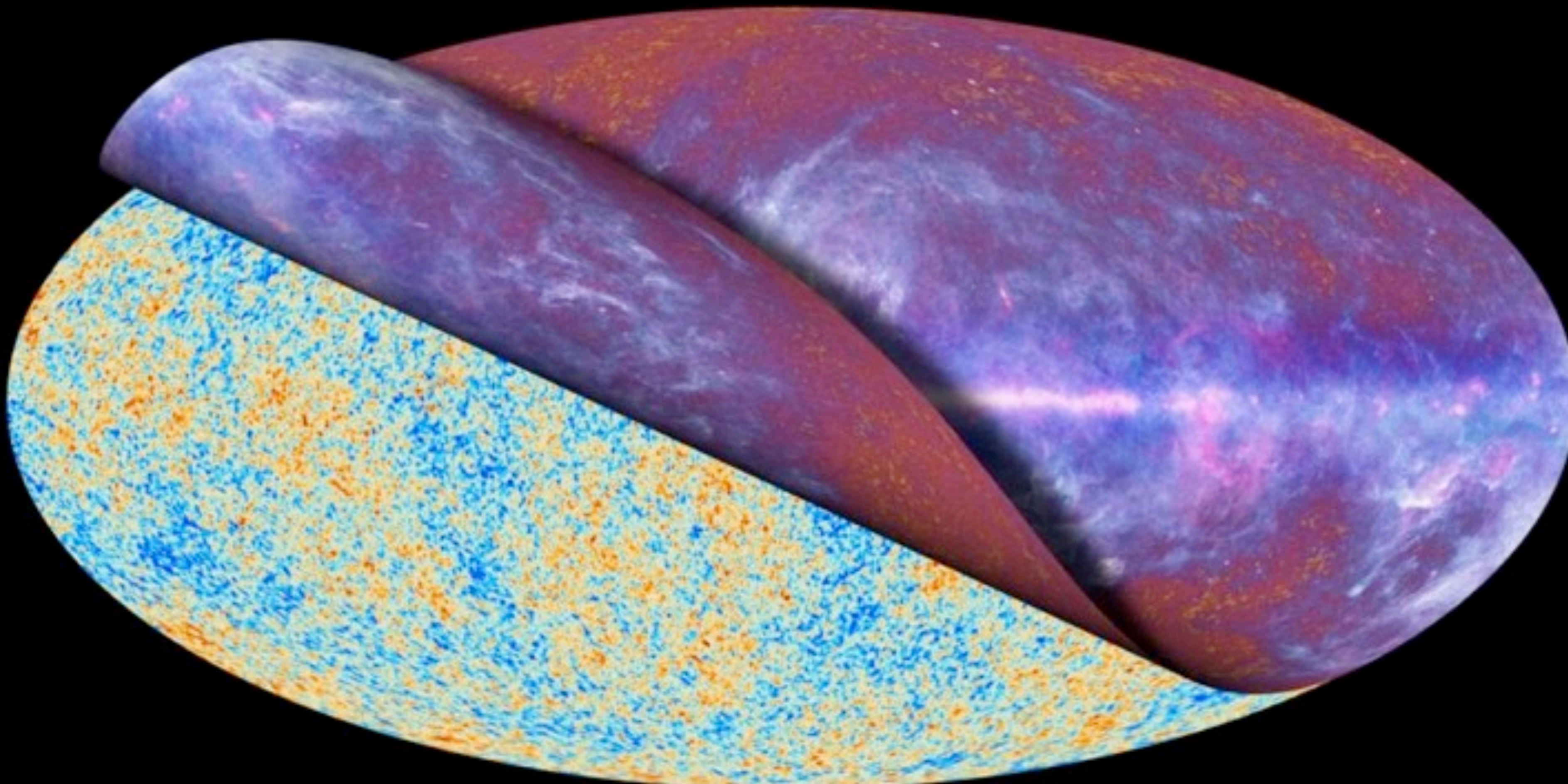
First Cosmology Results from Planck

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



Planck unveils the Cosmic Microwave Background

Planck Collaboration 300+ names

Planck 2013 results. XVI. Cosmological parameters

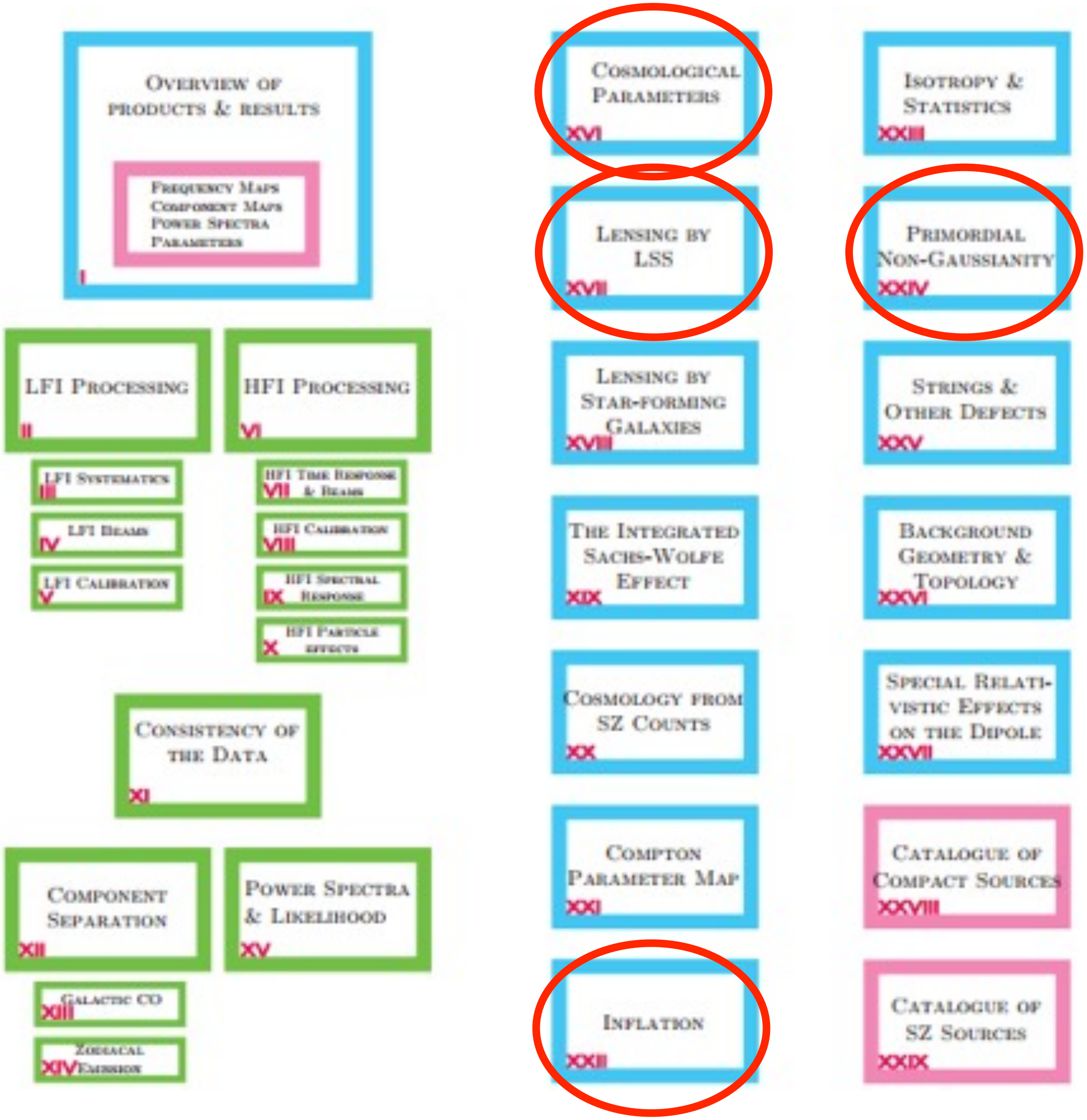
Planck Collaboration: P. A. R. Ade[90], N. Aghanim[63], C. Armitage-Caplan[96], M. Arnaud[77], M. Ashdown[74,6], F. Atrio-Barandela[19], J. Aumont[63], C. Baccigalupi[89], A. J. Banday[99,10], R. B. Barreiro[70], J. G. Bartlett[1,72], E. Battaner[102], K. Benabed[64,98], A. Benoît[61], A. Benoit-Lévy[26,64,98], 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)

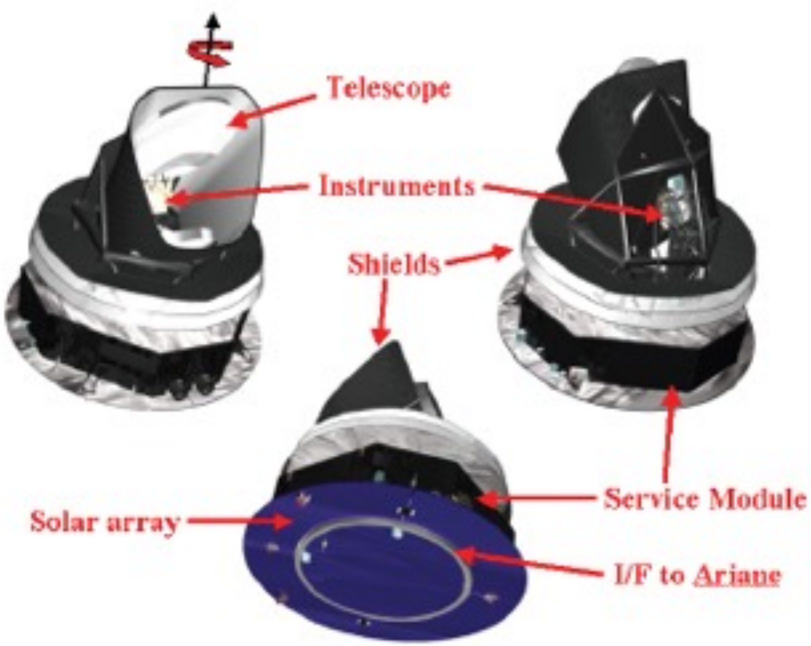
Planck History in Brief

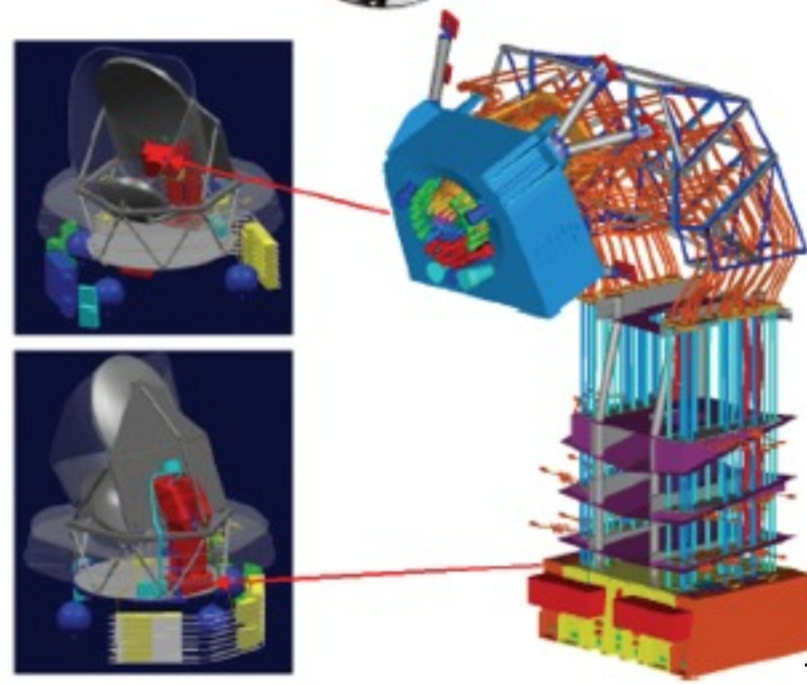
- **First conceived in 1992, proposed to ESA in 1993**
- **Payload approved in 1996**
- **Launched in May 2009, started to survey the sky in August of the same year**
- **Nominal mission completed at the end of 2010**
  - **but continued to gather data with the full payload until January 2012**
  - **... and it continues to gather data with LFI only until the fall (August end of 8 full sky survey)**
- **Planck is an ESA mission: ESA, European industries, and the international technological and scientific community have contributed to its realisation and success**
- **Planck has been founded by the European members state Space Agencies and by NASA: ASI and CNES are the leading Agencies.**
  - **Thousands of engineers and scientists were involved from ~100 scientific institutes in Europe, the USA, and Canada**
  - **Two scientific Consorzia (LFI led by N. Mandolesi and HFI by Jean Loup Puget) were responsible for the delivery of the Instruments to ESA, the mission data analysis and the delivery of the data and results to the open scientific community**

First cosmology release: 29 papers…about 1000 pages !!!!



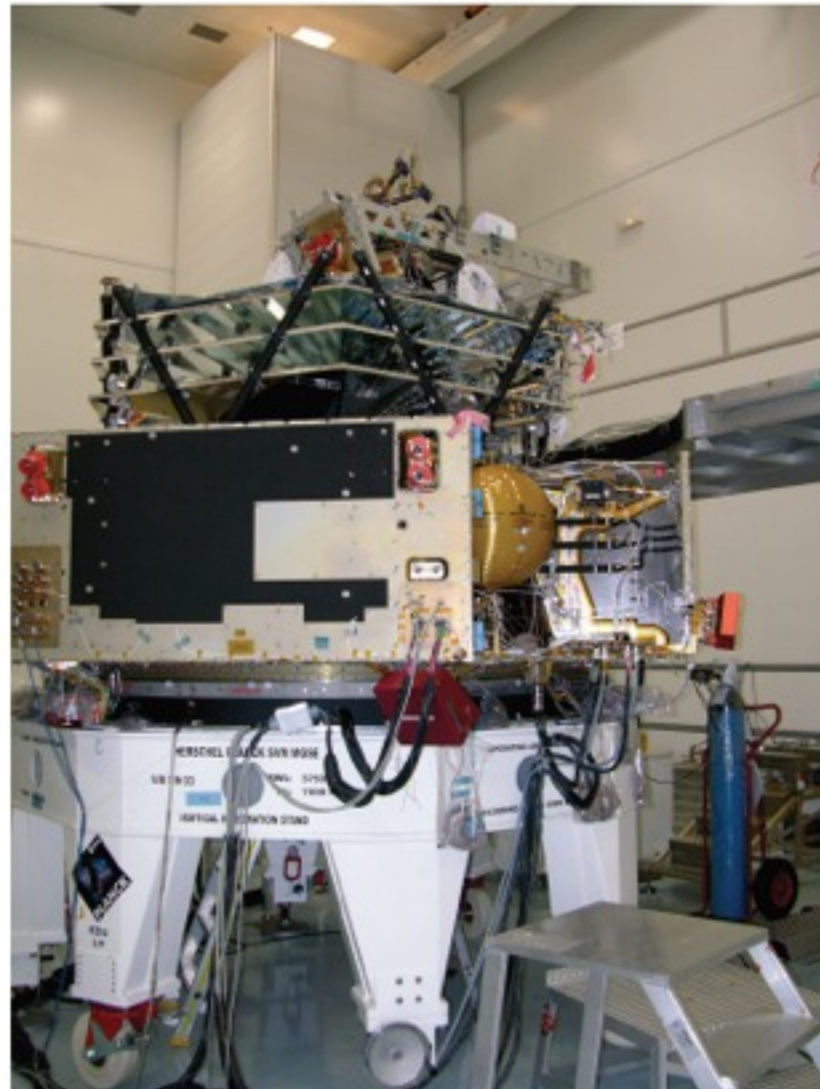
Planck in cartoons





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.

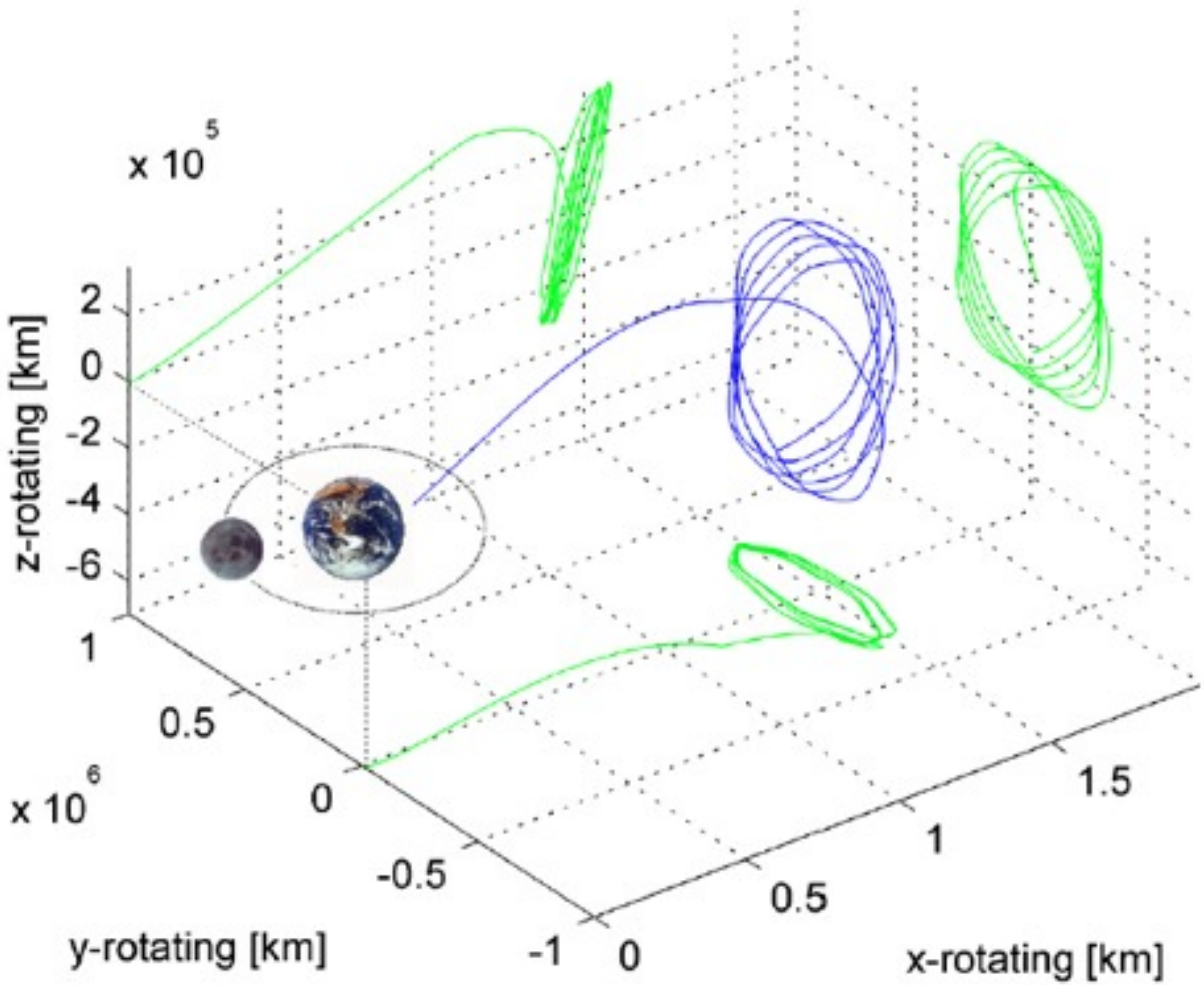
Planck being assembled

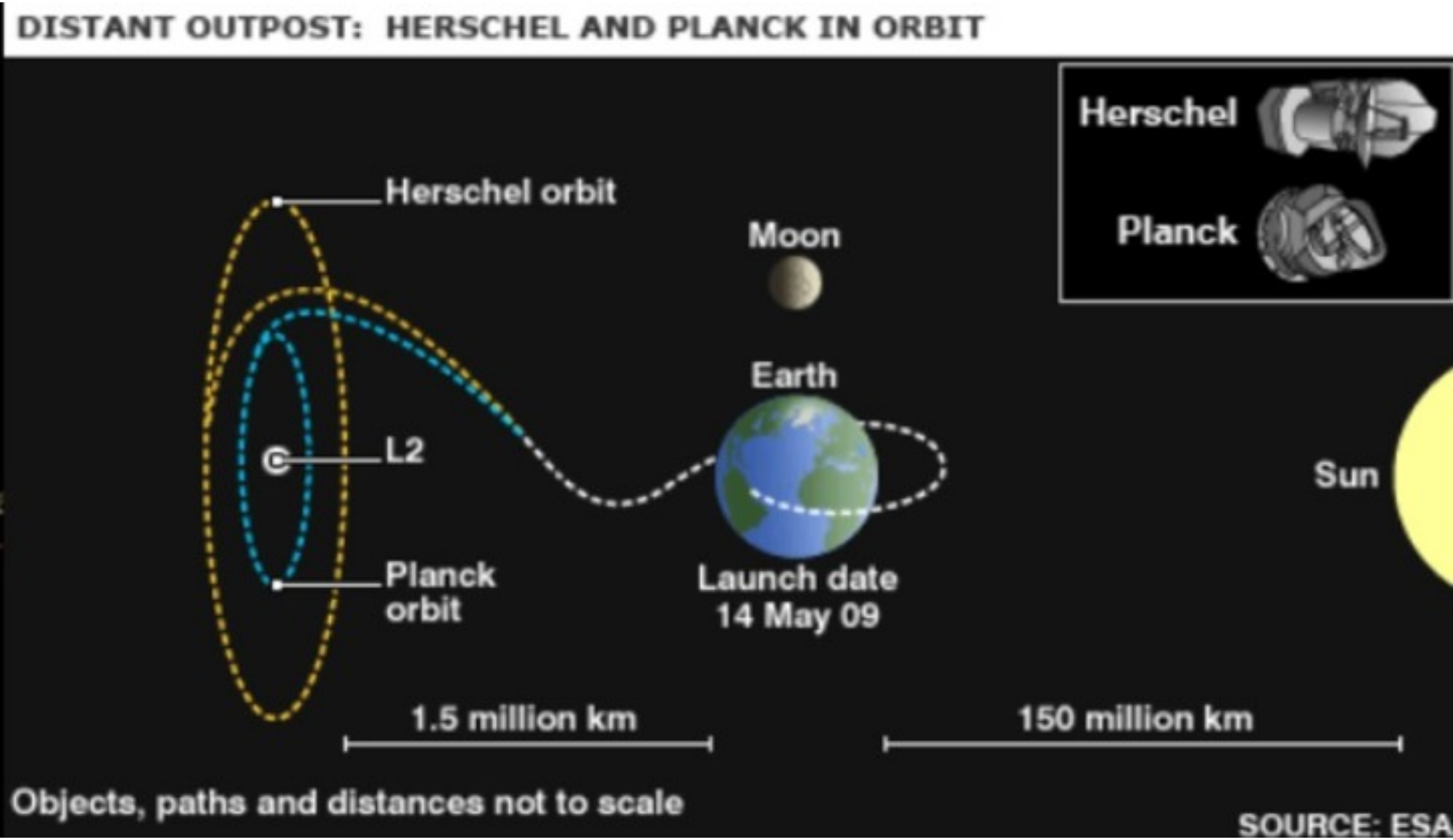


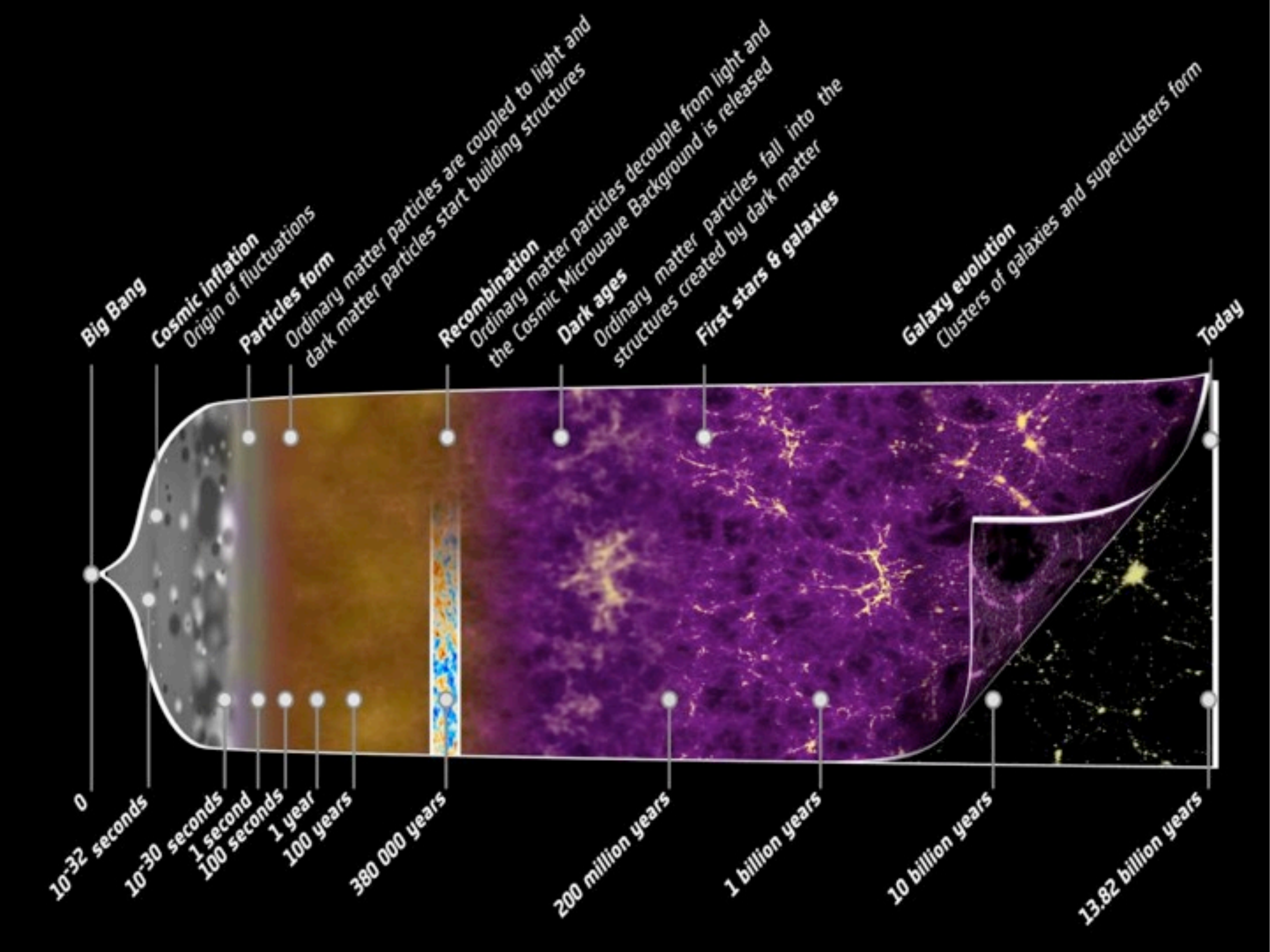
Planck in February 2009


Planck
Satellite launch
14/5/2009
esa
ariane

Planck in L2 Orbit since 7/2009




DISTANT OUTPOST: HERSCHEL AND PLANCK IN ORBIT
Herschel
Planck
Herschel orbit
Moon
Earth
L2
Sun
Planck orbit
Launch date 14 May 09
1.5 million km
150 million km
Objects, paths and distances not to scale
SOURCE: ESA



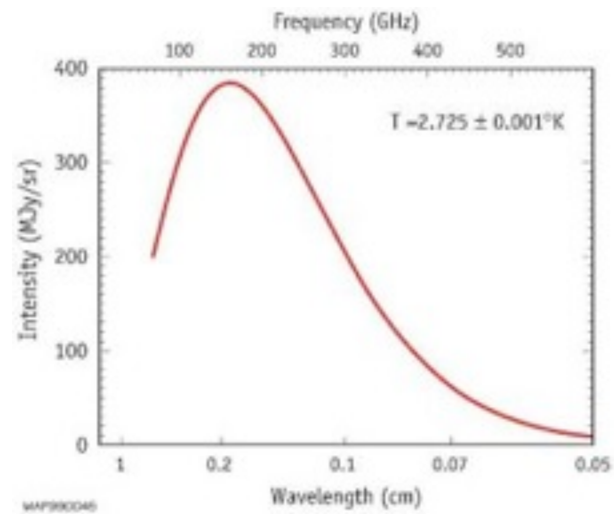
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles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

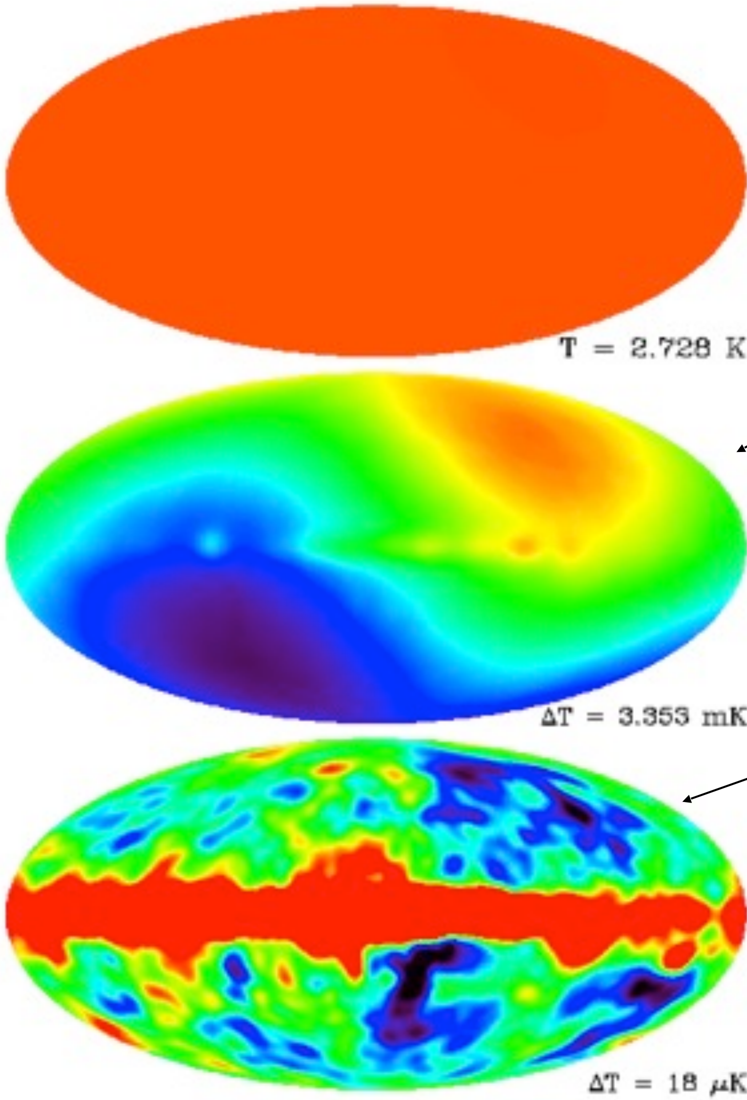
It is an image of the universe at the time of recombination (near baryon-photons decoupling), when the universe was just a few thousand years old (z~1000).

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

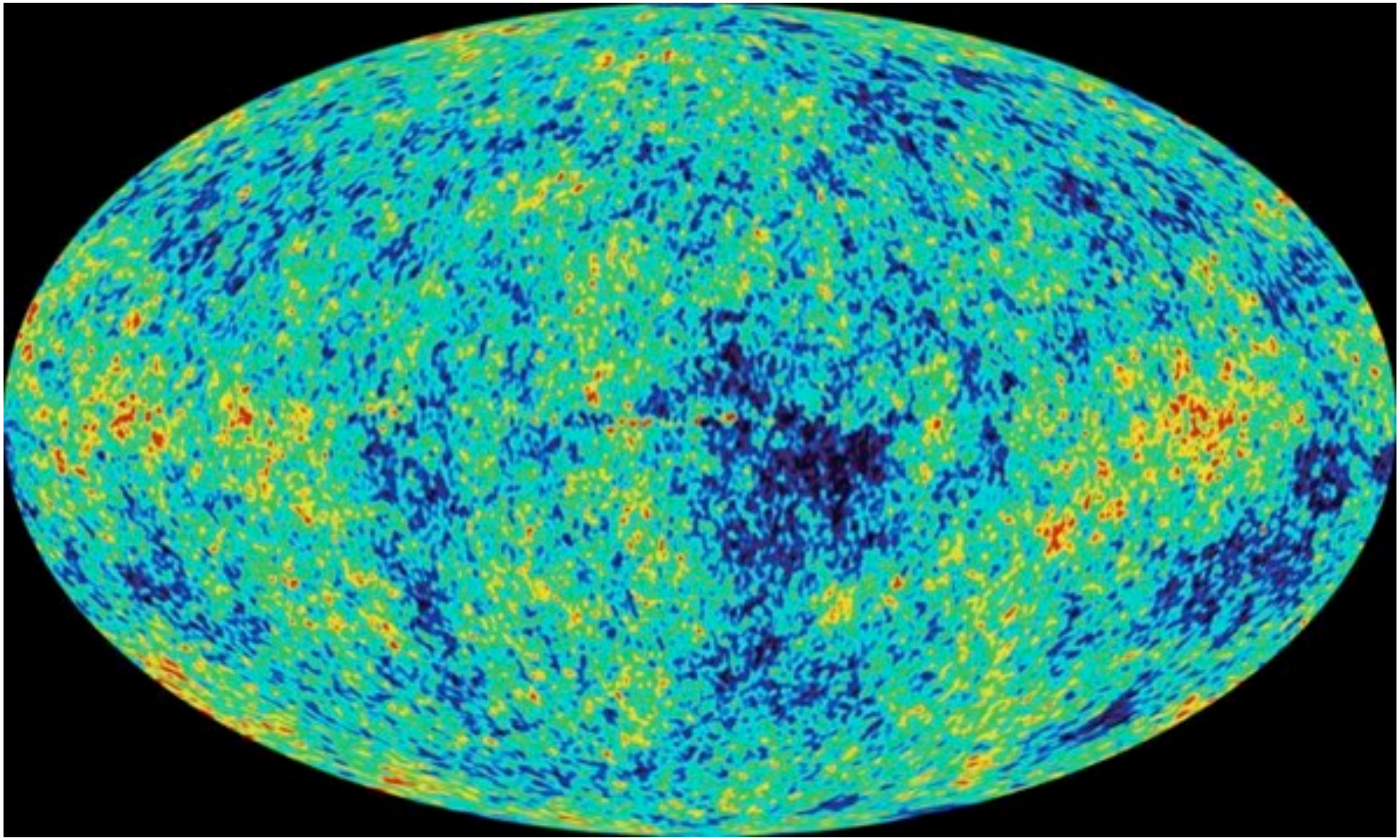


Uniform…

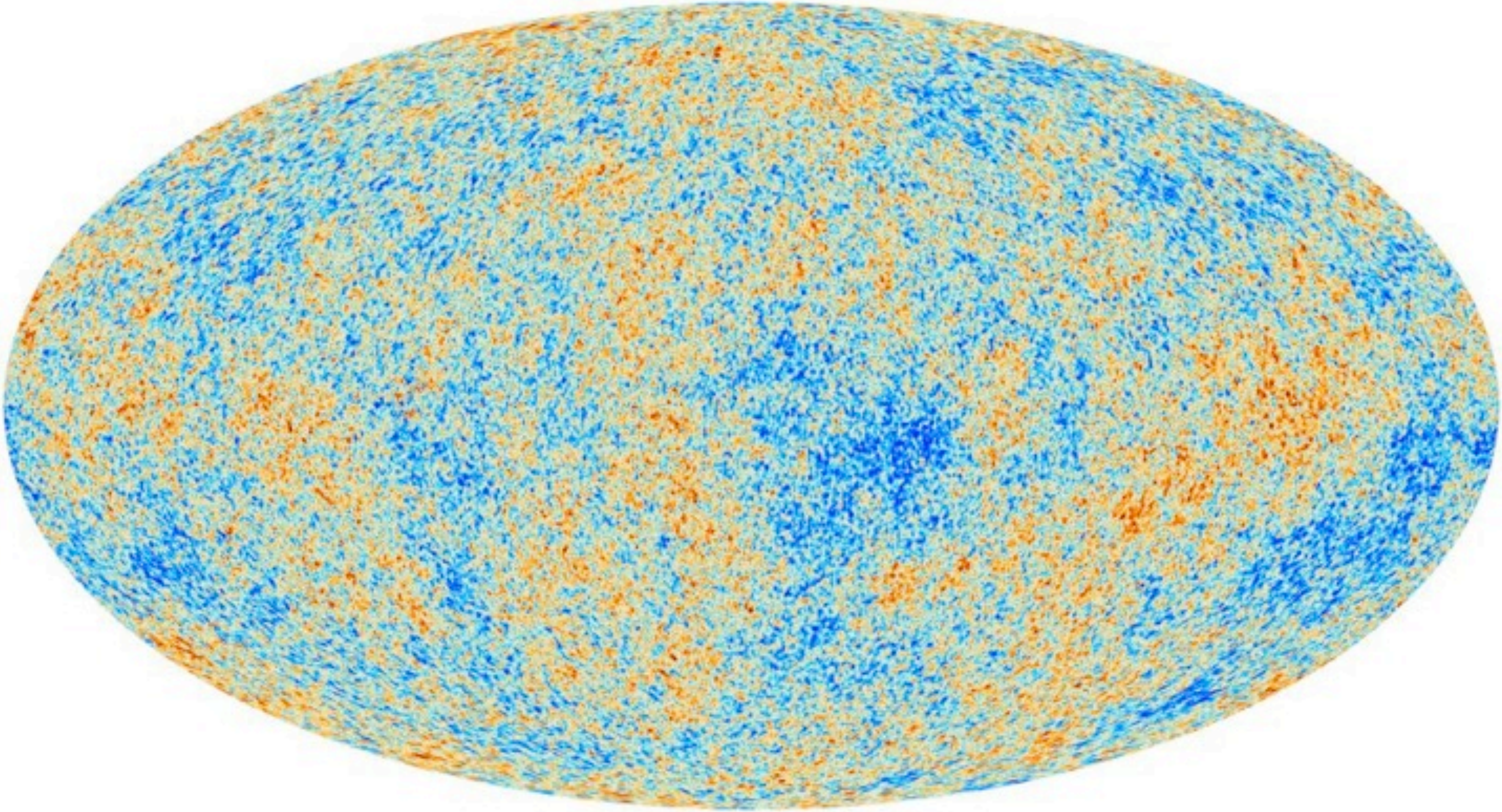
First Anisotropy we see is a Dipole anisotropy:
Implies solar-system barycenter has velocity v/c~0.00123 relative to 'rest-frame' of CMB.

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

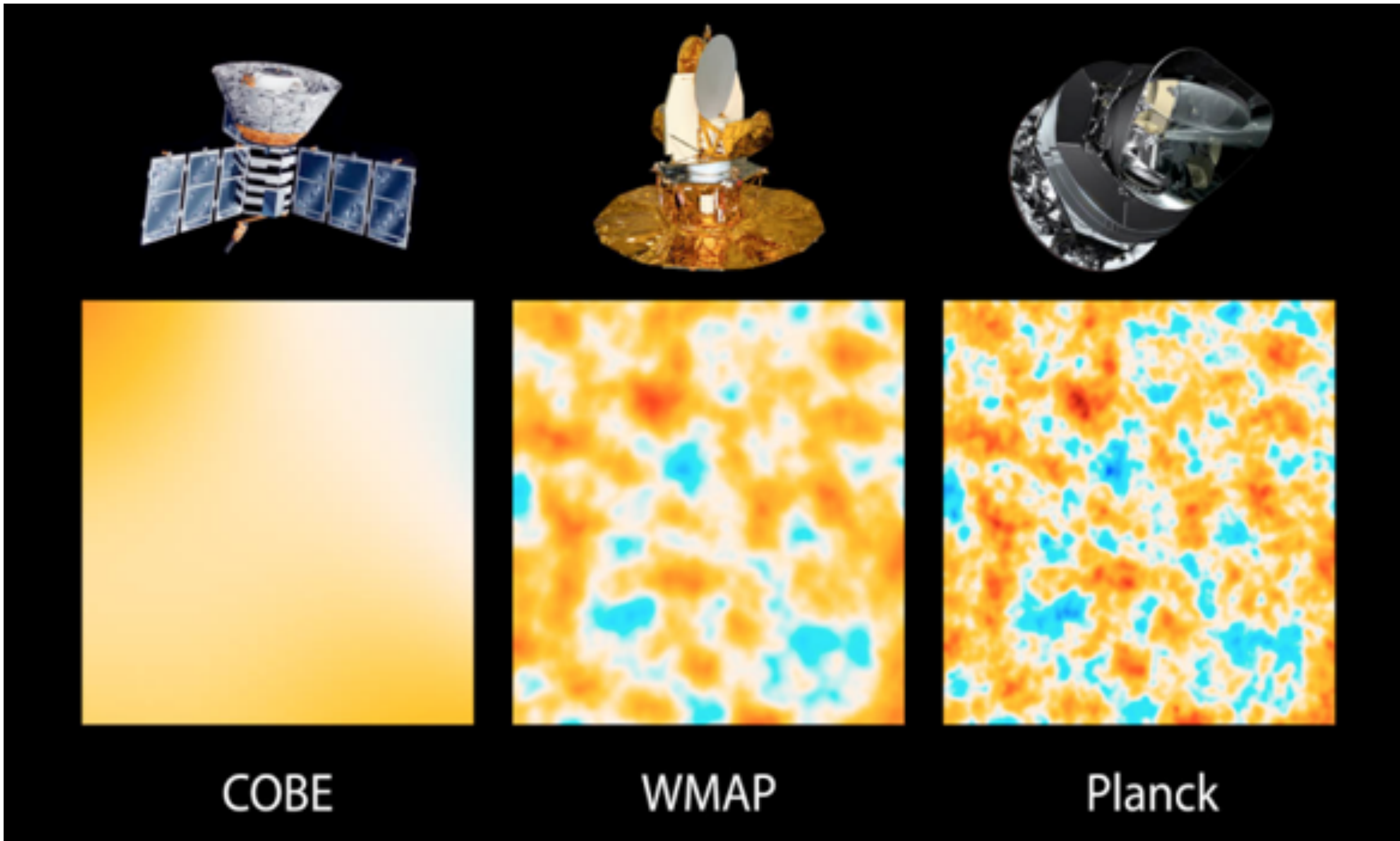
Best Full Sky Map of the CMB before Planck: WMAP satellite (2002-2010)
(linear combination of 30,60 and 90 GHz channels)



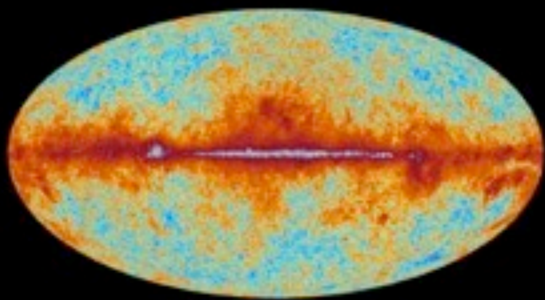
Planck 2013 CMB Map



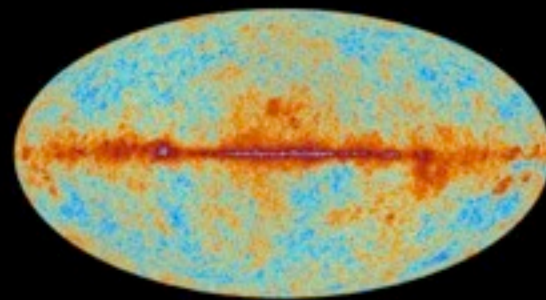
Comparison with COBE and WMAP



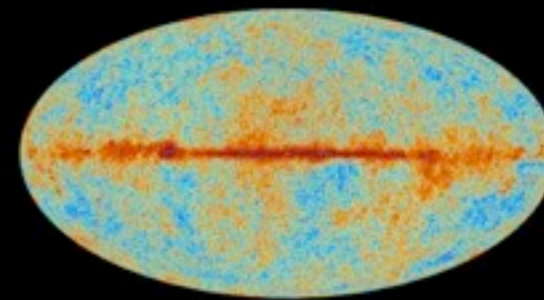
The sky as seen by Planck



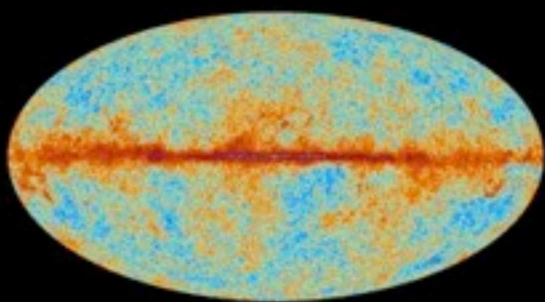
30 GHz



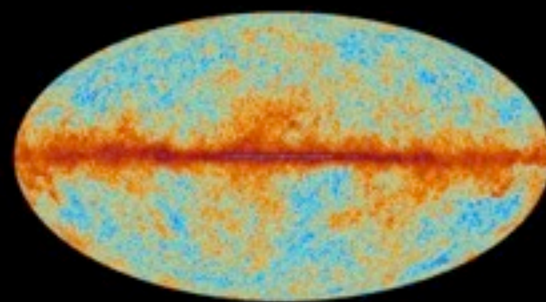
44 GHz



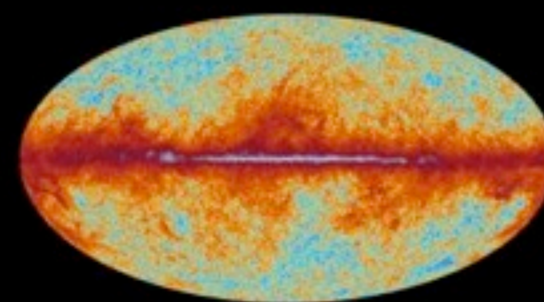
70 GHz



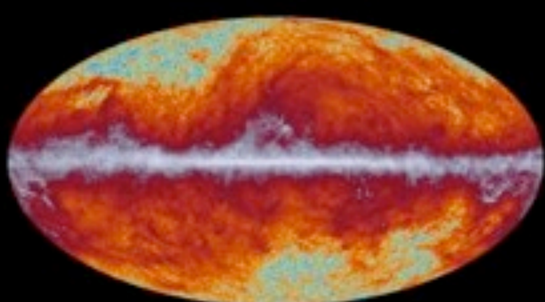
100 GHz



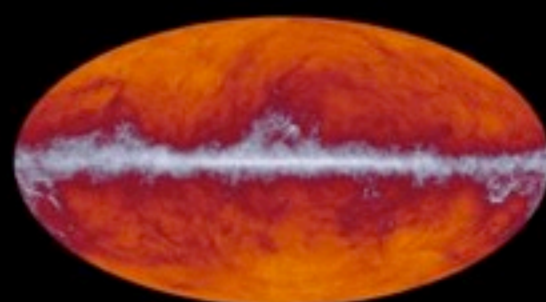
143 GHz



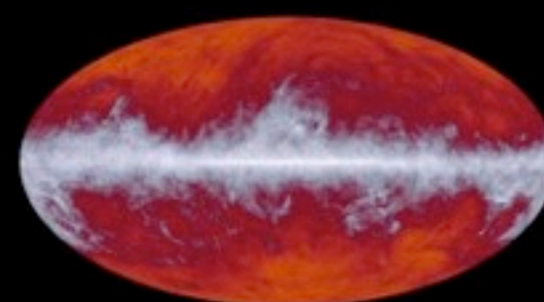
217 GHz



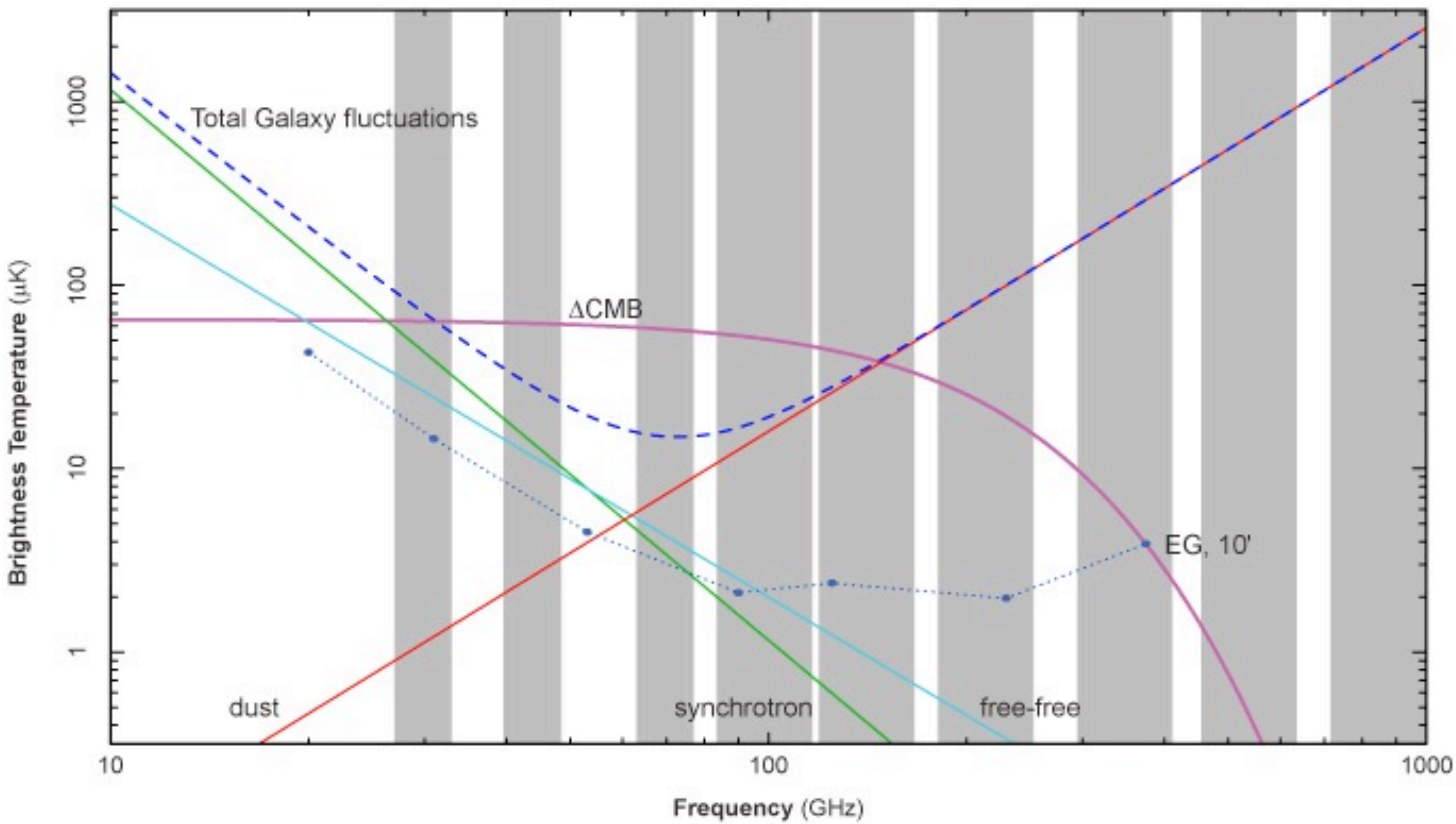
353 GHz



545 GHz



857 GHz

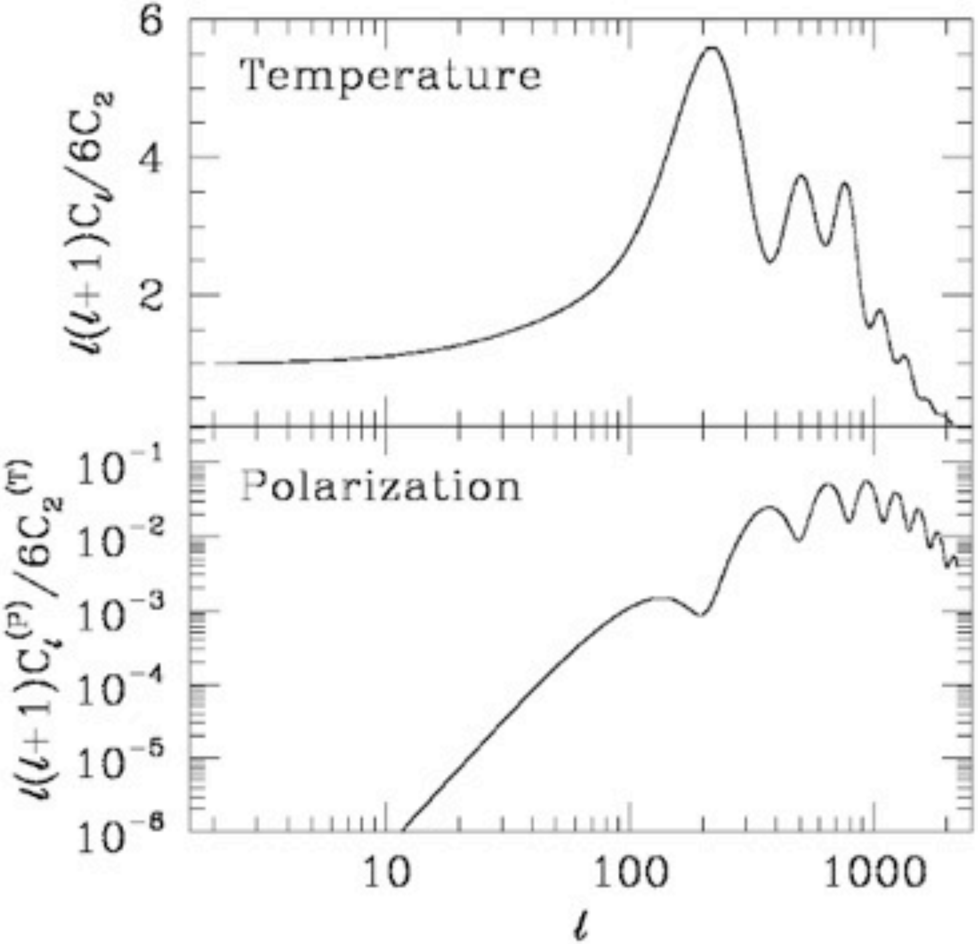

Total Galaxy fluctuations
ΔCMB
EG, 10'
dust
synchrotron
free-free
Brightness Temperature (μK)
Frequency (GHz)
1000
100
10
1
10
100
1000

The CMB Angular Power Spectrum

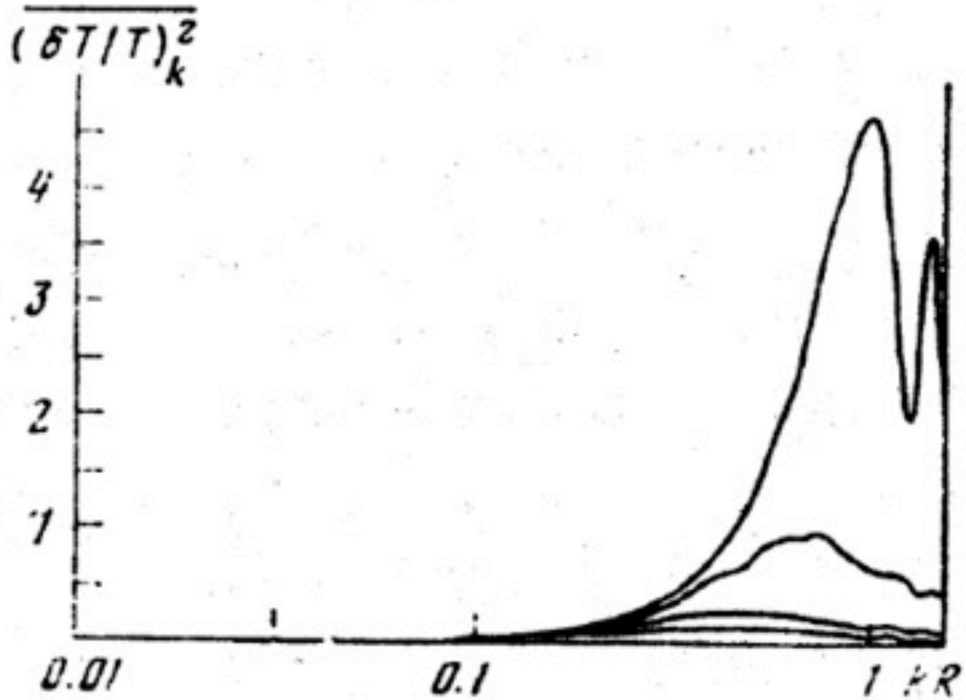
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

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

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



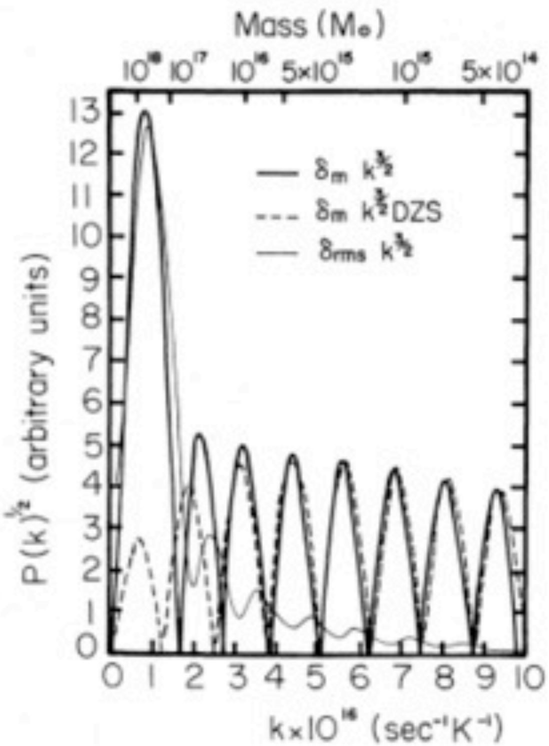
A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



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

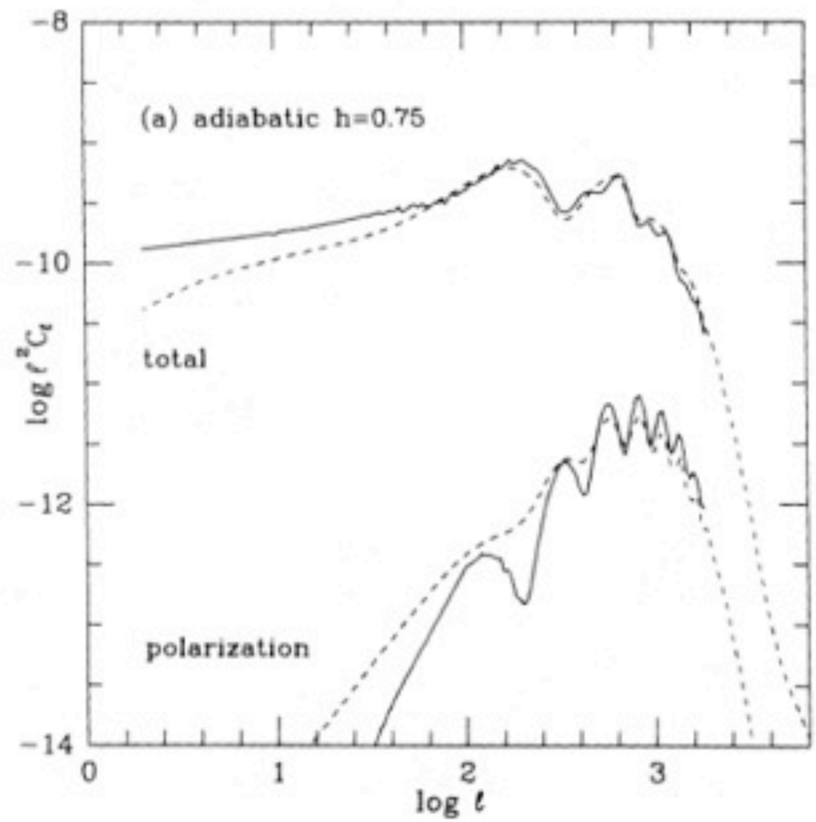
Soviet Astronomy, Vol. 22, p.523, 1978

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



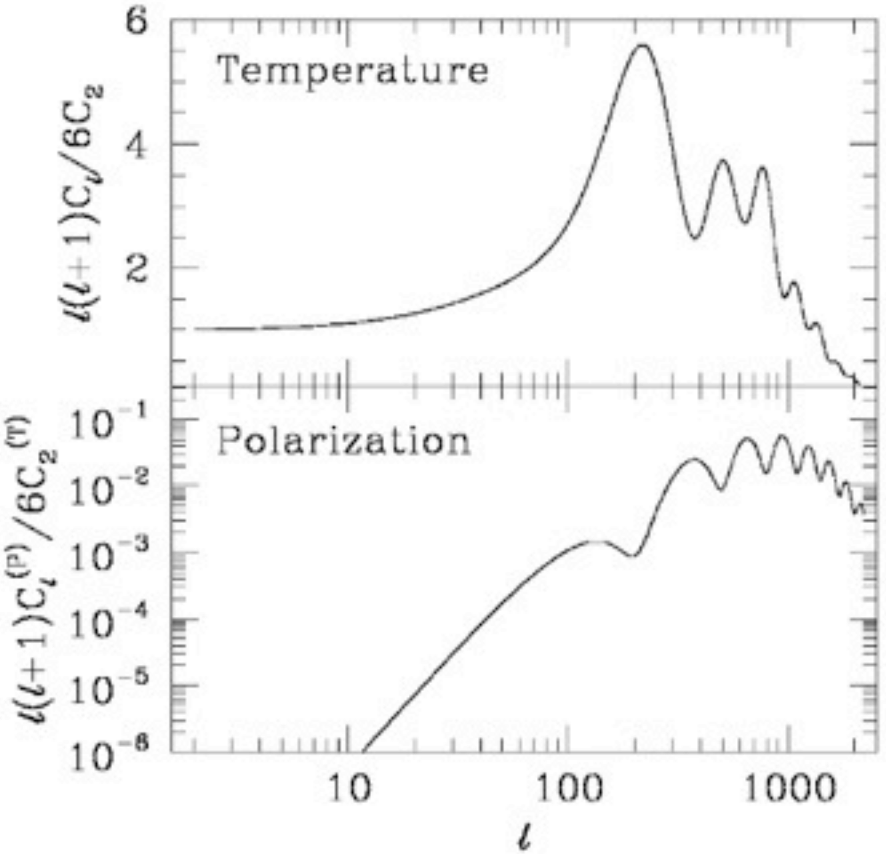
Wilson, M. L.; Silk, J., Astrophysical Journal, Part 1, vol. 243, Jan. 1, 1981, p. 14-25.
1981

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



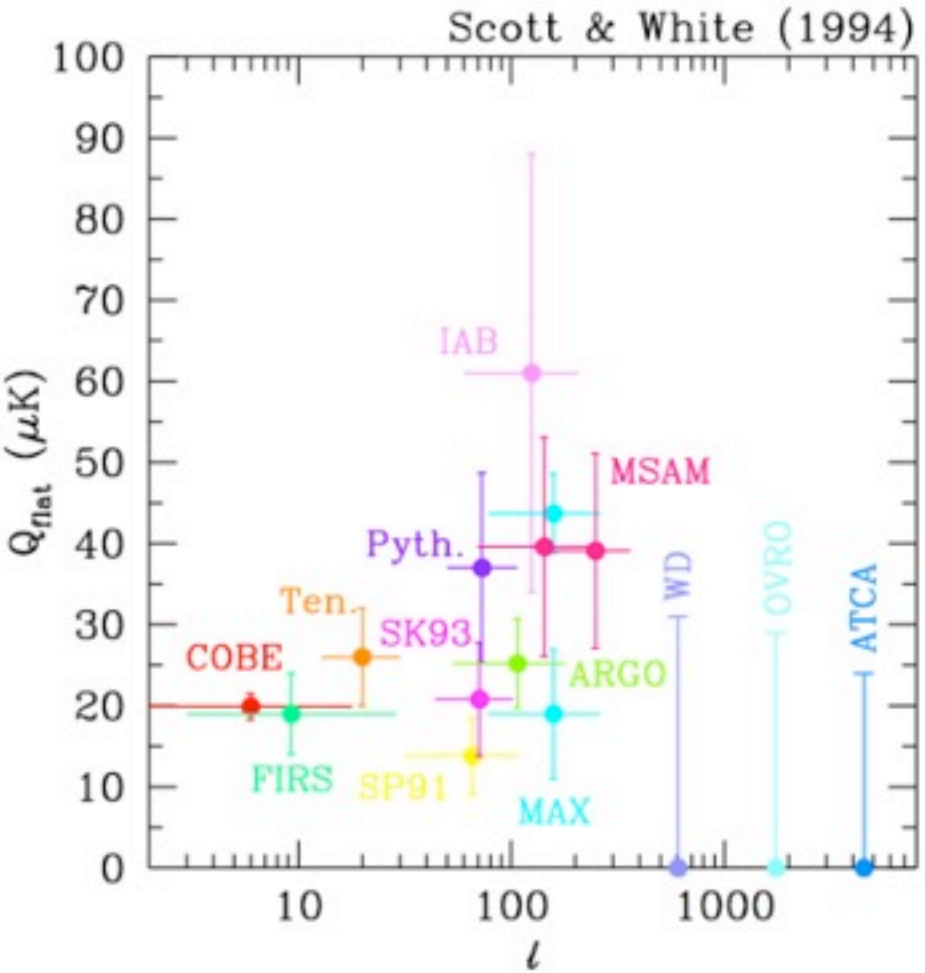
Bond, J. R.; Efstathiou, G.; Royal Astronomical Society, Monthly Notices (ISSN 0035-8711), vol. 226, June 1, 1987, p. 655-687, 1987

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…

nature International weekly journal of science

Search this journal go Advance

Access

To read this story in full you will need to login or make a payment (see right).

nature.com > Journal home > Table of Contents

News and Views

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

Big Bang not yet dead but in decline

John Maddox

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.

Top

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.

To read this story in full you will need to login or make a payment (see right).

ARTICLE TOOLS

- Send to a friend
- Export citation
- Rights and permissions
- Order commercial reprints
- Bookmark in Connotea

SEARCH PUBMED FOR

- John Maddox

I want to purchase this article

Price: US$18

In order to purchase this article you be a registered user.

Register now

I want to subscribe to *Nature*

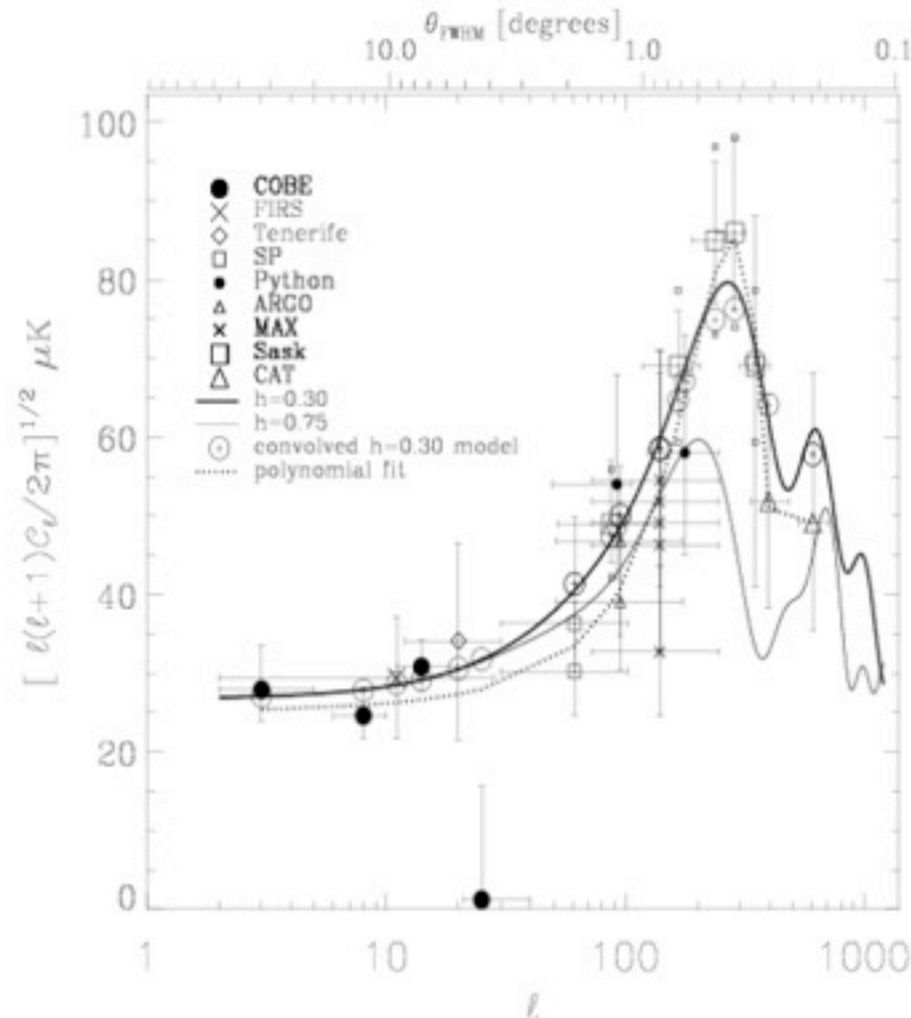
Price: US$199

This includes a free subscription to *N News* together with *Nature Journal*.

Subscribe now

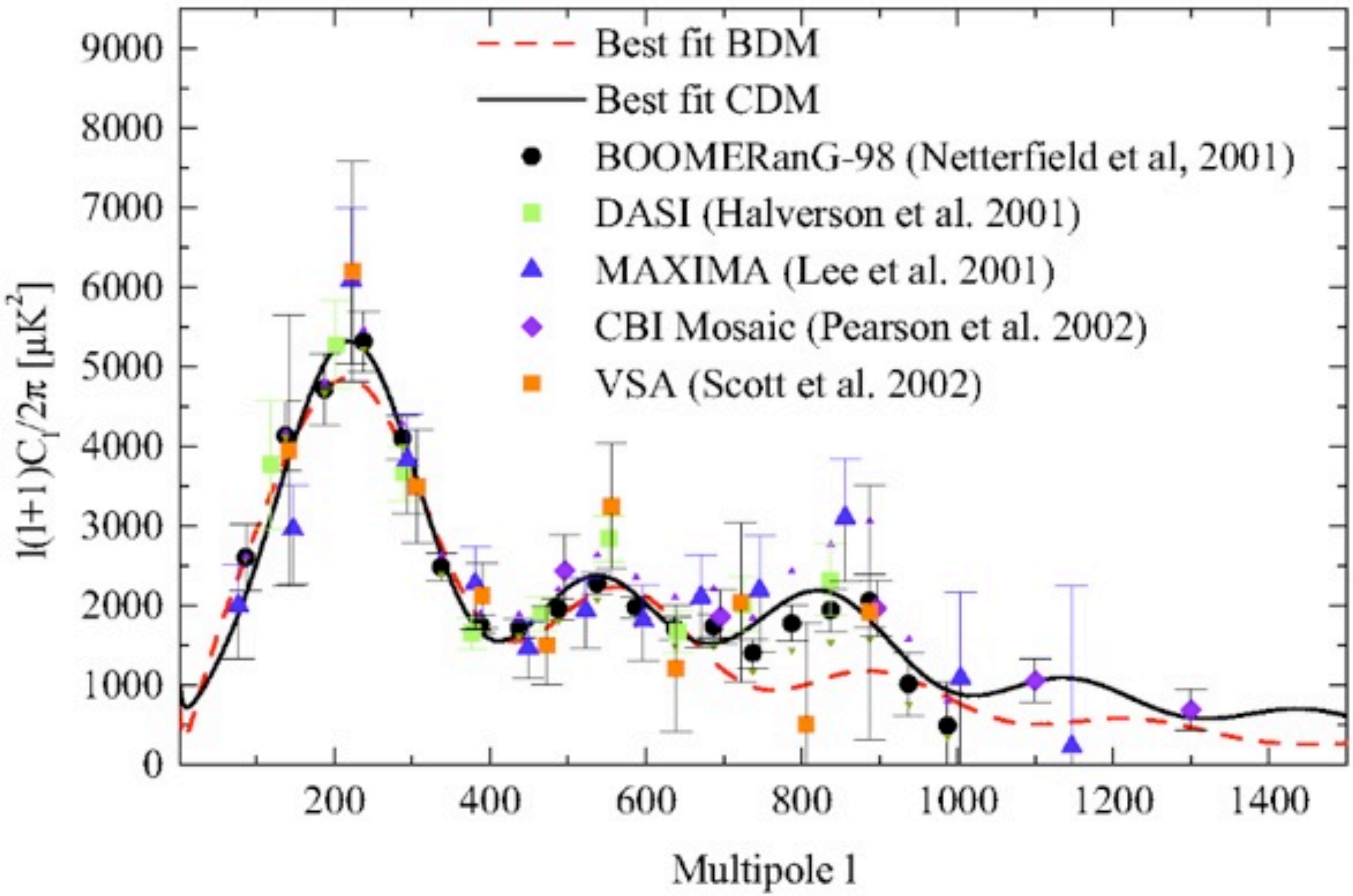
Personal subscribers to *Nature* can v articles published from 1997 to the current issue. To do this, associate y subscription with your registration v

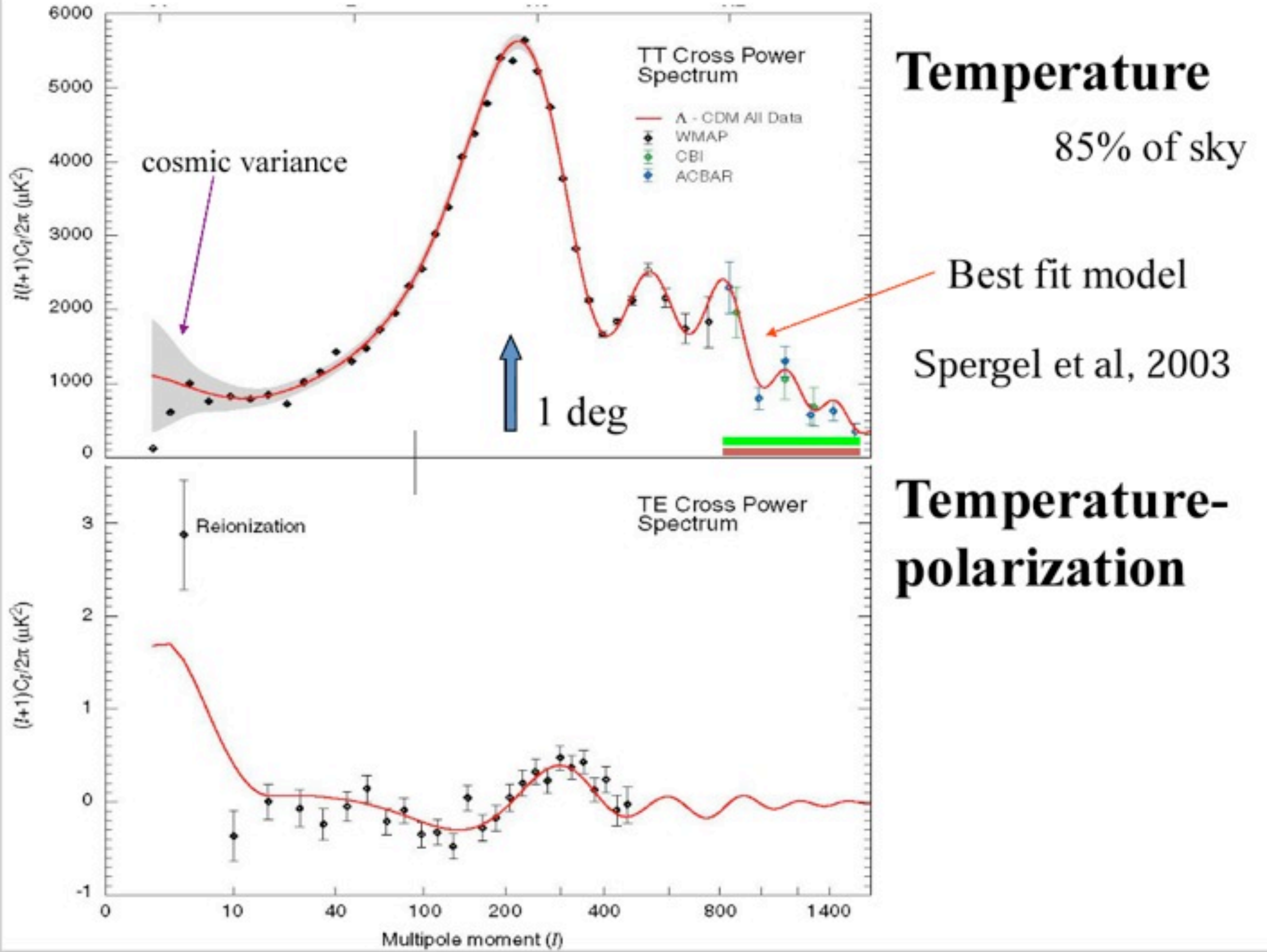
A Brief History of the CMB Anisotropies Angular Spectrum (Experimental Data)



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

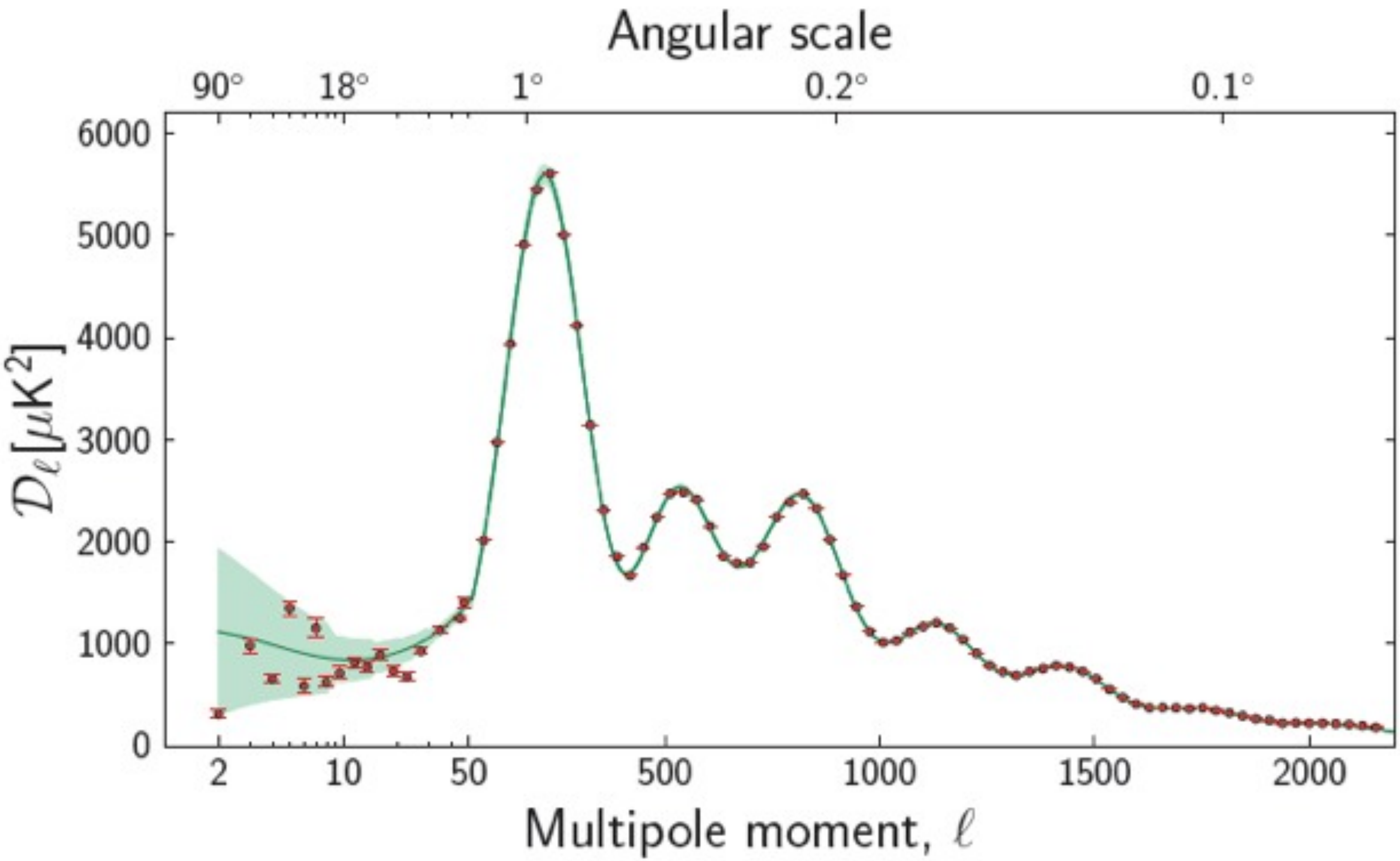
CMB anisotropies pre-WMAP (January 2003)





TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
cosmic variance
1 deg
$l(l+1)C_l/2\pi$ (μK^2)
Temperature
85% of sky
Best fit model
Spergel et al, 2003
TE Cross Power Spectrum
Reionization
$(l+1)C_l/2\pi$ (μK^2)
Temperature-polarization
Multipole moment (l)

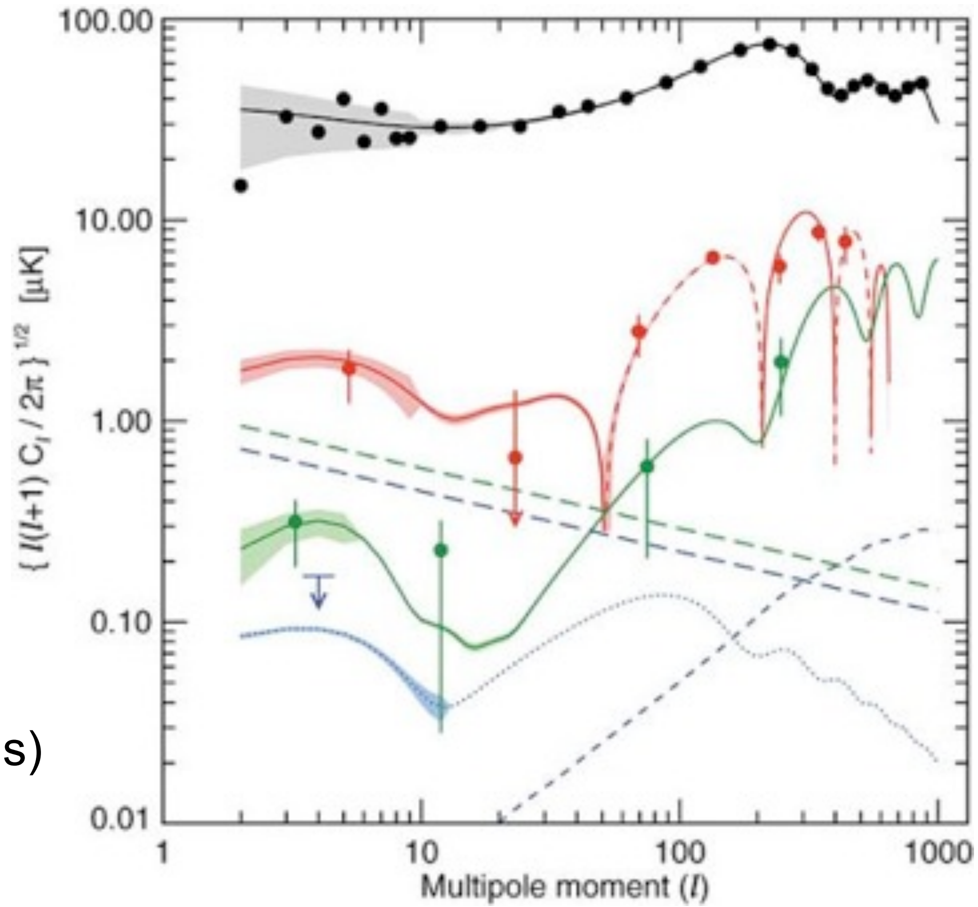
Planck 2013 TT angular spectrum



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:

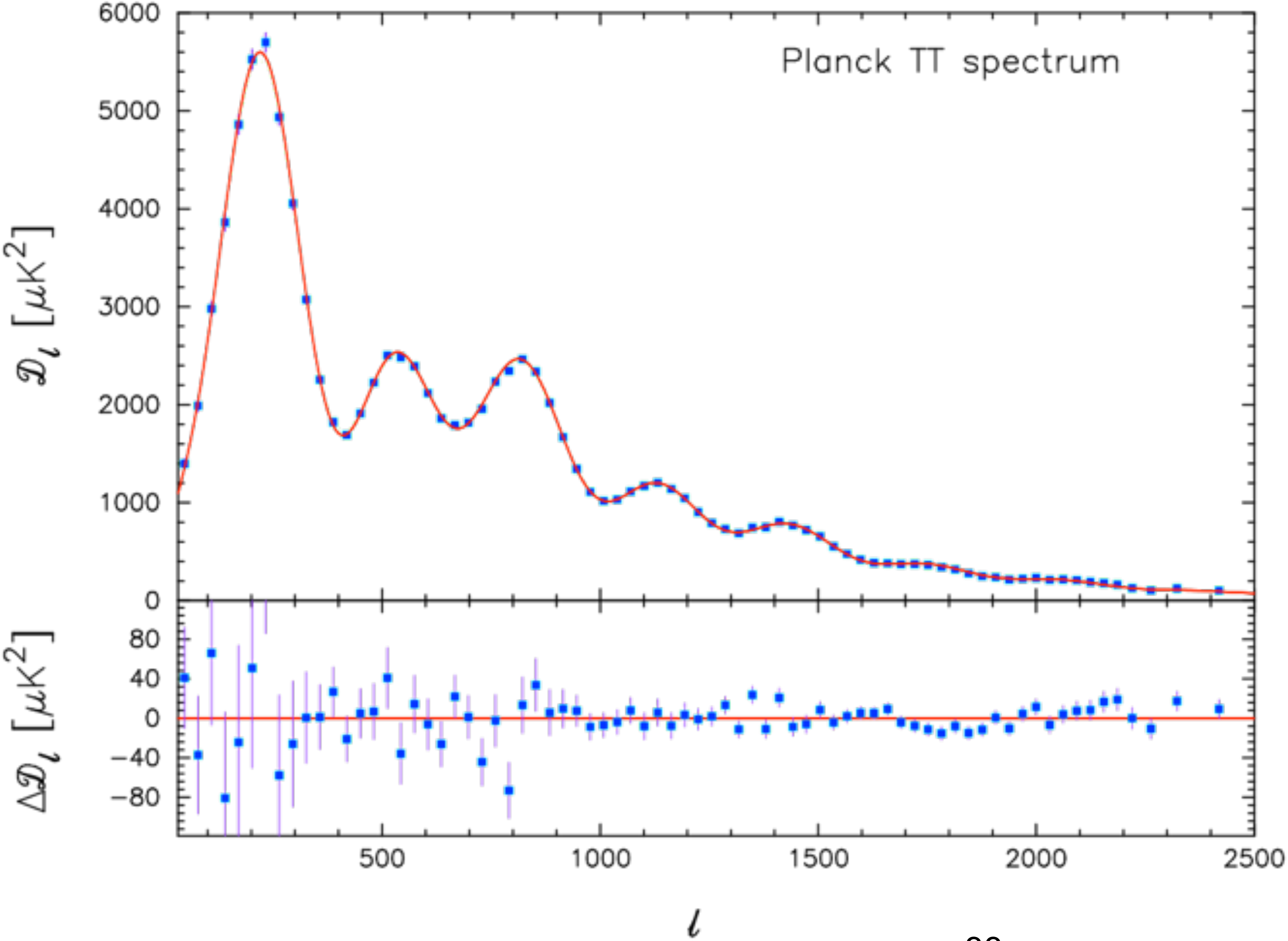
$$\left\langle (\Delta T / T)^2 \right\rangle_{rms} = \sum_l \frac{(2l+1)}{4\pi} C_l \approx \int \frac{l(l+1)}{2\pi} C_l \, d\ln l$$



We can extract 4 independent angular spectra from the CMB:

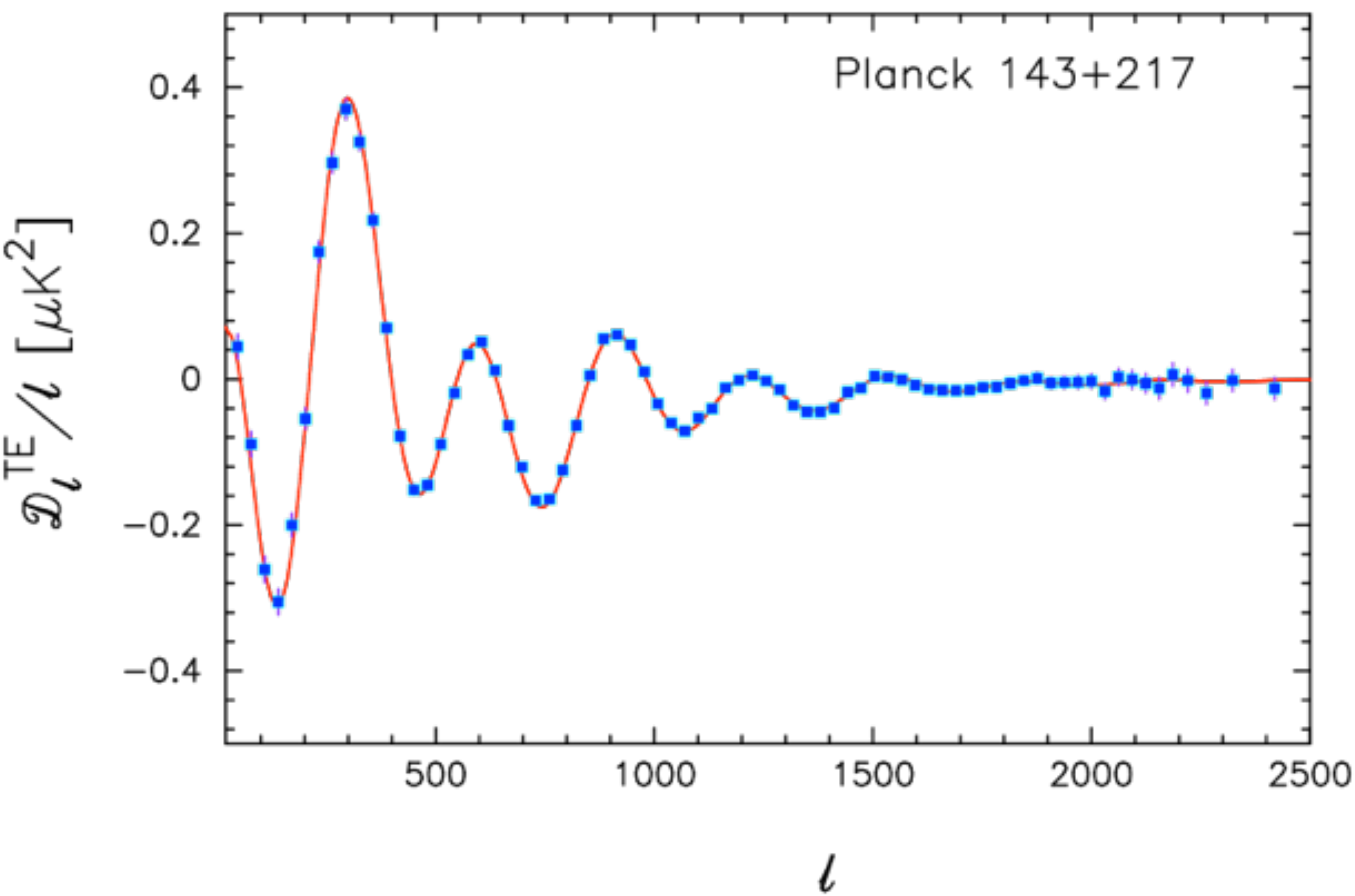
- Temperature
- Cross Temperature Polarization
- Polarization type E (density fluctuations)
- Polarization type B (gravity waves)

Planck 2013 release is only temperature ps.



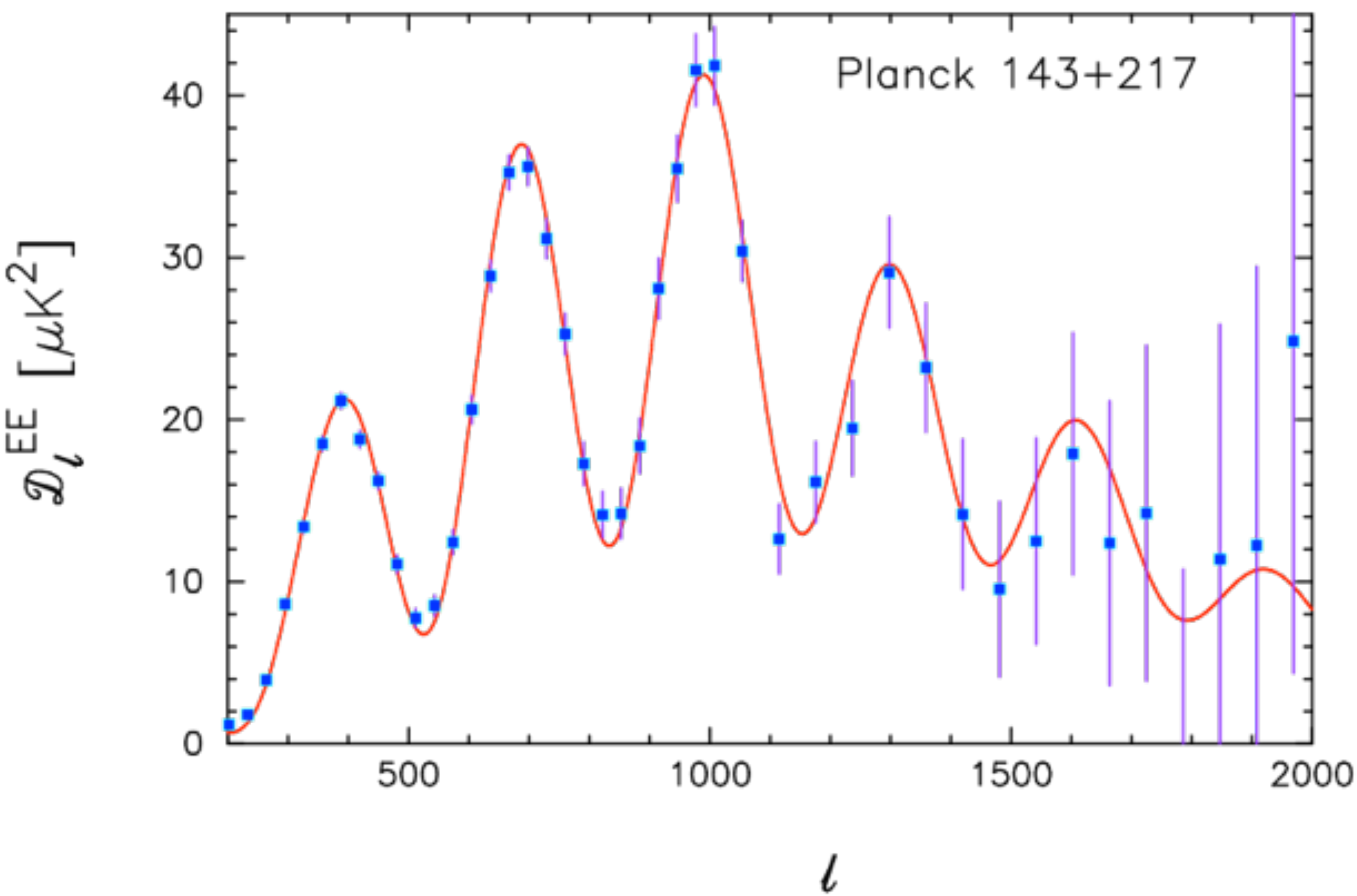
Planck TT spectrum
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
2500
$\mathcal{D}_\ell\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
ℓ

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



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

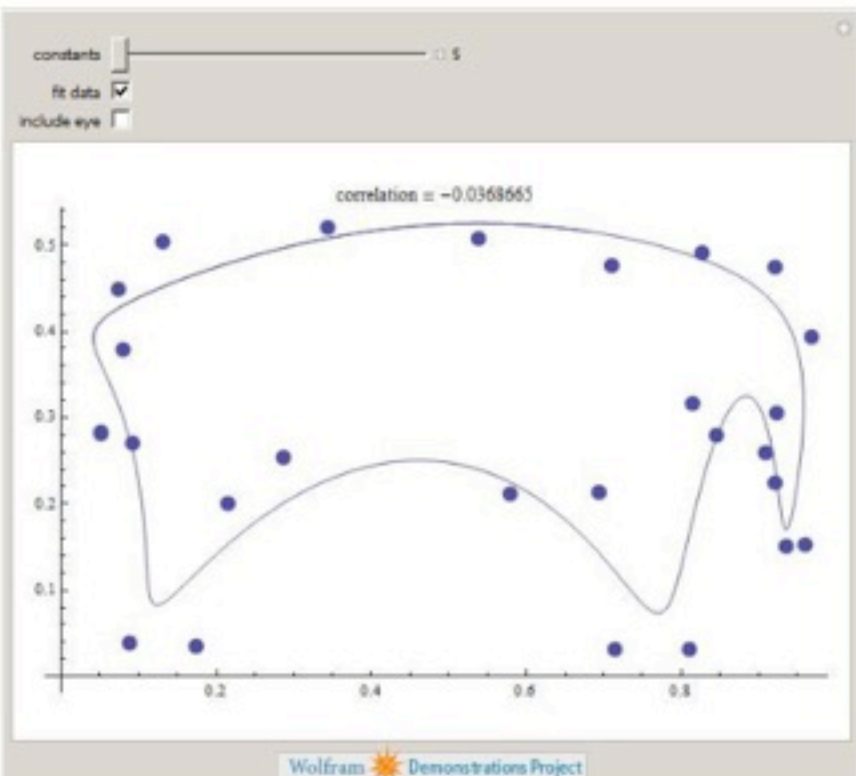
Polarization spectrum
(not present in this release)

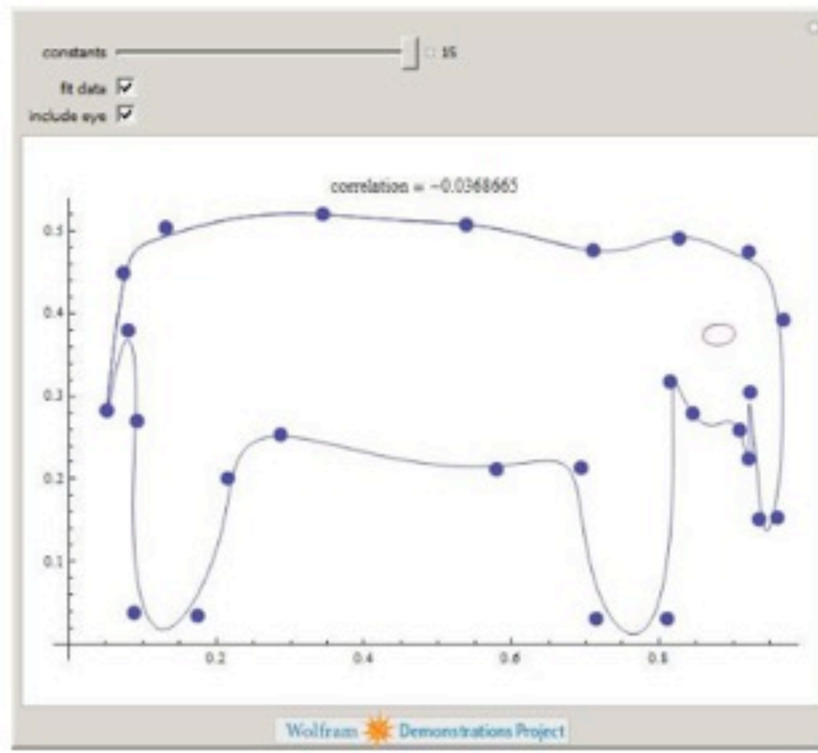


Red line: best fit model from the temperature angular spectrum!!

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:

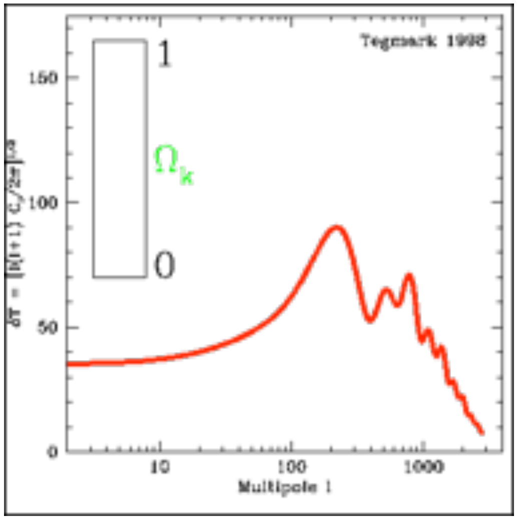
$$k_0 = 0.002\ hMpc^{-1}$$

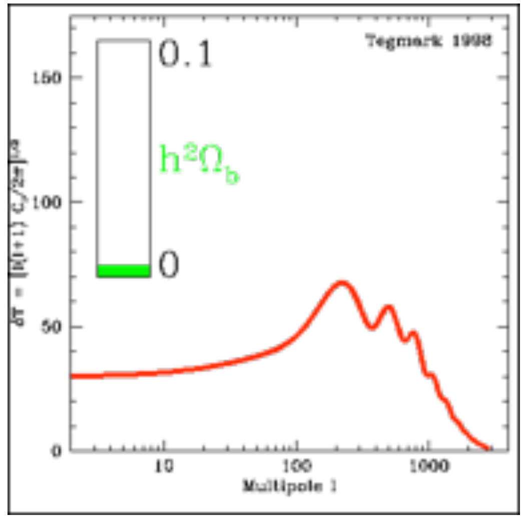
- Late universe reionization characterized with a single parameter(+1) : optical depth τ or reionization redshift z_r.

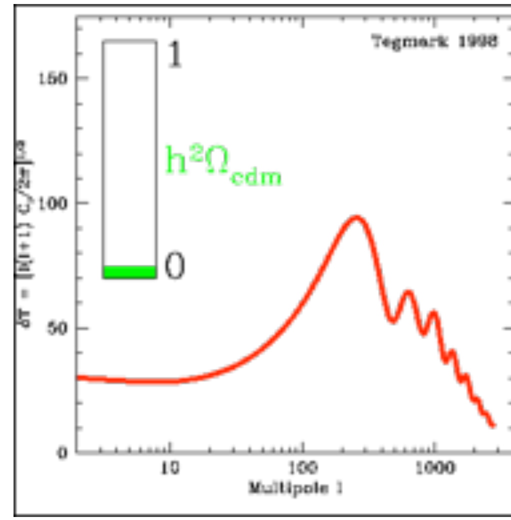
Total: 1+3-1+2+1= 6 parameters.

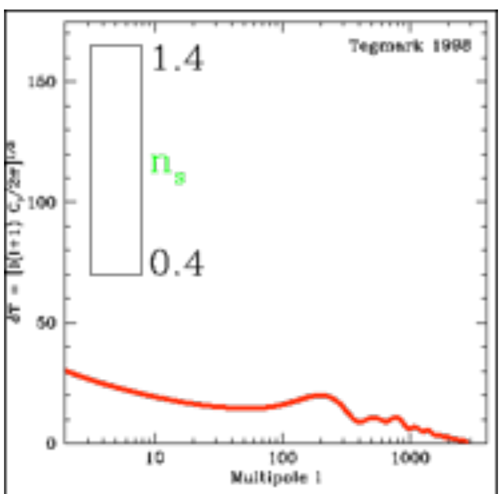
We can measure cosmological parameters with CMB !

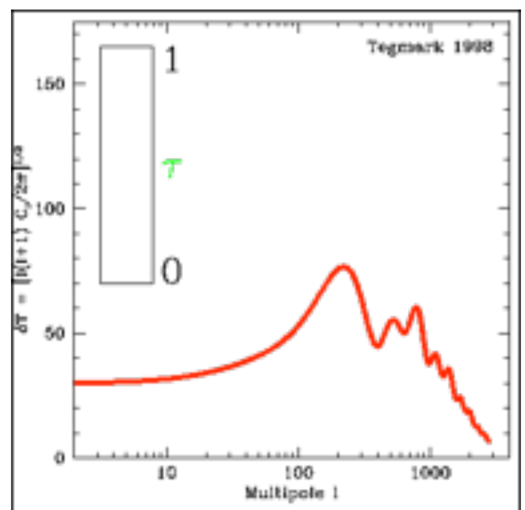
Temperature Angular spectrum varies with Ω_{tot} , Ω_b , Ω_c, Λ, τ, h, n_s, …





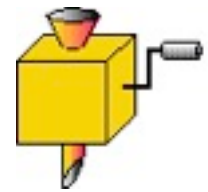


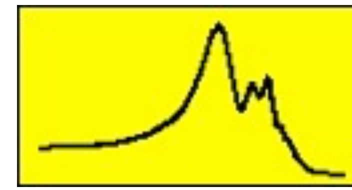


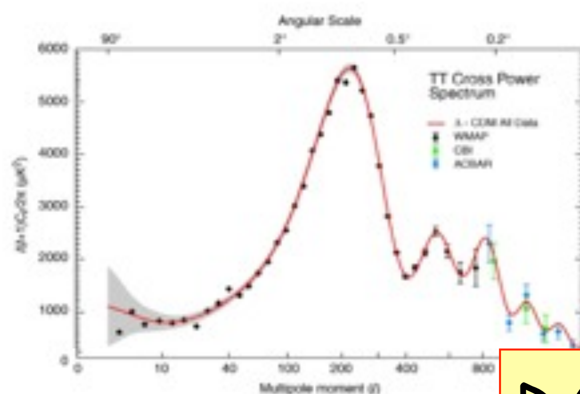


How to get a bound on a cosmological parameter

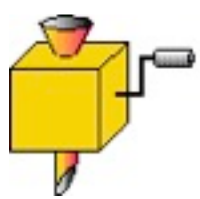
Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau , \Sigma m_\nu)$







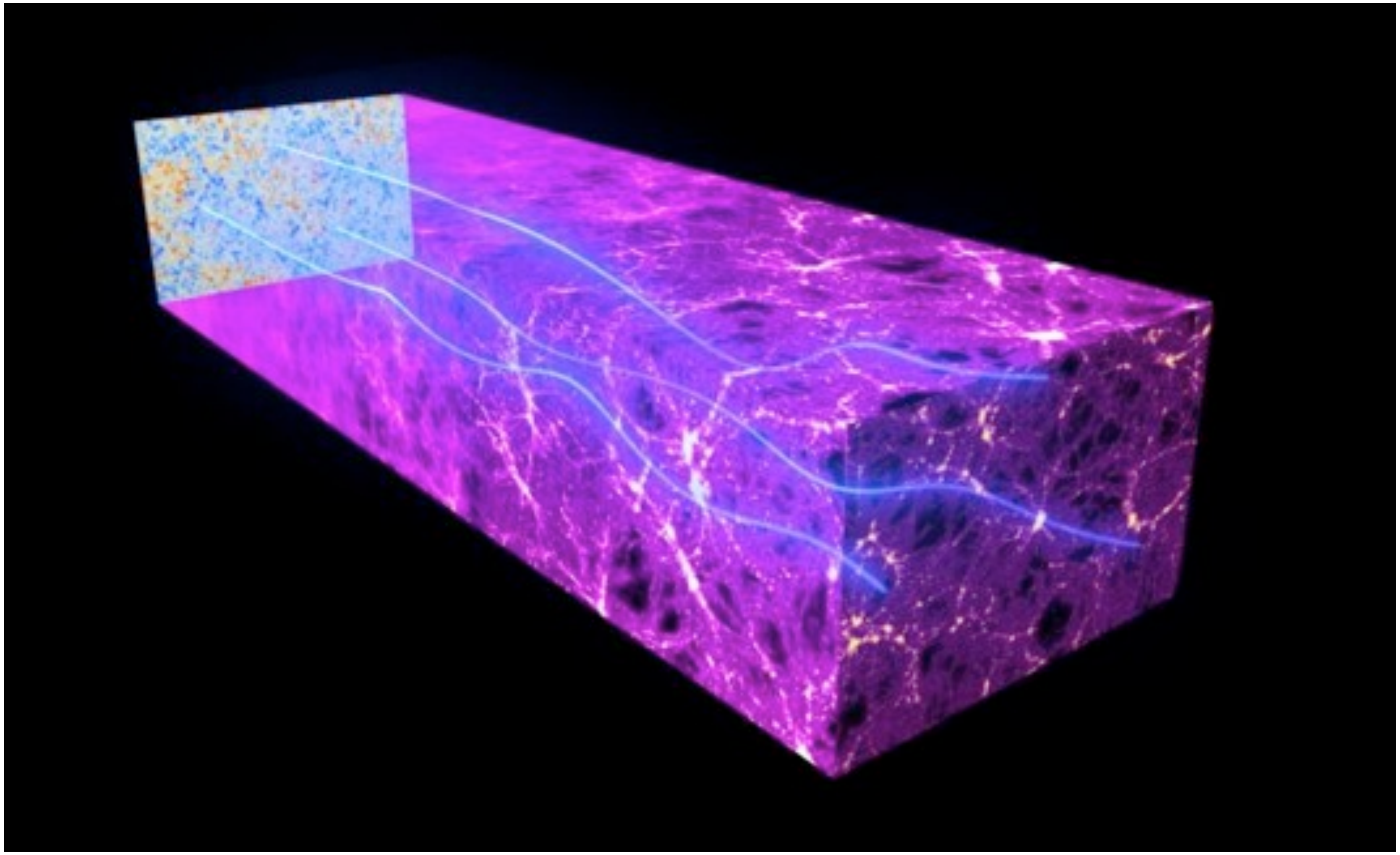
DATA



PARAMETER ESTIMATES

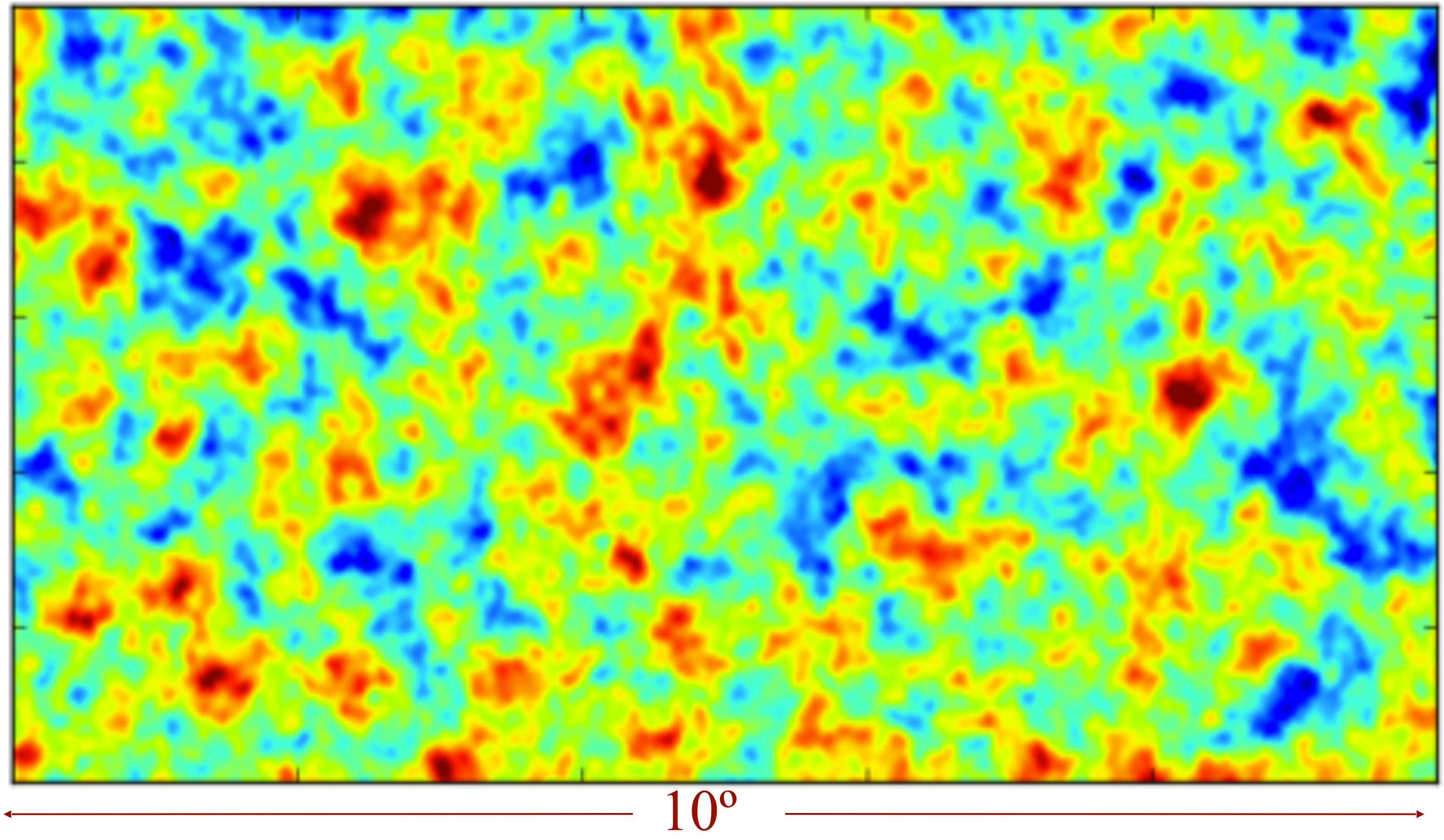
Gravitational Lensing

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



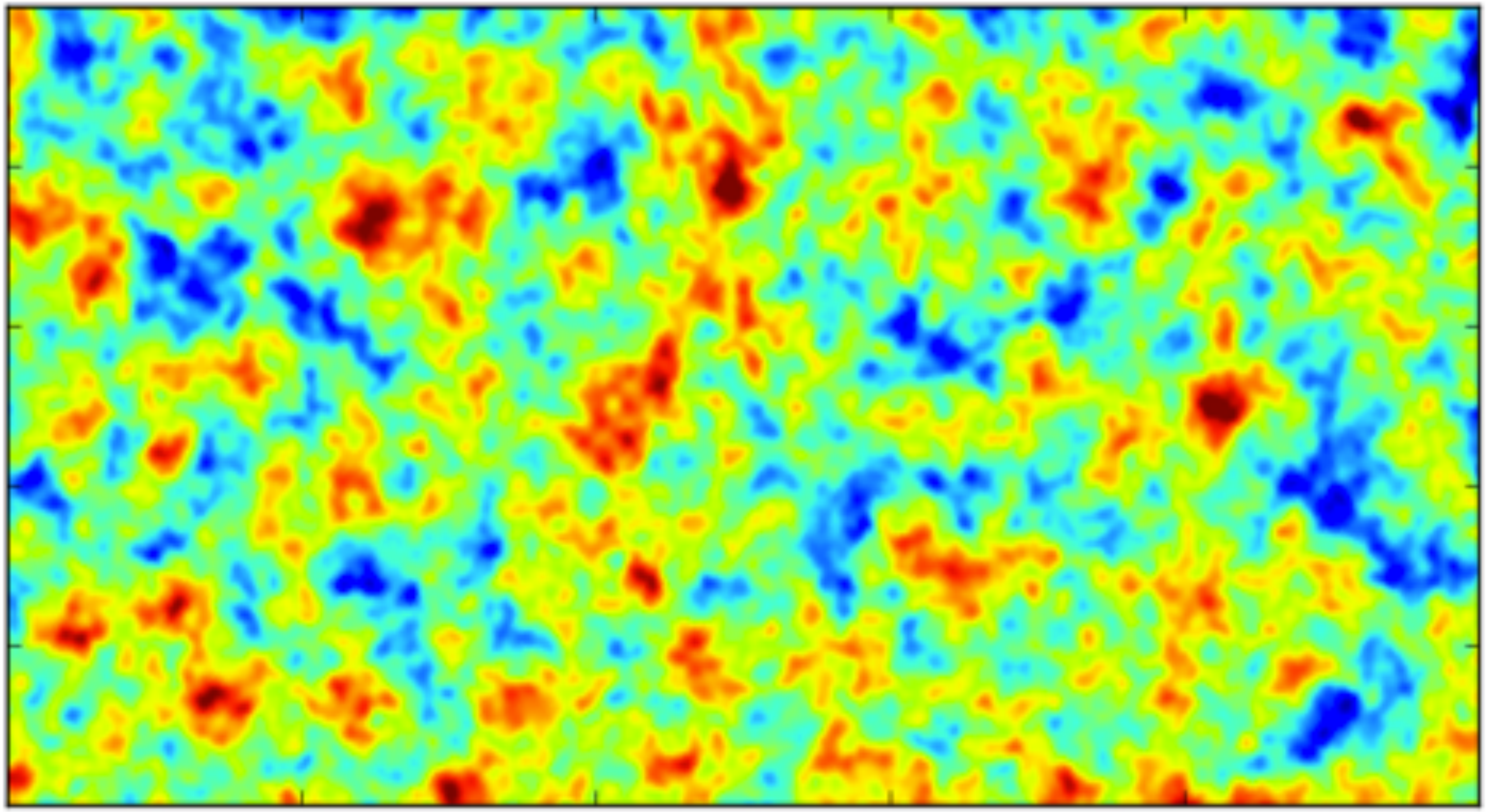
Gravitational Lensing

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



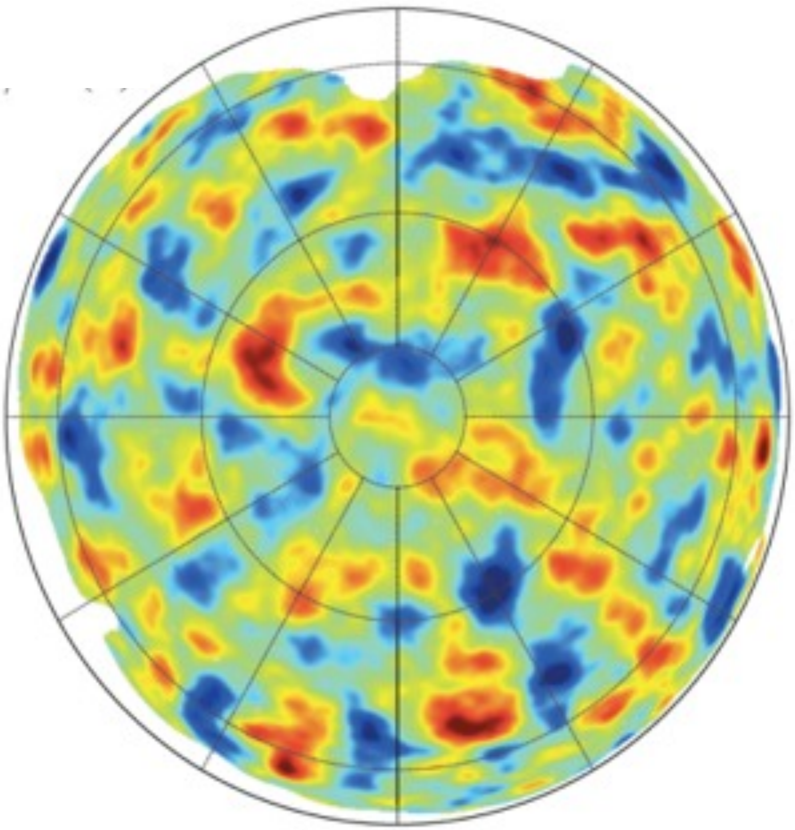
Gravitational Lensing

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

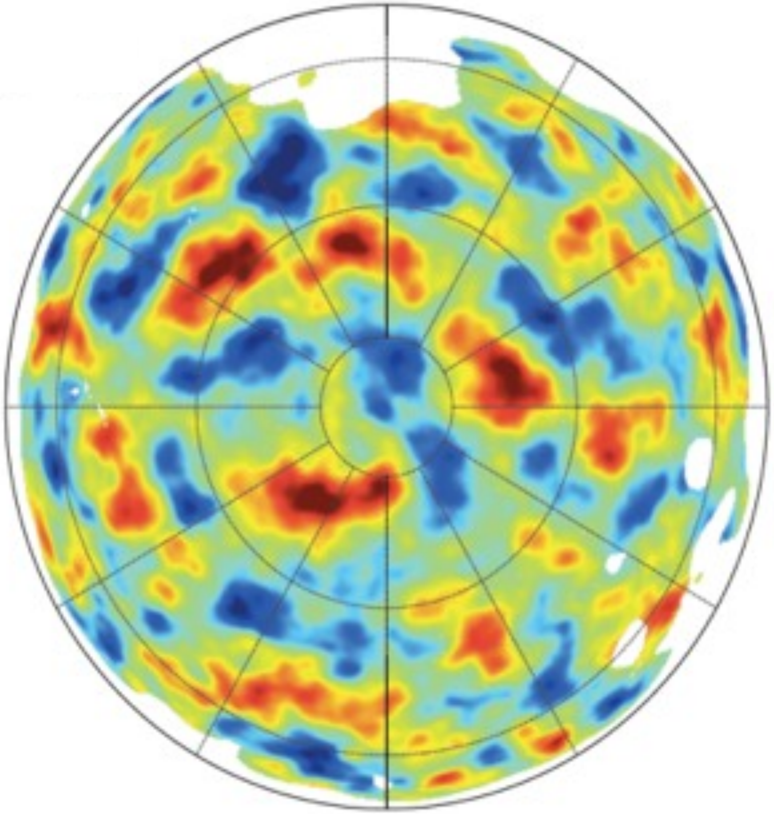


10°

Planck dark matter distribution throught CMB lensing

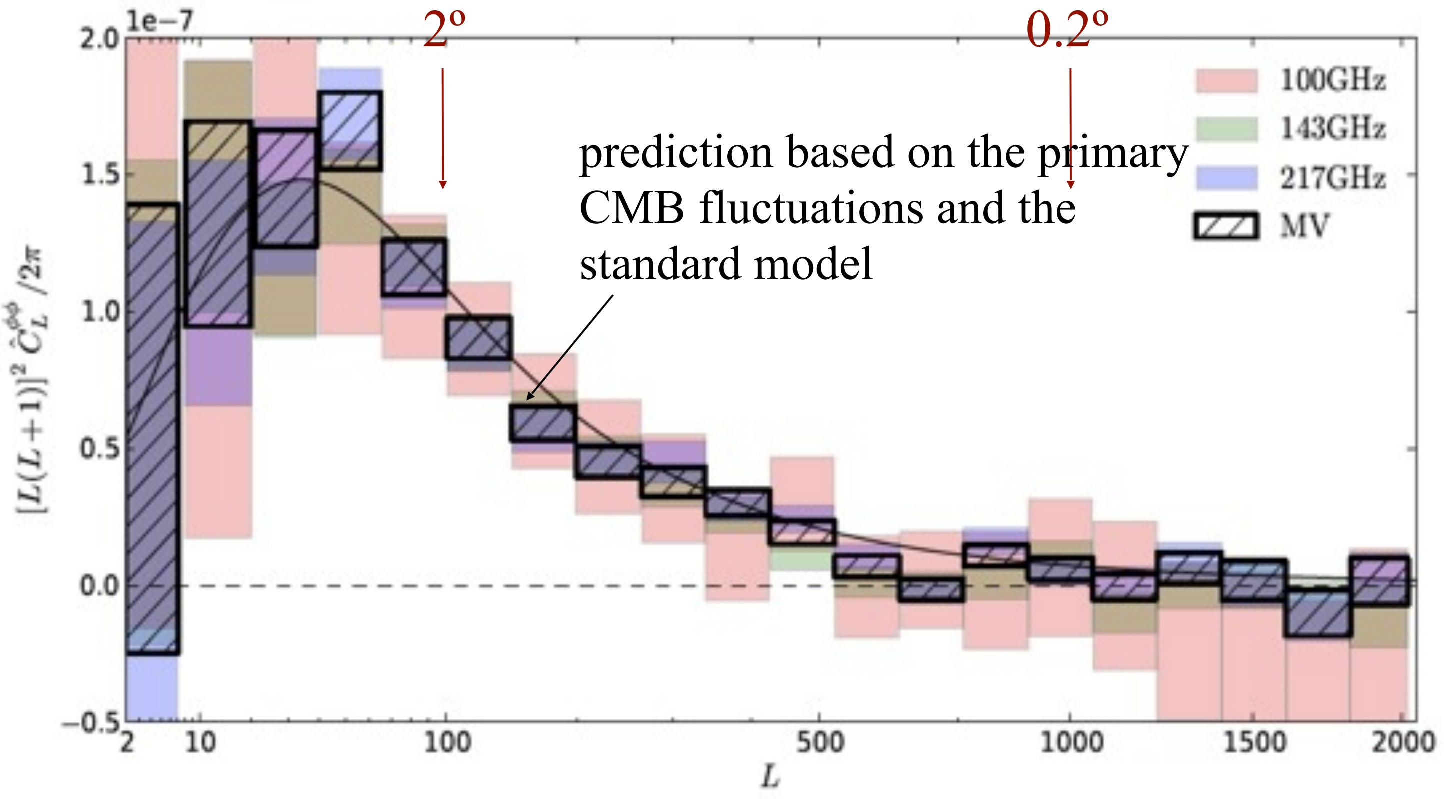


Galactic North



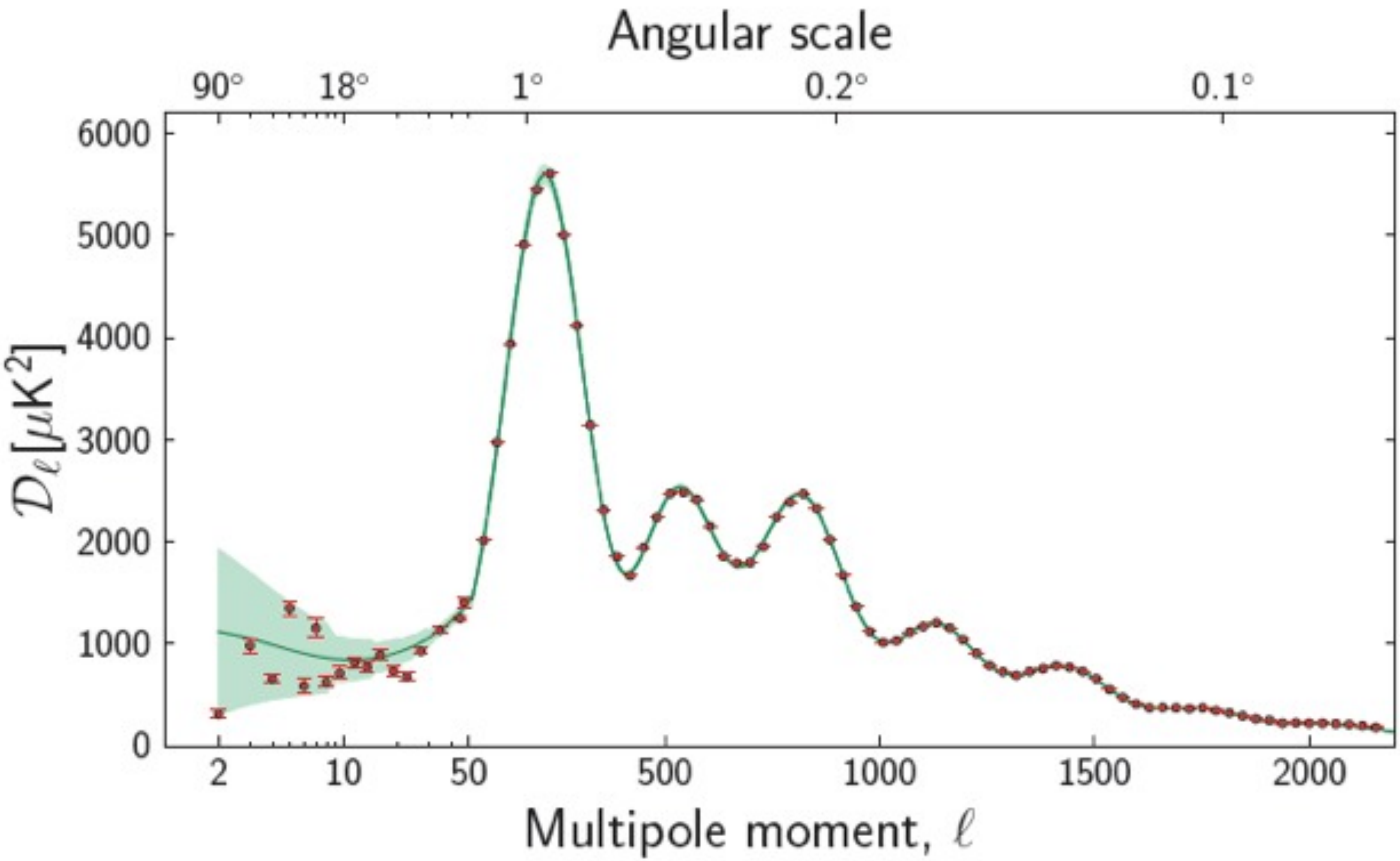
Galactic South

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



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

Planck 2013 TT angular spectrum



Constraints on LCDM

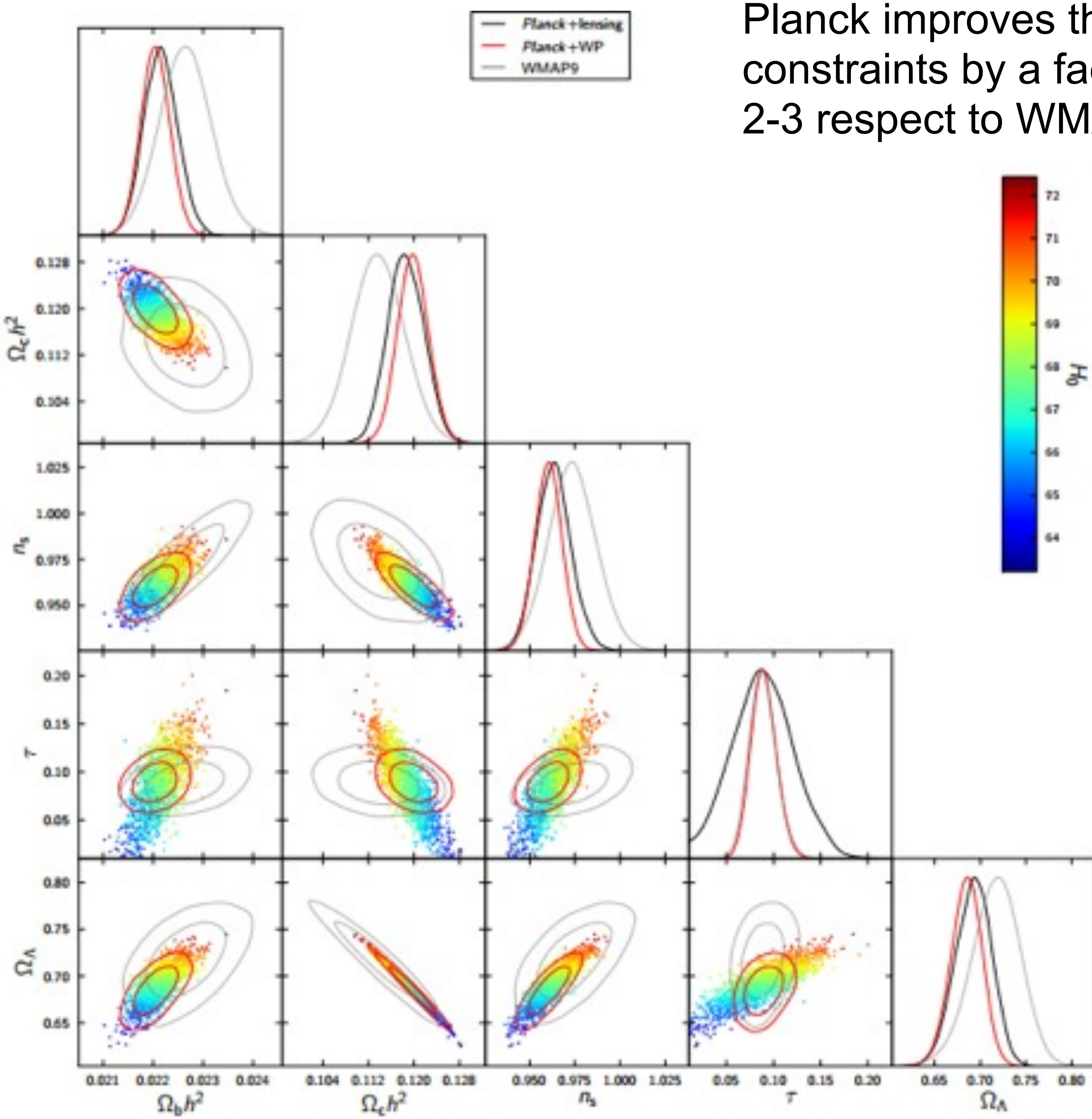
Planck improves the constraints by a factor 2-3 respect to WMAP9

Lower Baryon Density

Higher CDM Density

Lower Spectral index

Smaller Cosmological Constant



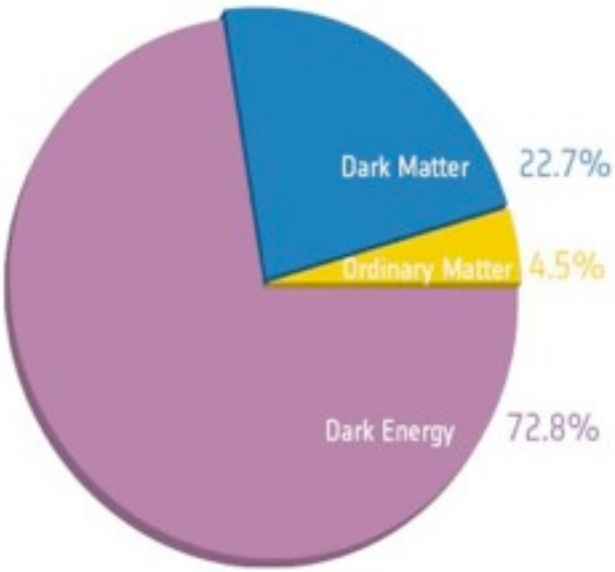
Constraints

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	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	[illegible]	[illegible]	[illegible].018	0.8347	0.829 ± 0.012
z_{re}	11.35	[illegible]	[illegible]	[illegible]$^{.1}_{.5}$	11.37	11.1 ± 1.1
H_0	67.11	[illegible]	[illegible]	[illegible]1.5	67.04	67.3 ± 1.2

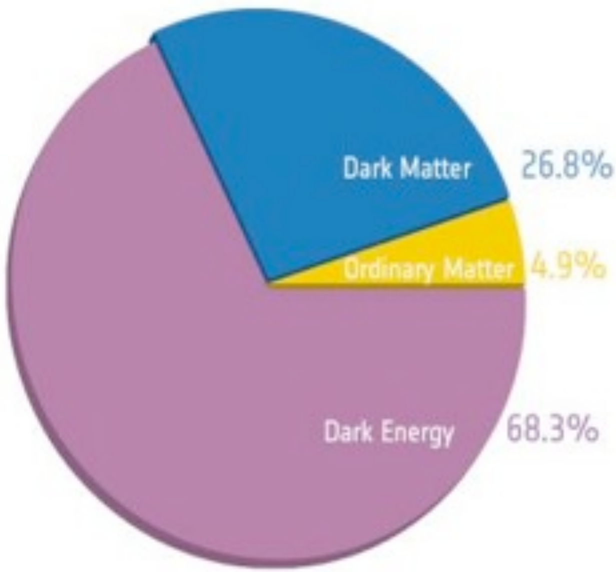
WMAP9

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



Before Planck



After Planck

...has changed!

You are currently viewing the **U.S. Edition** of NYTimes.com. To switch to the Global Edition, select from the menu below.

HOME PAGE | TODAY'S PAPER | VIDEO | MOST POPULAR | U.S. Edition

Try a Digital Subscription | Log In | Register Now

The New York Times

Monday, July 29, 2013 Last Update: 4:29 AM ET

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

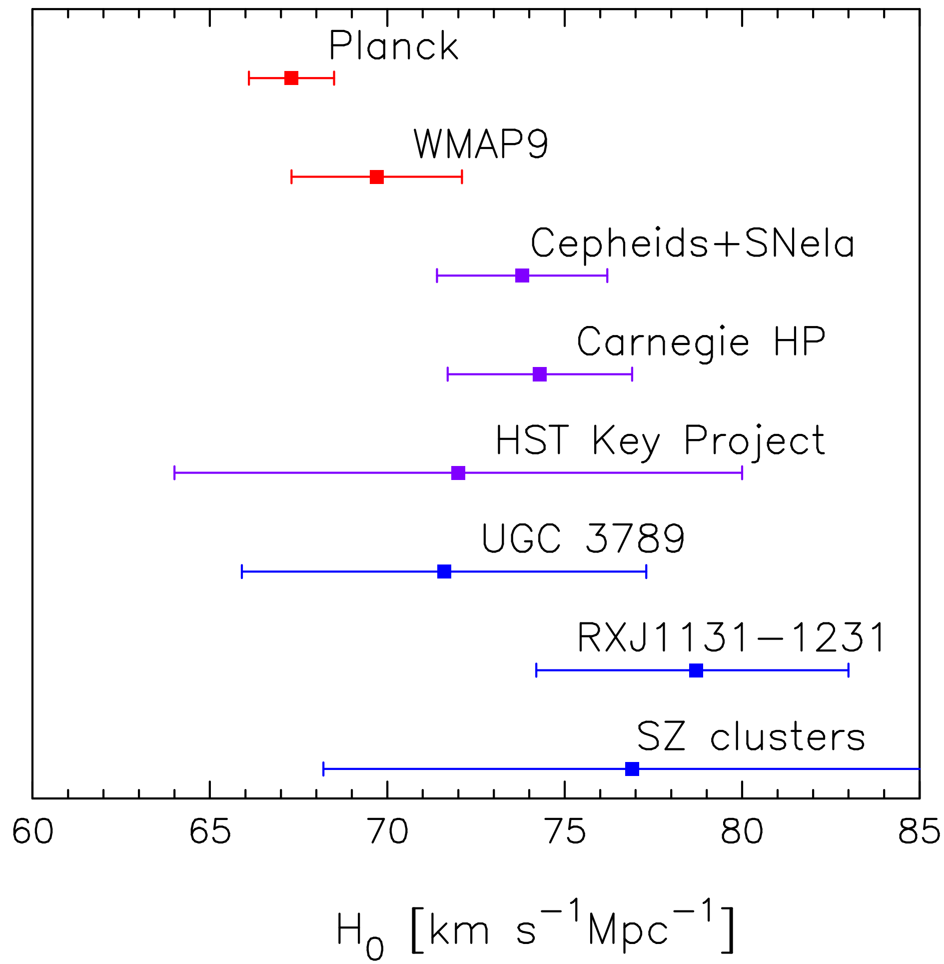
"Typical. You give birth to a few trillion galaxies and then people just talk about how old and fat you've gotten."

"Just like it says in Leviticus."

Chris Vanderhorst – Systems Analyst

Comparison with other datasets: Hubble Constant

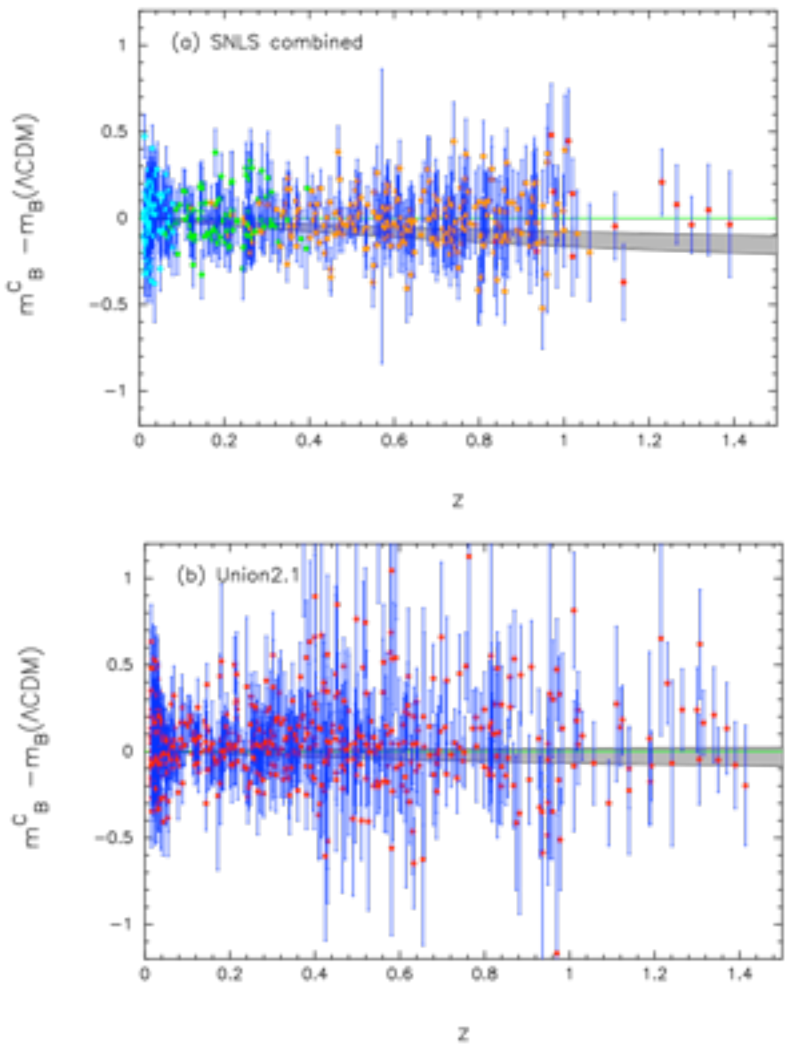
The value of the Hubble constant from Planck is in tension with the Riess et al. 2011 result.

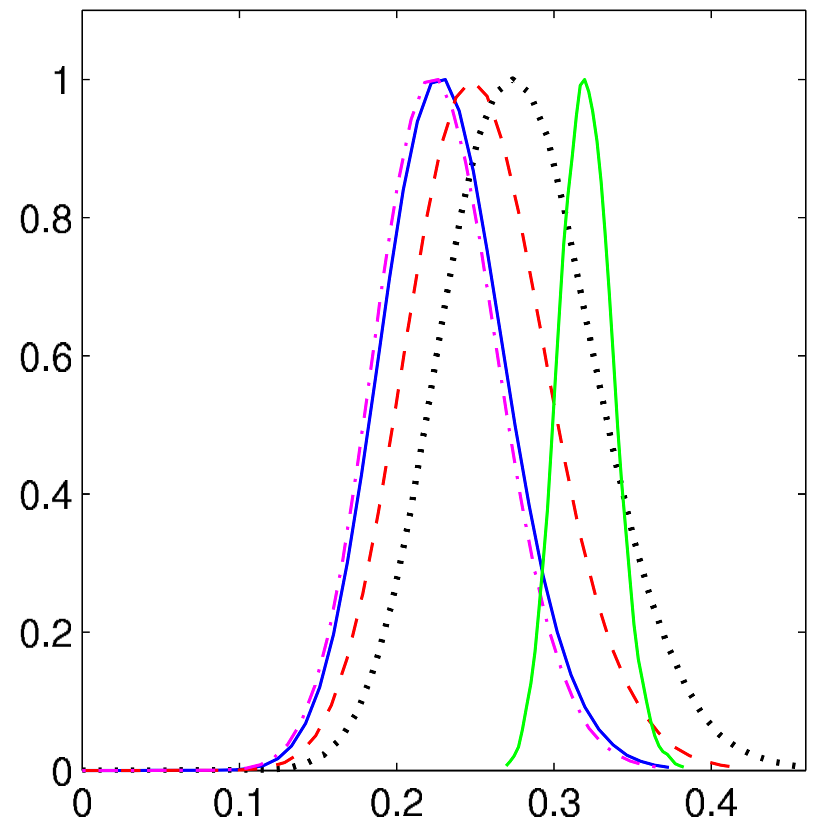


$$\text{Planck + WP} \qquad H_0 = 67.3^{+1.2}_{-1.1}\ [\text{km/s/Mpc}]$$

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

Comparison with SN-Ia data



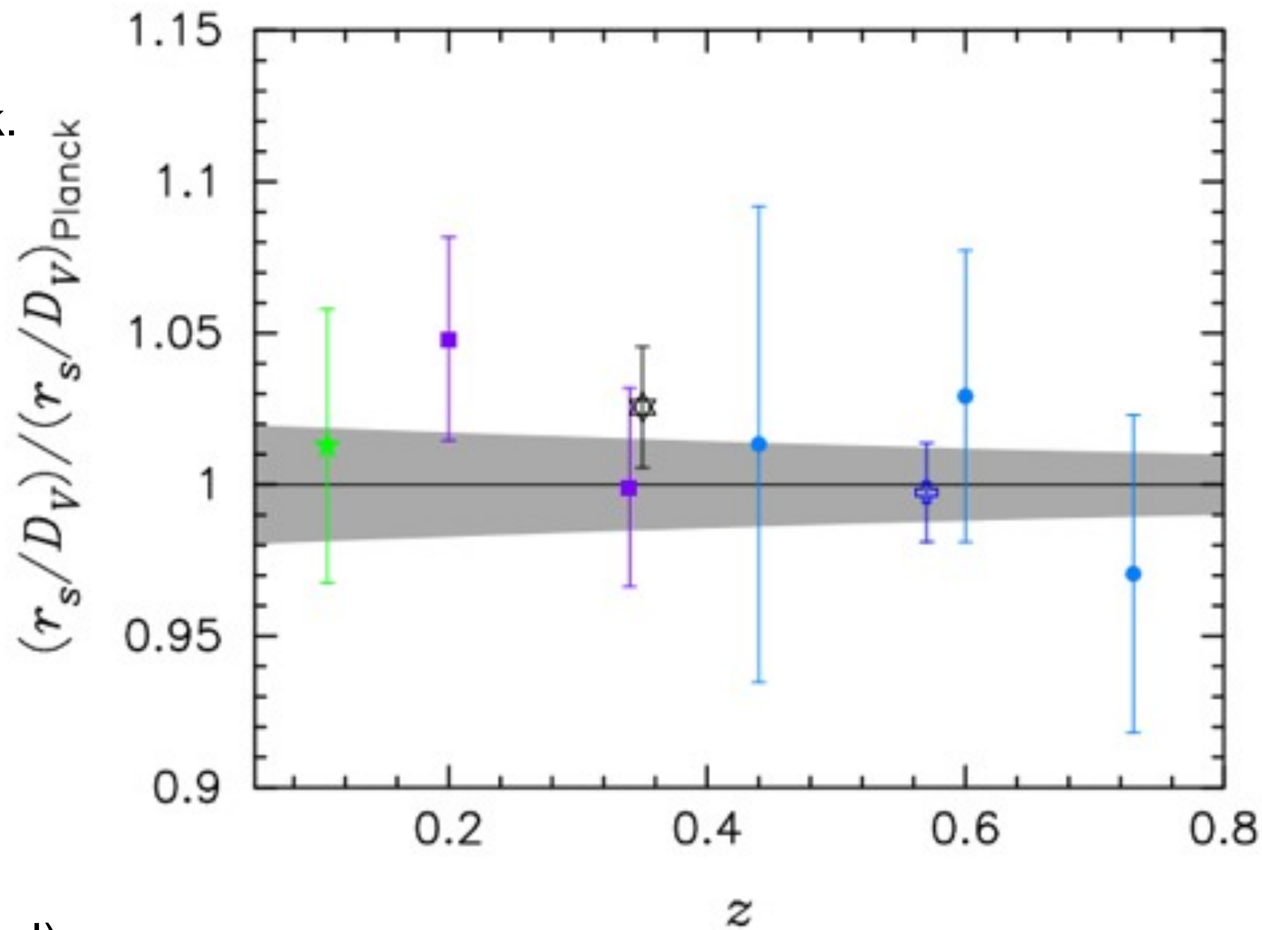


The value for the matter density inferred from SNLS survey is smaller than what observed with Planck assuming a flat universe.
Better agreement with the Union2 catalog.

Comparison with BAO surveys

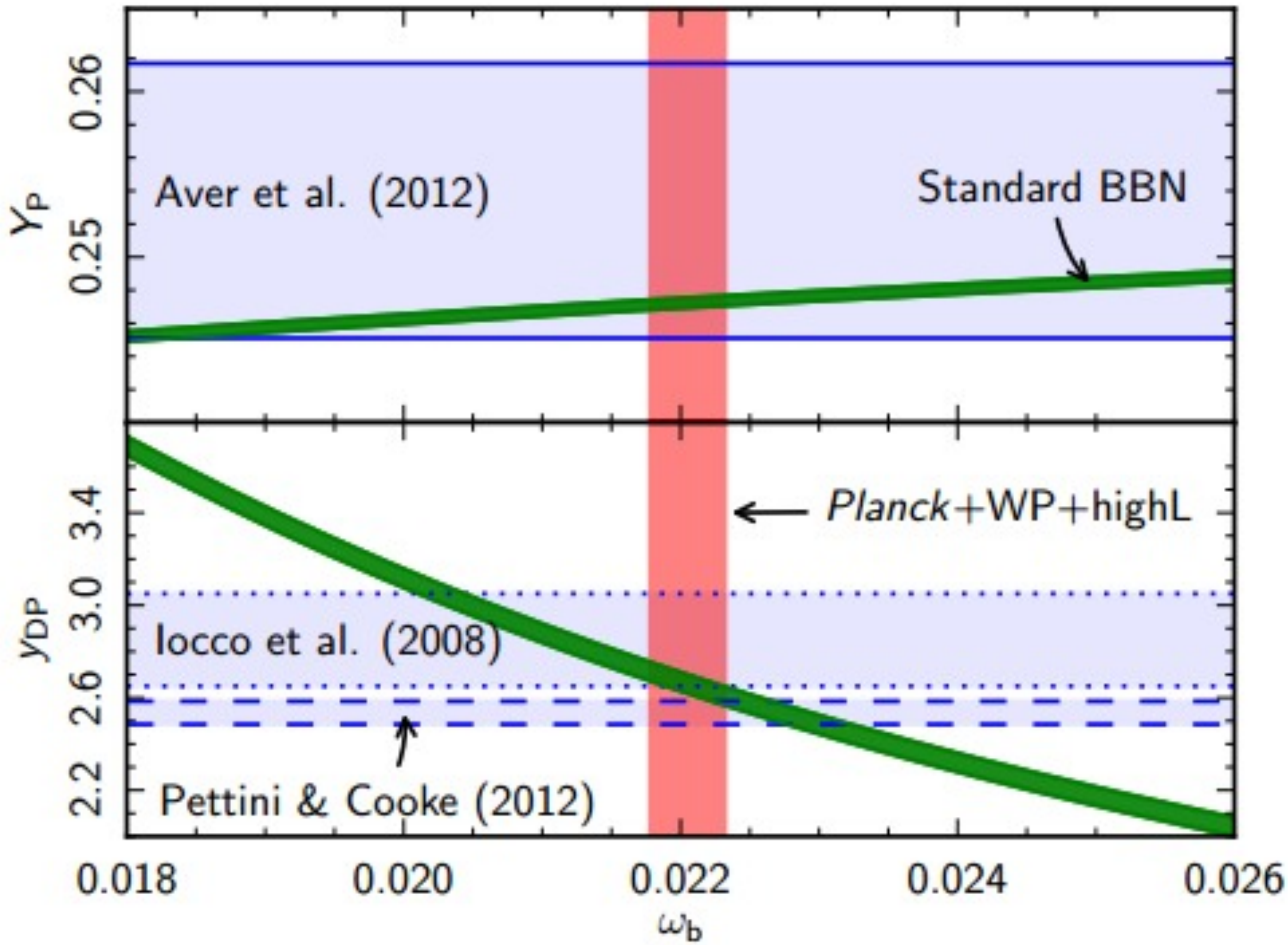
Acoustic scale – Distance ratio from BAO and Planck. Planck uncertainties are in grey.

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:

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

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:

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

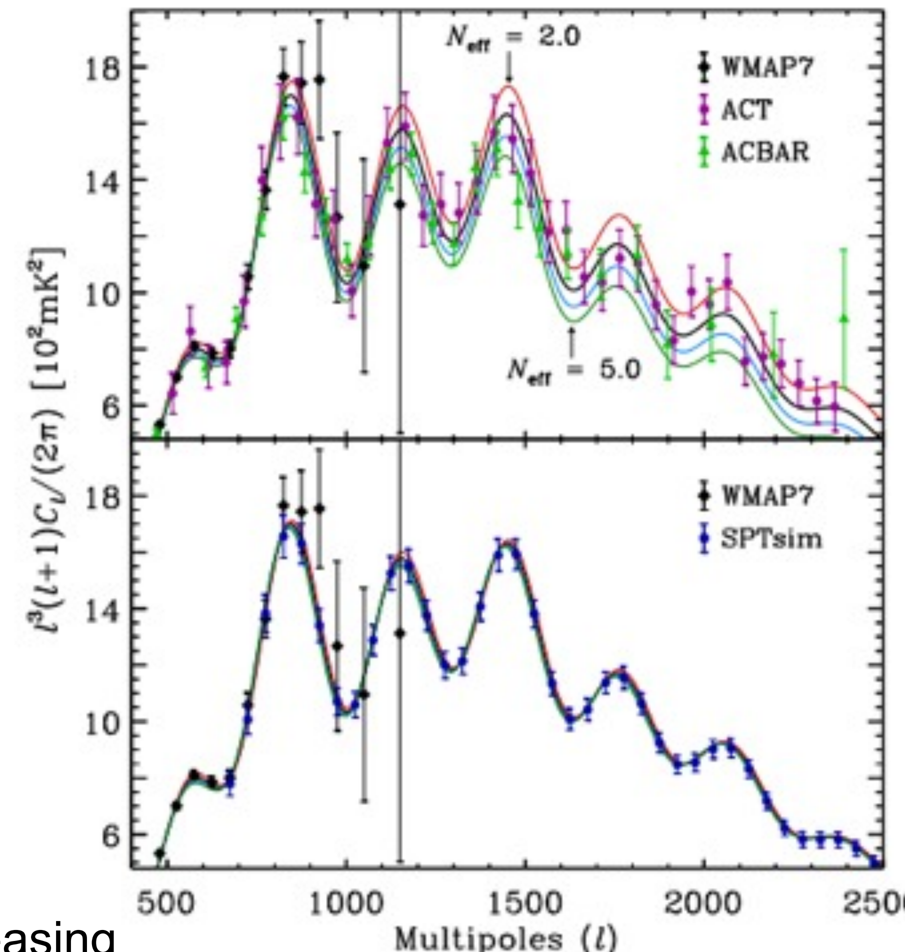
Probing the Neutrino Number with CMB data

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 E 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.)

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

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

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

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

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.):

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

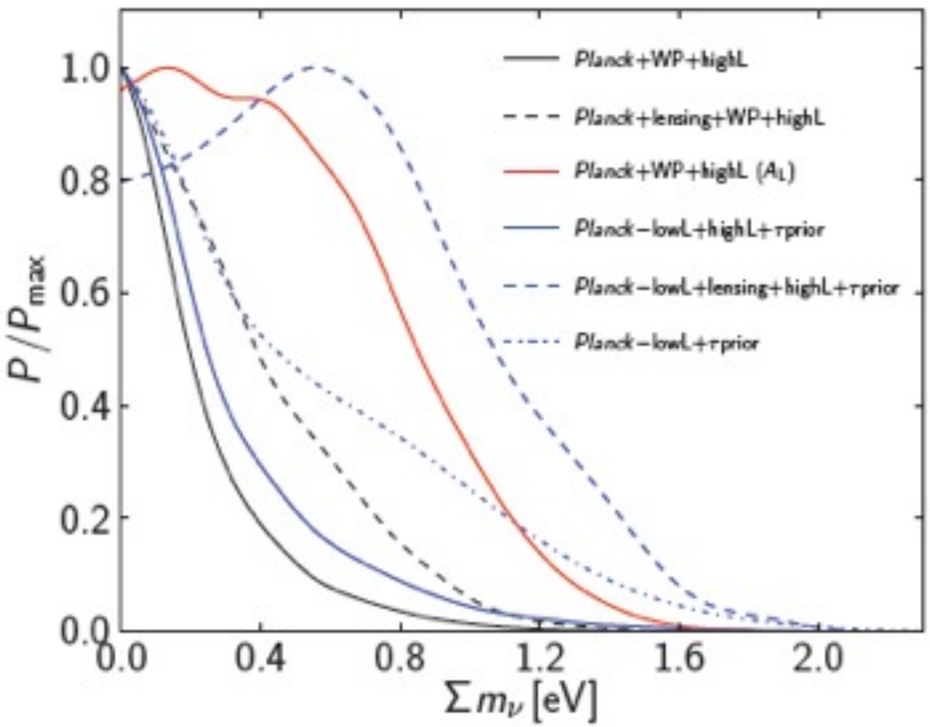
$$\text{HST (Riess et al.)} \qquad H_0 = 73.8^{+2.4}_{-2.4}\ [\text{km/s/Mpc}]$$

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 on Neutrino Mass (standard 3 neutrino framework)



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

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

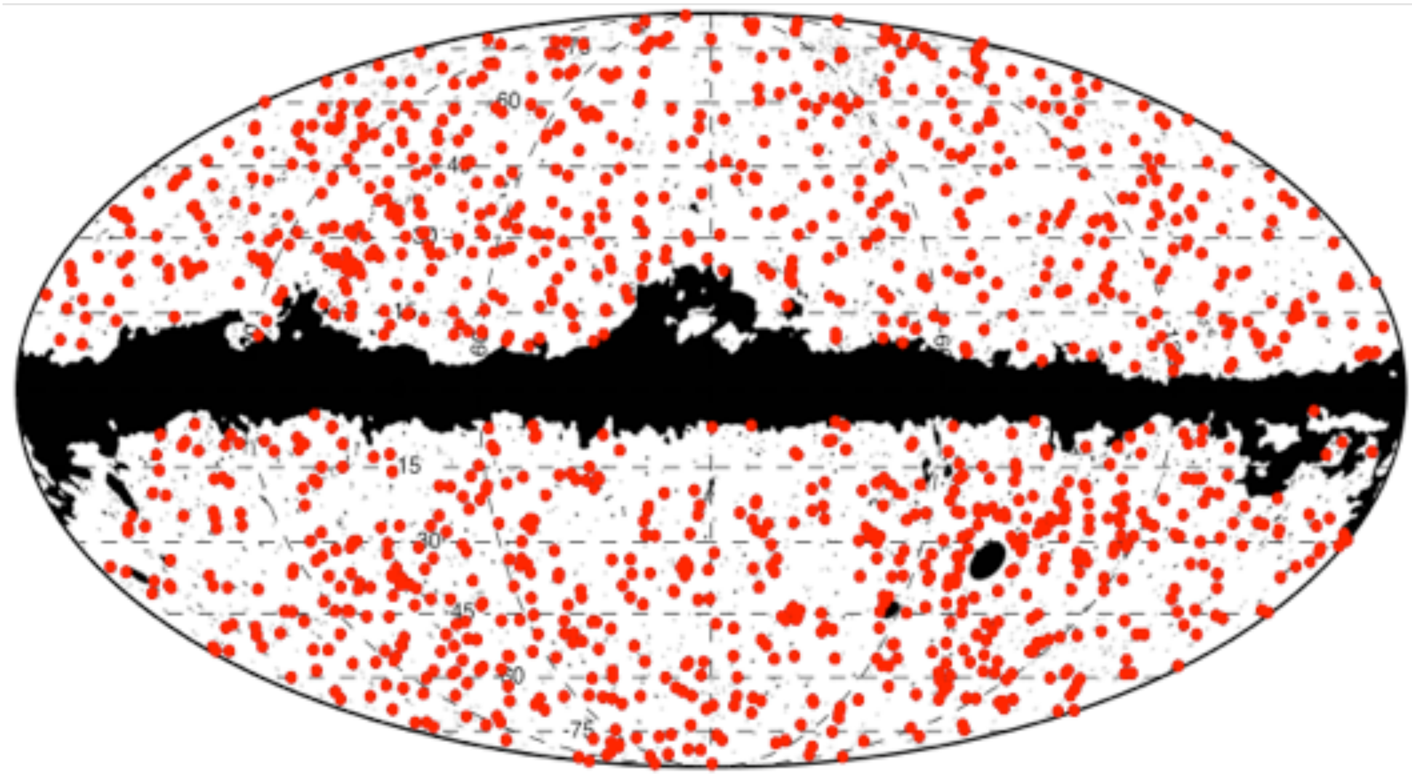
$$\sum m_\nu < 0.85\,\mathrm{eV} \quad (95\%;\ \mathit{Planck}\text{+lensing+WP+highL}),$$

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

- 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

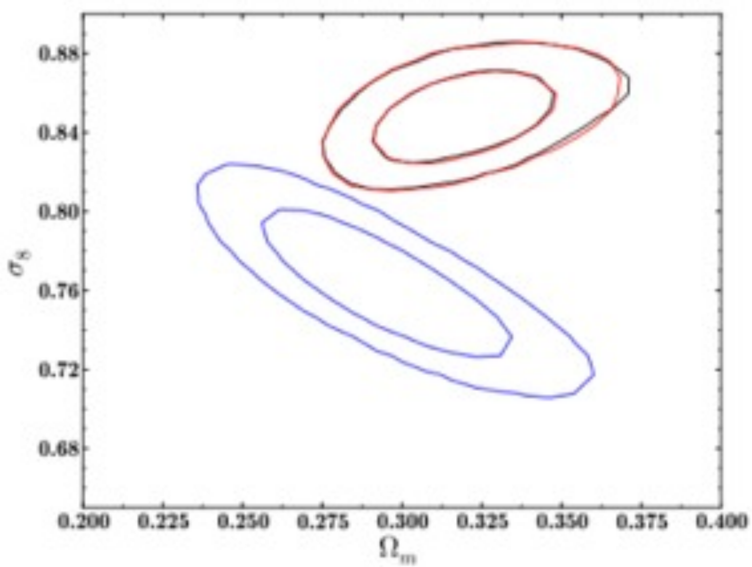
Planck SZ catalog

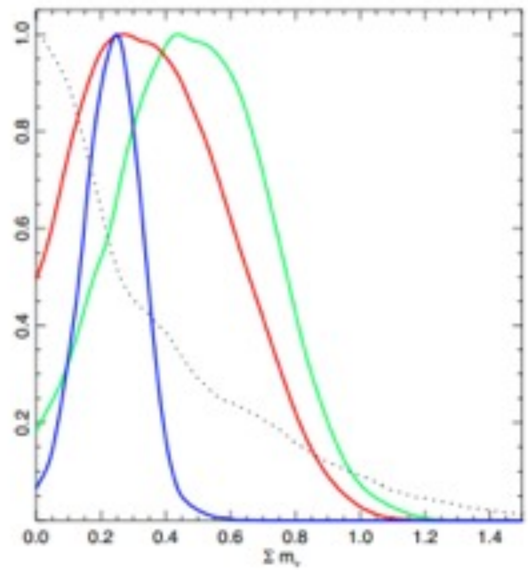


- 1227 clusters & candidates
  - 683 previously known
  - 178 new clusters
  - 366 candidates

- 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]

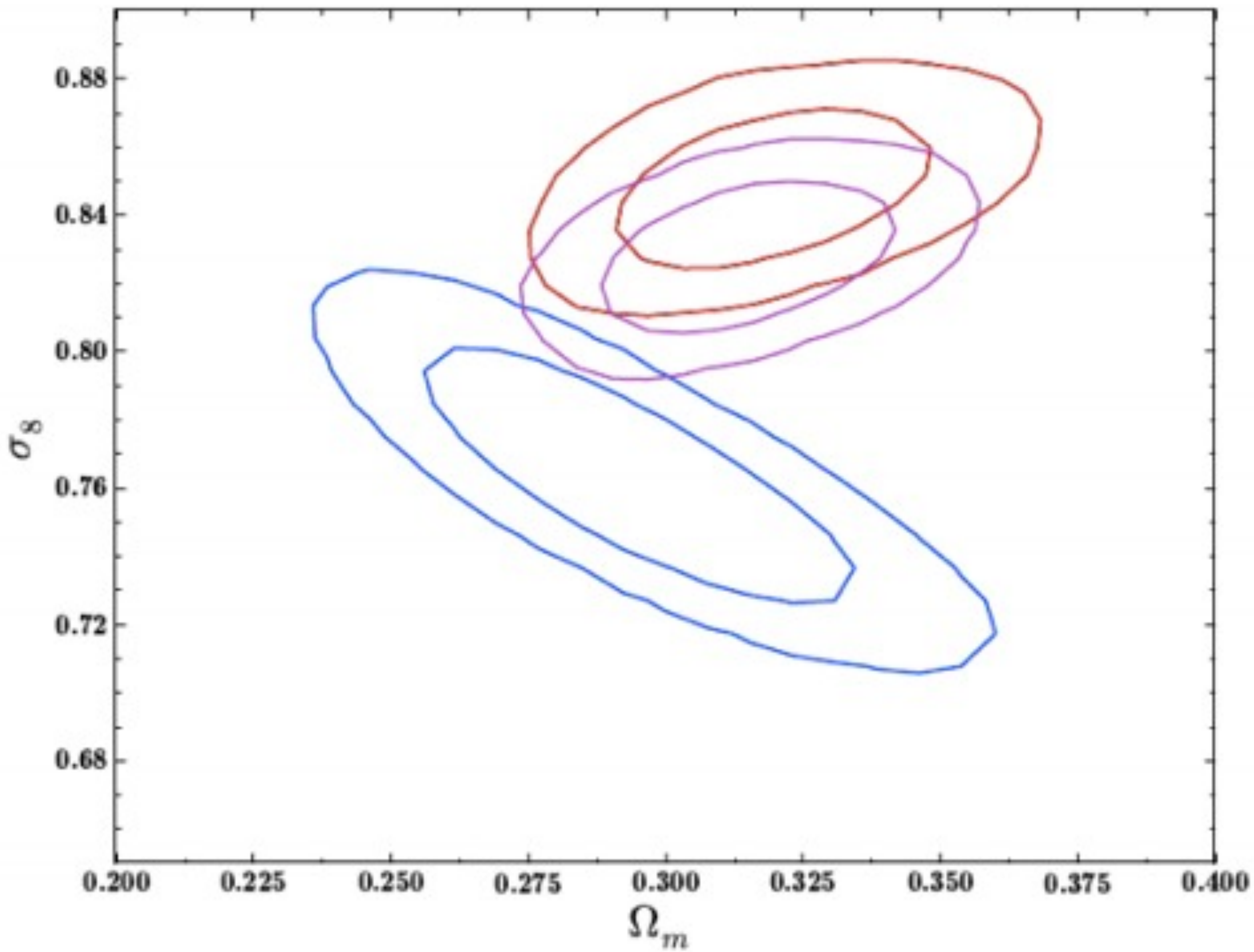
Green:
Planck CMB+SZ
(1-b)=0.8

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).

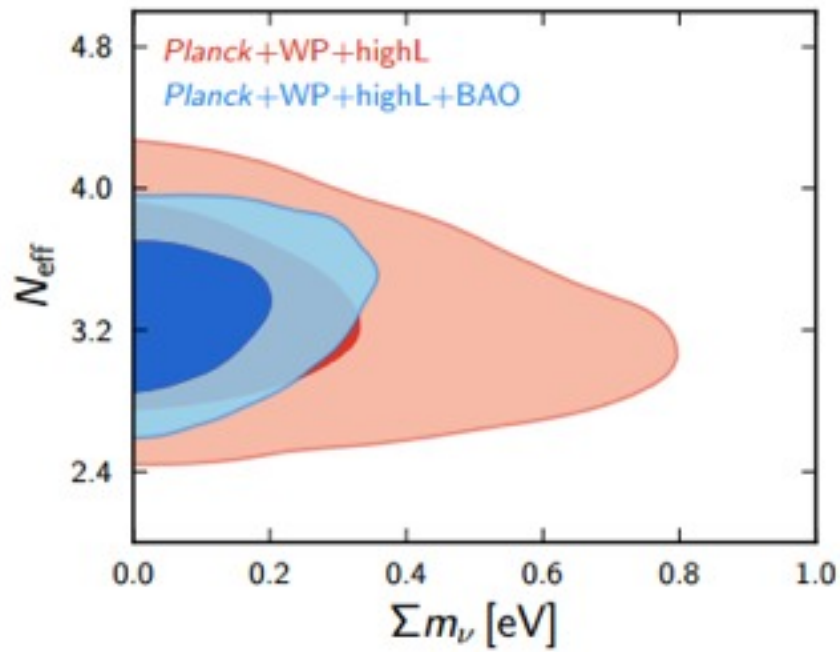


Red:
Planck+WP TT analysis with massless neutrinos.

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 $N_{\rm eff}$ and the mass of the 3 **active** massive neutrinos.

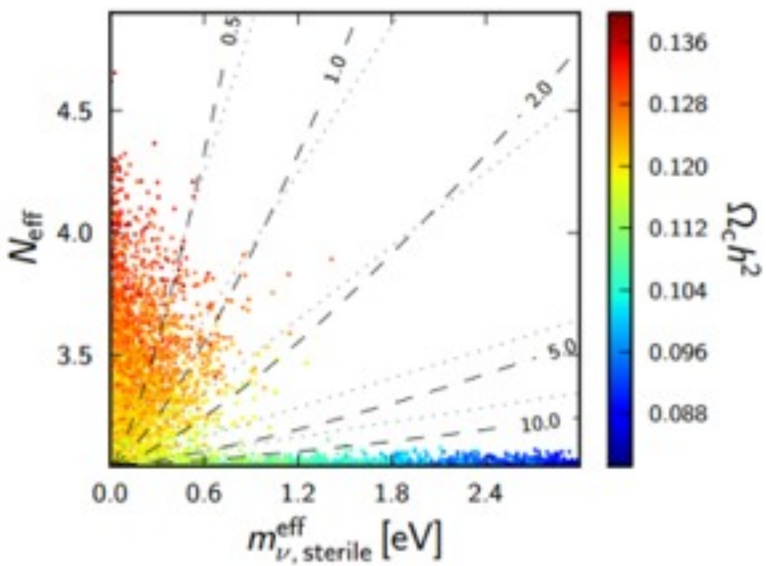
Constraints on a massive sterile neutrino

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

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

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:

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

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

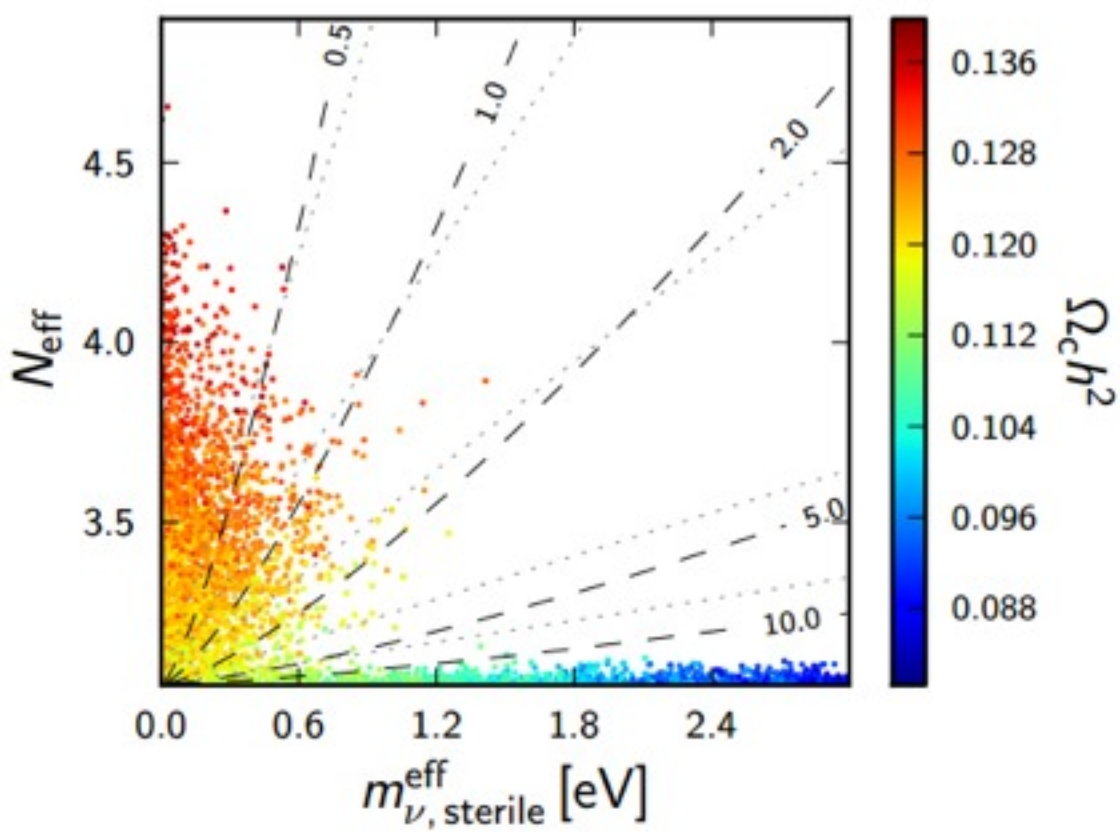
$$m^{\mathrm{eff}}_{\nu,\,\mathrm{sterile}} = \chi_{\mathrm{s}} m^{\mathrm{DW}}_{\mathrm{sterile}} \quad \text{with } \Delta N_{\mathrm{eff}} = \chi_{\mathrm{s}}.$$

Constraints on a massive sterile neutrino

Please note:

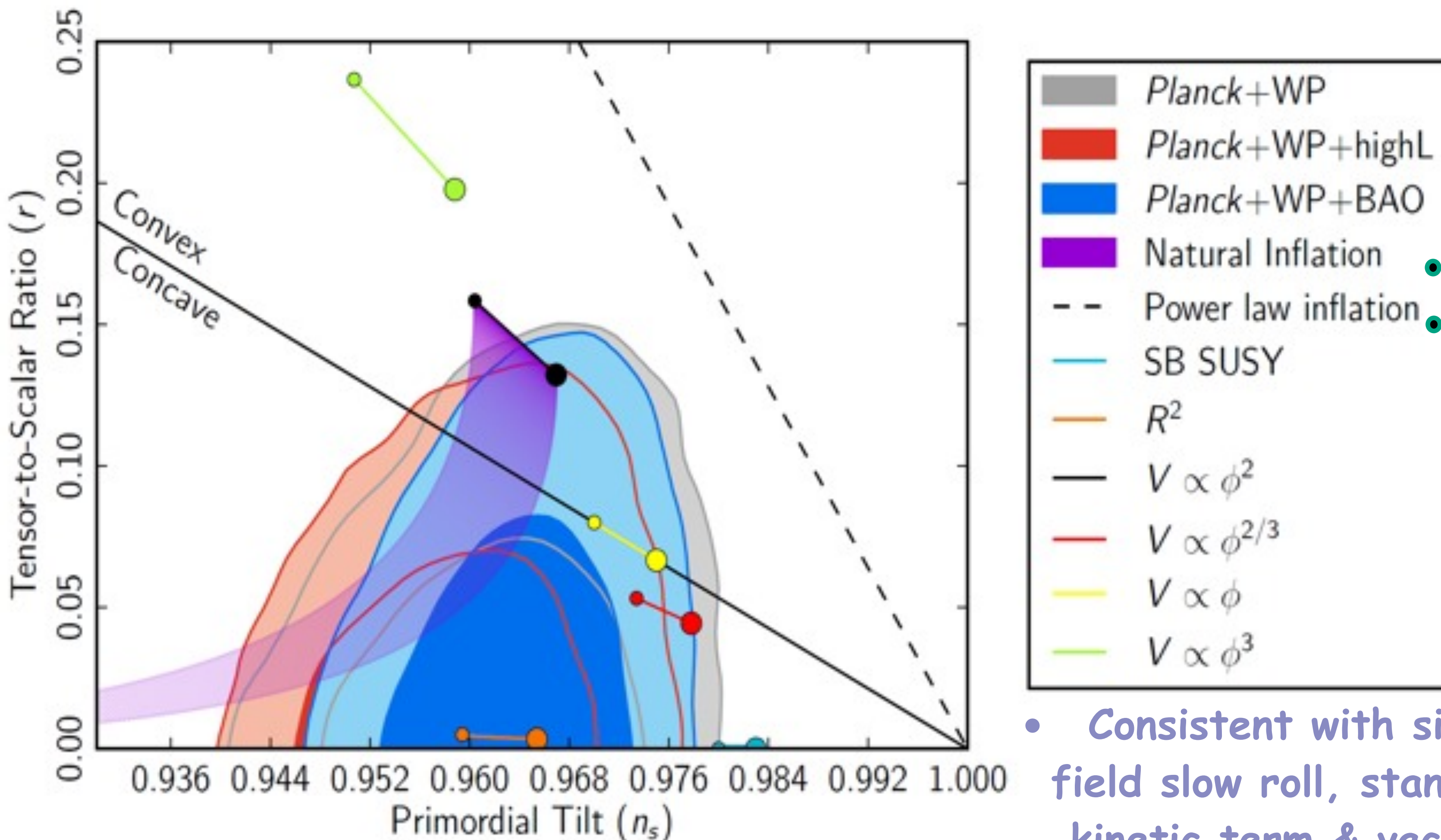
Neff refers **only** to relativistic neutrinos at recombination !

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



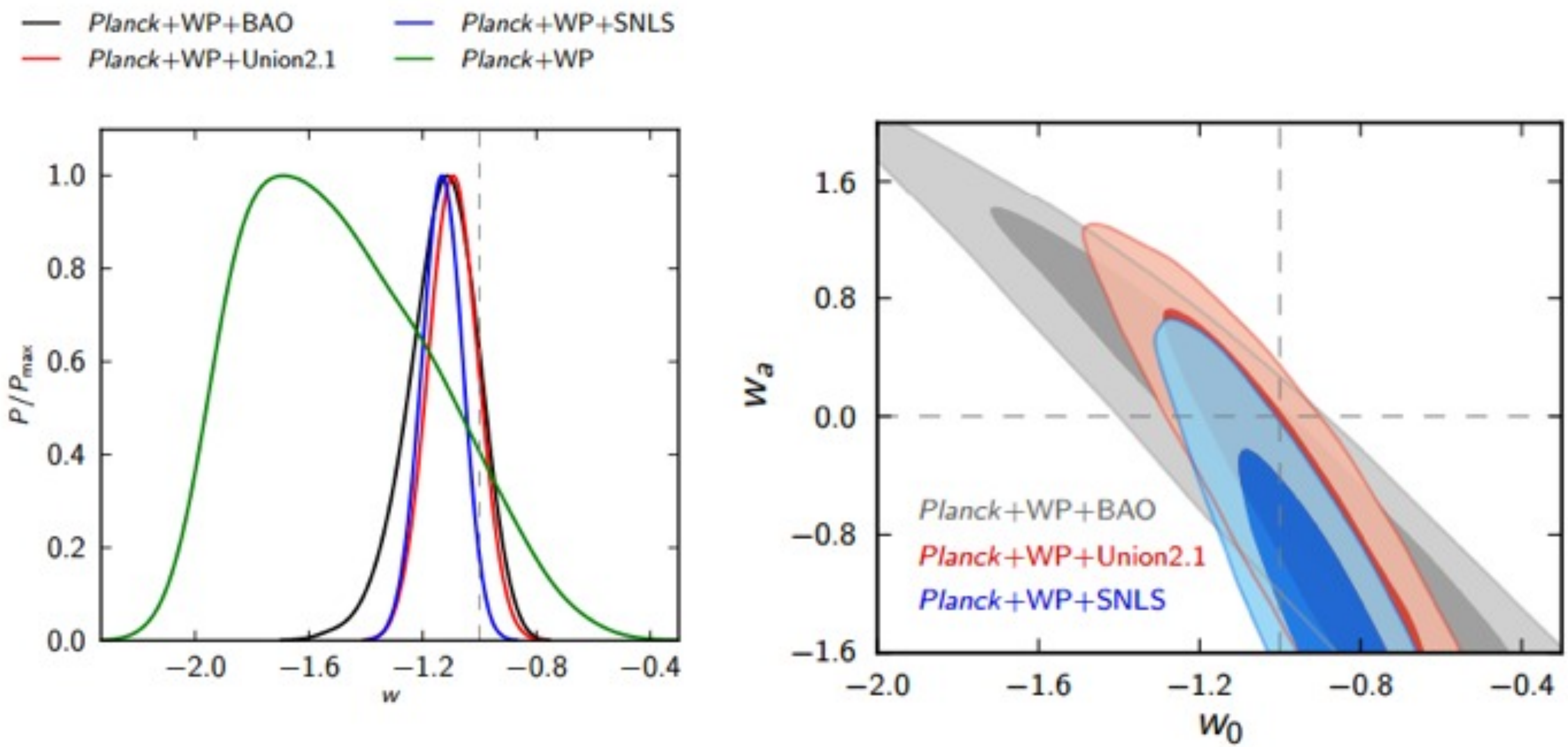
$$\left.\begin{aligned} N_{\rm eff} &< 3.91 \\ m^{\rm eff}_{\nu,\,\rm sterile} &< 0.59\,\rm eV \end{aligned}\right\} \quad (95\%;\ \text{CMB for } m^{\rm thermal}_{\rm sterile} < 10\,\rm eV)$$

Main constraint on Inflation physics



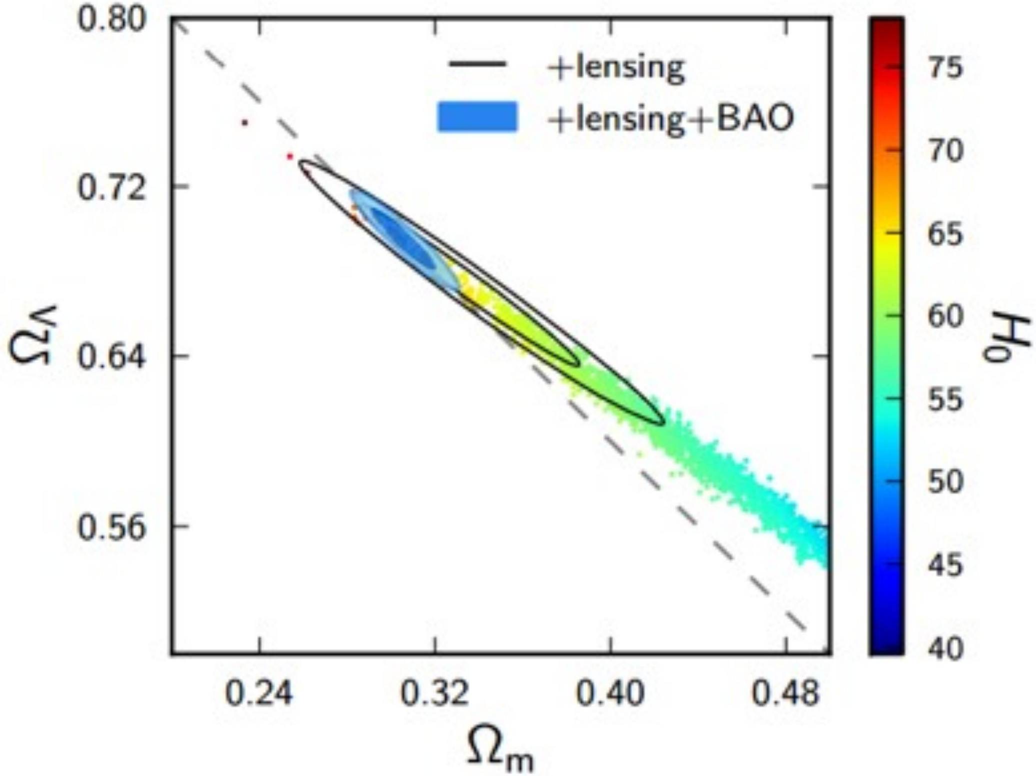
- Consistent with single field slow roll, standard kinetic term & vacuum (with f_{NL} upper limits),

Constraints on Dark Energy



Planck in combination with SN-Ia datasets provides constraints on the dark energy equation of state.
Planck+SNLS hints for w<-1 or for evolving w(z) at more than 95% c.l..
Similar conclusions from the Union2 dataset but with less statistical significance (68% c.l.). However the SNLS will revise their data (Pain talk at ESLAB-47). !

Constraints on Curvature



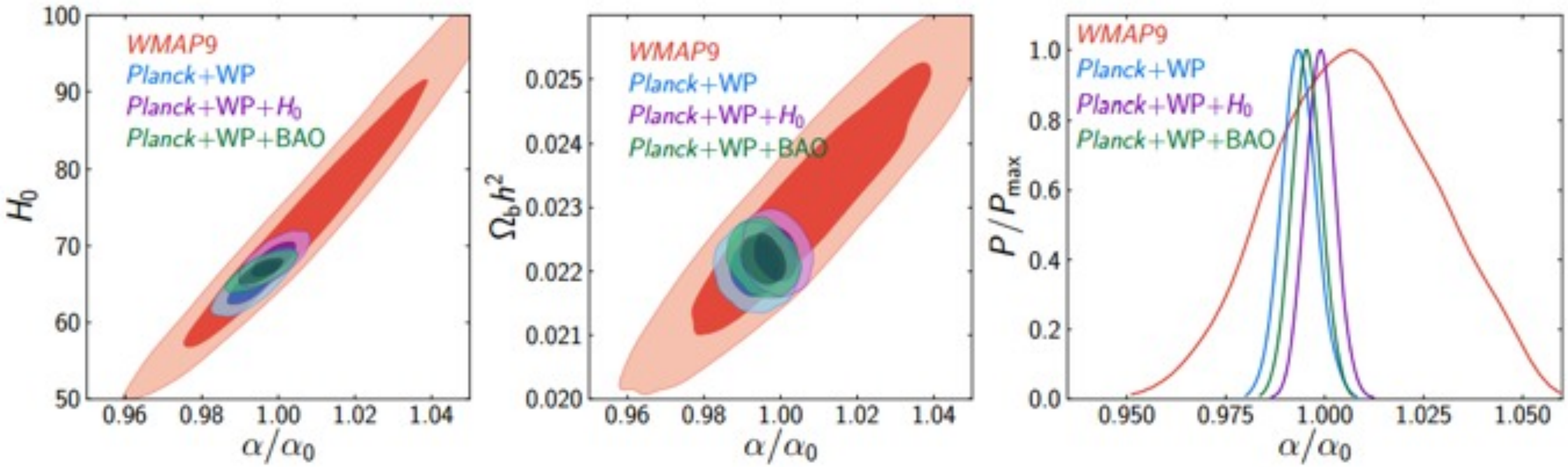
$$100\Omega_K = -4.2^{+4.3}_{-4.8} \quad (95\%;\ \textit{Planck}\text{+WP+highL});$$
$$100\Omega_K = -1.0^{+1.8}_{-1.9} \quad (95\%;\ \textit{Planck}\text{+lensing + WP+highL}).$$

$$100\Omega_K = -0.05^{+0.65}_{-0.66} \quad (95\%;\ \textit{Planck}\text{+WP+highL+BAO}),$$
$$100\Omega_K = -0.10^{+0.62}_{-0.65} \quad (95\%;\ \textit{Planck}\text{+lensing+WP +highL+BAO}).$$

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 !

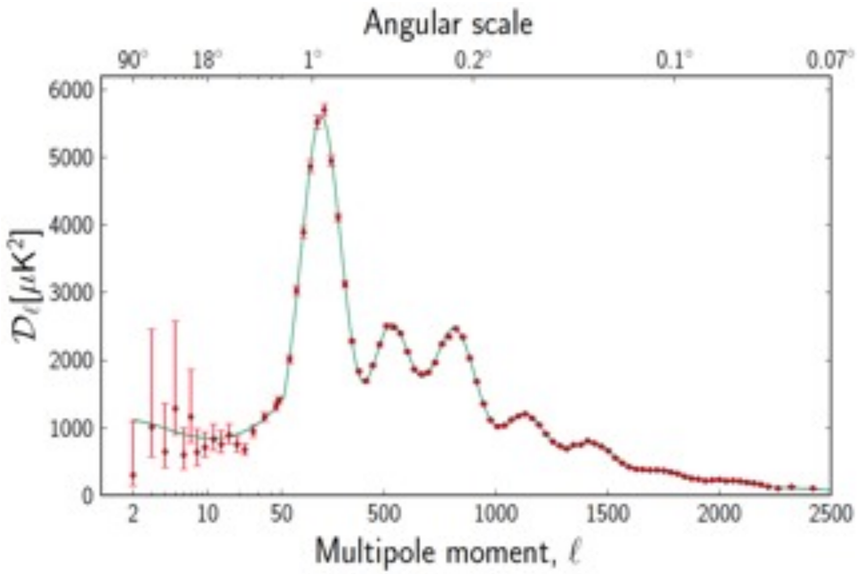
Constraints on Variations of Fine Structure Constant

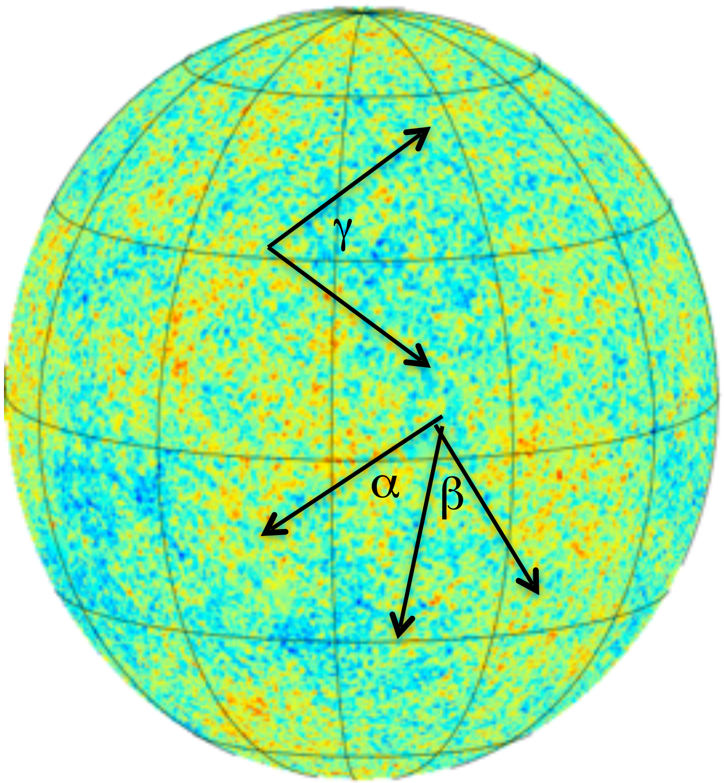
	Planck+WP	*Planck*+WP+BAO	*WMAP*-9
$\Omega_b h^2$	0.02206 ± 0.00028	0.02220 ± 0.00025	0.02309 ± 0.00130
$\Omega_c h^2$	0.1174 ± 0.0030	0.1161 ± 0.0028	0.1148 ± 0.0048
τ	0.095 ± 0.014	0.097 ± 0.014	0.089 ± 0.014
H_0	65.2 ± 1.8	66.7 ± 1.1	73.9 ± 10.9
n_s	0.975 ± 0.012	0.969 ± 0.012	0.973 ± 0.014
$\log(10^{10} A_s)$	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



How test for Gaussianity? And how?

The power spectrum compares two points separated by one angle:





To check for non Gaussianity you can compare three points at two angles: the “power” bispectrum.

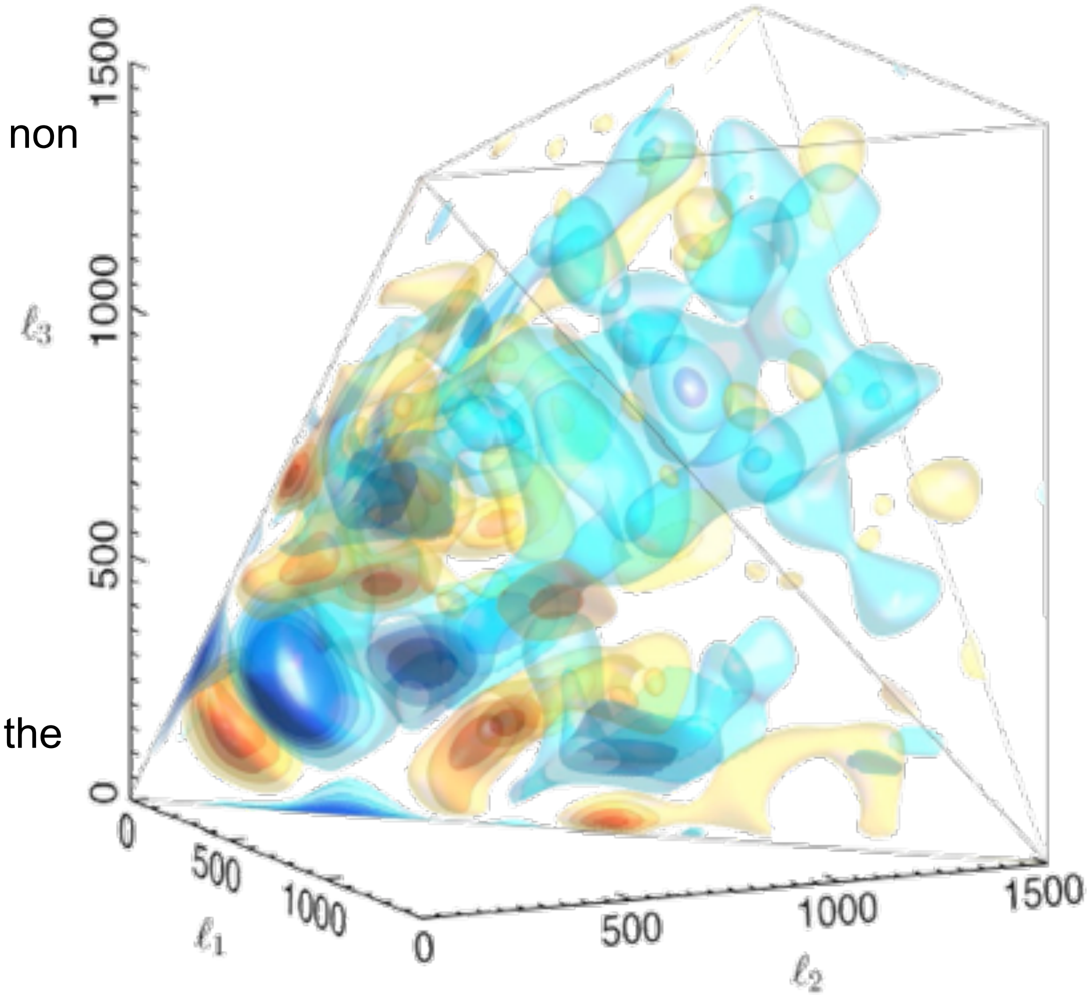
Primordial non Gaussianity

- Bispectrum measured by Planck
- Can be used to constrain models of non Gaussianity
- One number for all:

$$f^{NL} = 2.7 \pm 5.8$$

.

- The fluctuations are consistent with the Gaussian assumption. This is yet another confirmation of the inflation theory.



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 $3.5° \pm 1.0°$ 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 !

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 $N_{eff}=3.28 \pm 0.3$ 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 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).