Constraining fundamental physics with Planck

Alessandro Melchiorri
University of Rome La Sapienza
On behalf of the Planck collaboration

Planck Collaboration 300+ names

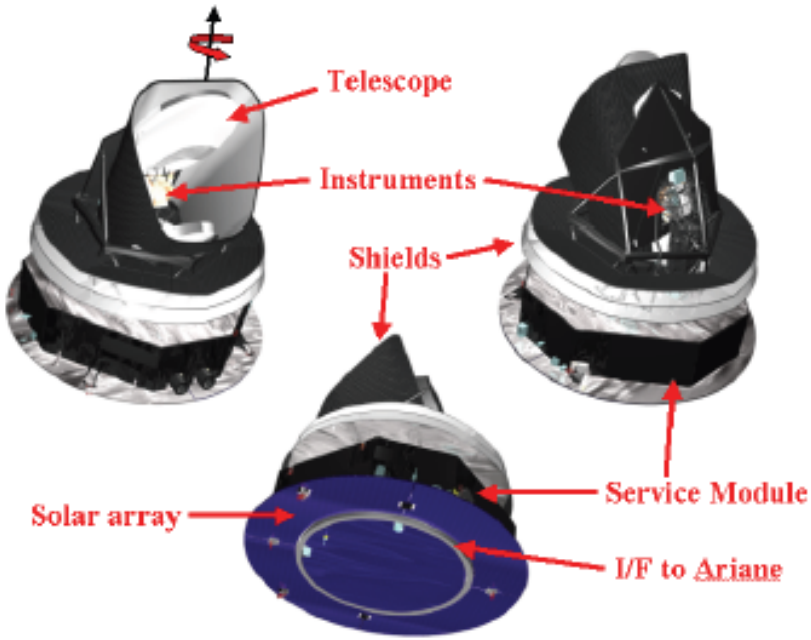
Planck 2013 results. XVI. Cosmological parameters

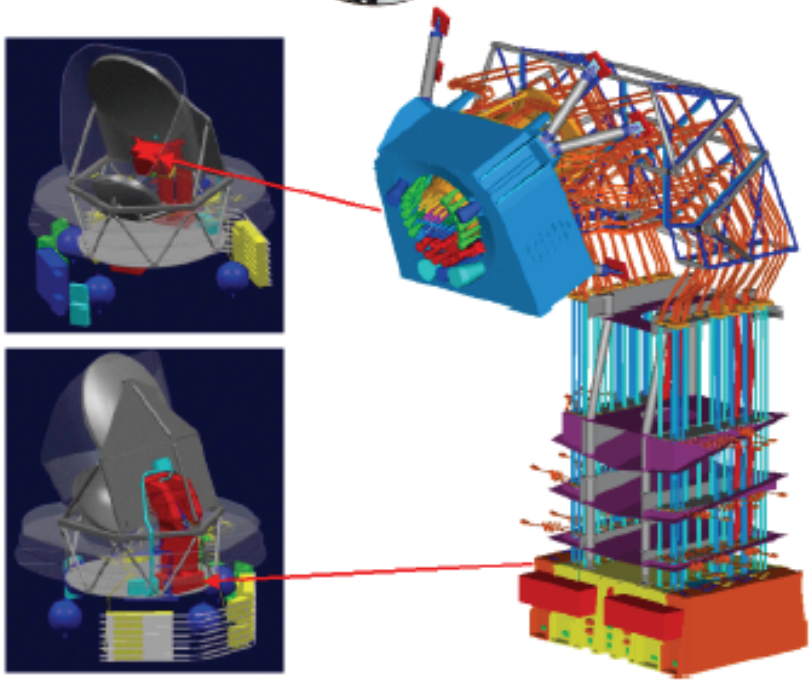
Planck Collaboration: P. A. R. Ade[90], N. Aghanim[63], C. Armitage-Caplan[96], M. Arnaud[77], M. Ashdown[74,6], F. Atrio-Barandela[19], J. Aumont[63], C. Baccigalupi[89], A. J. Banday[99,10], R. B. Barreiro[70], J. G. Bartlett[1,72], E. Battaner[102], K. Benabed[64,98], A. Benoît[61], A. Benoit-Lévy[26,64,98], J.-P. Bernard[10], M. Bersanelli[37,53], P. Bielewicz[99,10,89], J. Bobin[77], J. J. Bock[72,11], A. Bonaldi[73], J. R. Bond[9], J. Borrill[14,93], F. R. Bouchet[64,98], M. Bridges[74,6,67], M. Bucher[1], C. Burigana[52,35], R. C. Butler[52], E. Calabrese[96], B. Cappellini[53], J.-F. Cardoso[78,1,64], A. Catalano[79,76], A. Challinor[67,74,12], A. Chamballu[77,16,63], R.-R. Chary[60], X. Chen[60], L.-Y Chiang[66], H. C. Chiang[29,7], P. R. Christensen[85,40], S. Church[95], D. L. Clements[59], S. Colombi[64,98], L. P. L. Colombo[25,72], F. Couchot[75], A. Coulais[76], B. P. Crill[72,86], A. Curto[6,70], F. Cuttaia[52], L. Danese[89], R. D. Davies[73], R. J. Davis[73], P. de Bernardis[36], A. de Rosa[52], G. de Zotti[49,89], J. Delabrouille[1], J.-M. Delouis[64,98], F.-X. Désert[56], C. Dickinson[73], J. M. Diego[70], K. Dolag[101,82], H. Dole[63,62], S. Donzelli[53], O. Doré[72,11], M. Douspis[63], J. Dunkley[96], X. Dupac[43], G. Efstathiou[67*], F. Elsner[64,98], T. A. Enßlin[82], H. K. Eriksen[68], F. Finelli[52,54], O. Forni[99,10], M. Frailis[51], A. A. Fraisse[29], E. Franceschi[52], T. C. Gaier[72], S. Galeotta[51], S. Galli[64], K. Ganga[1], M. Giard[99,10], G. Giardino[44], Y. Giraud-Héraud[1], E. Gjerløw[68], J. González-Nuevo[70,89], K. M. Górski[72,104], S. Gratton[74,67], A. Gregorio[38,51], A. Gruppuso[52], J. E. Gudmundsson[29], J. Haissinski[75], J. Hamann[97], F. K. Hansen[68], D. Hanson[83,72,9], D. Harrison[67,74], S. Henrot-Versillé[75], C. Hernández-Monteagudo[13,82], D. Herranz[70], S. R. Hildebrandt[11], E. Hivon[64,98], M. Hobson[6], W. A. Holmes[72], A. Hornstrup[17], Z. Hou[31], W. Hovest[82], K. M. Huffenberger[103], T. R. Jaffe[99,10], A. H. Jaffe[59], J. Jewell[72], W. C. Jones[29], M. Juvela[28], E. Keihänen[28], R. Keskitalo[23,14], T. S. Kisner[81], R. Kneissl[42,8], J. Knoche[82], L. Knox[31], M. Kunz[18,63,3], H. Kurki-Suonio[28,47], G. Lagache[63], A. Lähteenmäki[2,47], J.-M. Lamarre[76], A. Lasenby[6,74], M. Lattanzi[35], R. J. Laureijs[44], C. R. Lawrence[72], S. Leach[89], J. P. Leahy[73], R. Leonardi[43], J. León-Tavares[45,2], J. Lesgourgues[97,88], A. Lewis[27], M. Liguori[34], P. B. Lilje[68], M. Linden-Vørnle[17], M. López-Caniego[70], P. M. Lubin[32], J. F. Macías-Pérez[79], B. Maffei[73], D. Maino[37,53], N. Mandolesi[52,5,35], M. Maris[51], D. J. Marshall[77], P. G. Martin[9], E. Martínez-González[70], S. Masi[36], S. Matarrese[34], F. Matthai[82], P. Mazzotta[39], P. R. Meinhold[32], A. Melchiorri[36,55], J.-B. Melin[16], L. Mendes[43], E. Menegoni[36], A. Mennella[37,53], M. Migliaccio[67,74], M. Millea[31], S. Mitra[58,72], M.-A. Miville-Deschênes[63,9], A. Moneti[64], L. Montier[99,10], G. Morgante[52], D. Mortlock[59], A. Moss[91], D. Munshi[90], P. Naselsky[85,40], F. Nati[36], P. Natoli[35,4,52], C. B. Netterfield[21], H. U. Nørgaard-Nielsen[17], F. Noviello[73], D. Novikov[59], I. Novikov[85], I. J. O'Dwyer[72], S. Osborne[95], C. A. Oxborrow[17], F. Paci[89], L. Pagano[36,55], F. Pajot[63], D. Paoletti[52,54], B. Partridge[46], F. Pasian[51], G. Patanchon[1], D. Pearson[72], T. J. Pearson[11,60], H. V. Peiris[26], O. Perdereau[75], L. Perotto[79], F. Perrotta[89], V. Pettorino[18], F. Piacentini[36], M. Piat[1], E. Pierpaoli[25], D. Pietrobon[72], S. Plaszczynski[75], P. Platania[71], E. Pointecouteau[99,10], G. Polenta[4,50], N. Ponthieu[63,56], L. Popa[65], T. Poutanen[47,28,2], G. W. Pratt[77], G. Prézeau[11,72], S. Prunet[64,98], J.-L. Puget[63], J. P. Rachen[22,82], W. T. Reach[100], R. Rebolo[69,15,41], M. Reinecke[82], M. Remazeilles[63,1], C. Renault[79], S. Ricciardi[52], T. Riller[82], I. Ristorcelli[99,10], G. Rocha[72,11], C. Rosset[1], G. Roudier[1,76,72], M. Rowan-Robinson[59], J. A. Rubiño-Martín[69,41], B. Rusholme[60], M. Sandri[52], D. Santos[79], M. Savelainen[28,47], G. Savini[87], D. Scott[24], M. D. Seiffert[72,11], E. P. S. Shellard[12], L. D. Spencer[90], J.-L. Starck[77], V. Stolyarov[6,74,94], R. Stompor[1], R. Sudiwala[90], R. Sunyaev[82,92], F. Sureau[77], D. Sutton[67,74], A.-S. Suur-Uski[28,47], J.-F. Sygnet[64], J. A. Tauber[44], D. Tavagnacco[51,38], L. Terenzi[52], L. Toffolatti[20,70], M. Tomasi[53], M. Tristram[75], M. Tucci[18,75], J. Tuovinen[84], M. Türler[57], G. Umana[48], L. Valenziano[52], J. Valiviita[47,28,68], B. Van Tent[80], P. Vielva[70], F. Villa[52], N. Vittorio[39], L. A. Wade[72], B. D. Wandelt[64,98,33], I. K. Wehus[72], M. White[30], S. D. M. White[82], A. Wilkinson[73], D. Yvon[16], A. Zacchei[51], and A. Zonca[32]

Planck Core-Team

(a fraction of it)

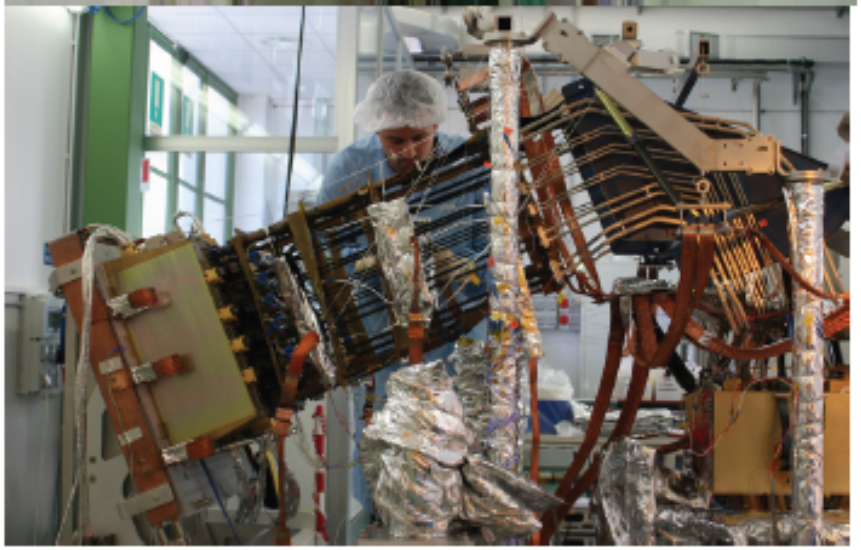
Planck in cartoons

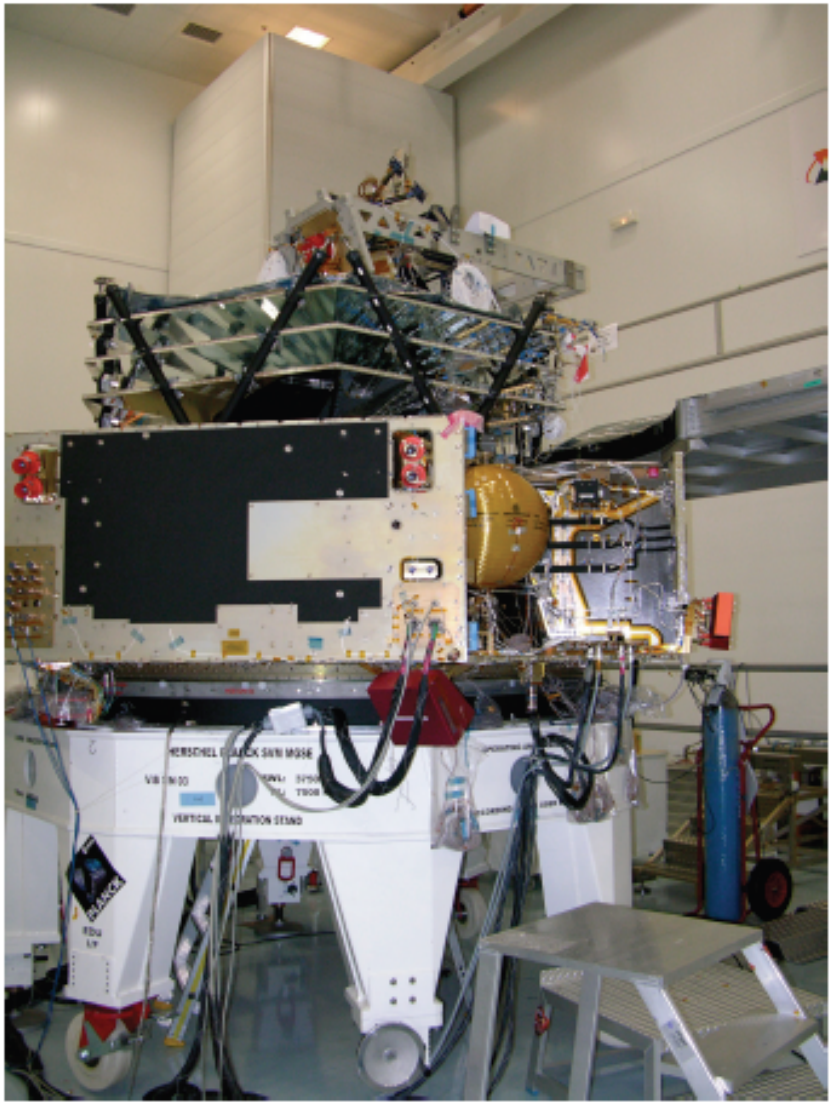




Planck has two instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI) in a shared focal plane containing 74 channels and covering 8 degrees on the sky.

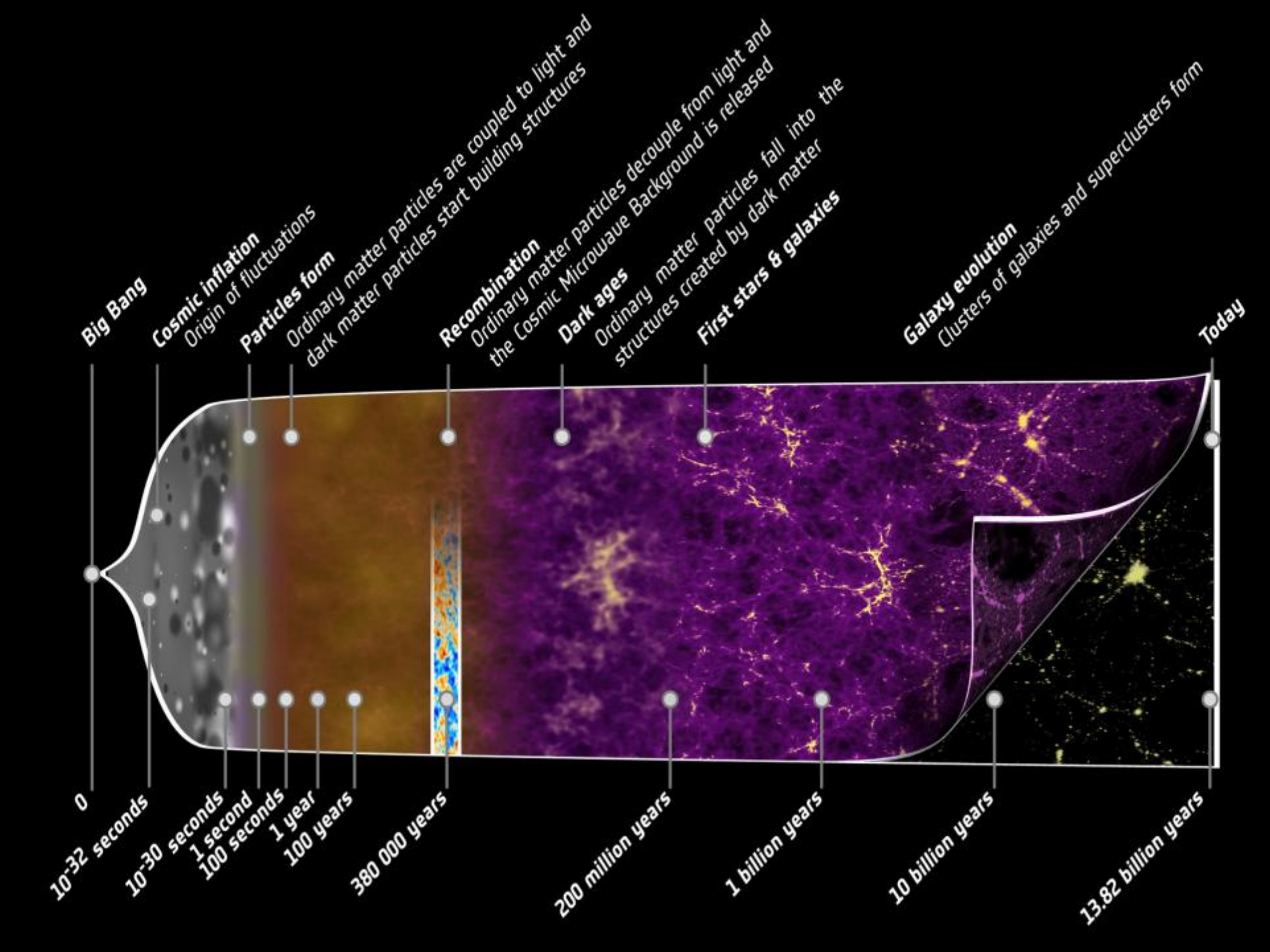
Planck being assembled



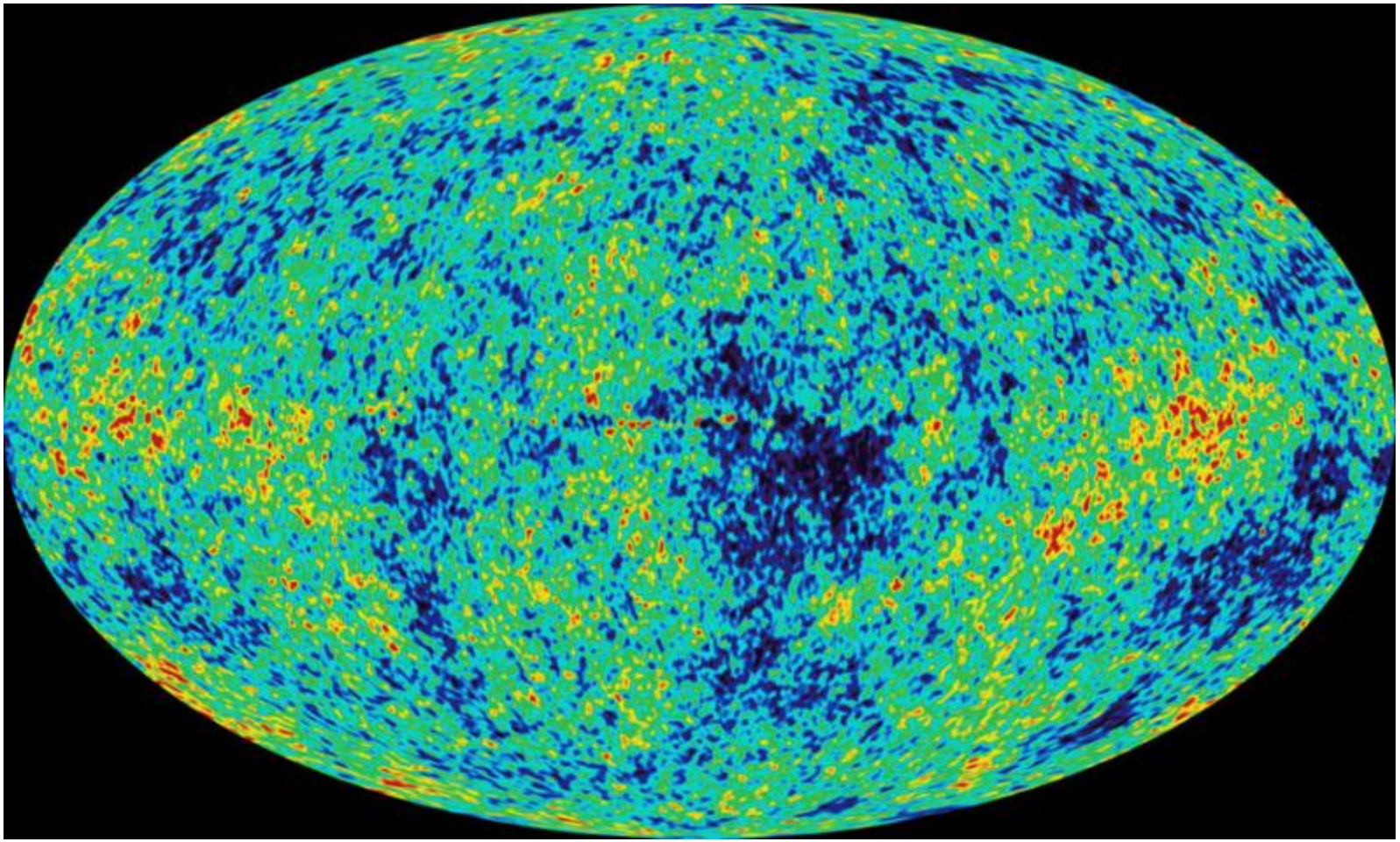


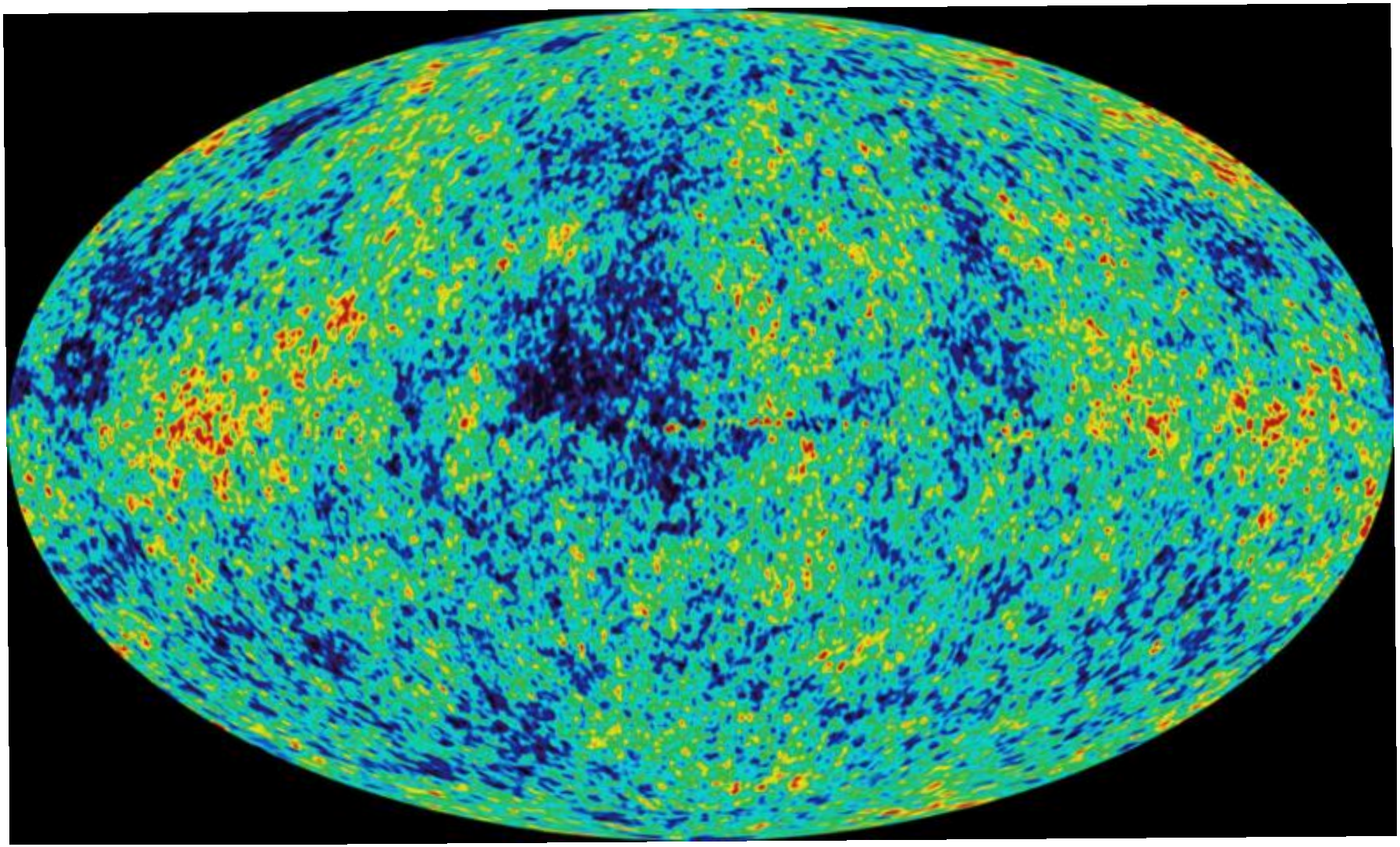
Planck in February 2009

Planck
Satellite launch
14/5/2009

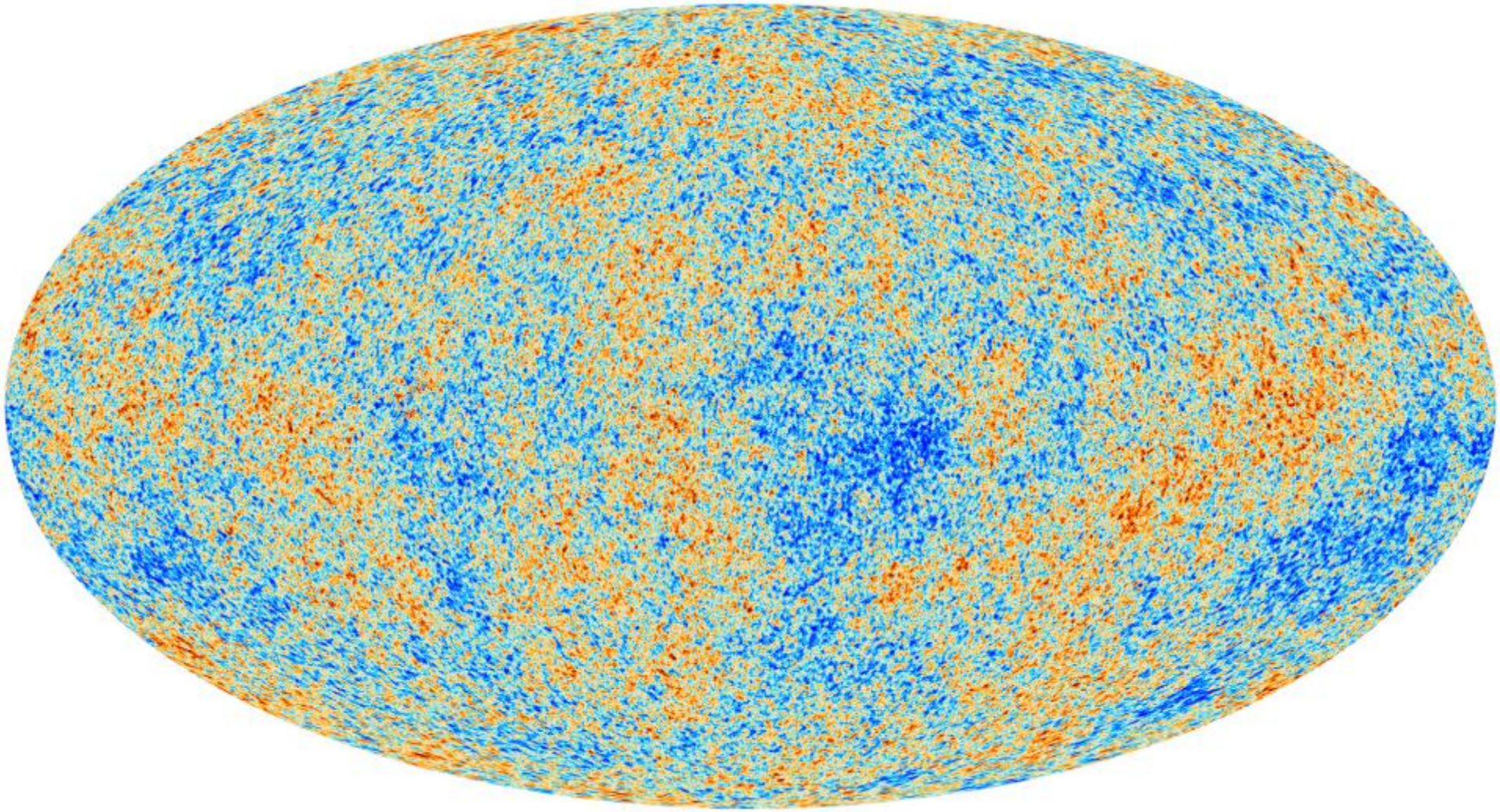

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles 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

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

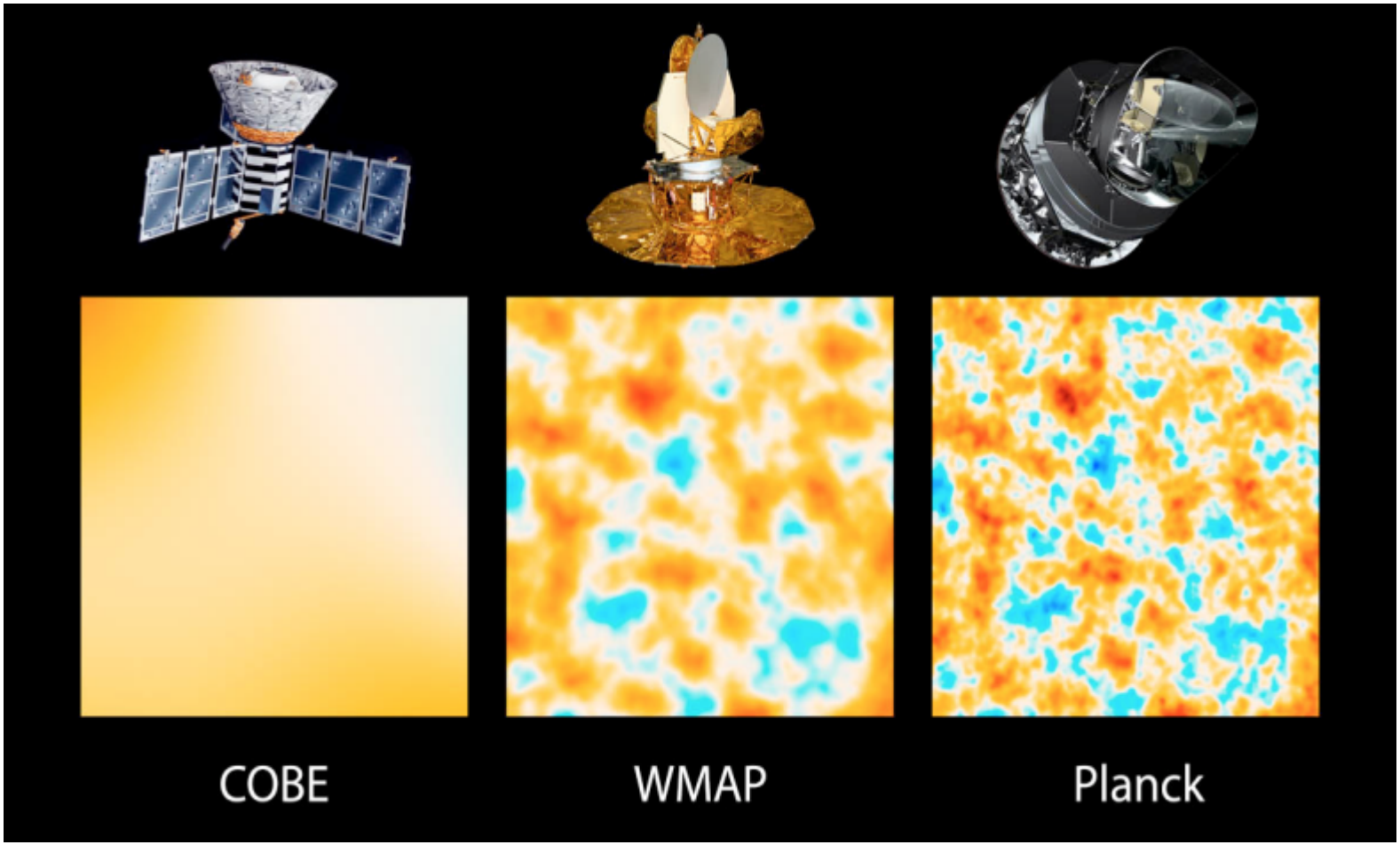




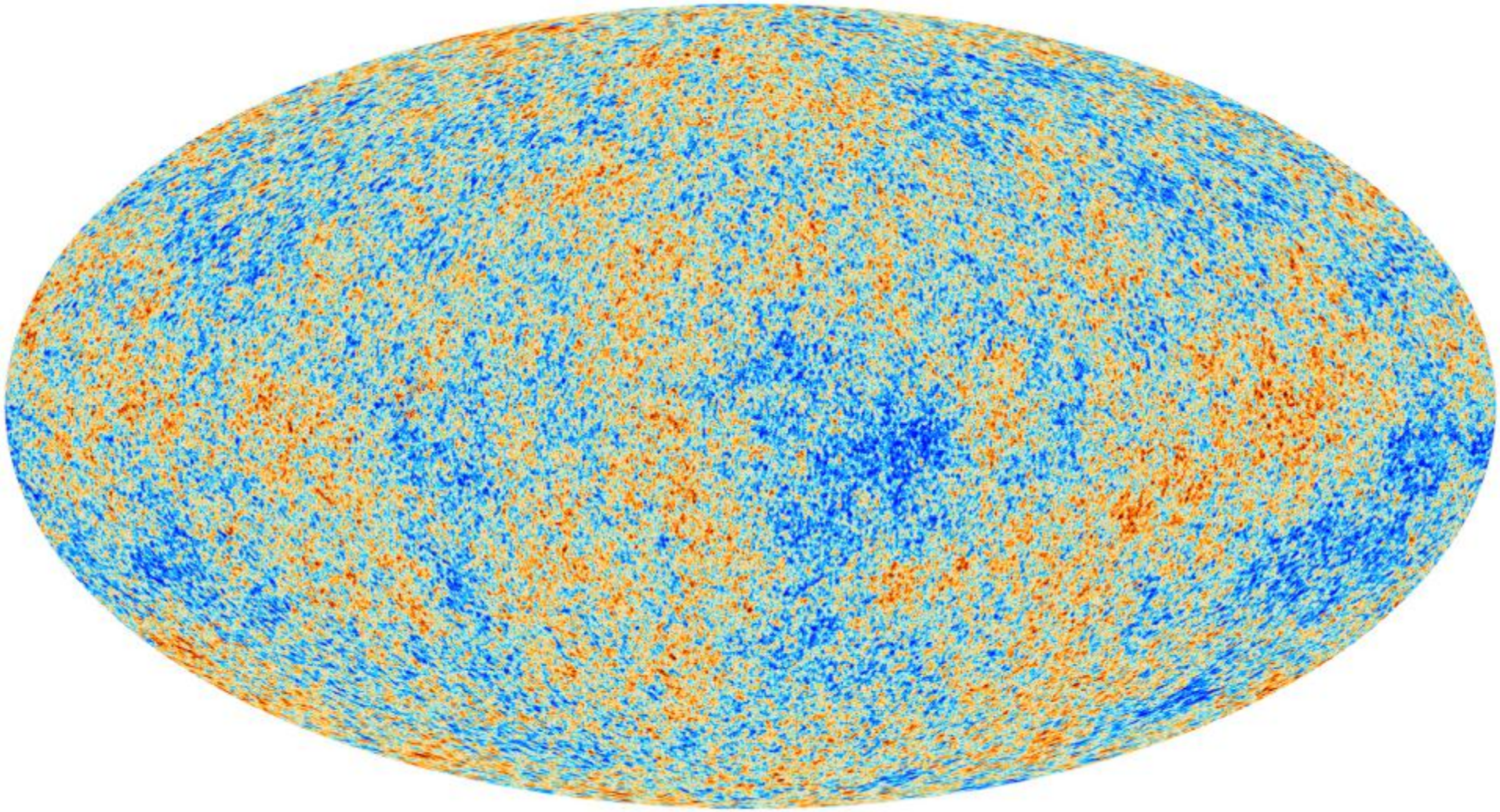
Planck 2013 CMB Map

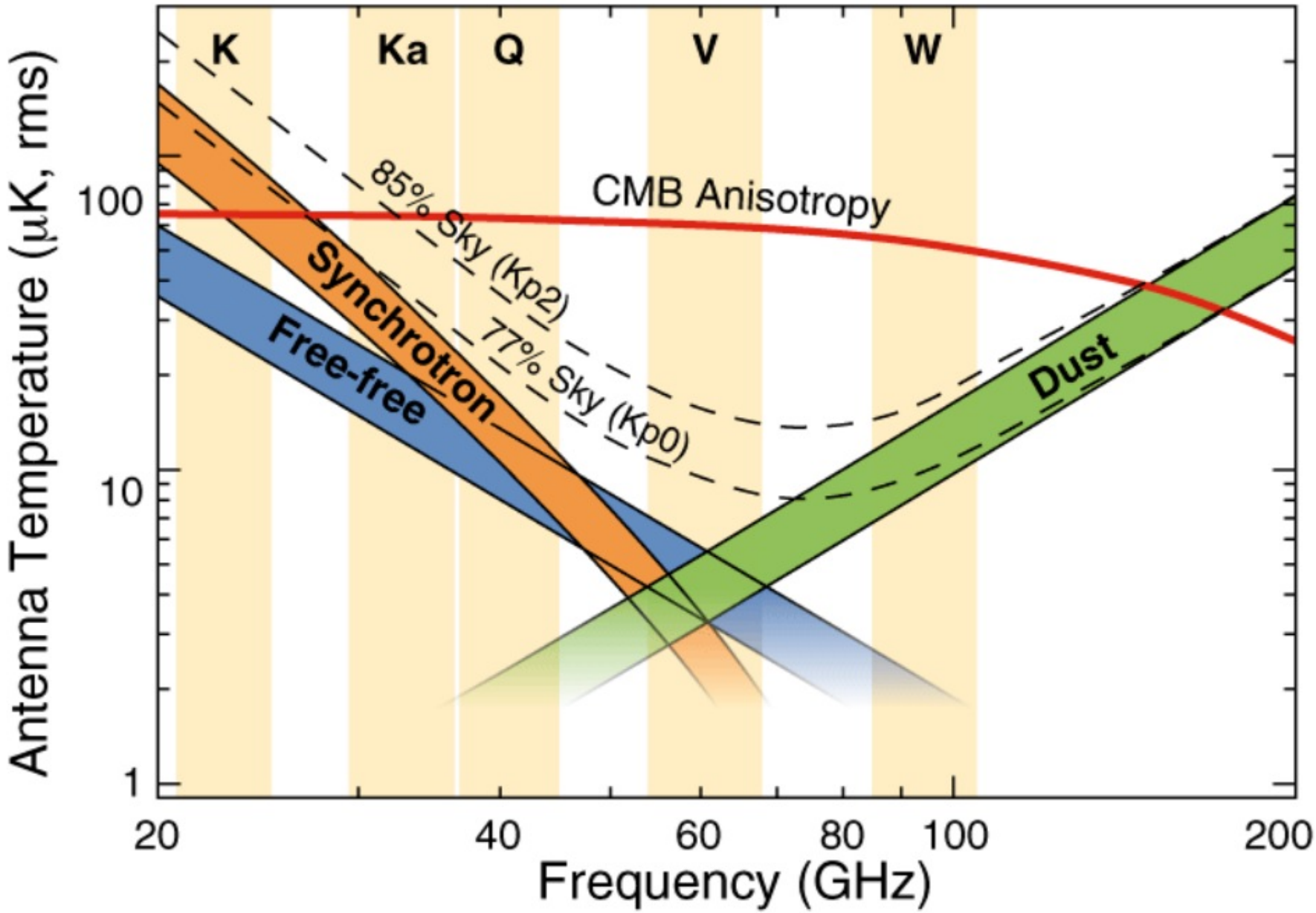


Comparison with COBE and WMAP



Planck 2013 CMB Map

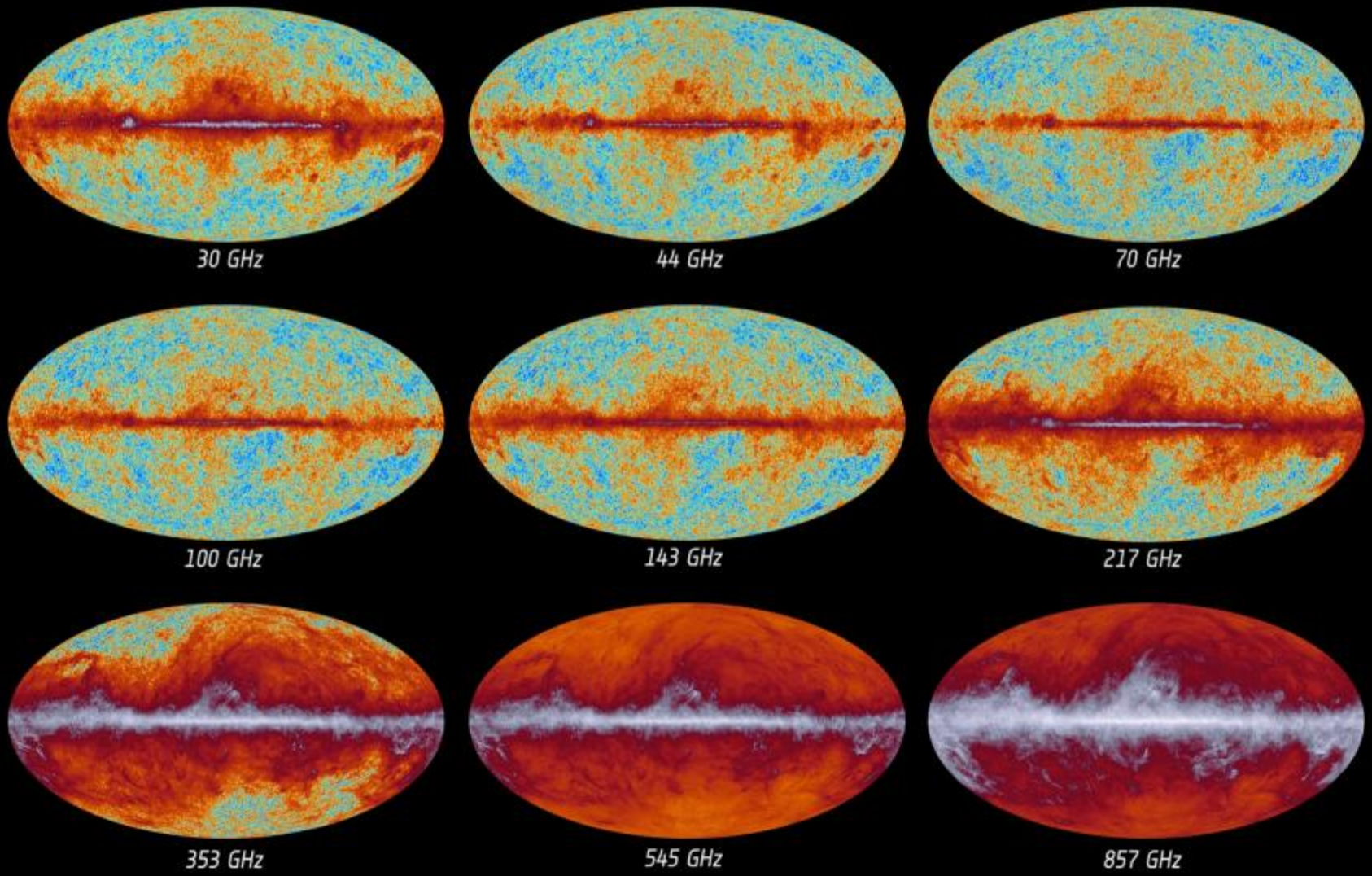



K
Ka
Q
V
W
CMB Anisotropy
85% Sky (Kp2)
77% Sky (Kp0)
Synchrotron
Free-free
Dust
Antenna Temperature (μK, rms)
100
10
1
20
40
60
80
100
200
Frequency (GHz)

planck

The sky as seen by Planck

esa

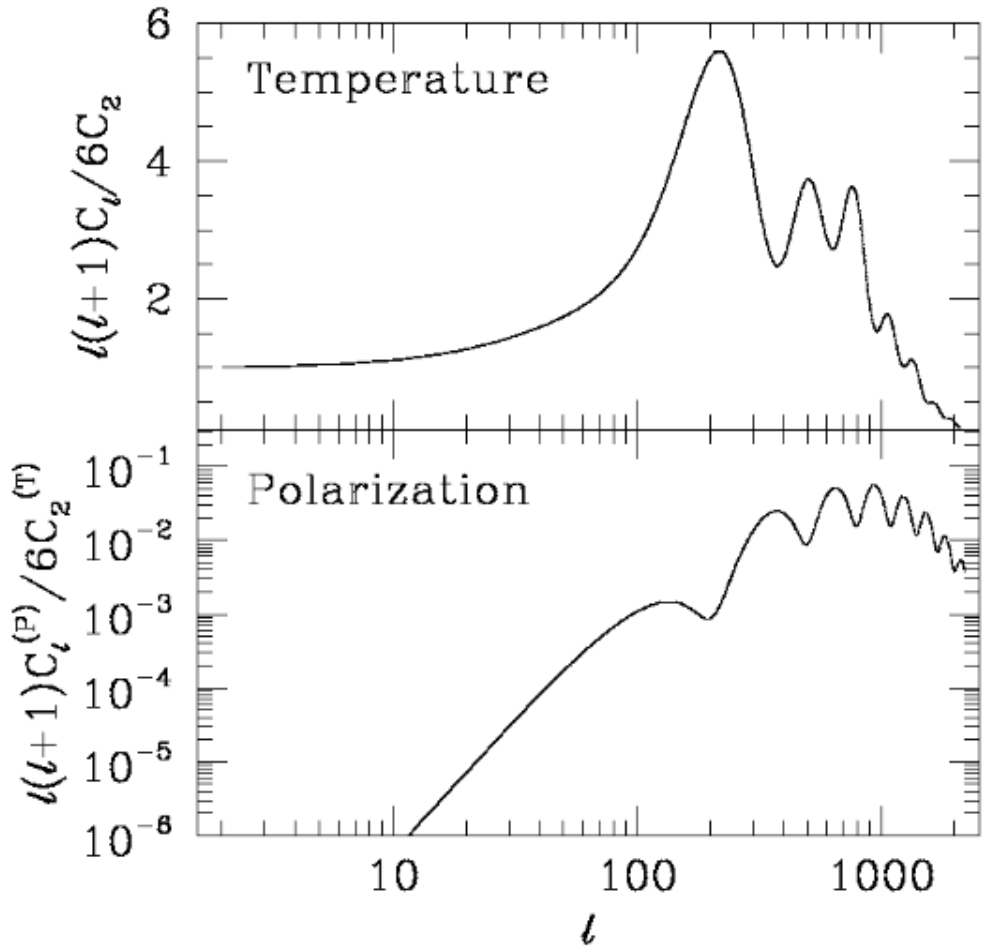


The CMB Angular Power Spectrum

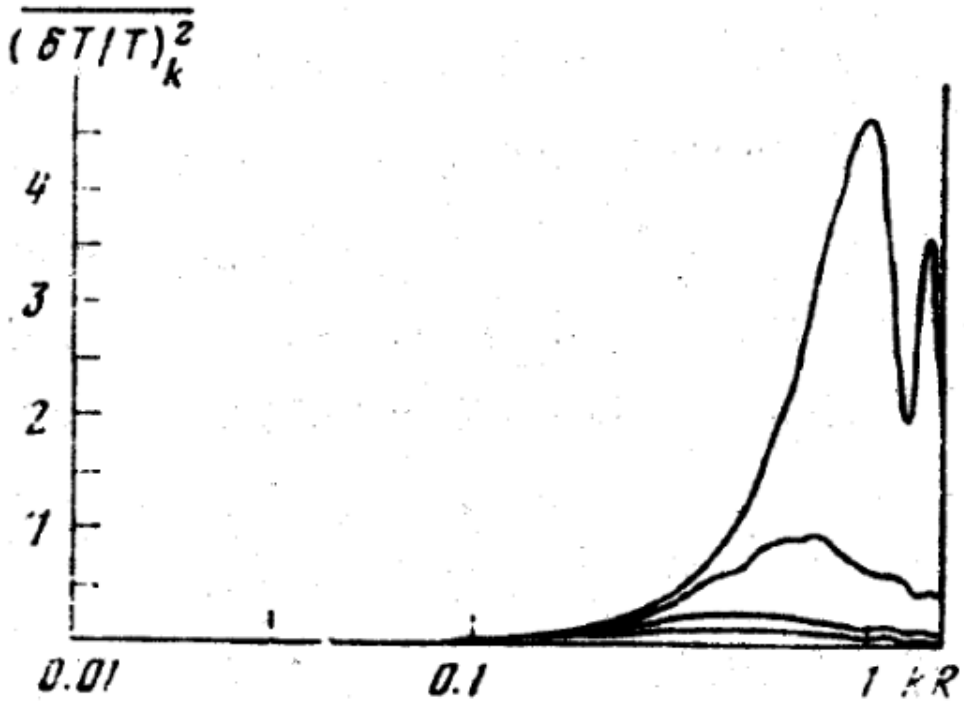
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)\,C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

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

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



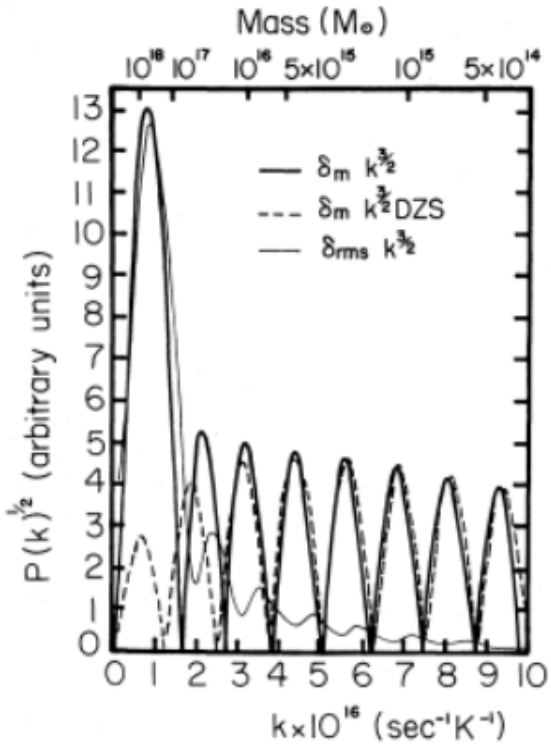
A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



Doroshkevich, A. G.; Zel'Dovich, Ya. B.; Syunyaev, R. A.

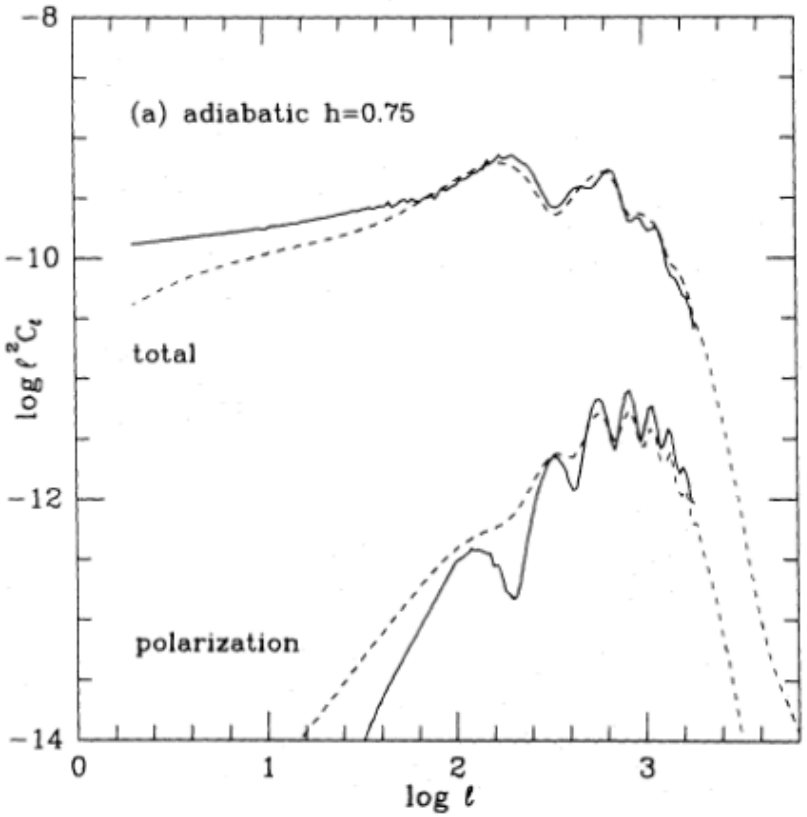
Soviet Astronomy, Vol. 22, p.523, 1978

A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



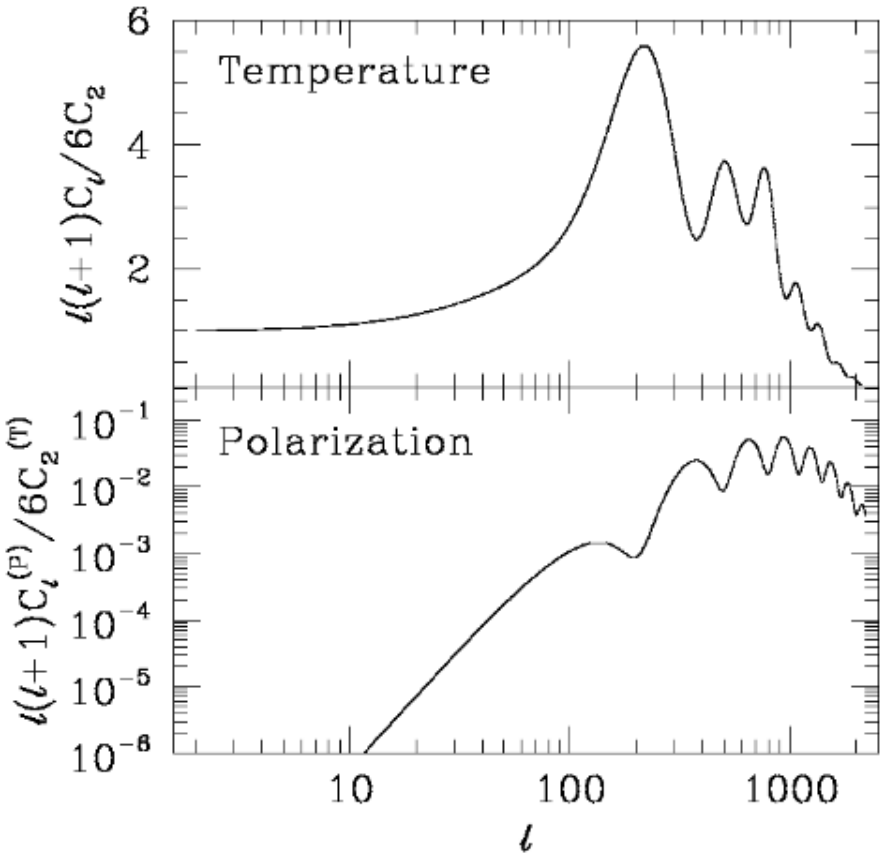
Wilson, M. L.; Silk, J., Astrophysical Journal, Part 1, vol. 243, Jan. 1, 1981, p. 14-25. 1981

A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



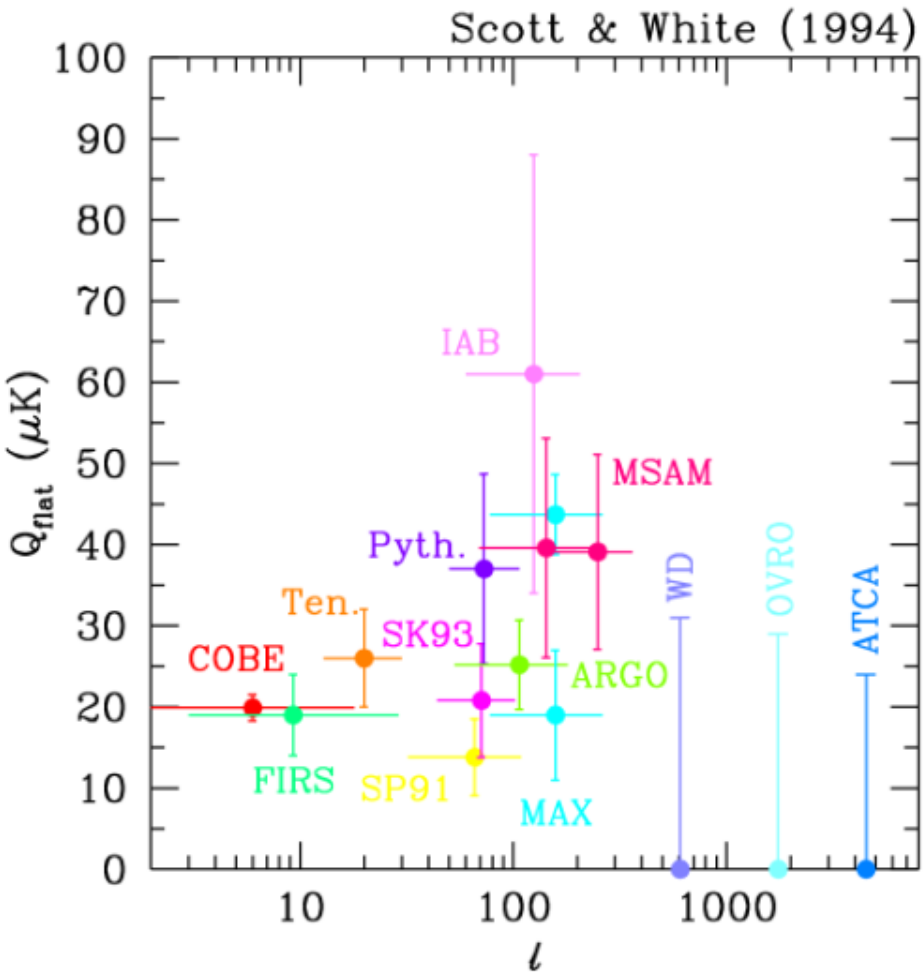
Bond, J. R.; Efstathiou, G.; Royal Astronomical Society, Monthly Notices (ISSN 0035-8711), vol. 226, June 1, 1987, p. 655-687, 1987

A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



Hu, Wayne; Scott, Douglas; Sugiyama, Naoshi; White, Martin.
Physical Review D, Volume 52, Issue 10, 15 November 1995, pp.5498-5515

A Brief History of the CMB Anisotropies Angular Spectrum (Experimental Data)



In 1995 Big Bang Model was nearly dead…

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News and Views

Nature **377**, 99 (14 September 1995) |

Big Bang not yet dead but in decline

John Maddox

Top

The latest measurements of the Hubble constant make the Big Bang account of the origin of the Universe more dependent on the coincidence of numbers than it has so far been. But it remains the only theory in the field.

Is there a crisis in cosmology, or is it that the latest measurement of the Hubble constant is yet another of those numeri-cal disagreements that plague the field from time to time? That is the question inevitably prompted by last week's article by N.

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- John Maddox

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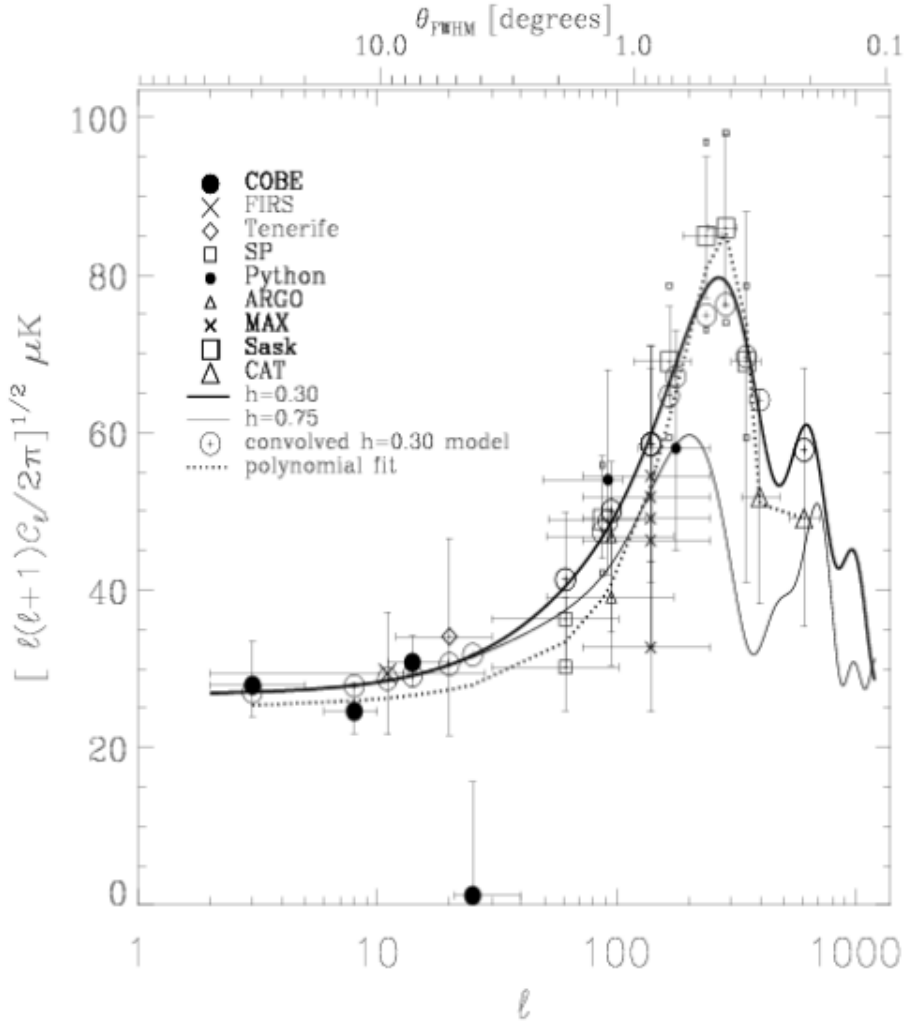
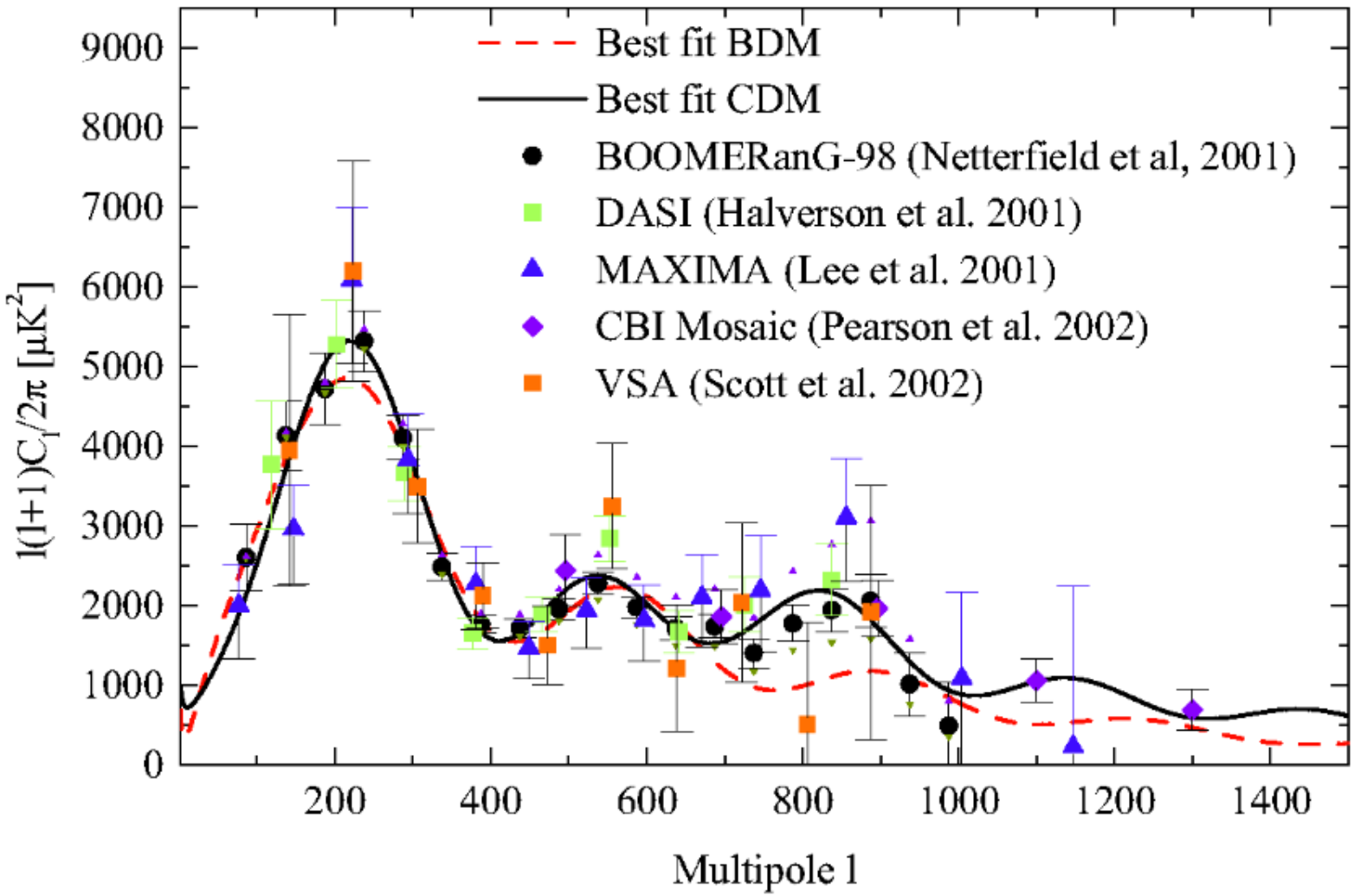
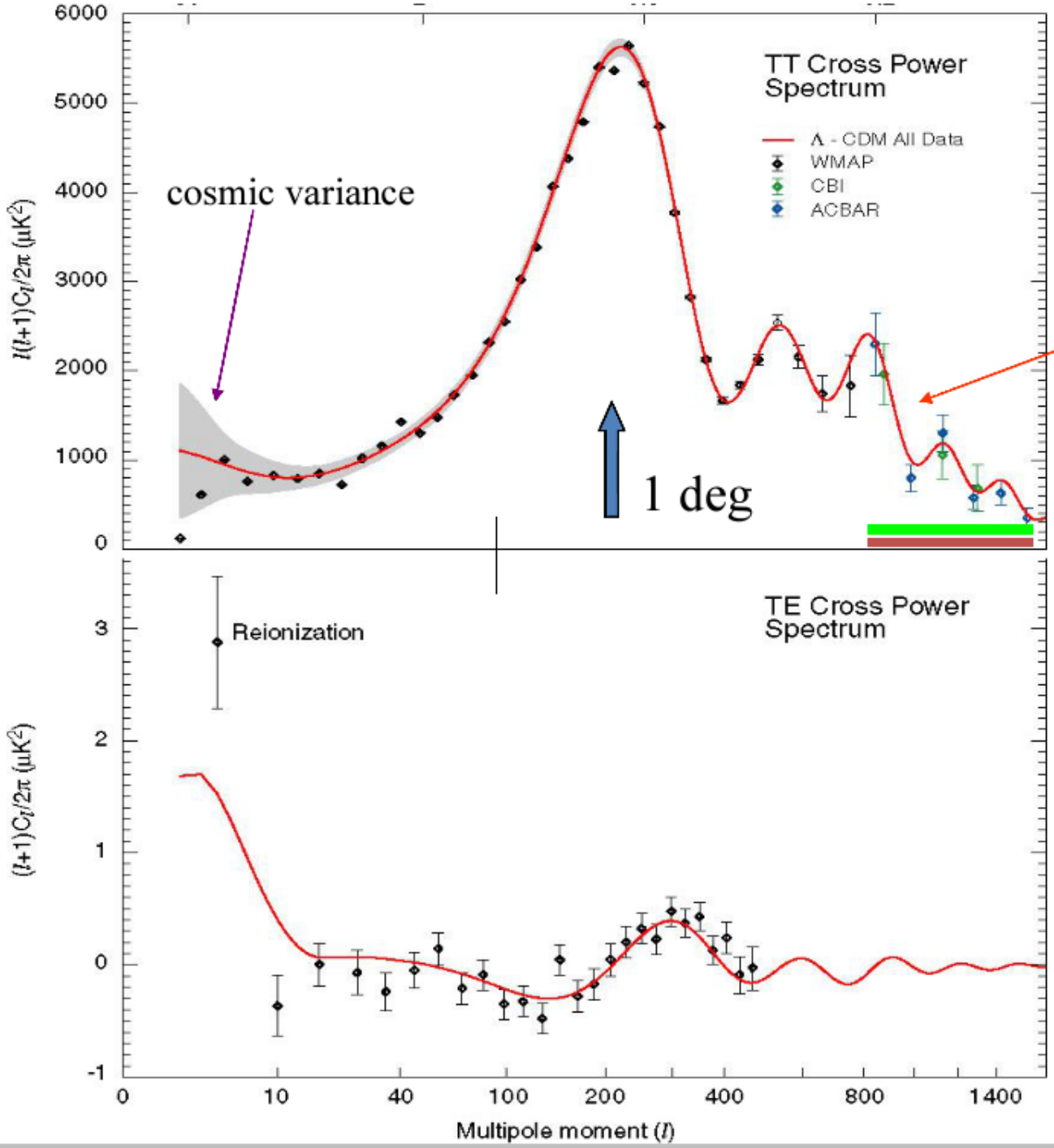
A Brief History of the CMB Anisotropies Angular Spectrum (Experimental Data)



Collection of CMB anisotropy data from C. Lineweaver et al., 1996

CMB anisotropies pre-WMAP (January 2003)





Temperature

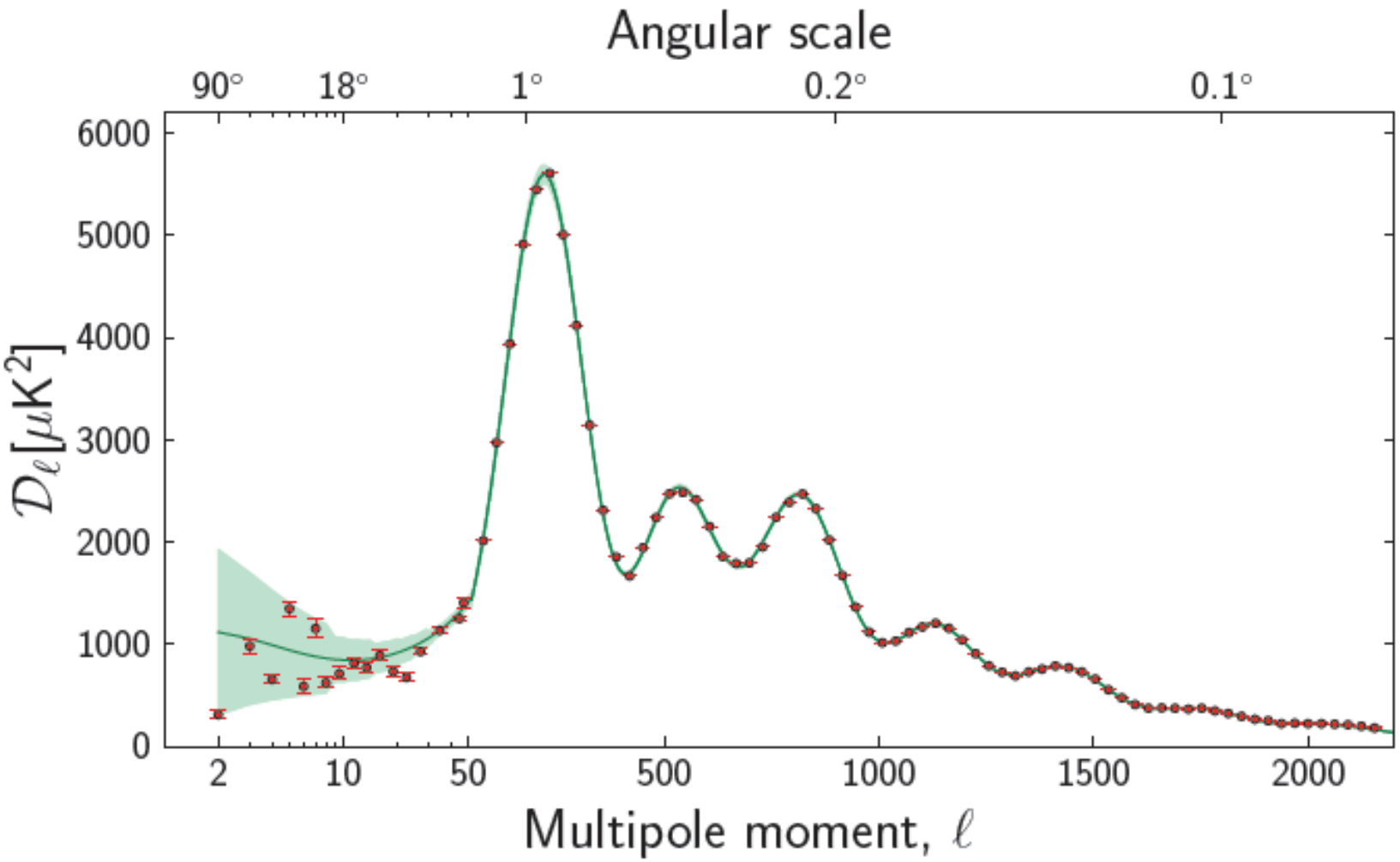
85% of sky

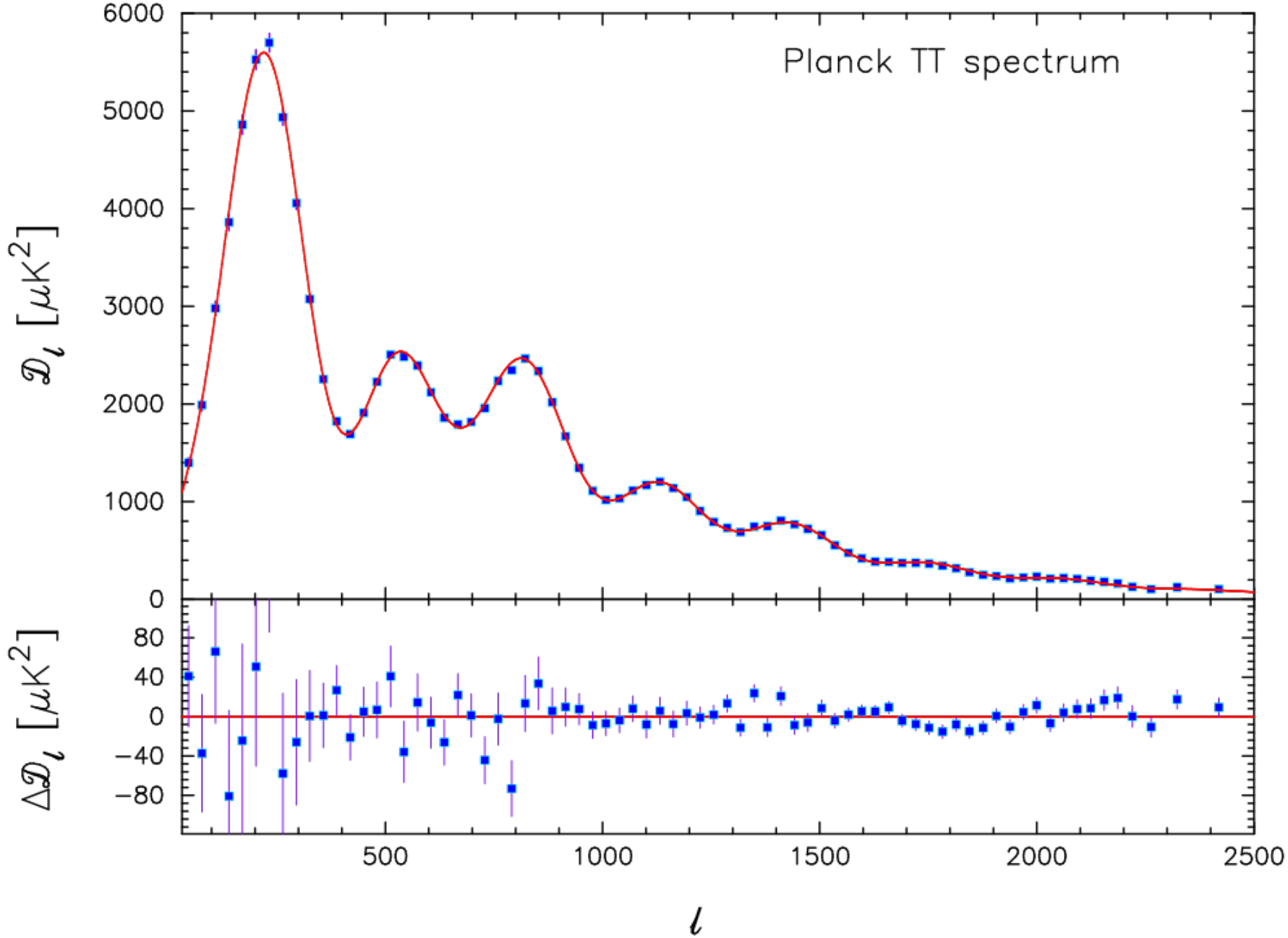
Best fit model

Spergel et al, 2003

Temperature-polarization

Planck 2013 TT angular spectrum




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

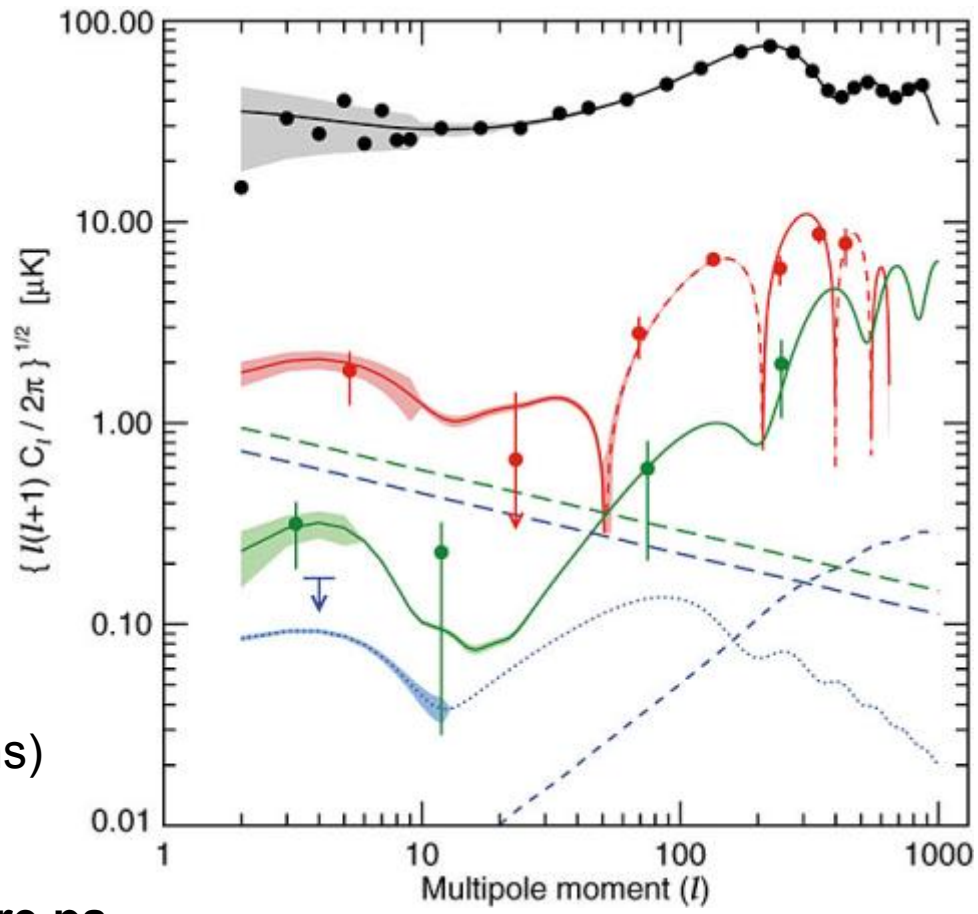
The CMB Angular Power Spectrum

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

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

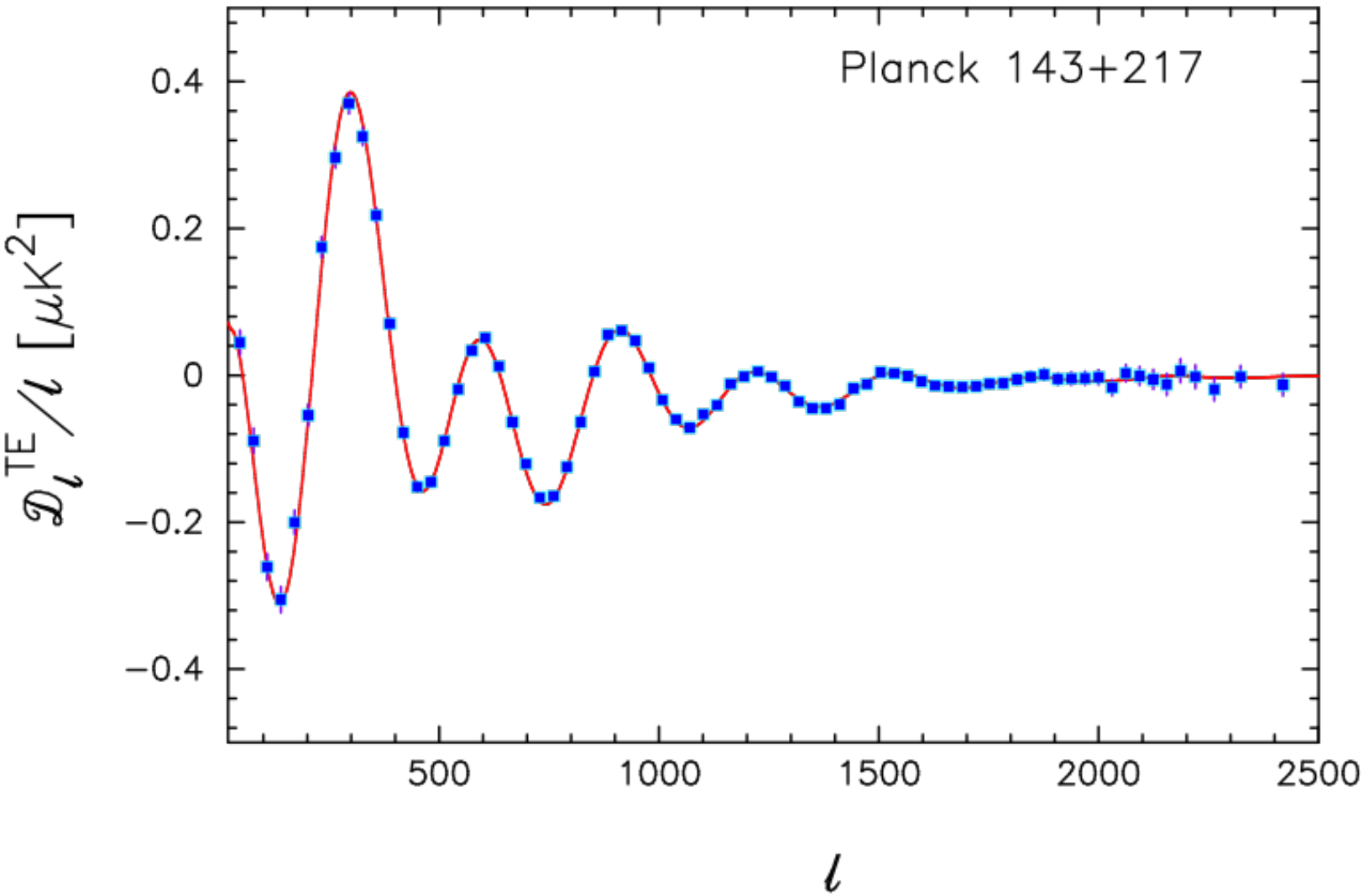
We can extract 4 independent angular spectra from the CMB:

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



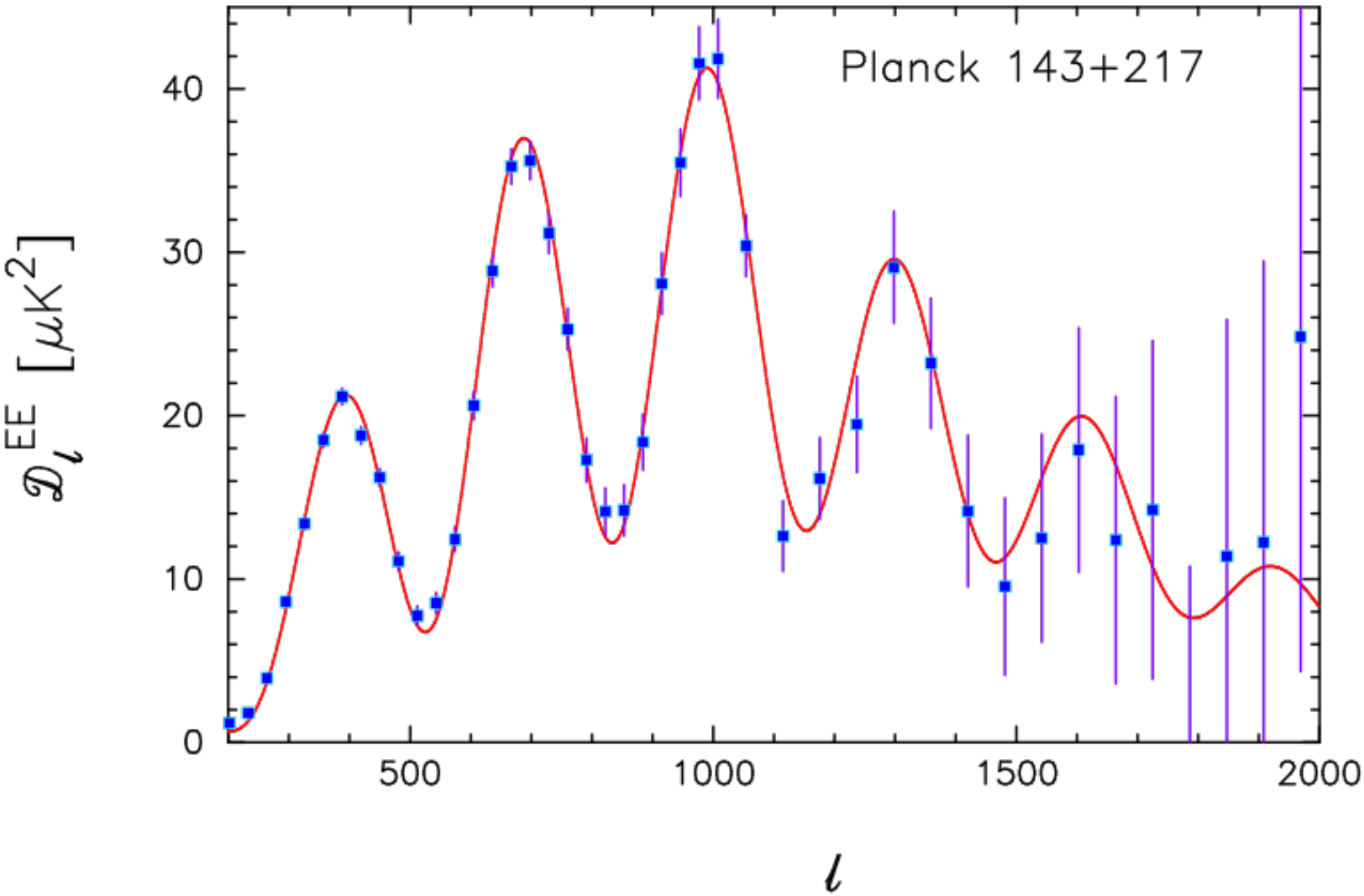
Planck 2013 release is only temperature ps.

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



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

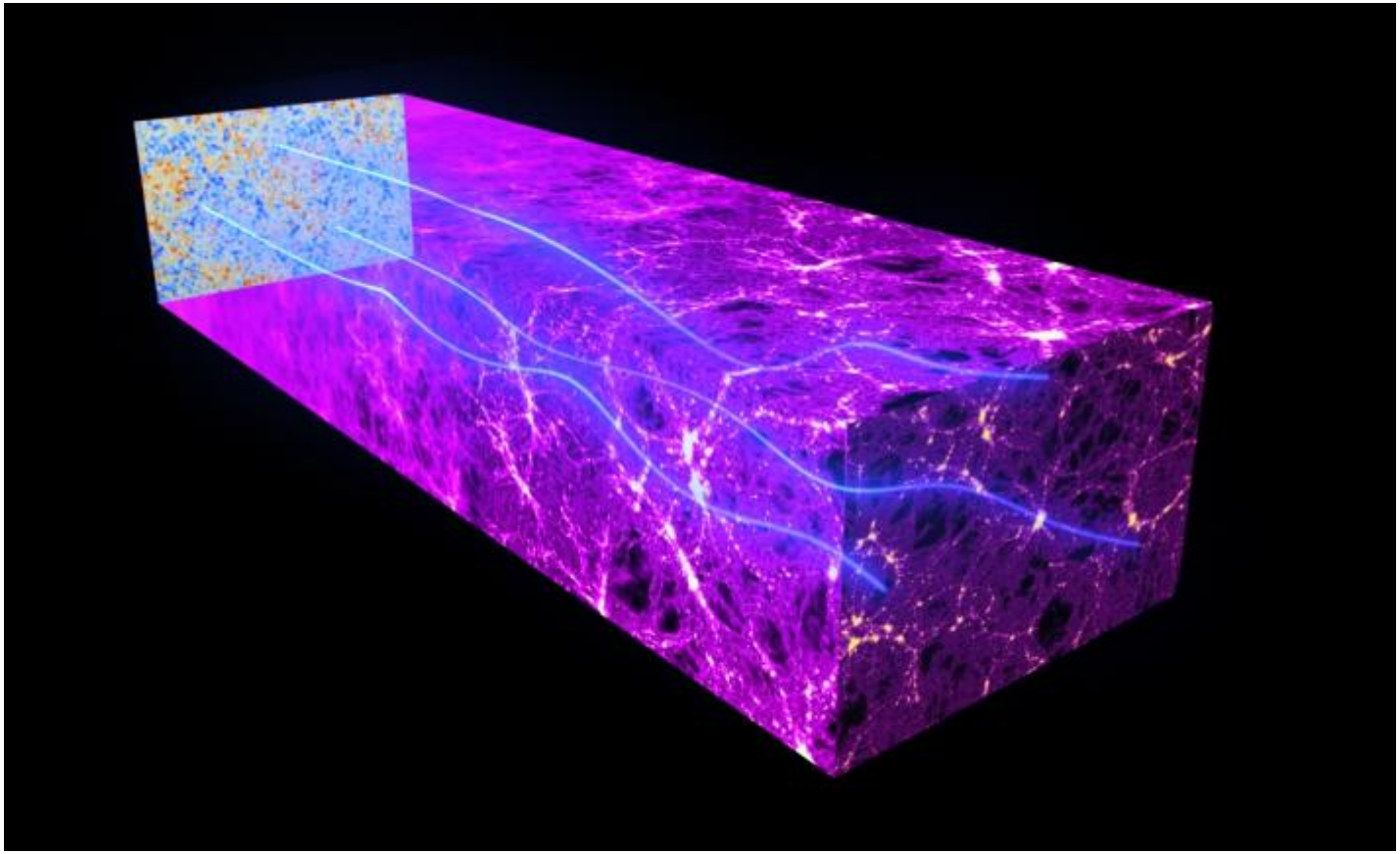
Polarization spectrum
(not present in this release)



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

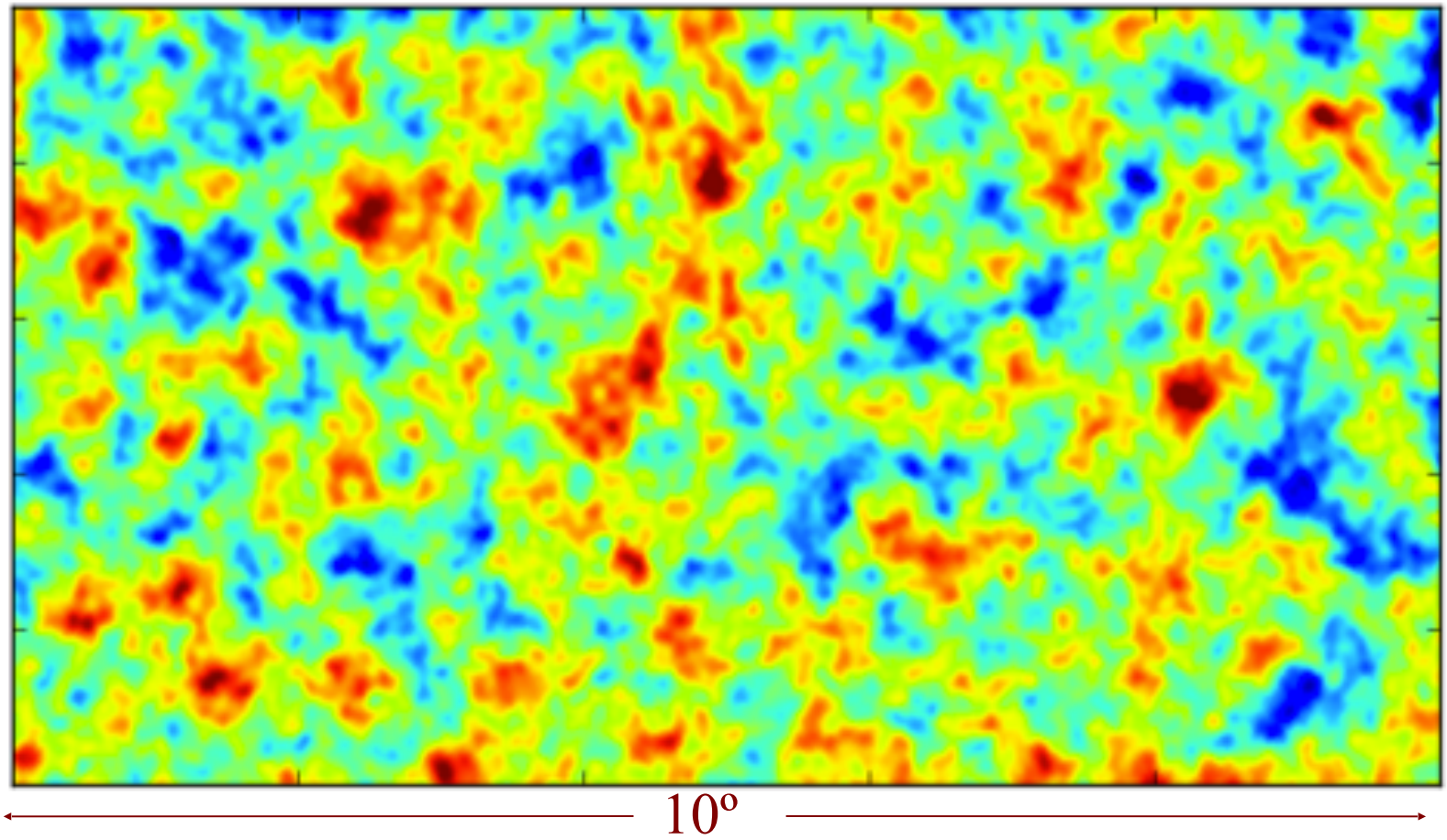
Gravitational Lensing

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



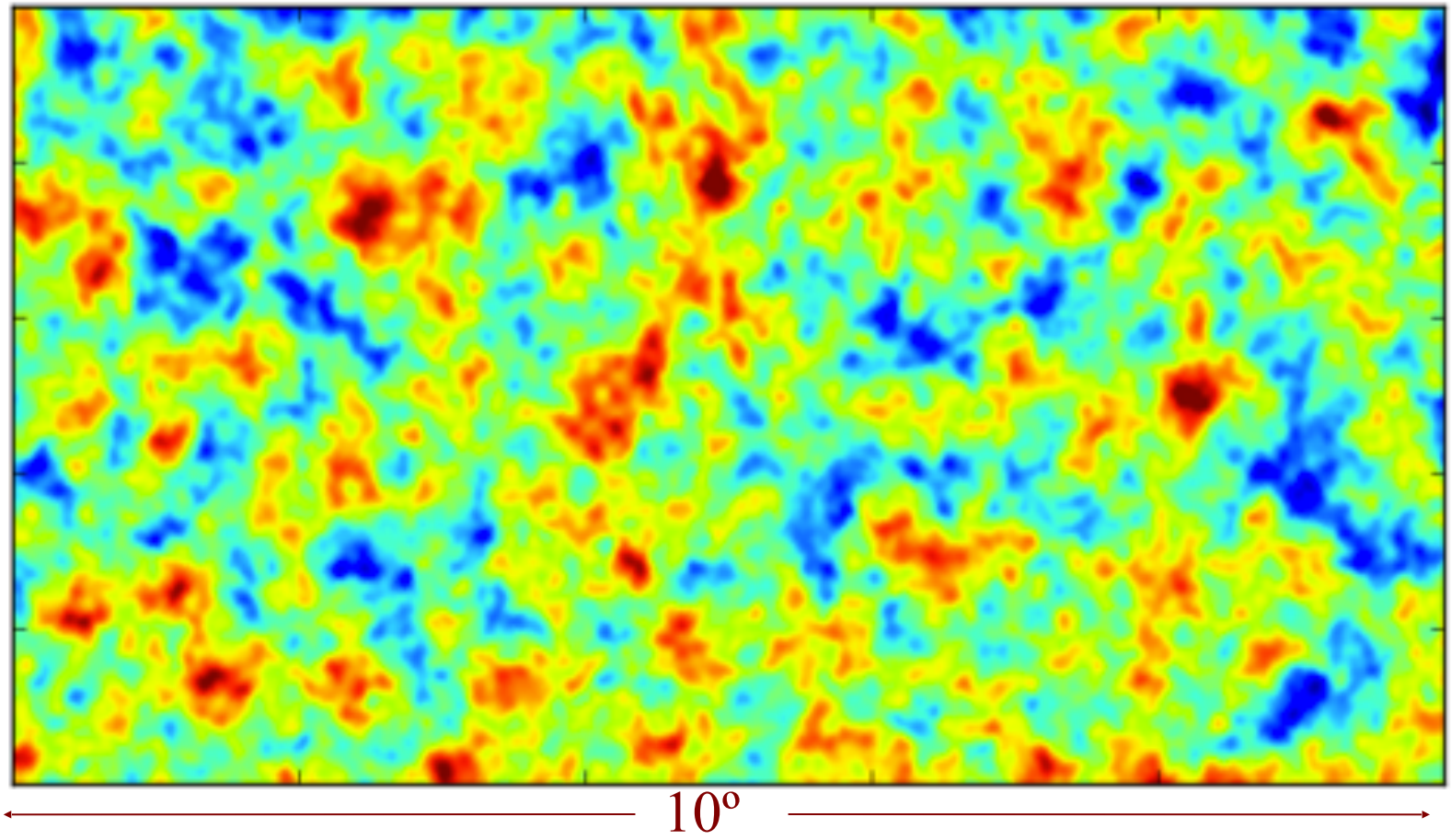
Gravitational Lensing

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

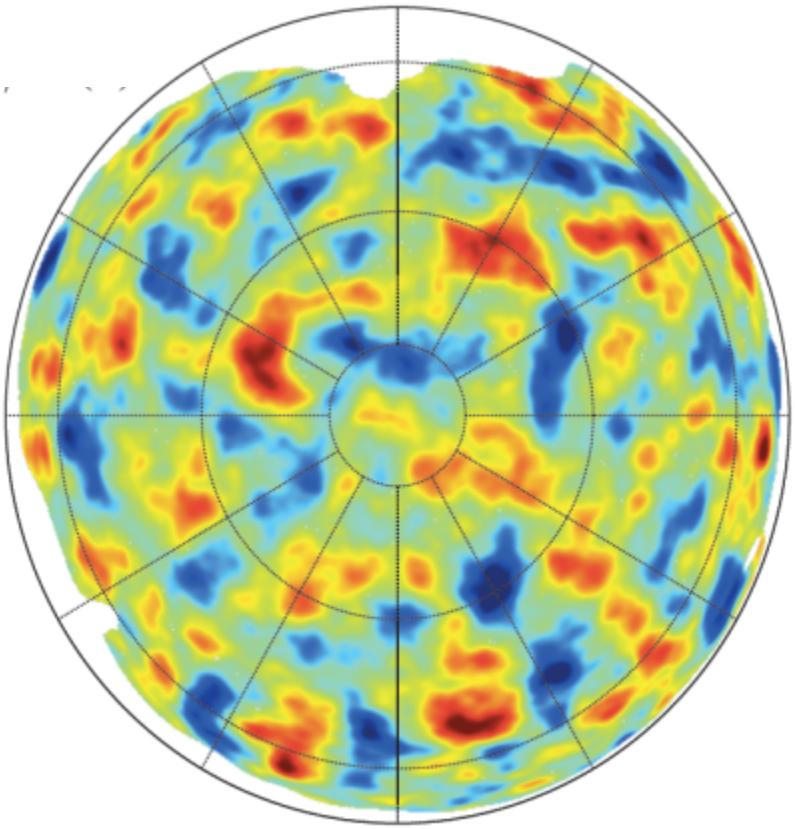


Gravitational Lensing

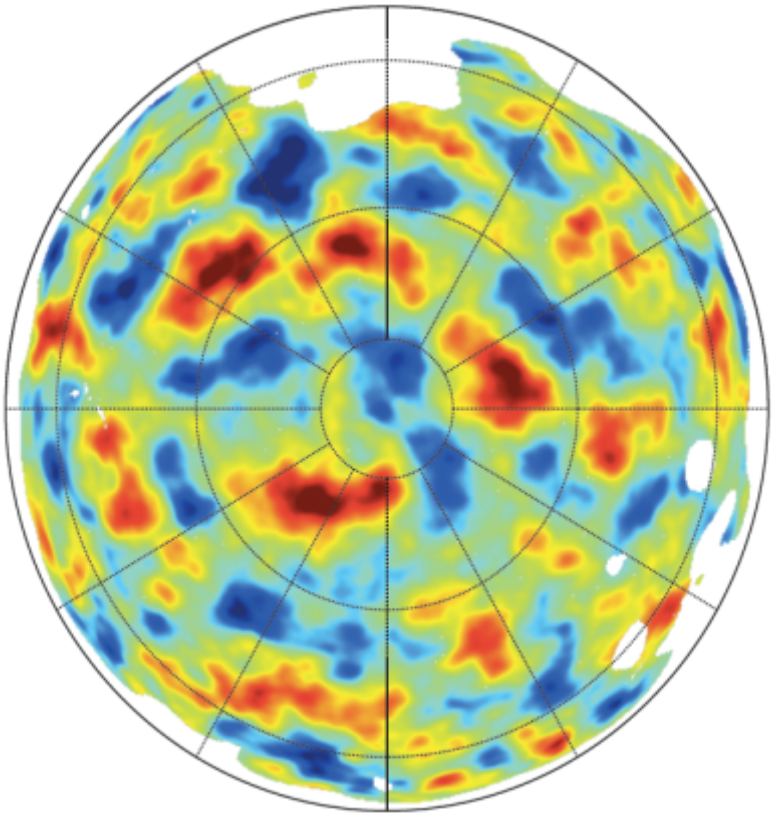
A simulated patch of CMB sky – **after lensing**



Planck dark matter distribution throught CMB lensing

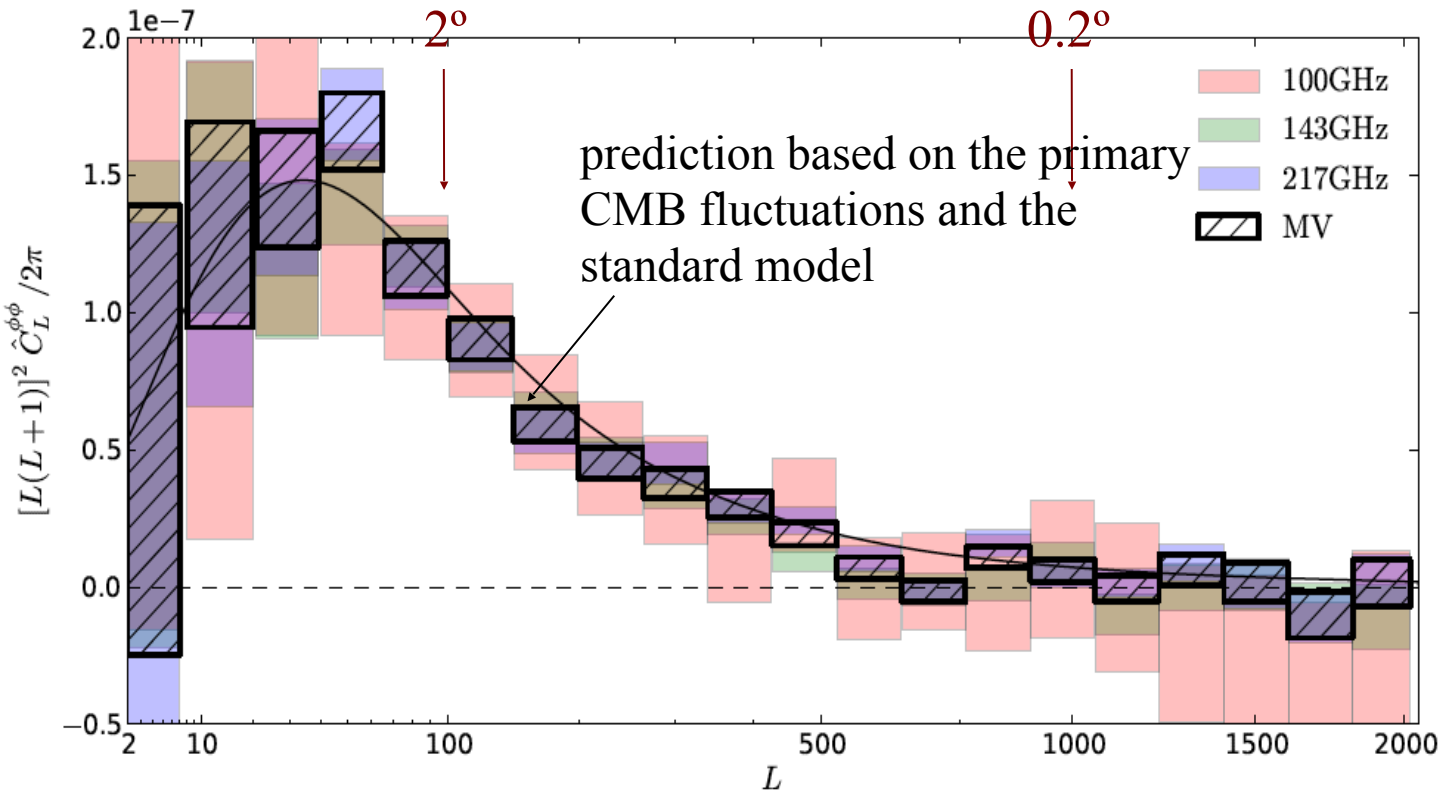


Galactic North



Galactic South

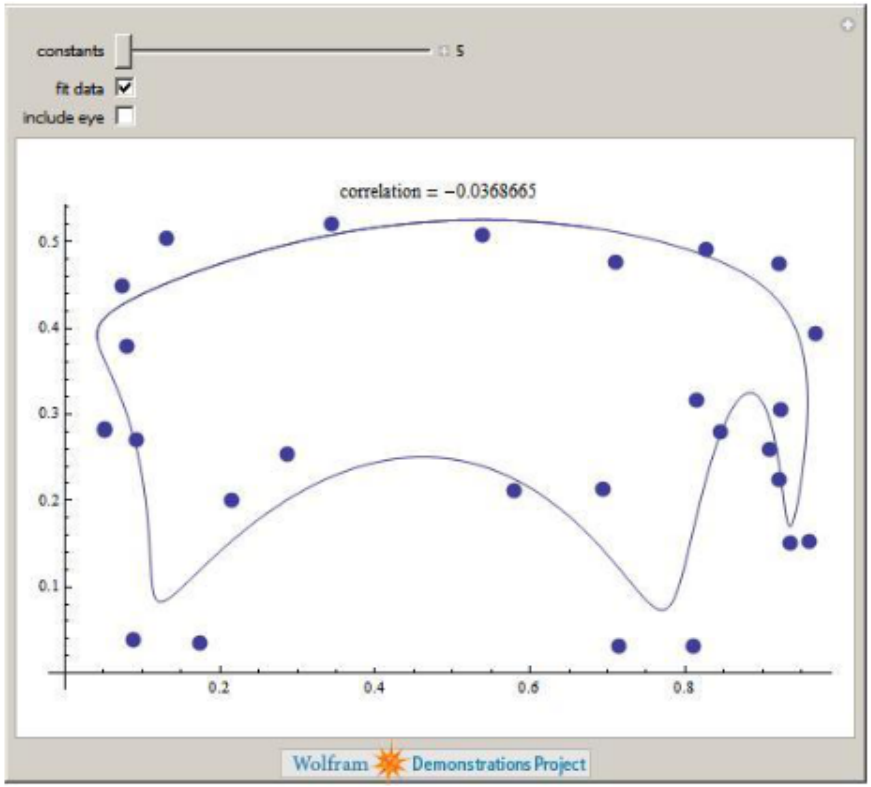
PLANCK LENSING POTENTIAL POWER SPECTRUM
Measured from the Trispectrum (4-point correlation)

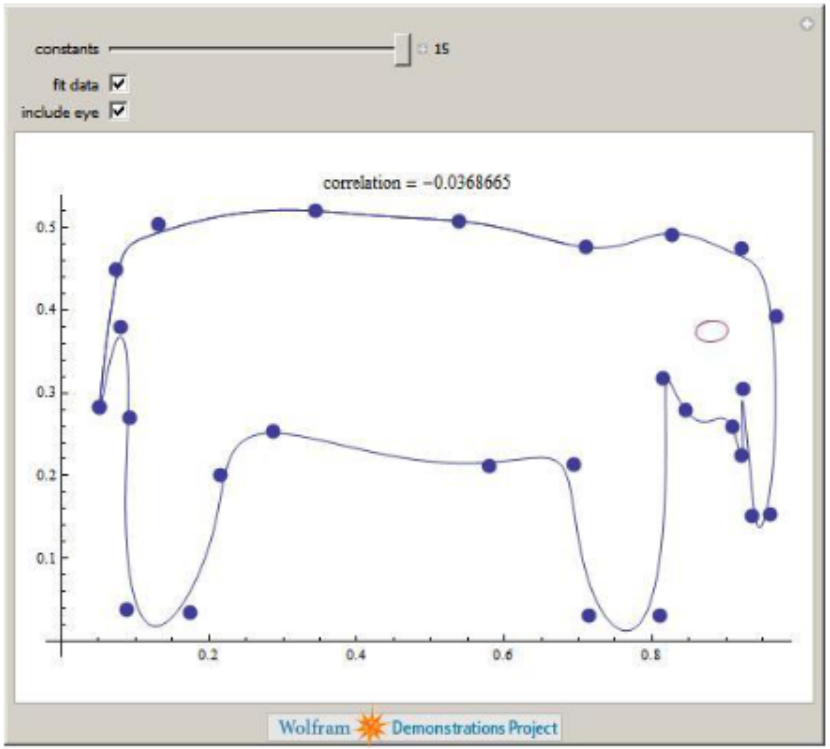


It is a 25 sigma effect!!
This spectrum helps in constraining parameters

How many parameters are needed to describe the CMB anisotropies ?

Enrico Fermi:"I remember my friend Johnny von Neumann used to say, 'with four parameters I can fit an elephant and with five I can make him wiggle his trunk.'"





The standard cosmological model

- Assumes General Relativity, Inflation, Adiabatic and Scalar Perturbations, flat universe.

- Friedmann-Robertson-Walker (or Friedmann-Lemaitre) metric. Hubble Constant (+1)

$$H_0 = 100h\ km/s/Mpc$$

- 3 Energy components: Baryons, Cold Dark Matter, Cosmological Constant (+3). Flat Universe (-1).

$$\omega_b = \Omega_b h^2 \quad \omega_{CDM} = \Omega_{CDM} h^2$$

- Initial conditions for perturbations given by Inflation: Adiabatic, nearly scale invariant initial power spectrum, only scalar perturbations. Two free parameters (+2): Amplitude and Spectral index.

$$P(k) \approx A_S \left(\frac{k}{k_0} \right)^{n_S}$$

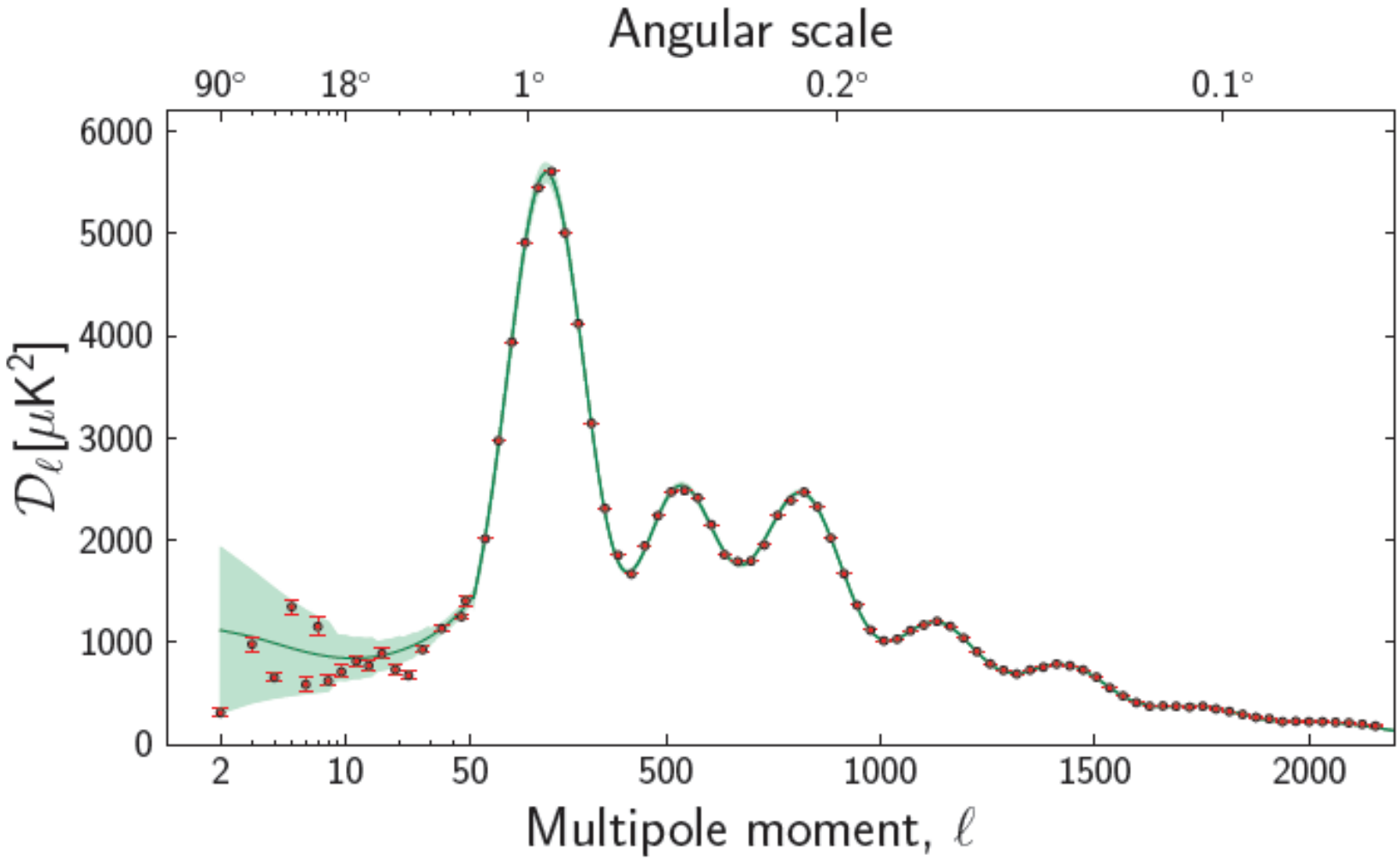
Pivot scale is usually fixed to:

$$k_0 = 0.002\ \ hMpc^{-1}$$

- Late universe reionization characterized with a single parameter(+1) : optical depth τ or reionization redshift z_r.

Total: 1+3-1+2+1= 6 parameters.

Planck 2013 TT angular spectrum



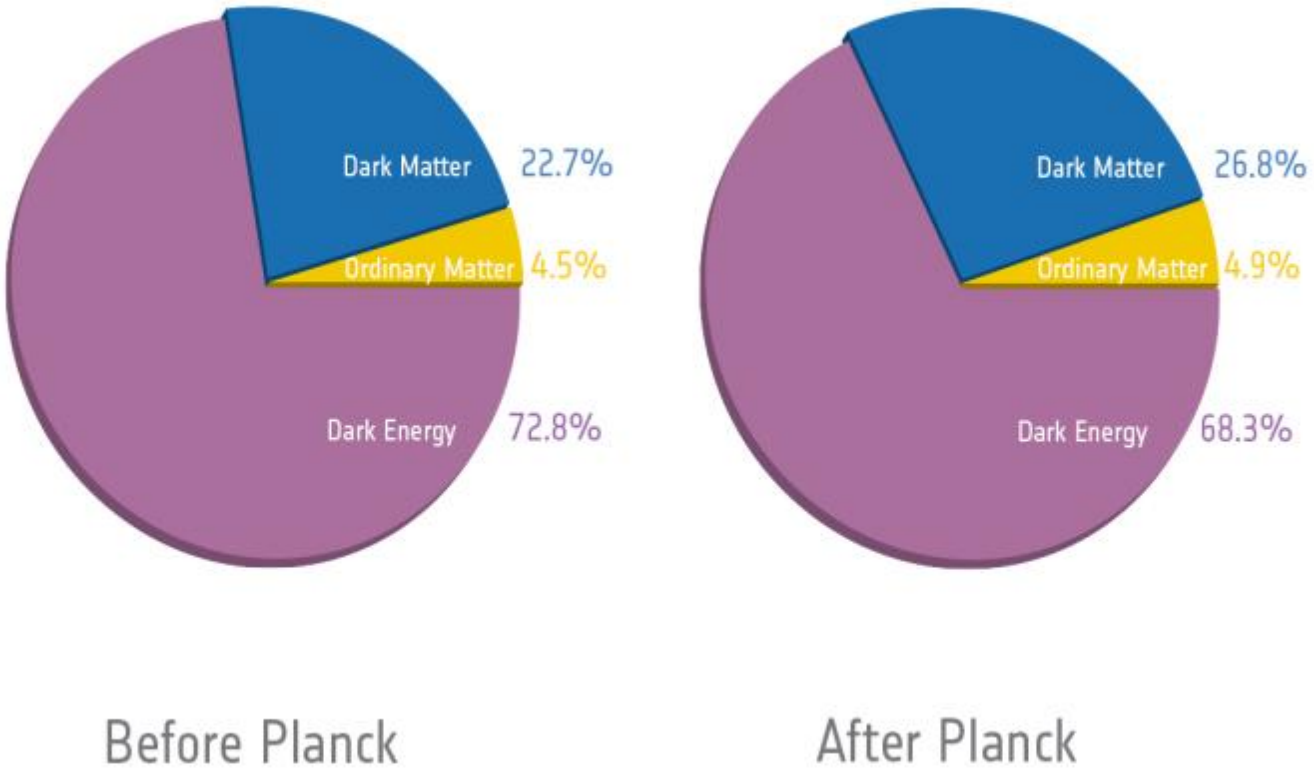
Constraints

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10}A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	[illegible]	[illegible]	[illegible]	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	[illegible]	[illegible]	[illegible]	0.8347	0.829 ± 0.012
z_{re}	11.35	[illegible]	[illegible]	[illegible]	11.37	11.1 ± 1.1
H_0	67.11	[illegible]	[illegible]	[illegible]	67.04	67.3 ± 1.2

WMAP9

Parameter	Nine-year
Fit parameters	
$\Omega_b h^2$	0.02264 ± 0.00050
$\Omega_c h^2$	0.1138 ± 0.0045
Ω_Λ	0.721 ± 0.025
$10^9 \Delta^2_{\mathcal{R}}$	2.41 ± 0.10
n_s	0.972 ± 0.013
τ	0.089 ± 0.014
Derived parameters	
t_0 (Gyr)	13.74 ± 0.11
H_0 (km/s/Mpc)	70.0 ± 2.2
σ_8	0.821 ± 0.023
Ω_b	0.0463 ± 0.0024
Ω_c	0.233 ± 0.023
z_{reion}	10.6 ± 1.1

The basic content of the Universe



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Astronomers determined that the universe is actually 13.8 billion years old, about 80 to 100 million years older than previously believed, and that it is also a bit wider than once thought. What do *you* think?

"How embarrassing."

Victoria Rosegard –
Street Cleaner

"Typical. You give birth to a few trillion galaxies and then people just talk about how old and fat you've gotten."

"Just like it says in Leviticus."

Chris Vanderhorst –
Systems Analyst

Constraints on LCDM

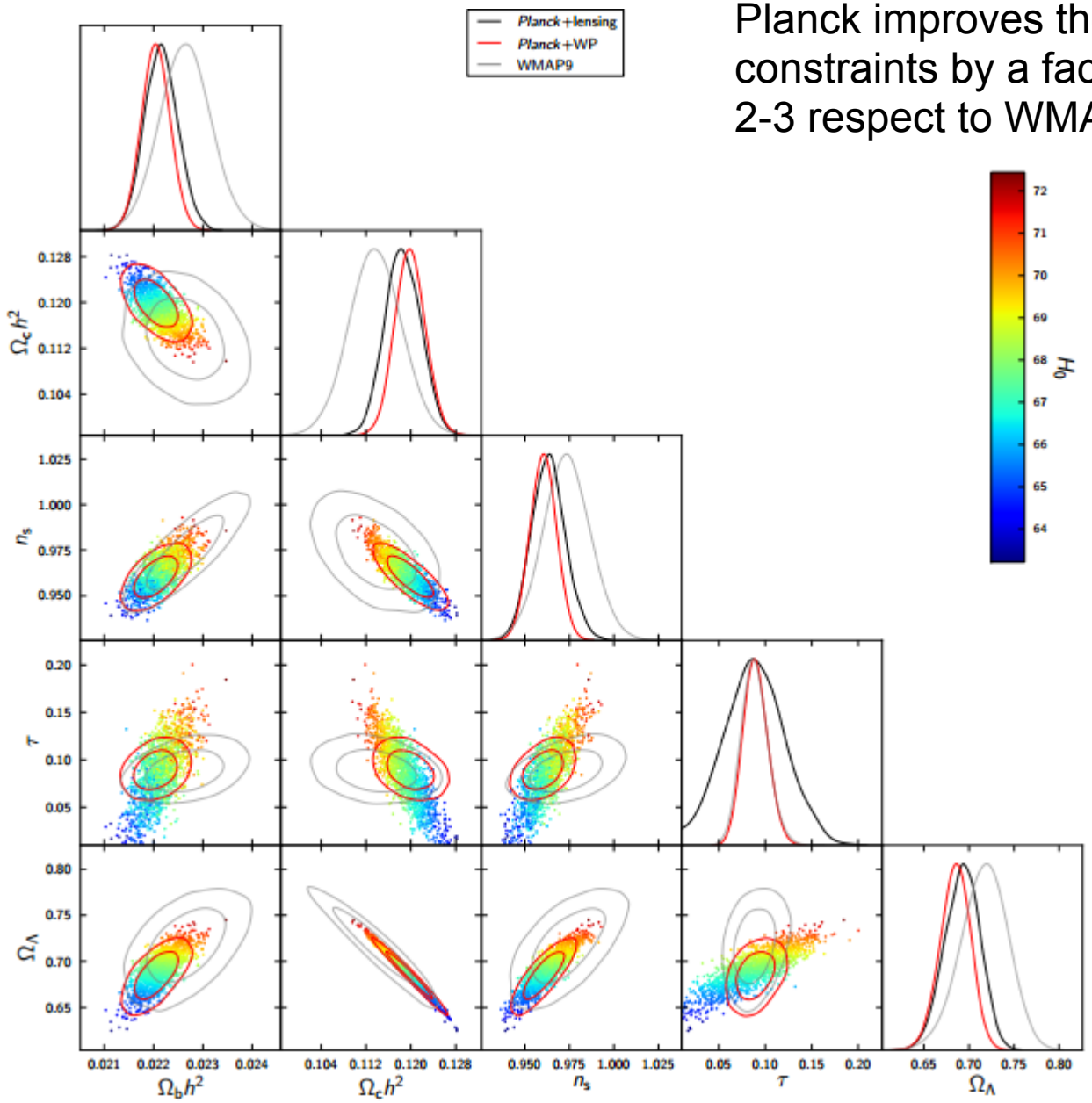
Planck improves the constraints by a factor 2-3 respect to WMAP9

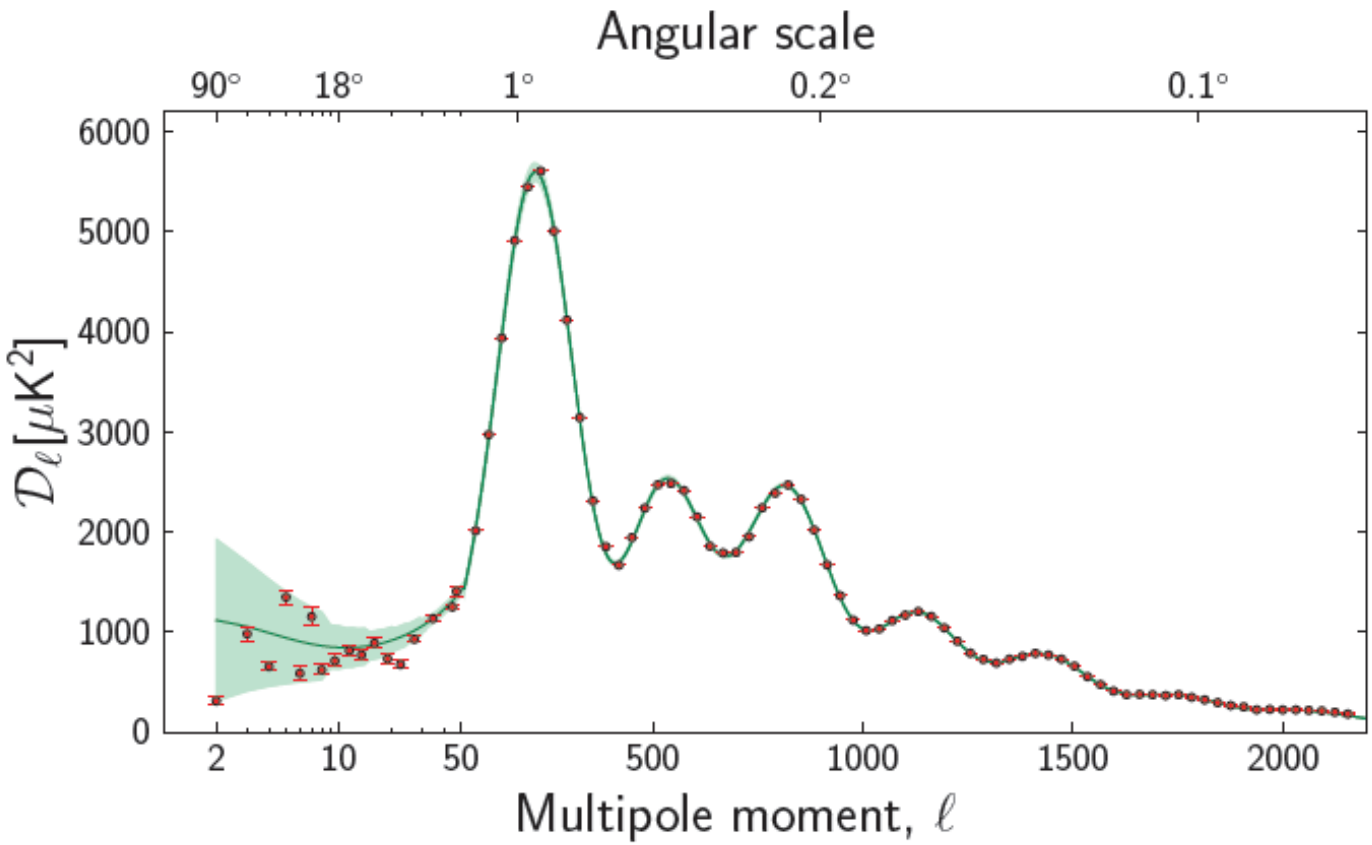
Lower Baryon Density

Higher CDM Density

Lower Spectral index

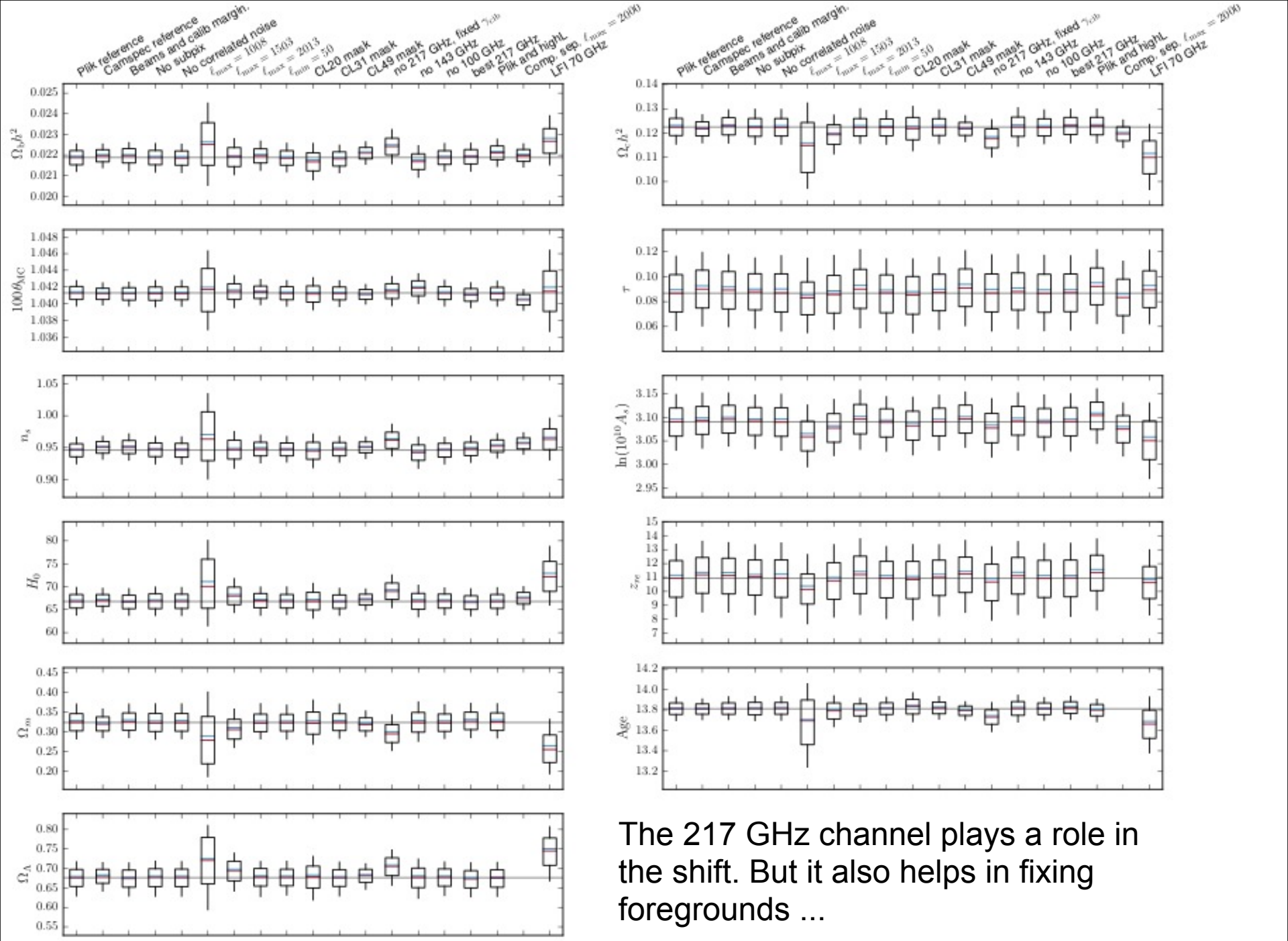
Smaller Cosmological Constant





Why we see this shift ?

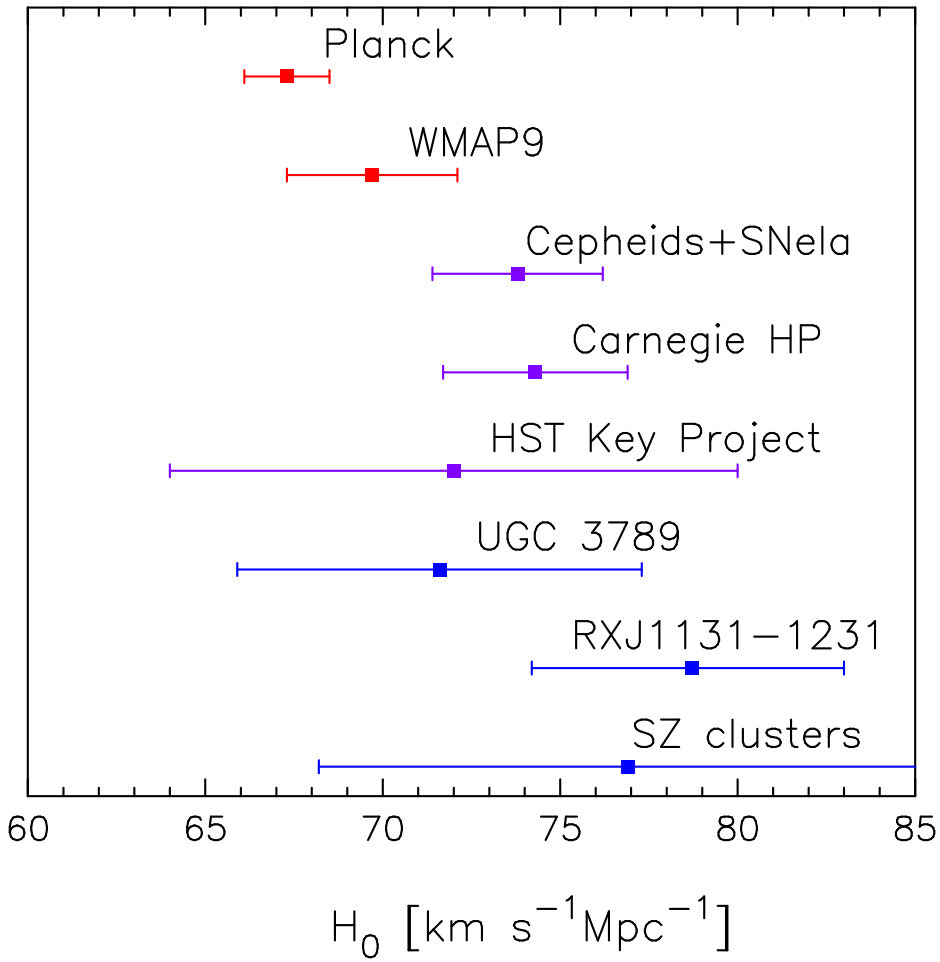
- Planck at WMAP resolution gives similar answer to WMAP.
- Shift is compatible in between two standard deviation.
- Not clear if connected with systematic at high-l or to anomalies at low-l. Planck high-l data makes these anomalies more significant.



The 217 GHz channel plays a role in the shift. But it also helps in fixing foregrounds ...

Comparison with other datasets: Hubble Constant

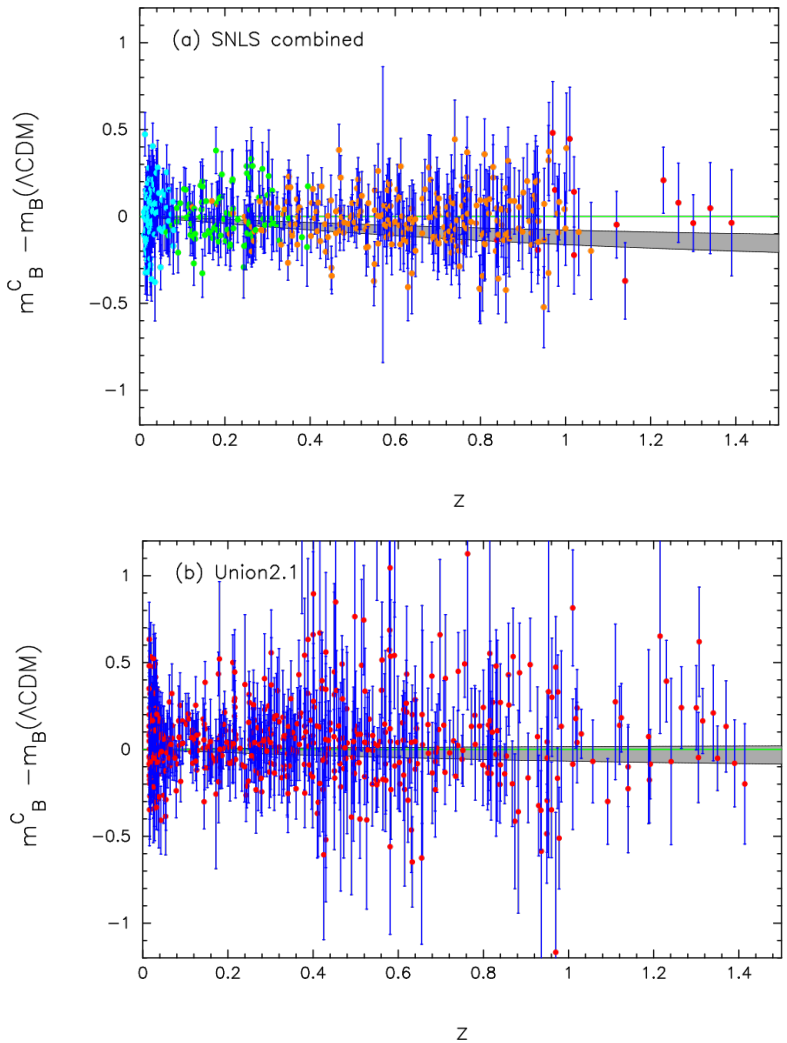
The value of the Hubble constant from Planck is in tension with the Riess et al. 2011 result.

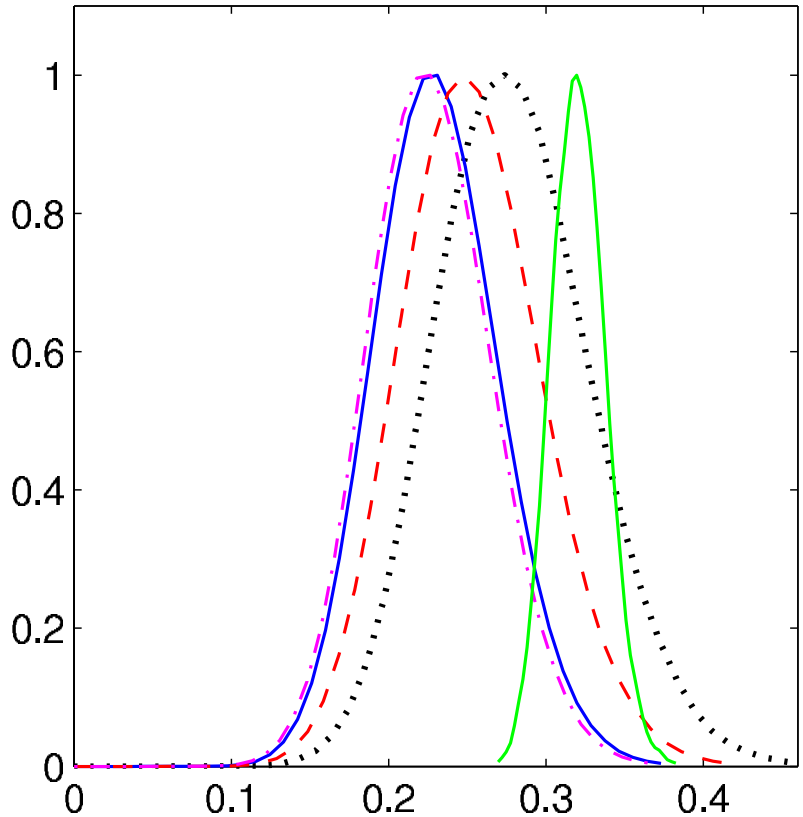


Planck + WP $H_0 = 67.3^{+1.2}_{-1.1}$ [km/s/Mpc]

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

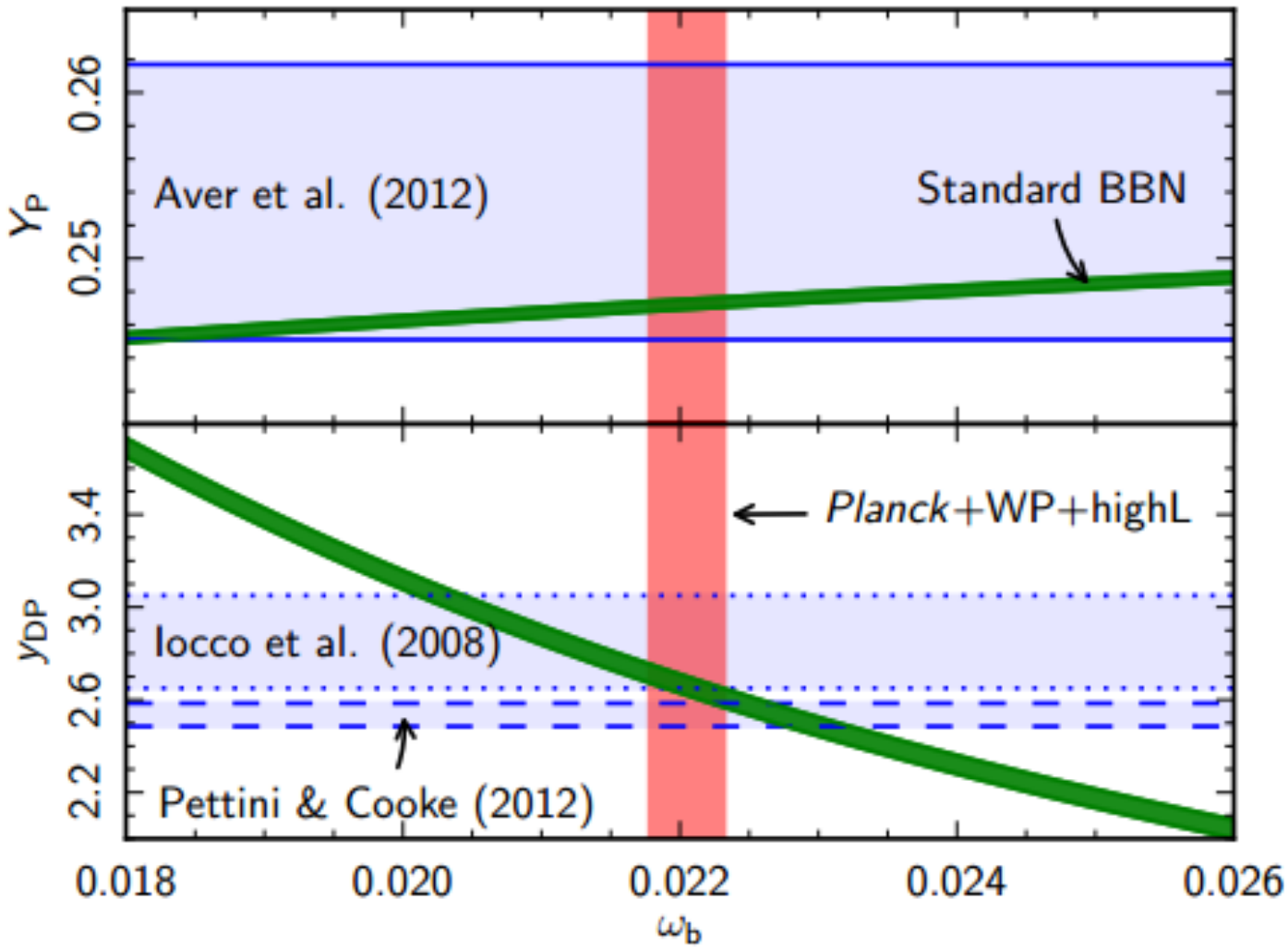
Comparison with SN-Ia data





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 BBN and primordial He and D



Very good agreement. Lower baryon density. But the recent Pettini and Cooke D measurement is a bit too low for Planck (1 sigma tension).

Should we care about a 2-3 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 $3.5° \pm 1.0°$ 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

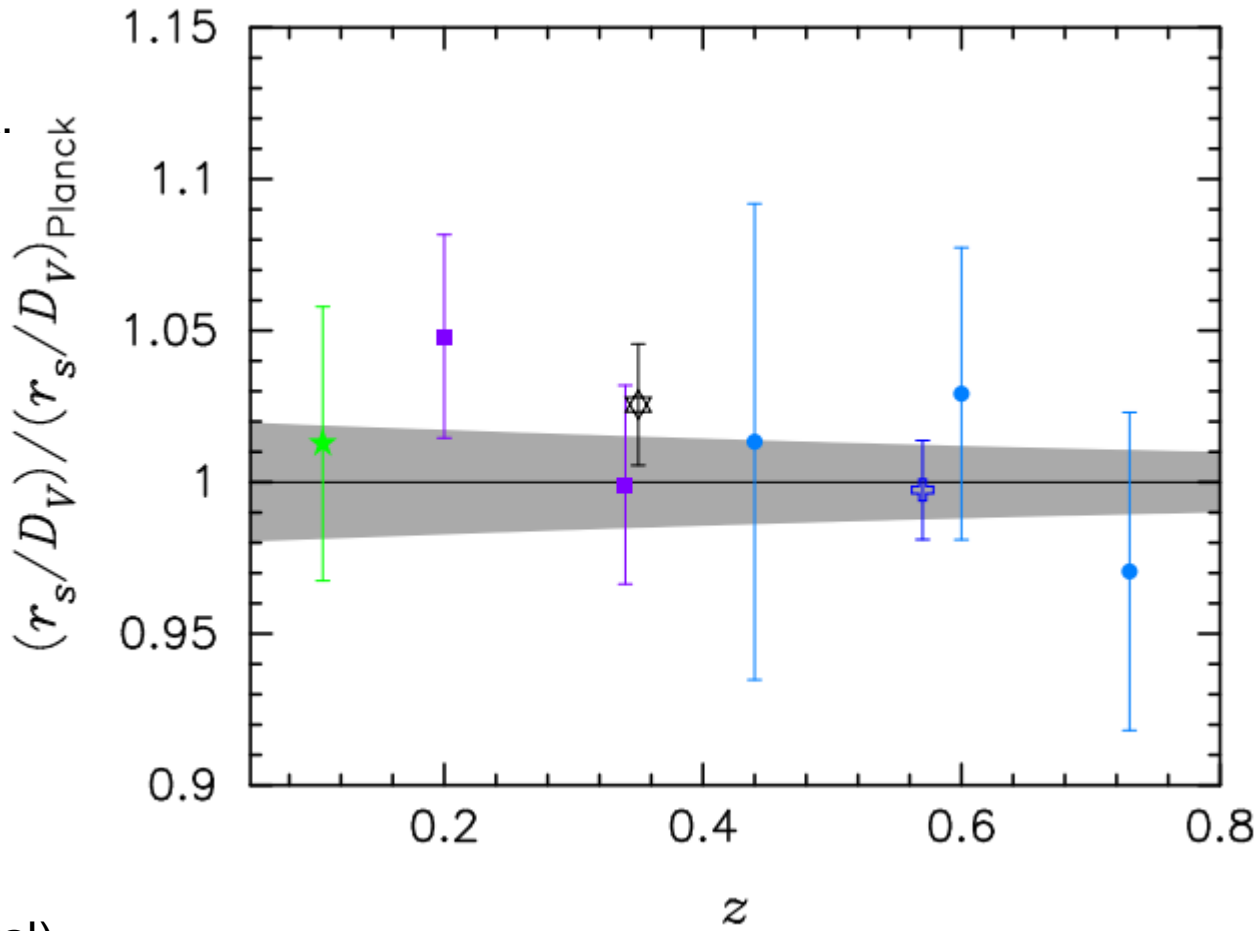
of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8σ

Discovery of the accelerating universe was made at 2.8 σ !

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

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:

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

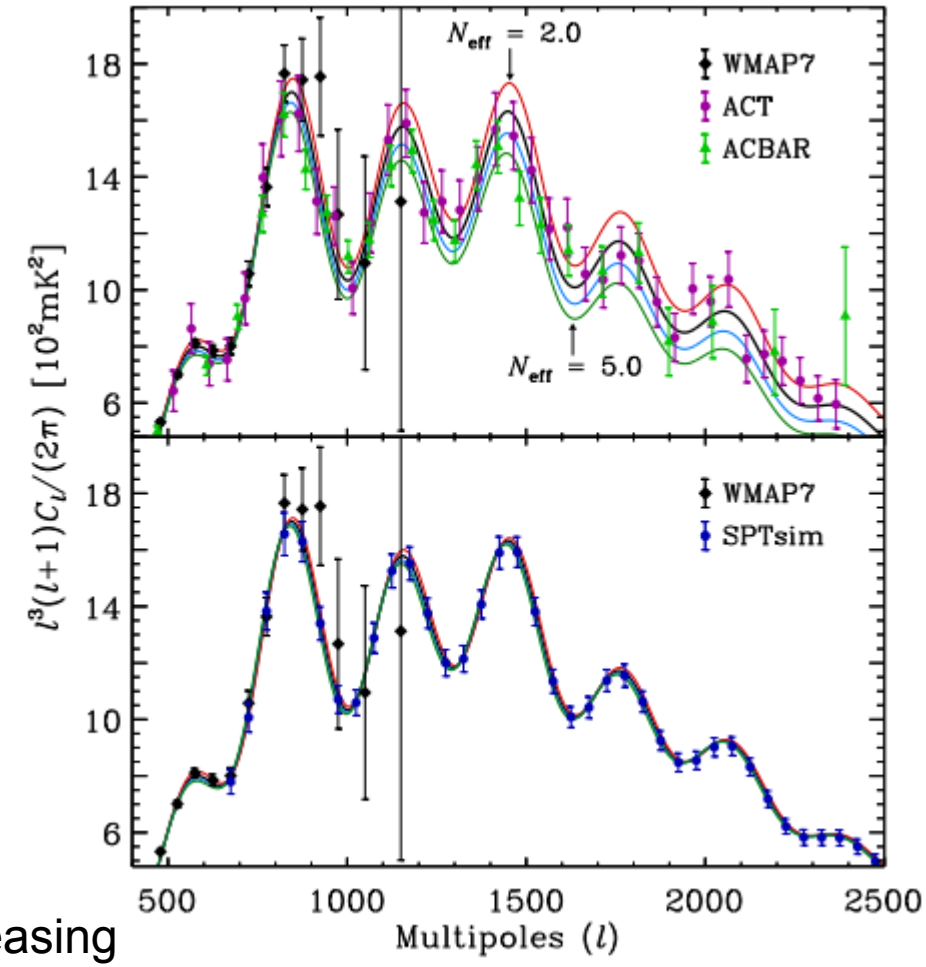
Probing the Neutrino Number with CMB data

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_{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.)

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

Conclusions:

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

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

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

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

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

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.):

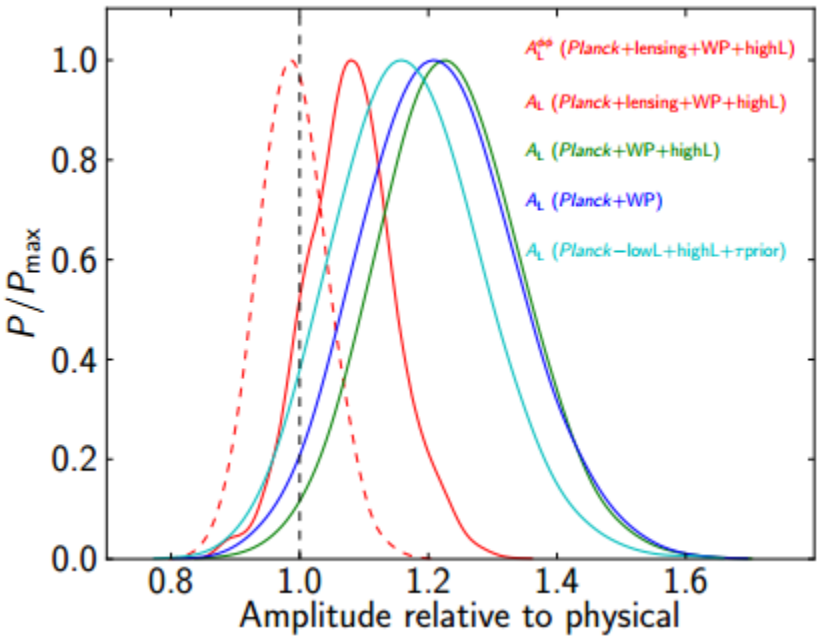
Planck + WP	$H_0 = 67.3^{+1.2}_{-1.1}$ [km/s/Mpc]
HST (Riess et al.)	$H_0 = 73.8^{+2.4}_{-2.4}$ [km/s/Mpc]

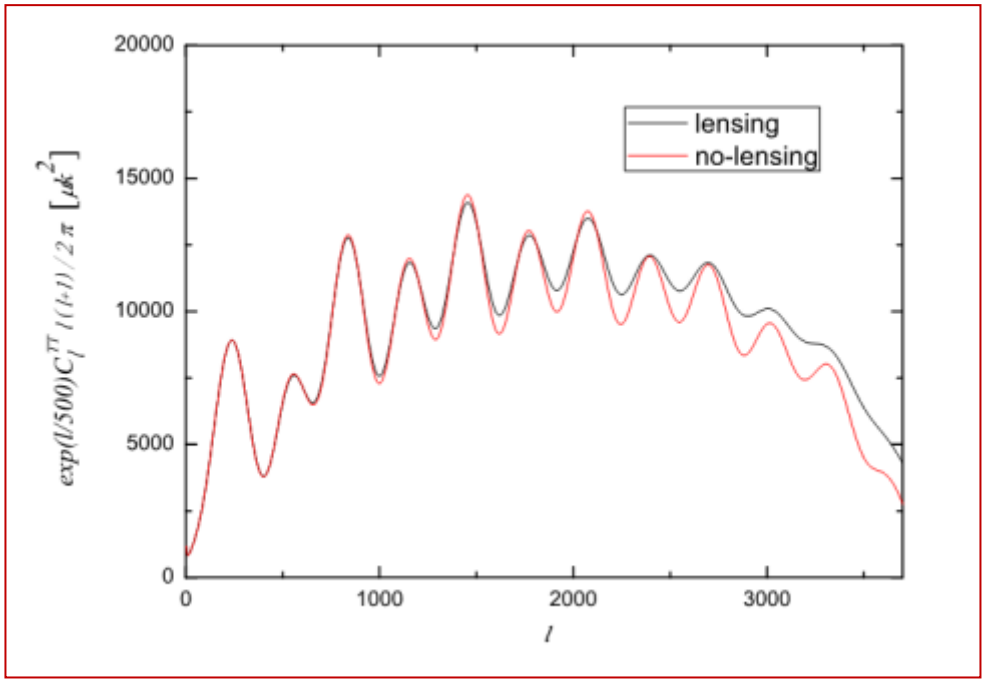
But the Planck result is obtained under the assumption of N_{eff}=3.046.
If leave N_{eff} as a free parameter we get:

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

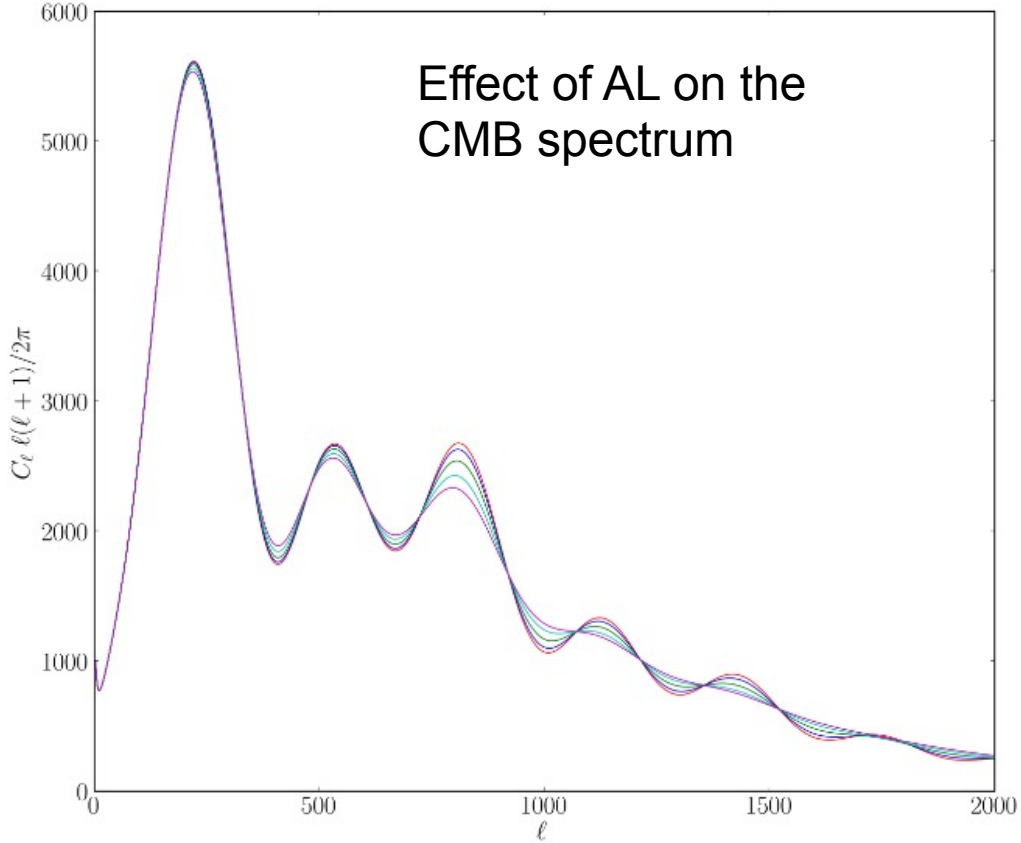
That is now compatible with HST (but we now need dark radiation).
The CMB determination of the Hubble constant is **model dependent**.

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.

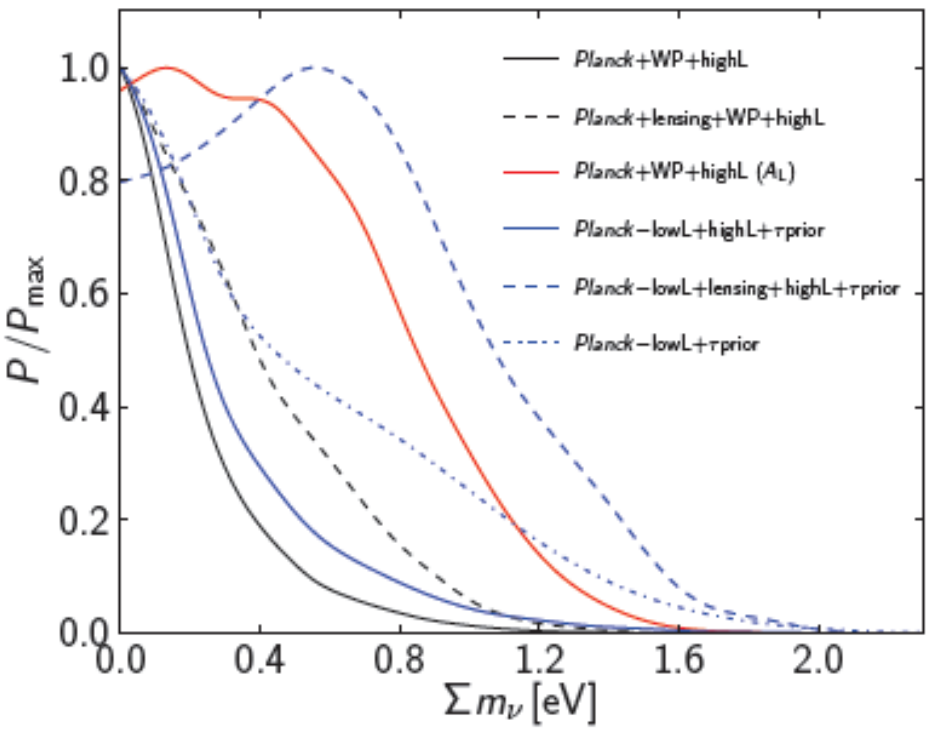


Calabrese, Slosar, Melchiorri, Smoot, Zahn, 2008

Varies with data cuts, can be > 3σ discrepant with $A_L = 1$!

Parameter	CamSpec 95% limits	Plik 95% limits	$l_{\rm max} = 2000$ 95% limits	$l_{\rm min} = 1200$ 95% limits	no 217×217 95% limits
$A_{\rm L}$	$1.23^{+0.22}_{-0.21}$	$1.26^{+0.26}_{-0.25}$	$1.38^{+0.26}_{-0.25}$	$1.31^{+0.24}_{-0.23}$	$1.30^{+0.24}_{-0.22}$

Constraints on Neutrino Mass (standard 3 neutrino framework)



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

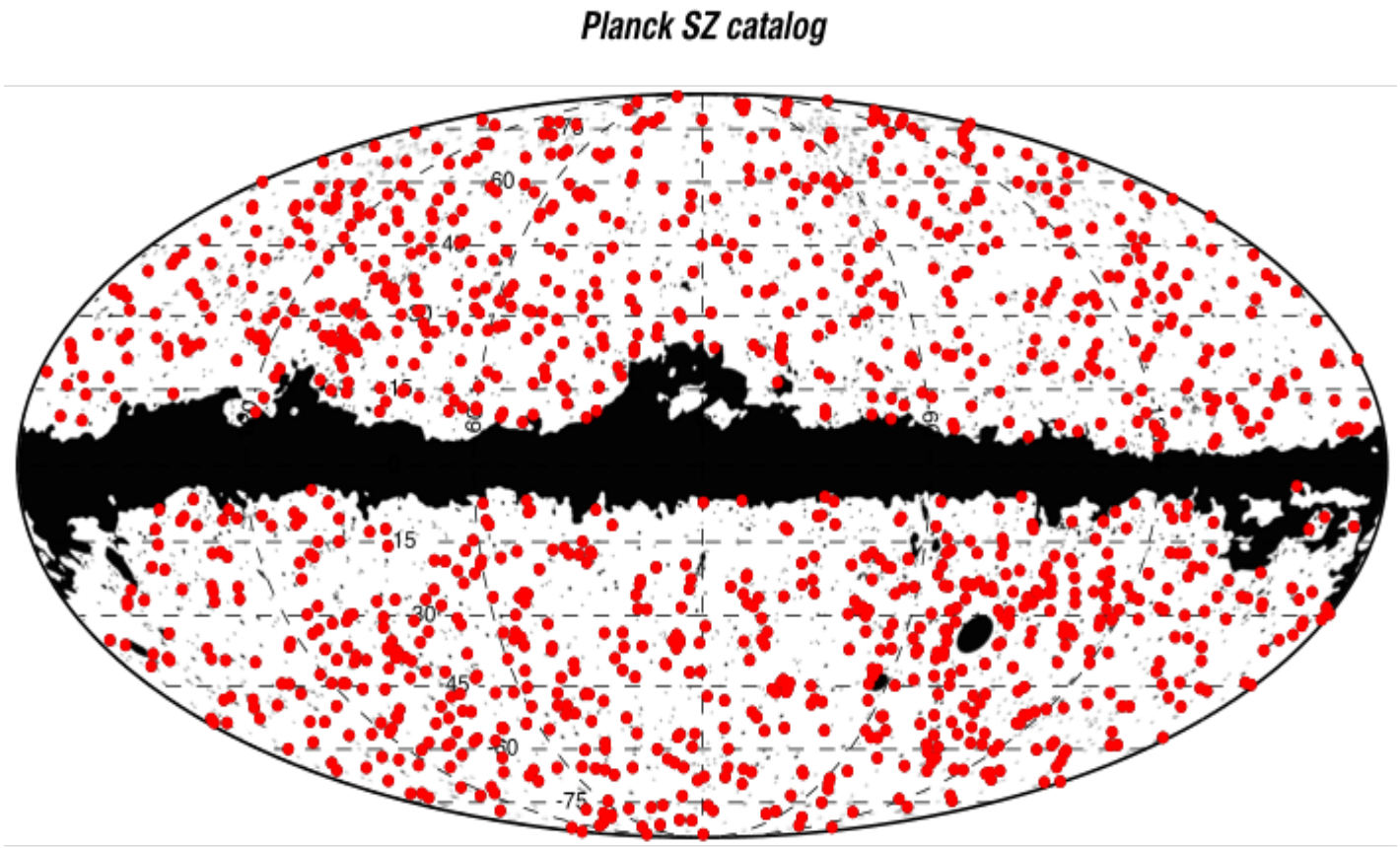
$$\sum m_\nu < 1.08\,\text{eV} \quad [95\%;\ \textit{Planck}+\text{WP}+\text{highL}\ (A_{\text{L}})],$$

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

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

- 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

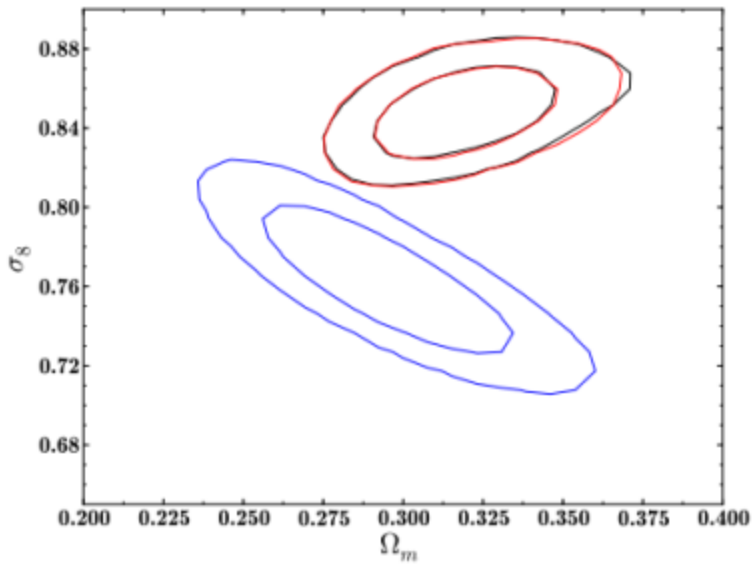
Clusters of galaxies

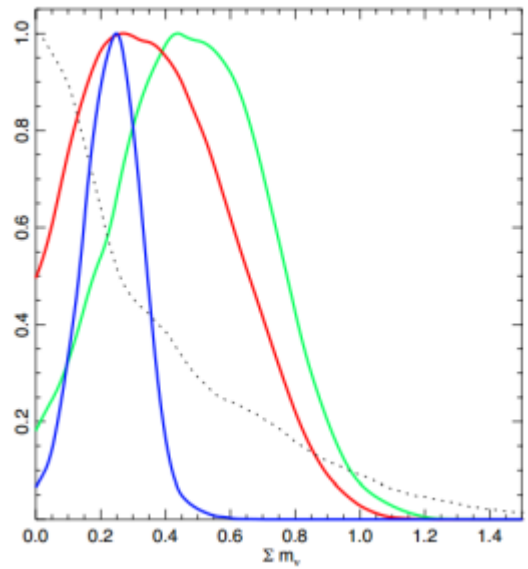


- 1227 clusters & candidates
  - 683 previously known
  - 178 new clusters
  - 366 candidates

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

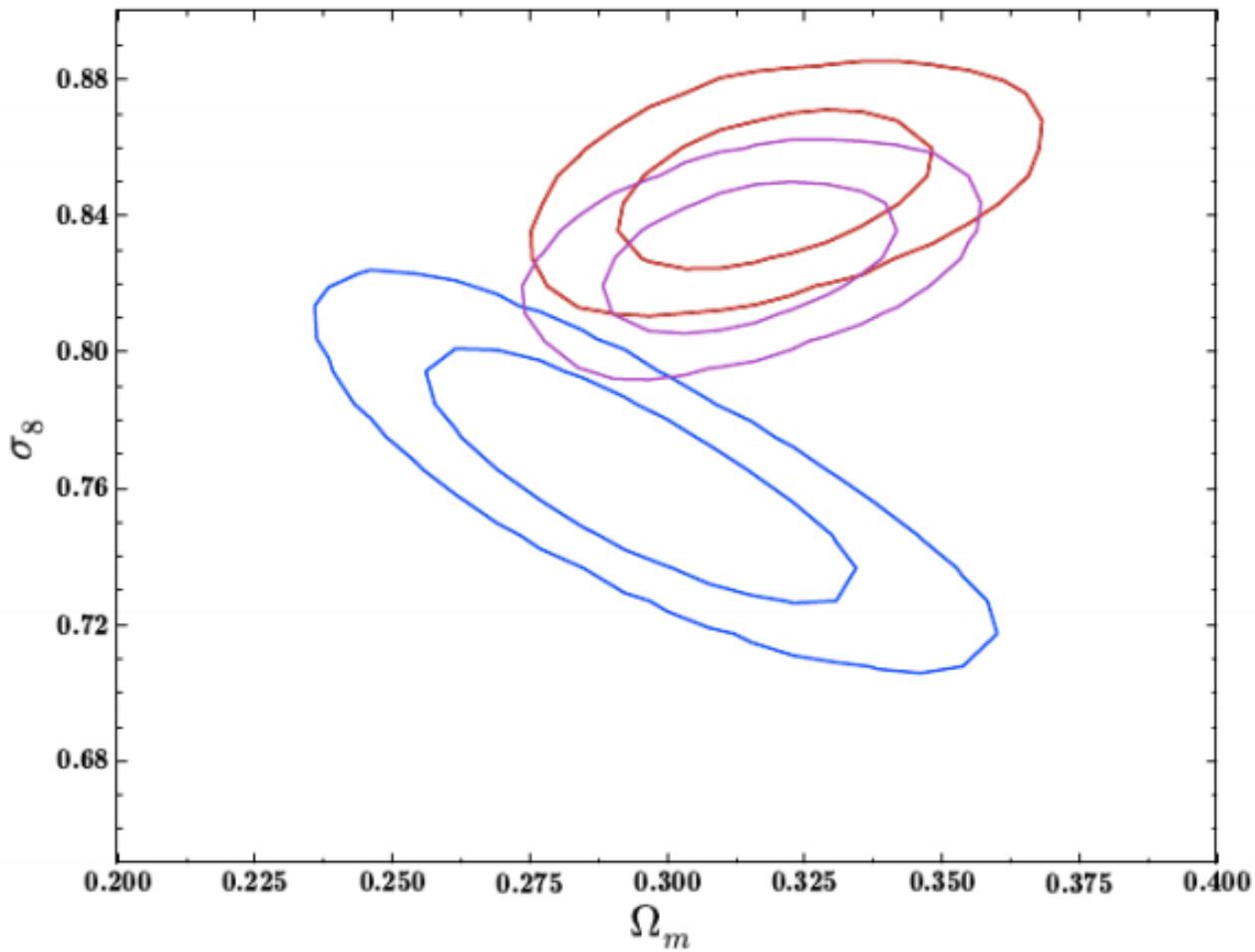
Green:
Planck CMB+SZ
(1-b)=0.8

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).

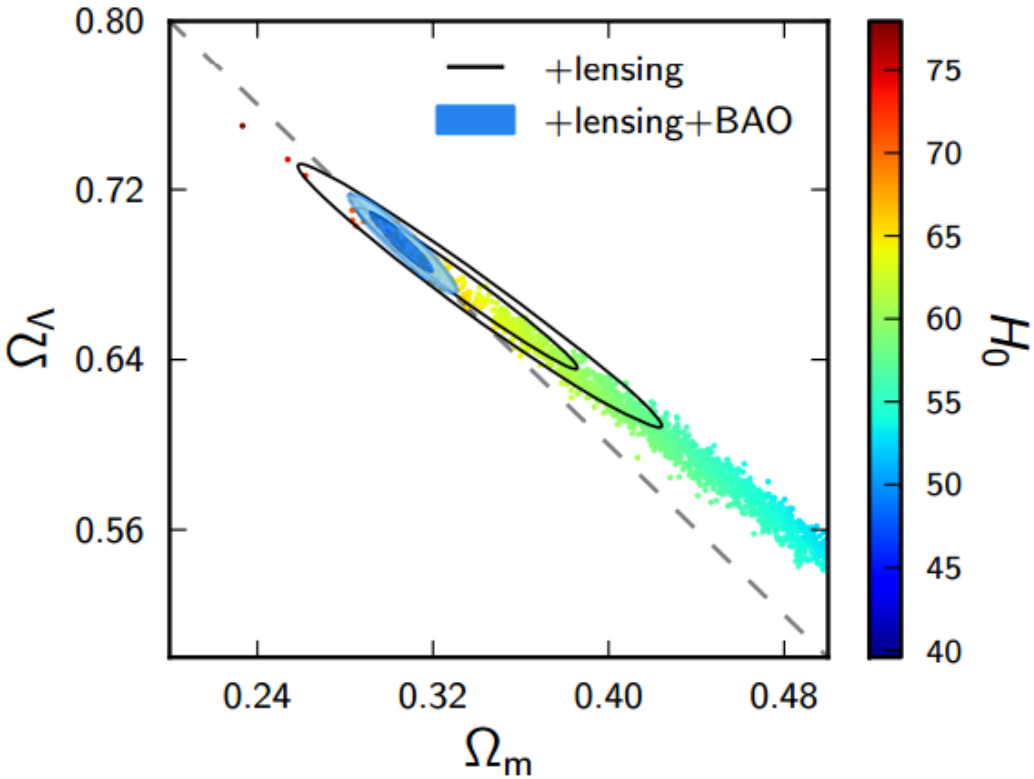


Red:
Planck+WP TT analysis with massless neutrinos.

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

Blue:
Planck Clusters

Constraints on Curvature



$100\Omega_K = -4.2^{+4.3}_{-4.8}$ (95%; *Planck*+WP+highL);

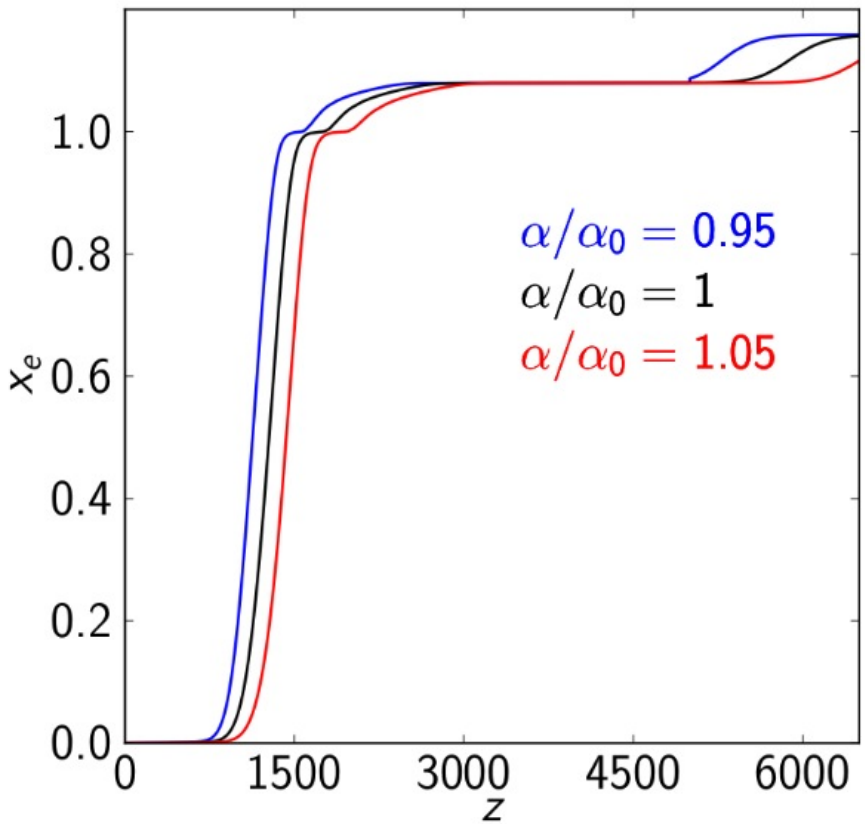
$100\Omega_K = -1.0^{+1.8}_{-1.9}$ (95%; *Planck*+lensing + WP+highL).

$100\Omega_K = -0.05^{+0.65}_{-0.66}$ (95%; *Planck*+WP+highL+BAO),

$100\Omega_K = -0.10^{+0.62}_{-0.65}$ (95%; *Planck*+lensing+WP +highL+BAO).

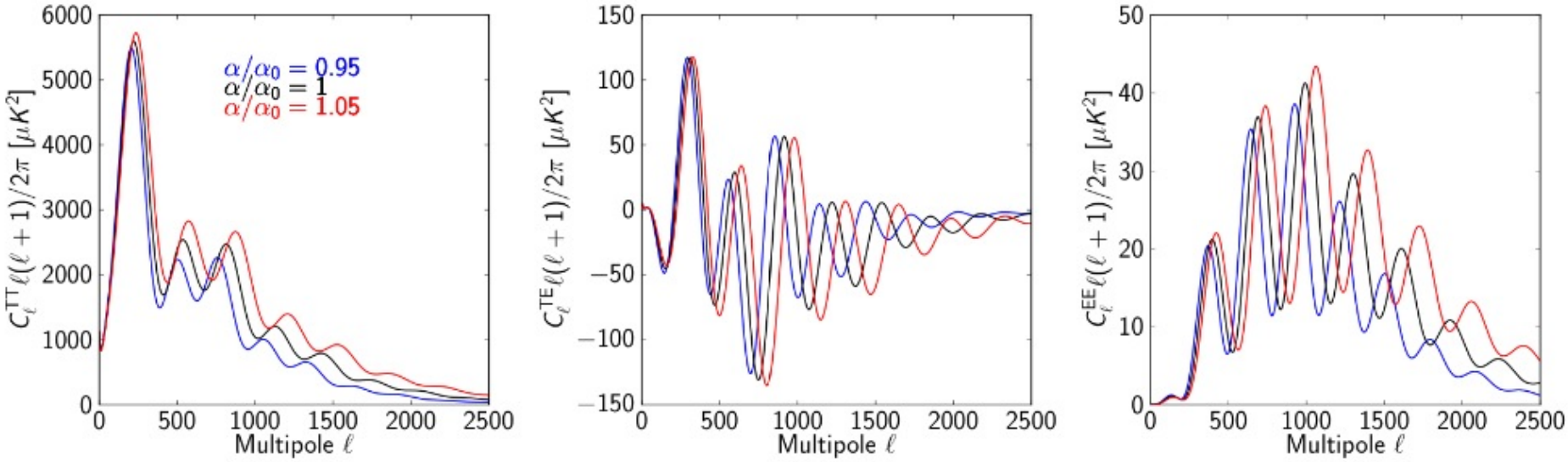
Lensing breaks geometrical degeneracies and allows a precise measurement of curvature at 1% level.
Universe is flat, no evidence for curvature.
When BAO data is included constraints are at the level of 0.3% on curvature !

Constraints on Variations of Fine Structure Constant



A different value of the fine structure constant in the past would change the process of recombination. Higher alpha, quicker is the recombination...

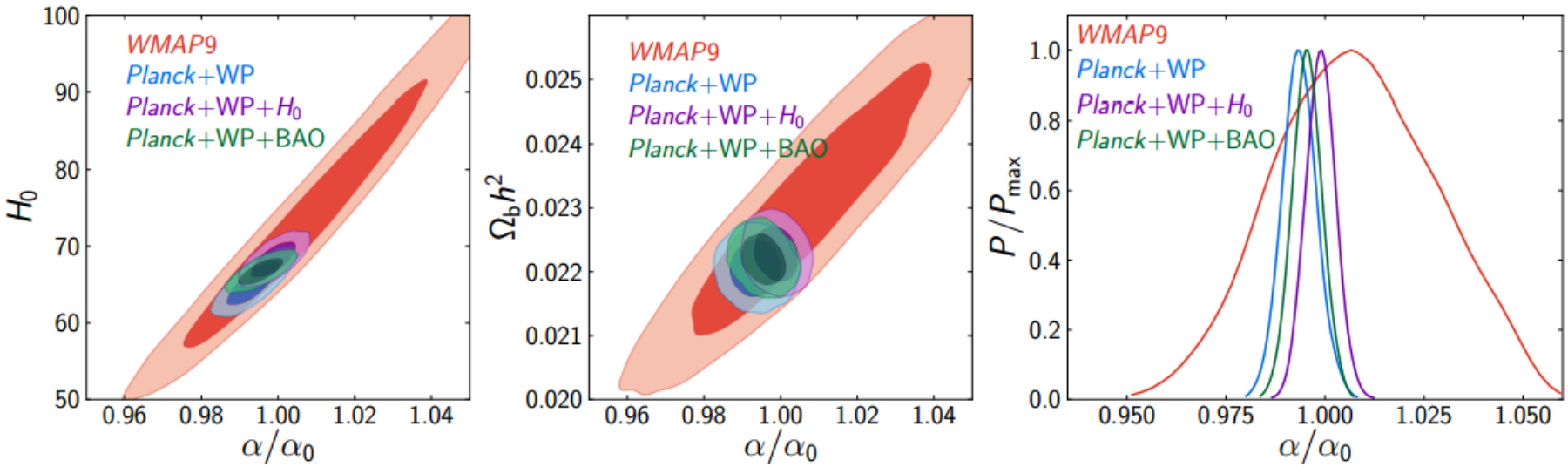
Constraints on Variations of Fine Structure Constant



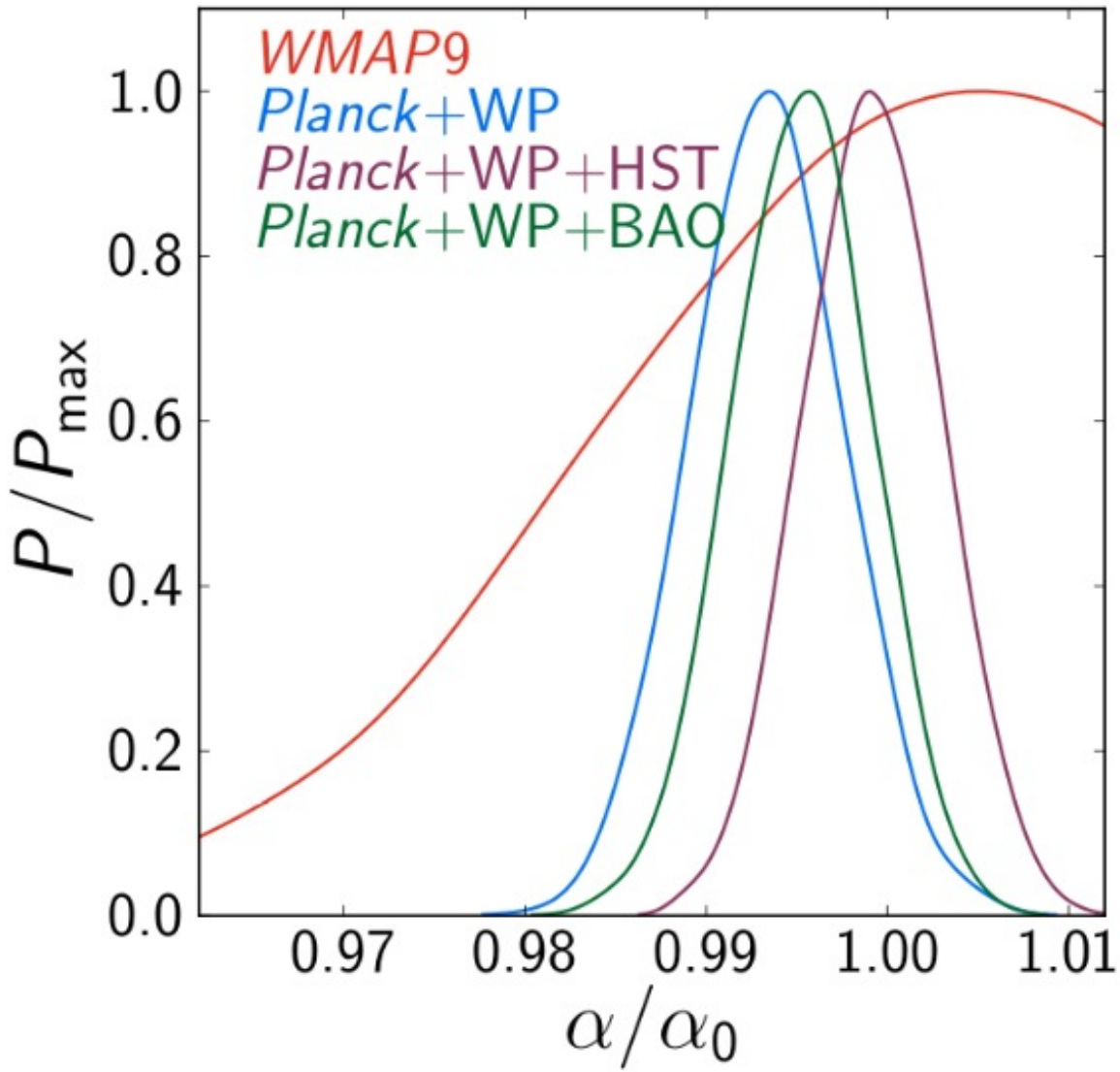
... and if you change the recombination you change the horizon size at recombination
quicker recombination, smaller horizon size, peaks are shifted to smaller scales...

Constraints on Variations of Fine Structure Constant

	Planck+WP	*Planck*+WP+BAO	*WMAP*-9
$\Omega_b h^2$	0.02206 ± 0.00028	0.02220 ± 0.00025	0.02309 ± 0.00130
$\Omega_c h^2$	0.1174 ± 0.0030	0.1161 ± 0.0028	0.1148 ± 0.0048
τ	0.095 ± 0.014	0.097 ± 0.014	0.089 ± 0.014
H_0	65.2 ± 1.8	66.7 ± 1.1	73.9 ± 10.9
n_s	0.975 ± 0.012	0.969 ± 0.012	0.973 ± 0.014
$\log(10^{10} A_s)$	3.106 ± 0.029	3.100 ± 0.029	3.090 ± 0.039
α/α_0	0.9936 ± 0.0043	0.9989 ± 0.0037	1.008 ± 0.020



Constraints on Variations of Fine Structure Constant



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

- 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 ± 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).