Cosmological measurements of neutrino properties

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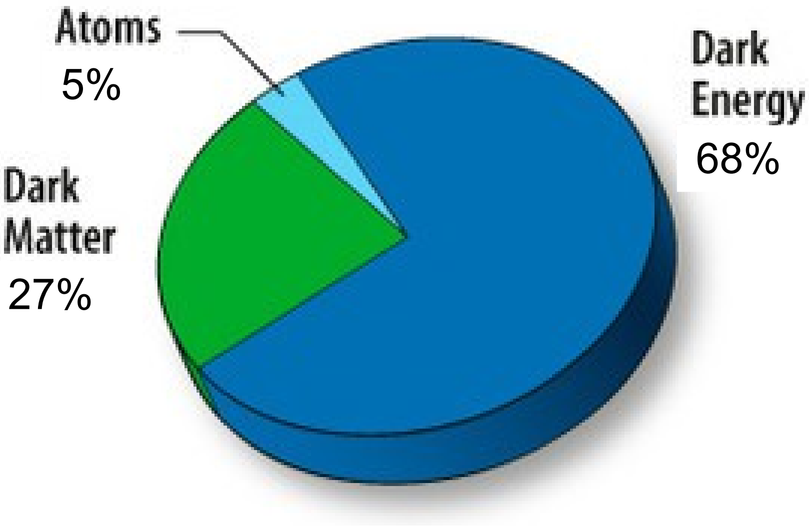
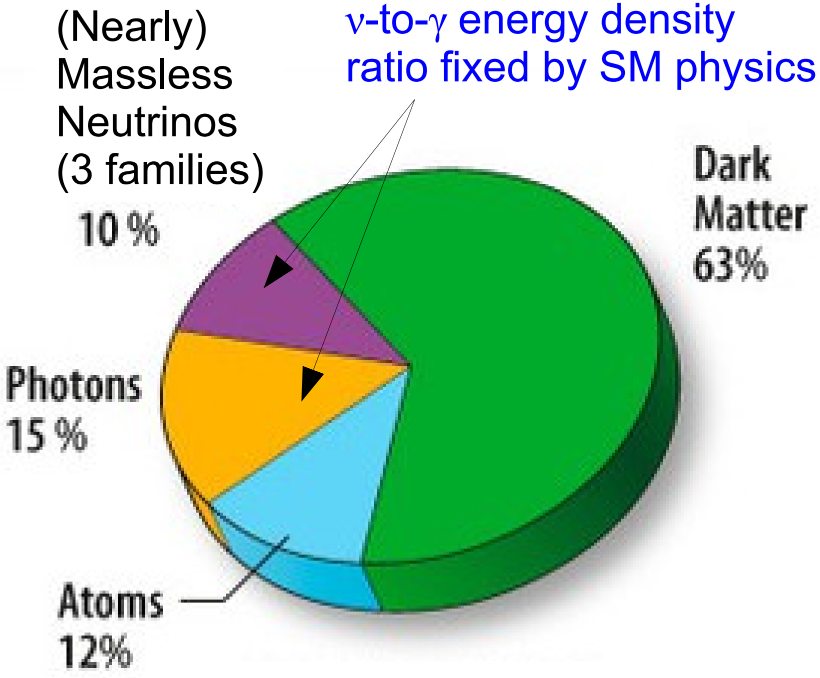
NuFact2013, Beijing, August 19 – 24, 2013

The concordance flat ΛCDM model...

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



Composition today



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

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 0.05 eV. $\Omega_{\nu,0}h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}} = ??$
  - No reason to fix at the minimum mass.
  - Laboratory upper limit $\Sigma m_\nu < 7\ \mathrm{eV}$ from β-decay endpoint.
- **More than three flavours**. $N_{\mathrm{eff}} \neq 3\,??$
  - Sterile neutrinos? (LSND/MiniBooNE/Reactor anomalies)

This talk

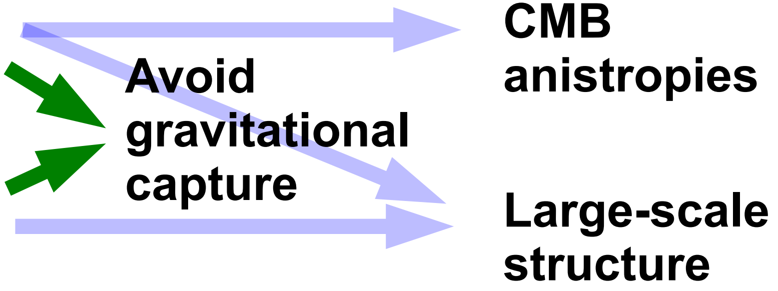
- **Hidden interactions**
  - Neutrino-neutrino, neutrino-dark matter, neutrino-dark energy.

1. 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.

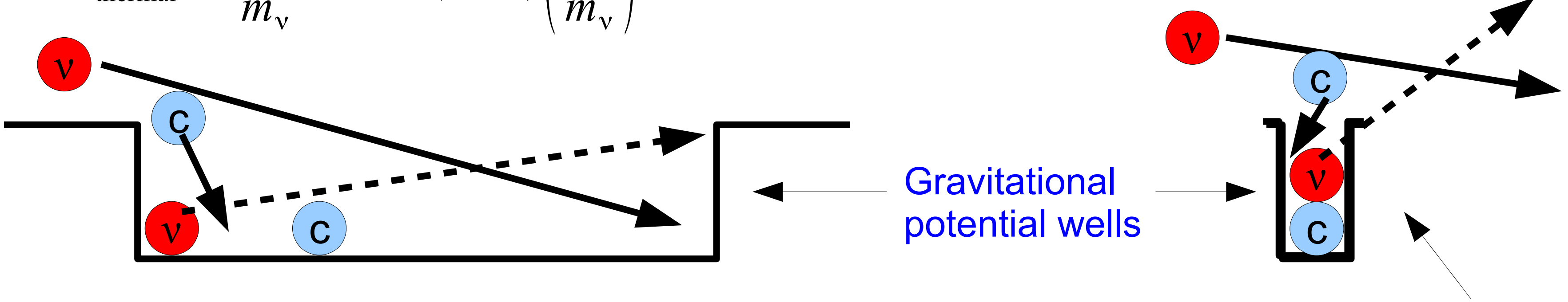


Avoid gravitational capture

CMB anistropies

Large-scale structure

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



Non-clustering

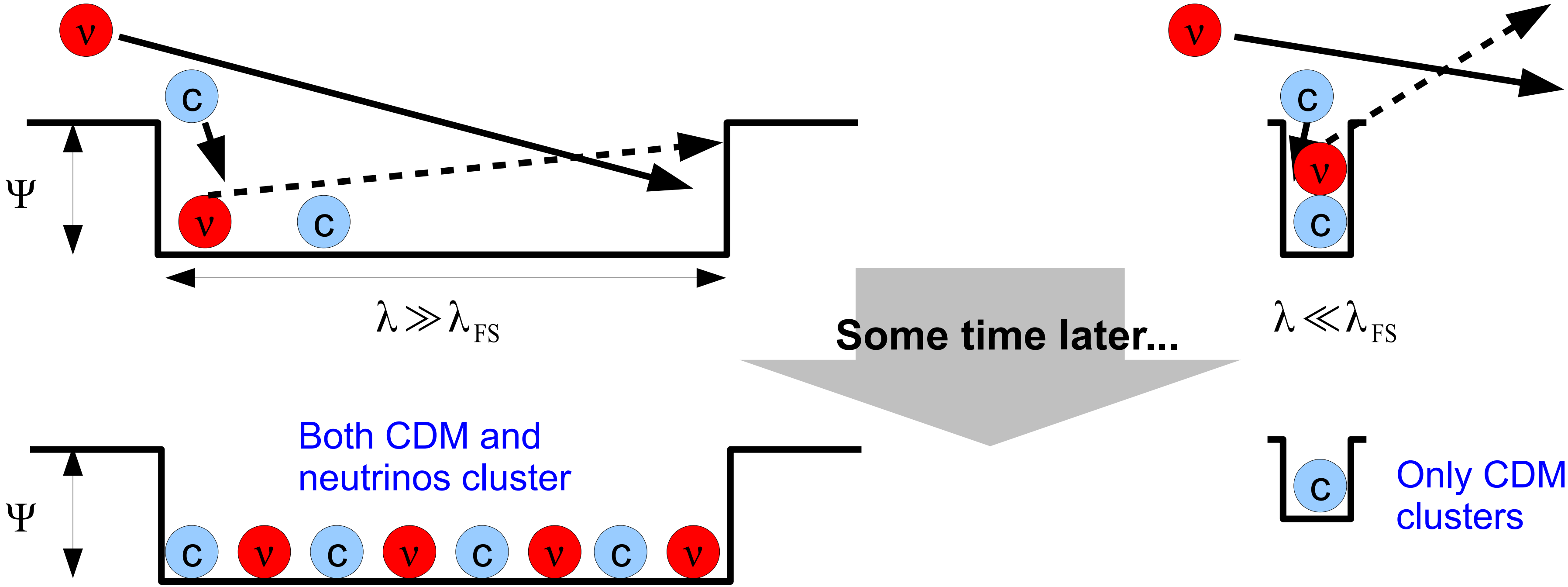
$\lambda \ll \lambda_{\text{FS}}$

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

Free-streaming scale:

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

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

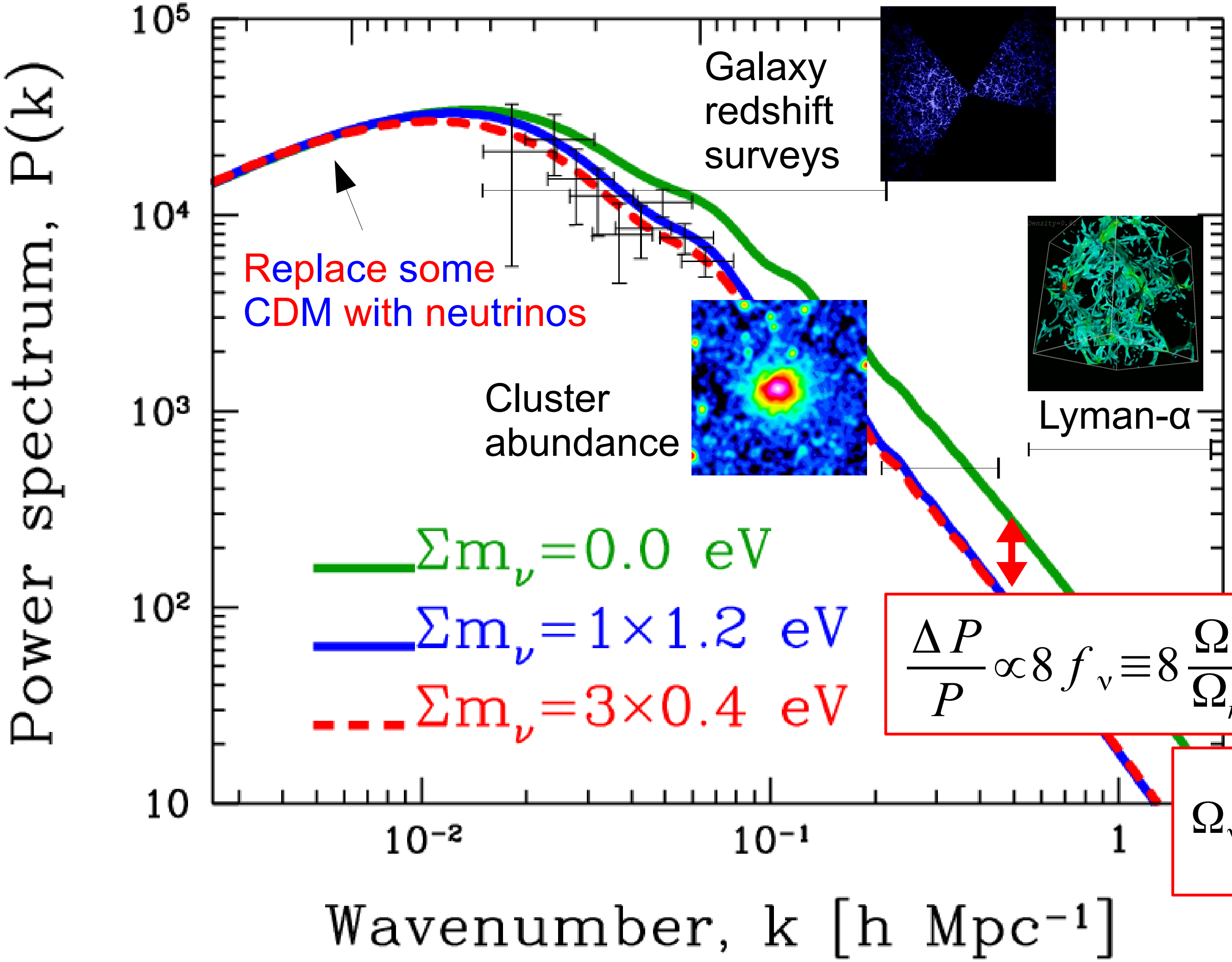
Potential stays the same (during matter domination)

Potential decays

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

Large-scale matter distribution...

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



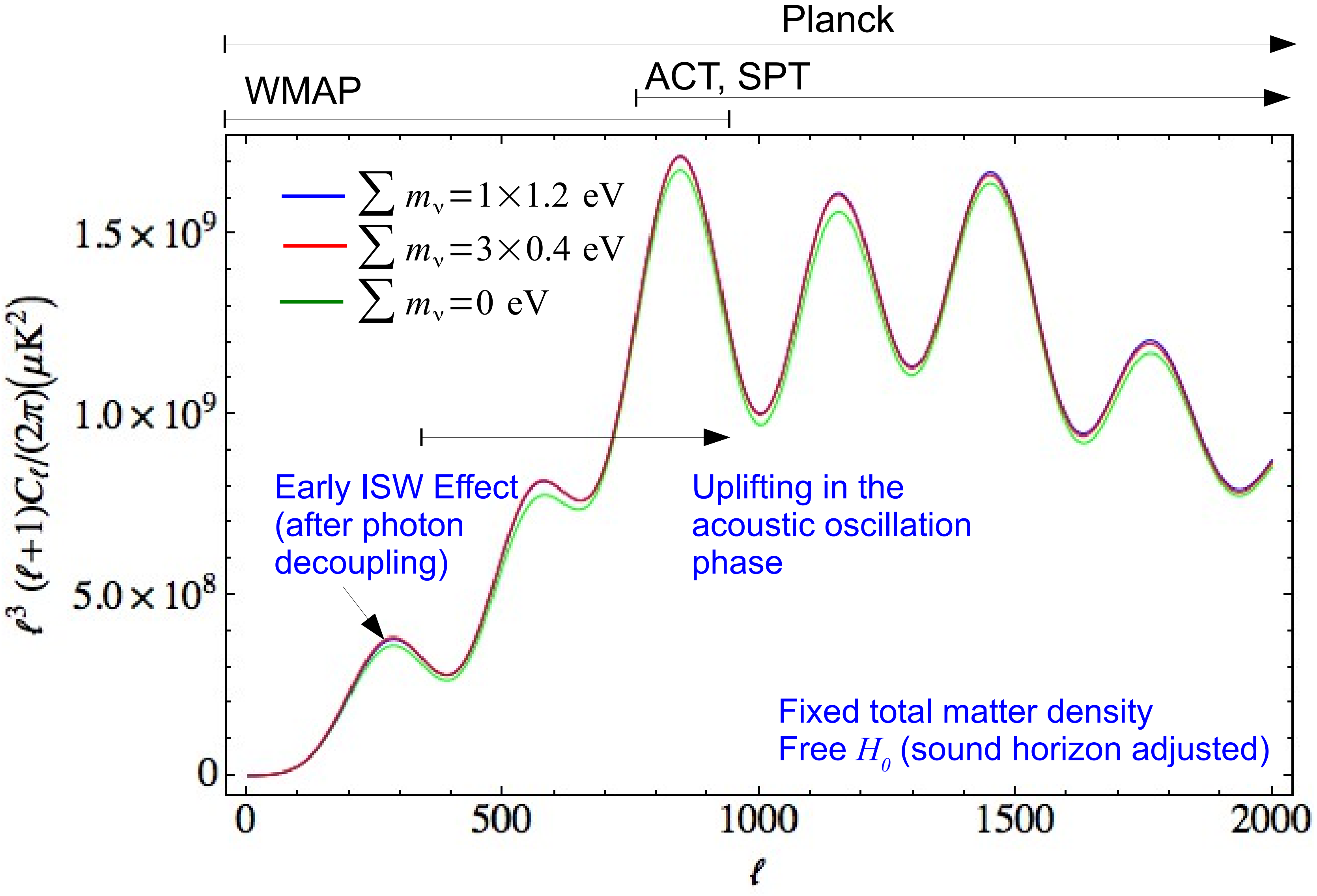
Replace some CDM with neutrinos

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

f_ν = Neutrino fraction

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

CMB anisotropies...

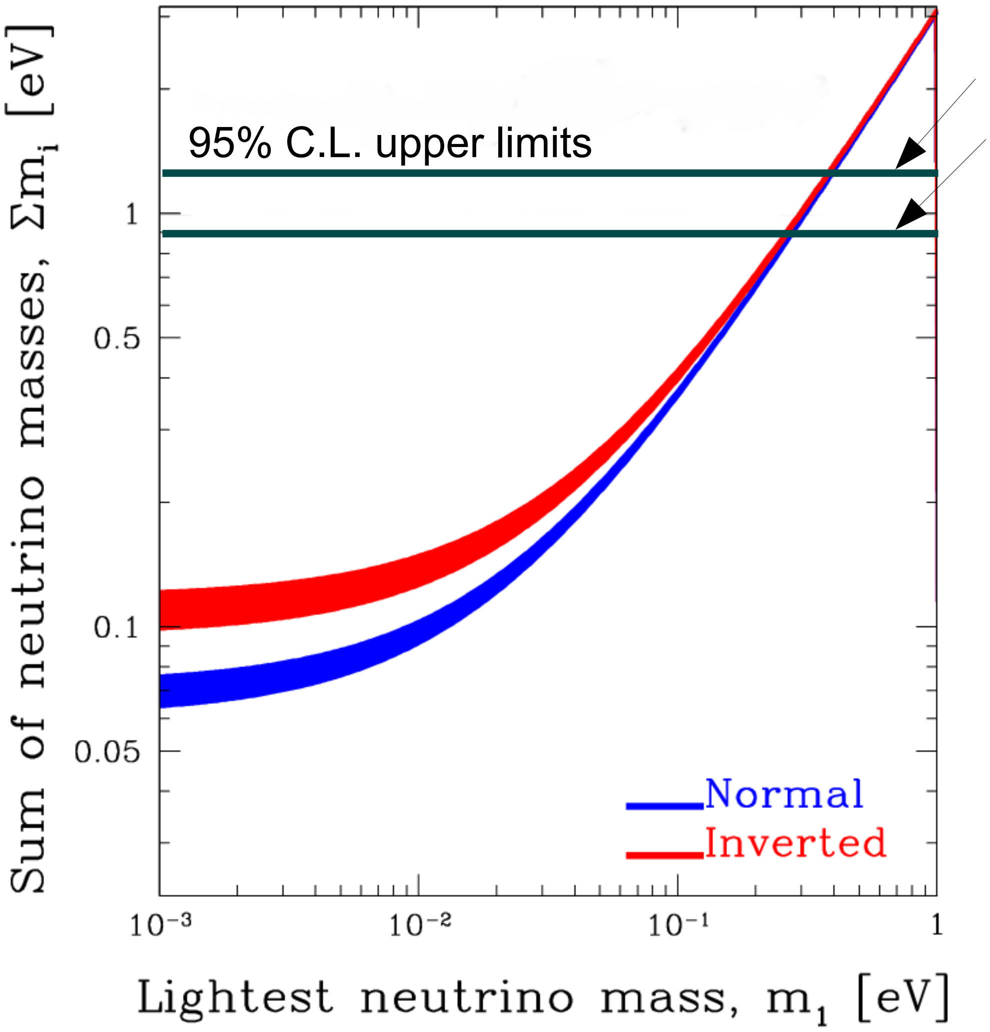


Early ISW Effect (after photon decoupling)

Uplifting in the acoustic oscillation phase

Fixed total matter density
Free H_0 (sound horizon adjusted)

Pre-Planck constraints...



ΛCDM+neutrino mass (7 parameters)

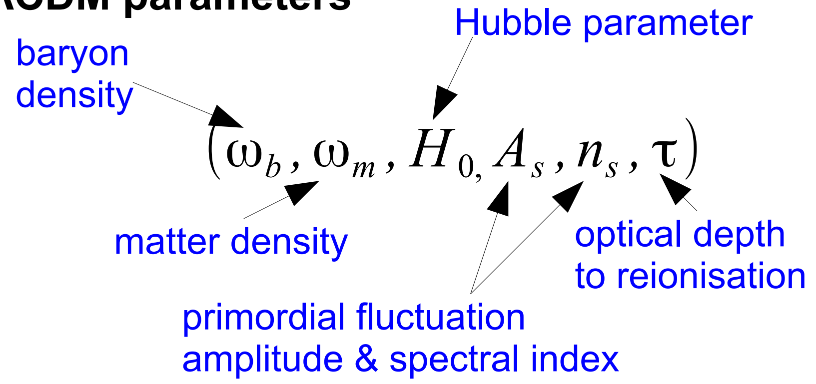
WMAP (9 years)

W9 + **ACT**

W9 + **SPT**

$$\sum m_\nu = 1.14 \pm 0.41\,\mathrm{eV}\,(1\sigma)$$

ΛCDM parameters



Hubble parameter

baryon density

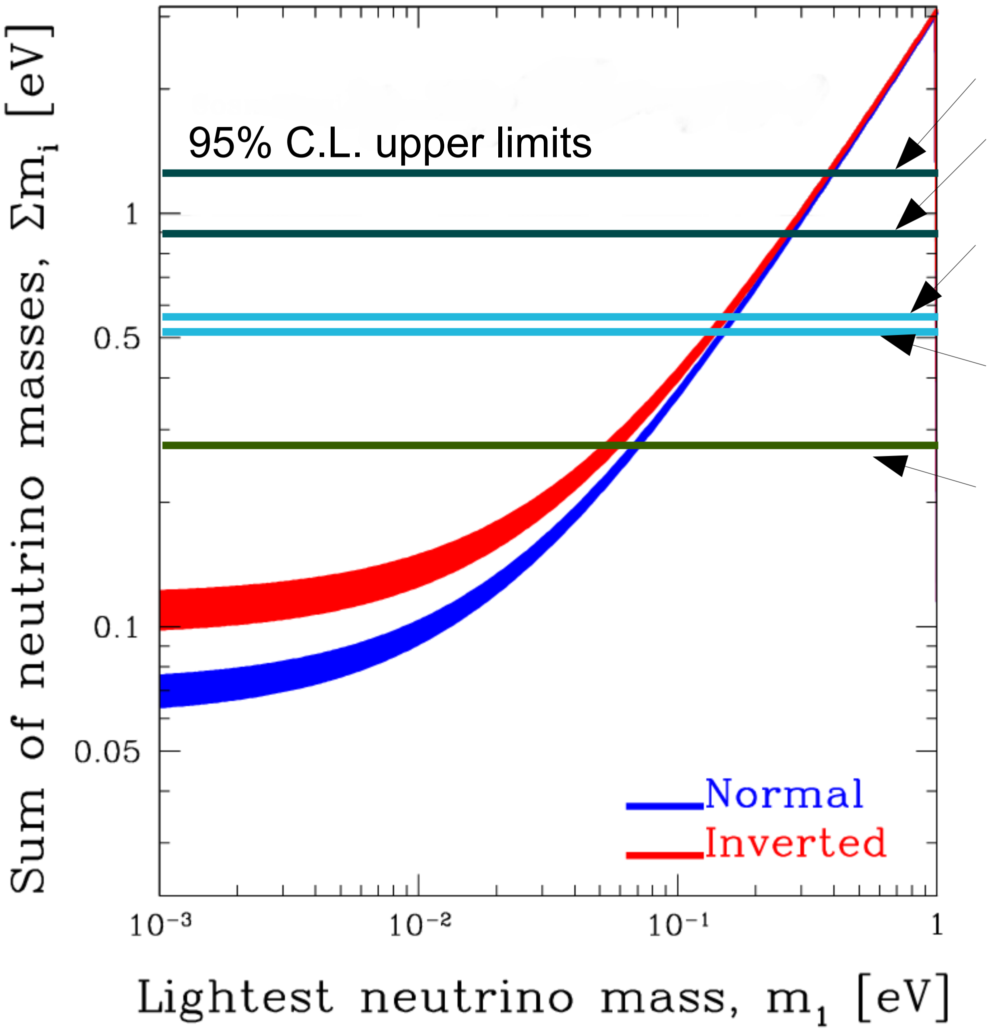
$$(\omega_b, \omega_m, H_0, A_s, n_s, \tau)$$

matter density

optical depth to reionisation

primordial fluctuation amplitude & spectral index

Pre-Planck constraints...



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W7 + **matter power spectrum**

e.g., de Putter et al. [SDSS DR8] 2012

W9 + **baryon acoustic oscillations**

e.g., Hinshaw et al. [WMAP9] 2012

W7+ matter power spectrum + **HST H_0**

de Putter et al. [SDSS DR8] 2012

ΛCDM parameters

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

baryon density

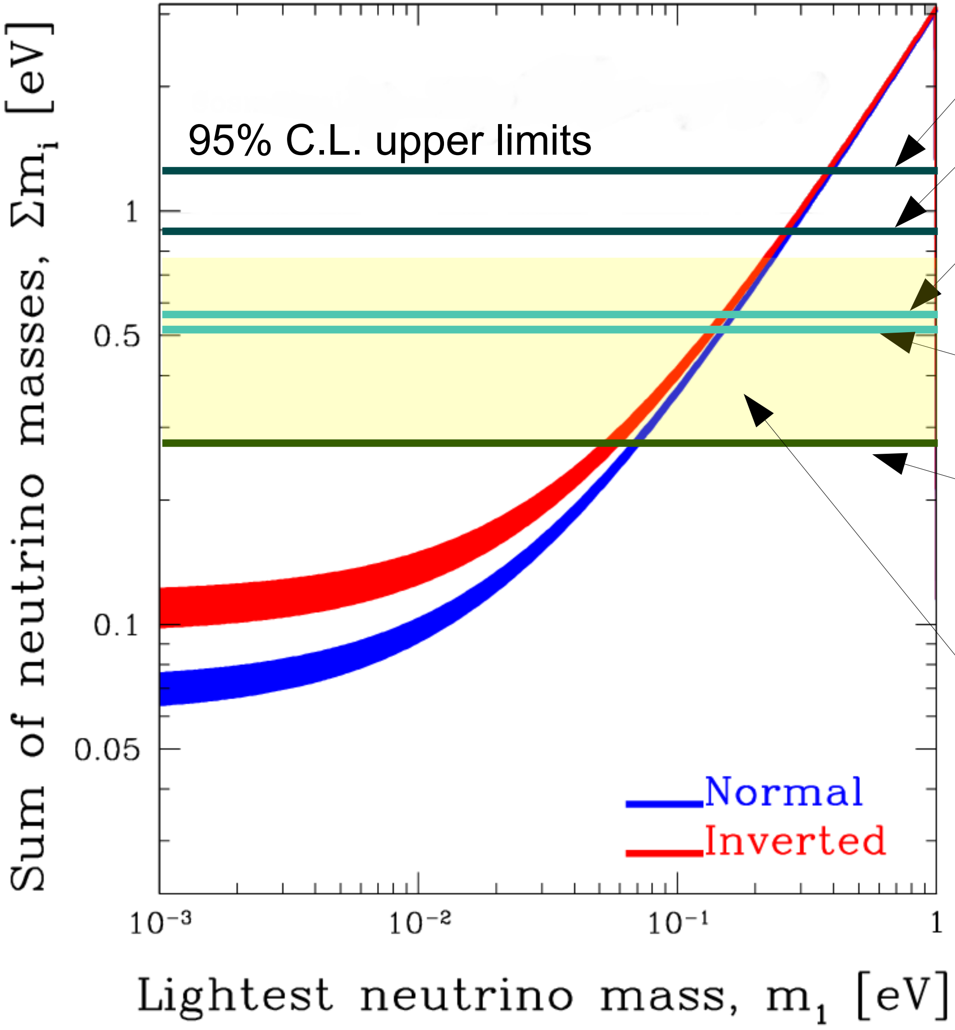
matter density

Hubble parameter

primordial fluctuation amplitude & spectral index

optical depth to reionisation

Pre-Planck constraints...



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W7+ matter power spectrum + **HST H_0**

de Putter et al. [SDSS DR8] 2012

More complex parameter space

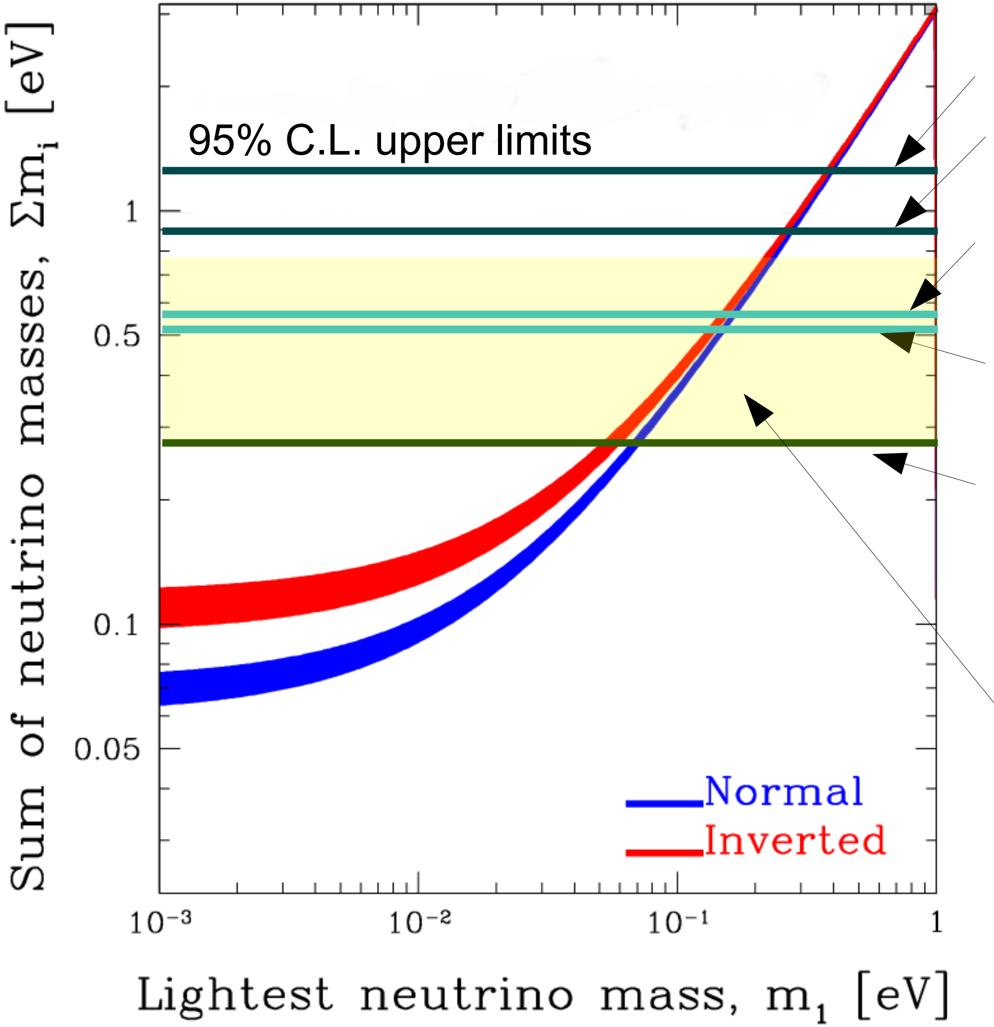
$$\sum m_\nu < 0.3 \rightarrow 0.76\,\text{eV} \quad (95\,\%\,\text{C.L.})$$

W7+ LSS + H_0 + **SNIa**

e.g., Gonzalez-Garcia et al. 2010

Includes uncertainties in
- Number of neutrino species
- Dark energy equation of state
- Inflation physics (tensors, running)
- Spatial curvature

Pre-Planck constraints: buyers beware!!



WMAP (9 years)

W9 + **ACT**

SZ modelling

W9 + **SPT**

$$\sum m_\nu = 1.14 \pm 0.41\,\mathrm{eV}\,(1\sigma)$$

W7 + **matter power spectrum**

Nonlinear modelling (moderate)

W9 + **baryon acoustic oscillations**

Nonlinear modelling (mild)

W7+ matter power spectrum + **HST H_0**

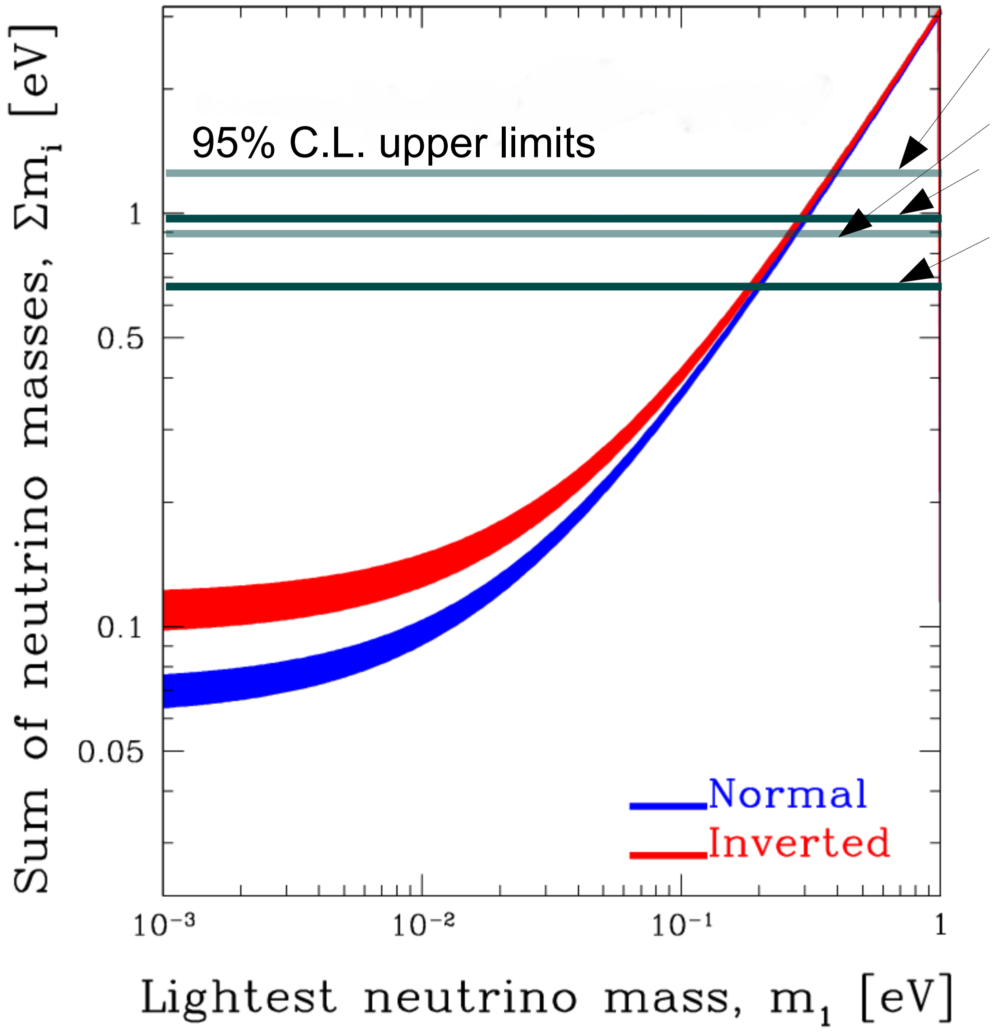
Local inhomogeneities;
astrophysics

W7+ LSS + H_0 + **SNIa**

Incompatible lightcurve fitters

Post-Planck...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

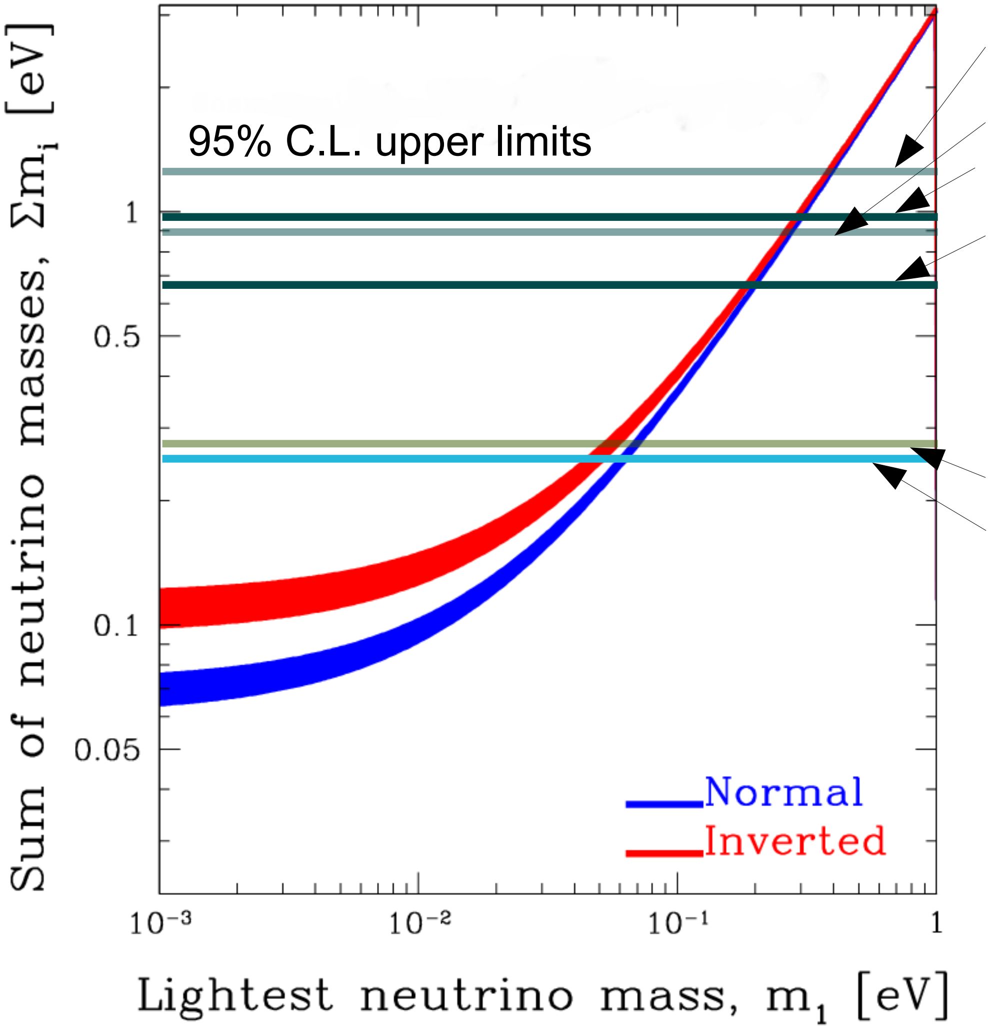
Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

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

Best CMB-only bound

Post-Planck...

Ade et al.[Planck] 2013



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

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

Best CMB-only bound

W7+ matter power spectrum + HST H_0

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

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

Best minimal bound

Dropping assumption of spatial flatness:

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

Other extensions??

A quick summary about neutrino masses...

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

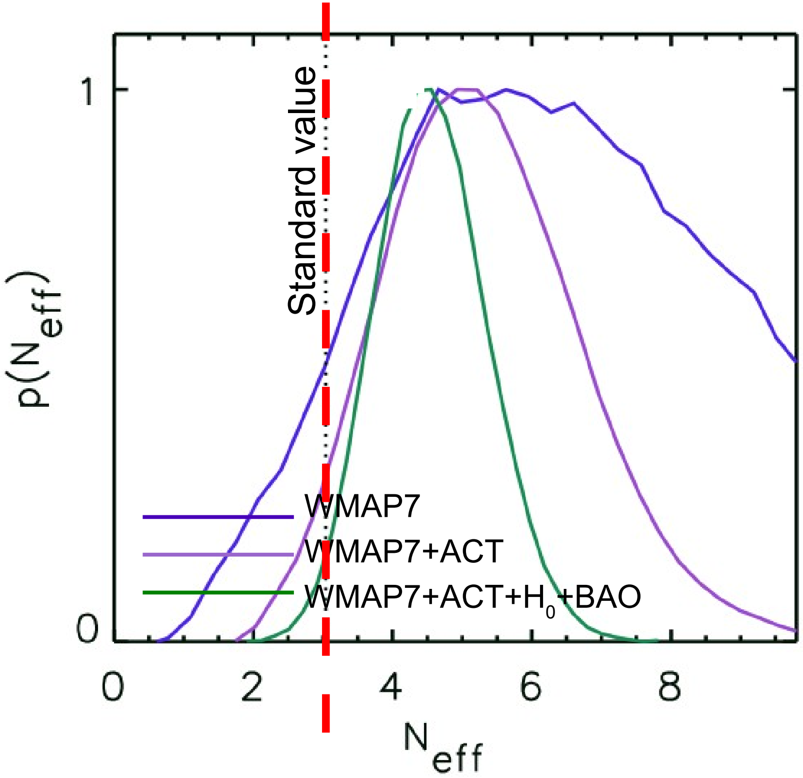
- The bound has however become more robust against uncertainties:
  - Less nonlinearities in BAO than in the matter power spectrum.
  - Does not rely on local measurement of the Hubble parameter...
  - … or on the choice of lightcurve fitters for the Supernova Ia data.

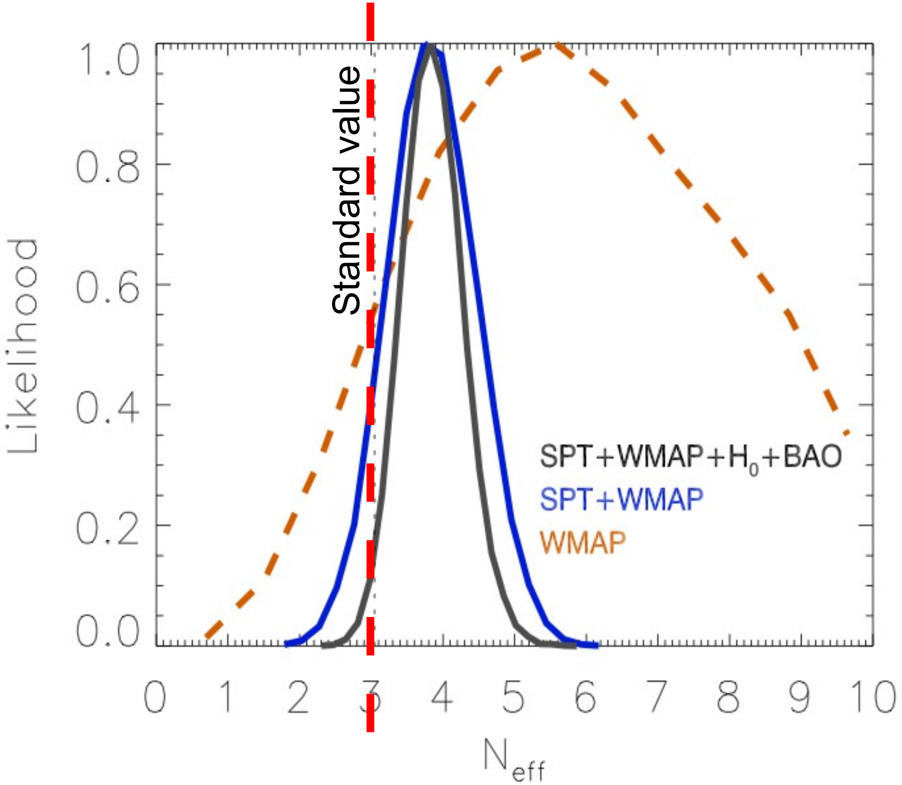
- **Dependence on cosmological model** used for inference?

2. The fourth neutrino??

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

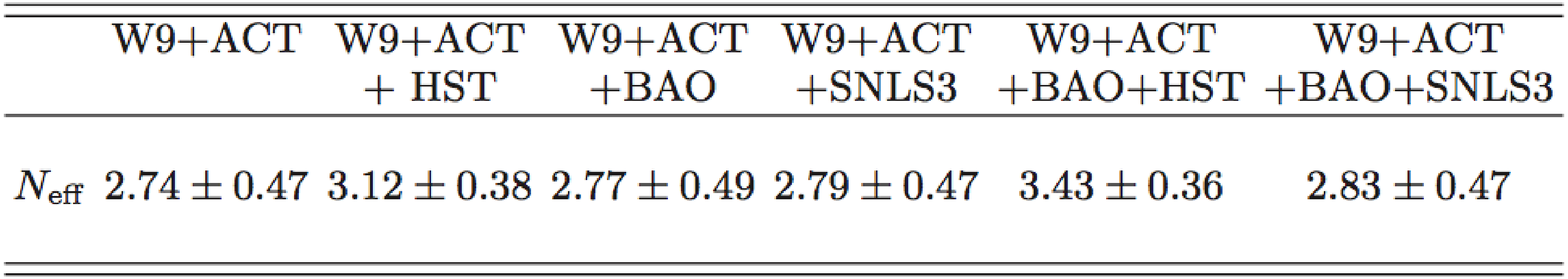
Keisler et al. [South Pole Telescope] 2011

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

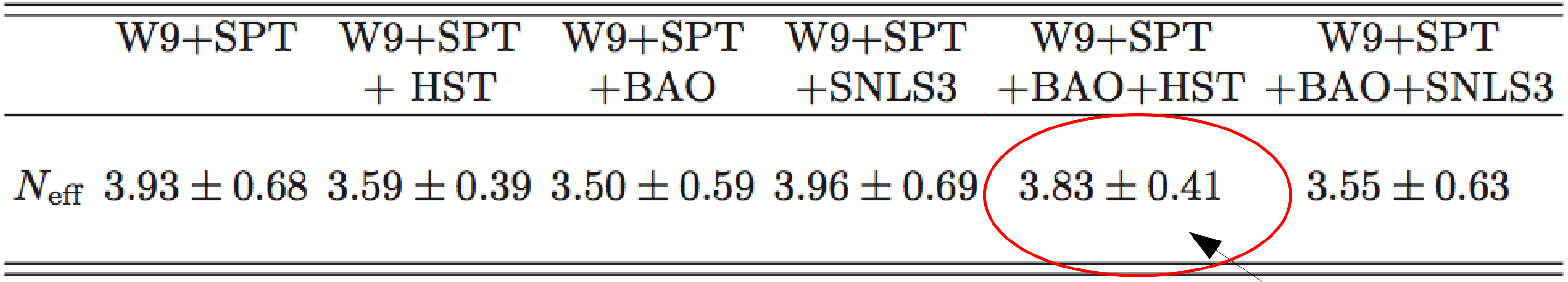
New data from WMAP, ACT and SPT in late 2012 – early 2013 favour an $N_{\rm eff}$ value **compatible with the standard value** of 3.046.

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
$N_{\rm eff}$	2.74 ± 0.47	3.12 ± 0.38	2.77 ± 0.49	2.79 ± 0.47	3.43 ± 0.36	2.83 ± 0.47



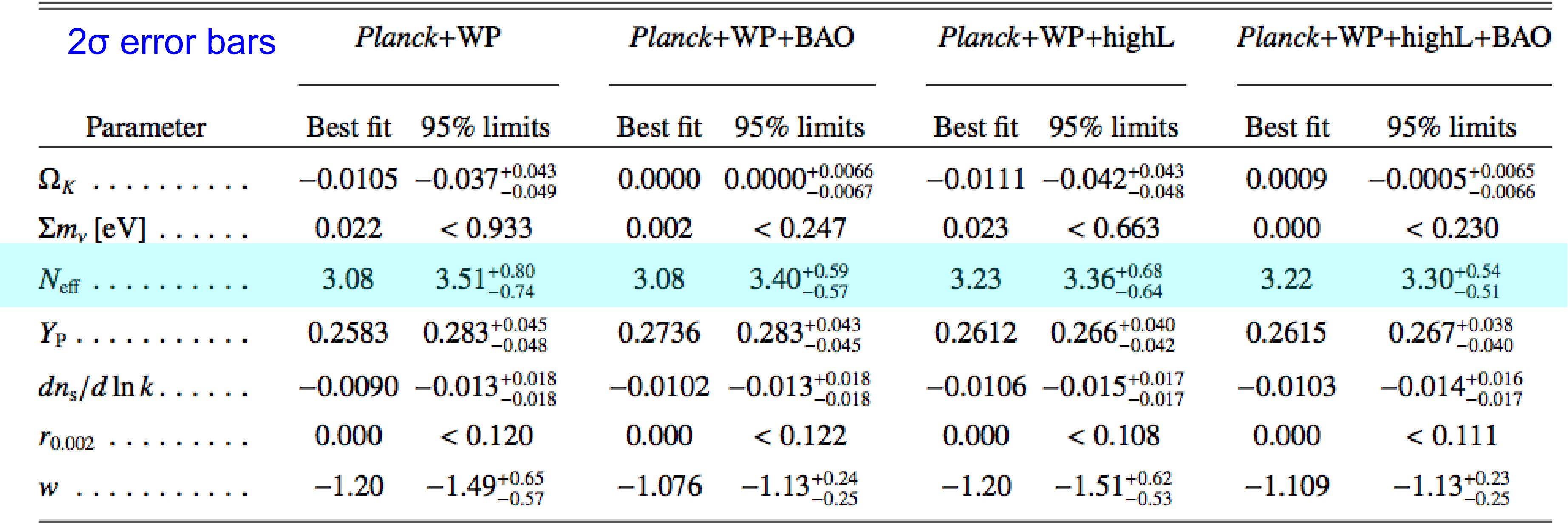
	W9+SPT	W9+SPT + HST	W9+SPT +BAO	W9+SPT +SNLS3	W9+SPT +BAO+HST	W9+SPT +BAO+SNLS3
$N_{\rm eff}$	3.93 ± 0.68	3.59 ± 0.39	3.50 ± 0.59	3.96 ± 0.69	3.83 ± 0.41	3.55 ± 0.63

Archidiacono, Giusarma, Melchiorri & Mena,1303.0143

$N_{\rm eff} > 3$ at 2σ+.

Post-Planck N_{eff} ...

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



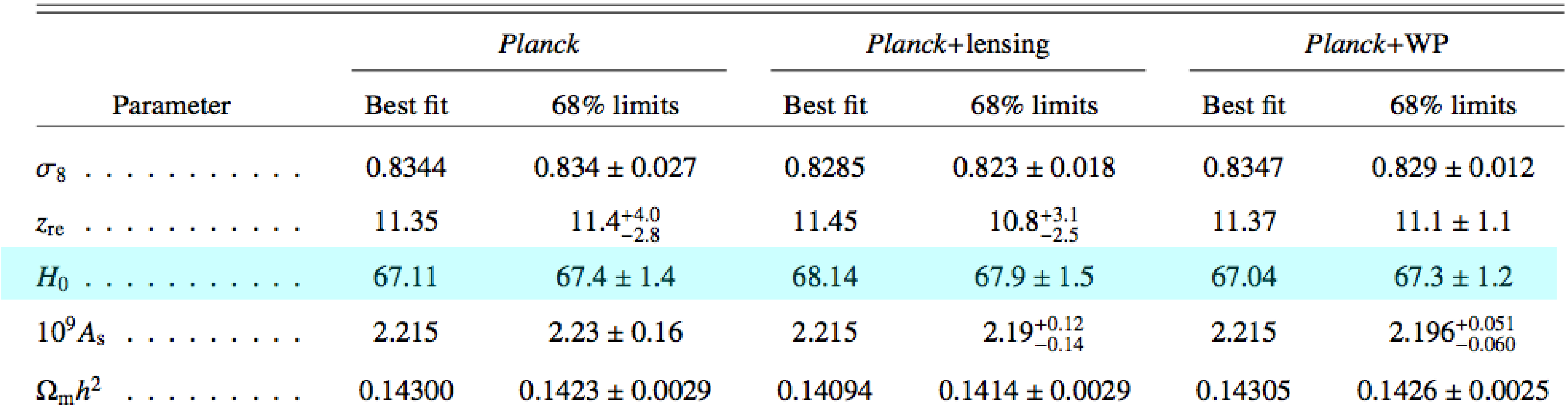
2σ error bars	*Planck*+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
N_{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_{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_{eff} story...

BUT...

Alleviating discrepancy using N_{eff}?

The Planck-inferred Hubble parameter is incompatible with HST measurement.



Parameter	*Planck*		*Planck*+lensing		*Planck*+WP	
	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
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025

Ade et al. [Planck collaboration] 2013

Hubble space telescope

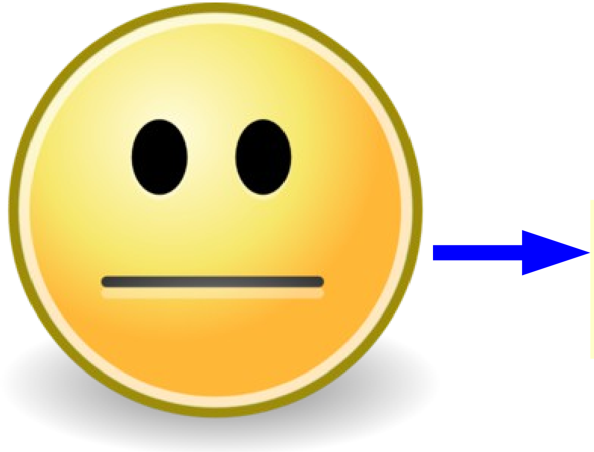
$$H_0 = 73.8 \pm 2.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

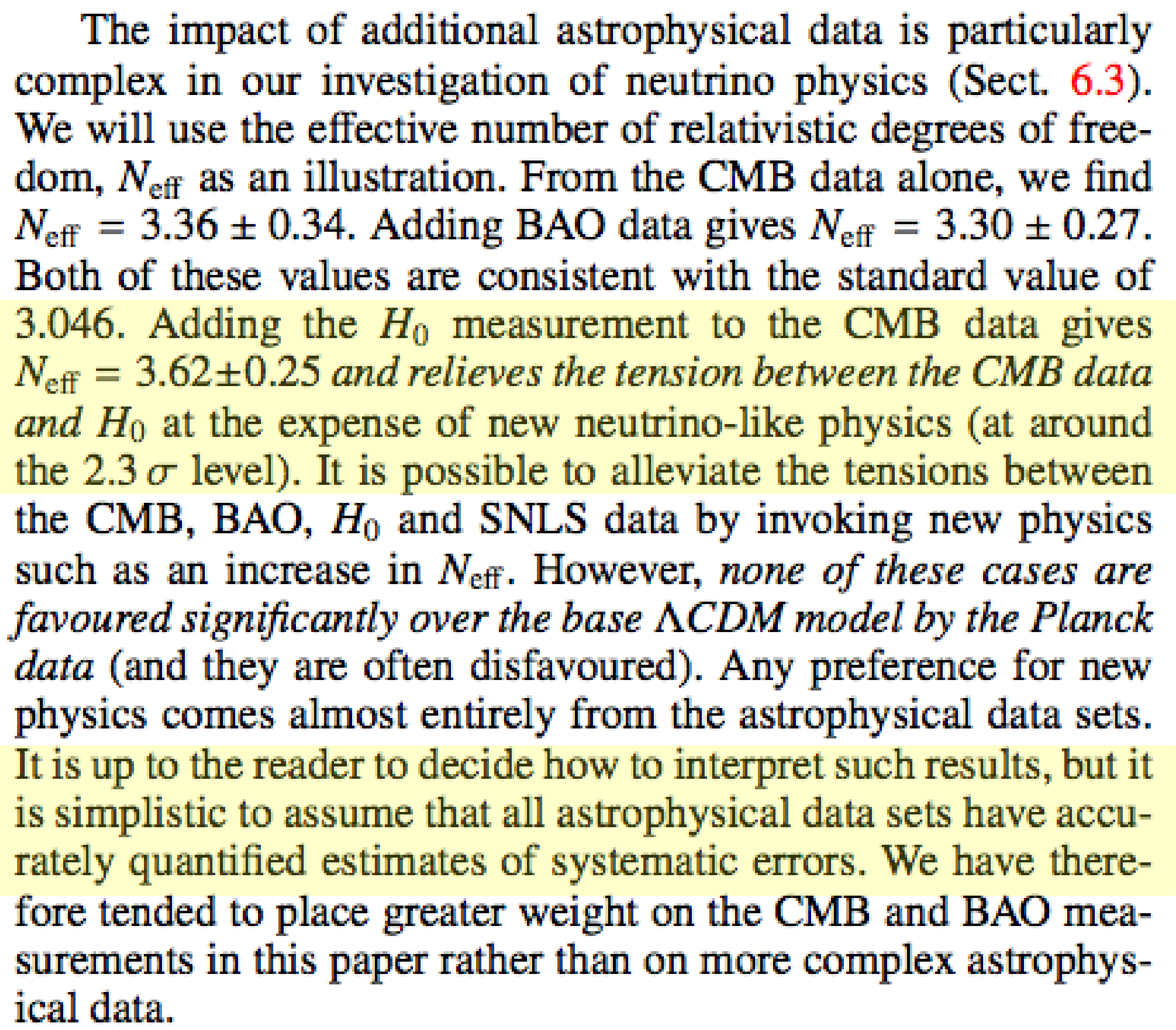
Riess et al. 2011

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

Planck + HST

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





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

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.

- Maybe there's a “**fourth neutrino**”, or maybe not, depending on how much you trust the HST determination of H_0.
  - Either way, things are looking very bad for the SBL sterile neutrino, unless there's some **new physics** to suppress its production in the early universe.