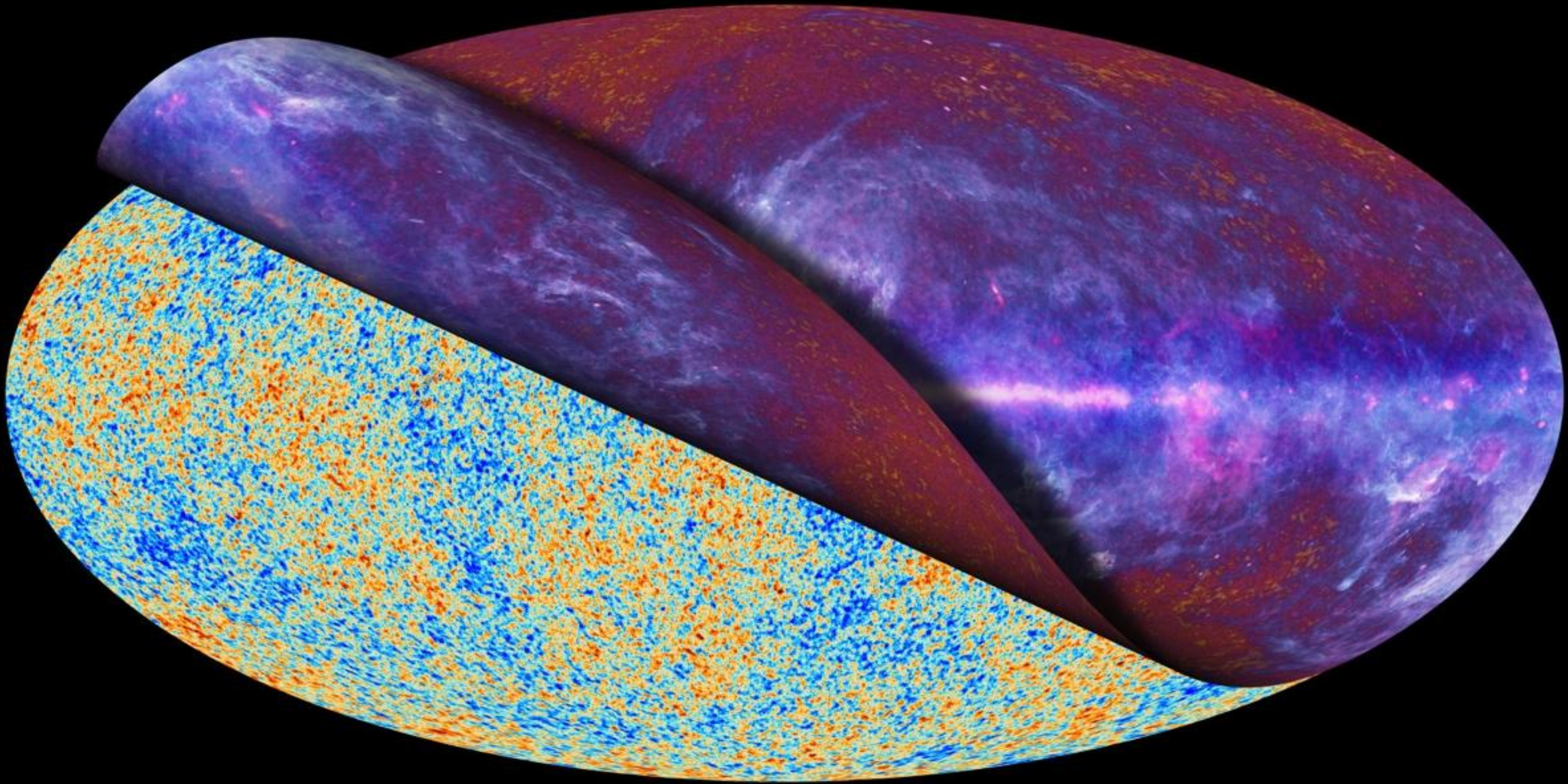
planck

esa



Planck unveils the Cosmic Microwave Background

Constraints on Neutrino Physics from Planck

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On behalf of the Planck collaboration

Results presented are taken from
Planck paper XVI
Planck paper XX
Planck public parameters Table:
http://www.sciops.esa.int/SYS/WIKI/uploads/Planck_Public_PLA/3/32/Grid_limit95.pdf

Cosmological (Massless) Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_{\nu} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma} \approx 1.945K \rightarrow kT_{\nu} \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

$$n_f = \frac{3}{4} \frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k, \bar{\nu}_k} \approx 0.1827 \cdot T_{\nu}^3 \approx 112 cm^{-3}$$

for a relativistic neutrino translates in a extra radiation component of:

$$\Omega_{\nu} h^2 = \frac{7}{4} \left(\frac{4}{11}\right)^{4/3} N_{eff}^{\nu} \Omega_{\gamma} h^2$$

Standard Model predicts:

$$N_{eff}^{\nu} = 3.046$$

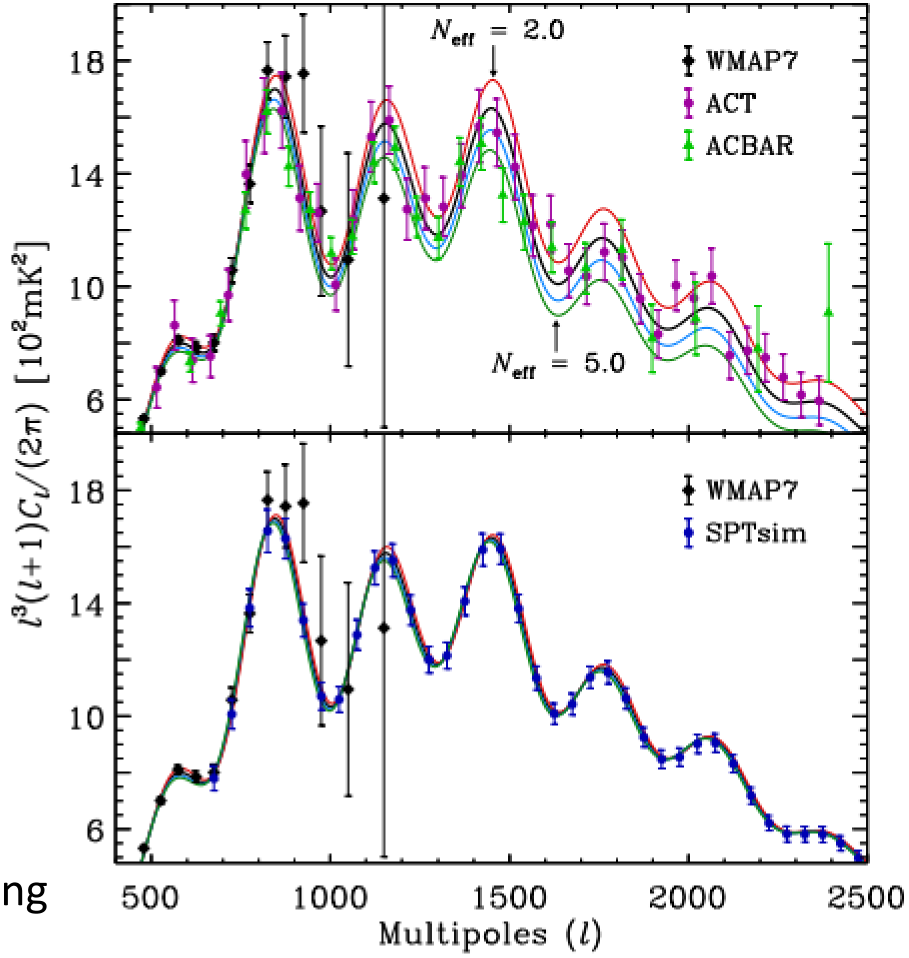
Probing the Neutrino Number with CMB data

Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the sound horizon at recombination:

$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}.$$

and the damping scale at recombination:

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$



Once the sound horizon scale is fixed, increasing $N_{\rm eff}$ decreases the damping scale and
the result is an increase in the small angular scale anisotropy.
We expect degeneracies with the Hubble constant and the Helium abundance.
(see e.g. Hou, Keisler, Knox et al. 2013, Lesgourgues and Pastor 2006).

Constraints from Planck and other CMB datasets (95% c.l.)

We combine the constraints from the Planck temperature power spectrum with the following datasets:

- **WP** is WMAP Polarization. We include the large angular scale EE polarization data from WMAP9.

- **highL** includes the ACT dataset in the region 540 < l < 9440 (Das et al., 2013) and the SPT dataset in the Region 2000 < l < 10000 (Reichardt et al., 2012). The ACT and SPT datasets are used mainly for foregrounds subtraction. ACT dataset has also mild effects on cosmological parameters.

- **Lensing** includes information on the CMB lensing amplitude from Planck trispectrum data (see Planck cosmology paper XVII).

Caveat: all the results that we are going to show have been obtained assuming a value for the primordial Helium computed assuming Big Bang Nucleosynthesis. Removing this assumption would slightly affect the values for N_{eff}.

Constraints from Planck and other CMB datasets (95% c.l.)

Planck alone (no pol.)	$N_{eff}^{\nu} = 4.53_{-1.4}^{+1.5}$
Planck + WP	$N_{eff}^{\nu} = 3.51_{-0.74}^{+0.80}$
Planck + WP + Lensing	$N_{eff}^{\nu} = 3.39_{-0.70}^{+0.77}$
Planck + WP + highL	$N_{eff}^{\nu} = 3.36_{-0.64}^{+0.68}$
Planck + WP + highL + Lensing	$N_{eff}^{\nu} = 3.28_{-0.64}^{+0.67}$

Conclusions:

- $N_{eff}=0$ is excluded at high significance (about 10 standard deviations). We need a neutrino background to explain Planck observations !

- **No evidence** (i.e. > 3 σ) for extra radiation from CMB only measurements.

- $N_{eff}=4$ is also consistent in between 95% c.l.

- $N_{eff}=2$ and $N_{eff}=5$ excluded at more than 3 σ (massless).

Constraints from Planck + astrophysical datasets (95% c.l.)

$$\mathrm{Planck} + \mathrm{WP} + \mathrm{BAO} \qquad N_{eff}^{\nu} = 3.40^{+0.59}_{-0.57}$$

$$\mathrm{Planck} + \mathrm{WP} + \mathrm{SNLS} \qquad N_{eff}^{\nu} = 3.68^{+0.77}_{-0.78}$$

$$\mathrm{Planck} + \mathrm{WP} + \mathrm{Union2} \qquad N_{eff}^{\nu} = 3.56^{+0.77}_{-0.73}$$

$$\mathrm{Planck} + \mathrm{WP} + \mathrm{HST} \qquad N_{eff}^{\nu} = 3.73^{+0.54}_{-0.51}$$

Conclusions:

- When the BAO dataset is included there is a better agreement with Neff=3.046.

- When luminosity distance data are included (supernovae, HST) the data prefers extra «dark radiation». Systematics in luminosity distances or new physics ?

- With HST we have extra dark radiation at about 2.7 σ. This is clearly driven by the tension between Planck and HST on the value of the Hubble constant in the standard LCDM framework.

Can we combine Planck and HST ?

Planck and HST give very different values for the Hubble constant (68% c.l.):

$$\text{Planck} + \text{WP} \qquad H_0 = 67.3^{+1.2}_{-1.1}\ [\text{km/s/Mpc}]$$

$$\text{HST (Riess et al.)} \qquad H_0 = 73.8^{+2.4}_{-2.4}\ [\text{km/s/Mpc}]$$

But the Planck result is obtained under the assumption of N_{eff}=3.046.
If leave N_{eff} as a free parameter we get:

$$\text{Planck} + \text{WP} \qquad H_0 = 70.7^{+3.0}_{-3.2}\ [\text{km/s/Mpc}]$$

That is now compatible with HST (but we now need dark radiation).
The CMB determination of the Hubble constant is **model dependent**.

Constraints from CMB (Planck+WP+highL) + astrophysical datasets (95% c.l.)

$$\mathrm{CMB}+\mathrm{HST} \qquad N_{eff}^{\nu}=3.62_{-0.48}^{+0.50}$$

$$\mathrm{CMB}+\mathrm{SNLS} \qquad N_{eff}^{\nu}=3.51_{-0.63}^{+0.67}$$

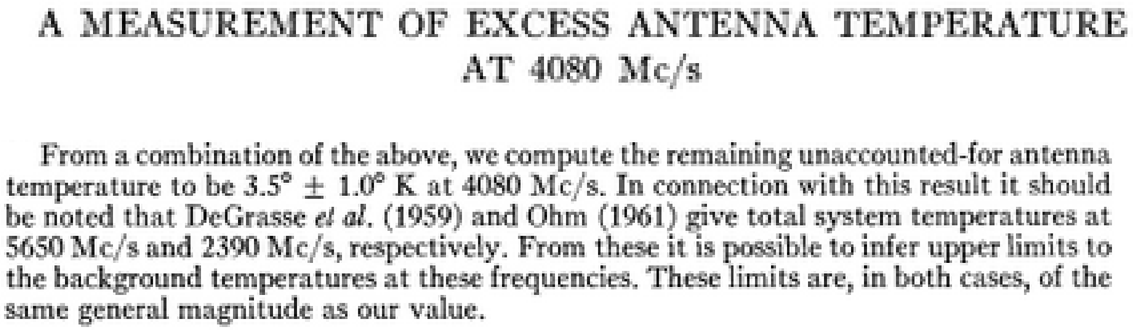
$$\mathrm{CMB}+\mathrm{Union2} \qquad N_{eff}^{\nu}=3.40_{-0.63}^{+0.67}$$

$$\mathrm{CMB}+\mathrm{BAO} \qquad N_{eff}^{\nu}=3.30_{-0.51}^{+0.54}$$

Conclusions:

- When the highL dataset is included there is a better agreement with Neff=3.046.
- Combination with HST hints for extra dark radiation but now at 2.4 σ.
- CMB+BAO rules out N_{eff} =4.04 at about 2.7 σ.

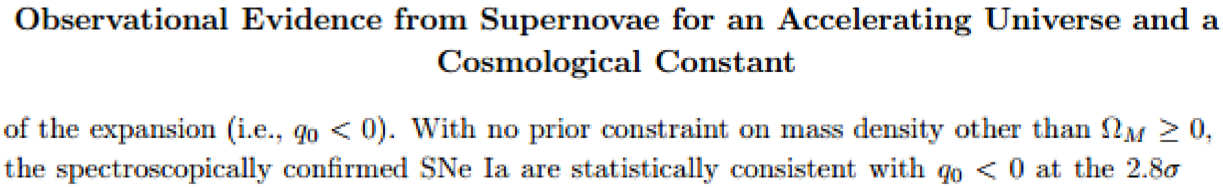
Should we care about a 2.7 σ signal ?



A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be $3.5^\circ \pm 1.0^\circ$ K at 4080 Mc/s. In connection with this result it should be noted that DeGrasse *et al.* (1959) and Ohm (1961) give total system temperatures at 5650 Mc/s and 2390 Mc/s, respectively. From these it is possible to infer upper limits to the background temperatures at these frequencies. These limits are, in both cases, of the same general magnitude as our value.

Discovery of the CMB was made at 3.5 σ !



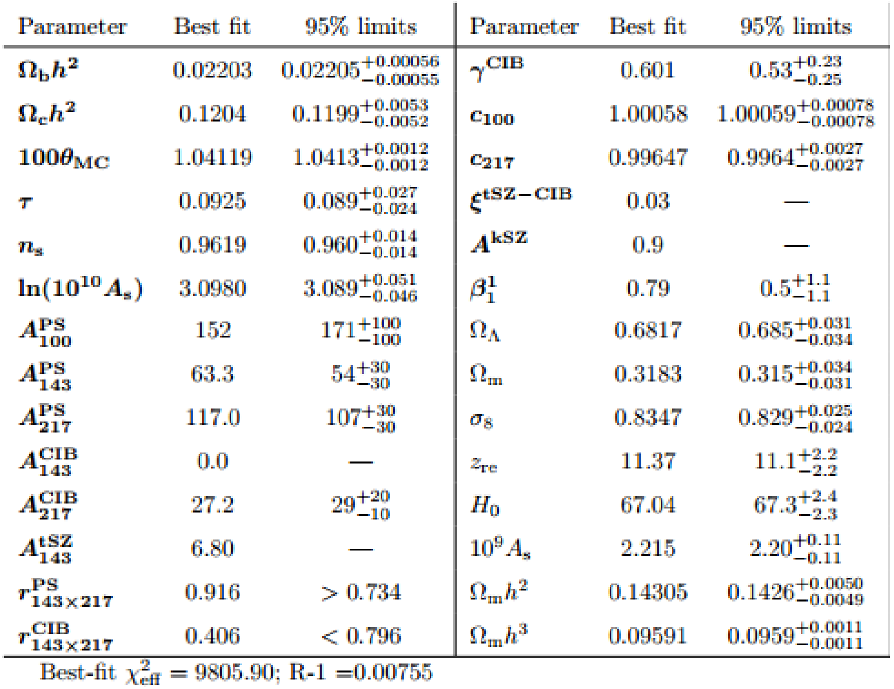
Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant

of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8σ

Discovery of the accelerating universe was made at 2.8 σ !

Impact on Parameters

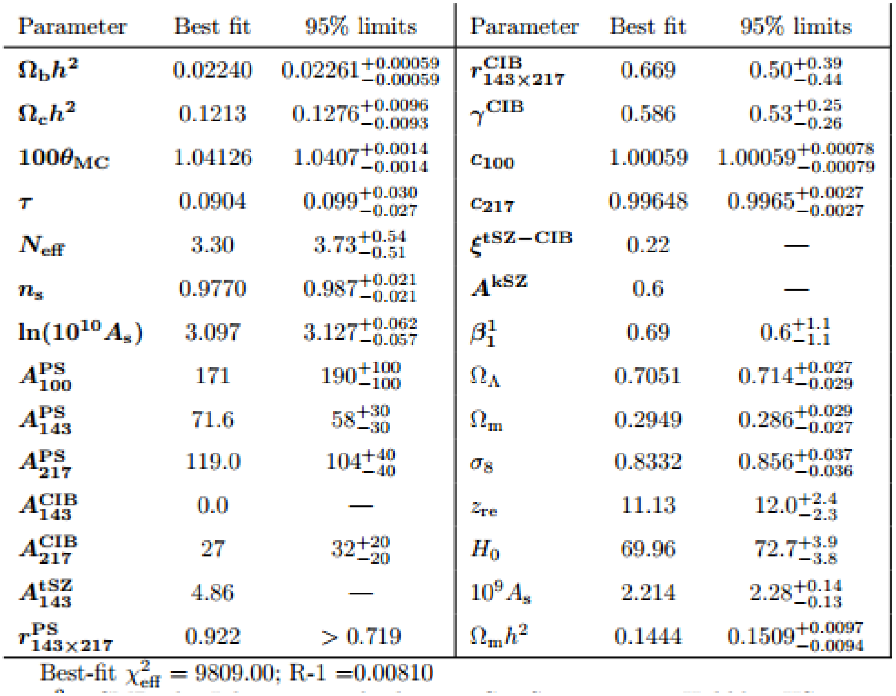
Planck+WP



Parameter	Best fit	95% limits	Parameter	Best fit	95% limits
$\Omega_b h^2$	0.02203	$0.02205^{+0.00056}_{-0.00055}$	γ^{CIB}	0.601	$0.53^{+0.23}_{-0.25}$
$\Omega_c h^2$	0.1204	$0.1199^{+0.0053}_{-0.0052}$	c_{100}	1.00058	$1.00059^{+0.00078}_{-0.00078}$
$100\theta_{\mathrm{MC}}$	1.04119	$1.0413^{+0.0012}_{-0.0012}$	c_{217}	0.99647	$0.9964^{+0.0027}_{-0.0027}$
τ	0.0925	$0.089^{+0.027}_{-0.024}$	$\xi^{\mathrm{tSZ-CIB}}$	0.03	—
n_s	0.9619	$0.960^{+0.014}_{-0.014}$	A^{kSZ}	0.9	—
$\ln(10^{10}A_s)$	3.0980	$3.089^{+0.051}_{-0.046}$	β_1^1	0.79	$0.5^{+1.1}_{-1.1}$
A_{100}^{PS}	152	171^{+100}_{-100}	Ω_Λ	0.6817	$0.685^{+0.031}_{-0.034}$
A_{143}^{PS}	63.3	54^{+30}_{-30}	Ω_m	0.3183	$0.315^{+0.034}_{-0.031}$
A_{217}^{PS}	117.0	107^{+30}_{-30}	σ_8	0.8347	$0.829^{+0.025}_{-0.024}$
A_{143}^{CIB}	0.0	—	z_{re}	11.37	$11.1^{+2.2}_{-2.2}$
A_{217}^{CIB}	27.2	29^{+20}_{-10}	H_0	67.04	$67.3^{+2.4}_{-2.3}$
A_{143}^{tSZ}	6.80	—	$10^9 A_s$	2.215	$2.20^{+0.11}_{-0.11}$
$r_{143\times217}^{\mathrm{PS}}$	0.916	> 0.734	$\Omega_m h^2$	0.14305	$0.1426^{+0.0050}_{-0.0049}$
$r_{143\times217}^{\mathrm{CIB}}$	0.406	< 0.796	$\Omega_m h^3$	0.09591	$0.0959^{+0.0011}_{-0.0011}$

Best-fit $\chi^2_{\mathrm{eff}} = 9805.90$; R-1 =0.00755

Planck+WP+HST

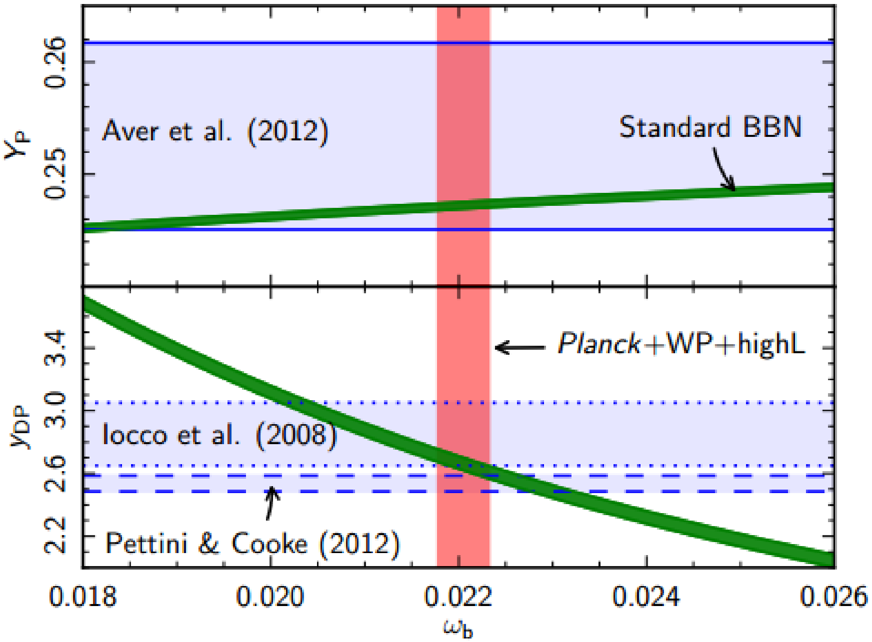


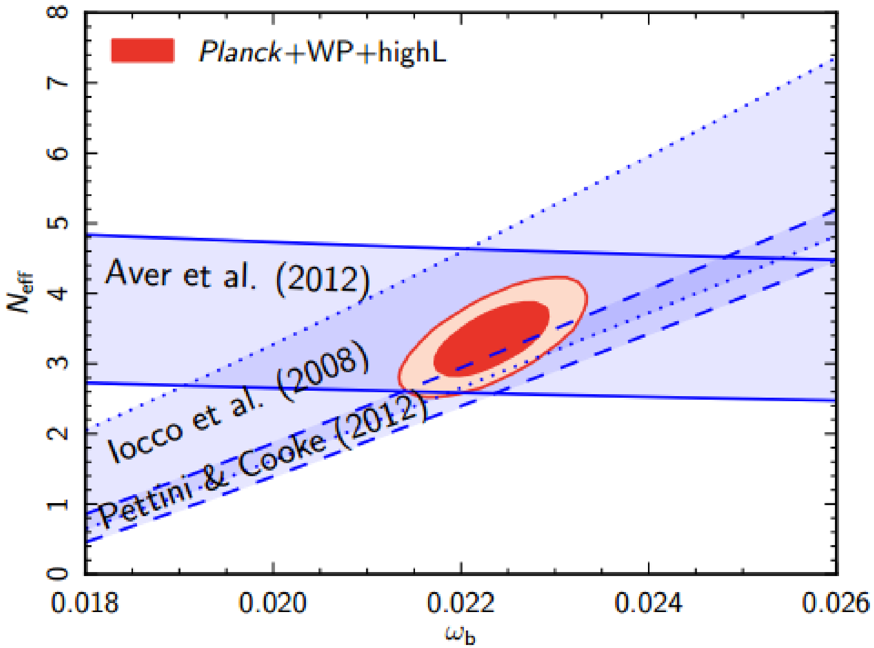
Parameter	Best fit	95% limits	Parameter	Best fit	95% limits
$\Omega_b h^2$	0.02240	$0.02261^{+0.00059}_{-0.00059}$	$r_{143\times217}^{\mathrm{CIB}}$	0.669	$0.50^{+0.39}_{-0.44}$
$\Omega_c h^2$	0.1213	$0.1276^{+0.0096}_{-0.0093}$	γ^{CIB}	0.586	$0.53^{+0.25}_{-0.26}$
$100\theta_{\mathrm{MC}}$	1.04126	$1.0407^{+0.0014}_{-0.0014}$	c_{100}	1.00059	$1.00059^{+0.00078}_{-0.00079}$
τ	0.0904	$0.099^{+0.030}_{-0.027}$	c_{217}	0.99648	$0.9965^{+0.0027}_{-0.0027}$
N_{eff}	3.30	$3.73^{+0.54}_{-0.51}$	$\xi^{\mathrm{tSZ-CIB}}$	0.22	—
n_s	0.9770	$0.987^{+0.021}_{-0.021}$	A^{kSZ}	0.6	—
$\ln(10^{10}A_s)$	3.097	$3.127^{+0.062}_{-0.057}$	β_1^1	0.69	$0.6^{+1.1}_{-1.1}$
A_{100}^{PS}	171	190^{+100}_{-100}	Ω_Λ	0.7051	$0.714^{+0.027}_{-0.029}$
A_{143}^{PS}	71.6	58^{+30}_{-30}	Ω_m	0.2949	$0.286^{+0.029}_{-0.027}$
A_{217}^{PS}	119.0	104^{+40}_{-40}	σ_8	0.8332	$0.856^{+0.037}_{-0.036}$
A_{143}^{CIB}	0.0	—	z_{re}	11.13	$12.0^{+2.4}_{-2.3}$
A_{217}^{CIB}	27	32^{+20}_{-20}	H_0	69.96	$72.7^{+3.9}_{-3.8}$
A_{143}^{tSZ}	4.86	—	$10^9 A_s$	2.214	$2.28^{+0.14}_{-0.13}$
$r_{143\times217}^{\mathrm{PS}}$	0.922	> 0.719	$\Omega_m h^2$	0.1444	$0.1509^{+0.0097}_{-0.0094}$

Best-fit $\chi^2_{\mathrm{eff}} = 9809.00$; R-1 =0.00810

When you include HST you also have an increase in the spectral index n_s !
The Harrison-Zel’dovich-Peebles spectrum with ns =1 is now compatible with Planck !
If laboratory experiments will confirm the existance of a fourth sterile neutrino then we will need to drastically change our view about inflation !

Constraints from BBN





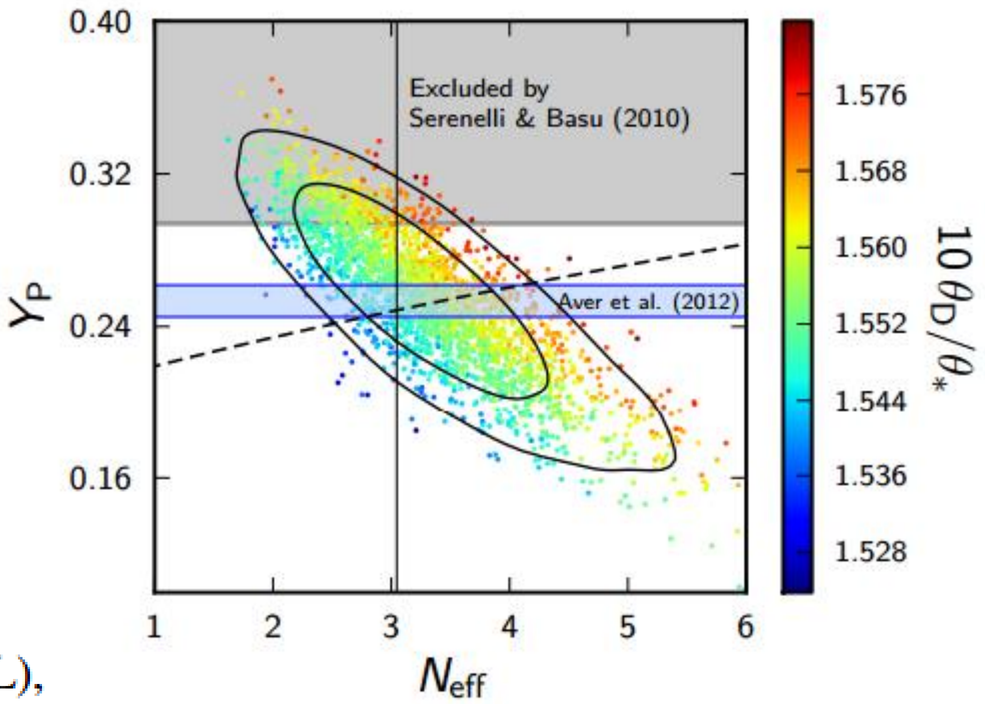
BBN can constrain Neff around T≈ 1 Mev.

- Helium and conservative deuterium measurements agree with Neff ≈ 3.5.

- New (single) D measurement by Pettini and Cooke is in perfect agreement with Neff=3.046.

$$N_{\rm eff} = \begin{cases} 3.41 \pm 0.30, & Y_{\rm P} \text{ (Aver et al.)}, \\ 3.43 \pm 0.34, & y_{\rm DP} \text{ (Iocco et al.)}, \\ 3.02 \pm 0.27, & y_{\rm DP} \text{ (Pettini and Cooke)}. \end{cases}$$

Neutrinos and Helium Abundance



N_{eff} and Helium abundance constraints from CMB are anticorrelated, while constraints from BBN are correlated.

Current constraints in the N_{eff} vs Y_p plane from CMB are Weak but in good agreement with Helium experimental bounds and expectations from BBN.

$$N_{\rm eff} = 3.33^{+0.59}_{-0.83} \quad (68\%; \textit{Planck}+\text{WP}+\text{highL}),$$
$$Y_{\rm P} = 0.254^{+0.041}_{-0.033} \quad (68\%; \textit{Planck}+\text{WP}+\text{highL}).$$

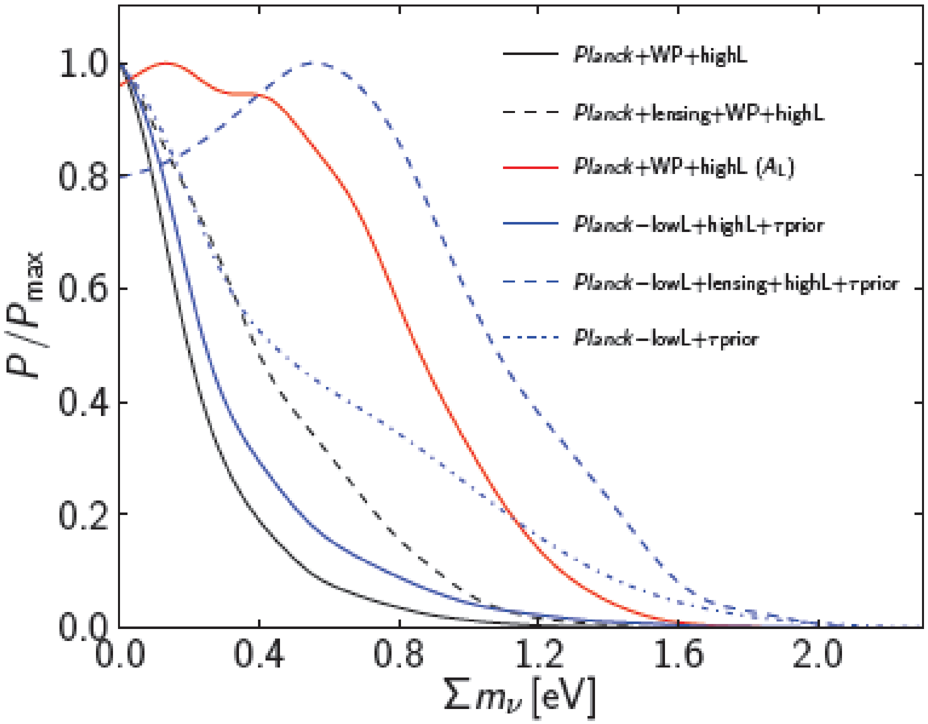
Including BAO (95% c.l.):

$$\boldsymbol{N_{\rm eff}} \quad 3.19^{+0.99}_{-0.94}$$
$$\boldsymbol{Y_{\rm He}} \quad 0.260^{+0.057}_{-0.065}$$

Including HST (95% c.l.):

$$\boldsymbol{N_{\rm eff}} \quad 3.83^{+0.87}_{-0.79}$$
$$\boldsymbol{Y_{\rm He}} \quad 0.236^{+0.058}_{-0.059}$$

Constraints on Neutrino Mass (standard 3 neutrino framework)



$$\sum m_\nu < 0.66\,\mathrm{eV} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}).$$

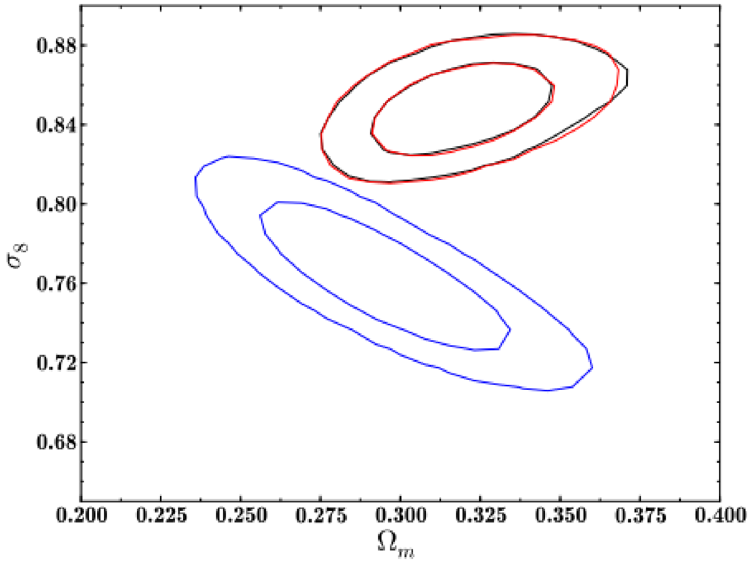
$$\sum m_\nu < 1.08\,\mathrm{eV} \quad [95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}\ (A_\mathrm{L})],$$

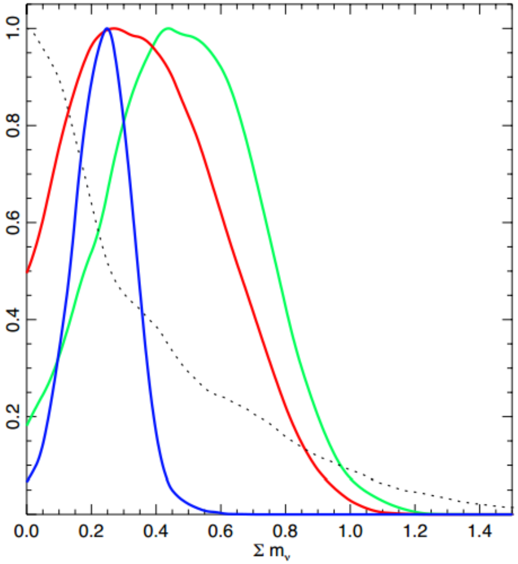
$$\sum m_\nu < 0.85\,\mathrm{eV} \quad (95\%;\ \textit{Planck}+\mathrm{lensing}+\mathrm{WP}+\mathrm{highL}),$$

$$\sum m_\nu < 0.23\,\mathrm{eV} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}+\mathrm{BAO}).$$

- Planck strongly improves previous constraints on neutrino masses.
- Planck TT spectrum prefers a lensing amplitude higher than expected (A_{LENS}=1.2).
- Inclusion of lensing from TTTT weakens the Planck constraint by 20%
- Including BAO results in the best current constraint on neutrino masses of 0.23 eV

Evidence for a Neutrino mass from SZ Clusters counts ?





Dashed:
Planck CMB

Red:
Planck CMB+SZ
(1-b)=[0.7,1]

Green:
Planck CMB+SZ
(1-b)=0.8

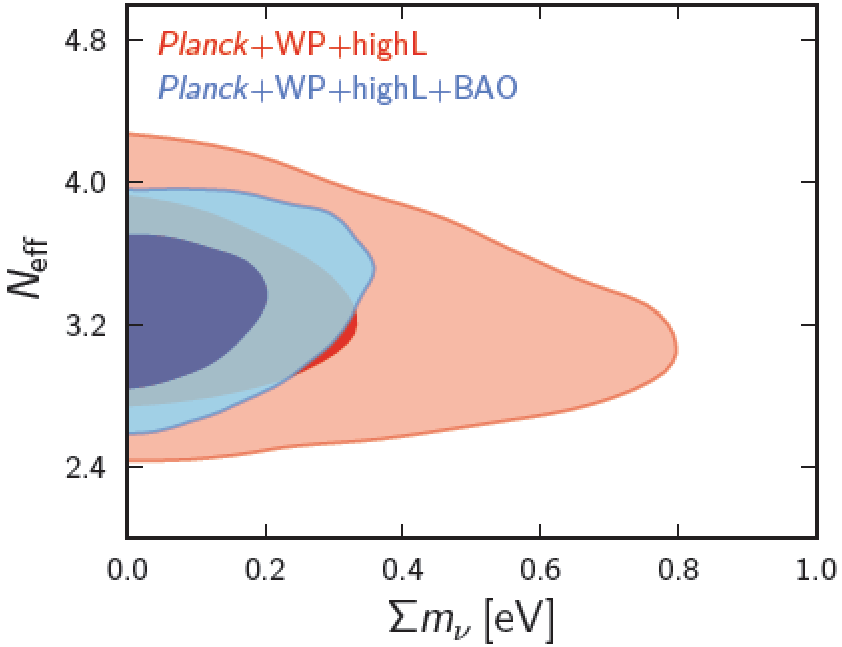
Blue:
Planck CMB+SZ+BAO
(1-b)=[0.7,1]

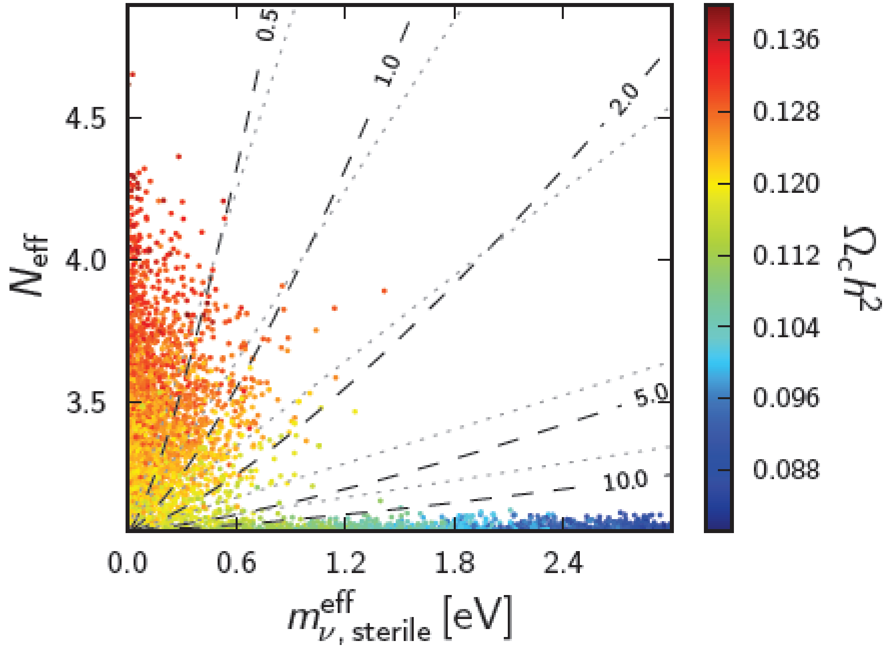
- Cosmological parameters as σ_8 and Ω_m derived from Planck SZ clusters number counts are in strong tension with the parameters derived from CMB TT measurements.
- Massive neutrinos could solve the tension.
- Cluster counts results are however affected by a bias b between the X-ray determined mass and the true mass. Assuming a flat prior of [0.7,1] on (1-b) we have from Planck+BAO+SZ (68% c.l):

$$\sum m_\nu = (0.22 \pm 0.09)\,\mathrm{eV}.$$

- Agreement could also be obtained by assuming (1-b)=0.55, a bias that is difficult to reconcile with numerical simulations and X-ray/weak lensing comparisons (see discussion in Paper XX).

Constraints on Neutrino masses (sterile neutrinos)





- No correlation between Neff and the mass of the 3 **active** massive neutrinos.
- Considering one massive sterile neutrino with energy density given by Neff when is relativistic and meff when is not relativistic we get:

$$\left.\begin{array}{r} N_{\rm eff} < 3.91 \\ m^{\rm eff}_{\nu,\,\rm sterile} < 0.59\,{\rm eV} \end{array}\right\} \quad (95\%;\ {\rm CMB\ for\ } m^{\rm thermal}_{\rm sterile} < 10\,{\rm eV})$$

That is marginally compatible with a fourth, fully thermalized, neutrino.

Conclusions

- Planck data alone provides **no evidence** for extra relativistic particles at recombination. N_{eff} is consistent with 3.046, i.e. the expected value in the standard 3 active neutrino framework. However also a fourth neutrino **is not** significantly ruled out from Planck data alone.

- When highL and BAO data are included we obtain Neff=3.28 ± 0.3 at 68% c.l.., excluding a fourth, massless, neutrino at about 95% c.l..

- The Planck-HST tension on the Hubble constant is alleviated when variations in N_{eff} are considered. An agreement between Planck and HST on the Hubble parameter can be achieved at the expenses of a dark radiation component with $N_{eff}=3.52 \pm 0.48$ at 95% c.l.

- Planck significantly improves current bounds on neutrino masses. Tension with SZ clusters number counts can be removed with a neutrino mass.

- Bounds on a fourth, massive, sterile neutrino are only marginally compatible with hints from oscillation experiments.

- All the results presented here are for **light** neutrinos at recombination. If the sterile neutrino has a mass larger than 10 eV then Planck can't exclude it (bounds from BBN).

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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ISTI

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Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.