4TH IDPASC SCHOOL

Braga, 20 - 28 January 2014

CMB and Galaxy Clusters at Planck frequencies

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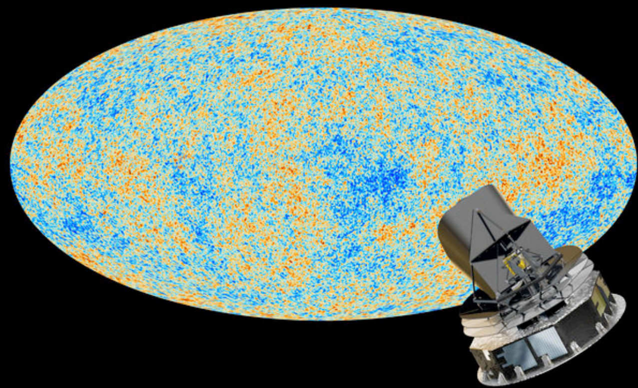


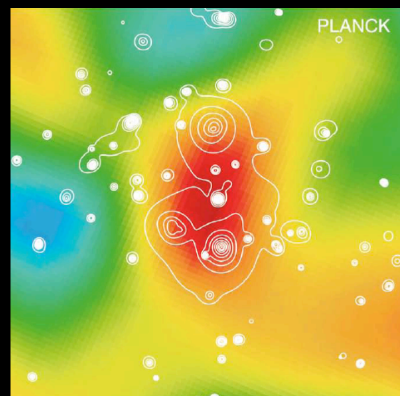


Fig. credits: ESA and the Planck collaboration

Syllabus:

Outline: This course provides a short introduction to the Cosmic Microwave Background (CMB) radiation and Galaxy clusters as probes of Cosmology and Large Scale Structure (LSS). After briefly reviewing the current standard model of cosmology, we will describe the main properties of the CMB and Sunyaev-Zeld'ovich (SZ) clusters and finalize with an overview of the latest findings obtained with the Planck satellite (ESA).

Contents:

Part 1: Review of the Standard Model of Cosmology (SMC):

Part 2: CMB and Sunyaev-Zel'dovich (SZ) Galaxy Clusters

Part 3: Latest results from the Planck Satellite

Bibliography:

- Primordial cosmology, P. Peter, J.-P. Uzan, Oxford University Press, 2009
- An Introduction to Modern Cosmology, A. Liddle, J. Wiley & Sons, 2003
- Course notes by the module's responsible

Part III: CMB observations by the Planck Satellite

Planck Surveyor: looking back to the dawn of time

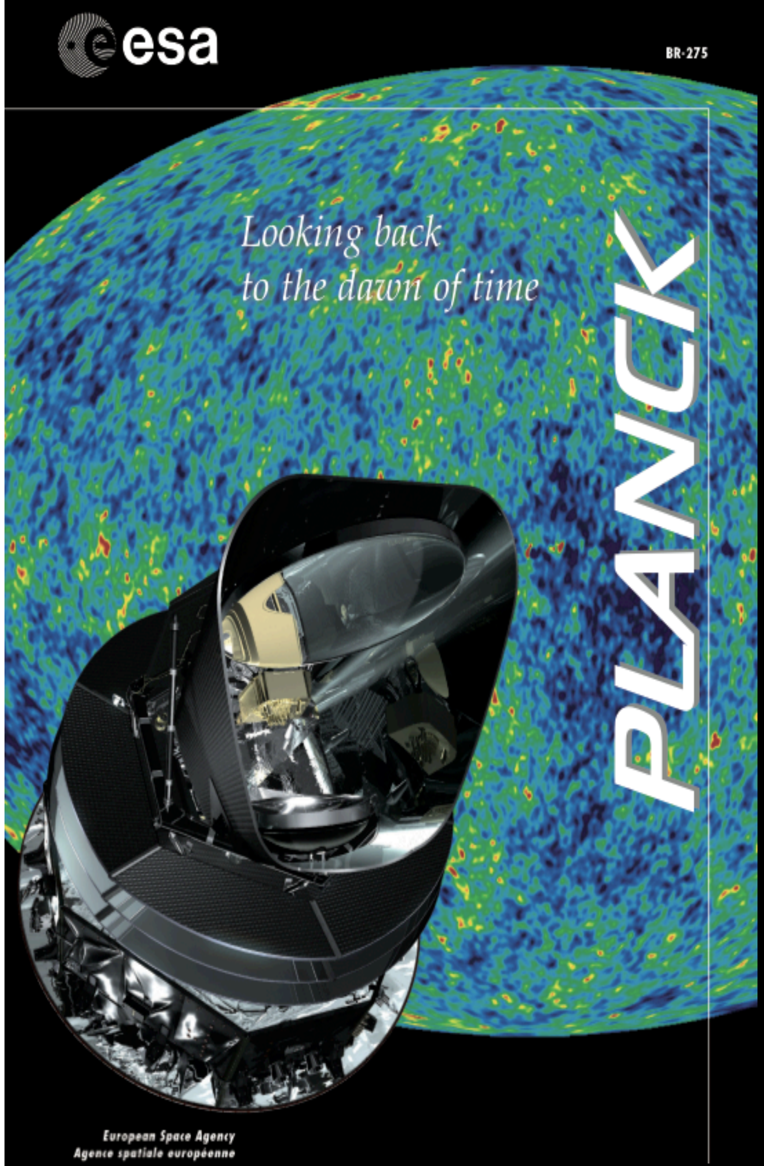


Fig. credits: ESA

Project: ESA lead mission to observe the temperature and polarization anisotropies of the Cosmic Microwave Background (CMB) radiation with unprecedented precision.

Total Cost: about €700 million (€1 / person in EU)

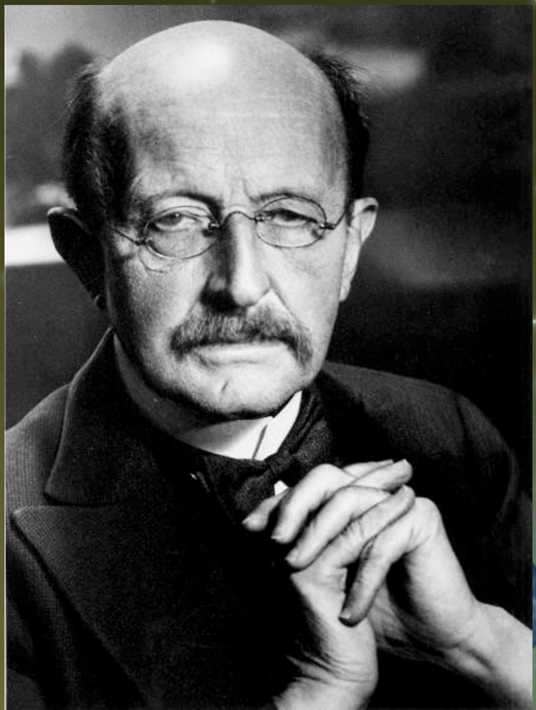
Mission timeline:

- Launch: 14 May 2009
- Operational orbit at L2: July 2009
- Nominal science phase: end of January 2011
- Extended mission: Shut down date: 19 Oct. 2013

Payload:

- Telescope: 1.5 m projected apertures
- Low Frequency Instrument (LFI): array of 22 tuned radio receivers operating at 30, 44 and 70 GHz.
- High Frequency Instrument (HFI): array of 52 bolometers operating at 100, 143, 217, 353, 545, and 857 GHz.

Planck Surveyor

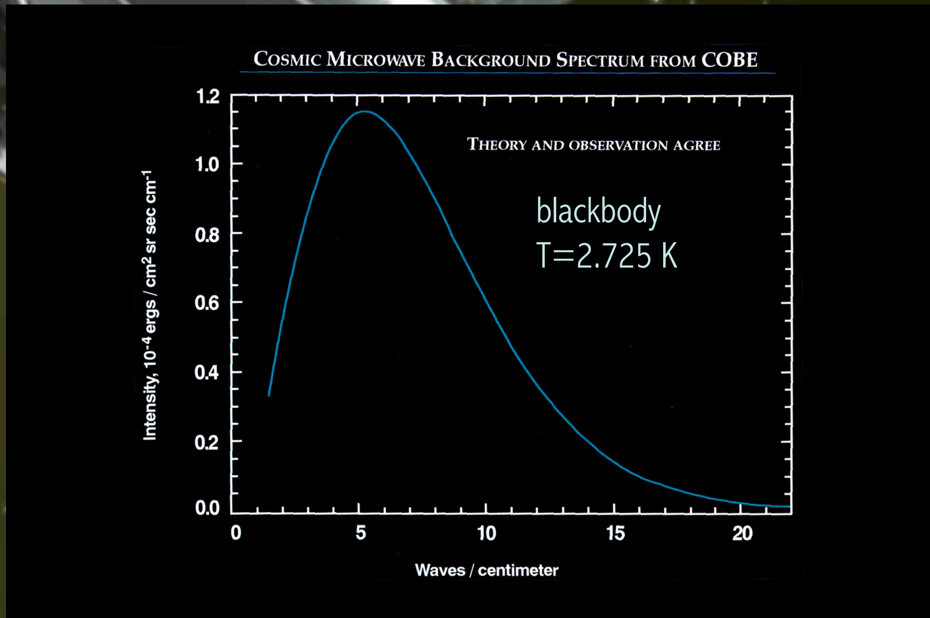


Max Planck (1858-1947) - Physicist

1918: Nobel prize for the theory of quanta of light

Also known for the Planck's law of black body radiation

And his contributions to quantum mechanics



Planck Surveyor: Scientific Objectives

Planck will address a number of fundamental questions in Cosmology and Astrophysics:

- what are the initial conditions for the evolution in the Universe's structure?
- what is the nature and dynamics of dark energy?
- what is the nature and amount of dark matter?

Specific investigations to take place:

- The determination of the Universe's fundamental characteristics, eg,:
  - space geometry,
  - mater-energy densities,
  - Age, expansion rate, etc

- Test of whether the Universe experienced an inflationary phase and search for primordial gravitational waves.

- The search for 'topological defects' in space, e.g. cosmic strings

- The first all-sky survey of galaxy cluster, filaments and voids at CMB frequencies

- The study of our and other galaxies emission in the microwave

Fig. credits: ESA

Planck Surveyor: Latest Portuguese participation and contributions

Scientists in Consortium Science and Data structures:

- Core Team and Data Processing Centre:
  Graça Rocha (IPAC/Caltech, USA); Luis Mendes (ESAC, Spain)

- Planck Associate and Data Agreed:
  Antonio da Silva (CAUP/DF-FCUL, Portugal)

- Core Team:
  Pedro Carvalho (Cambridge, Uk)

ESA's Industrial Team:

- Prime contractor: Thales Alenia Space (France)
- Subcontractors from Portugal:

Portugal	
Almeida and Silva	Spacecraft Mechanical Ground Support Equipment and Container - Structural components
Altrantec	Thermal Analysis Support
OGMA	Telescope and Cryostructure - Reference template
Skysoft	Project Office Support
Tegopi	Spacecraft Mechanical Ground Support Equipment and Container - Structural components and frame

Fig. credits: ESA

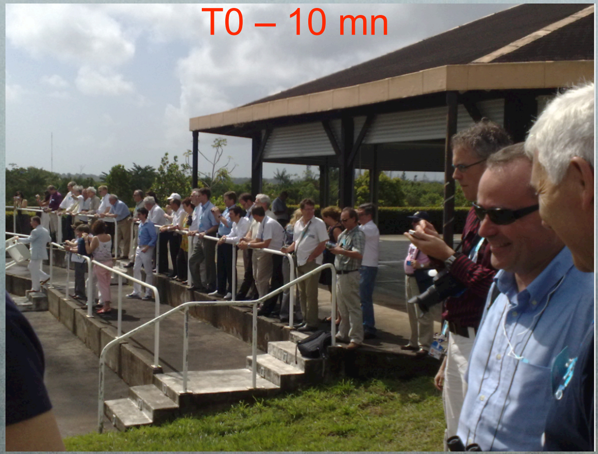
Herschel and Planck Launch

Planck: looking back to the dawn of time

- Launch: 14-May-2009 13:12 UT, French Guyana

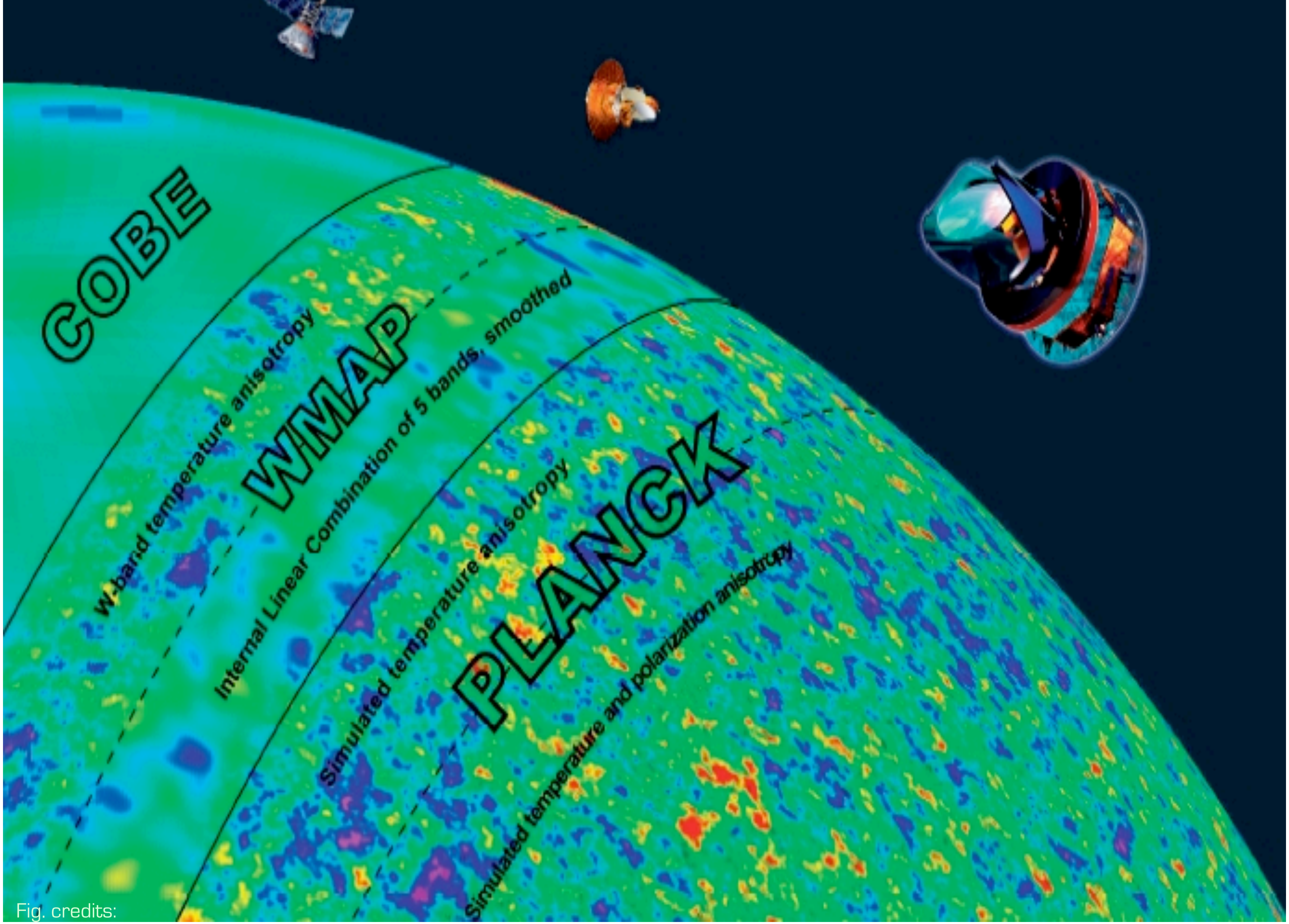
T0 – 1 day

T0 – 10 mn

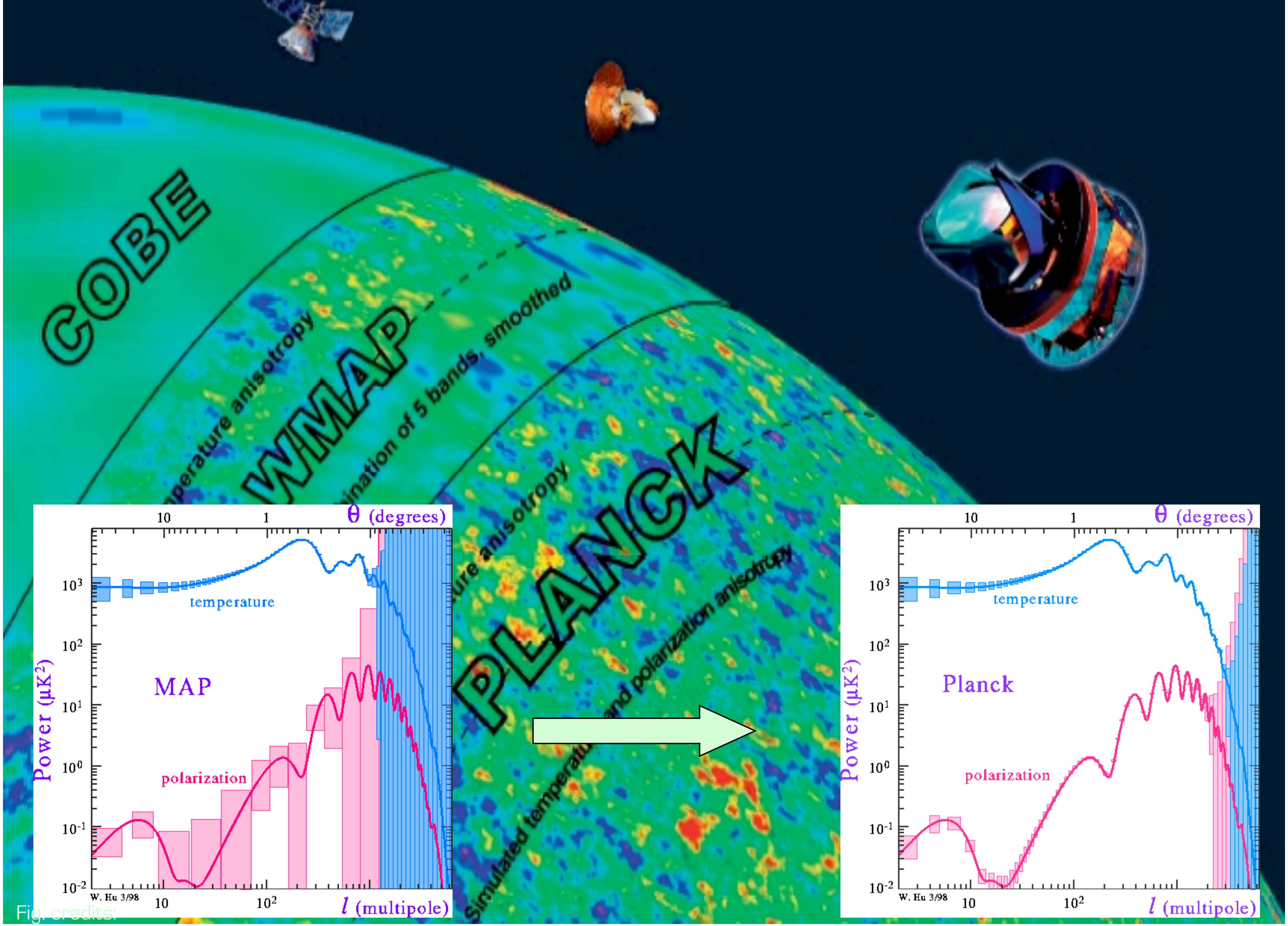


T0 + 3 mn

CMB observations: COBE vs WMAP vs Planck



CMB observations: COBE vs WMAP vs Planck



CMB Observations: COBE

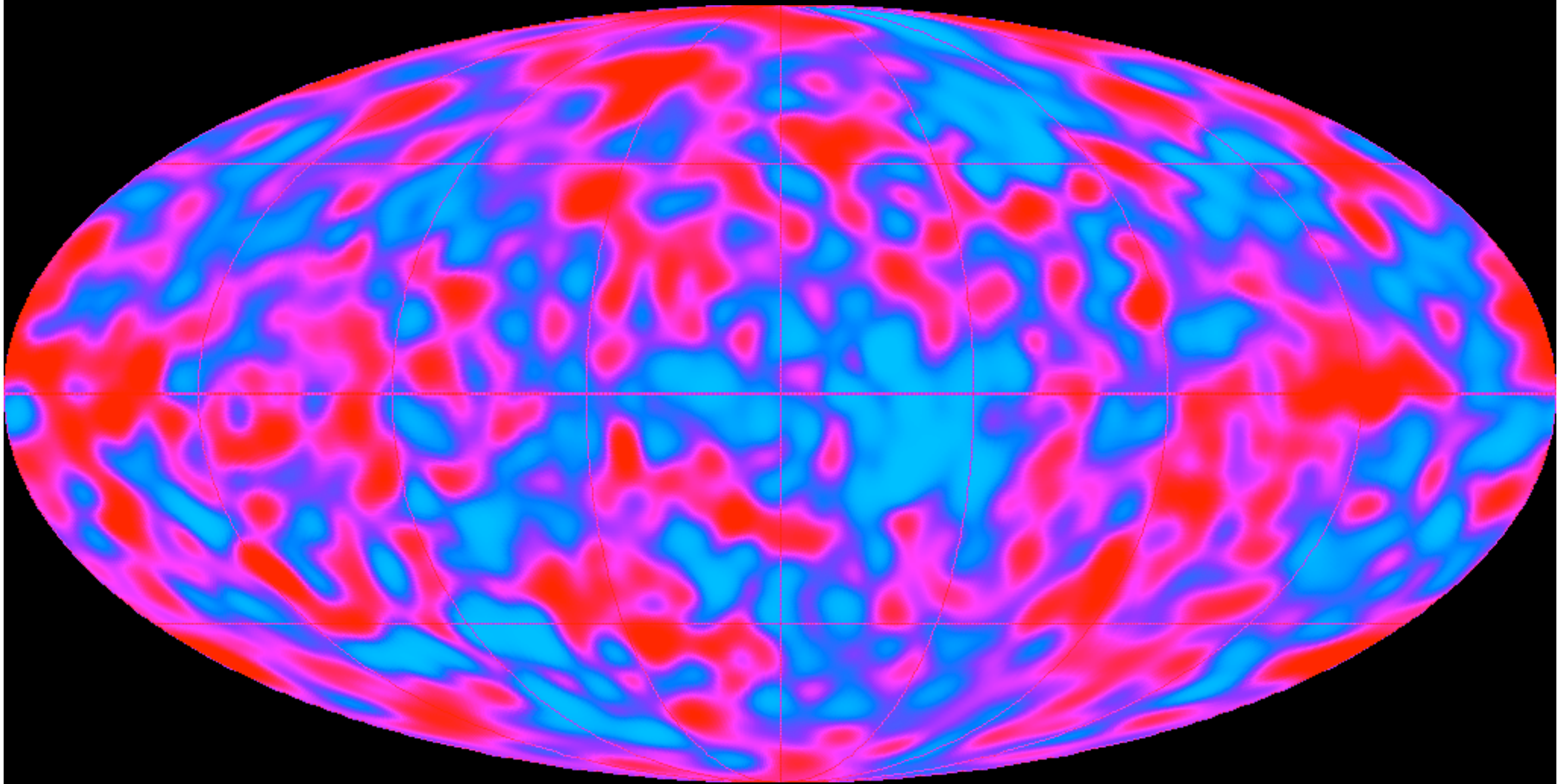


Fig. credits: NASA / COBE

CMB Observations: WMAP

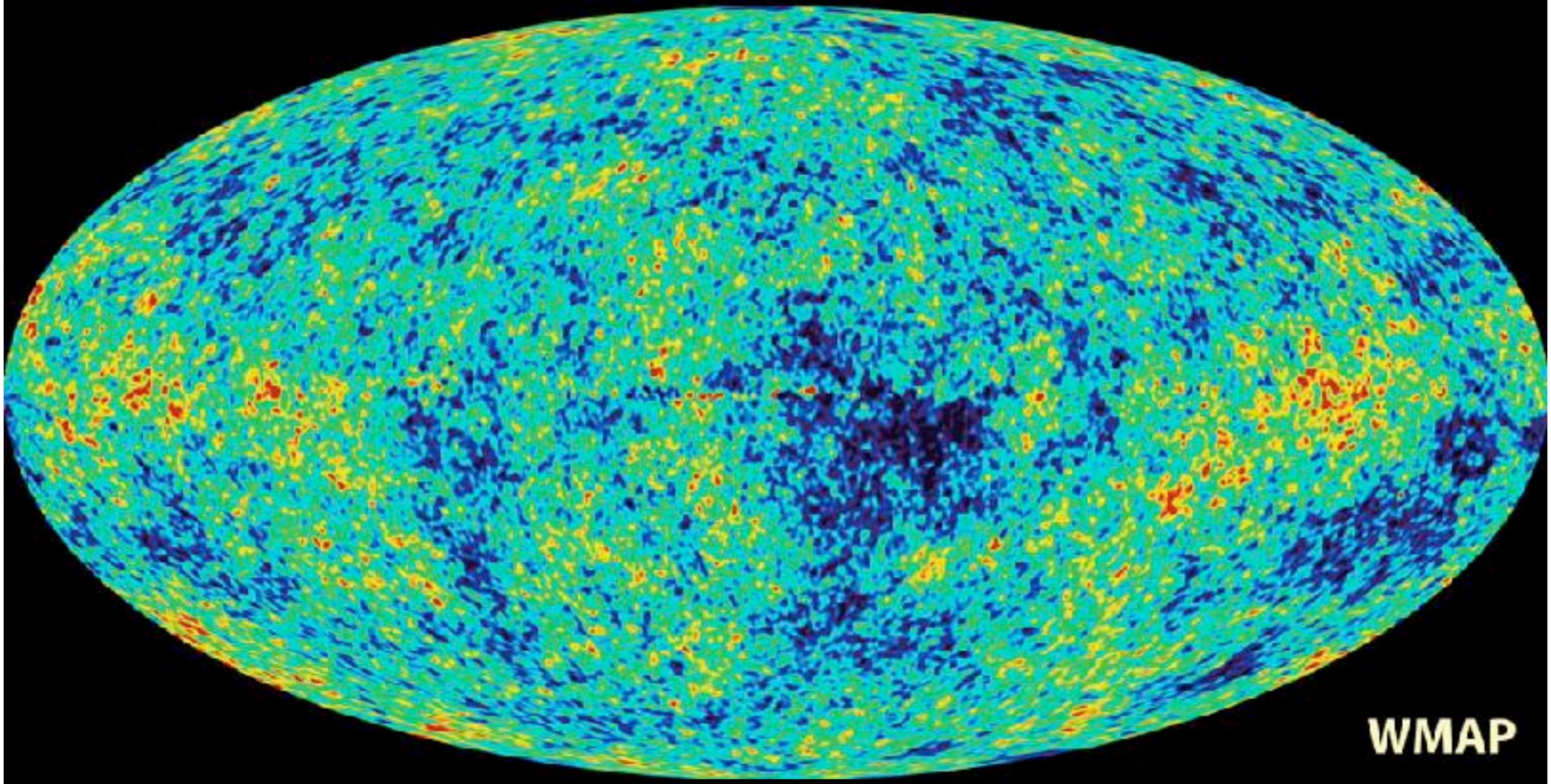


Fig. credits: NASA / WMAP

CMB Observations: Planck

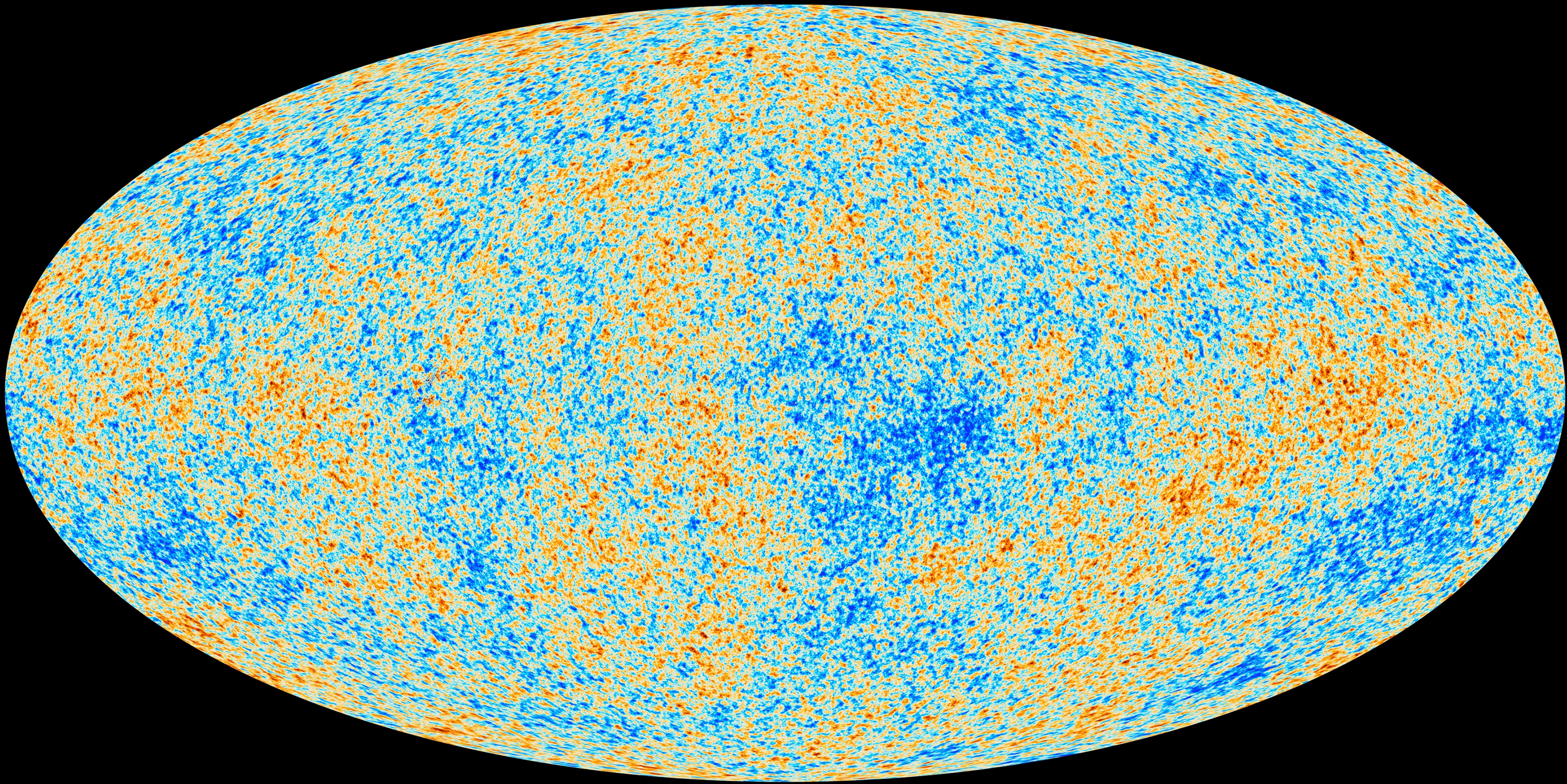
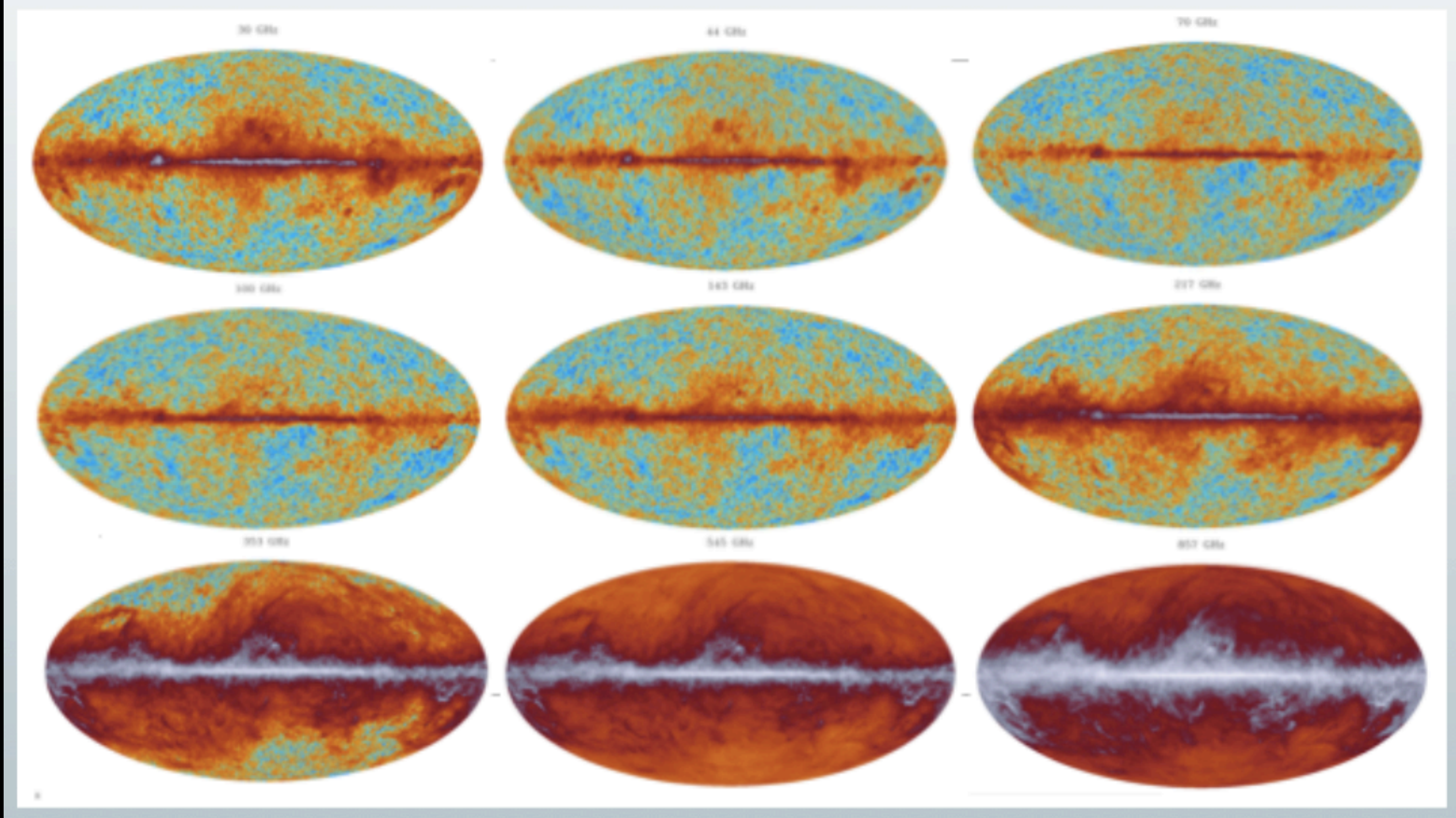


Fig. credits: ESA / PLANCK collaboration

Planck frequency maps:



From: Planck collaboration.

Planck Products and Publications:

http://pla.esac.esa.int/pla/aio/planckProducts.html

http://www.sciops.esa.int/index.php?project=PLANCK&page=Planck_Published_Papers

Source Catalogues

Film credits: ESA / PLANCK collaboration

Planck foreground removal:

multi-frequency component separation techniques

Film credits: ESA / PLANCK collaboration

Planck temperature fluctuation map:

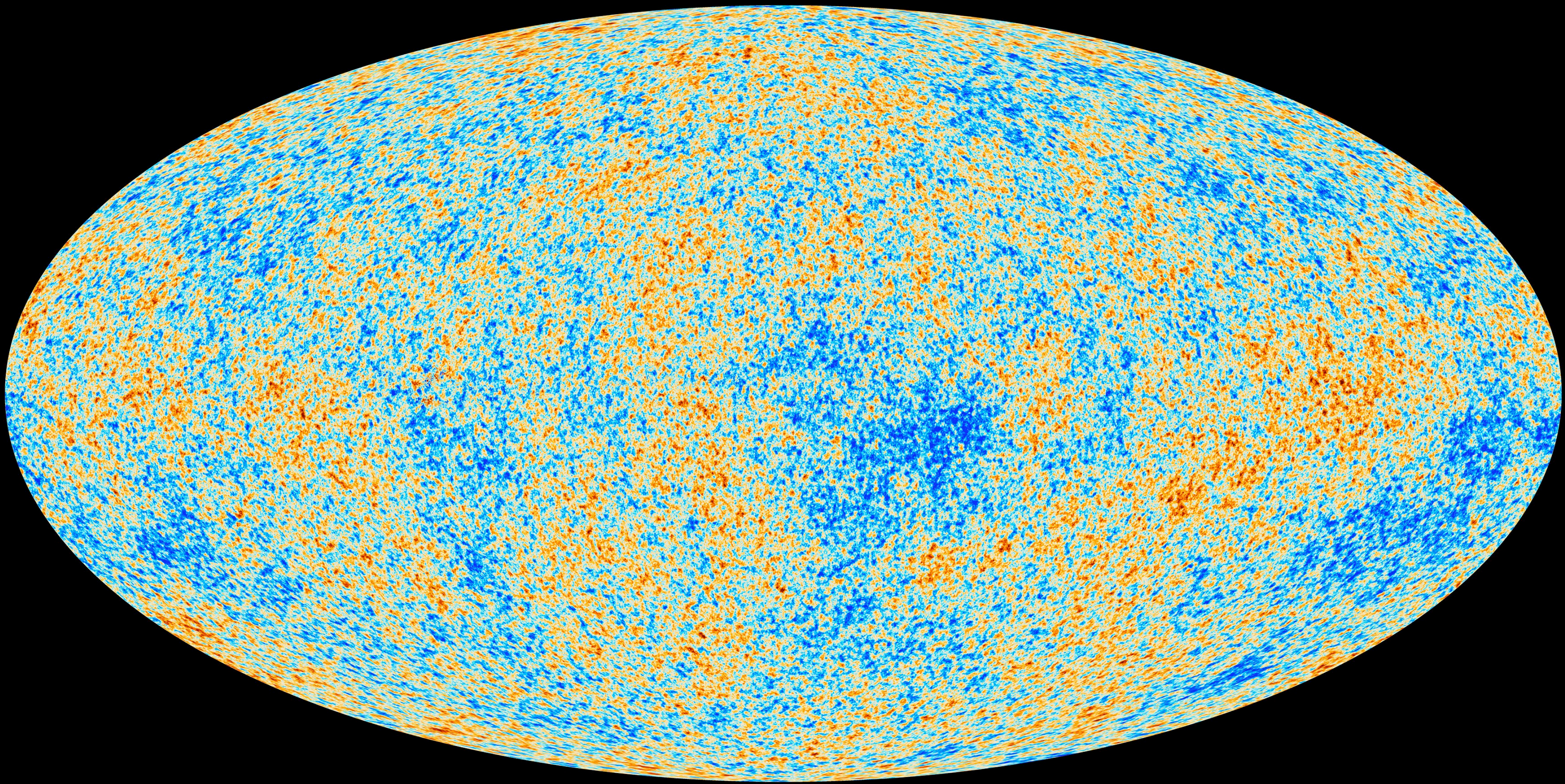
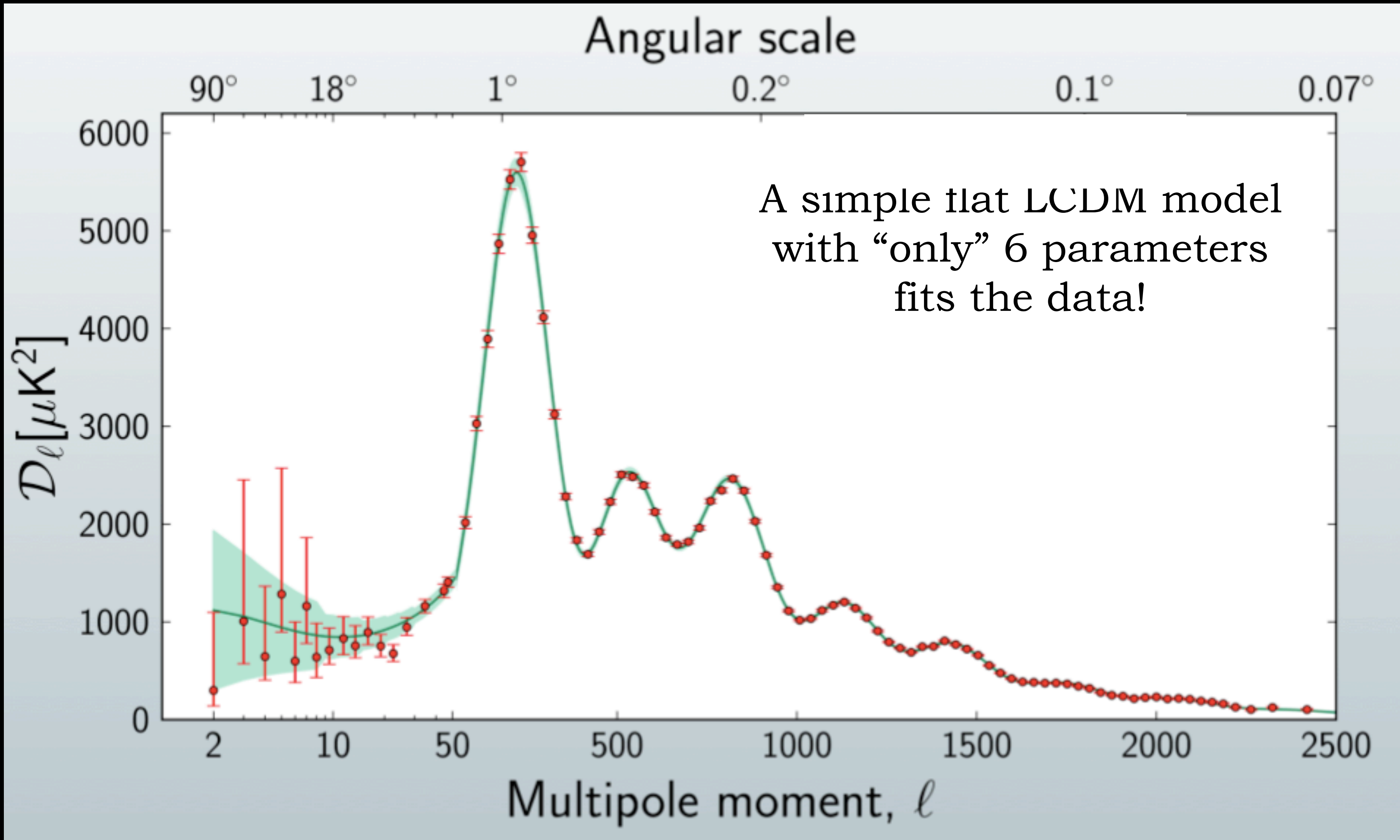


Fig. credits: ESA / PLANCK collaboration

Angular power spectrum estimation

Allows to constrain theoretical models (green curve)

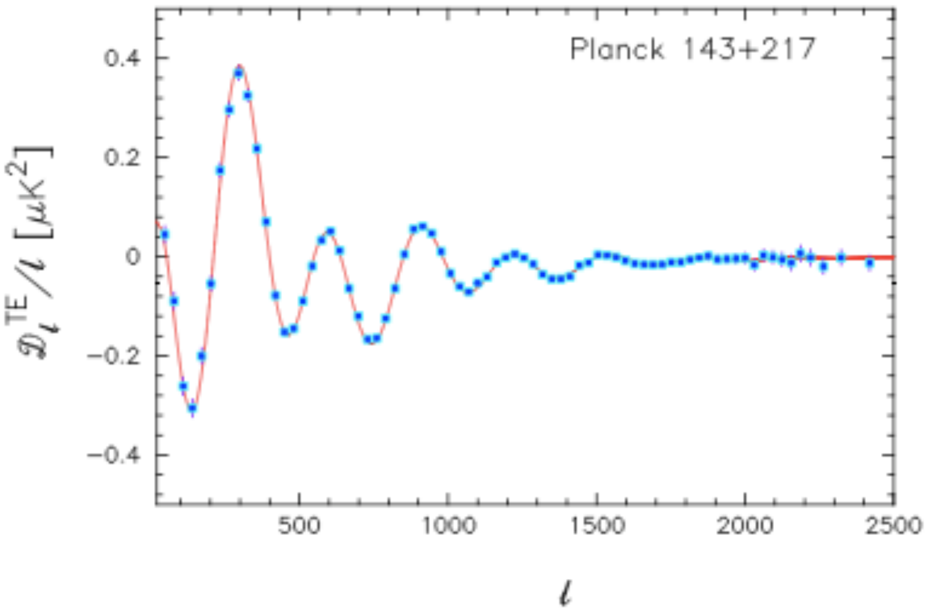
From: Planck collaboration. XVI. arXiv:1303.5076

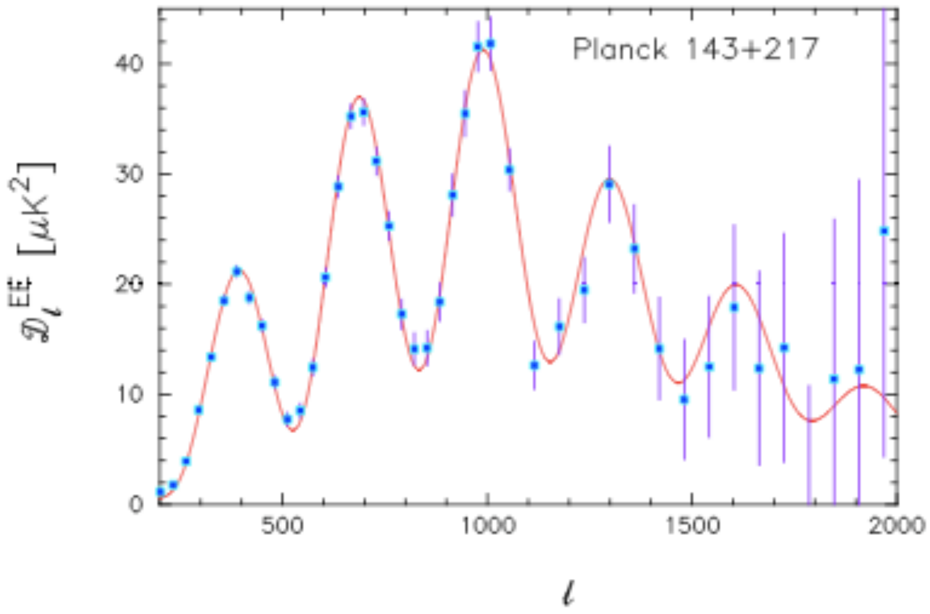


Polarization power spectra @ 143+217GhZ

Red line is the 6-parametrs best fit model

From: Planck collaboration. XVI. arXiv:1303.5076





Cosmological parameters

From: Planck collaboration. XVI. arXiv:1303.5076

Table 2. Cosmological parameter values for the six-parameter base ΛCDM model. Columns 2 and 3 give results for the *Planck* temperature power spectrum data alone. Columns 4 and 5 combine the *Planck* temperature data with *Planck* lensing, and columns 6 and 7 include *WMAP* polarization at low multipoles. We give best fit parameters (i.e. the parameters that maximise the overall likelihood for each data combination) as well as 68% confidence limits for constrained parameters. The first six parameters have flat priors. The remainder are derived parameters as discussed in Sect. 2. Beam, calibration parameters, and foreground parameters (see Sect. 4) are not listed for brevity. Constraints on foreground parameters for *Planck*+WP are given later in Table 5.

	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	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	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

Cosmological parameter changes?

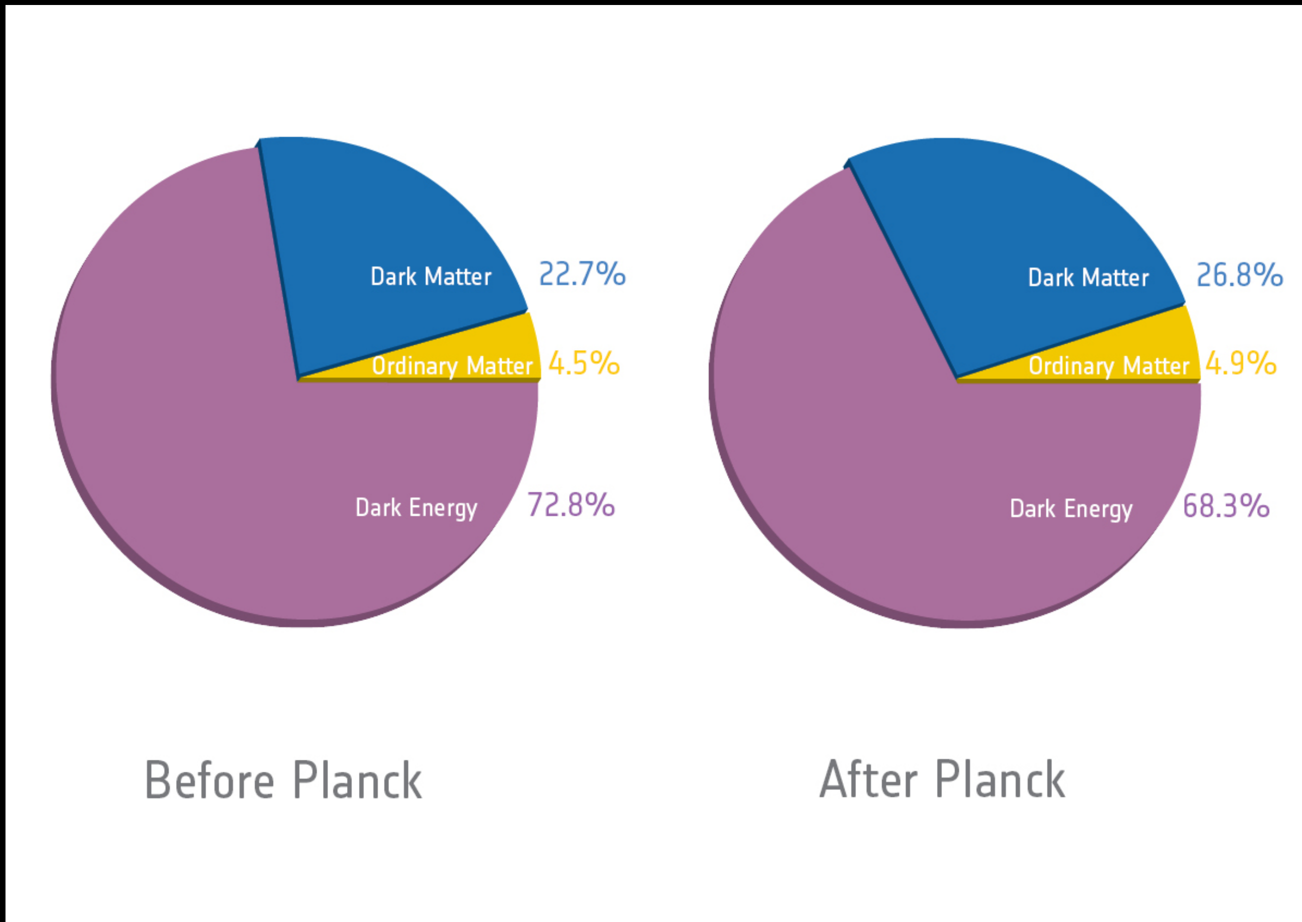
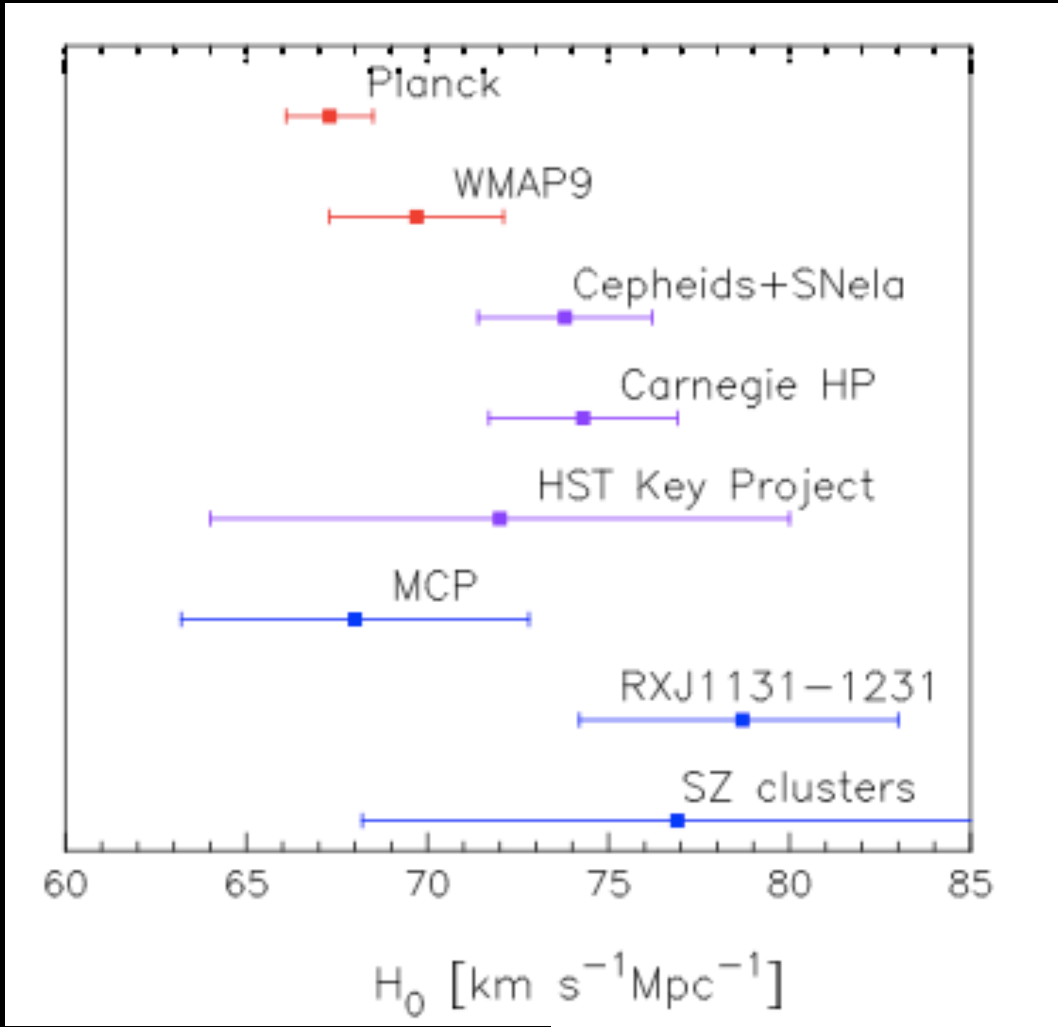
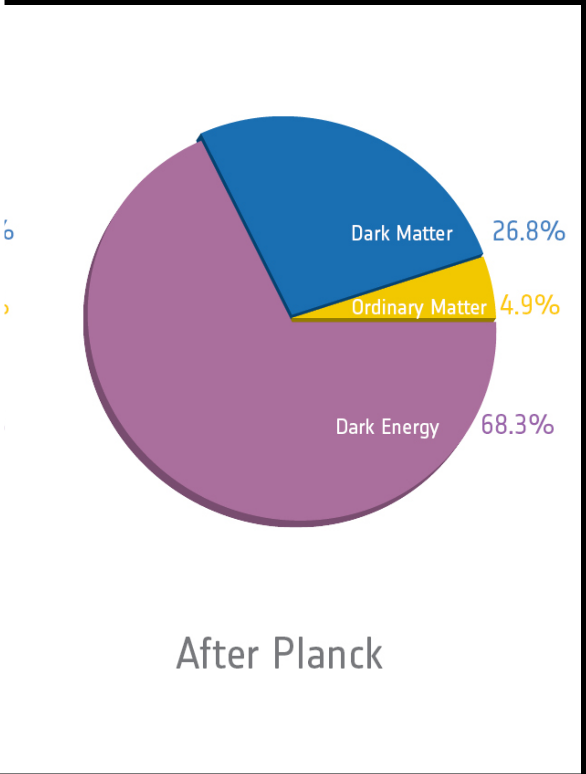


Fig. credits: ESA / PLANCK collaboration

Cosmological parameter changes?

From: Planck collaboration. XVI. arXiv:1303.5076





Cosmological parameters: Extensions to the 6-parameter model

From: Planck collaboration. XVI. arXiv:1303.5076

Table 10. Constraints on one-parameter extensions to the base ΛCDM model. Data combinations all include *Planck* combined with *WMAP* polarization, and results are shown for combinations with high-ℓ CMB data and BAO. Note that we quote 95% limits here.

	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0326	$-0.037^{+0.043}_{-0.049}$	0.0006	$0.0000^{+0.0066}_{-0.0067}$	-0.0389	$-0.042^{+0.043}_{-0.048}$	-0.0003	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.002	< 0.933	0.000	< 0.247	0.000	< 0.663	0.001	< 0.230
N_{eff}	3.25	$3.51^{+0.80}_{-0.74}$	3.32	$3.40^{+0.59}_{-0.57}$	3.38	$3.36^{+0.68}_{-0.64}$	3.33	$3.30^{+0.54}_{-0.51}$
Y_{P}	0.2896	$0.283^{+0.045}_{-0.048}$	0.2889	$0.283^{+0.043}_{-0.045}$	0.2652	$0.266^{+0.040}_{-0.042}$	0.2701	$0.267^{+0.038}_{-0.040}$
$dn_{\mathrm{s}}/d\ln k$	-0.0125	$-0.013^{+0.018}_{-0.018}$	-0.0097	$-0.013^{+0.018}_{-0.018}$	-0.0146	$-0.015^{+0.017}_{-0.017}$	-0.0143	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.94	$-1.49^{+0.65}_{-0.57}$	-1.106	$-1.13^{+0.24}_{-0.25}$	-1.94	$-1.51^{+0.62}_{-0.53}$	-1.113	$-1.13^{+0.23}_{-0.25}$

Cosmic Microwave Background
Planck
Anomalies (enhanced)!?

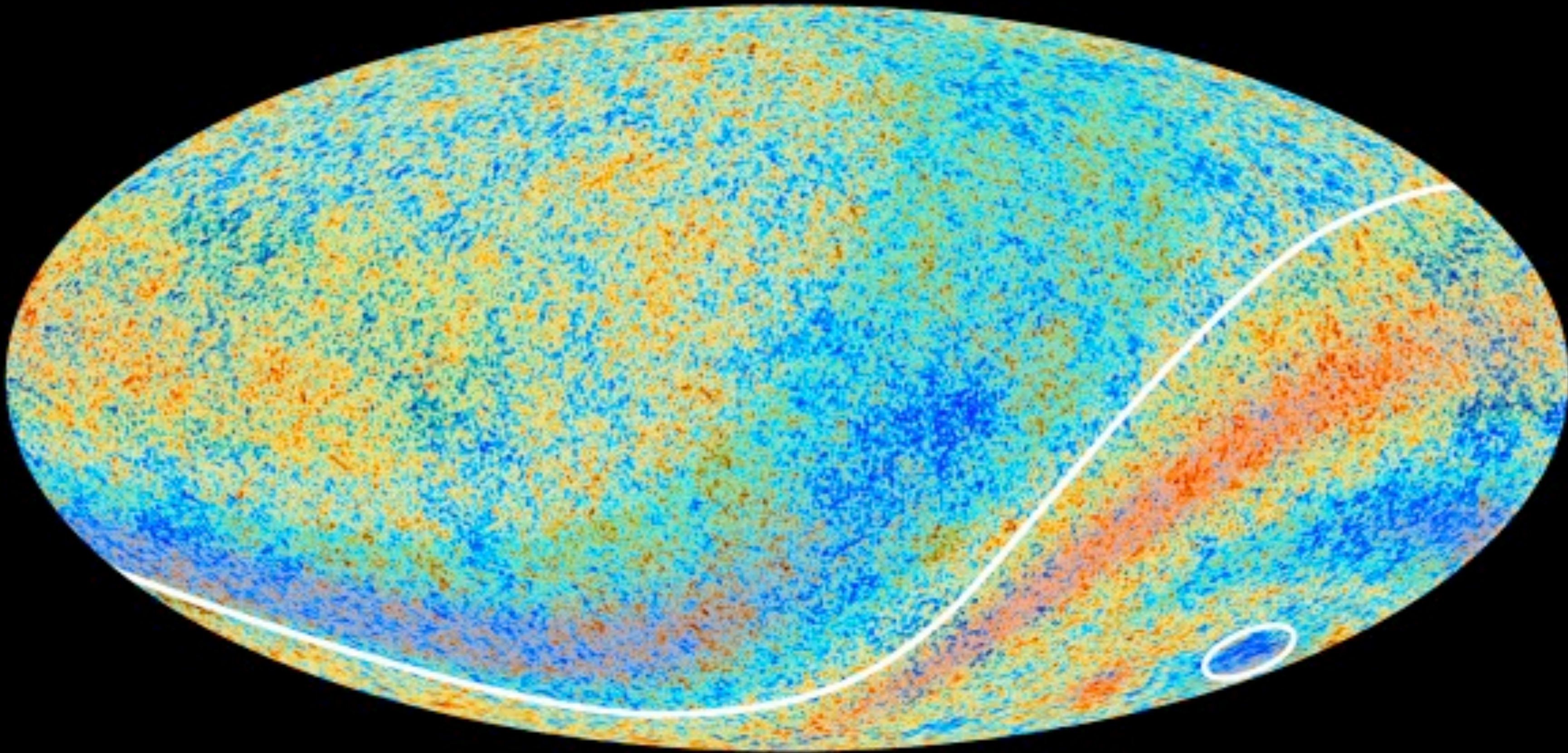


Fig. credits: ESA / PLANCK collaboration

Planck SZ cluster Population

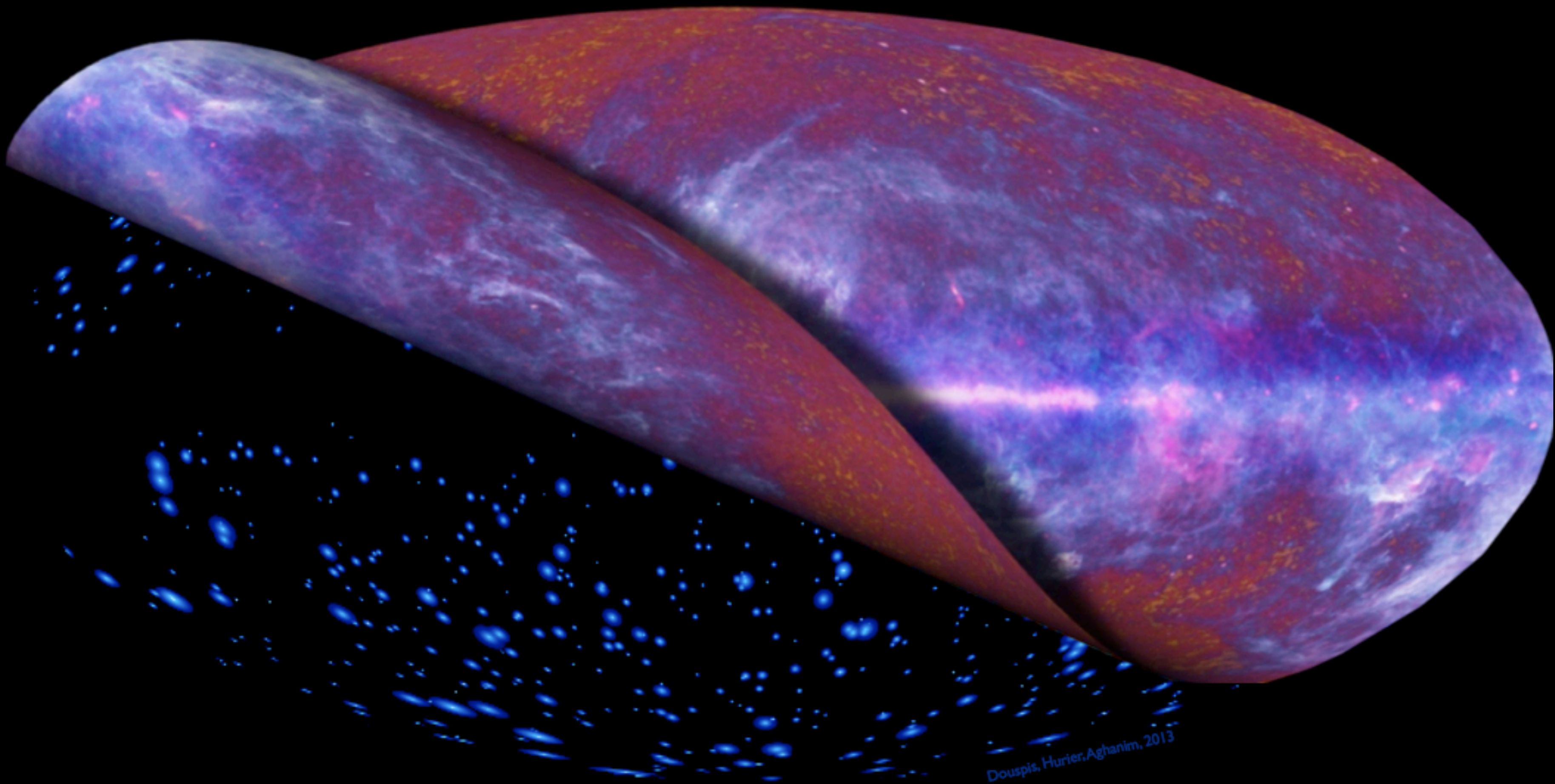
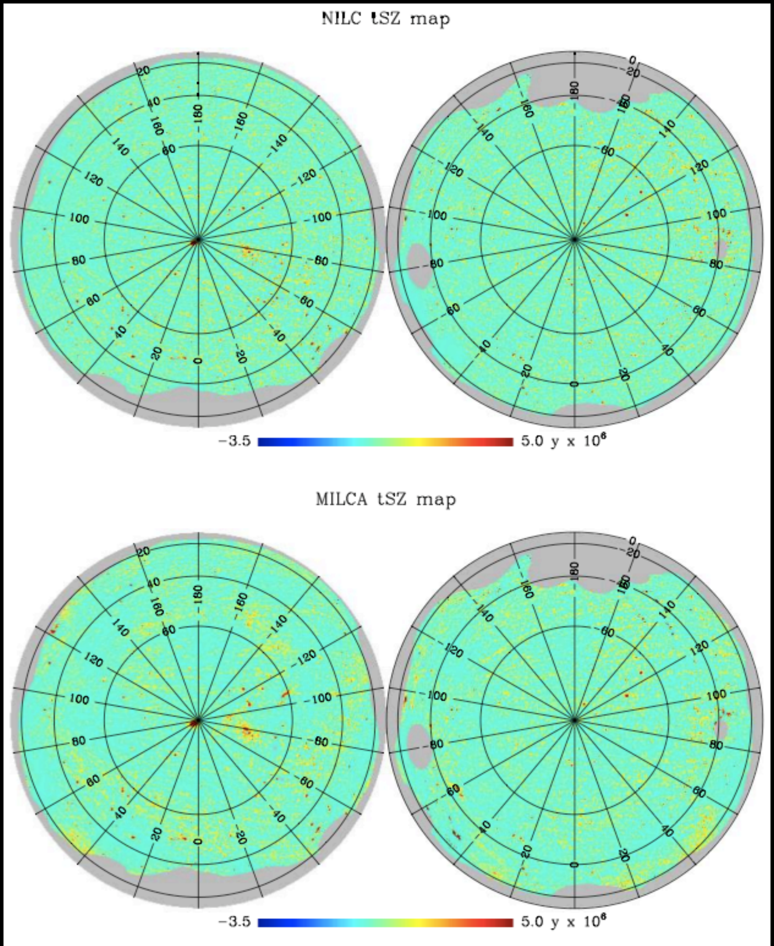


Fig. credits: ESA / PLANCK collaboration; cluster map by Douspis, Hurier, Aghanim, 2013

Cosmology from SZ power spectrum



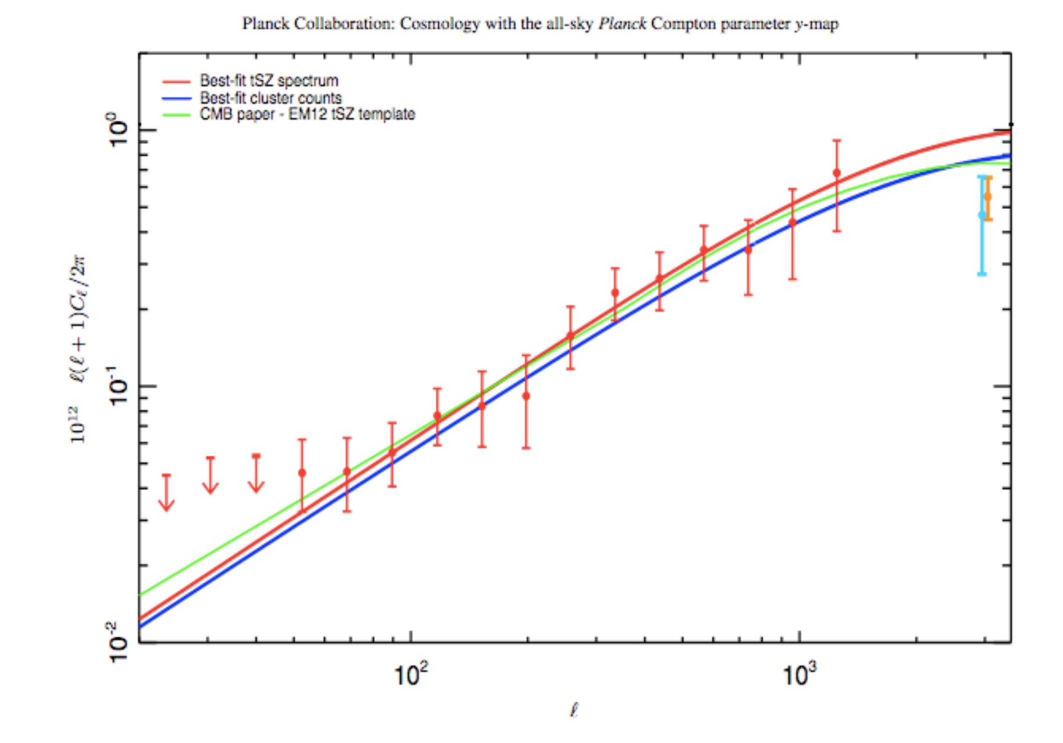


Fig. 15. Marginalized bandpowers of the *Planck* tSZ power spectrum with total (statistical plus foreground) uncertainties (red points). The red solid line represents the best-fit tSZ power spectrum model. We also show as a blue solid line the best-ft tSZ power-spectrum obtained from the analysis of cluster number counts (Planck Collaboration XX 2013). The tSZ power spectrum template used in the CMB cosmological analysis (Planck Collaboration XV 2013; Planck Collaboration XVI 2013) is presented as a green solid line.

From: Planck collaboration. XXI. arXiv:1303.5081

Cosmology from SZ power spectrum

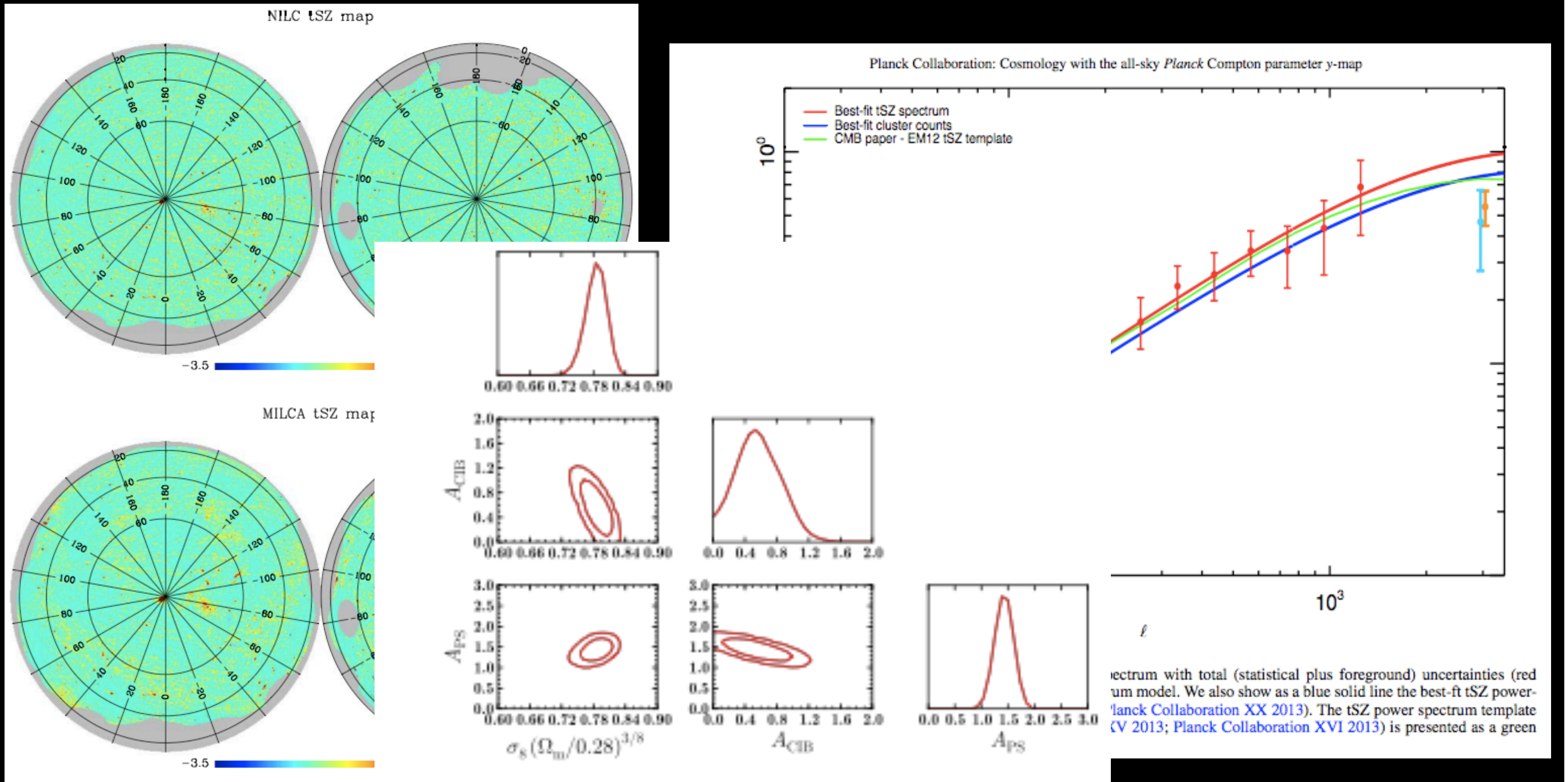


Fig. 13. 2D and 1D likelihood distributions for the combination of cosmological parameters $\sigma_8(\Omega_m/0.28)^{3.2/8.1}$, and for the foreground parameters A_{CIB} and A_{PS}. We show the 68% and 95.4% C.L. contours here.

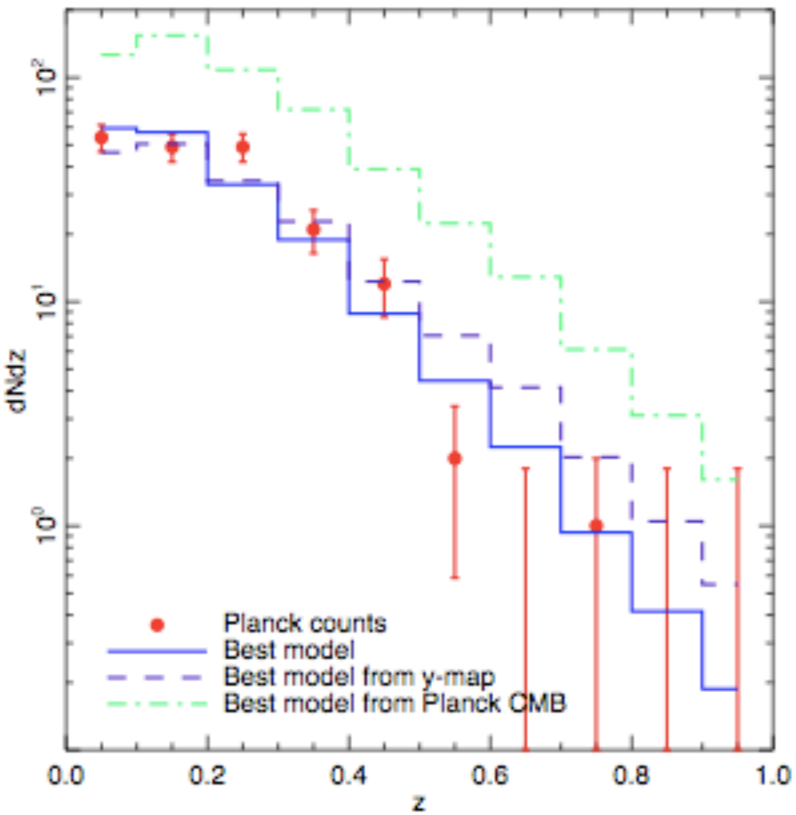
From: Planck collaboration. XXI. arXiv:1303.5081

Cosmology from SZ cluster counts

From: Planck collaboration. XX. arXiv:1303.5080

Table 2. Best-fit cosmological parameters for various combinations of data and analysis methods. Note that for the analysis using Watson et al. mass function, or (1-b) in [0.7-1], the degeneracy line is different and thus the value of $\sigma_8(\Omega_m/0.27)^{0.3}$ is just illustrative

	$\sigma_8(\Omega_m/0.27)^{0.3}$	Ω_m	σ_8	$1-b$
Planck SZ +BAO+BBN	0.782 ± 0.010	0.29 ± 0.02	0.77 ± 0.02	0.8
Planck SZ +HST+BBN	0.792 ± 0.012	0.28 ± 0.03	0.78 ± 0.03	0.8
MMF1 sample +BAO+BBN	0.800 ± 0.010	0.29 ± 0.02	0.78 ± 0.02	0.8
MMF3 S/N > 8 +BAO+BBN	0.785 ± 0.011	0.29 ± 0.02	0.77 ± 0.02	0.8
Planck SZ +BAO+BBN (MC completeness)	0.778 ± 0.010	0.30 ± 0.03	0.75 ± 0.02	0.8
Planck SZ +BAO+BBN (Watson et al. mass function)	0.802 ± 0.014	0.30 ± 0.01	0.77 ± 0.02	0.8
Planck SZ +BAO+BBN ($1-b$ in [0.7, 1.0])	0.764 ± 0.025	0.29 ± 0.02	0.75 ± 0.03	[0.7,1]



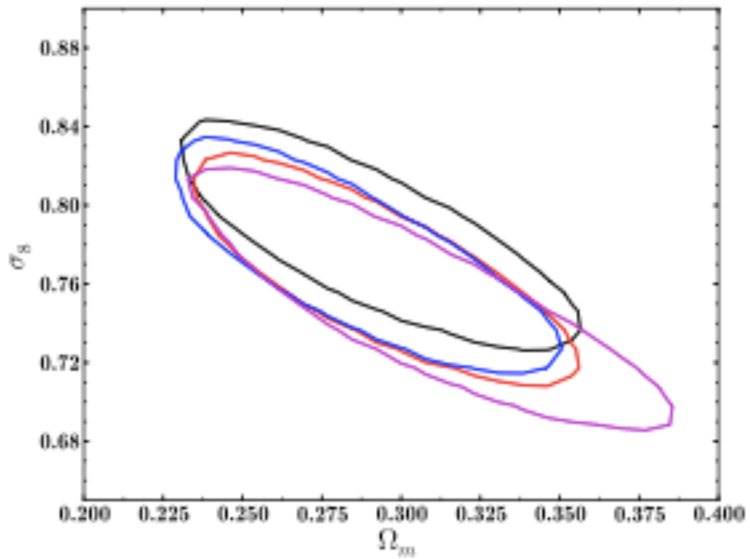
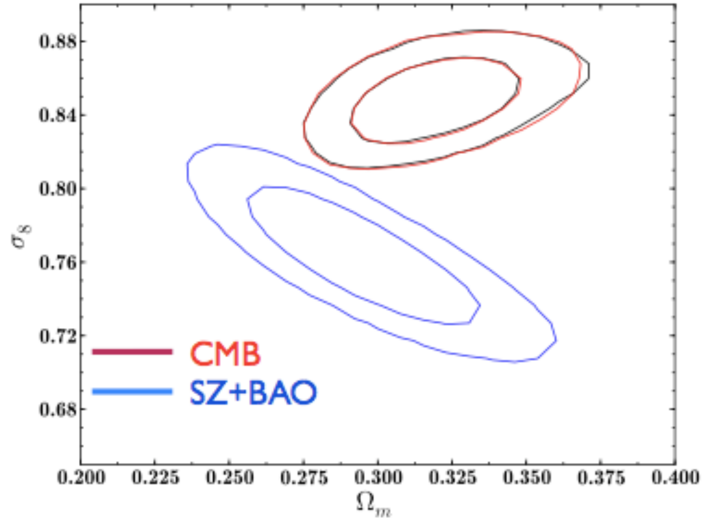
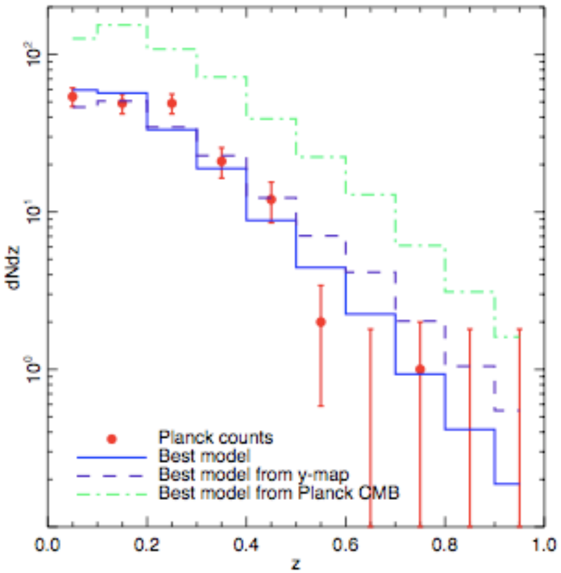


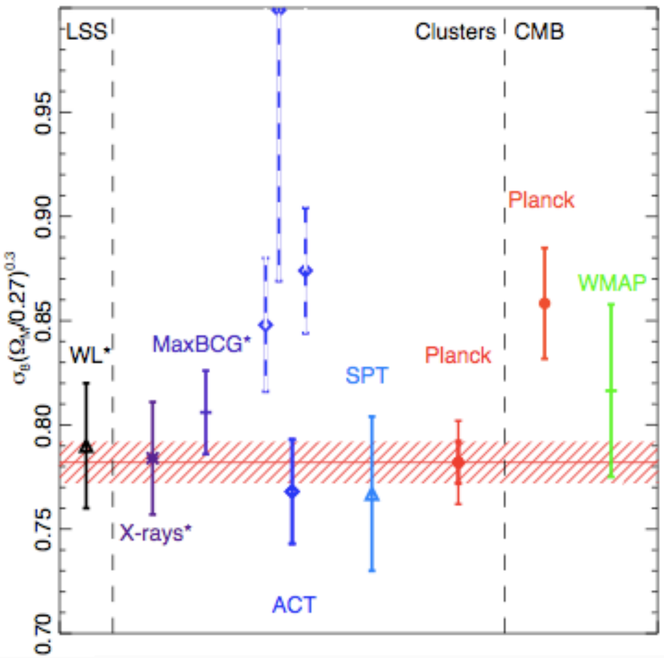
Fig. 8. 95% contours for different robustness tests: MMF3 with S/N cut at 7 in red; MMF3 with S/N cut at 8 in blue; and MMF1 with S/N cut at 7 in black; and MMF3 with S/N cut at 7 but assuming the MC completeness in purple.

Comparison with CMB

- Higher values of Ω_m, σ_8 in *Planck* CMB analysis
- 3σ tension
- More general tension between clusters and CMB ?

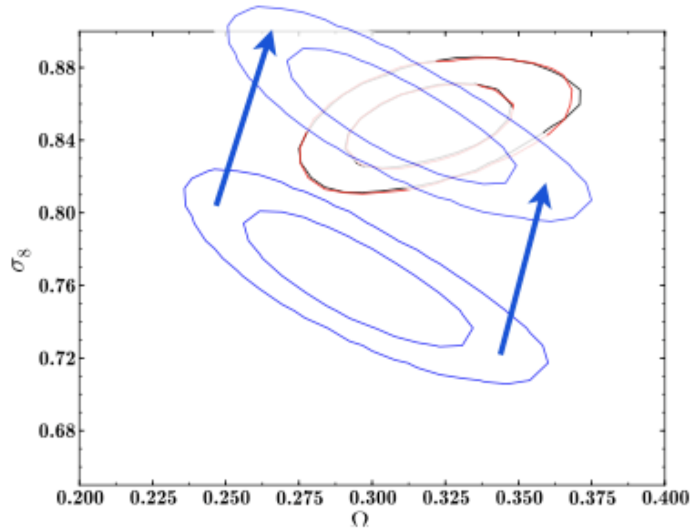




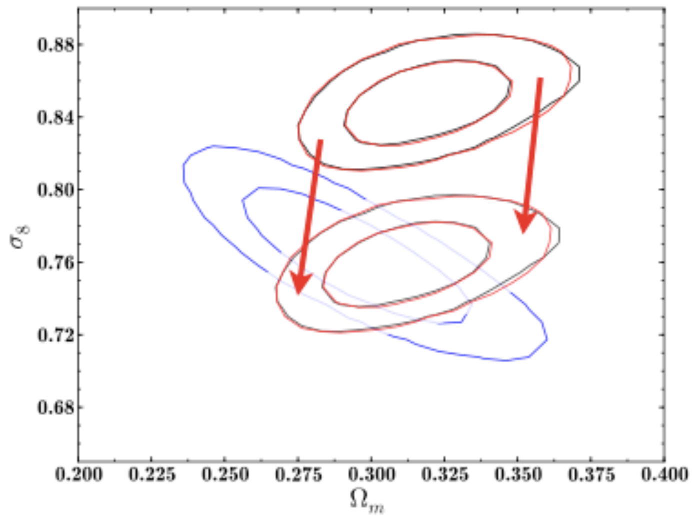


SZ & CMB

- Getting higher σ_8 from clusters
  - Change scaling
  - Change bias
  - Account for missing clusters



- Getting lower σ_8 from CMB
  - Change initial power spectrum
  - Change transfert function



Stay tuned for the next release of Planck results!

Summer, this year.

Cosmological parameters definitions

From: Planck collaboration. XVI. arXiv:1303.5076

Table 1. Cosmological parameters used in our analysis. For each, we give the symbol, prior range, value taken in the base ΛCDM cosmology (where appropriate), and summary definition (see text for details). The top block contains parameters with uniform priors that are varied in the MCMC chains. The ranges of these priors are listed in square brackets. The lower blocks define various derived parameters.

Parameter	Prior range	Baseline	Definition
$\omega_b \equiv \Omega_b h^2$	[0.005, 0.1]	...	Baryon density today
$\omega_c \equiv \Omega_c h^2$	[0.001, 0.99]	...	Cold dark matter density today
$100\theta_{MC}$	[0.5, 10.0]	...	$100 \times$ approximation to r_*/D_A (CosmoMC)
τ	[0.01, 0.8]	...	Thomson scattering optical depth due to reionization
Ω_K	[−0.3, 0.3]	0	Curvature parameter today with $\Omega_{tot} = 1 - \Omega_K$
$\sum m_\nu$	[0, 5]	0.06	The sum of neutrino masses in eV
$m^{eff}_{\nu,\,sterile}$	[0, 3]	0	Effective mass of sterile neutrino in eV
w_0	[−3.0, −0.3]	−1	Dark energy equation of state[a], $w(a) = w_0 + (1-a)w_a$
w_a	[−2, 2]	0	As above (perturbations modelled using PPF)
N_{eff}	[0.05, 10.0]	3.046	Effective number of neutrino-like relativistic degrees of freedom (see text)
Y_P	[0.1, 0.5]	BBN	Fraction of baryonic mass in helium
A_L	[0, 10]	1	Amplitude of the lensing power relative to the physical value
n_s	[0.9, 1.1]	...	Scalar spectrum power-law index ($k_0 = 0.05\mathrm{Mpc}^{-1}$)
n_t	$n_t = -r_{0.05}/8$	Inflation	Tensor spectrum power-law index ($k_0 = 0.05\mathrm{Mpc}^{-1}$)
$dn_s/d\ln k$	[−1, 1]	0	Running of the spectral index
$\ln(10^{10}A_s)$	[2.7, 4.0]	...	Log power of the primordial curvature perturbations ($k_0 = 0.05\,\mathrm{Mpc}^{-1}$)
$r_{0.05}$	[0, 2]	0	Ratio of tensor primordial power to curvature power at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
Ω_Λ		...	Dark energy density divided by the critical density today
t_0		...	Age of the Universe today (in Gyr)
Ω_m		...	Matter density (inc. massive neutrinos) today divided by the critical density
σ_8		...	RMS matter fluctuations today in linear theory
z_{re}		...	Redshift at which Universe is half reionized
H_0	[20,100]	...	Current expansion rate in $\mathrm{km\,s^{-1}Mpc^{-1}}$
$r_{0.002}$		0	Ratio of tensor primordial power to curvature power at $k_0 = 0.002\,\mathrm{Mpc}^{-1}$
$10^9 A_s$		...	$10^9 \times$ dimensionless curvature power spectrum at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
$\omega_m \equiv \Omega_m h^2$		...	Total matter density today (inc. massive neutrinos)
z_*		...	Redshift for which the optical depth equals unity (see text)
$r_* = r_s(z_*)$		...	Comoving size of the sound horizon at $z = z_*$
$100\theta_*$		...	$100 \times$ angular size of sound horizon at $z = z_*$ (r_*/D_A)
z_{drag}		...	Redshift at which baryon-drag optical depth equals unity (see text)
$r_{drag} = r_s(z_{drag})$		...	Comoving size of the sound horizon at $z = z_{drag}$
k_D		...	Characteristic damping comoving wavenumber (Mpc^{-1})
$100\theta_D$		...	$100 \times$ angular extent of photon diffusion at last scattering (see text)
z_{eq}		...	Redshift of matter-radiation equality (massless neutrinos)
$100\theta_{eq}$		...	$100 \times$ angular size of the comoving horizon at matter-radiation equality
$r_{drag}/D_V(0.57)$		...	BAO distance ratio at $z = 0.57$ (see Sect. 5.2)

[a] For dynamical dark energy models with constant equation of state, we denote the equation of state by w and adopt the same prior as for w_0.