Cosmology Results from Planck on Neutrinos

Alessandro Melchiorri
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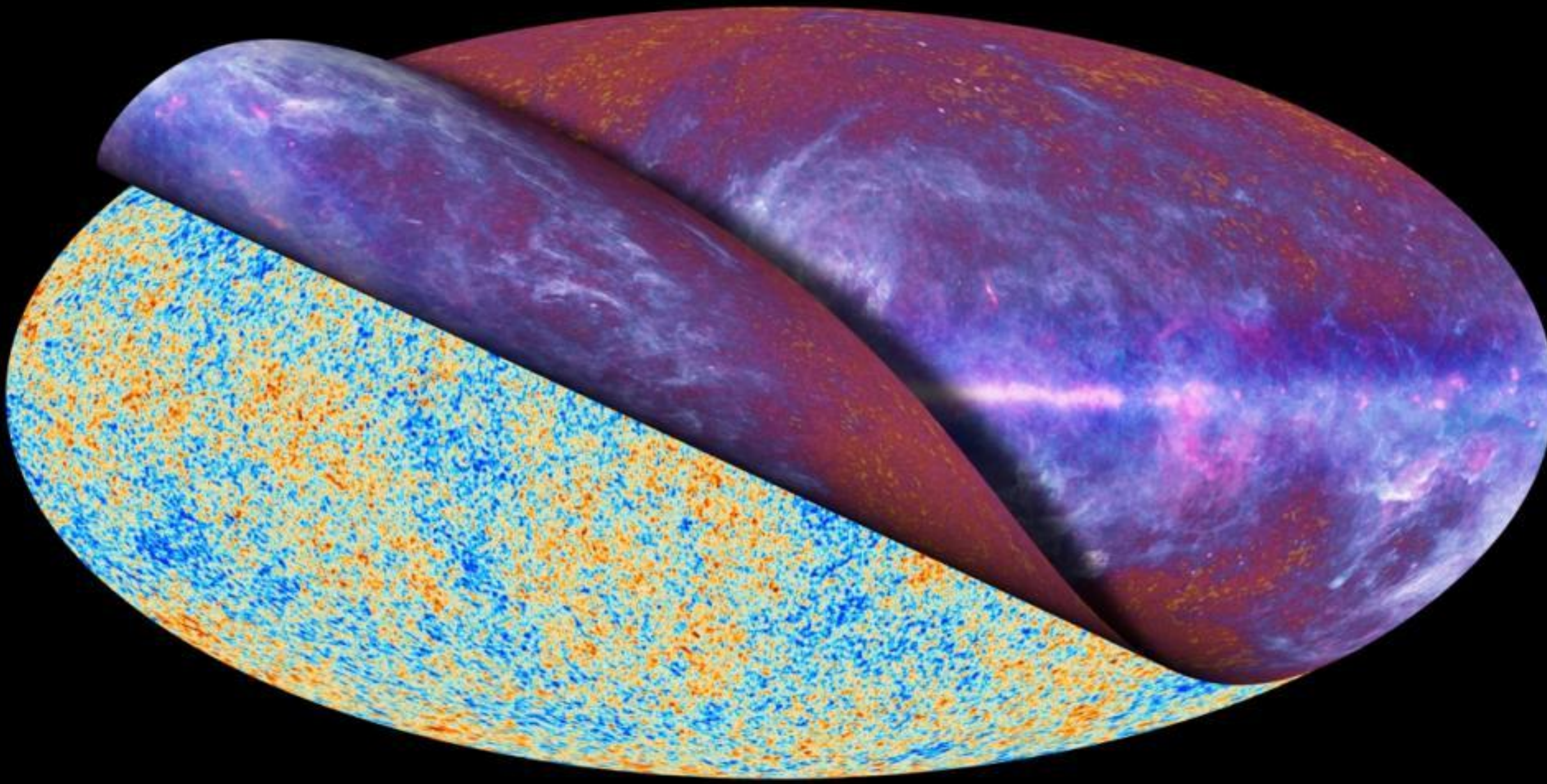
On behalf of the Planck collaboration



Planck unveils the Cosmic Microwave Background

Planck Collaboration 300+ names

Planck 2013 results. I. Overview of products and scientific results

Planck Collaboration: P. A. R. Ade[93], N. Aghanim[65], C. Armitage-Caplan[99], M. Arnaud[79], M. Ashdown[76,6], F. Atrio-Barandela[20], J. Aumont[65], C. Baccigalupi[92], A. J. Banday[103,11], R. B. Barreiro[72], M. Bartelmann[102,84], J. G. Bartlett[1,74], E. Battaner[105], K. Benabed[66,101], A. Benoît[63], A. Benoit-Lévy[27,66,101], J.-P. Bernard[11], M. Bersanelli[37,55], P. Bielewicz[103,11,92], J. Bobin[79], J. J. Bock[74,12], A. Bonaldi[75], J. R. Bond[9], J. Borrill[15,96], F. R. Bouchet[66,101], F. Boulanger[65], J. W. Bowyer[61], M. Bridges[76,6,69], M. Bucher[1], C. Burigana[54,35], R. C. Butler[54], B. Cappellini[55], J.-F. Cardoso[80,1,66], R. Carr[43], M. Casale[43], A. Catalano[81,78], A. Challinor[69,76,13], A. Chamballu[79,17,65], R.-R. Chary[62], X. Chen[62], L.-Y Chiang[68], H. C. Chiang[29,7], P. R. Christensen[88,40], S. Church[98], D. L. Clements[61], S. Colombi[66,101], L. P. L. Colombo[26,74], F. Couchot[77], A. Coulais[78], B. P. Crill[74,89], A. 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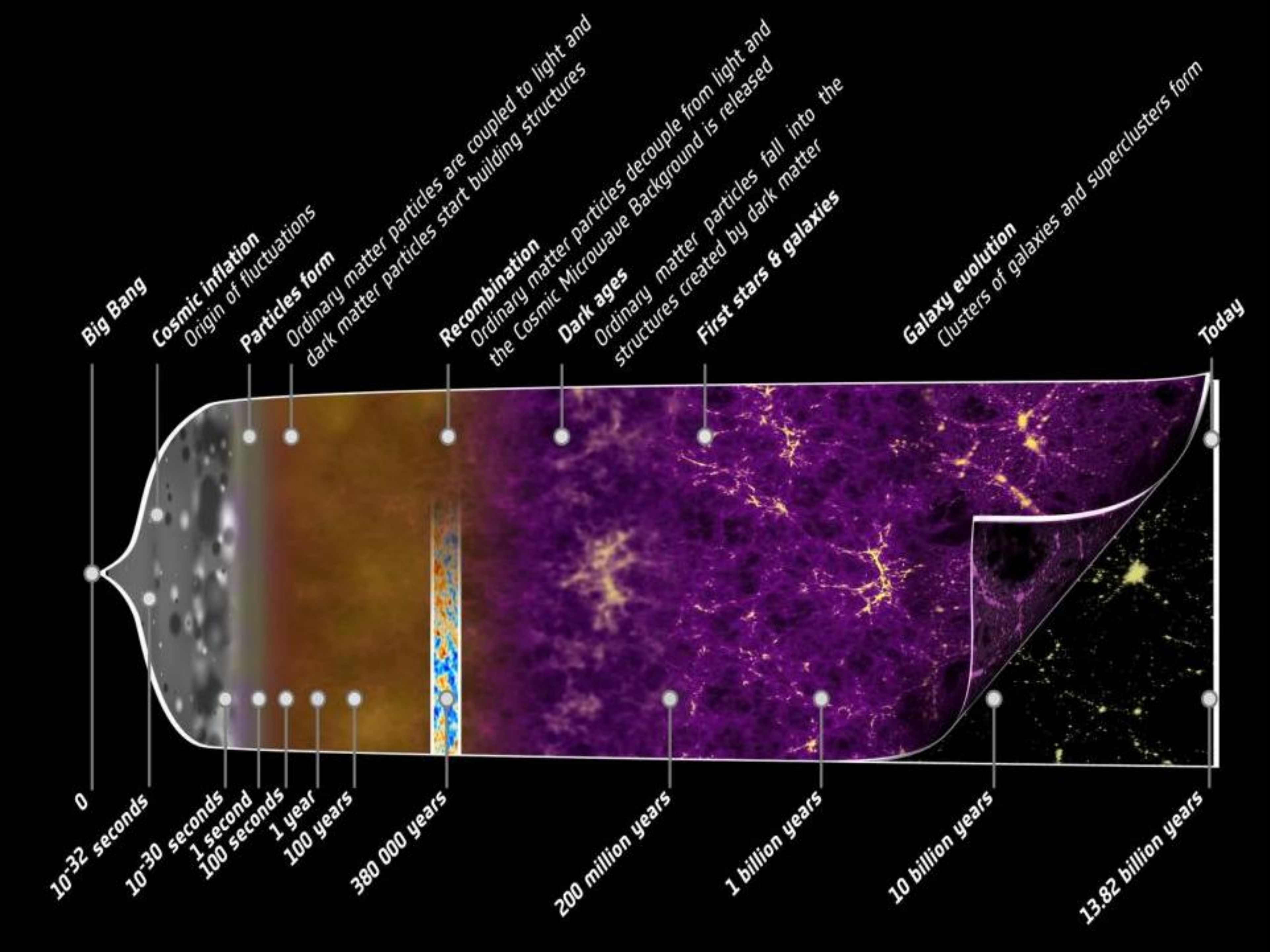
Planck Core-Team

(a fraction of it)

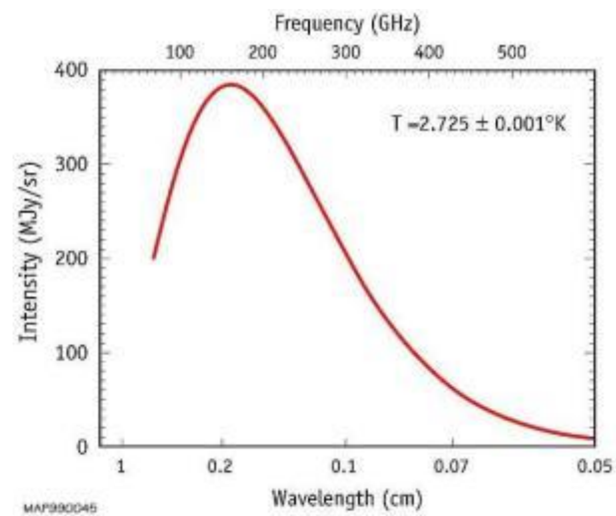

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

The Cosmic Microwave Background

Discovered By Penzias and Wilson in 1965.

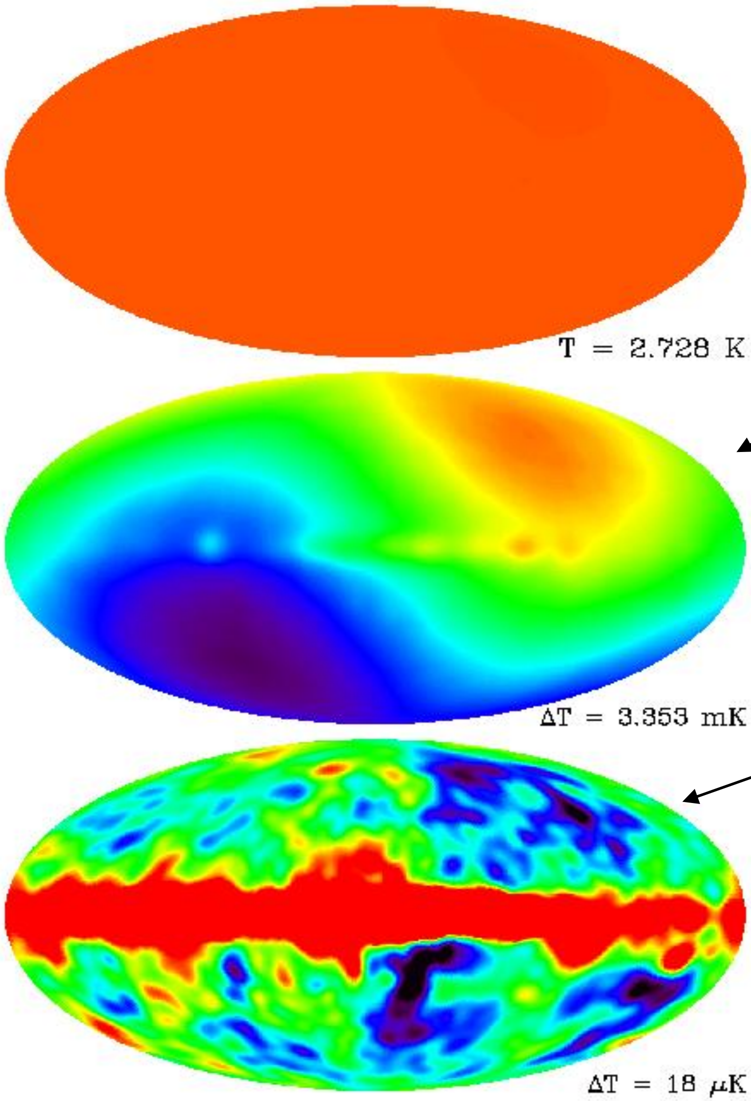
It is an image of the universe at the time of recombination (near baryon-photons decoupling), when the universe was just a few thousand years old (z~1000).

The CMB frequency spectrum is a perfect blackbody at T=2.73 K: this is an outstanding confirmation of the hot big bang model.



The Microwave Sky

COBE (circa 1995) @90GHz

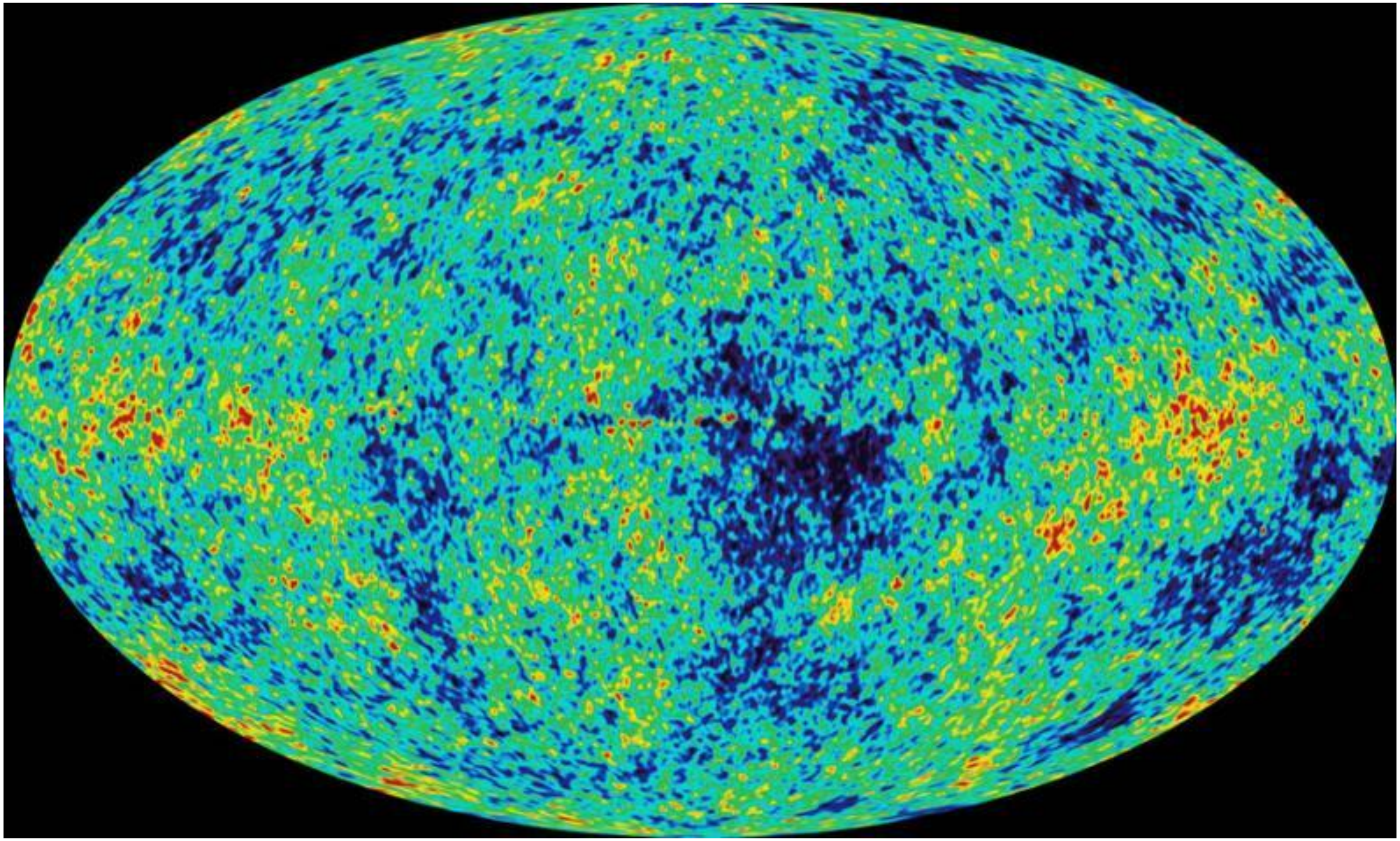


Uniform...

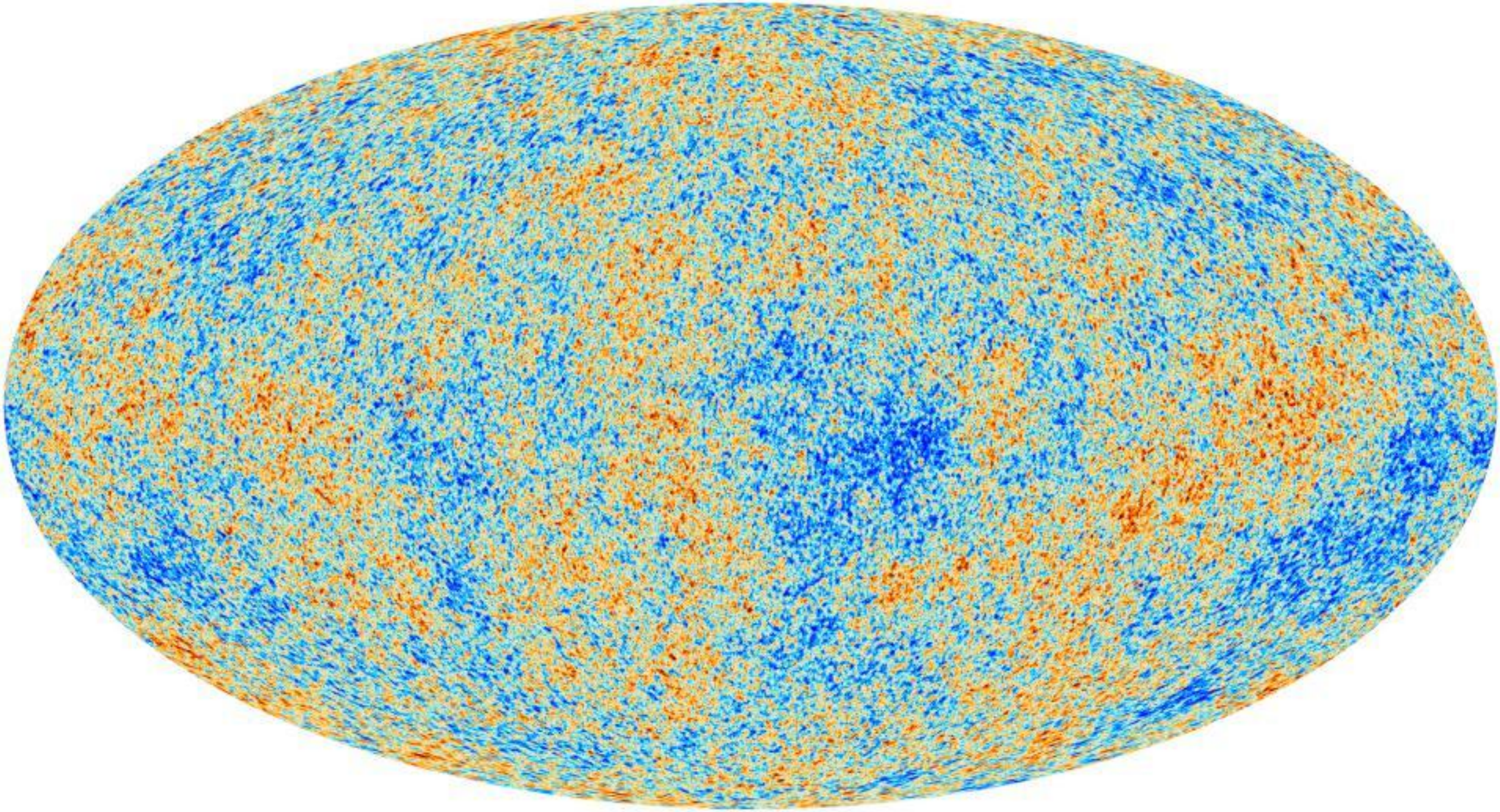
First Anisotropy we see is a Dipole anisotropy:
Implies solar-system barycenter has velocity v/c~0.00123 relative to 'rest-frame' of CMB.

If we remove the Dipole anisotropy and the Galactic emission, we see anisotropies at the level of $(\Delta T/T)_{rms}$~ 20 μK (smoothed on ~7° scale).
These anisotropies are the imprint left by primordial tiny density inhomogeneities (z~1000)..

Best Full Sky Map of the CMB before Planck: WMAP satellite (2002-2010)
(linear combination of 30,60 and 90 GHz channels)



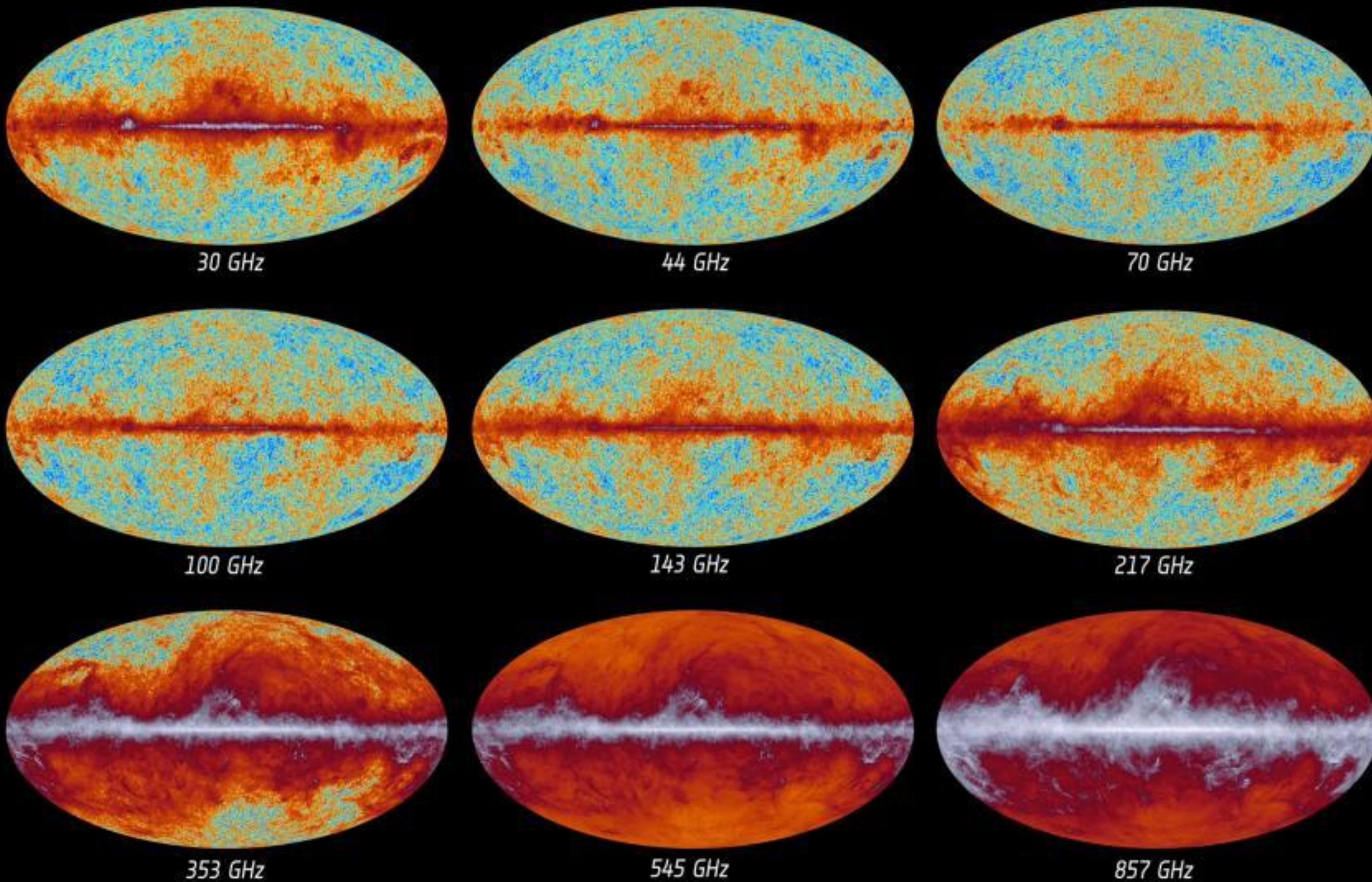
Planck 2013 CMB Map



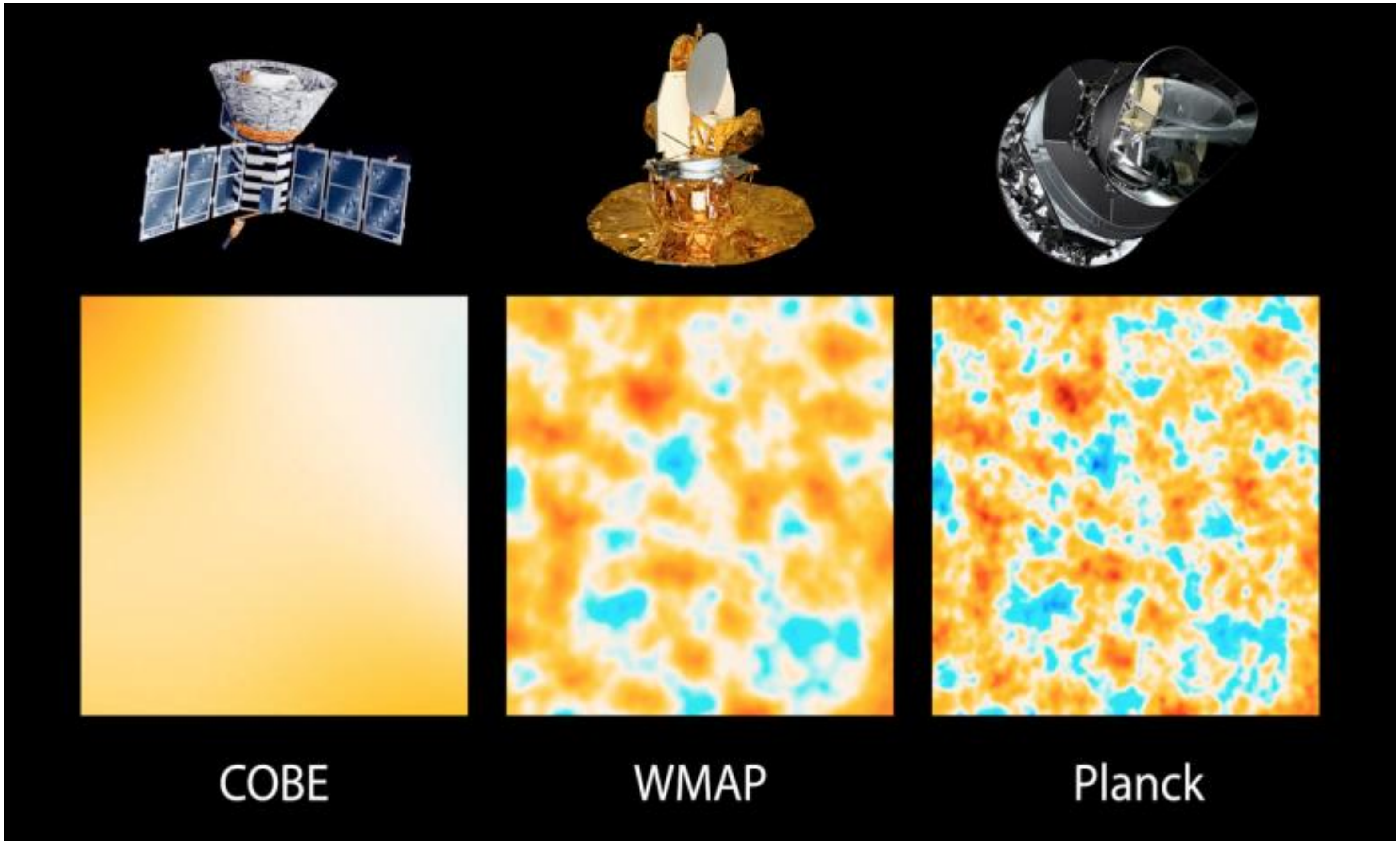
planck

The sky as seen by Planck

esa



Comparison with COBE and WMAP

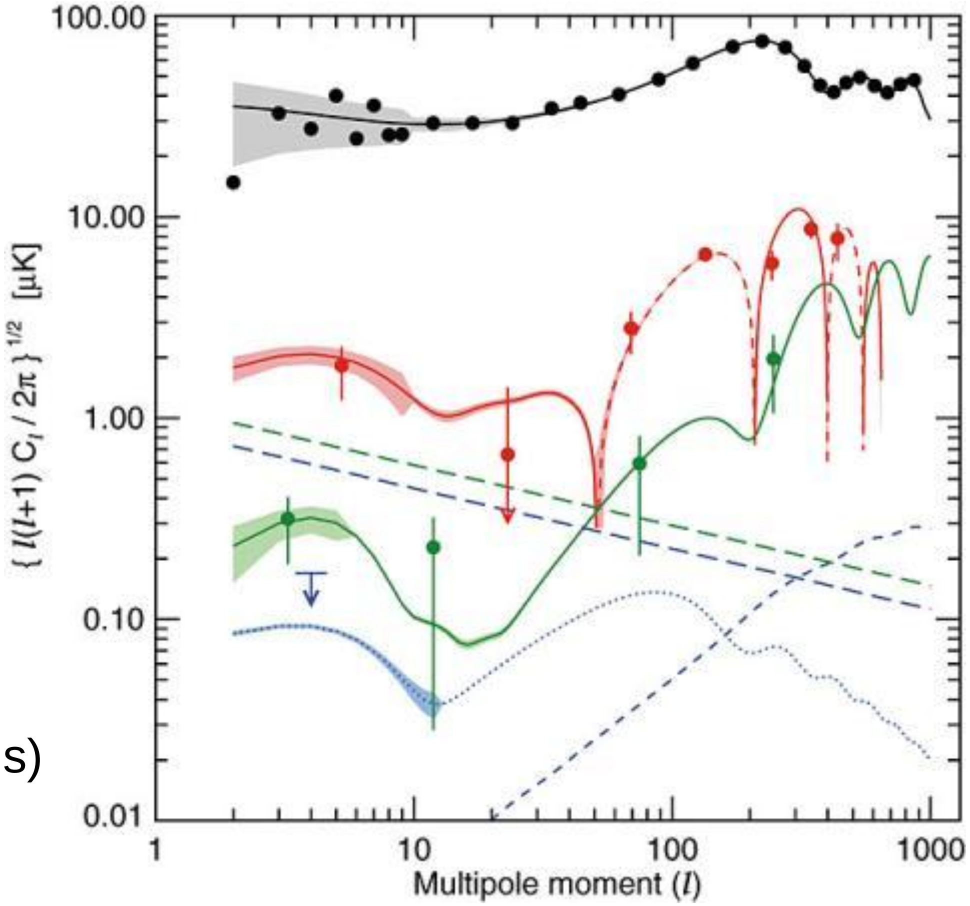


The CMB Angular Power Spectrum

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

R.m.s. of $\Delta T / T$ has $l(l+1)C_l / 2\pi$ power per decade in l:

$$\left\langle (\Delta T / T)^2 \right\rangle_{rms} = \sum_l \frac{(2l+1)}{4\pi} C_l \approx \int \frac{l(l+1)}{2\pi} C_l \, d\ln l$$

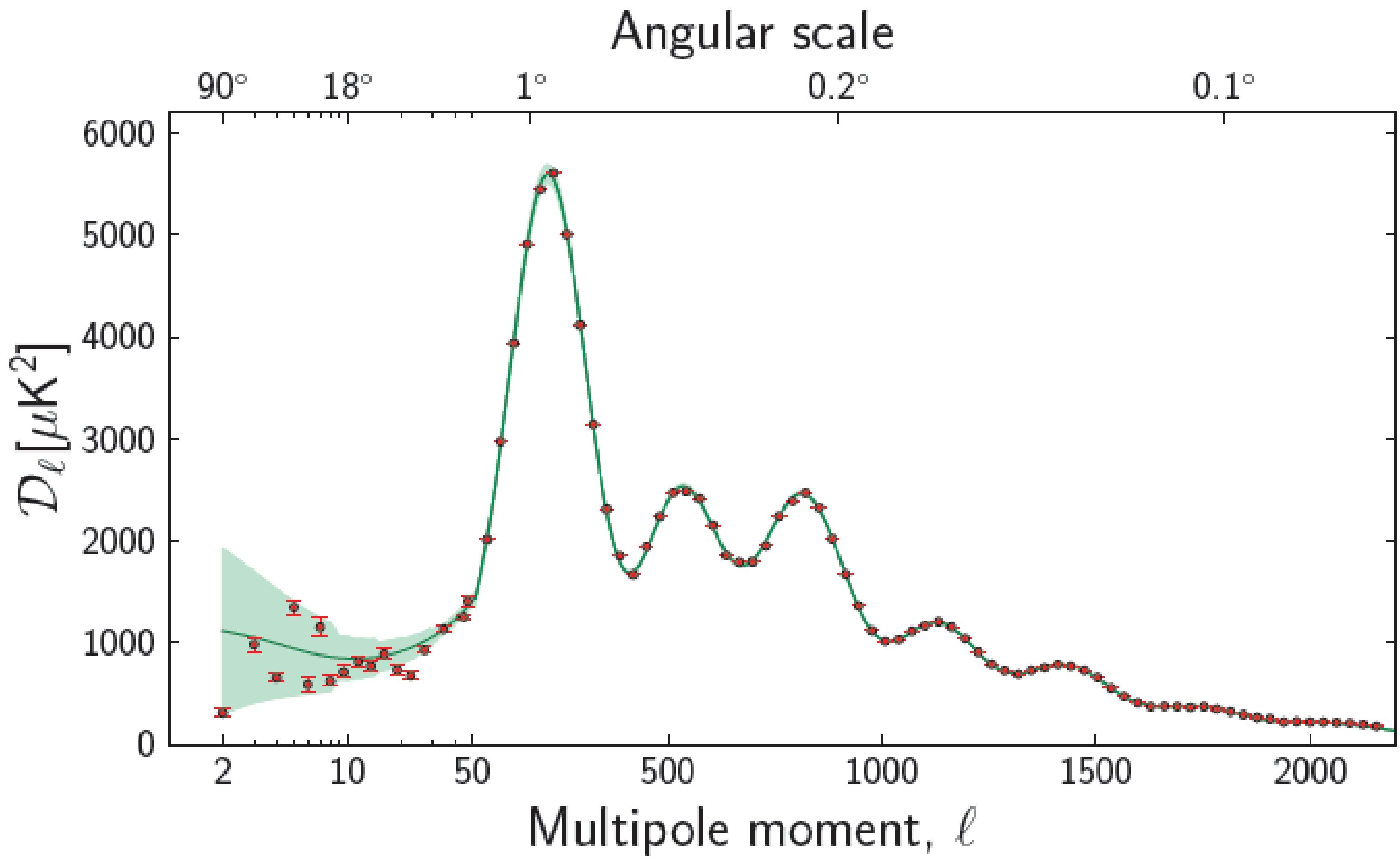


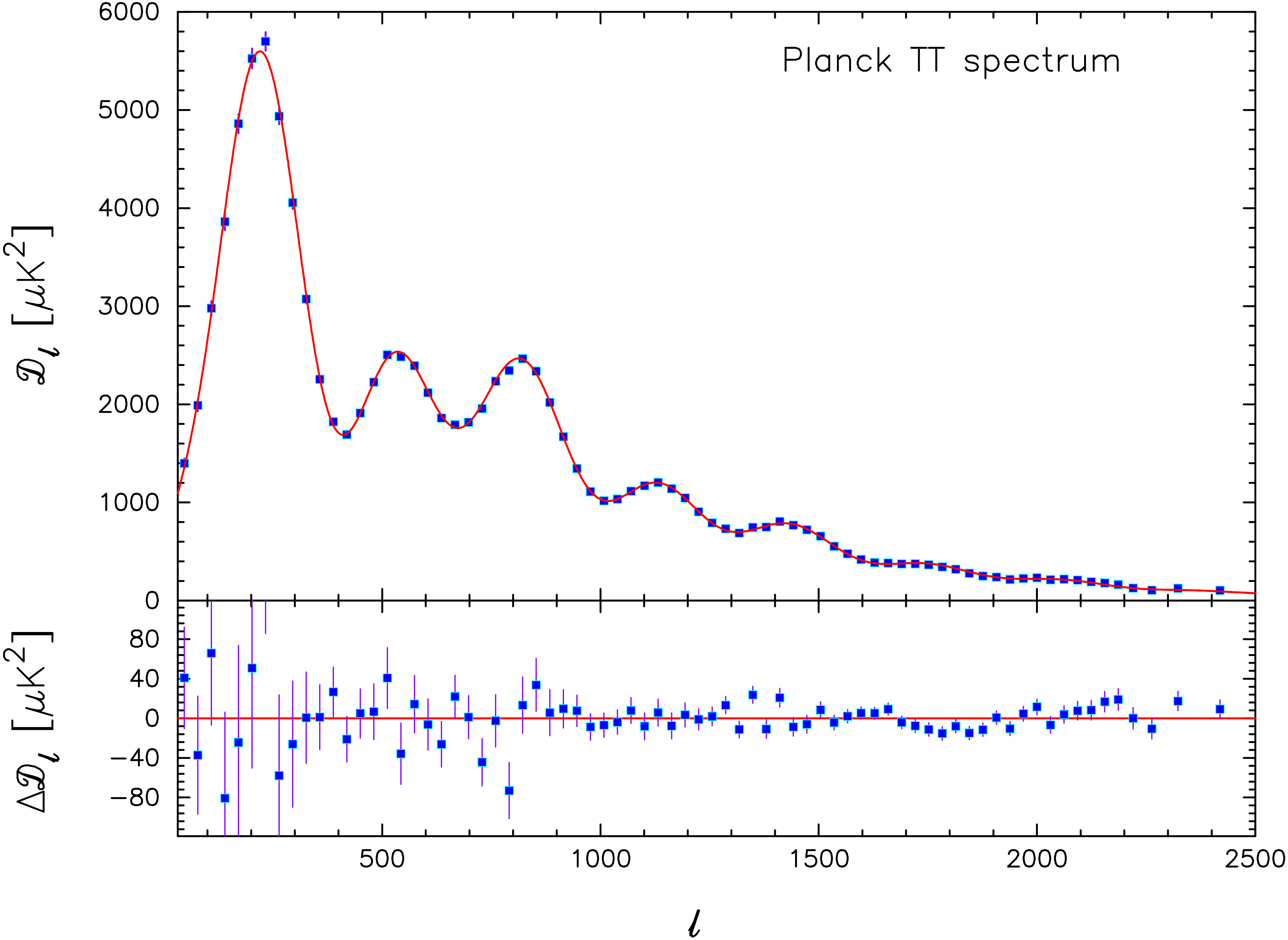
We can extract 4 independent angular spectra from the CMB:

- Temperature
- Cross Temperature Polarization
- Polarization type E (density fluctuations)
- Polarization type B (gravity waves)

Planck 2013 release is only temperature ps.

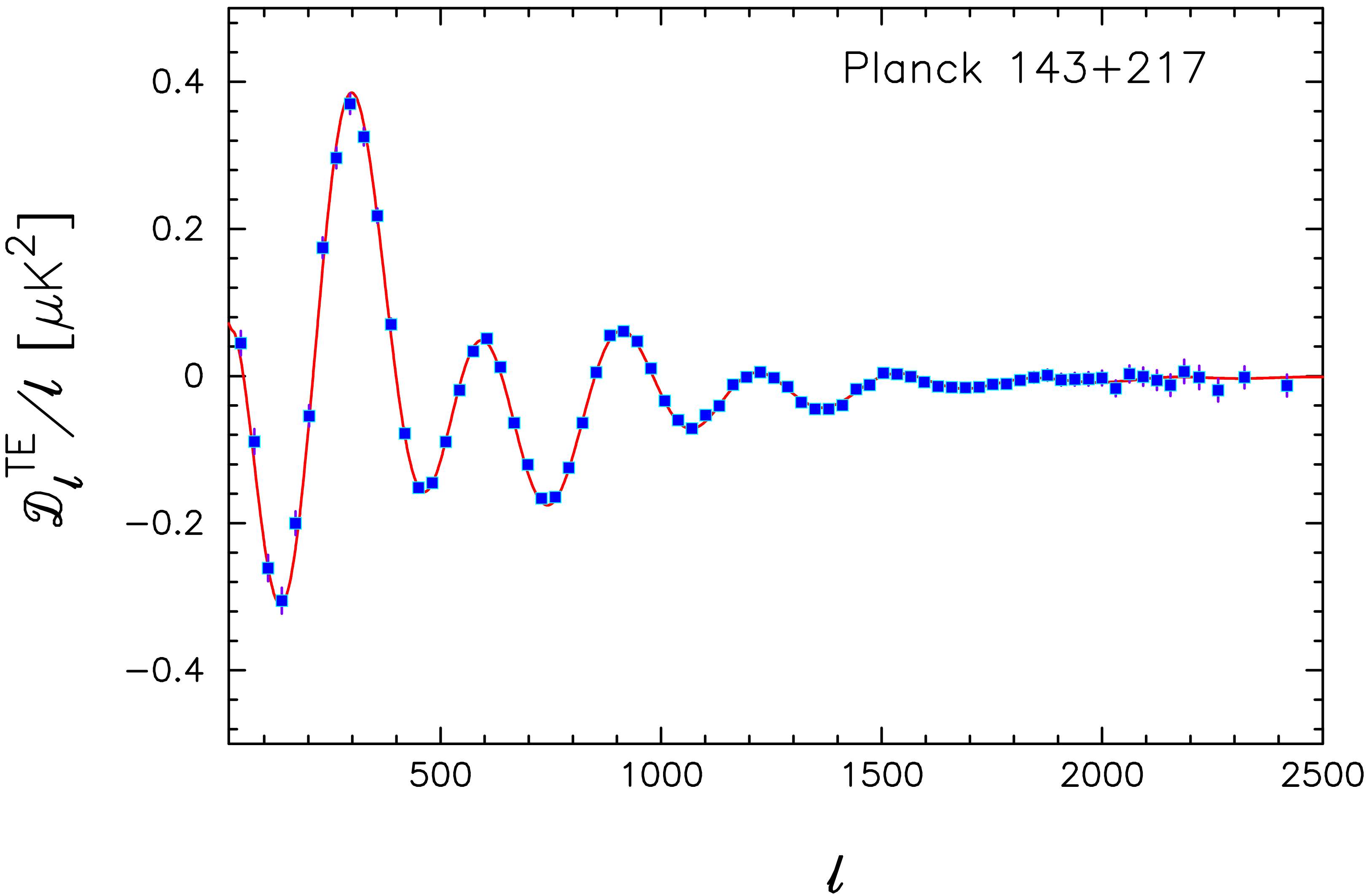
Planck 2013 TT angular spectrum





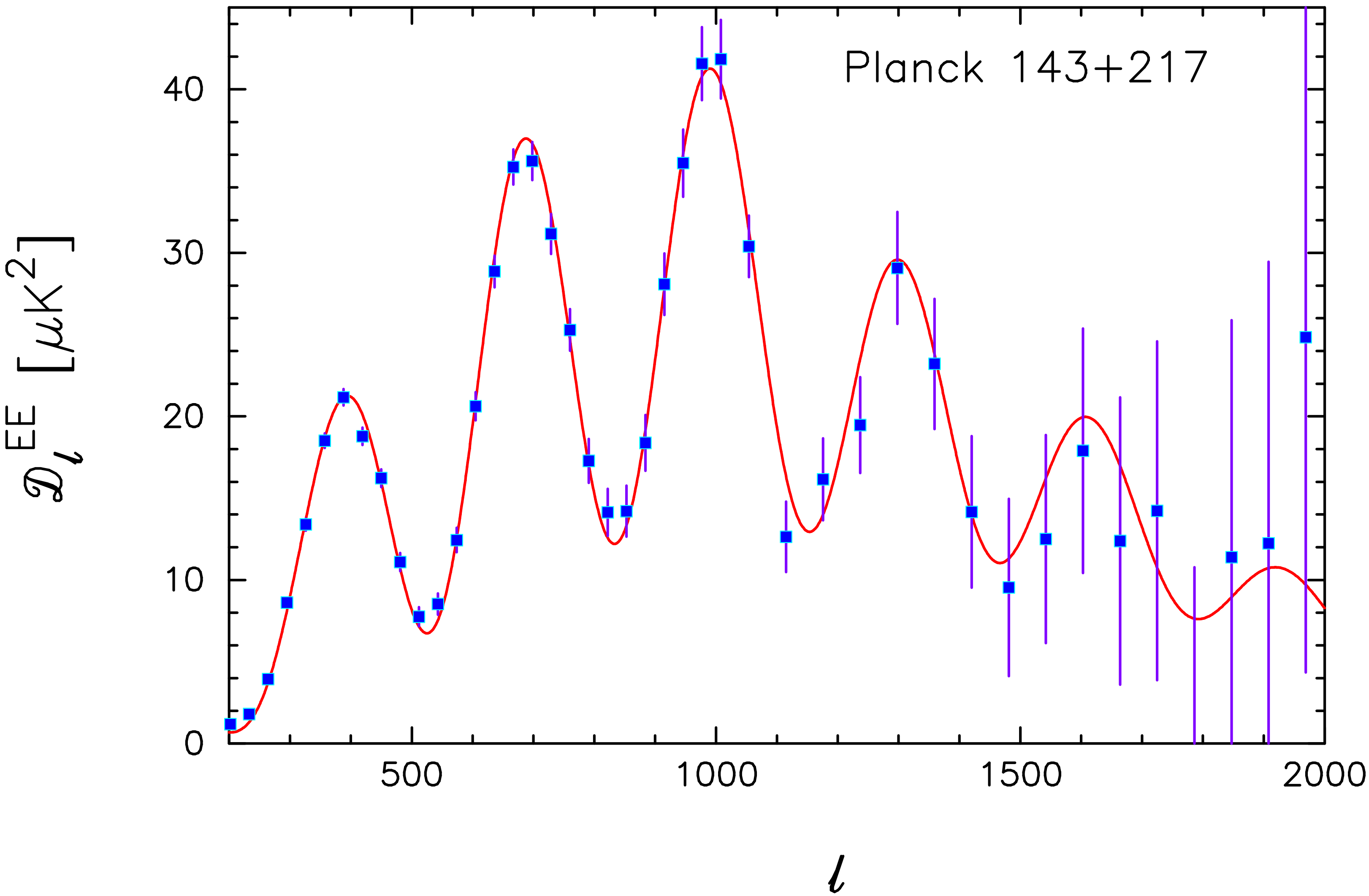
Planck TT spectrum
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
2500
$\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ

Cross Temperature-Polarization spectrum
(not present in this release)



Red line: best fit model from the temperature angular spectrum !!!

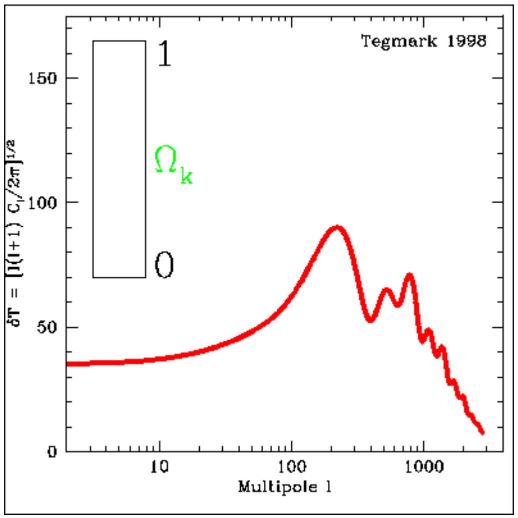
Polarization spectrum
(not present in this release)

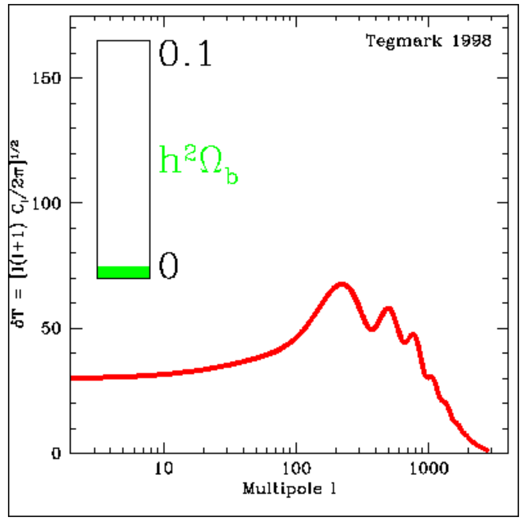


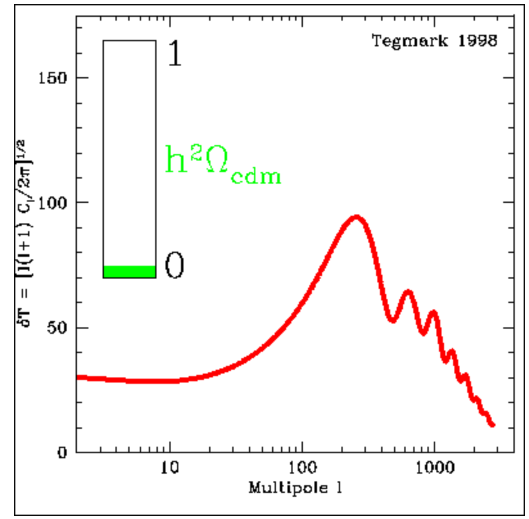
Red line: best fit model from the temperature angular spectrum !!!

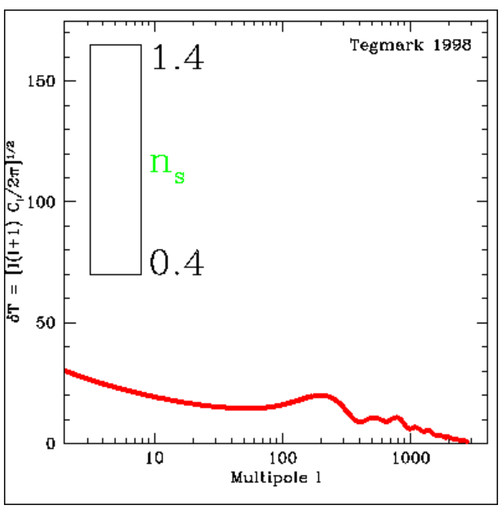
We can measure cosmological parameters with CMB !

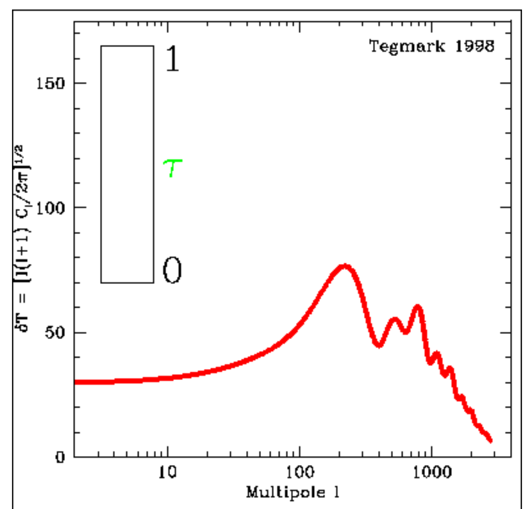
Temperature Angular spectrum varies with Ω_{tot} , Ω_b , Ω_c, Λ, τ, h, n_s, …





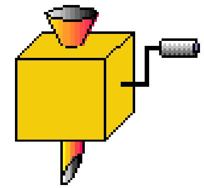


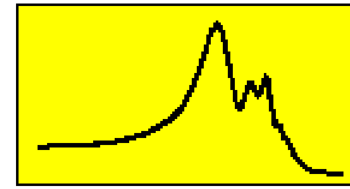


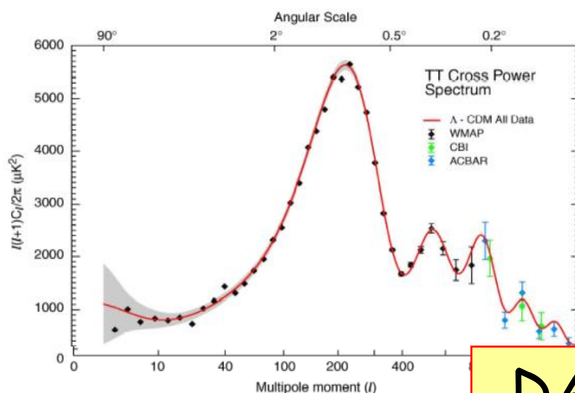


How to get a bound on a cosmological parameter

Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau , \Sigma m_\nu)$







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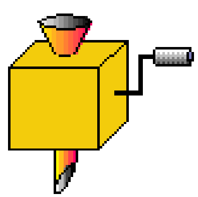
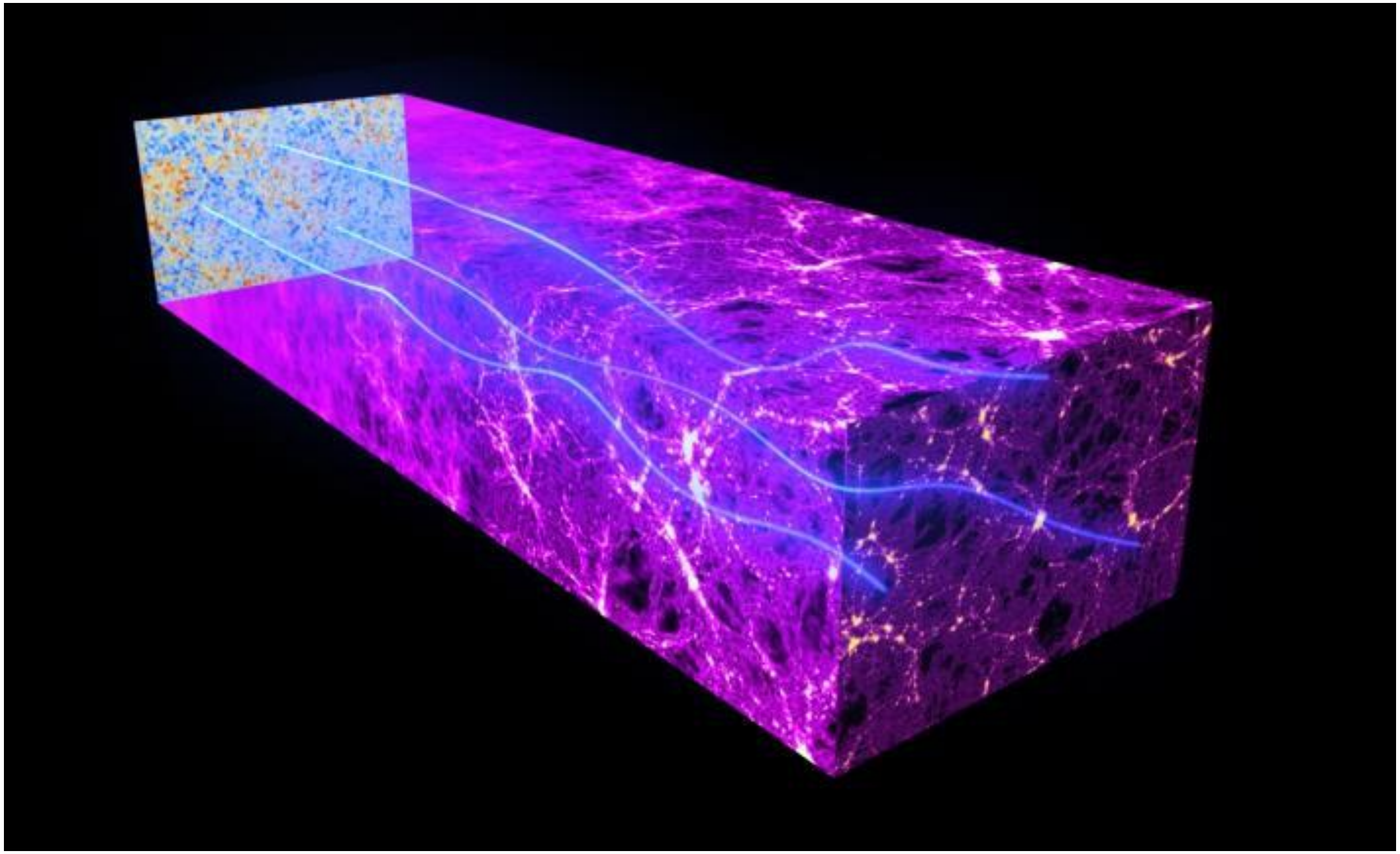


PARAMETER ESTIMATES

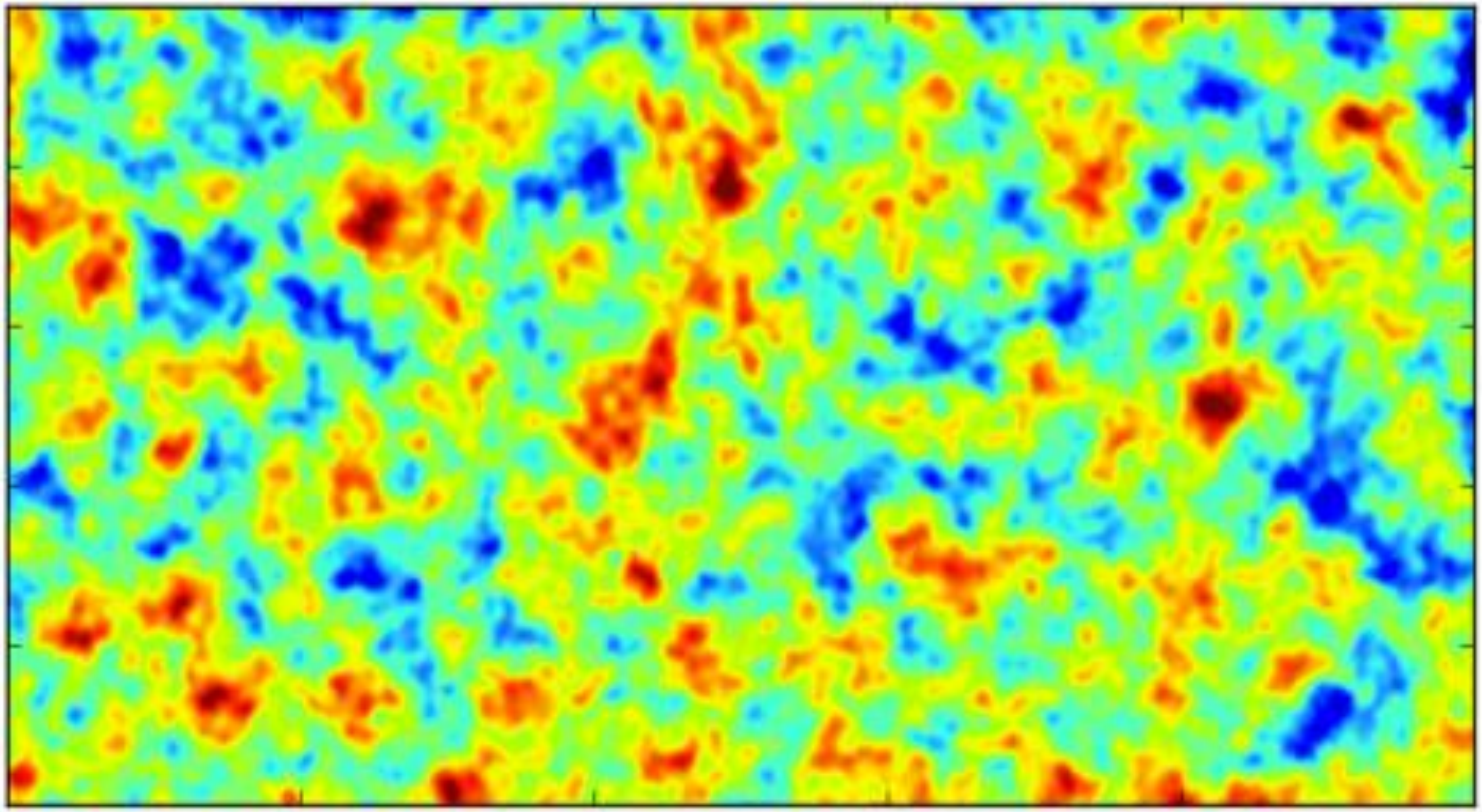
Gravitational Lensing

The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB



Gravitational Lensing

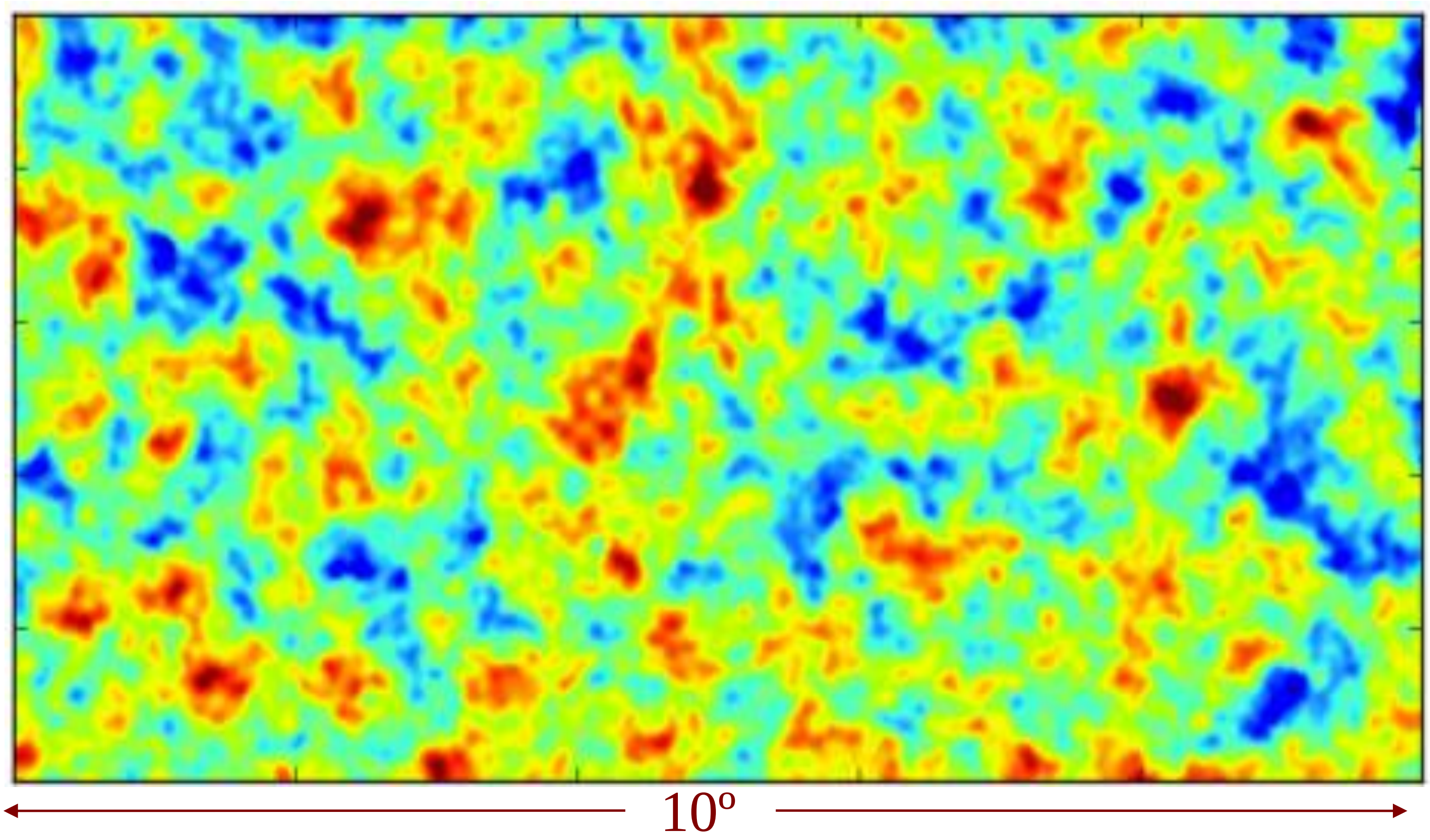
A simulated patch of CMB sky – **before lensing**



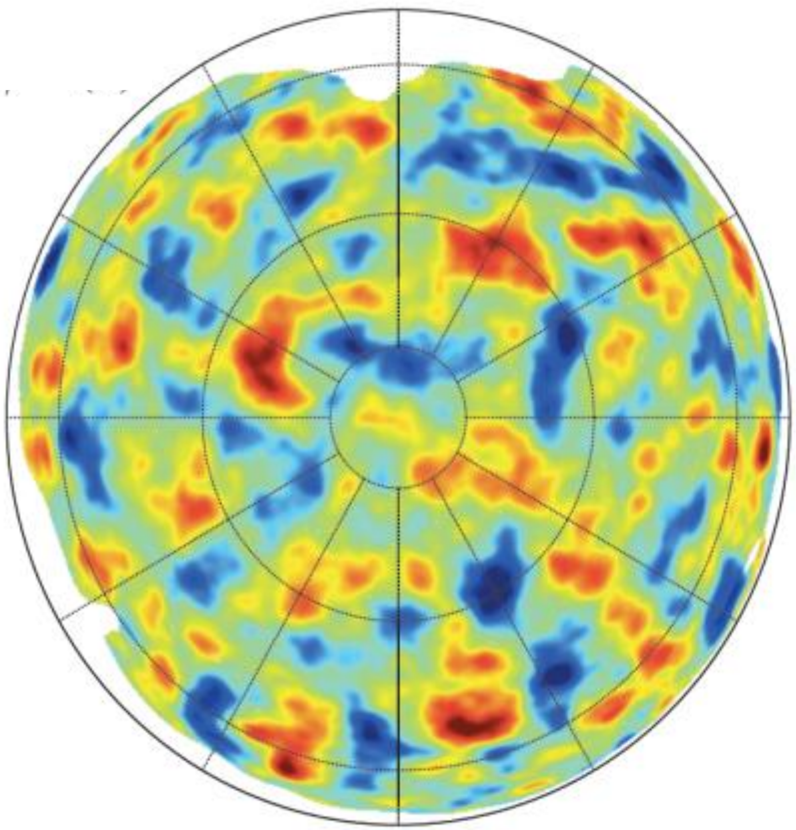
10°

Gravitational Lensing

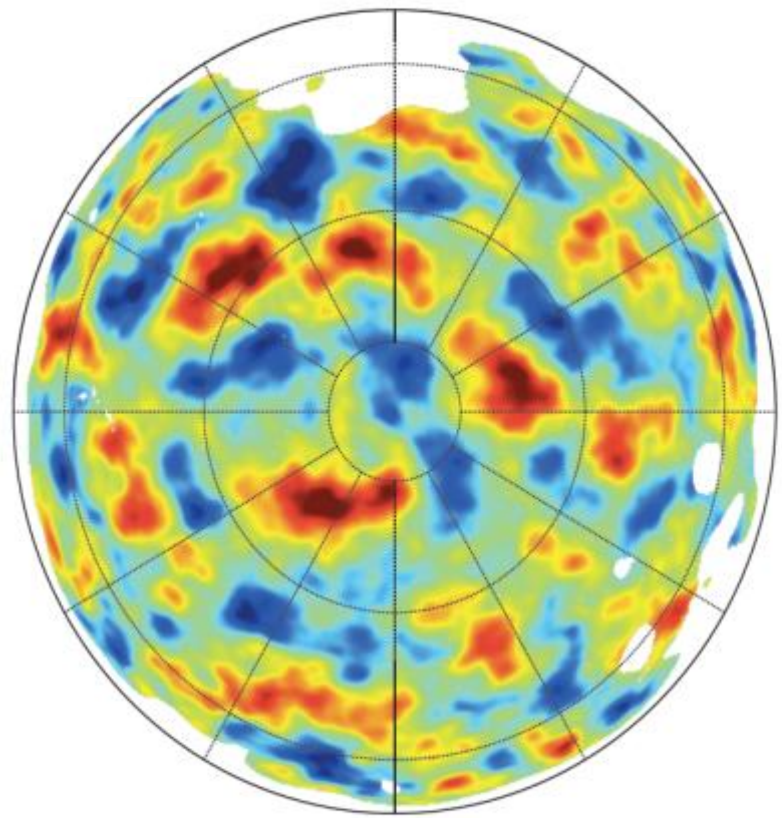
A simulated patch of CMB sky – **after lensing**



Planck dark matter distribution throught CMB lensing

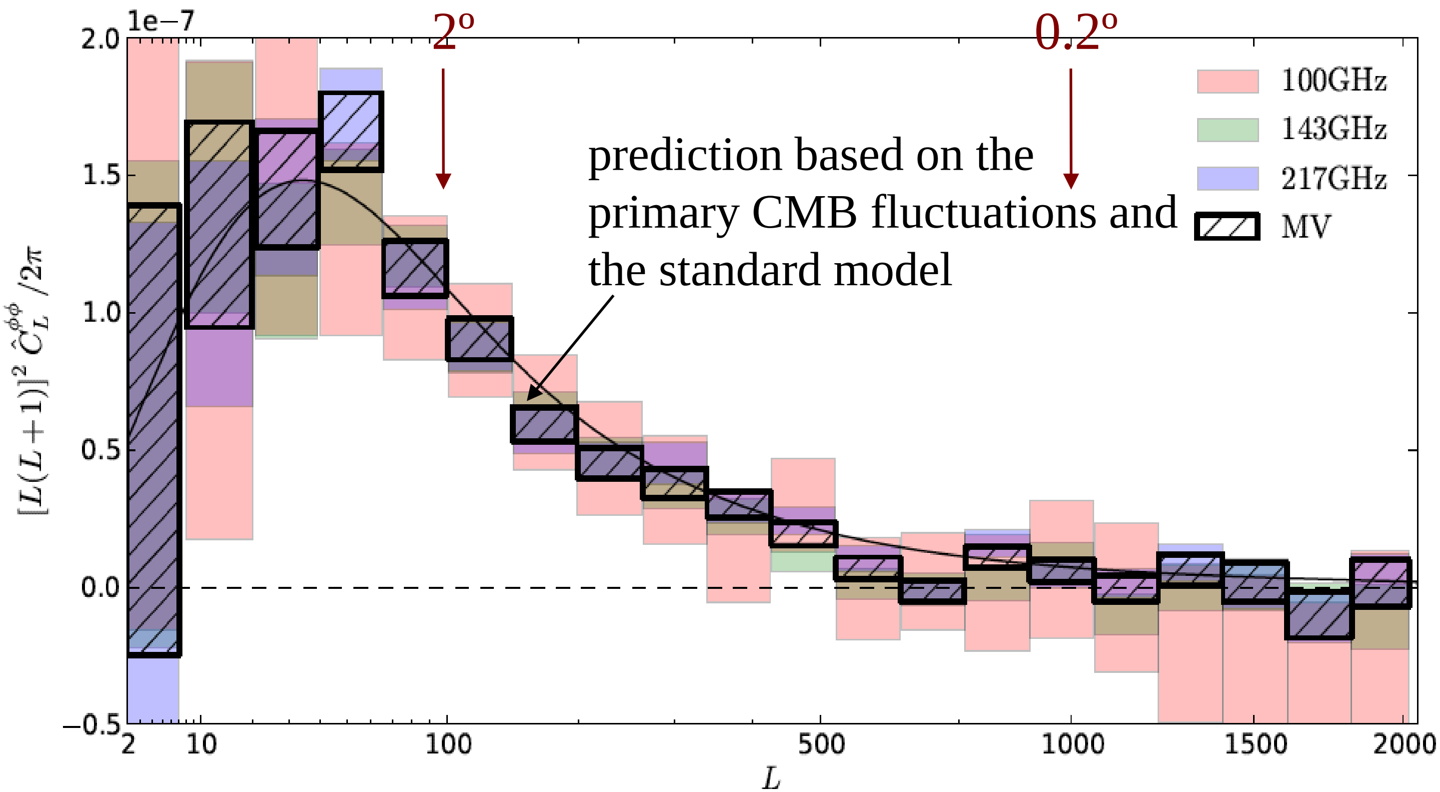


Galactic North



Galactic South

PLANCK LENSING POTENTIAL POWER SPECTRUM
Measured from the Trispectrum (4-point correlation)



It is a 25 sigma effect!!
This spectrum helps in constraining parameters

Constraints on LCDM

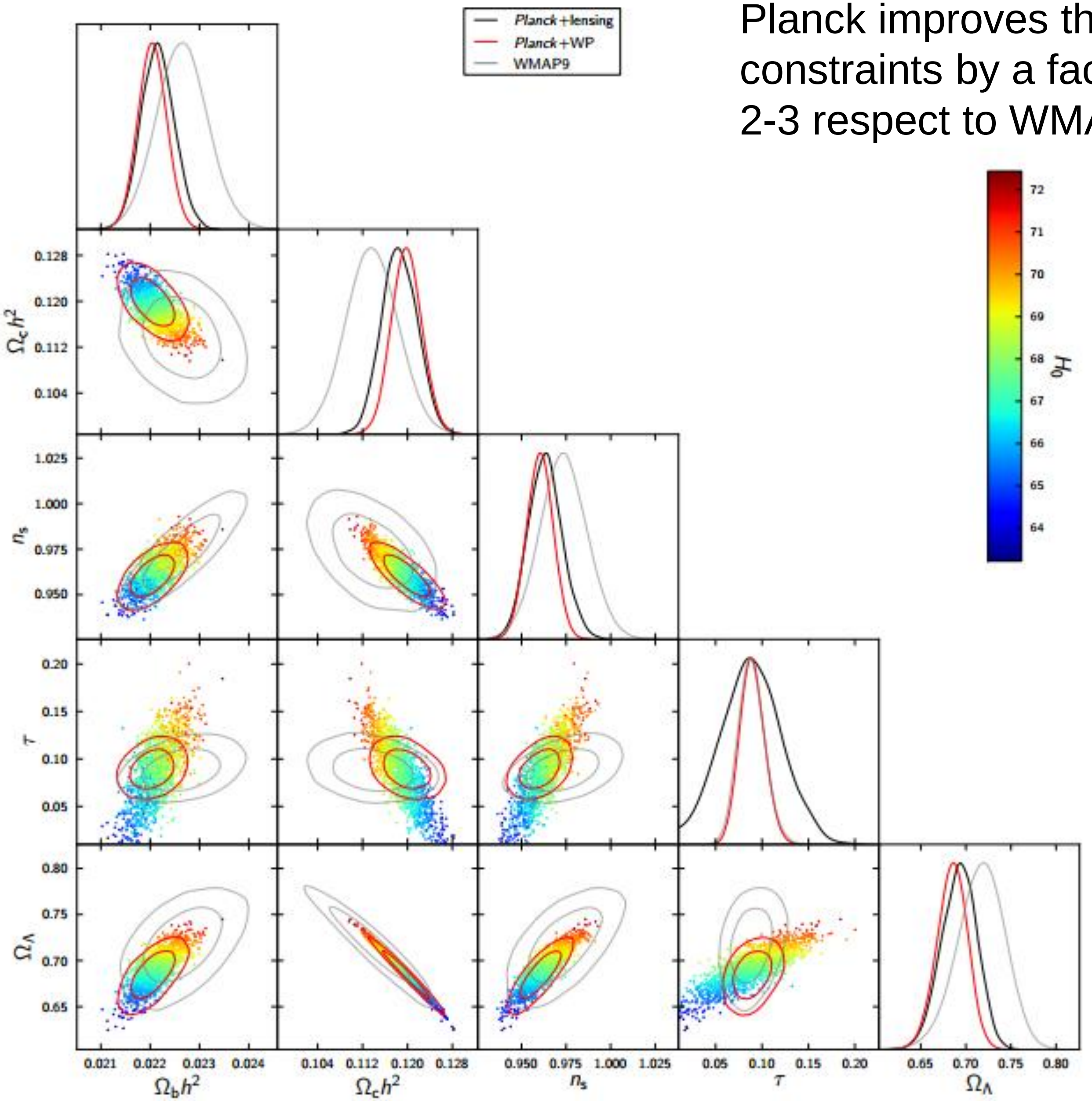
Planck improves the constraints by a factor 2-3 respect to WMAP9

Lower Baryon Density

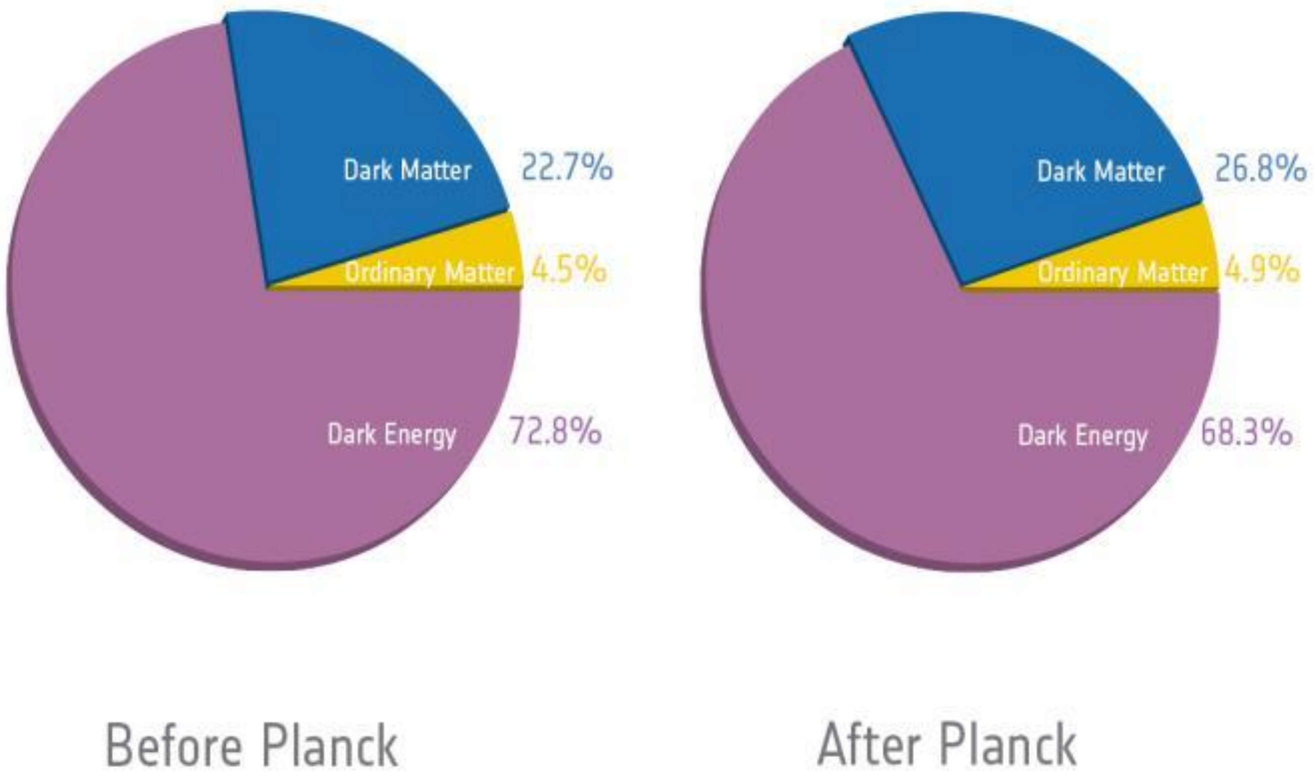
Higher CDM Density

Lower Spectral index

Smaller Cosmological Constant



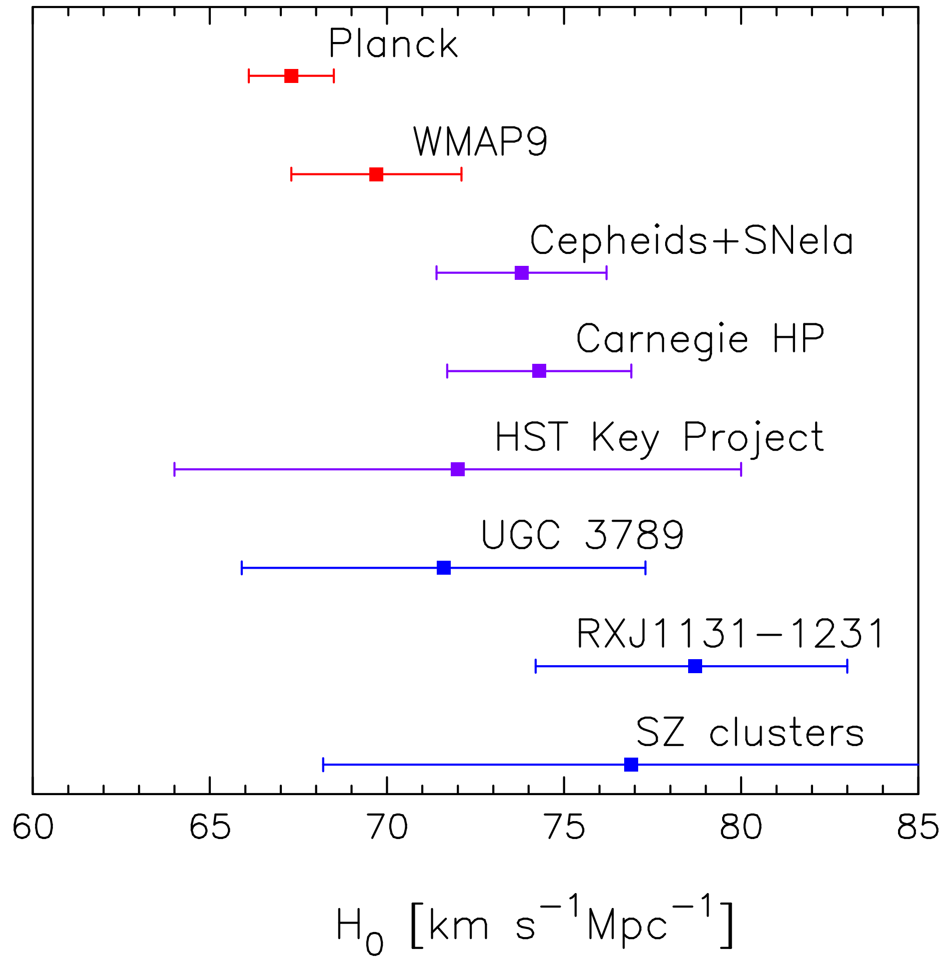
The basic content of the Universe



...has changed!

Comparison with other datasets: Hubble Constant

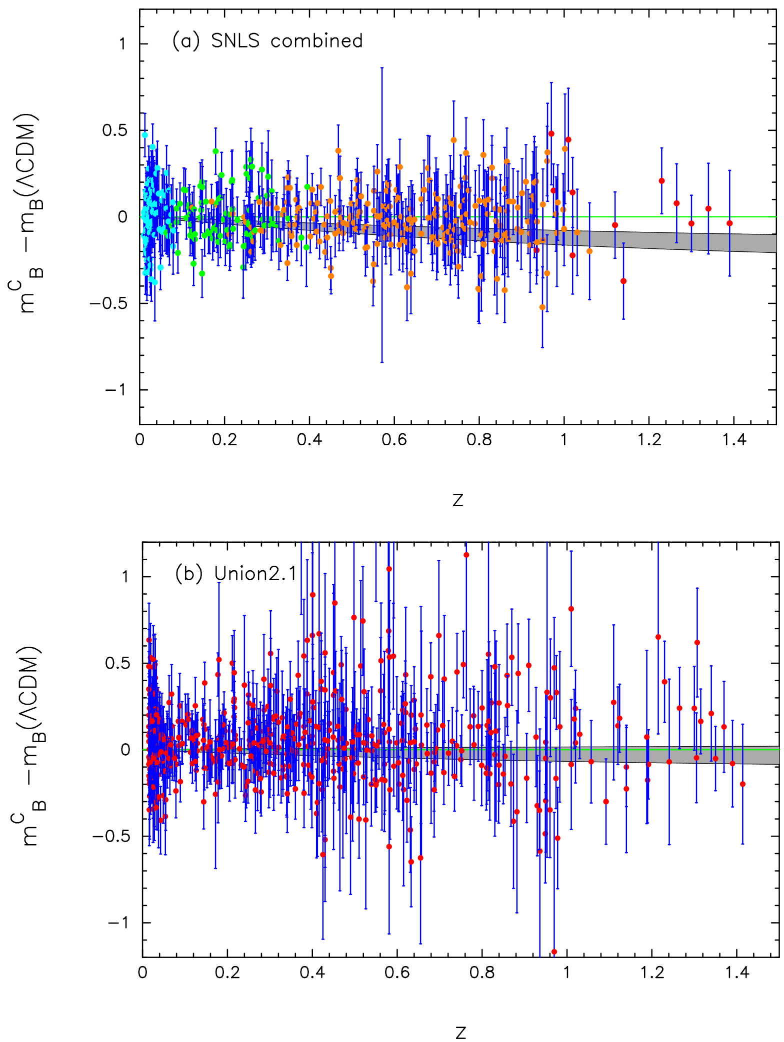
The value of the Hubble constant from Planck is in tension with the Riess et al. 2011 result.

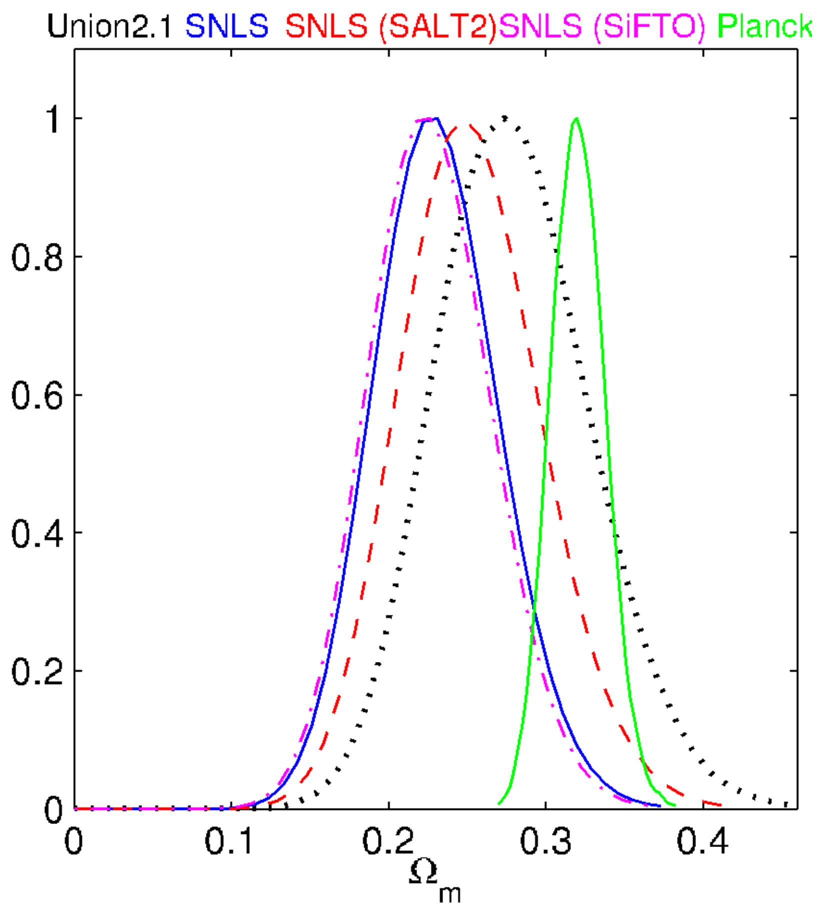


$$\text{Planck} + \text{WP} \qquad H_0 = 67.3^{+1.2}_{-1.1}\ [\text{km/s/Mpc}]$$

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

Comparison with SN-Ia data



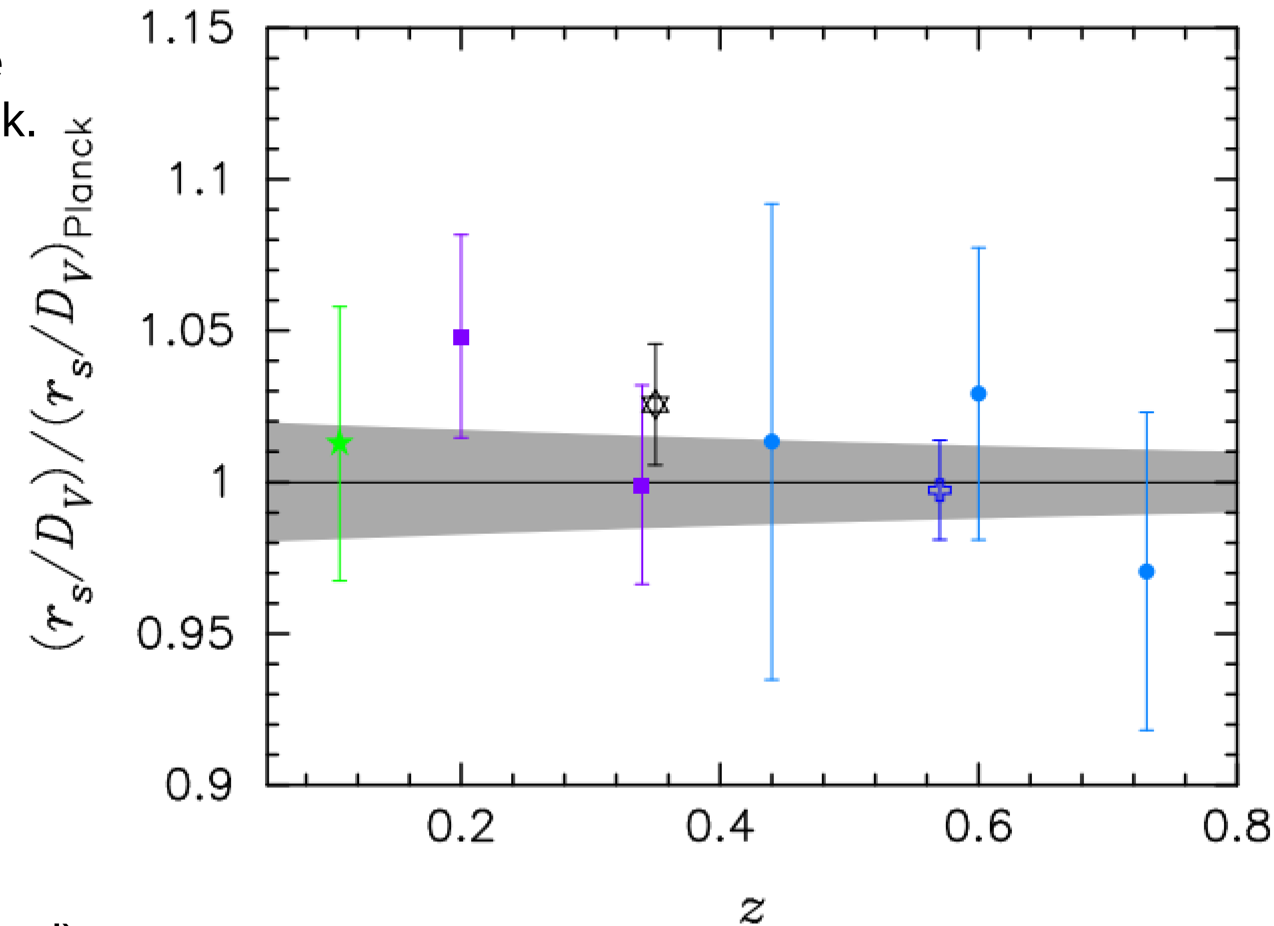


The value for the matter density inferred from SNLS survey is smaller than what observed with Planck assuming a flat universe.
Better agreement with the Union2 catalog.

Comparison with BAO surveys

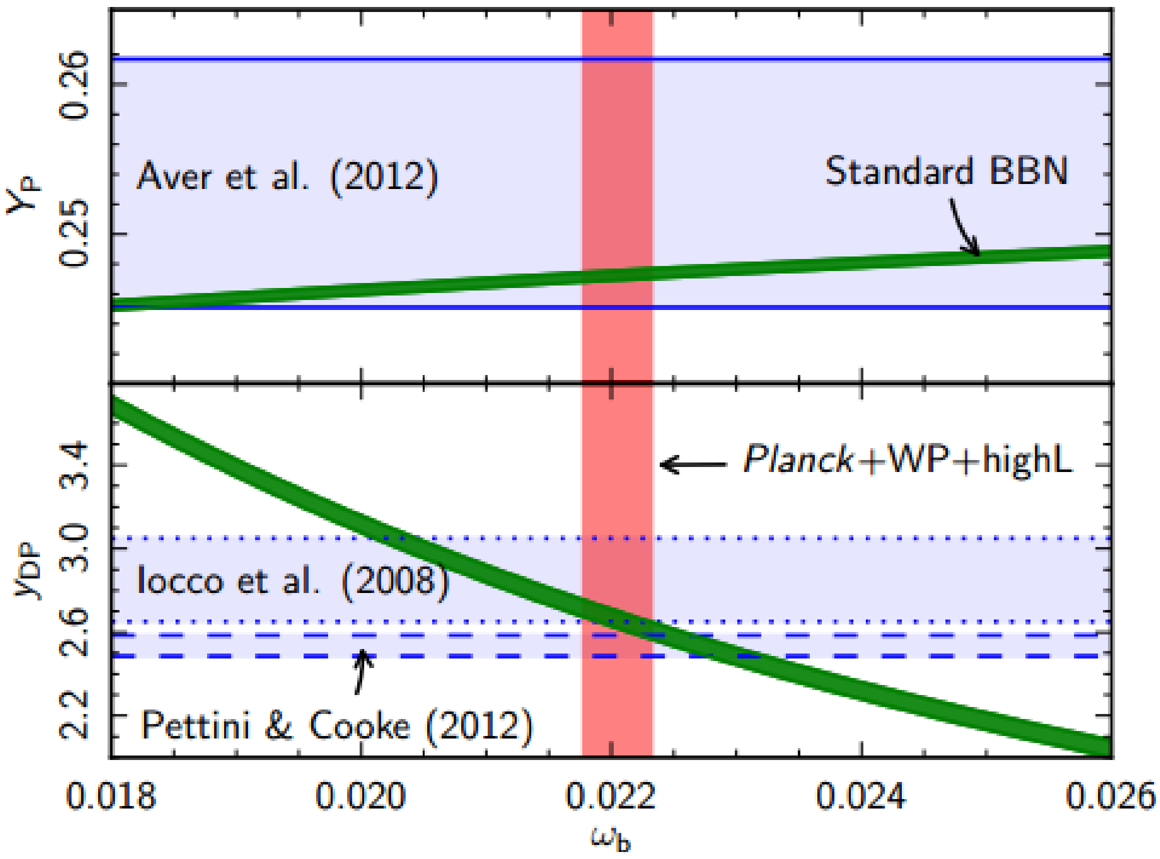
Acoustic scale – Distance ratio from BAO and Planck. Planck uncertainties are in grey.

Very good agreement with BAO surveys and Planck data in the LCDM framework.



Green: 6df
Purple: SDSS DR7 (Percival)
Black: DR7 (Padmanabhan)
Dark Blue: BOSS
Light Blue: Wiggle-z

Comparison with BBN and primordial He and D



Very good agreement. Lower baryon density. Recent Pettini and Cooke D measurement maybe a bit too low for Planck (1 sigma tension).

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:

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

With a density of:

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

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

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

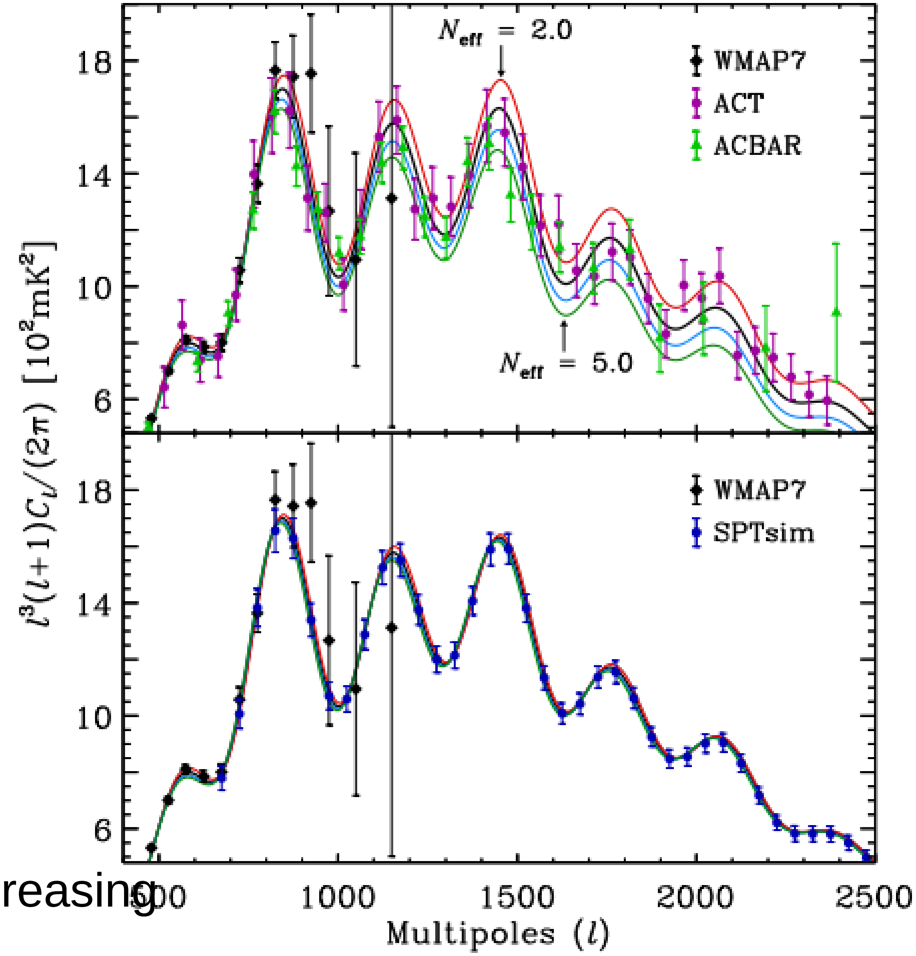
Standard Model predicts:

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

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_{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.)

$$\text{Planck alone (no pol.)} \qquad N_{eff}^{\nu} = 4.53^{+1.5}_{-1.4}$$

$$\text{Planck} + \text{WP} \qquad N_{eff}^{\nu} = 3.51^{+0.80}_{-0.74}$$

$$\text{Planck} + \text{WP} + \text{Lensing} \qquad N_{eff}^{\nu} = 3.39^{+0.77}_{-0.70}$$

$$\text{Planck} + \text{WP} + \text{highL} \qquad N_{eff}^{\nu} = 3.36^{+0.68}_{-0.64}$$

$$\text{Planck} + \text{WP} + \text{highL} + \text{Lensing} \qquad N_{eff}^{\nu} = 3.28^{+0.67}_{-0.64}$$

Conclusions:

- N_{eff}=0 is excluded at high significance (about 10 standard deviations). We need a neutr
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.)

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

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

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

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

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.

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	$1.00059^{+0.00078}_{-0.00078}$
$100\theta_{MC}$	1.04119	$1.0413^{+0.0012}_{-0.0012}$	c_{217}	0.99647	$0.9964^{+0.0027}_{-0.0027}$
τ	0.0925	$0.089^{+0.027}_{-0.024}$	$\xi^{tSZ-CIB}$	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^{PS}_{100}	152	171^{+100}_{-100}	Ω_Λ	0.6817	$0.685^{+0.031}_{-0.034}$
A^{PS}_{143}	63.3	54^{+30}_{-30}	Ω_m	0.3183	$0.315^{+0.034}_{-0.031}$
A^{PS}_{217}	117.0	107^{+30}_{-30}	σ_8	0.8347	$0.829^{+0.025}_{-0.024}$
A^{CIB}_{143}	0.0	—	z_{re}	11.37	$11.1^{+2.2}_{-2.2}$
A^{CIB}_{217}	27.2	29^{+20}_{-10}	H_0	67.04	$67.3^{+2.4}_{-2.3}$
A^{tSZ}_{143}	6.80	—	$10^9 A_s$	2.215	$2.20^{+0.11}_{-0.11}$
$r^{PS}_{143\times217}$	0.916	> 0.734	$\Omega_m h^2$	0.14305	$0.1426^{+0.0050}_{-0.0049}$
$r^{CIB}_{143\times217}$	0.406	< 0.796	$\Omega_m h^3$	0.09591	$0.0959^{+0.0011}_{-0.0011}$

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

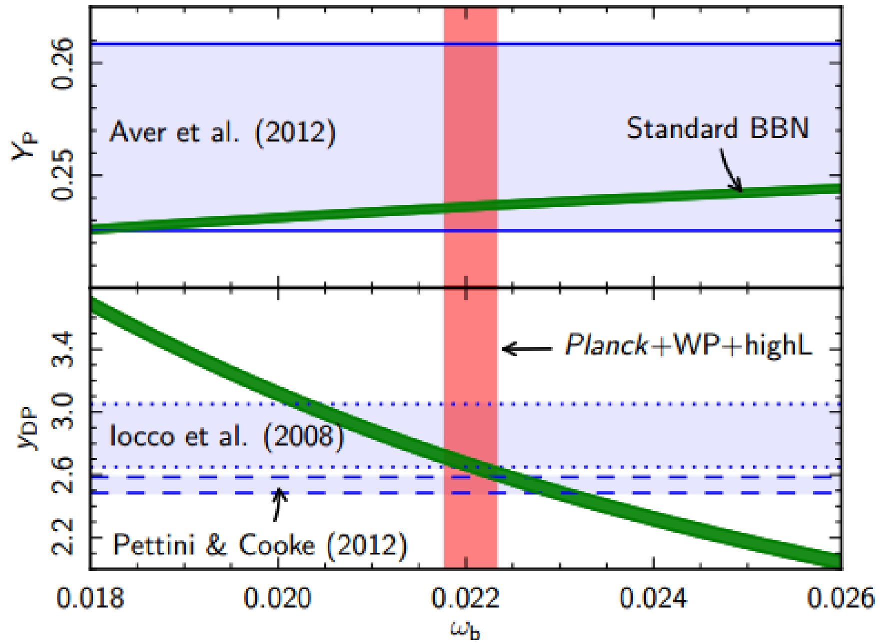
Planck+WP+HST

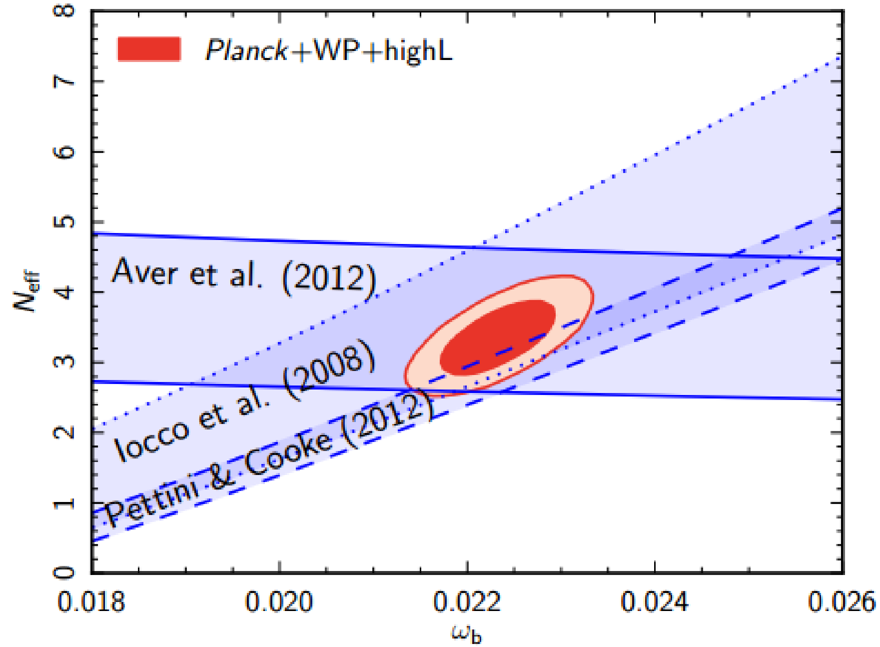
Parameter	Best fit	95% limits	Parameter	Best fit	95% limits
$\Omega_b h^2$	0.02240	$0.02261^{+0.00059}_{-0.00059}$	$r^{CIB}_{143\times217}$	0.669	$0.50^{+0.39}_{-0.44}$
$\Omega_c h^2$	0.1213	$0.1276^{+0.0096}_{-0.0093}$	γ^{CIB}	0.586	$0.53^{+0.25}_{-0.26}$
$100\theta_{MC}$	1.04126	$1.0407^{+0.0014}_{-0.0014}$	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	$3.73^{+0.54}_{-0.51}$	$\xi^{tSZ-CIB}$	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^{PS}_{100}	171	190^{+100}_{-100}	Ω_Λ	0.7051	$0.714^{+0.027}_{-0.029}$
A^{PS}_{143}	71.6	58^{+30}_{-30}	Ω_m	0.2949	$0.286^{+0.029}_{-0.027}$
A^{PS}_{217}	119.0	104^{+40}_{-40}	σ_8	0.8332	$0.856^{+0.037}_{-0.036}$
A^{CIB}_{143}	0.0	—	z_{re}	11.13	$12.0^{+2.4}_{-2.3}$
A^{CIB}_{217}	27	32^{+20}_{-20}	H_0	69.96	$72.7^{+3.9}_{-3.8}$
A^{tSZ}_{143}	4.86	—	$10^9 A_s$	2.214	$2.28^{+0.14}_{-0.13}$
$r^{PS}_{143\times217}$	0.922	> 0.719	$\Omega_m h^2$	0.1444	$0.1509^{+0.0097}_{-0.0094}$

Best-fit $\chi^2_{eff} = 9809.00$; 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.

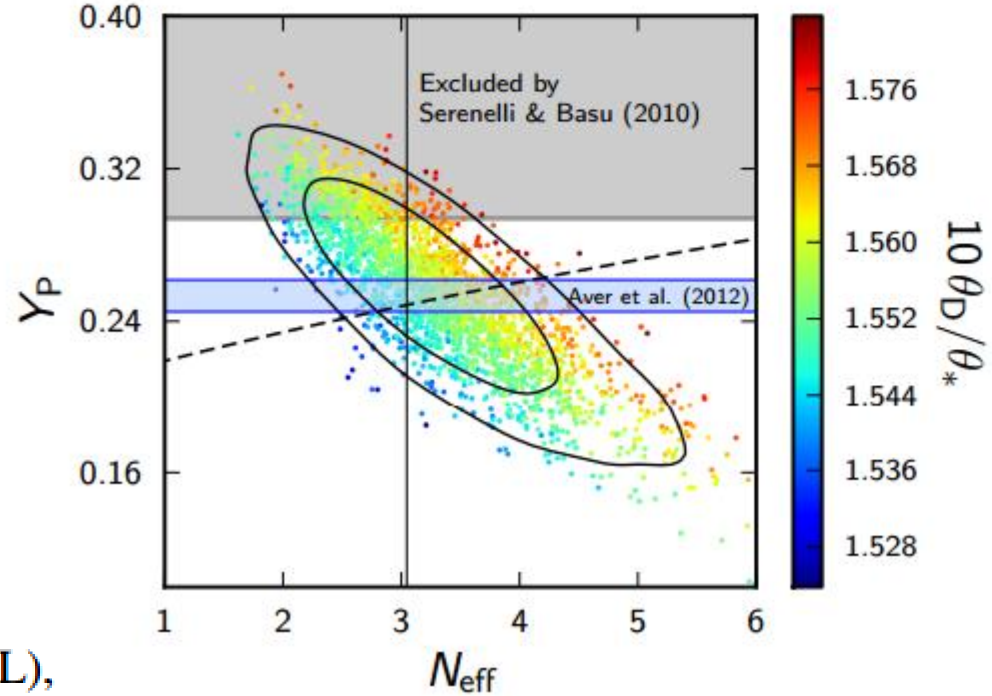
- New (single) D measurement by Pettini and Cooke is in perfect agreement with Neff=3.046.

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

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.



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

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

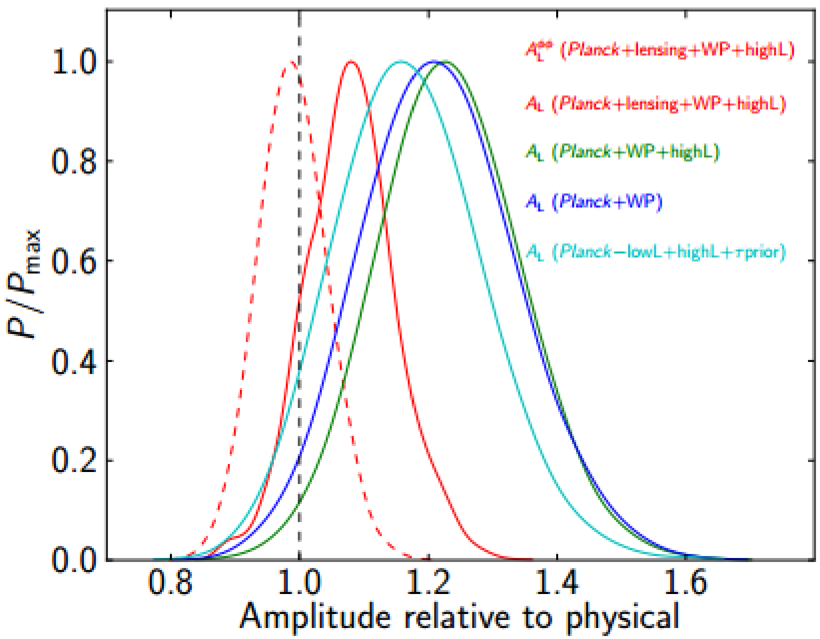
Including BAO (95% c.l.):

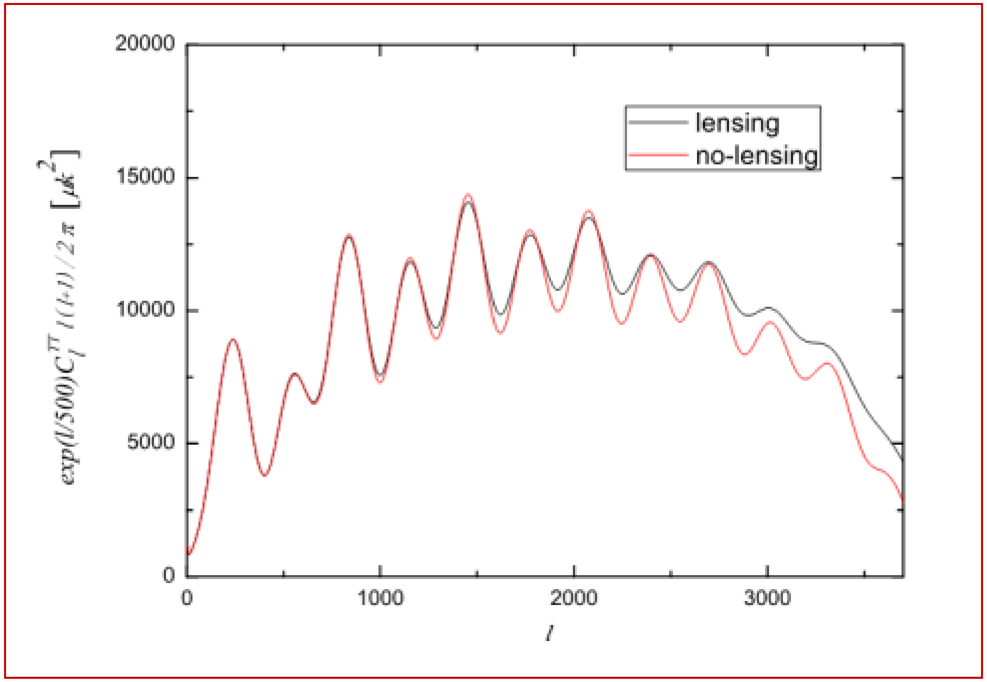
$N_{\rm eff}$	$3.19^{+0.99}_{-0.94}$
$Y_{\rm He}$	$0.260^{+0.057}_{-0.065}$

Including HST (95% c.l.):

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

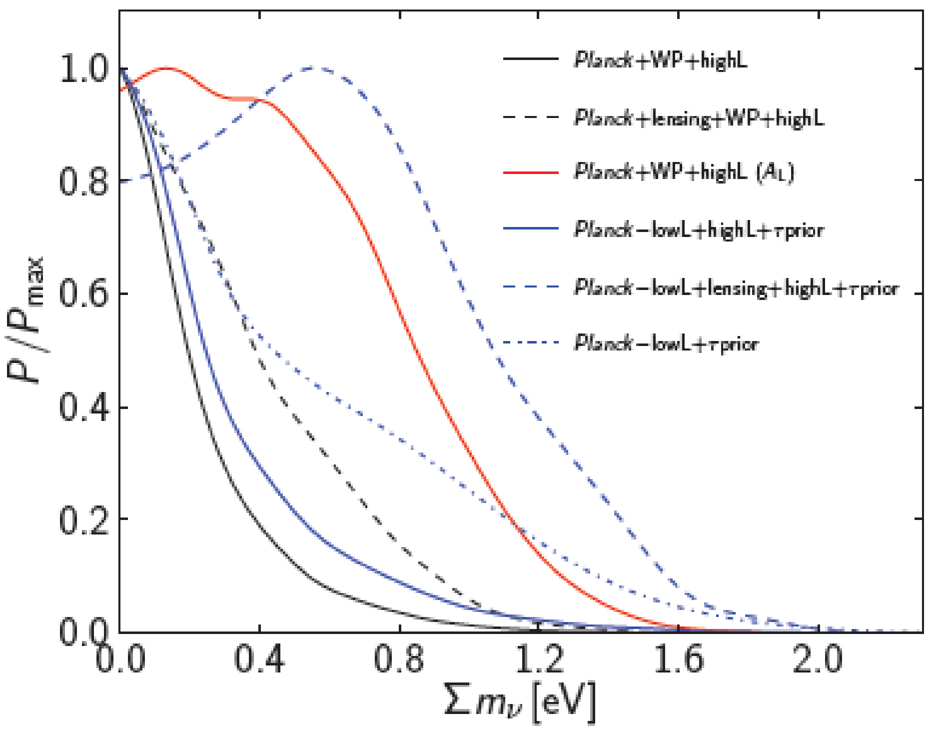
Anomalous Lensing Amplitude





Lensing also modifies the CMB angular spectrum.
It is possible to quantify the amount of lensing in the angular spectrum by introducing an effective amplitude.
Planck sees a **larger value** of the lensing in the TT spectrum at 95% c.l. respect to the expectations of LCDM.
This is in disagreement with the lensing trispectrum (TTTT) measurement that is consistent with LCDM. The origin of the anomalous TT lensing amplitude is yet unknown.

Constraints on Neutrino Mass (standard 3 neutrino framework)



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

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

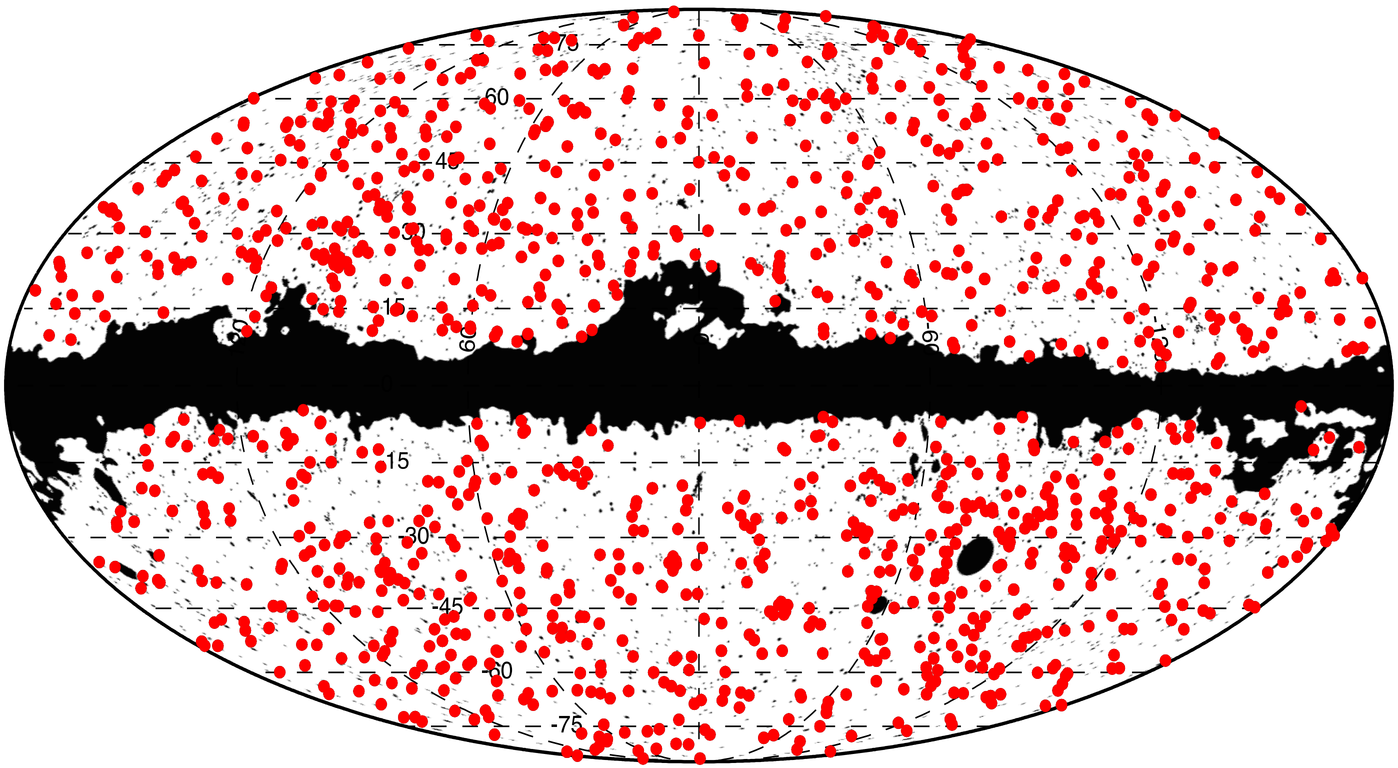
$$\sum m_\nu < 0.85\,\mathrm{eV} \quad (95\%;\ \mathit{Planck}+\mathrm{lensing}+\mathrm{WP}+\mathrm{highL}),$$

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

- 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

Clusters of galaxies

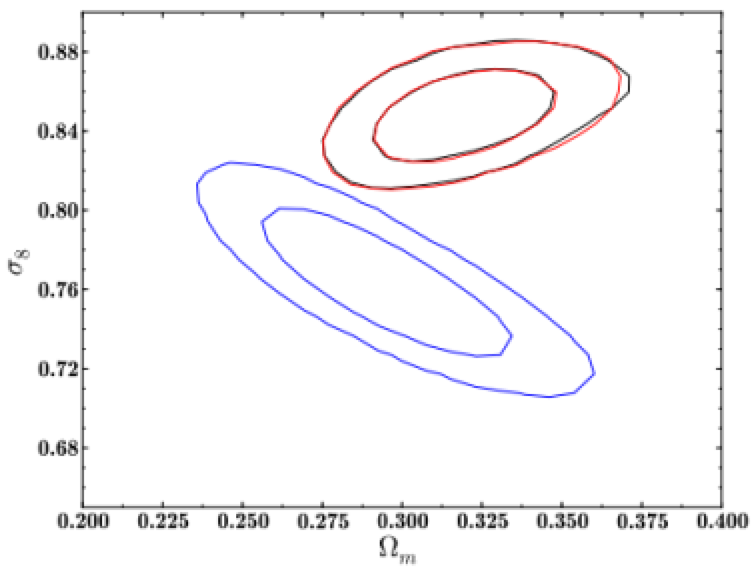
Planck SZ catalog

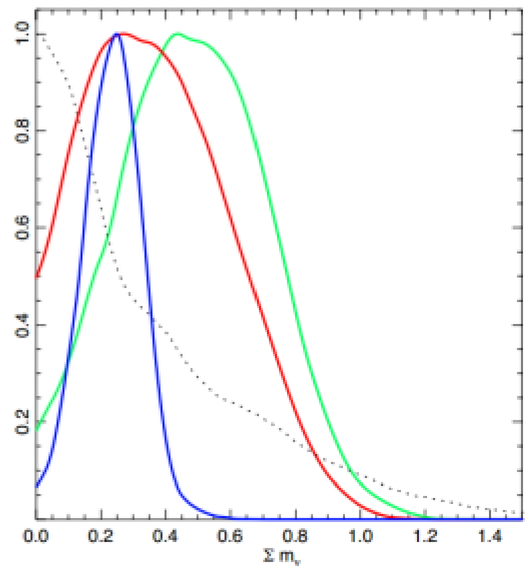


- 1227 clusters & candidates
  - 683 previously known
  - 178 new clusters
  - 366 candidates

- z in [0-1]
- M in [1~20] $10^{14}\ M_\odot$
- $M_{med} \sim 3.5\ 10^{14}\ M_\odot$

Evidence for a Neutrino mass from SZ Clusters counts ?





Dashed:
Planck CMB

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

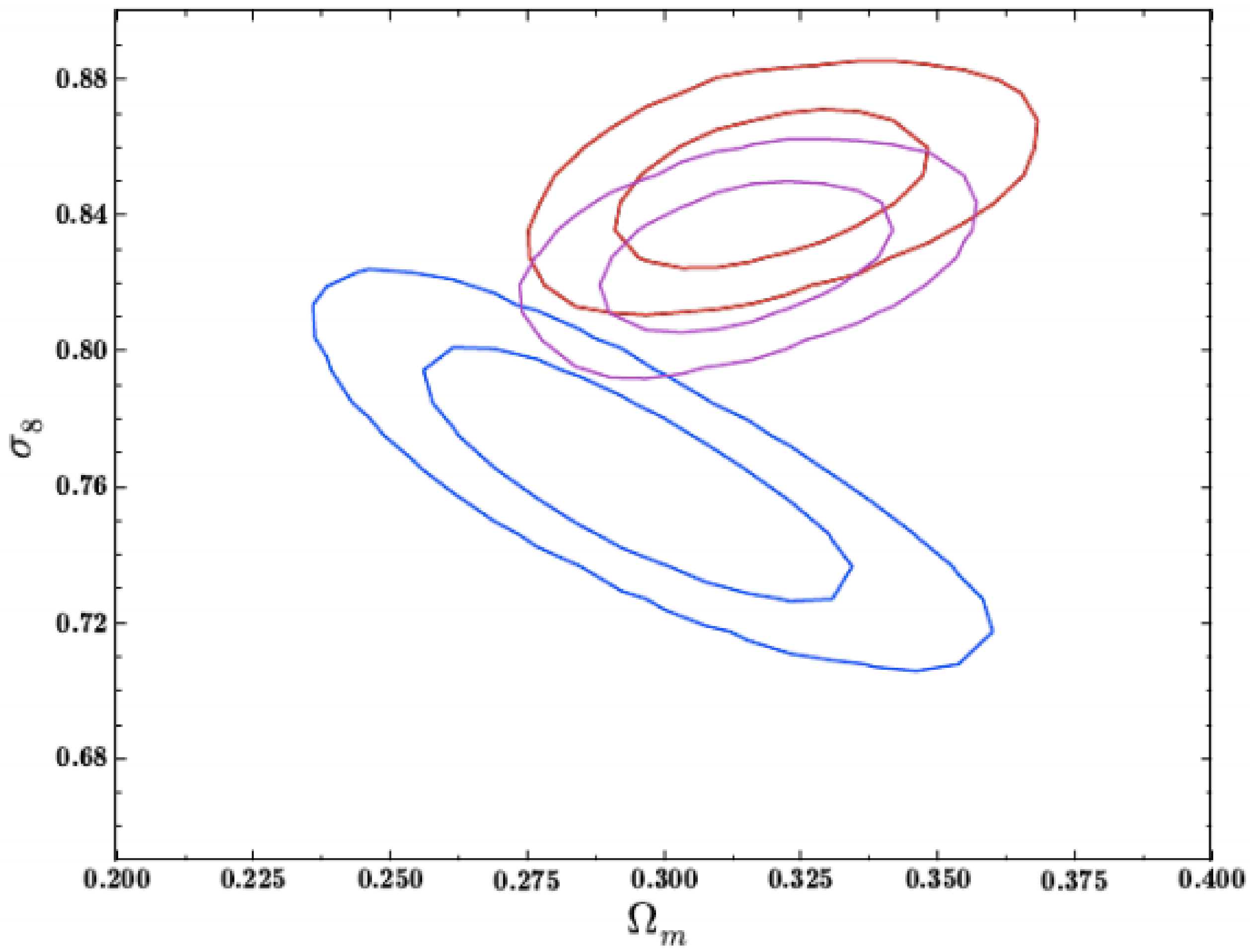
Green:
Planck CMB+SZ
(1-b)=0.8

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).

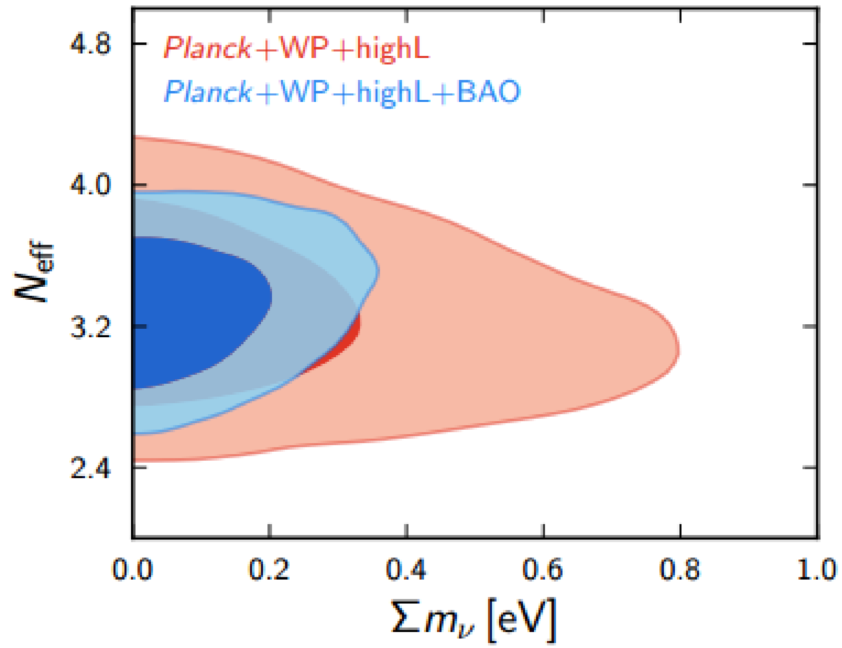


Red:
Planck+WP TT analysis with massless neutrinos.

Purple:
Planck+WP TT analysis with 3 0.02 eV neutrinos.

Blue:
Planck Clusters

Constraints on active neutrinos masses in presence of a massless sterile neutrino



- No correlation between N_{eff} and the mass of the 3 **active** massive neutrinos.

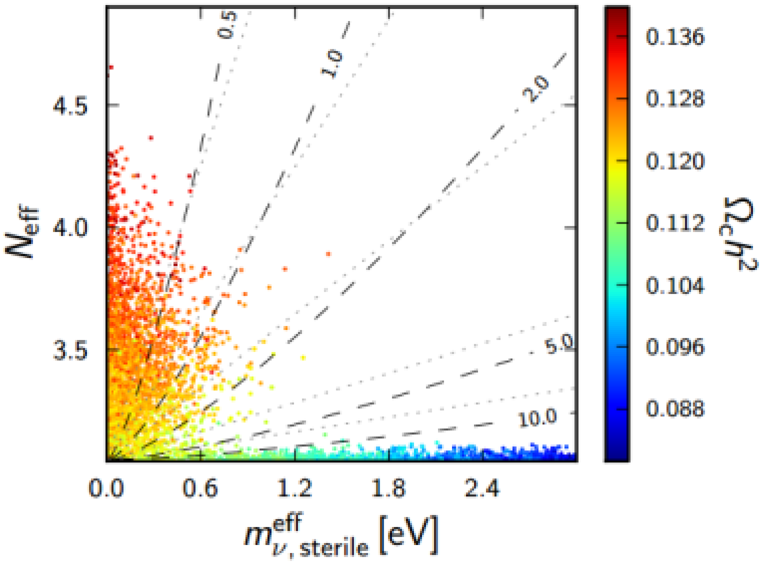
Constraints on a massive sterile neutrino

This is clearly **model dependent**.

We assume the extra neutrino to contribute to Neff when is relativistic and to contribute to the energy density as

$$m^{\rm eff}_{\nu,\,\rm sterile} \equiv (94.1\omega_{\nu,\,\rm sterile})\,\rm eV$$

when is non-relativistic.
If we now assume a model this introduces a relation between the two parameters.



If thermally distributed with a temperature Ts:

$$m^{\rm eff}_{\nu,\,\rm sterile} = (T_s/T_\nu)^3 m^{\rm thermal}_{\rm sterile} = (\Delta N_{\rm eff})^{3/4} m^{\rm thermal}_{\rm sterile}$$

If distributed proportionally to active neutrinos with an arbitrary scaling factor function of the active–sterile neutrino mixing angle (Dodelson-Widrow model):

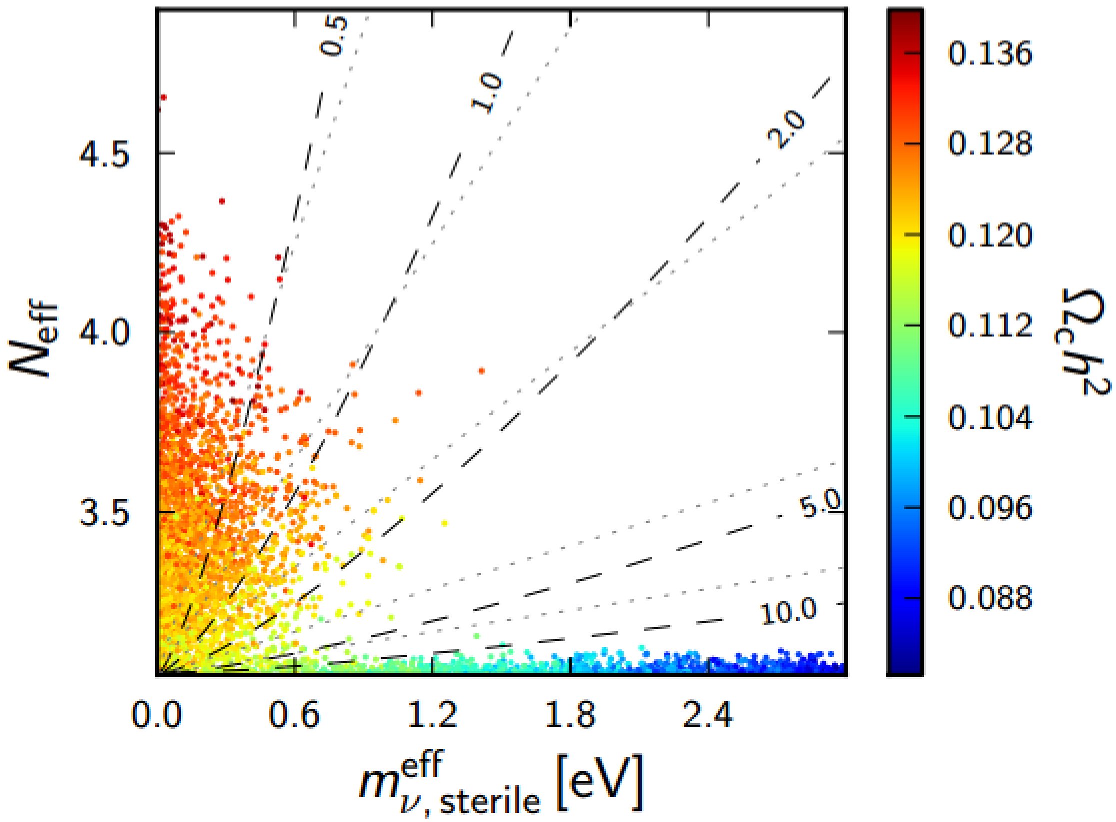
$$m^{\rm eff}_{\nu,\,\rm sterile} = \chi_s m^{\rm DW}_{\rm sterile} \qquad \text{with } \Delta N_{\rm eff} = \chi_s.$$

Constraints on a massive sterile neutrino

Please note:

Neff refers **only** to relativistic neutrinos at recombination !

If we have a mass above 10 eV CMB is not sensitive to this and is like adding a cdm component.



$$\left.\begin{aligned} N_{\rm eff} &< 3.91 \\ m_{\nu,\,\rm sterile}^{\rm eff} &< 0.59\,\rm eV \end{aligned}\right\} \quad (95\%;\ \text{CMB for } m_{\rm sterile}^{\rm thermal} < 10\,\rm eV)$$

Should we care about a 3 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° ± 1.0° 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 !

Conclusions

- Planck data alone provides **no evidence** for extra relativistic particles at recombination. Neff 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 $\pm$ 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 Neff are considered. An agreement between Planck and HST on the Hubble parameter can be achieved at the expenses of a dark radiation component with Neff=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).

Cosmological parameters

6-parameters model

Parameter		2013 uncertainty (Planck+WP)	Expected 2014 (Planck T+P)
Baryon density today	$\Omega_b h^2$	0.00028	0.00013
Cold dark matter density today	$\Omega_c h^2$	0.0027	0.0010
Thomson scattering optical depth	τ	0.013	0.0042
Hubble constant [km/s/Mpc]	H_0	1.2	0.53
Scalar spectrum power-law index	n_S	0.007	0.0031

Constraints on other parameters

Parameter		2013 uncertainty (Planck+WP)	Expected 2014 (Planck T+P)
Effective number of neutrino species	N_{eff}	0.42	0.18
Fraction of baryonic mass in helium	Y_p	0.035	0.010
Dark energy equation of state	w	0.32	0.20
Varying fine-structure constant	α/α_0	0.0043	0.0018

→ Expected reduction in error bars by factors of 2 or more

Conclusions

- The 2013 Planck T map anisotropy leaves behind it a legacy which will stay for many years (…before next Planck release) and will not be replaced easily.
- Excellent agreement between the Planck temperature spectrum at high l and the predictions of the ΛCDM model.
- But…anomalies are also seen and will be investigated
- Planck 2014 data release will help in solving most of the issues…and maybe will open new ones !

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

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.


"All the News That's Fit to Print"

The New York Times

NEW YORK, FRIDAY, MARCH 22, 2013

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

APPEAL AIMED AT YOUNG

In Jerusalem, He Eases Stance on Settlement Halt Before Talks

The Cosmos, Back in the Day

Bronx Inspector, Secretly Taped, Suggests Race Is a Factor in Stops

Once Few, Women Hold More Power in Senate

Fast-Growing Brokerage Firm Often Tangles With Regulators

Mood Darkens in Cyprus Ahead of Bailout Deadline

O Revelations! Letters, Once Banned, Flesh Out Willa Cather

Cartier

Impressive impact on the international press (with the exception of the italian one…)