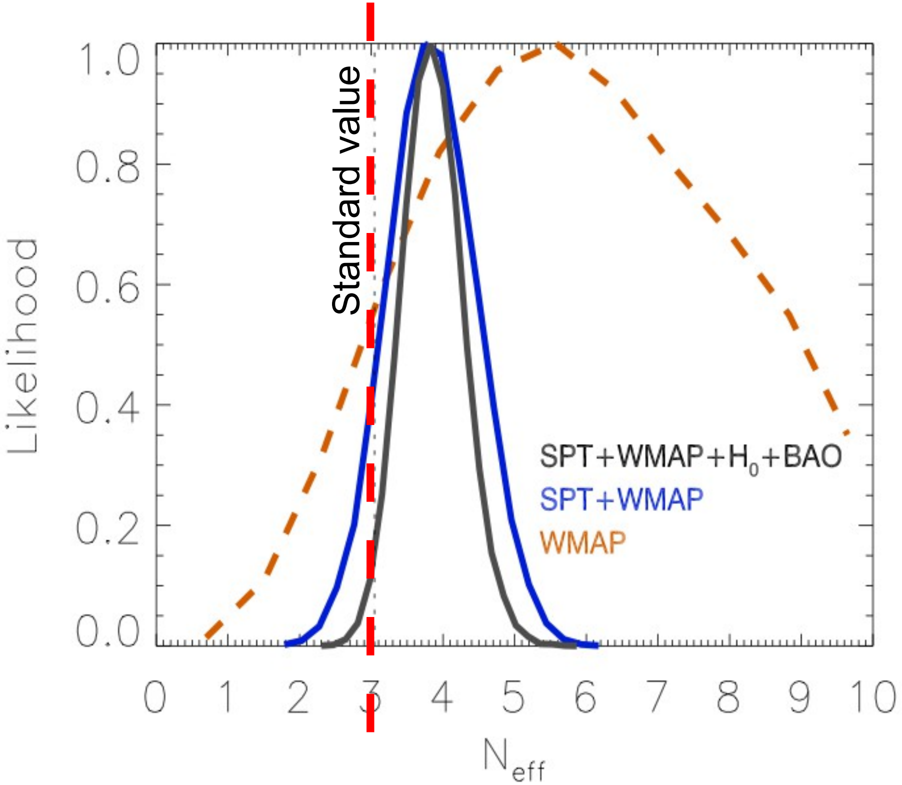
Corrections due to non-instantaneous decoupling,finite temperature effects, and flavour oscillations

Evidence for $N_{eff} > 3$ circa 2011...

Some pre-Planck observations preferred an **excess of non-interacting relativistic energy density** → **"extra neutrinos".**



Dunkley et al. [Atacama Cosmology Telescope] 2010



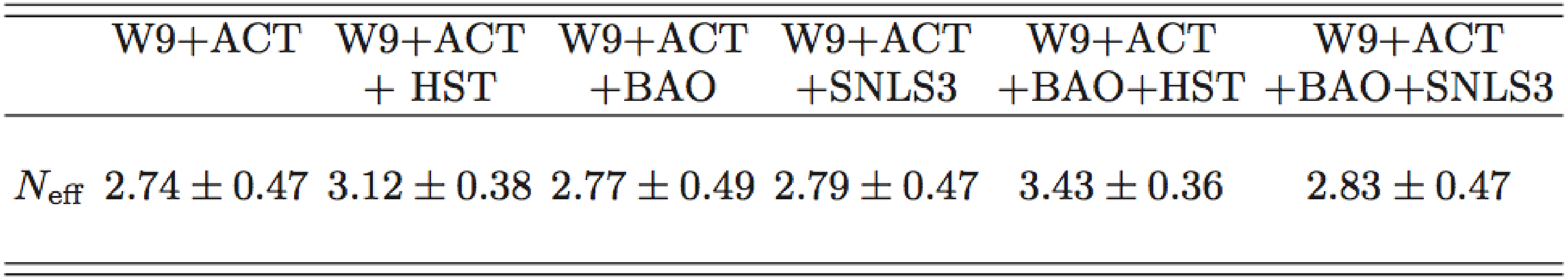
Keisler et al. [South Pole Telescope] 2011

Then the evidence disappeared again... largely...

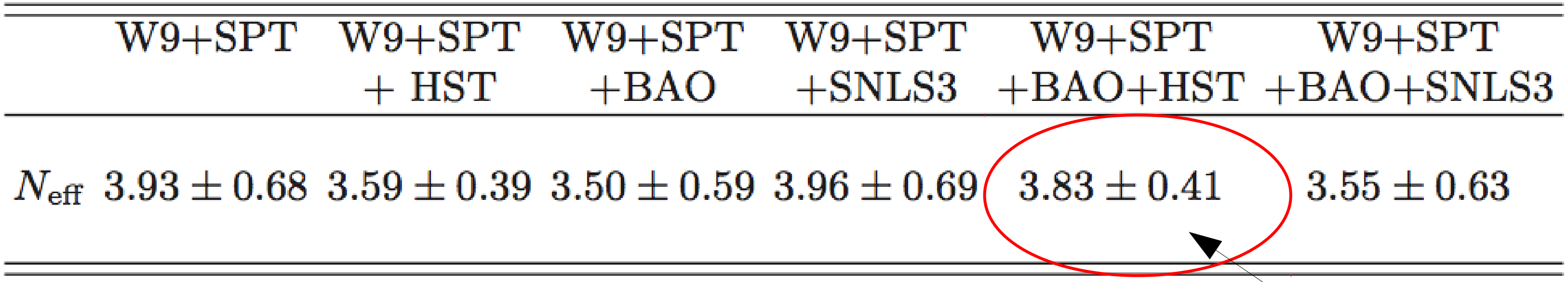
New data from WMAP, ACT and SPT in late 2012 – early 2013 favour an N_{eff} value **compatible with the standard value** of 3.046.

WMAP 9 years, 1212.5226;
ACT 3 seasons, 1301.0824
SPT (2540 deg^2), 1212.6267

1σ error bars



	W9+ACT	W9+ACT + HST	W9+ACT +BAO	W9+ACT +SNLS3	W9+ACT +BAO+HST	W9+ACT +BAO+SNLS3
N_{eff}	2.74 ± 0.47	3.12 ± 0.38	2.77 ± 0.49	2.79 ± 0.47	3.43 ± 0.36	2.83 ± 0.47



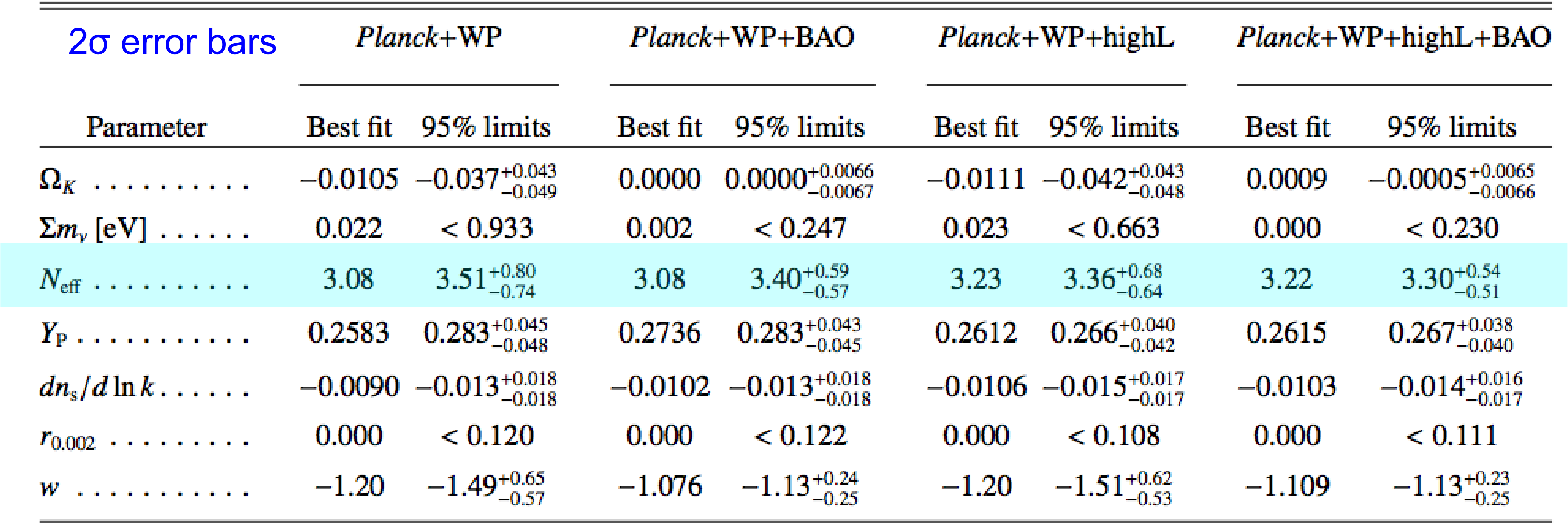
	W9+SPT	W9+SPT + HST	W9+SPT +BAO	W9+SPT +SNLS3	W9+SPT +BAO+HST	W9+SPT +BAO+SNLS3
N_{eff}	3.93 ± 0.68	3.59 ± 0.39	3.50 ± 0.59	3.96 ± 0.69	3.83 ± 0.41	3.55 ± 0.63

Archidiacono, Giusarma, Melchiorri & Mena,1303.0143

$N_{\mathrm{eff}} > 3$ at 2σ+.

Post-Planck $N_{\rm eff}$ ...

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



2σ error bars	*Planck*+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	−0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	−0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_s/d\ln k$	−0.0090	$-0.013^{+0.018}_{-0.018}$	−0.0102	$-0.013^{+0.018}_{-0.018}$	−0.0106	$-0.015^{+0.017}_{-0.017}$	−0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	−1.20	$-1.49^{+0.65}_{-0.57}$	−1.076	$-1.13^{+0.24}_{-0.25}$	−1.20	$-1.51^{+0.62}_{-0.53}$	−1.109	$-1.13^{+0.23}_{-0.25}$

Very possibly the end of the $N_{\rm eff}$ story...

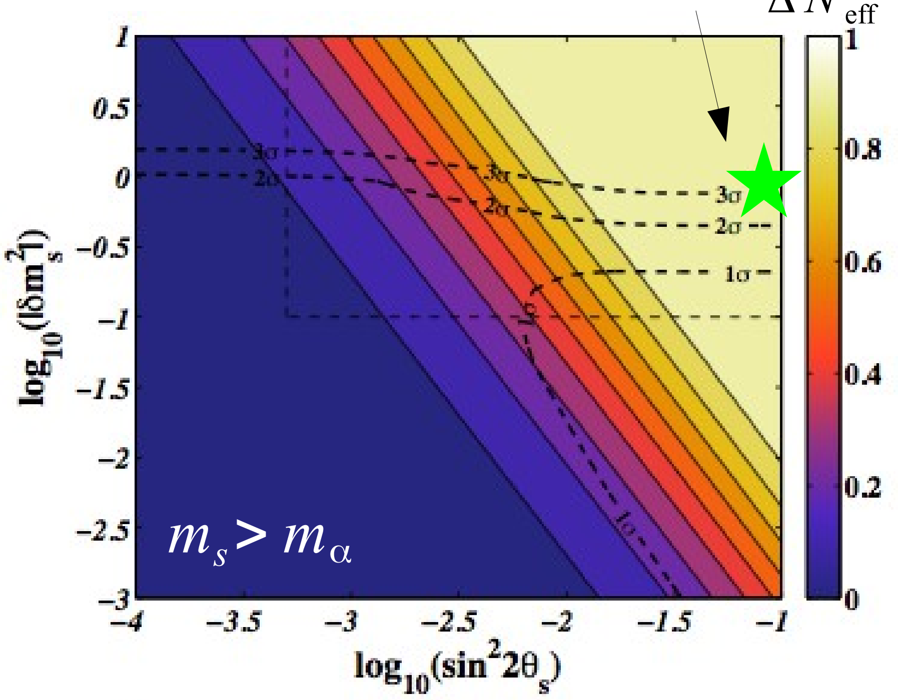
Or maybe not...
More later...

Implications for the short baseline sterile neutrino...

The **LSND/MiniBooNE/Reactor anomalies** can be explained by oscillations into a sterile neutrino with oscillation parameters:

$$\left.\begin{array}{rl} & \Delta m^2_{\mathrm{SBL}} \sim 1\,\mathrm{eV}^2 \\ (\nu_e \leftrightarrow \nu_\mu) & \sin^2 2\theta_{\mathrm{SBL}} \sim 3\times 10^{-3} \end{array}\right\} \Delta N_{\mathrm{eff}} = 1$$

Fully thermalised sterile neutrino population!



Hannestad, Tamborra & Tram 2012
also older works of Abazajian, Di Bari,
Foot, Kainulainen, etc. from 1990s-early 2000s

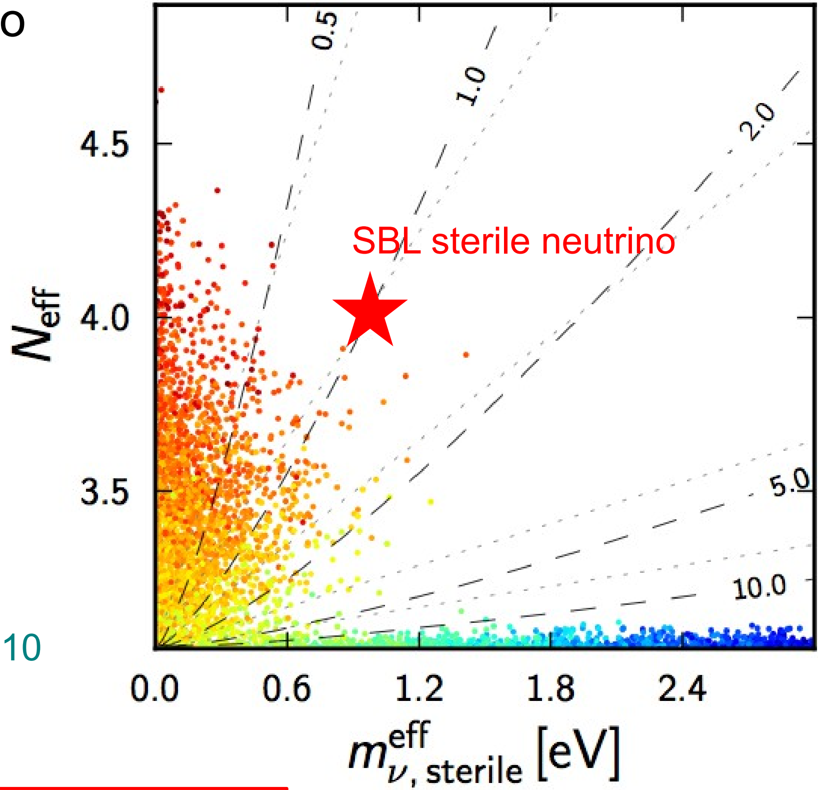
Implications for the short baseline sterile neutrino...

The **LSND/MiniBooNE/Reactor anomalies** can be explained by oscillations into a sterile neutrino with oscillation parameters:

$$\left.\begin{array}{l}\Delta m^2_{\rm SBL}\sim 1\,{\rm eV}^2\\ (\nu_e\leftrightarrow\nu_\mu)\quad \sin^2 2\theta_{\rm SBL}\sim 3\times 10^{-3}\end{array}\right\}\Delta N_{\rm eff}=1$$

$$\boxed{m_{\rm sterile}>\sqrt{\Delta m^2_{\rm SBL}}\sim 1\,{\rm eV}}$$

Ade et al. [Planck collaboration] 2013



- Already a problem for WMAP (+LSS+HST):

  $m_{\rm sterile}<0.45\,{\rm eV}\,(95\%\,{\rm C.L.})$ Hamann et al. 2010

- **Post-Planck**:

$$\boxed{m_{\rm sterile}<0.42\,{\rm eV}\,;\quad N_{\rm eff}<3.8\quad (95\%\,{\rm C.L.})}$$

Planck+WP+highL+BAO
(ΛCDM+$N_{\rm eff}$+$m_{\rm sterile}$)

Reconciling the SBL sterile neutrinos with cosmology??

The SBL sterile neutrino is problematic for cosmology only because it is produced in abundance in the early universe.

→ If production can be **suppressed**, then there is no conflict.

- **Some possible mechanisms**:
  - A large lepton asymmetry ($L \gg B \sim 10^{-10}$) generates an effective mass for the active neutrino to suppress effective active-sterile mixing; $L \sim 10^{-2}$ will do.

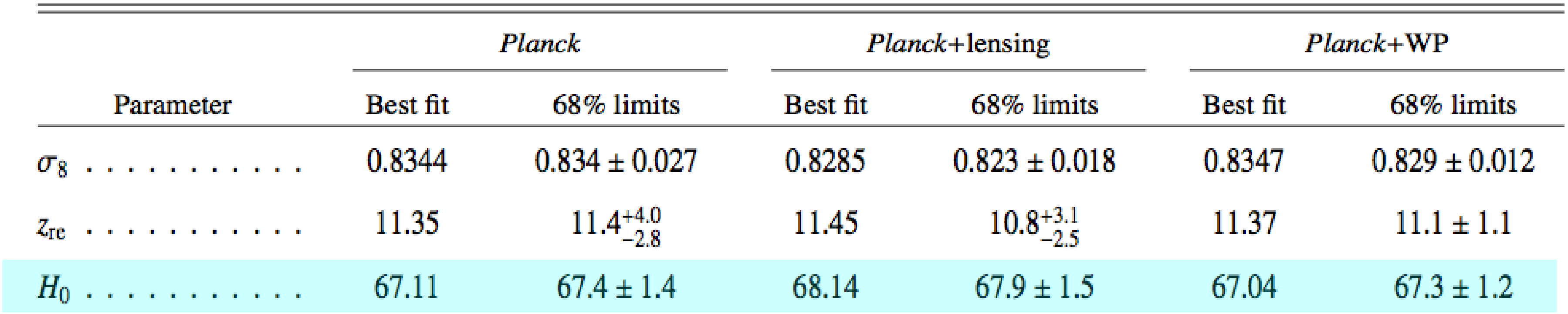
    Foot & Volkas 1995
  - Hidden sterile neutrino self-interaction generates an effective mass for the sterile neutrino.

    Dasgupta & Kopp 2014
    Hannestad, Hansen & Tram 2014
  - A low reheating temperature ($T_R < 10$ MeV) → incomplete thermalisation of even the SM neutrinos.

Discrepancies potentially resolved by a fourth neutrino??

Planck discrepancies with other observations... 1.

- **Hubble parameter H_0**: Planck-inferred value lower than local HST measurement.
- **Small-scale RMS fluctuation σ_8**: Planck CMB prefers a higher value than galaxy cluster count and galaxy shear from CFHTLens.



	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
$z_{\rm re}$	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2

Hubble space telescope

$$H_0 = 73.8 \pm 2.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Riess et al. 2011

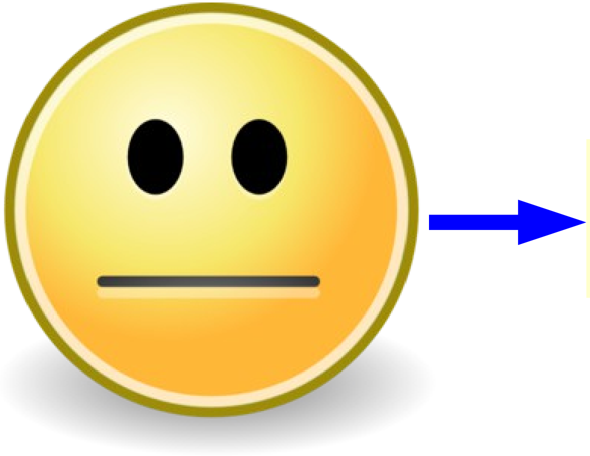
Exploit the $N_{\rm eff} - H_0$ degeneracy and introduce to a large $N_{\rm eff}$ to bring HST and Planck in line with one another.

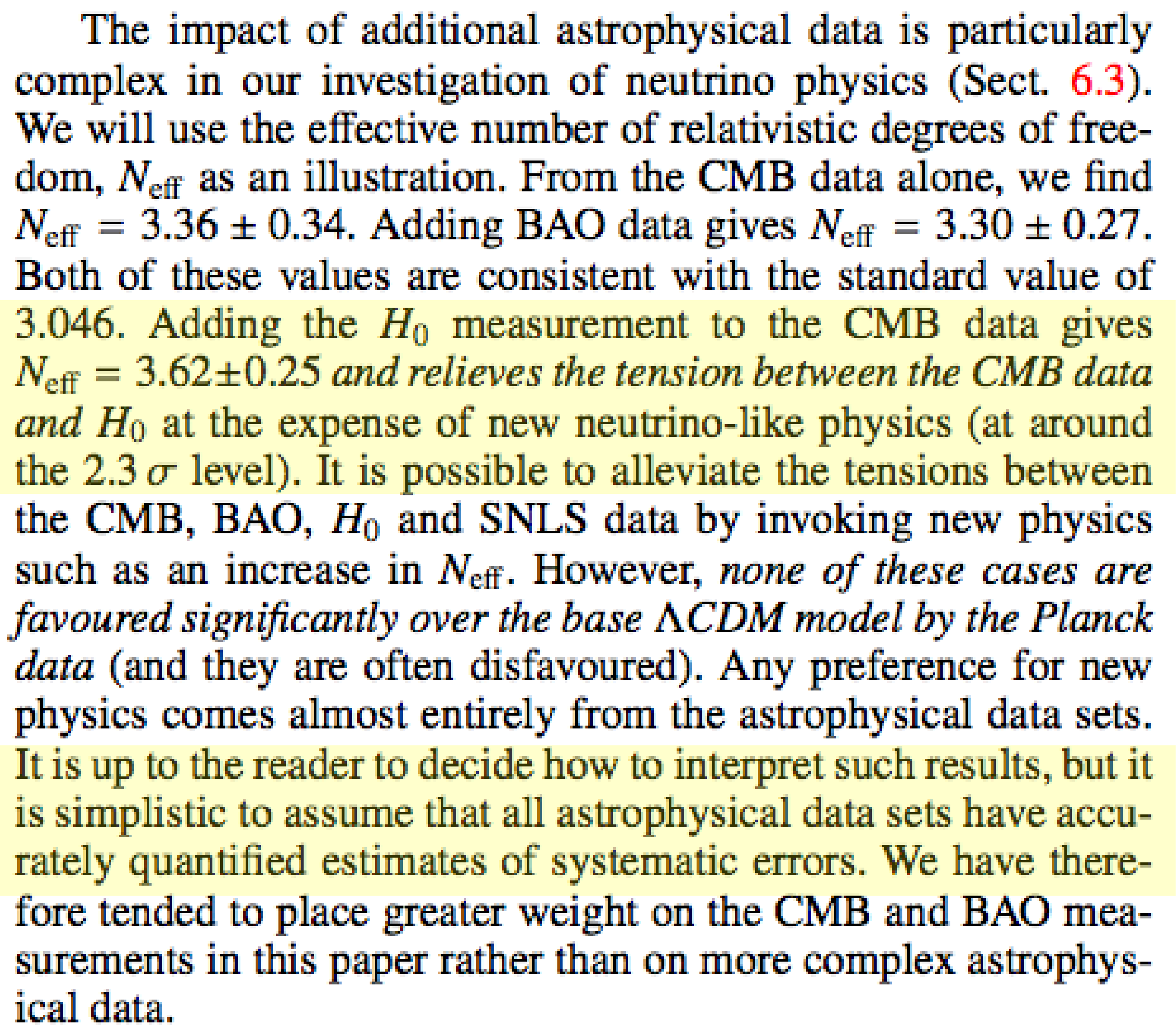
Planck + HST

$$N_{\mathrm{eff}} = 3.62 \pm 0.25\,(1\,\sigma)$$

(ΛCDM+ΔN_{eff}
7-parameter model)

… Not quite the SBL sterile neutrino because this fit assumes massless neutrinos...





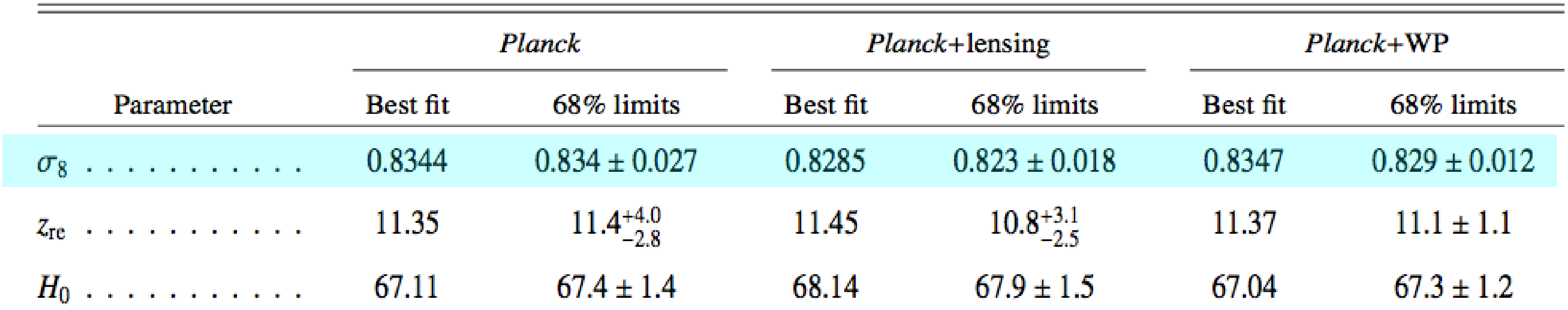
The impact of additional astrophysical data is particularly complex in our investigation of neutrino physics (Sect. 6.3). We will use the effective number of relativistic degrees of freedom, N_{eff} as an illustration. From the CMB data alone, we find $N_{\mathrm{eff}} = 3.36 \pm 0.34$. Adding BAO data gives $N_{\mathrm{eff}} = 3.30 \pm 0.27$. Both of these values are consistent with the standard value of 3.046. Adding the H_0 measurement to the CMB data gives $N_{\mathrm{eff}} = 3.62 \pm 0.25$ *and relieves the tension between the CMB data and* H_0 at the expense of new neutrino-like physics (at around the 2.3 σ level). It is possible to alleviate the tensions between the CMB, BAO, H_0 and SNLS data by invoking new physics such as an increase in N_{eff}. However, *none of these cases are favoured significantly over the base ΛCDM model by the Planck data* (and they are often disfavoured). Any preference for new physics comes almost entirely from the astrophysical data sets. It is up to the reader to decide how to interpret such results, but it is simplistic to assume that all astrophysical data sets have accurately quantified estimates of systematic errors. We have therefore tended to place greater weight on the CMB and BAO measurements in this paper rather than on more complex astrophysical data.

Ade et al. [Planck collaboration] 2013

Planck discrepancies with other observations... 2.

- **Hubble parameter H_0**: Planck-inferred value lower than local HST measurement.

- **Small-scale RMS fluctuation σ_8**: Planck CMB prefers a higher value than galaxy cluster counts and galaxy shear from CFHTLens.



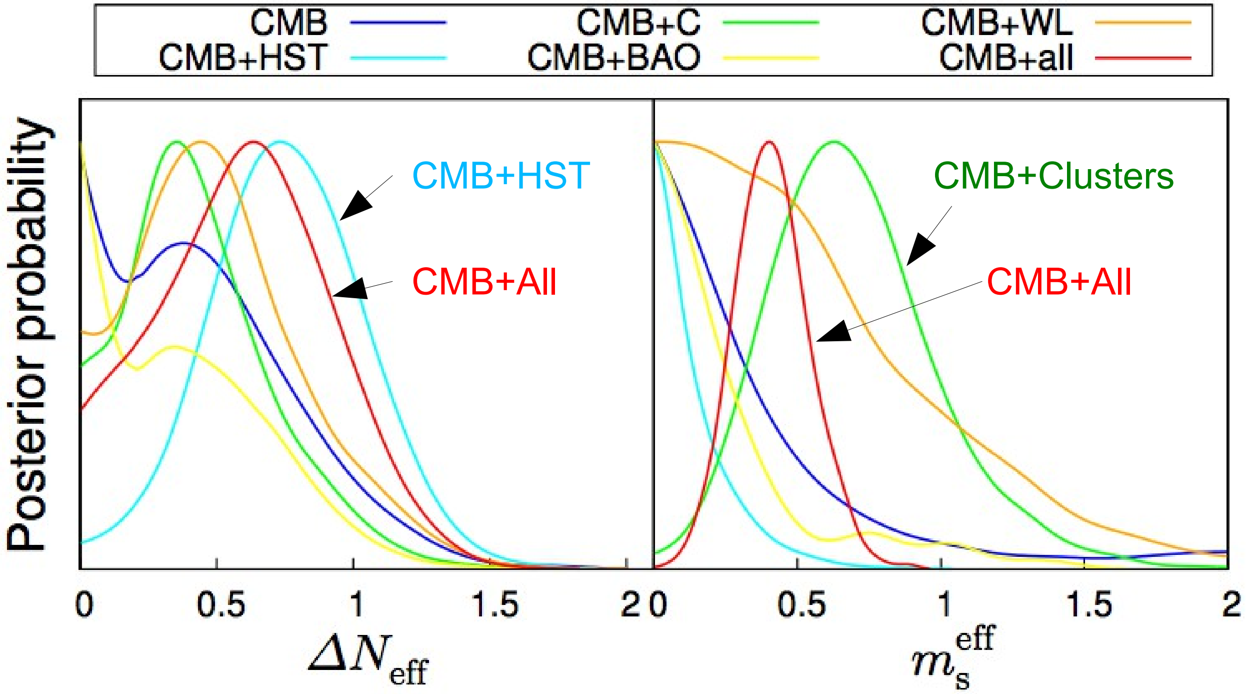
	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2

Planck SZ clusters $\sigma_8(\Omega_m/0.27)^{0.3} = 0.782 \pm 0.01$ Ade et al. [Planck collaboration] 2013

CFHTLens galaxy shear $\sigma_8(\Omega_m/0.27)^{0.46} = 0.774 \pm 0.04$ Heymans et al. 2013

Solved by a fourth, **massive** neutrino??

At face value a fourth, massive neutrino is a possible solution.



CMB+HST

CMB+All

CMB+Clusters

CMB+All

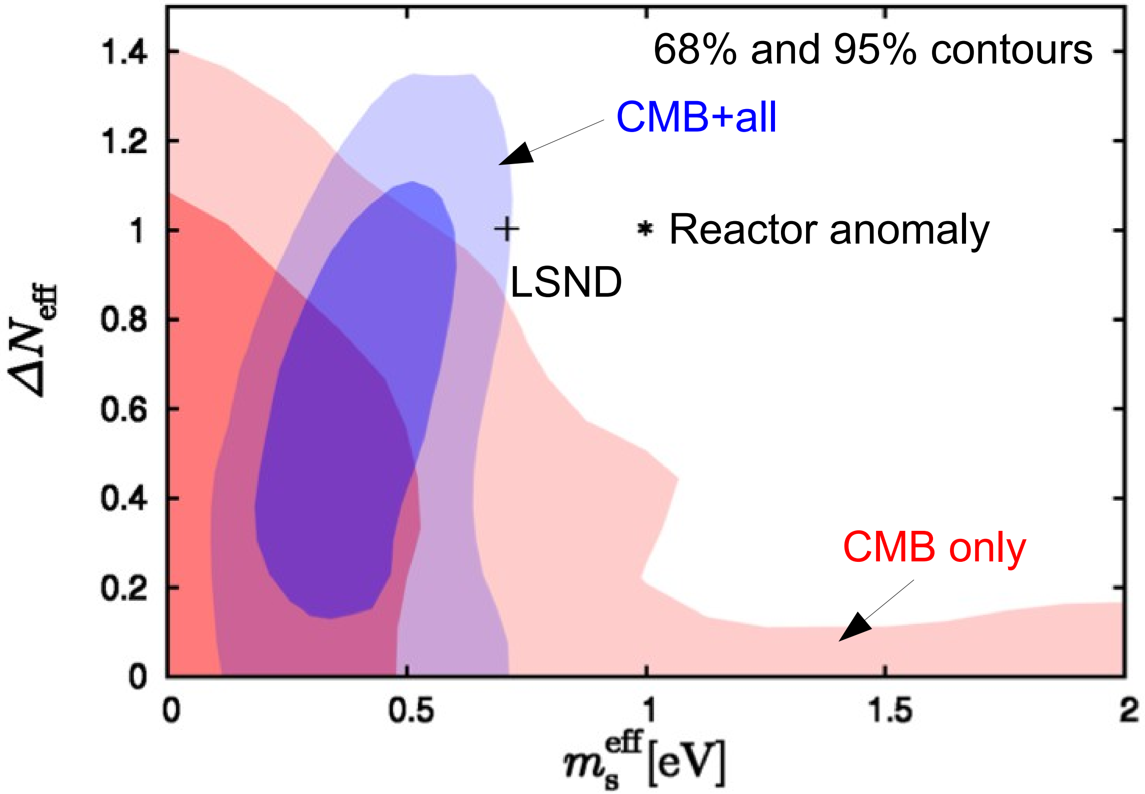
CMB+all
(ΛCDM+$\Delta N_{\rm eff}$+$m_{\rm s}$
8-parameter model)

$$\Delta N_{\rm eff} = 0.61 \pm 0.30$$
$$m_{\rm s} = (0.41 \pm 0.13)\ \mathrm{eV}$$

Hamann & Hasenkamp 2013
also Wyman et al. 2013,
Battye & Moss 2013

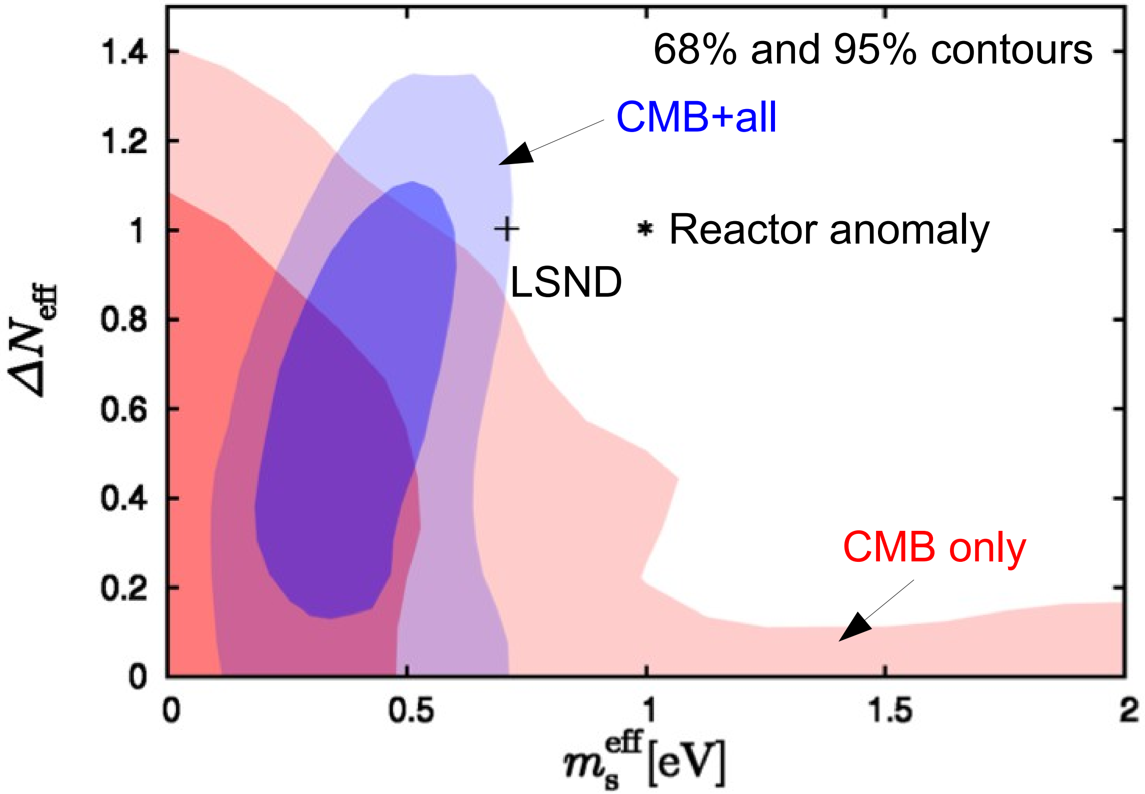
- Large $N_{\rm eff}$ driven mainly by HST
- Large $m_{\rm s}$ driven mainly by cluster counts.

Solved by a fourth, **massive** neutrino??



Hamann & Hasenkamp 2013
also Wyman et al. 2013
Battye & Moss 2013

Solved by a fourth, **massive** neutrino??



Hamann & Hasenkamp 2013
also Wyman et al. 2013
Battye & Moss 2013

My take: discrepancies are most likely due to poorly understood nonlinearities (cluster counts are particularly difficult to model).

- Take the fourth neutrino solution *cum magno grano salis*!

Summary...

- Precision cosmological observables can be used to “measure” the absolute neutrino mass scale based on the effect of **neutrino free-streaming**.

- **Existing precision cosmological data** already provide strong constraints on the neutrino mas sum.
  - No significant formal improvement between the best pre-Planck and post-Planck upper bounds (at least not for the minimal 7-parameter model).
  - But the **post-Planck** bound is arguably more robust.

- The **fourth neutrino**?? There are **outstanding discrepancies** between Planck and measurements from HST, clusters, and cosmic shear.
  - Taken at face value these discrepancies can be resolved by a fourth neutrino (although not necessarily the same one in all cases...).
  - But personally I'd take it *cum magno grano salis*.