Physics Colloquium, Bonn
April 2013

Cosmological results from *Planck*

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and the Planck Collaboration

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

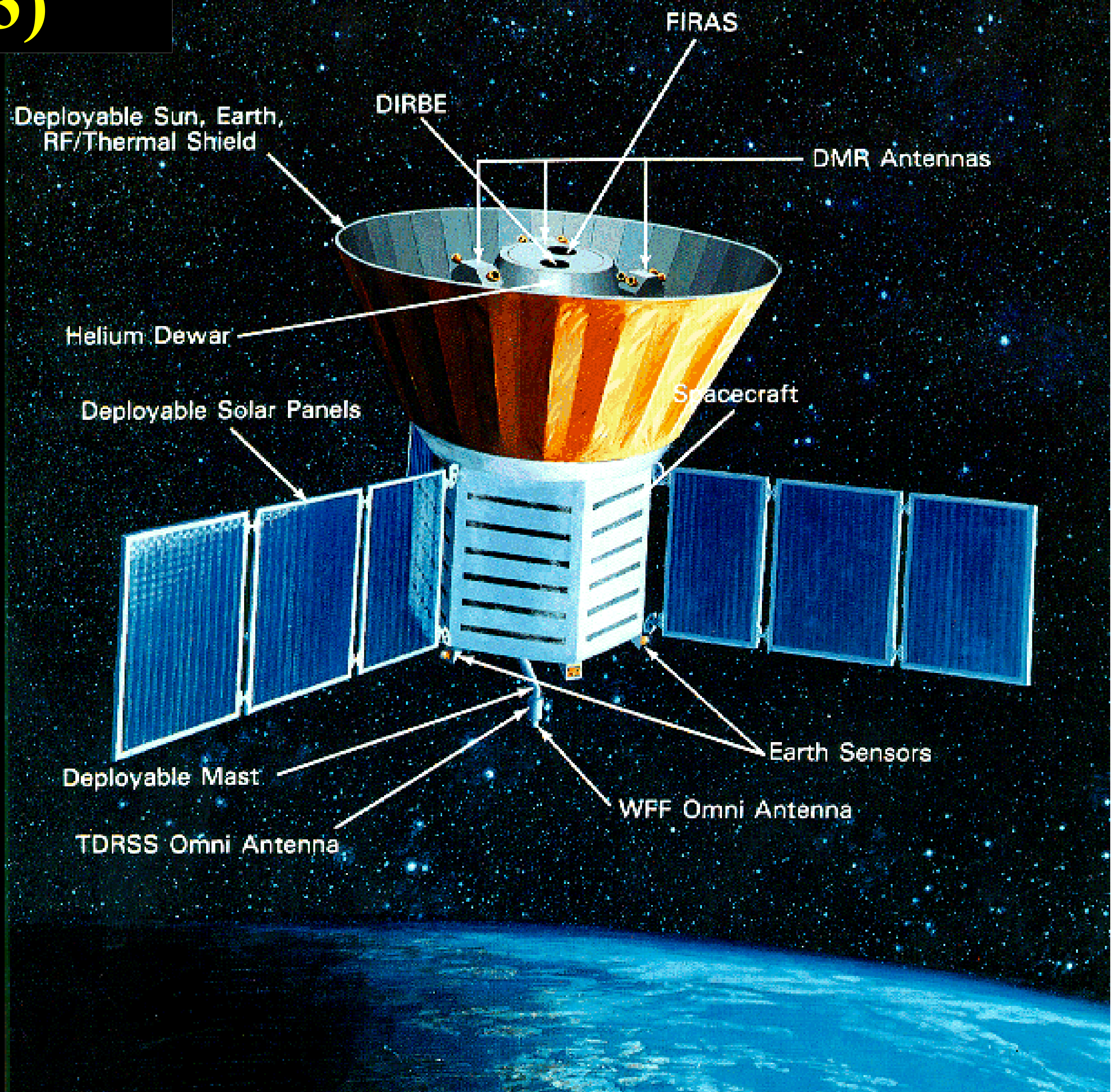
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

The Cosmic Microwave Background

predicted by Gamow (1946)
found: Penzias+Wilson (1964)
Nobel Physics Prize 1978

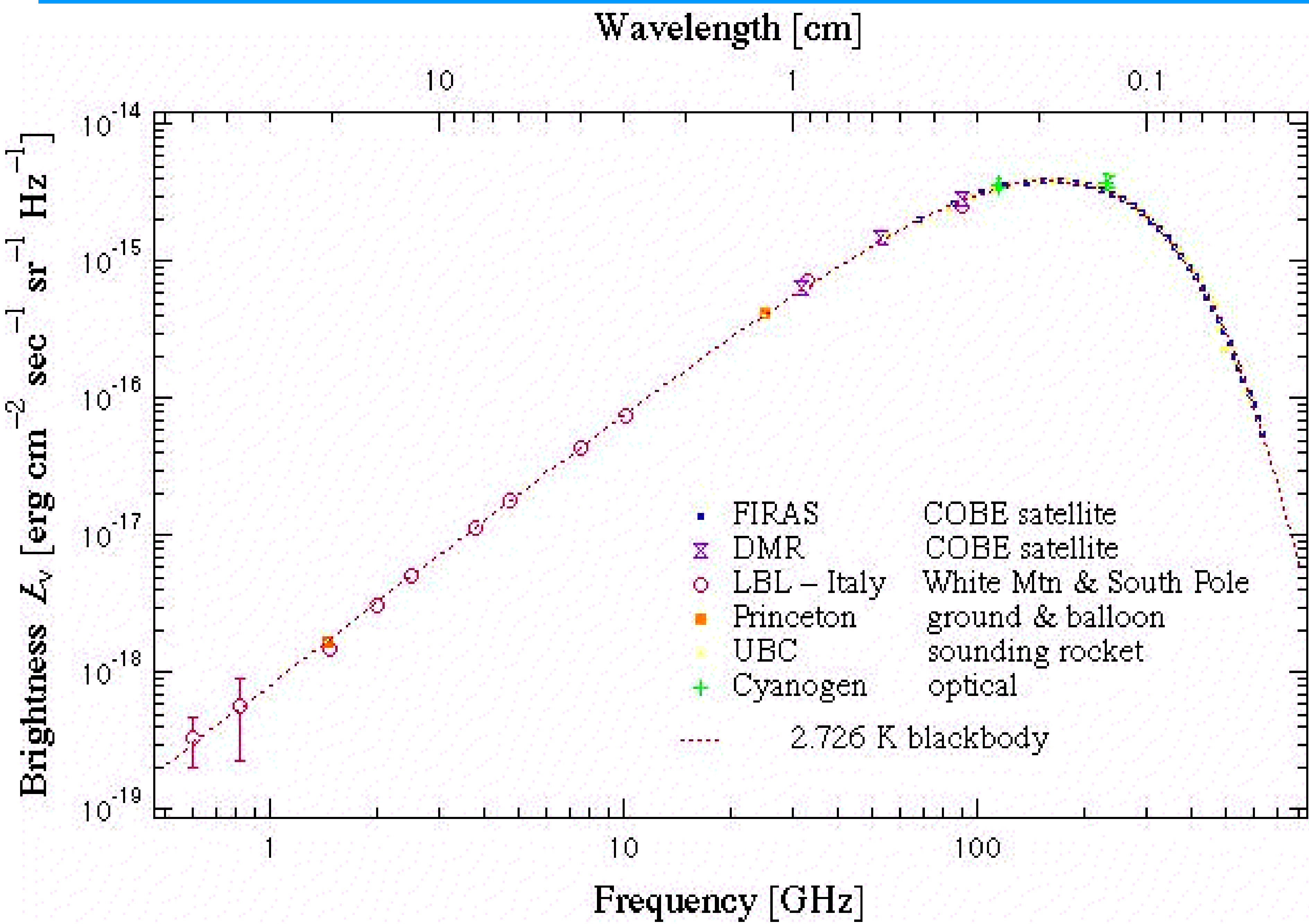
The COBE satellite (1989 - 1993)

- Two instruments made maps of the whole sky in microwaves and in infrared radiation
- One instrument took a precise spectrum of the sky in microwaves



Nobel Prize in Physics 2003

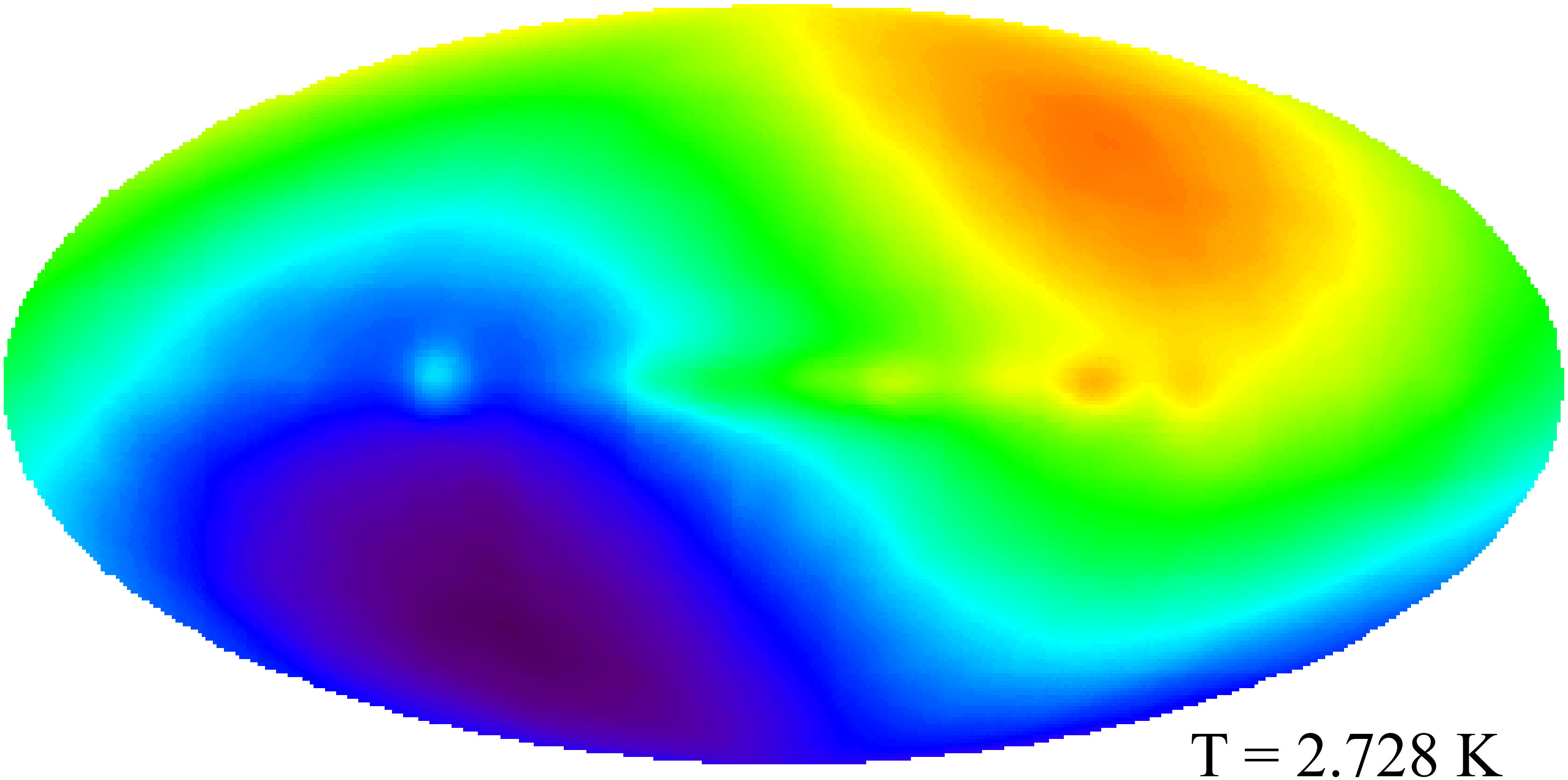
COBE spectrum of the microwave background



COBE's temperature map of the entire sky

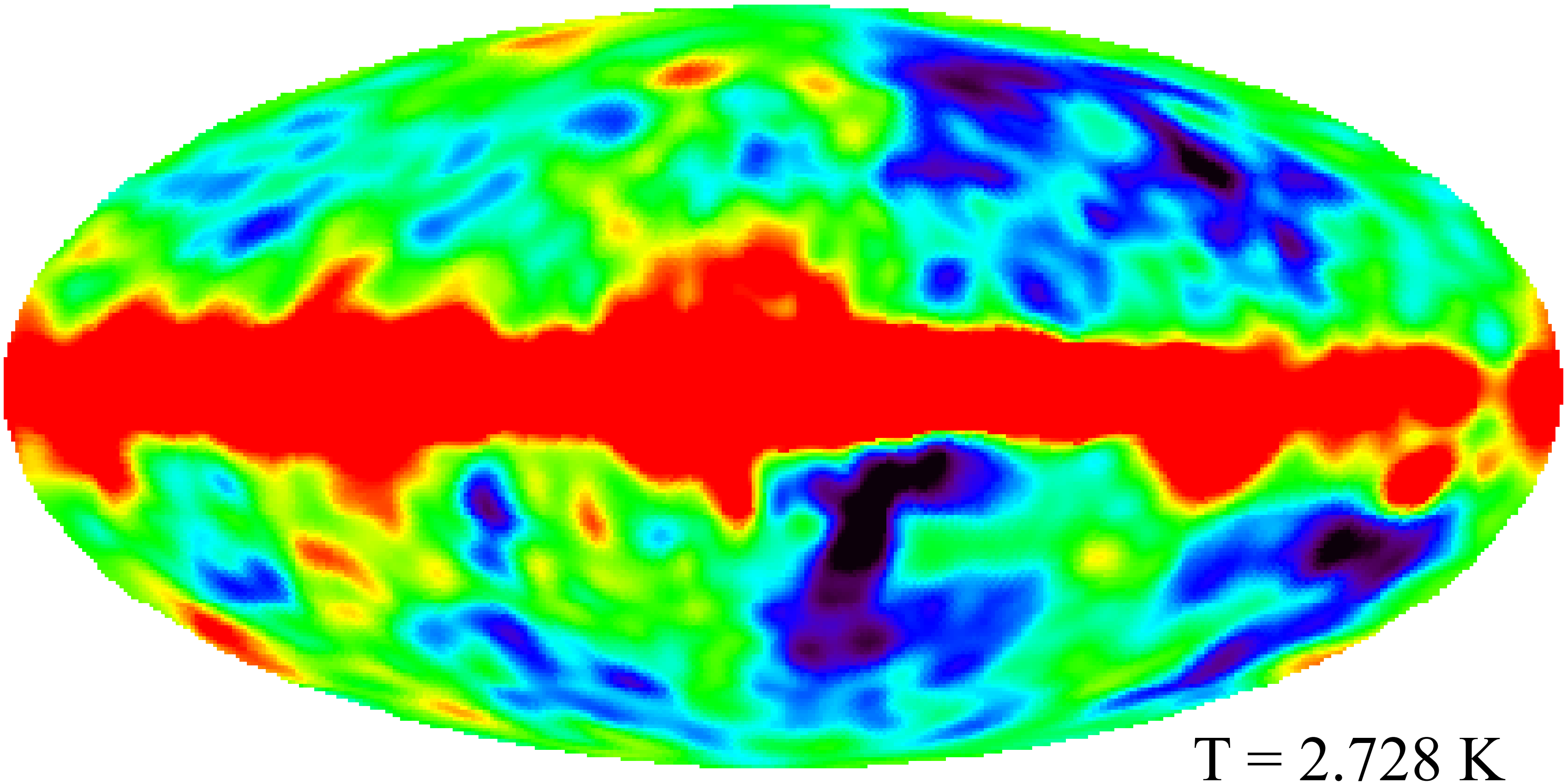
T = 2.728 K
$\Delta T = 0.1$ K

COBE's temperature map of the entire sky



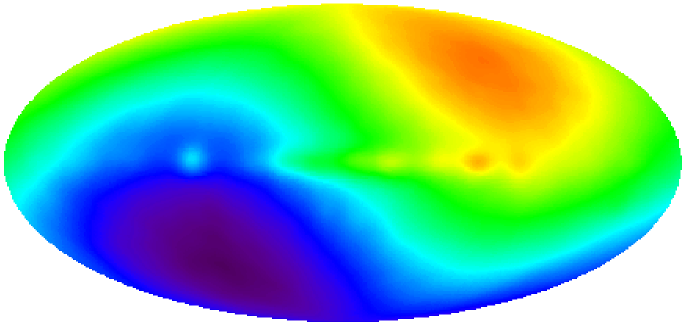
T = 2.728 K
ΔT = 0.0034 K

COBE's temperature map of the entire sky

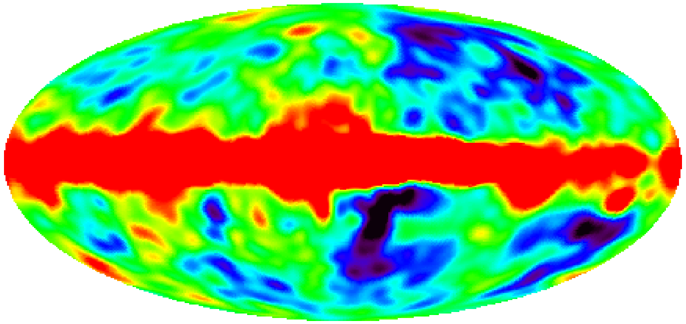


T = 2.728 K
ΔT = 0.00002 K

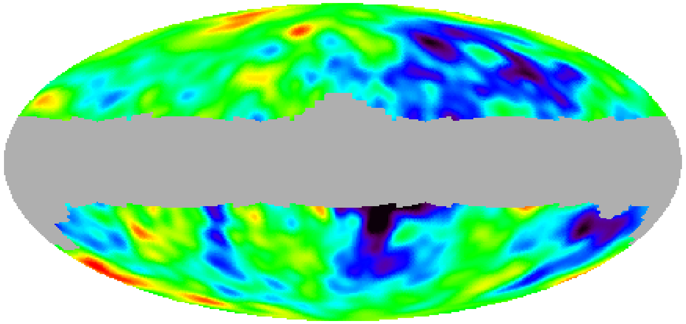
Structure in the COBE map



- One side of the sky is `hot', the other is `cold'
  the Earth's motion through the Cosmos
  ➡ $V_{\text{Milky Way}} = 600$ km/s

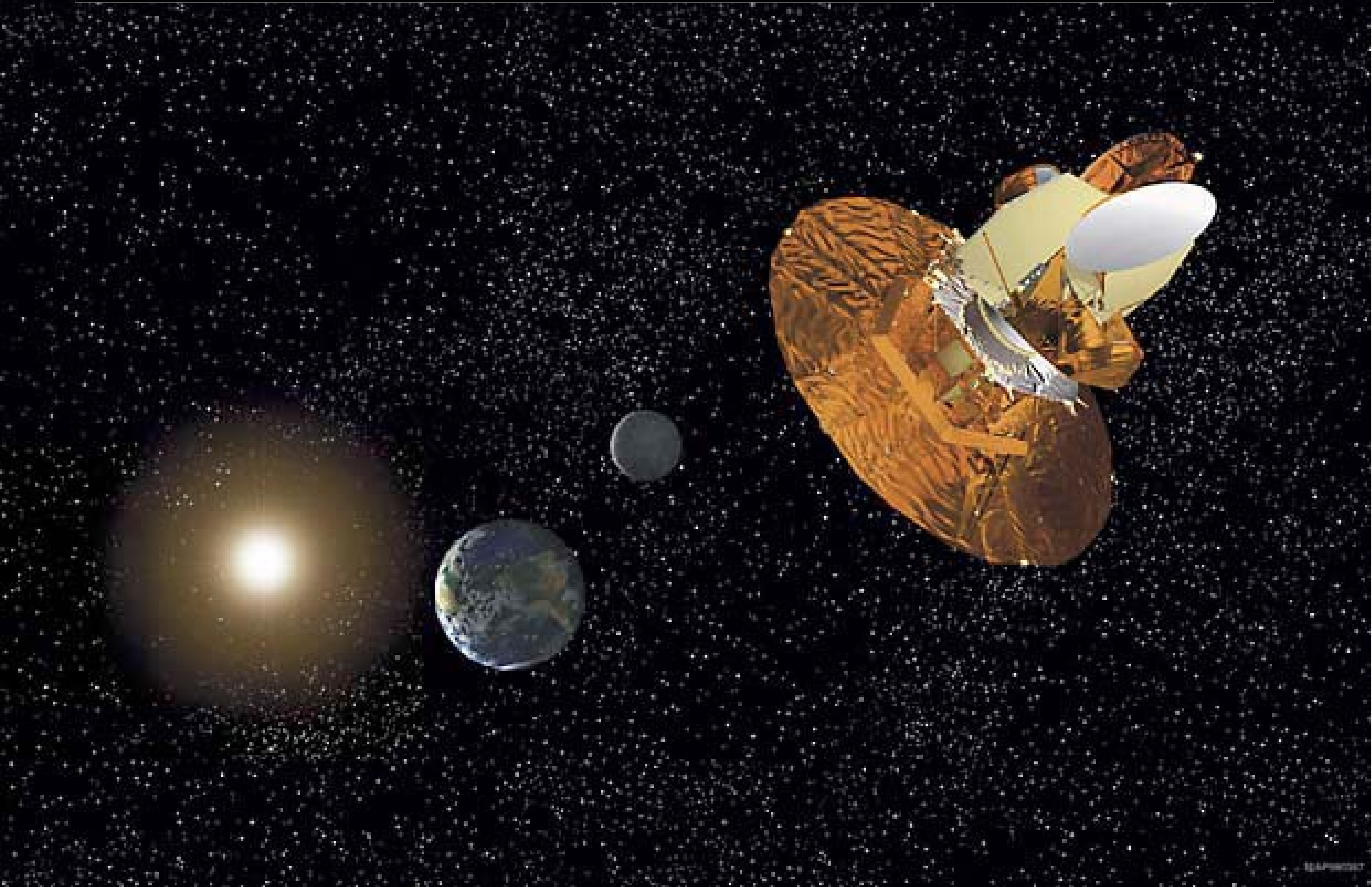


- Radiation from hot gas and dust in our own Milky Way

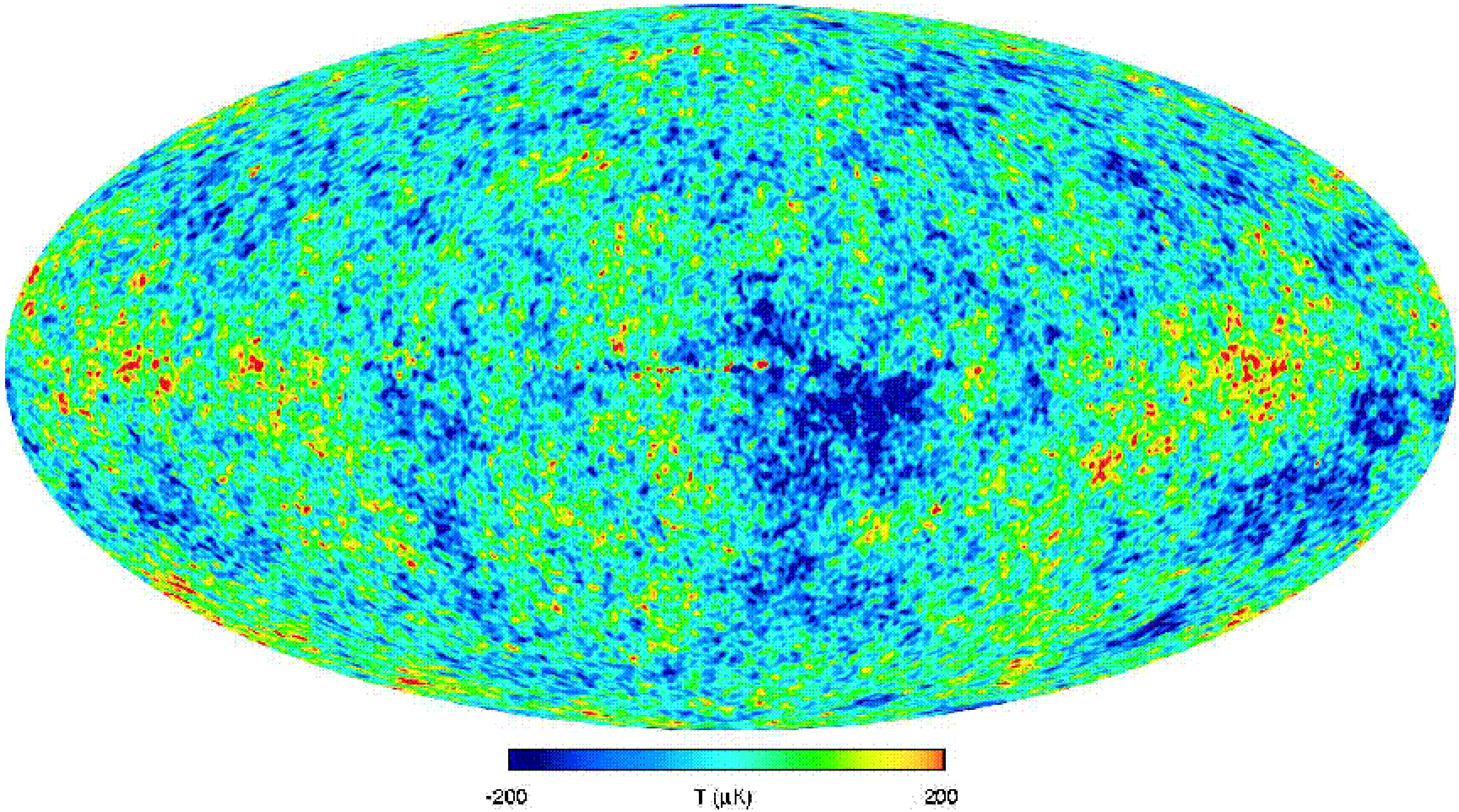


- Structure in the Microwave Background itself

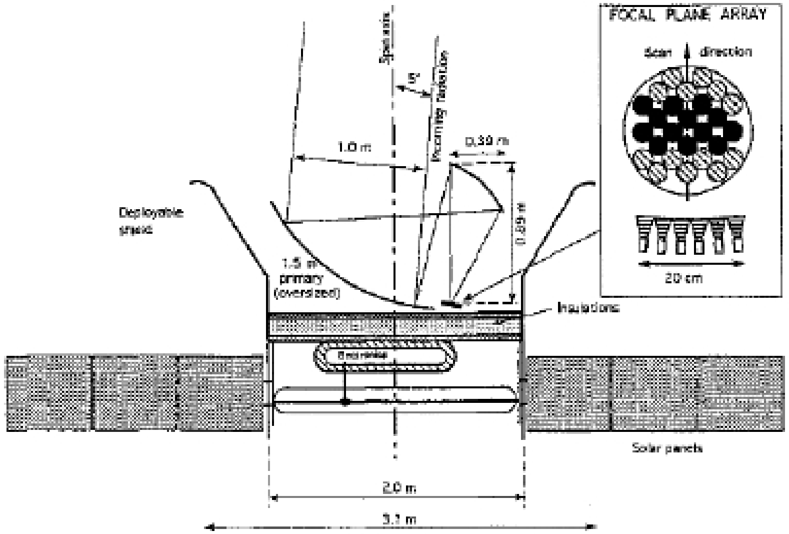
The *WMAP* Satellite at Lagrange-Point L2



The *WMAP* of the whole CMB sky

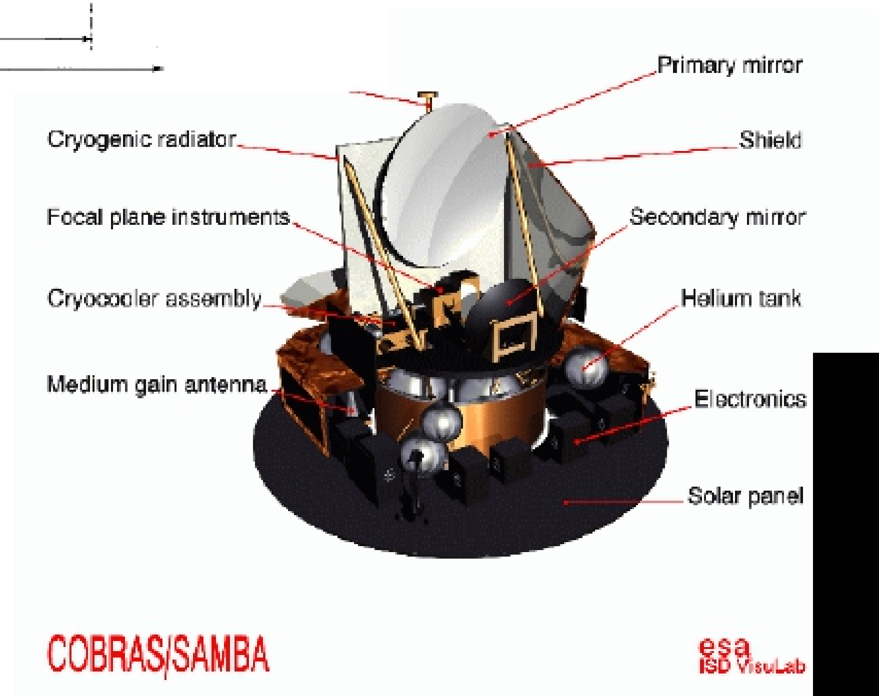


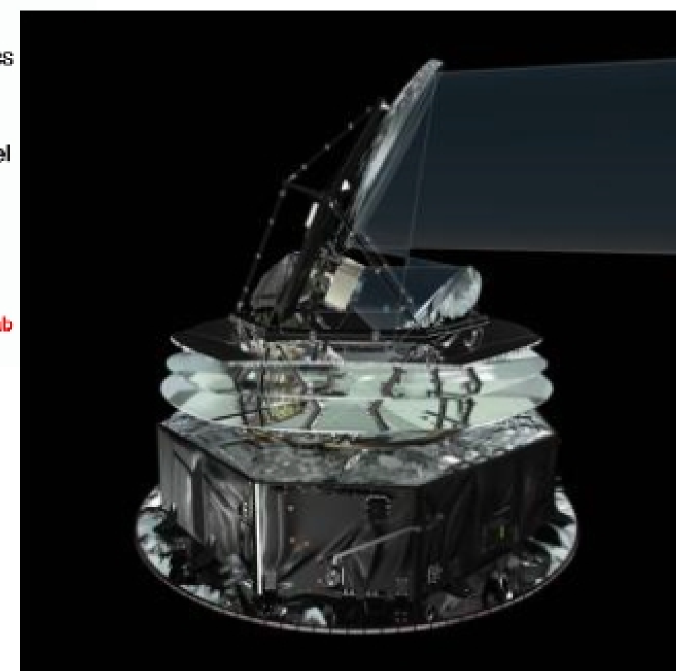
Bennett et al 2003



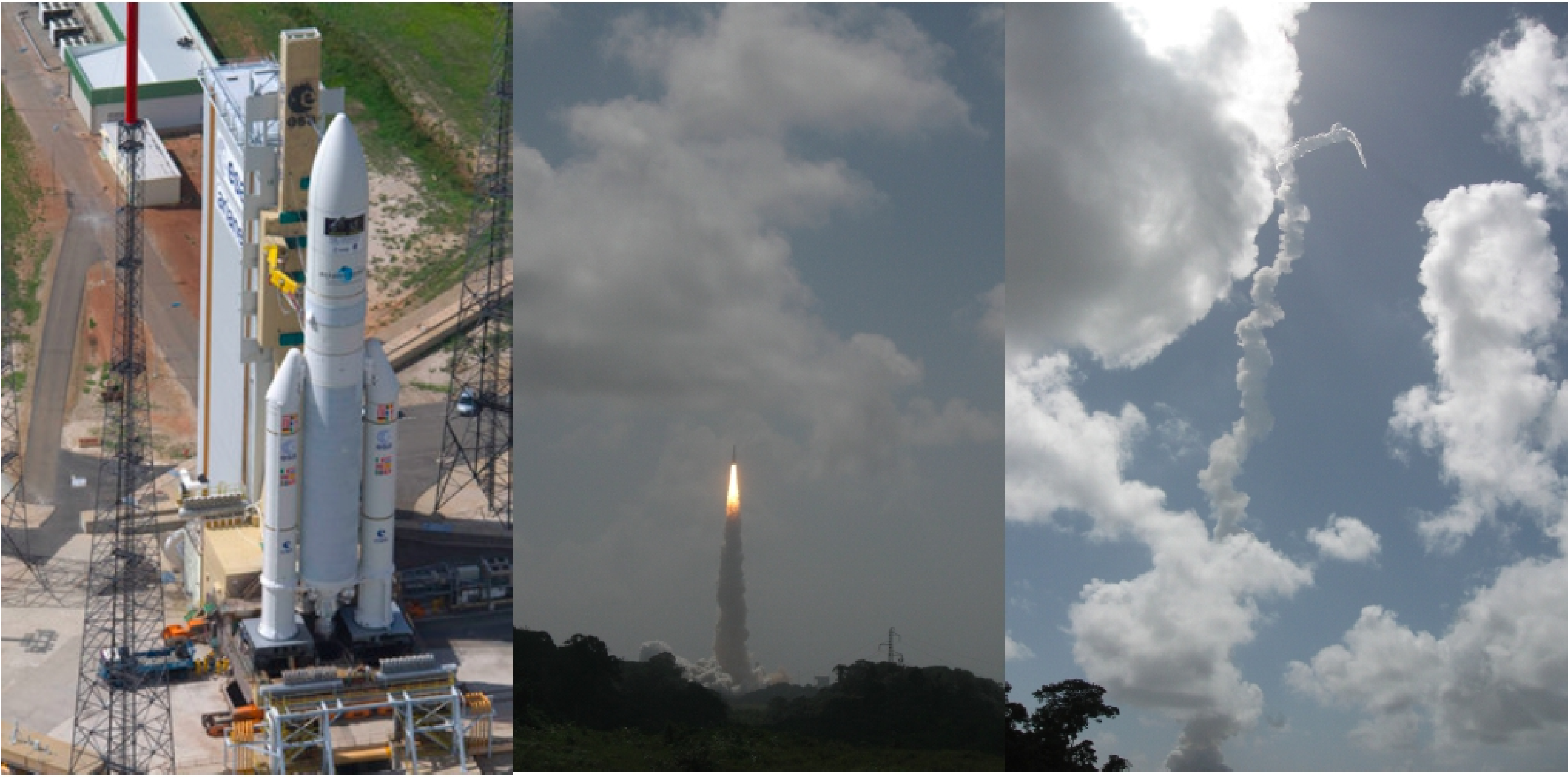
Proposal (1992)

Selection (1996)

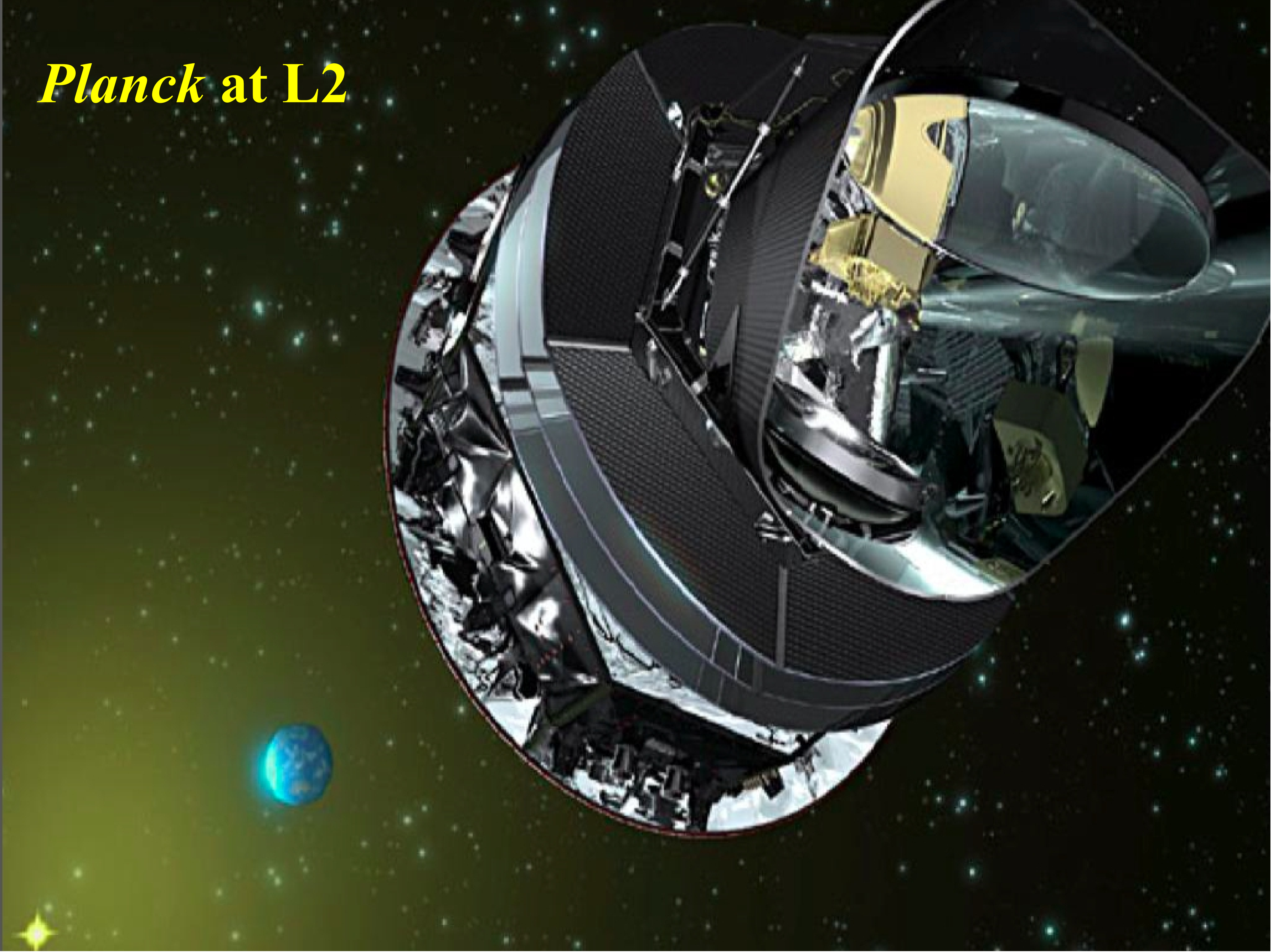




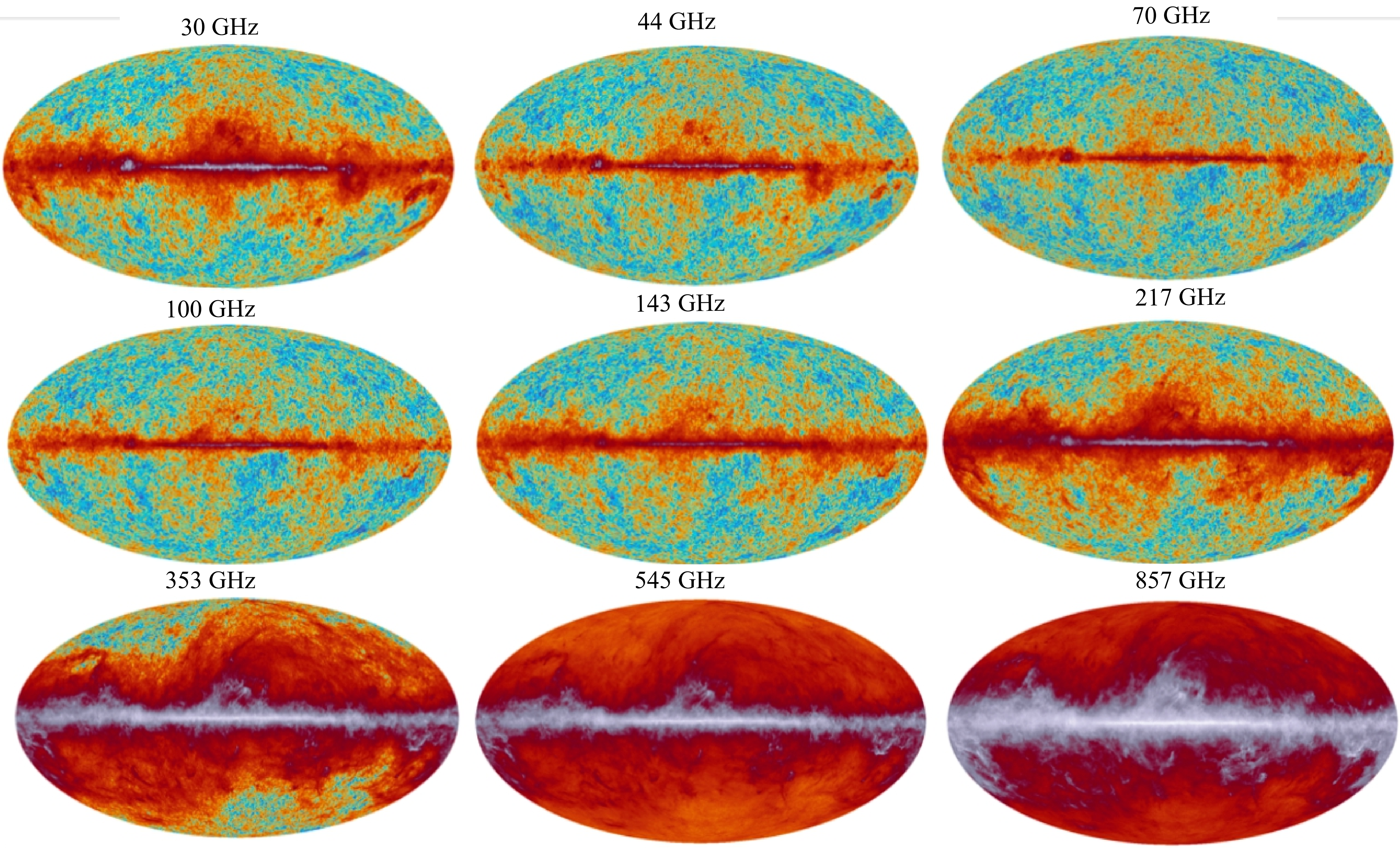
Launch May 2009!!



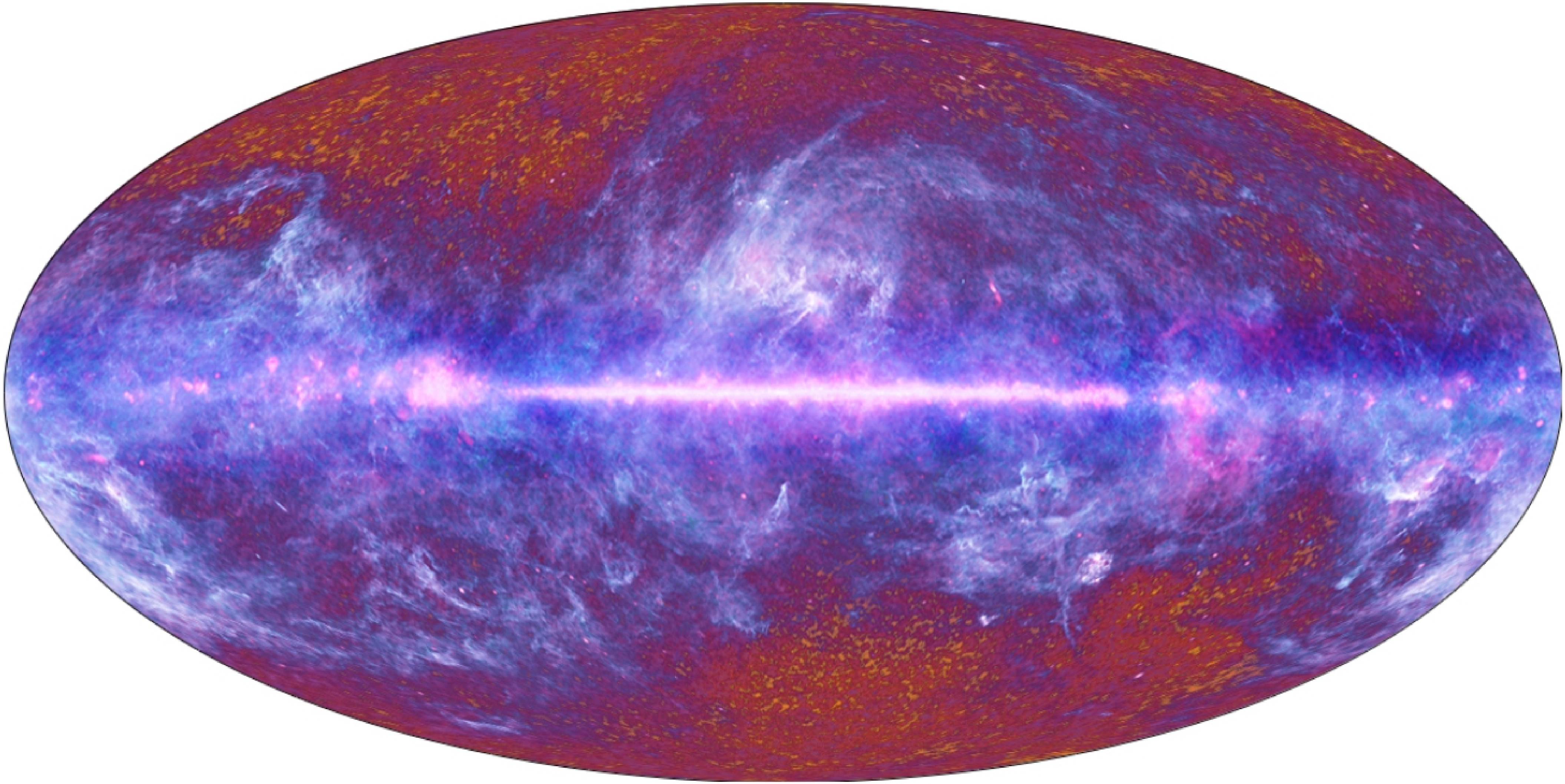
Planck at L2



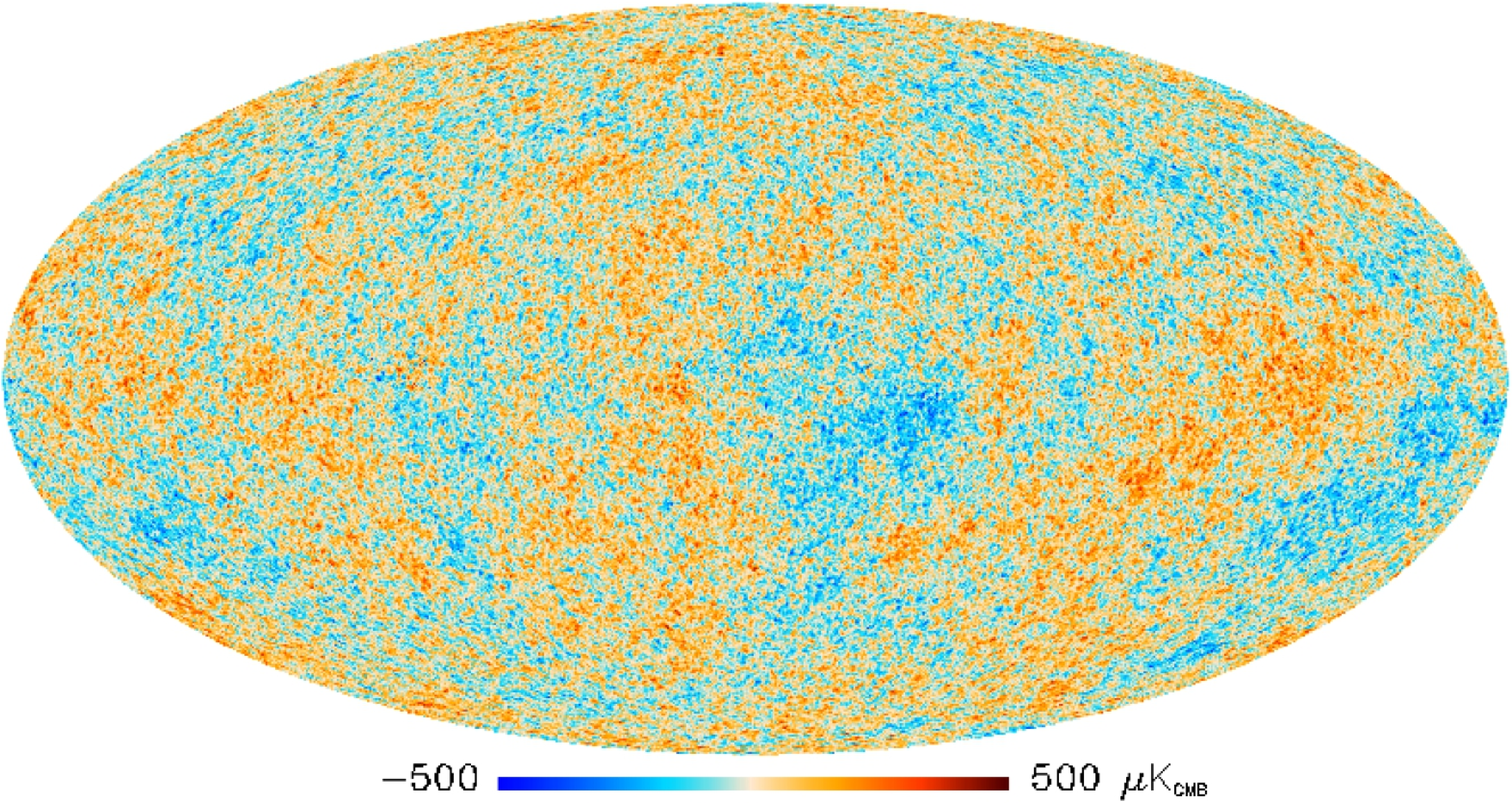
The nine *Planck* maps



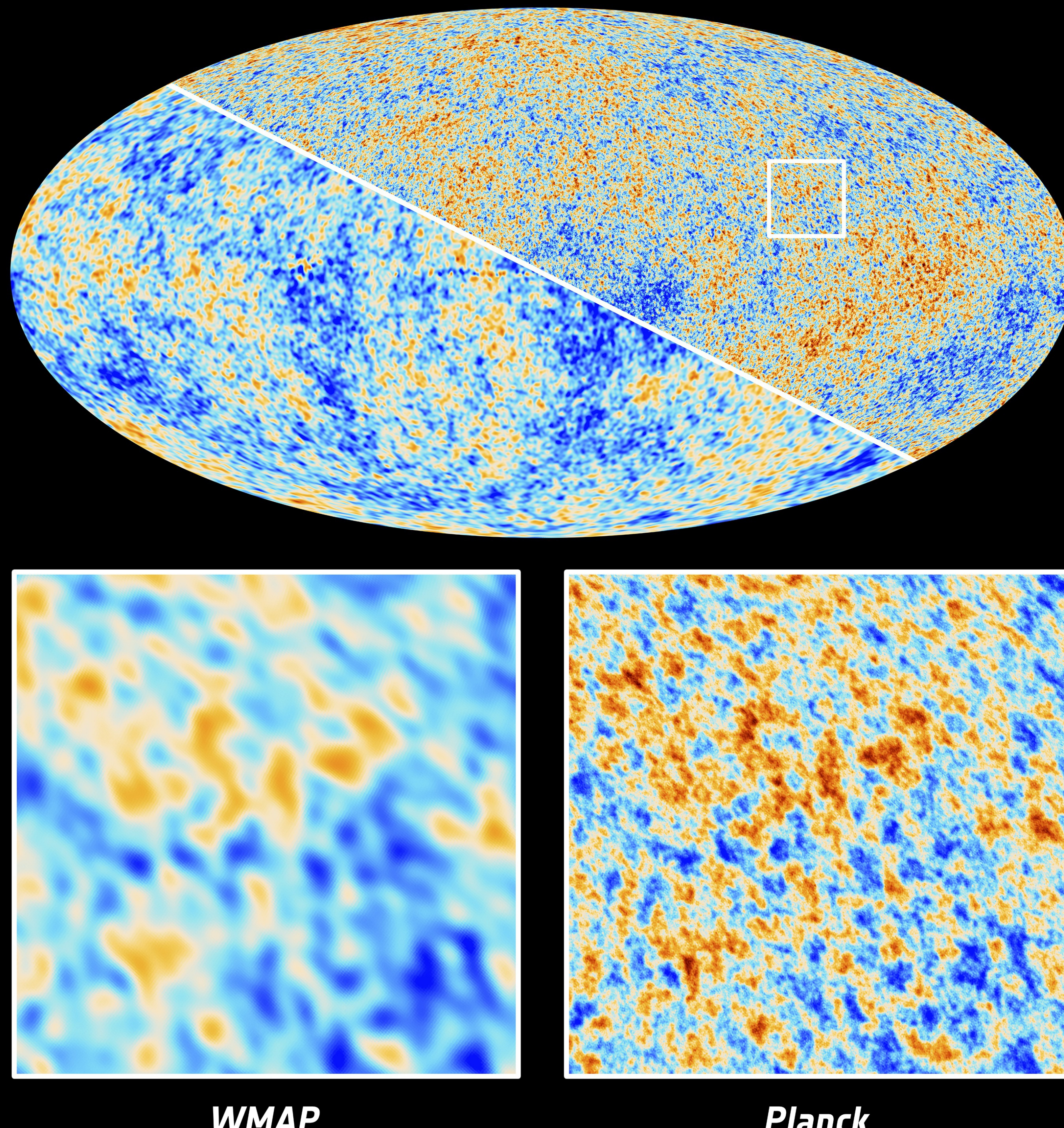
Public sky map after the first survey



CMB map after the first 2.5 surveys

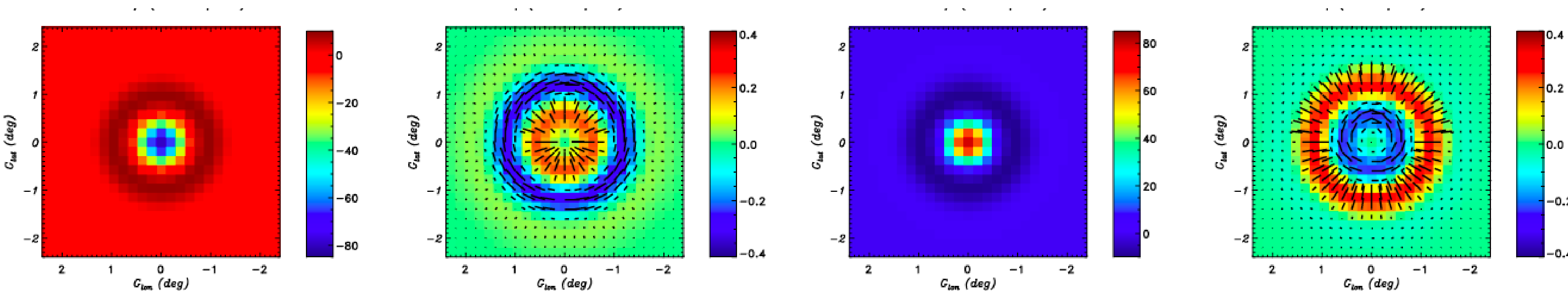


The Cosmic Microwave Background as seen by Planck and WMAP



Stacked temperature and polarisation maps

Predictions for standard recombination in a ΛCDM universe



intensity polarisation intensity polarisation

Temperature minima Temperature maxima

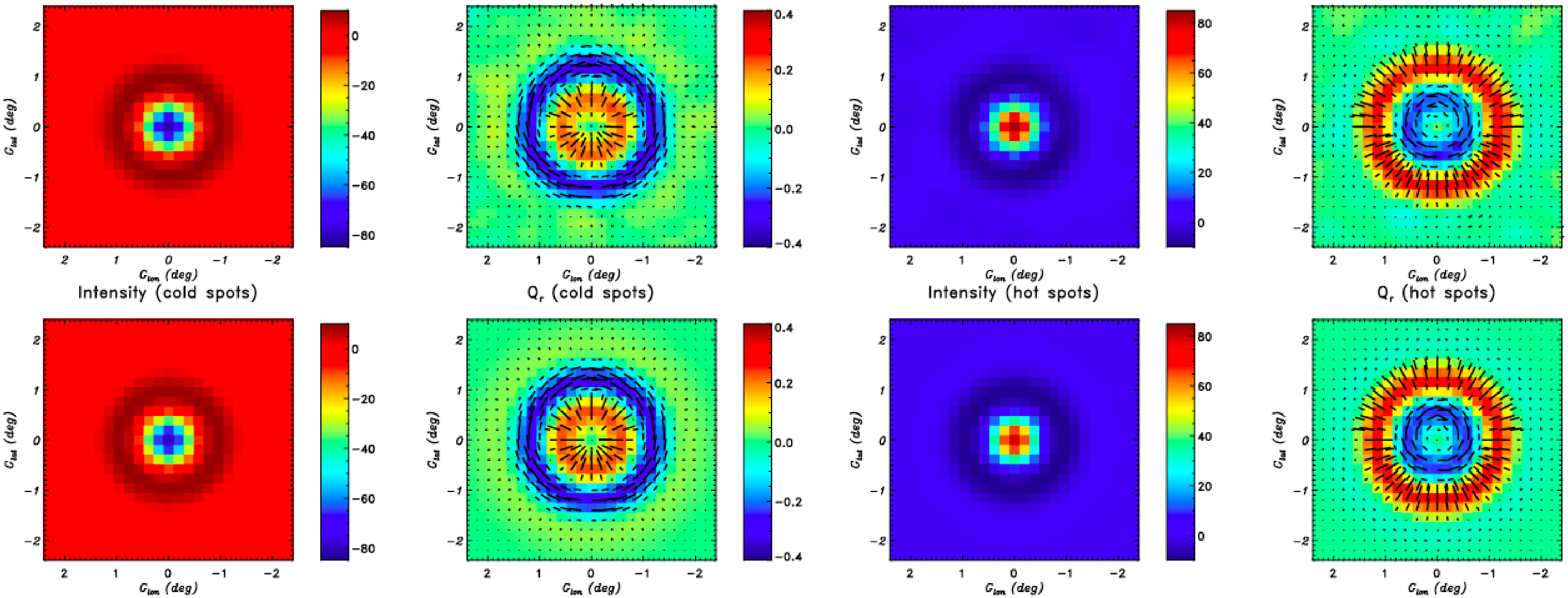
Thomson scattering in the last scattering surface is expected to induce characteristic polarisation patterns around extrema of the temperature field.

Stacked temperature and polarisation maps

Stacked Planck data, 30' smoothing

11,396 cold spots

10,468 hot spots



intensity

polarisation

Temperature minima

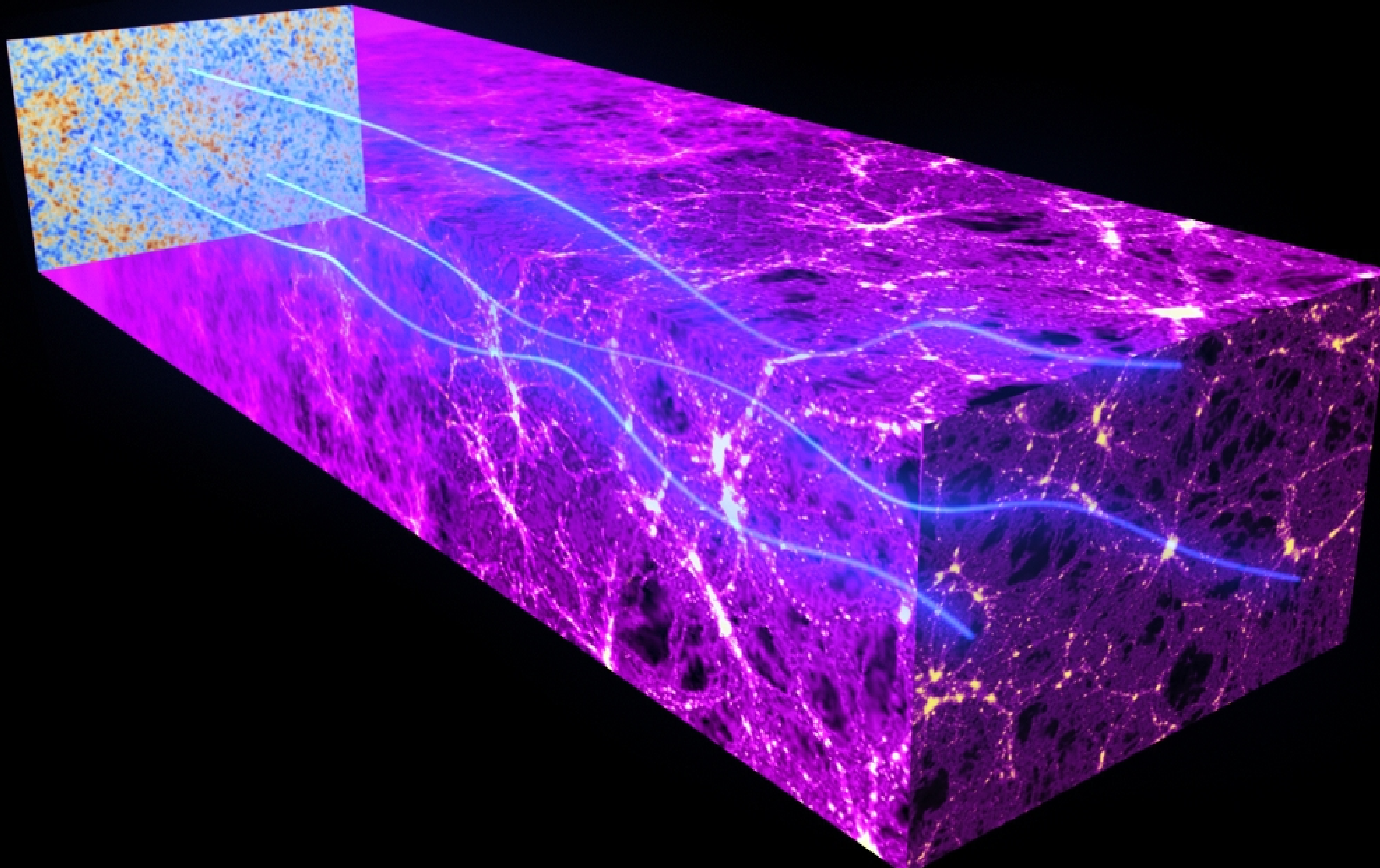
intensity

polarisation

Temperature maxima

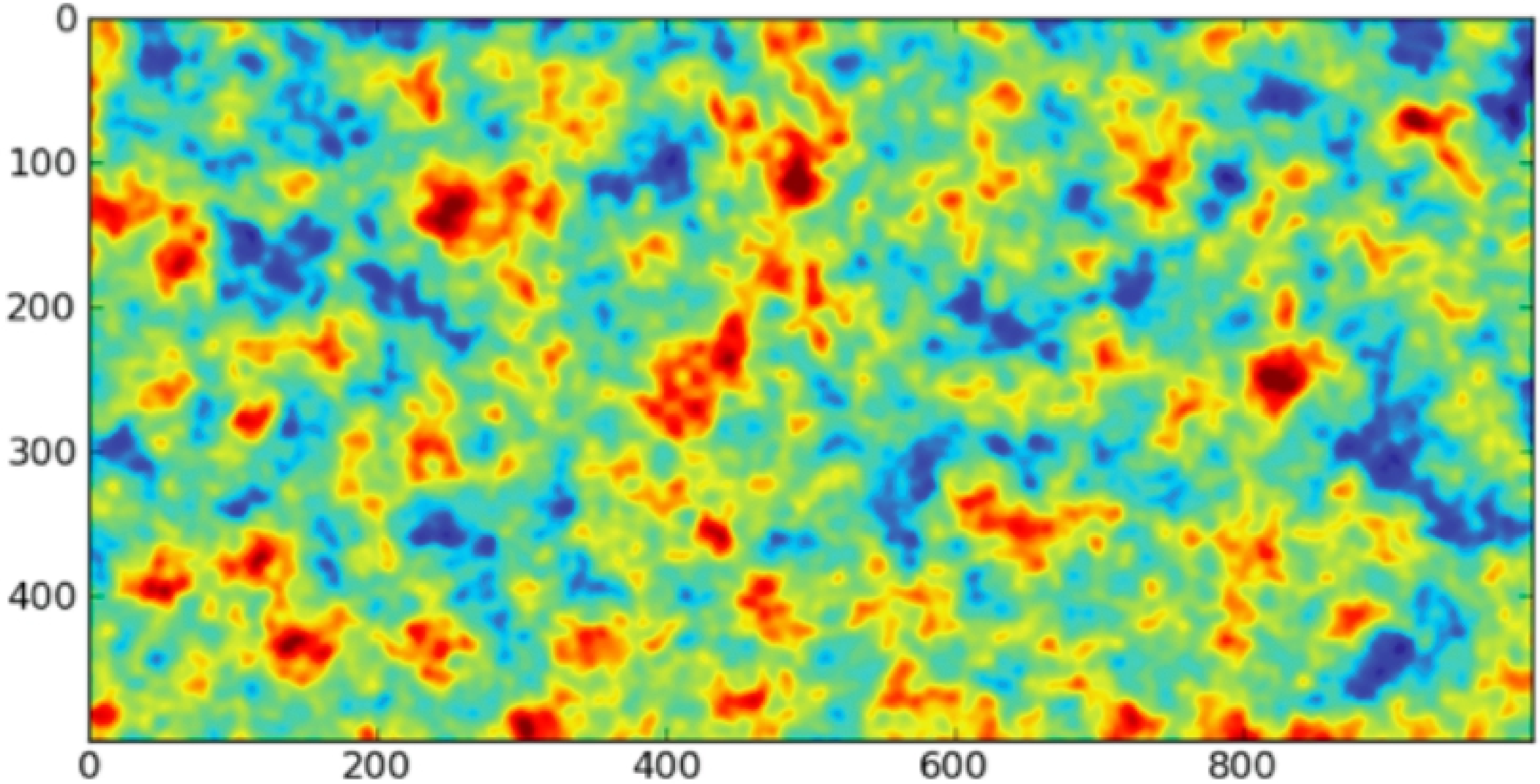
Thomson scattering in the last scattering surface is expected to induce characteristic polarisation patterns around extrema of the temperature field.

Gravitational lensing of the temperature map



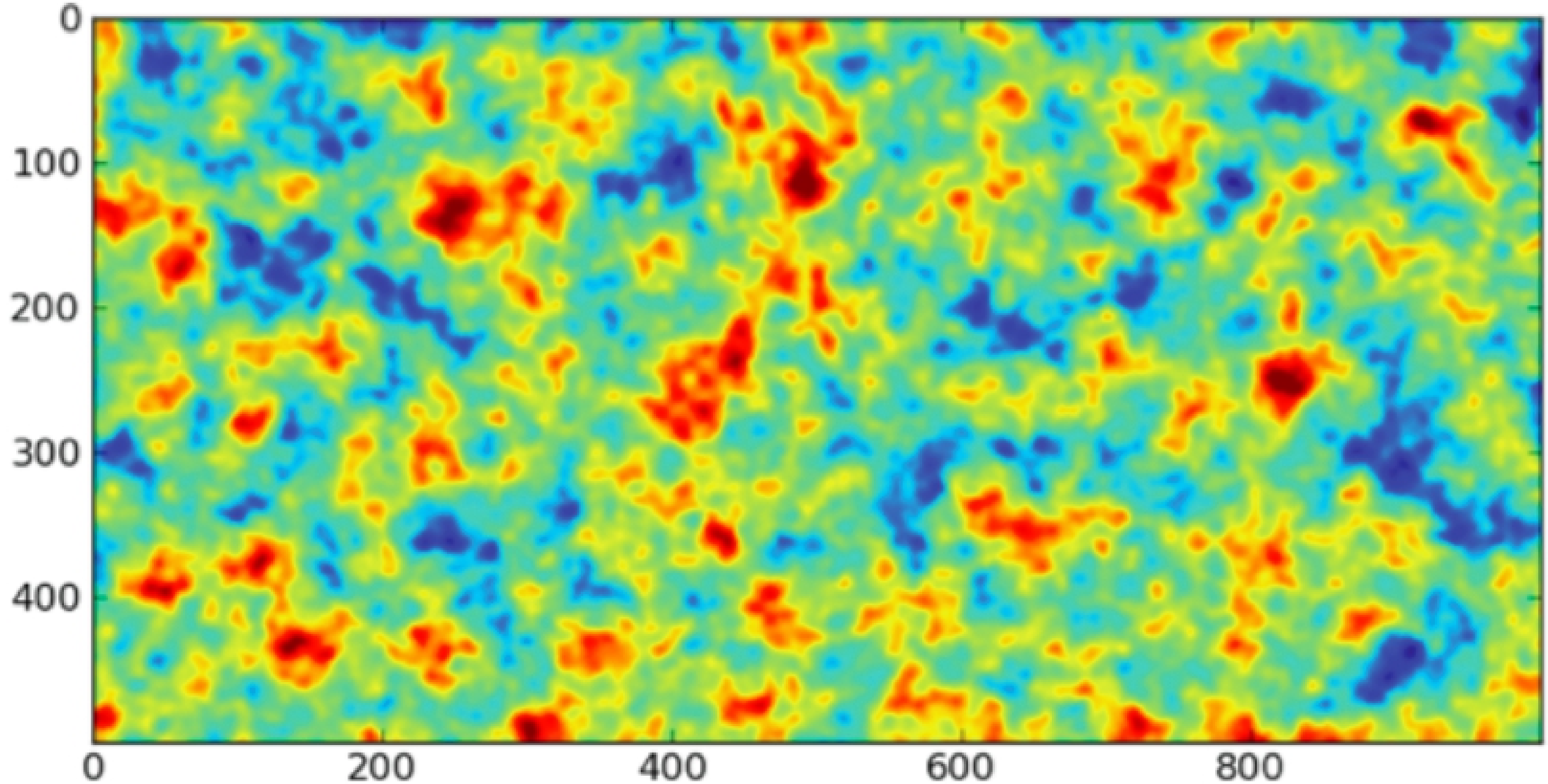
Gravitational lensing of the temperature map

Original unlensed map



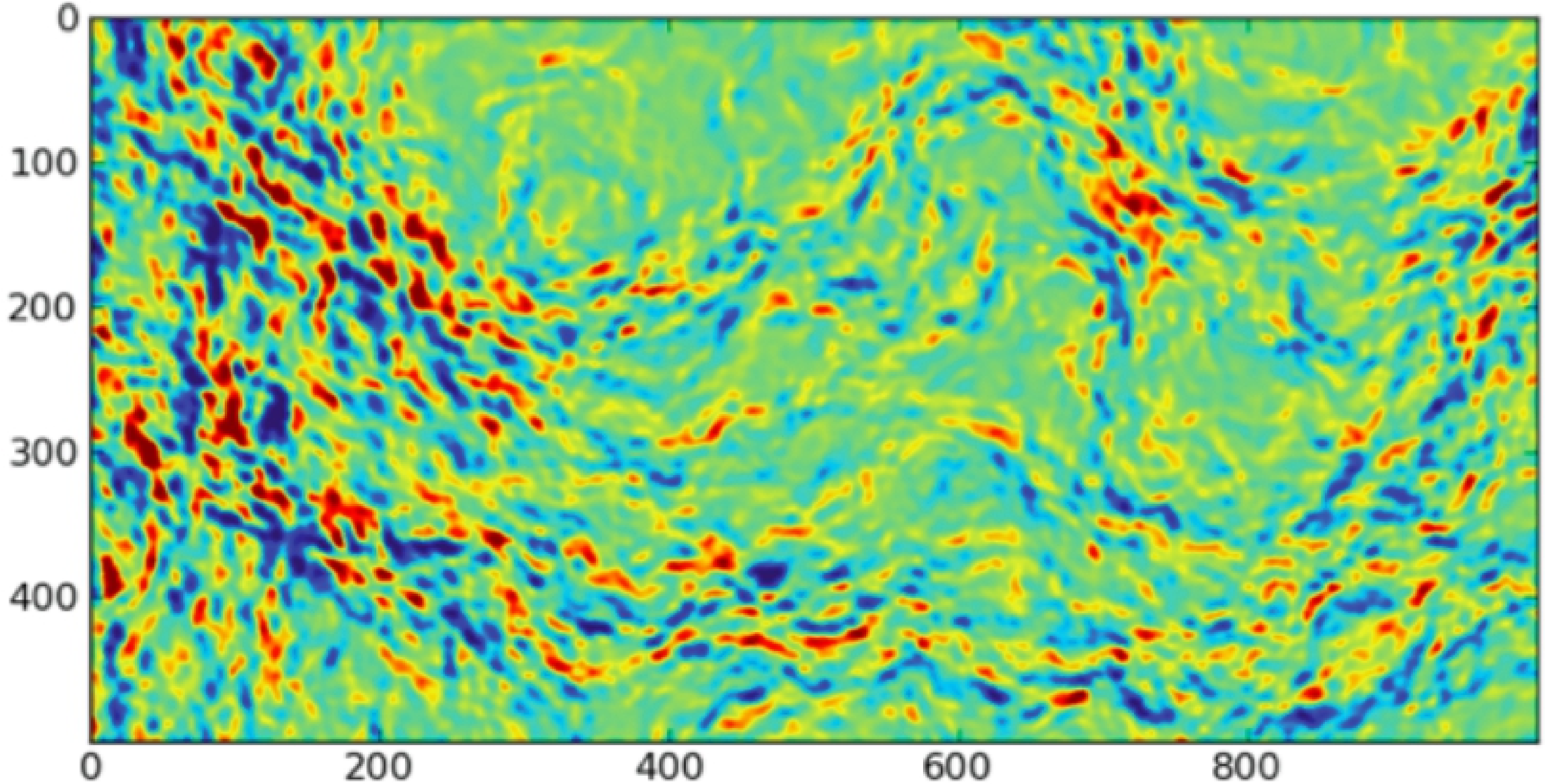
Gravitational lensing of the temperature map

Lensed map

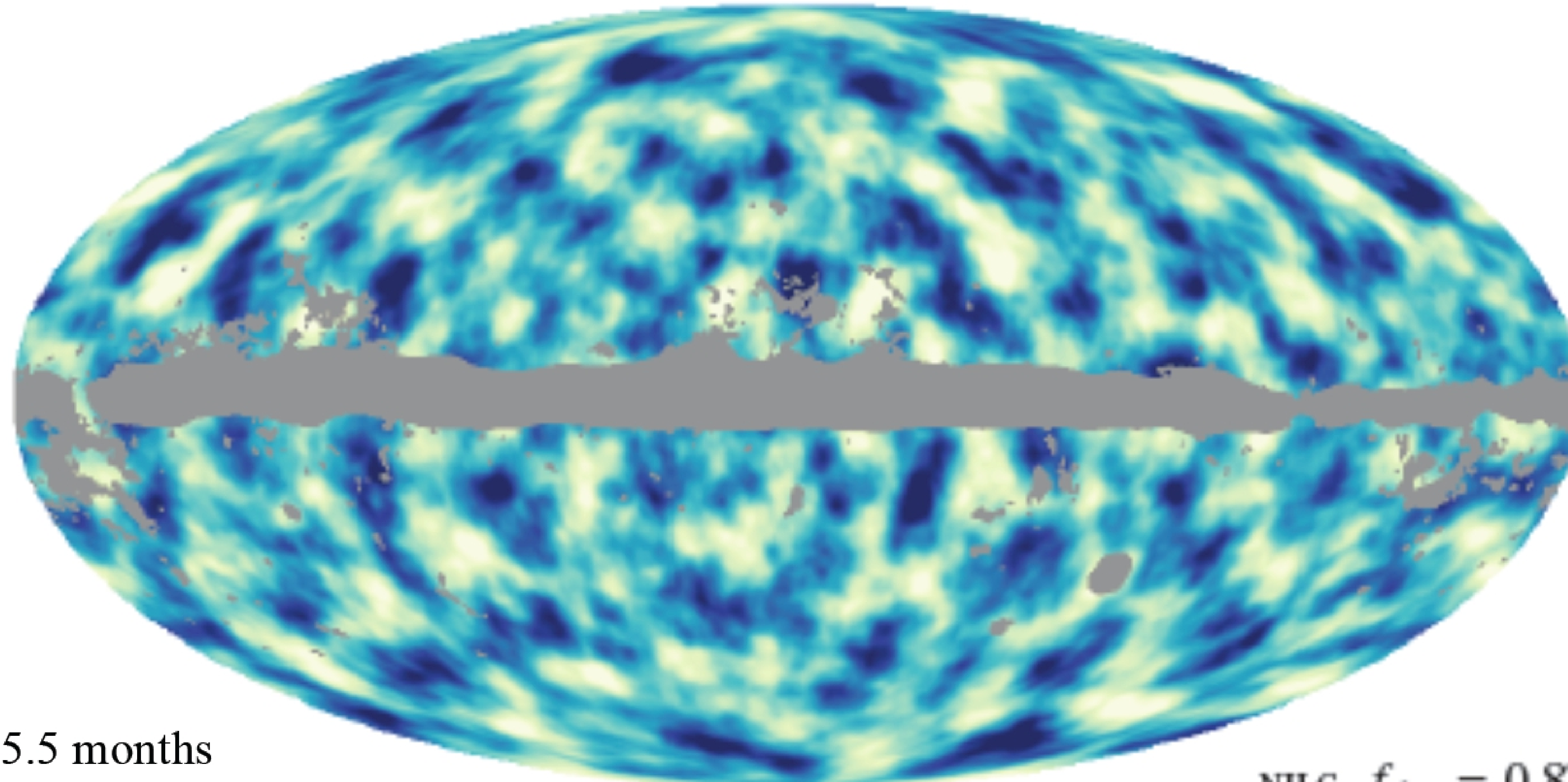


Gravitational lensing of the temperature map

Difference map



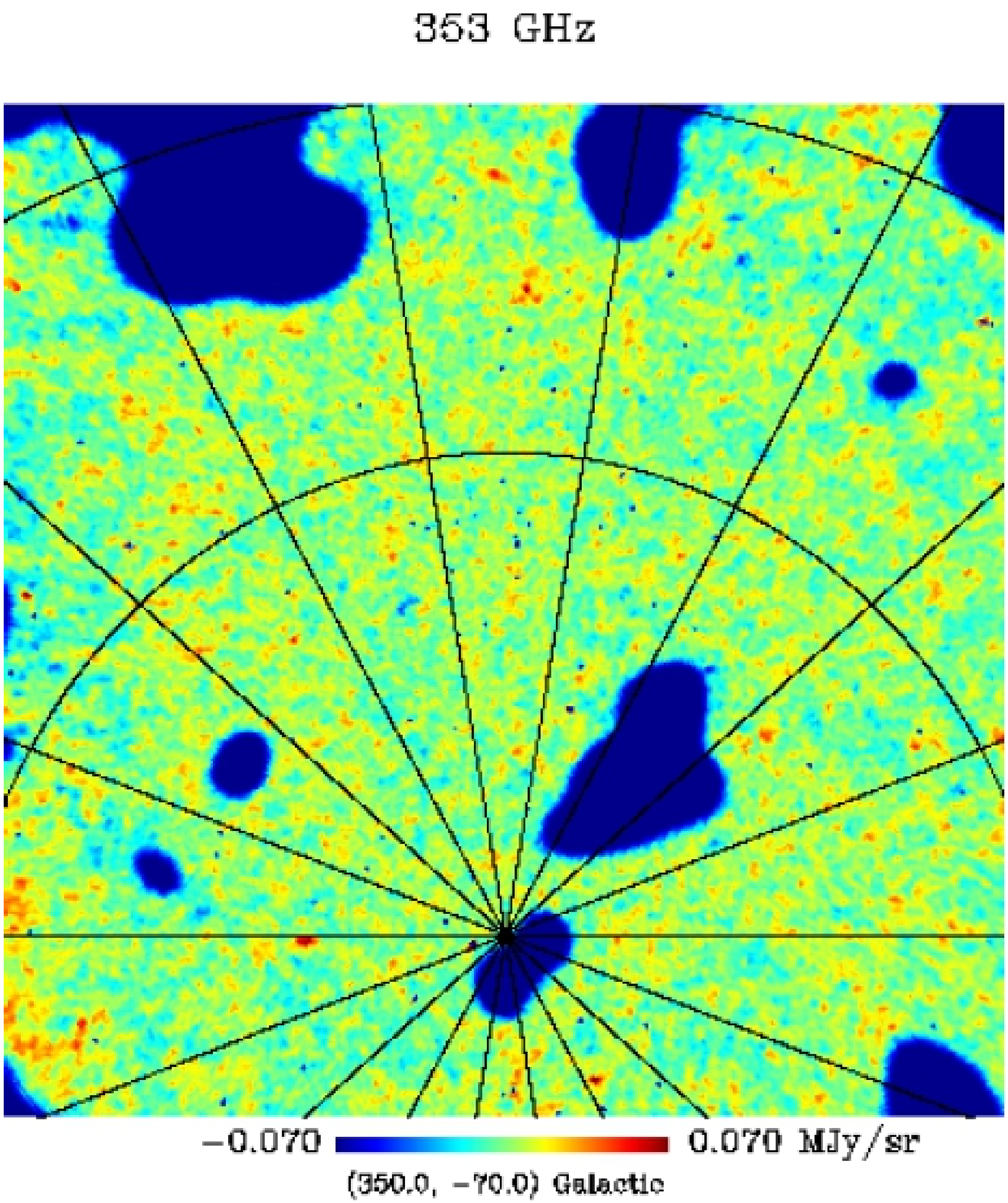
Lensing mass map from the first 2.5 surveys



15.5 months
S/N<1

NILC, $f_{\rm sky} = 0.87$

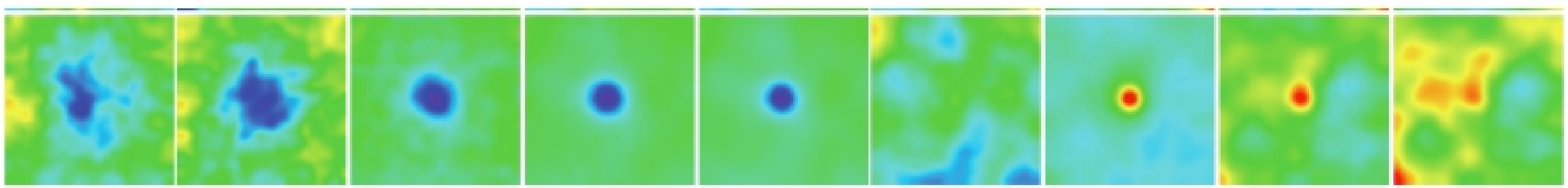
CIB map from the first 2.5 surveys



A projection of the cosmic star-formation history, re-radiated by dust.

The correlation with the projected mass map is detected at a level of 47 σ !

Detecting the (hot) baryons with *Planck*



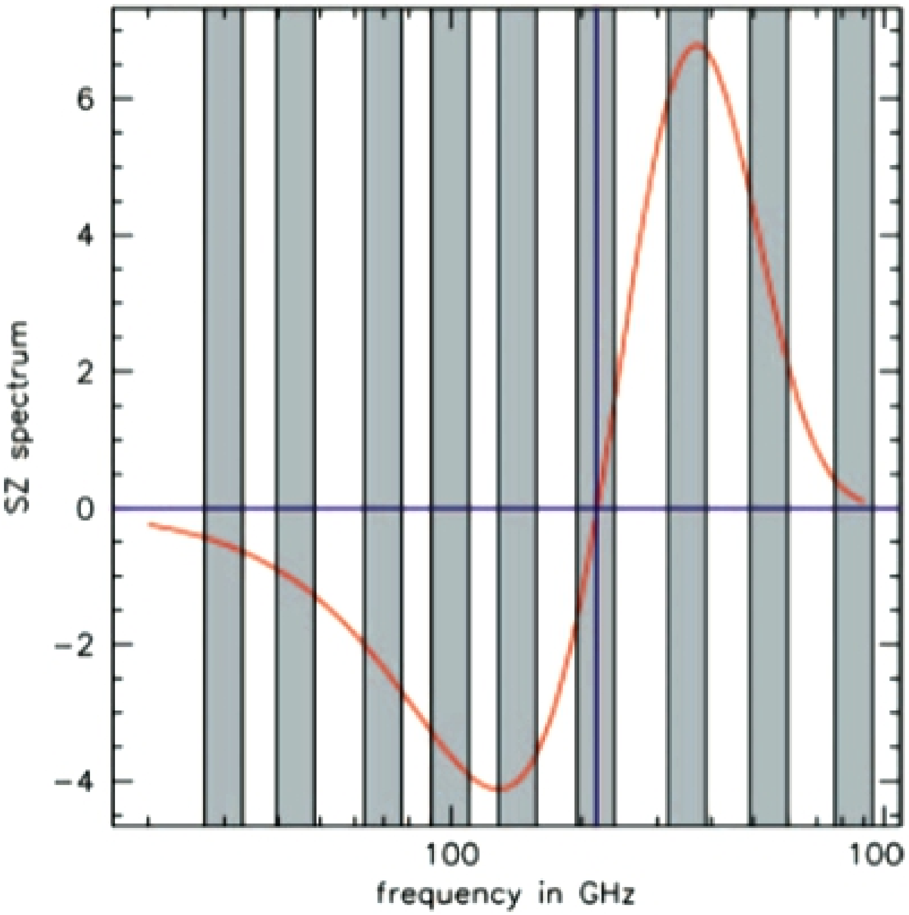
Planck can detect hot gas against the CMB through the spectral distortion introduced by Compton scattering,

$$\Delta i_\nu(\hat{n}) = y(\hat{n}) j_\nu \, ,$$

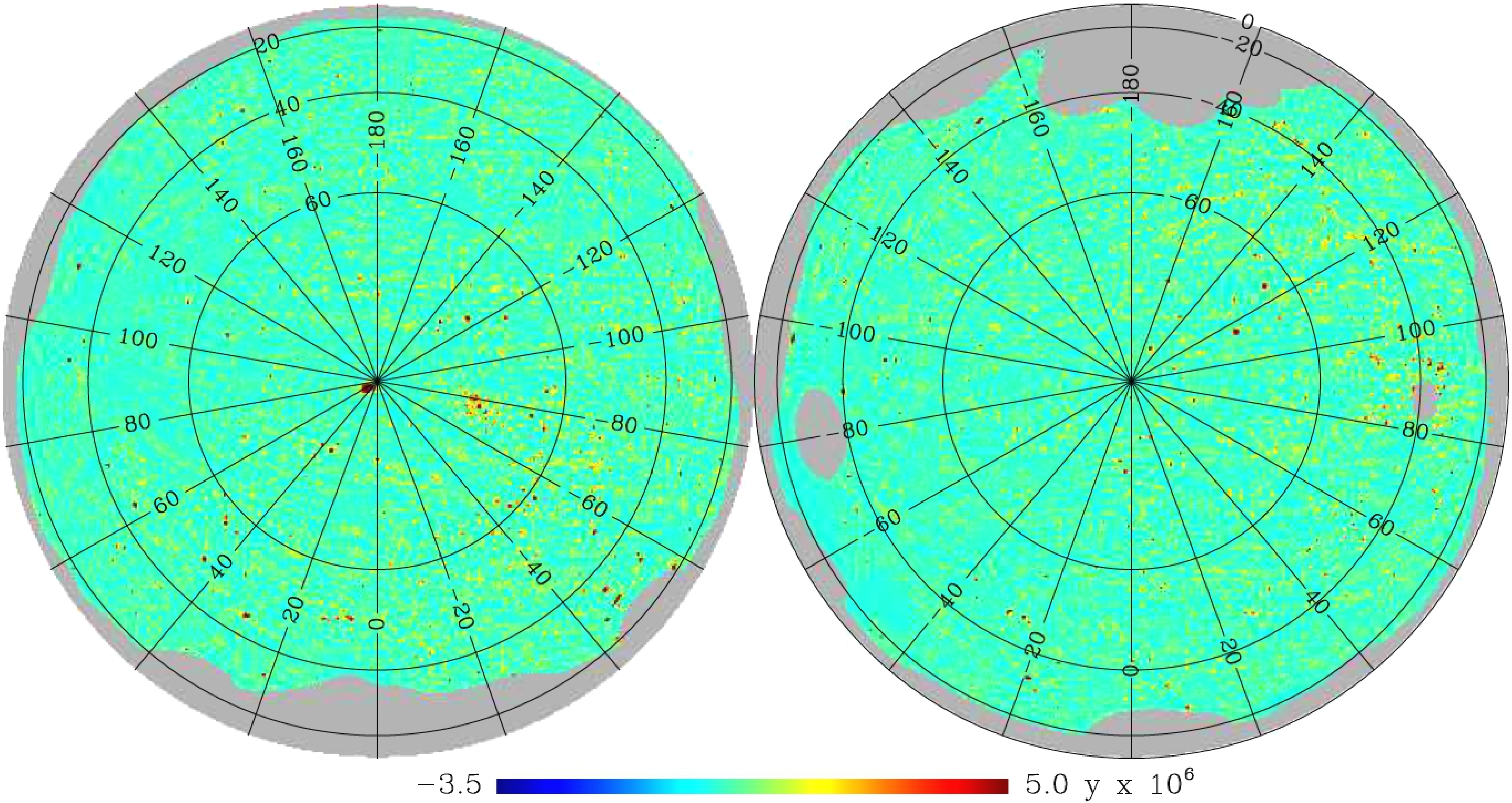
where j_ν is a characteristic spectral shape and y is the line-of-sight integral

$$y = k_{SZ} \int n_e \, T_e \, dl,$$

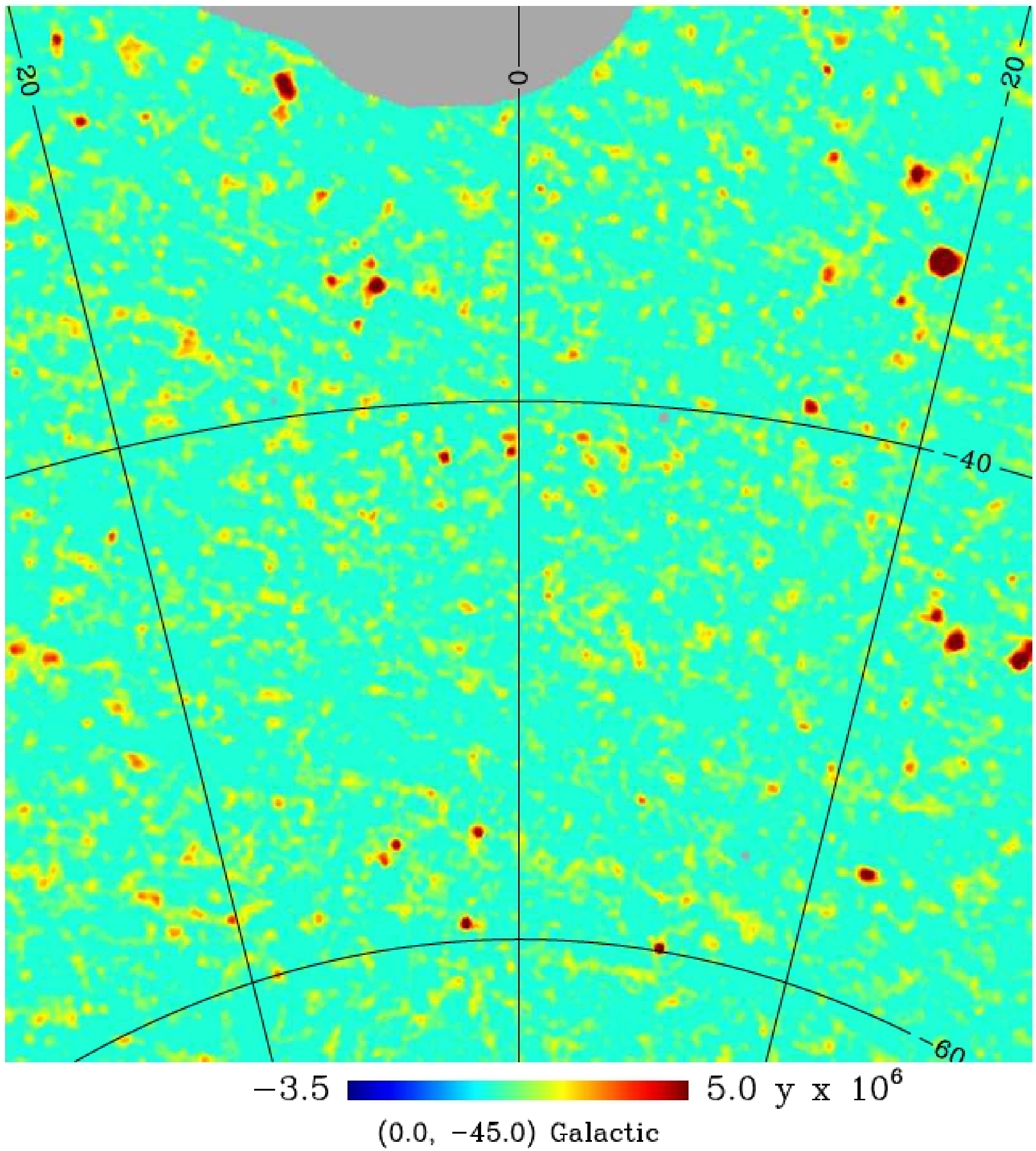
This is the Sunyaev-Zeldovich effect



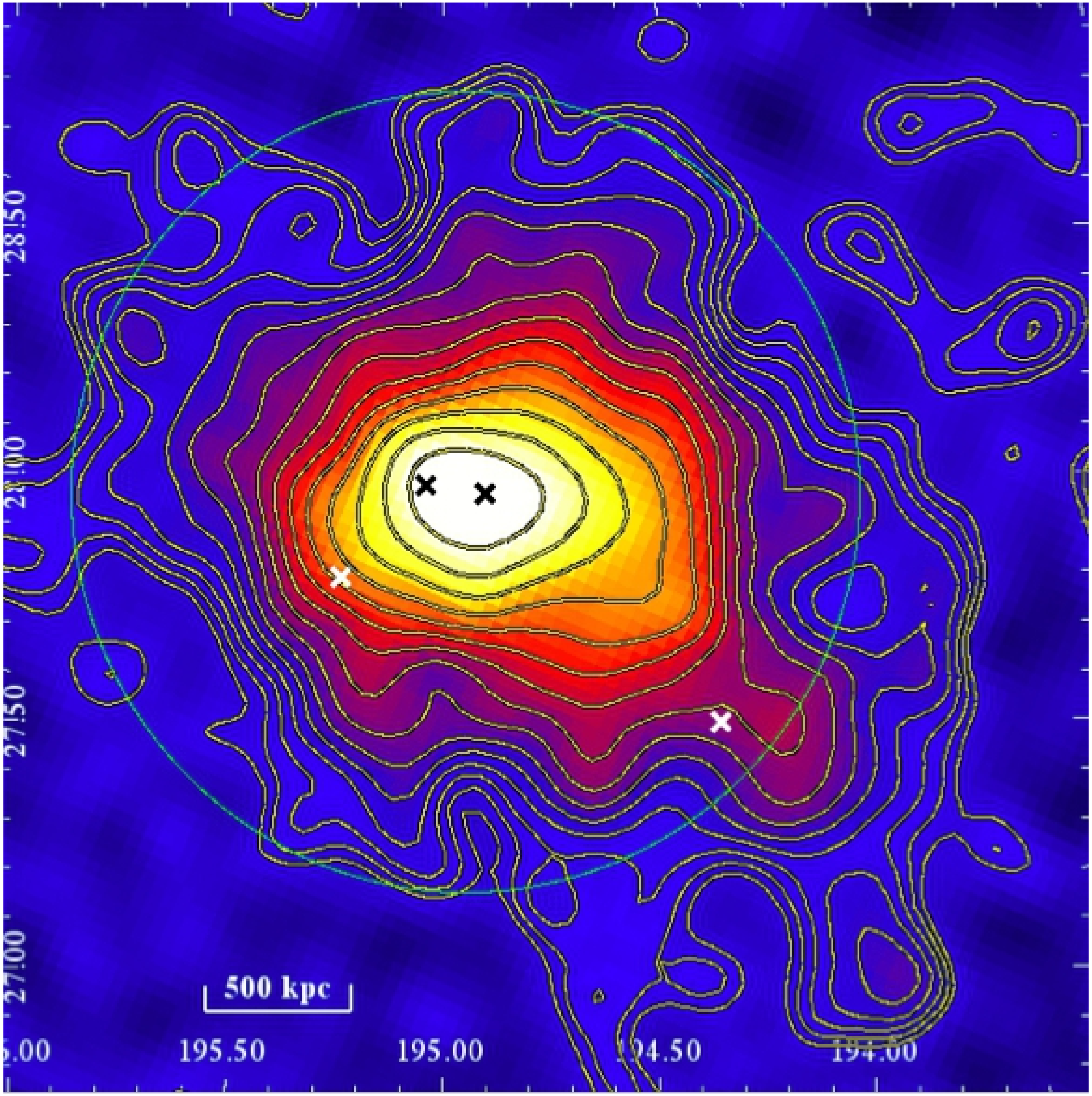
SZ map from the first 2.5 surveys



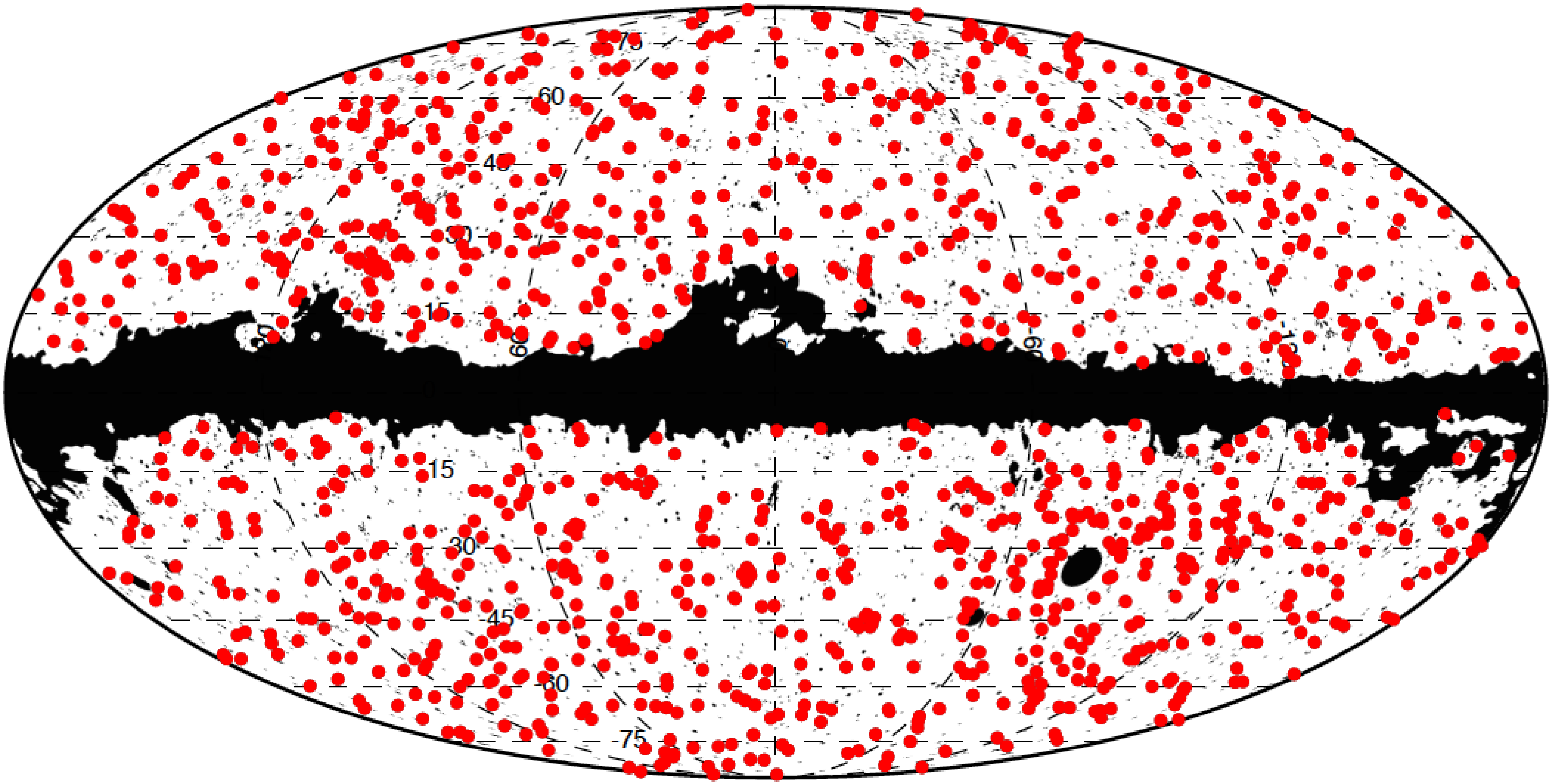
SZ map from the first 2.5 surveys



The Coma cluster

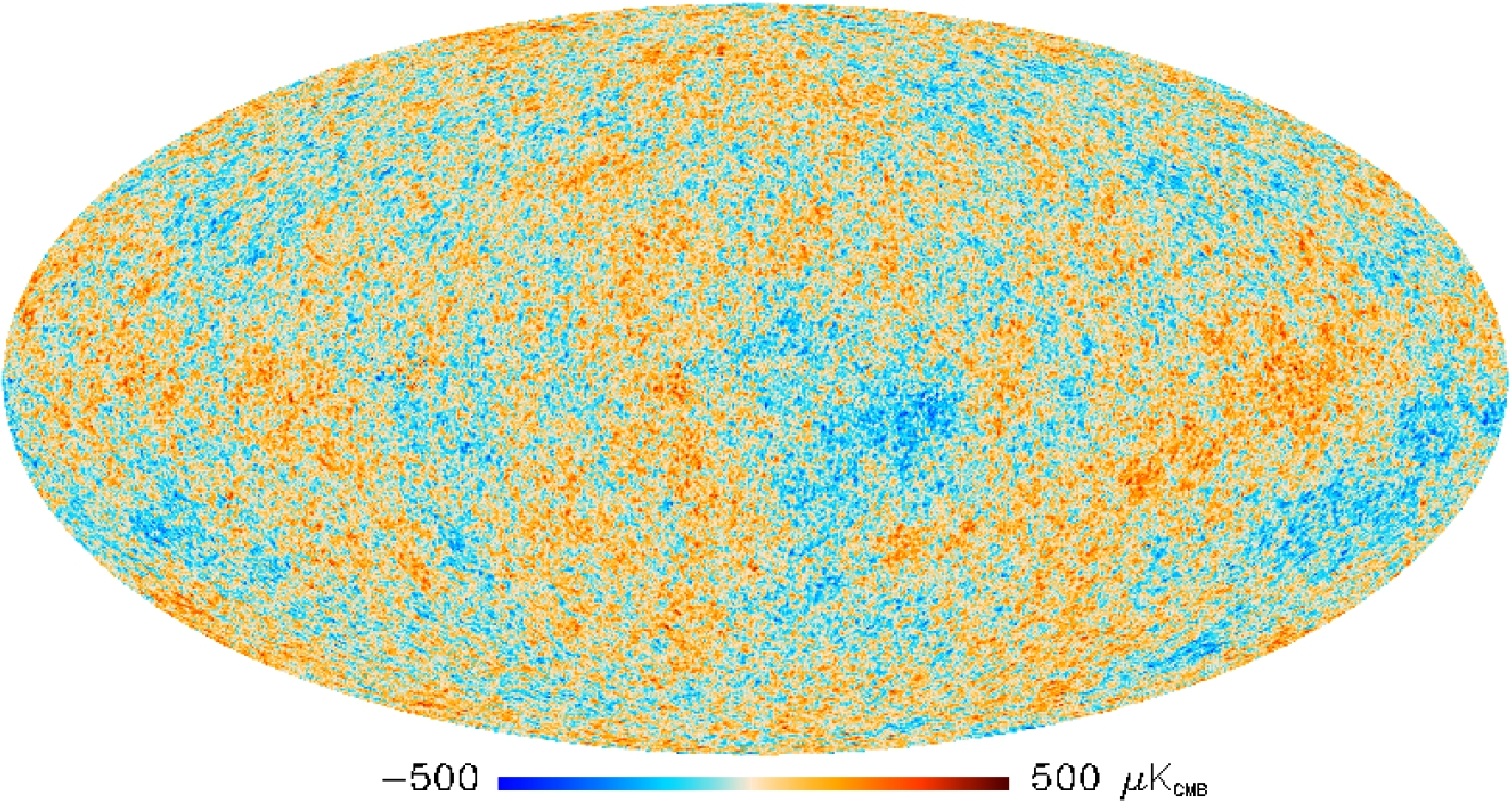


Planck's catalogue of SZ-detected sources

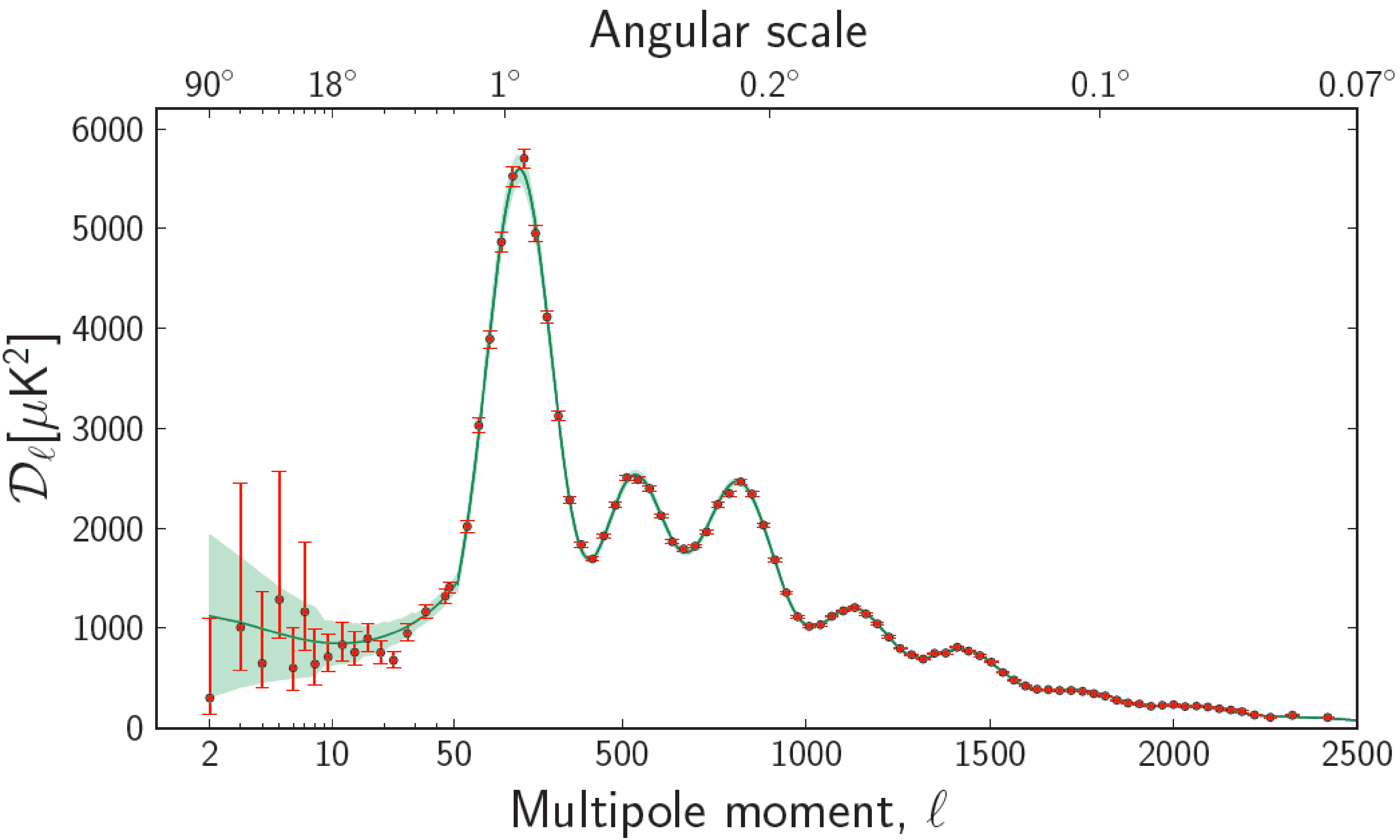


1227 SZ sources with S/N>4.5 over 83.7% of the sky. 861 confirmed clusters

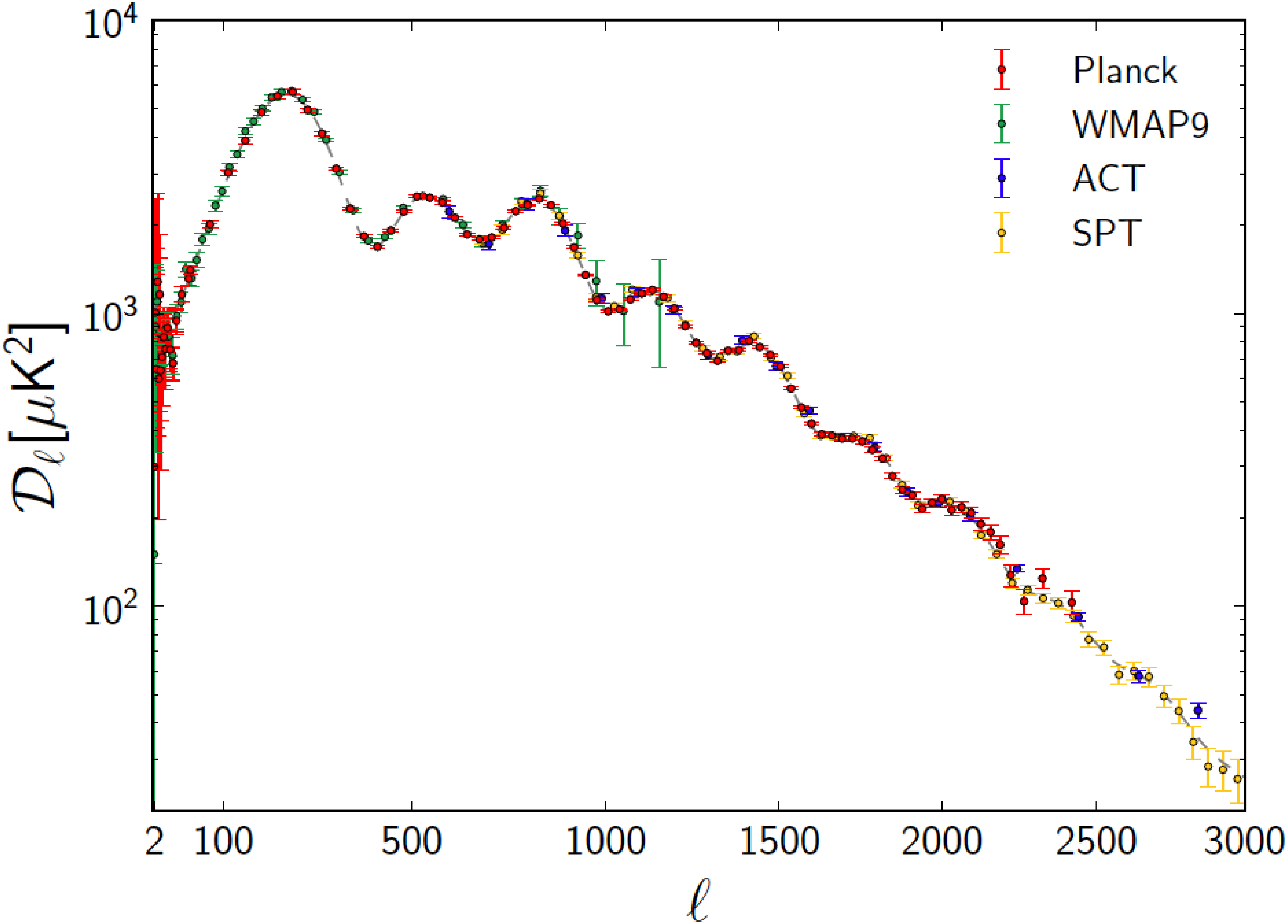
CMB map after the first 2.5 surveys



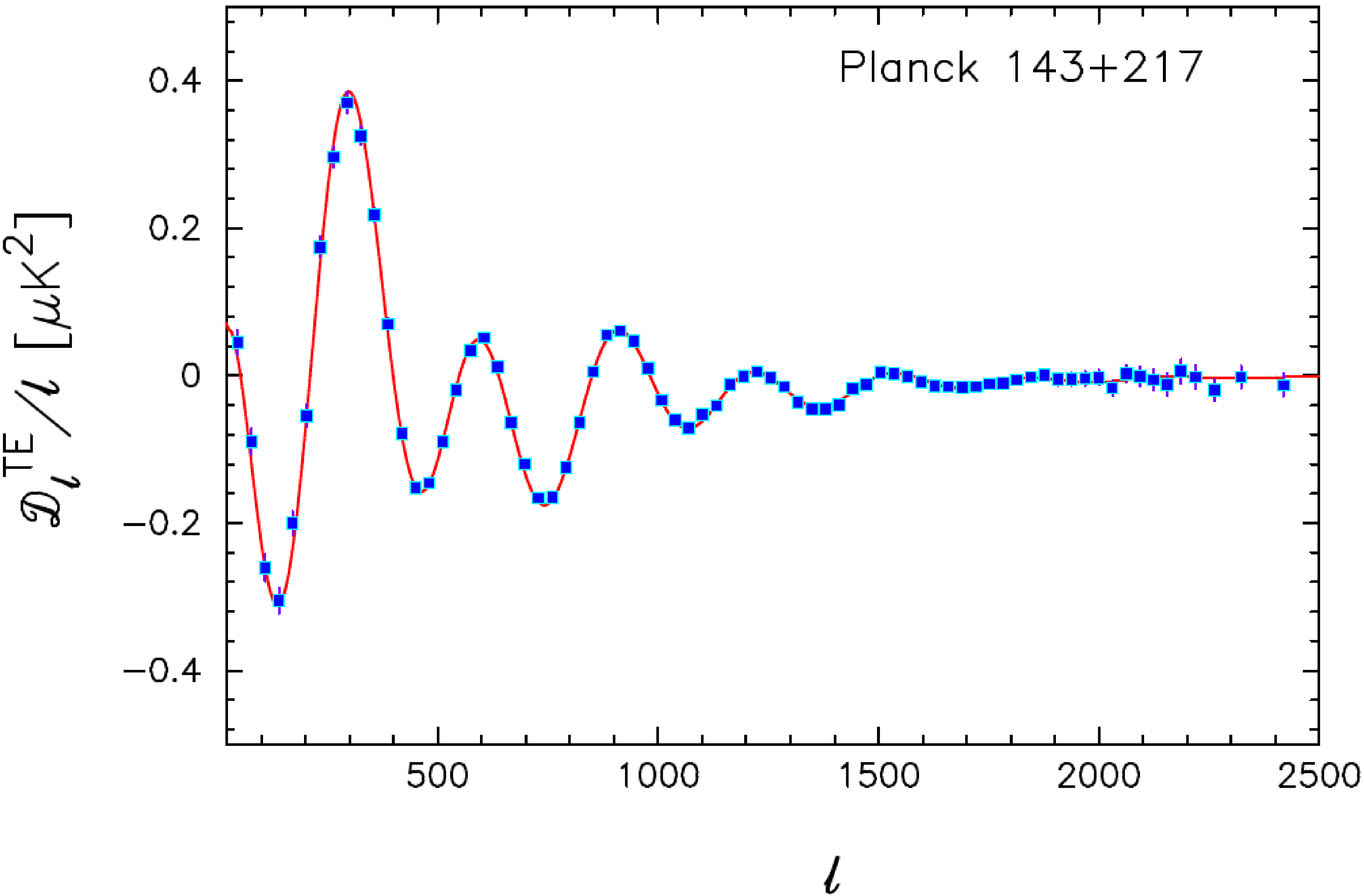
Planck CMB power spectrum from 2.5 surveys



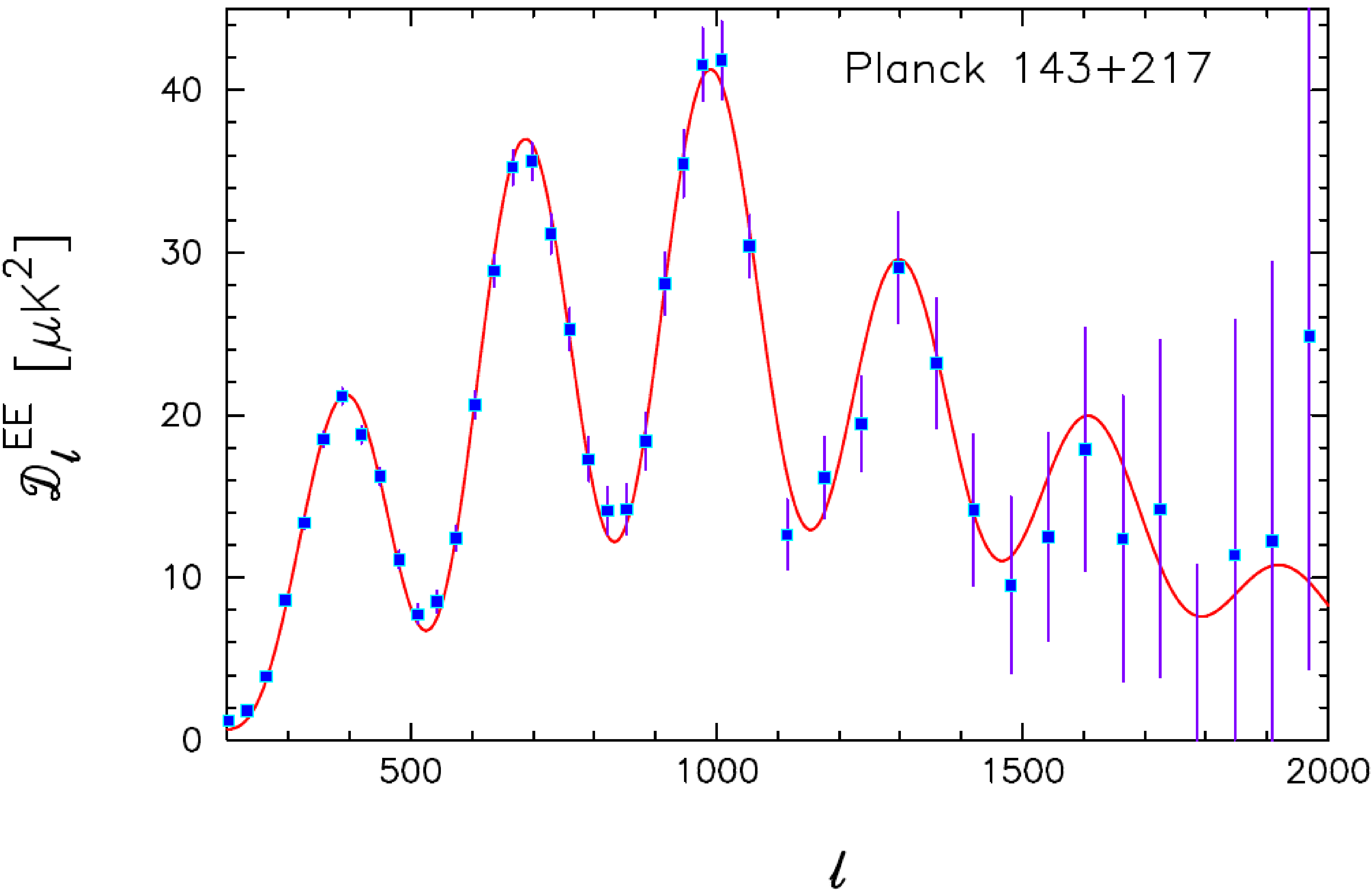
Planck CMB power spectrum from 2.5 surveys



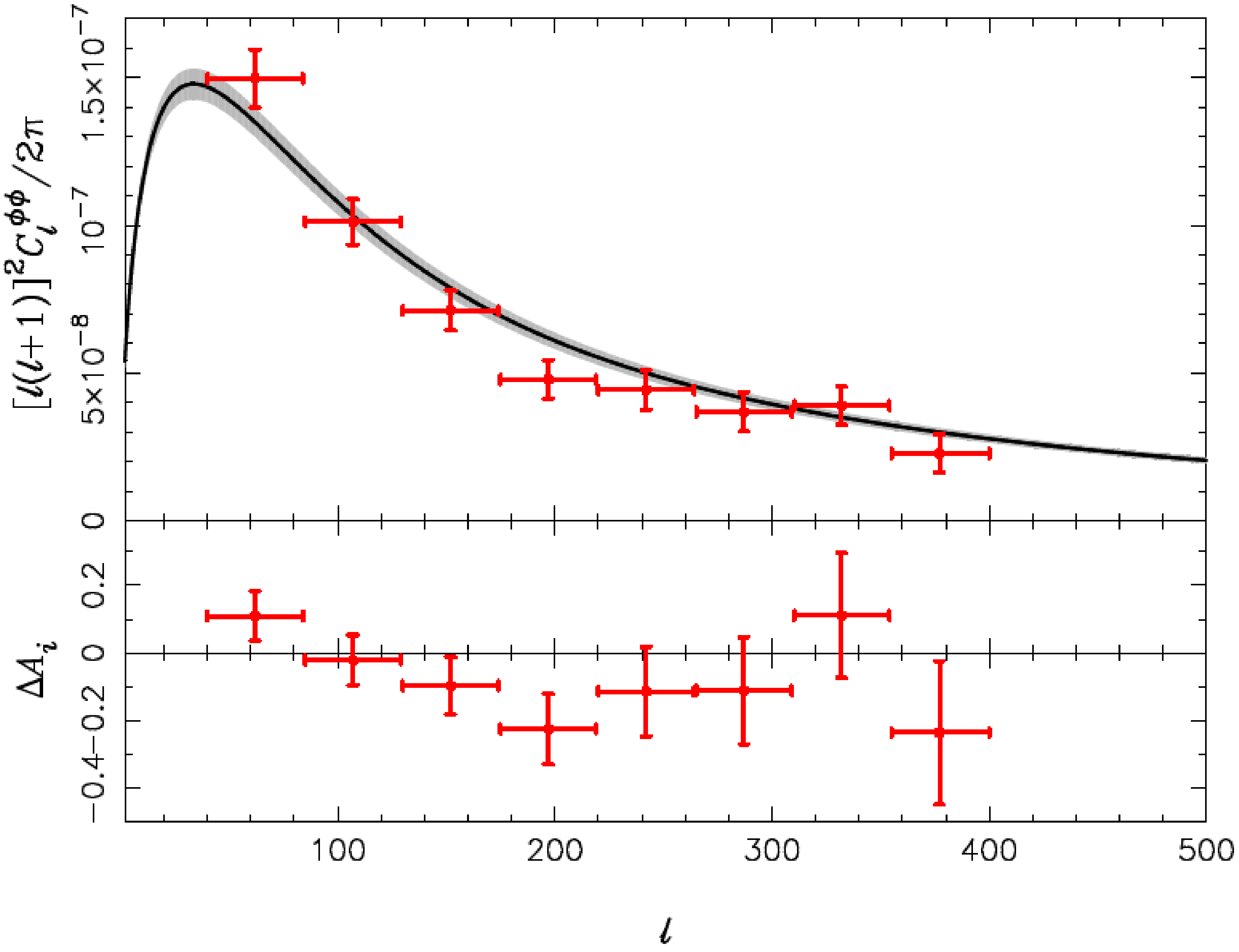
Planck TE power spectrum from 2.5 surveys



Planck EE power spectrum from 2.5 surveys



Planck gravitational lensing power spectrum

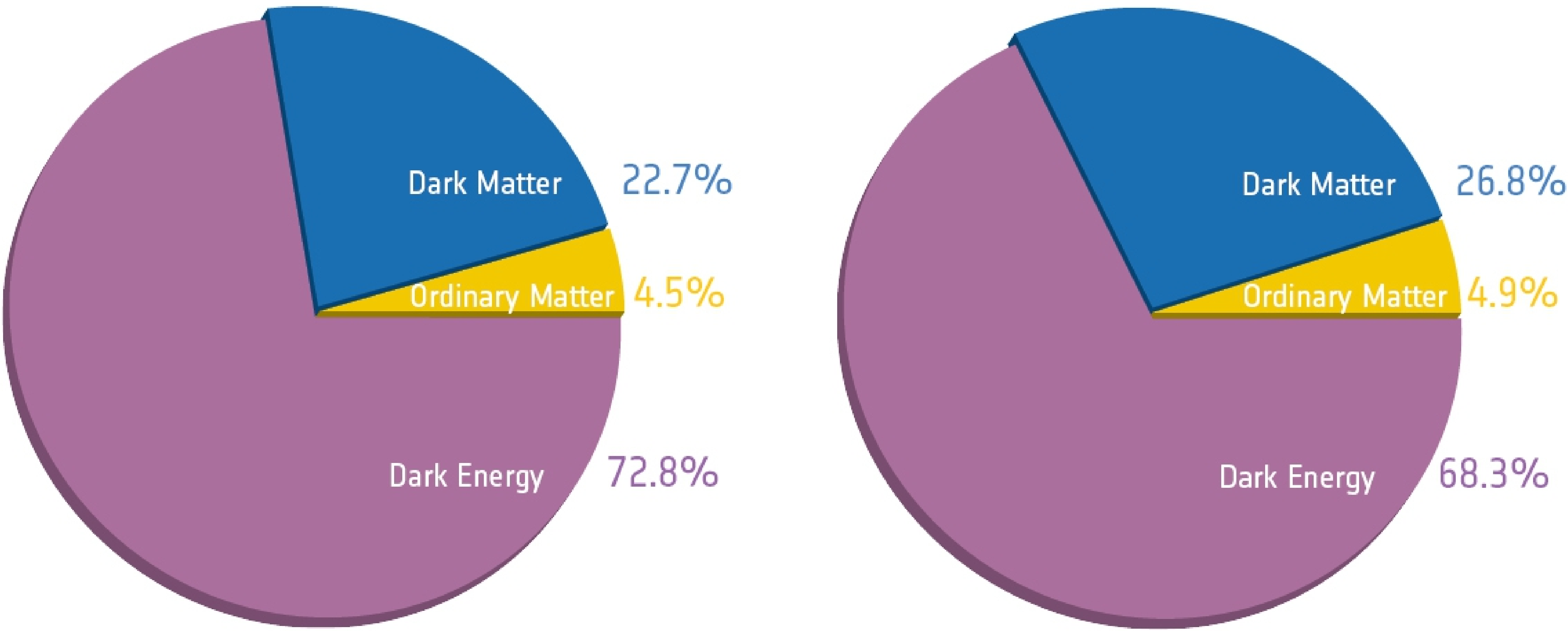


The six parameters of the base ΛCDM model

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

The six parameters of the base ΛCDM model

	Planck+WP	
Derived parameter	Best fit	68% limits
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$
σ_8	0.8347	0.829 ± 0.012
z_{re}	11.37	11.1 ± 1.1
H_0	67.04	67.3 ± 1.2
Age/Gyr	13.8242	13.817 ± 0.048



Before Planck

After Planck

The Universe is also expanding 7% slower than before and is 80,000,000 years older!

One parameter extensions of the base ΛCDM model

Parameter	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 95% limits
Ω_K	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.000	< 0.230
$N_{\rm eff}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\rm s}/d\ln k$	−0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.111
w	−1.109	$-1.13^{+0.23}_{-0.25}$

Planck results bearing on models of inflation

Parameter values

Parameter	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 95% limits
Ω_K	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
n_s	0.9619	0.9603 ± 0.0073
$dn_s/d\ln k$	−0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.111

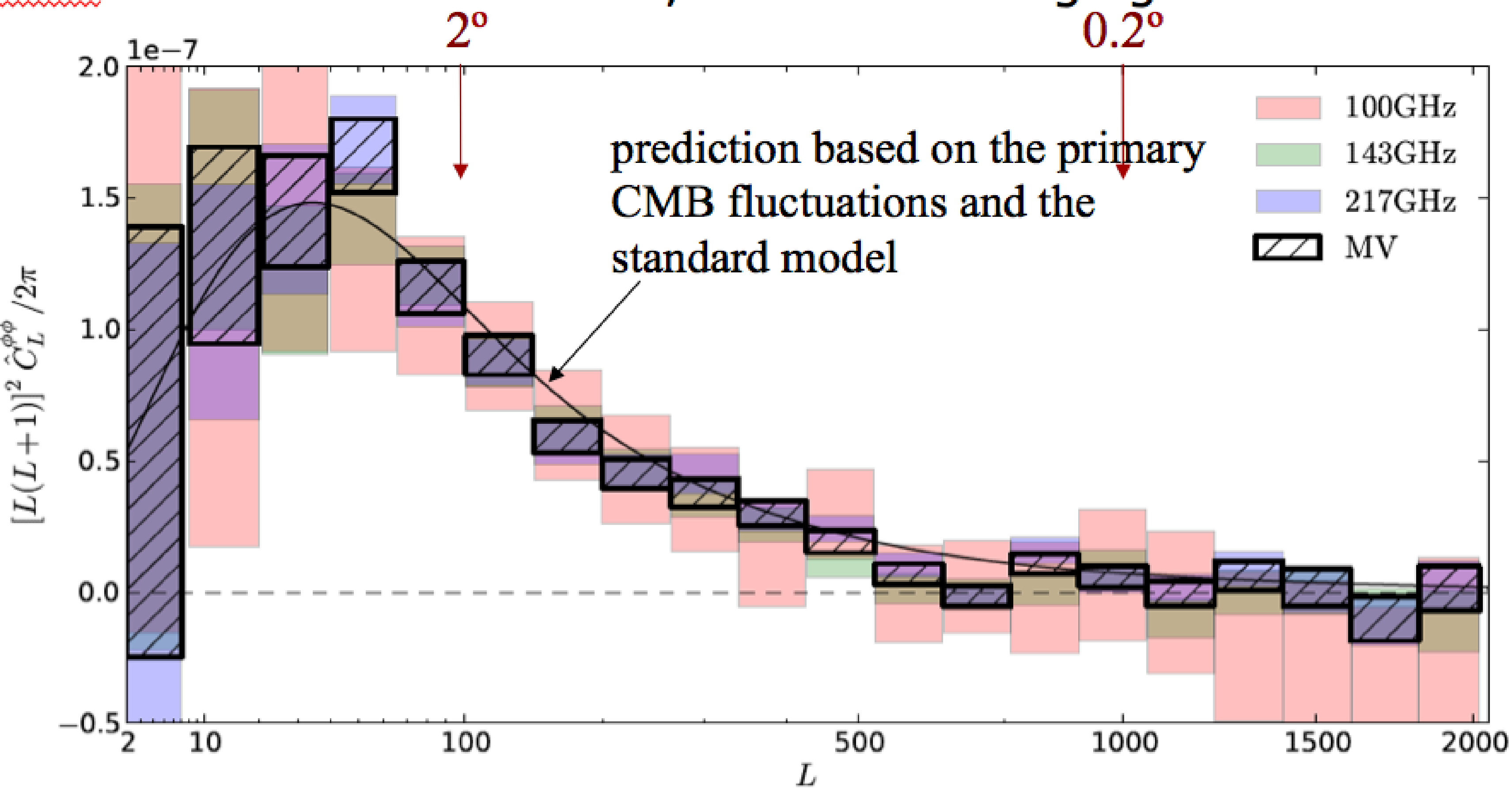
Non-Gaussianity constraints

f_{NL}

	Independent KSW	**ISW-lensing subtracted** KSW
SMICA		
Local	9.8 ± 5.8	**2.7 ± 5.8**
Equilateral	-37 ± 75	**−42 ± 75**
Orthogonal	-46 ± 39	**−25 ± 39**

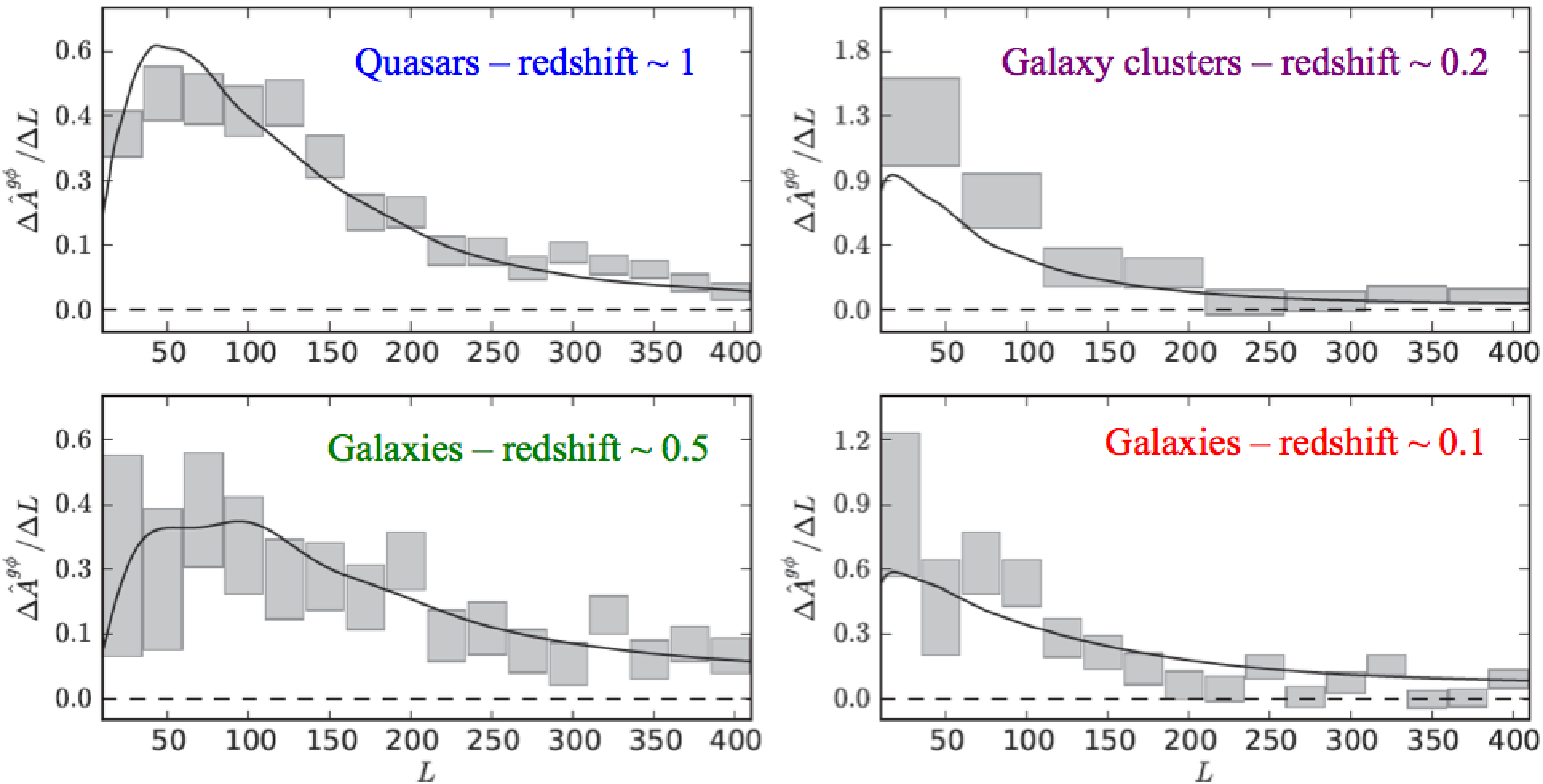
Planck results on DM in the visible Universe

Fluctuations in the Planck mass map as a function of angular scale. This is clumpiness in the modern universe, measured though gravitational lensing.



Planck results on DM in the visible Universe

The mass distribution seen in the Planck map follows the distributions of galaxies, galaxy clusters and quasars found by other telescopes

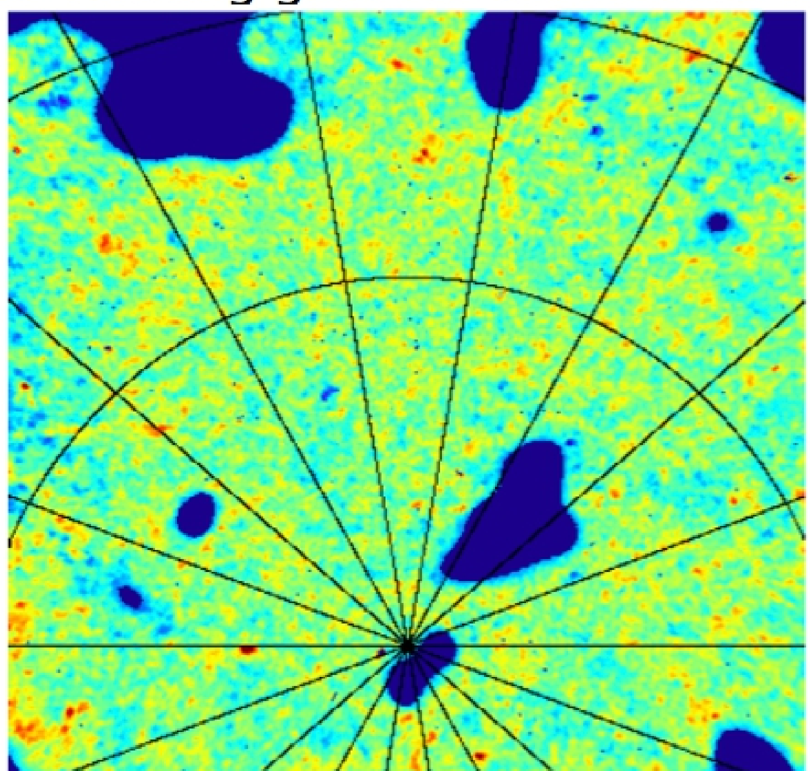


Planck results on DM in the visible Universe

Planck image of part of the sky with little Milky Way dust emission. What there is has been removed using Galactic hydrogen maps made by other telescopes.

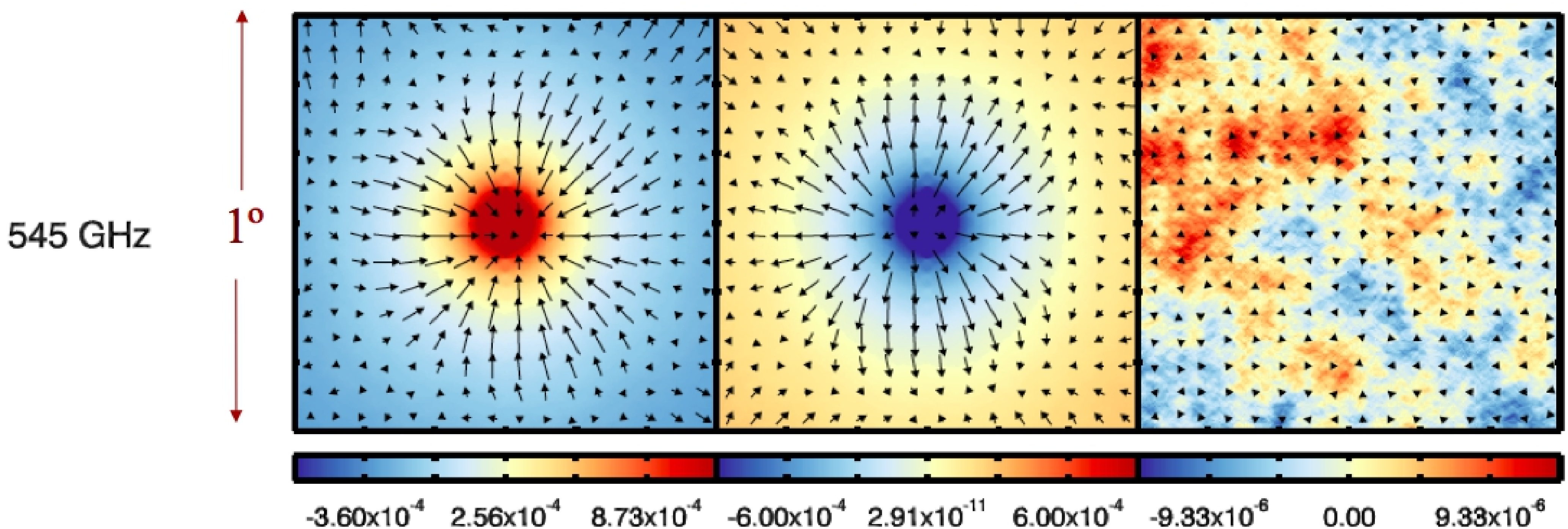
This map primarily shows the **Cosmic Infrared Background**, emission from warm dust in distant star-forming galaxies at redshifts between 1 and 3

545 GHz



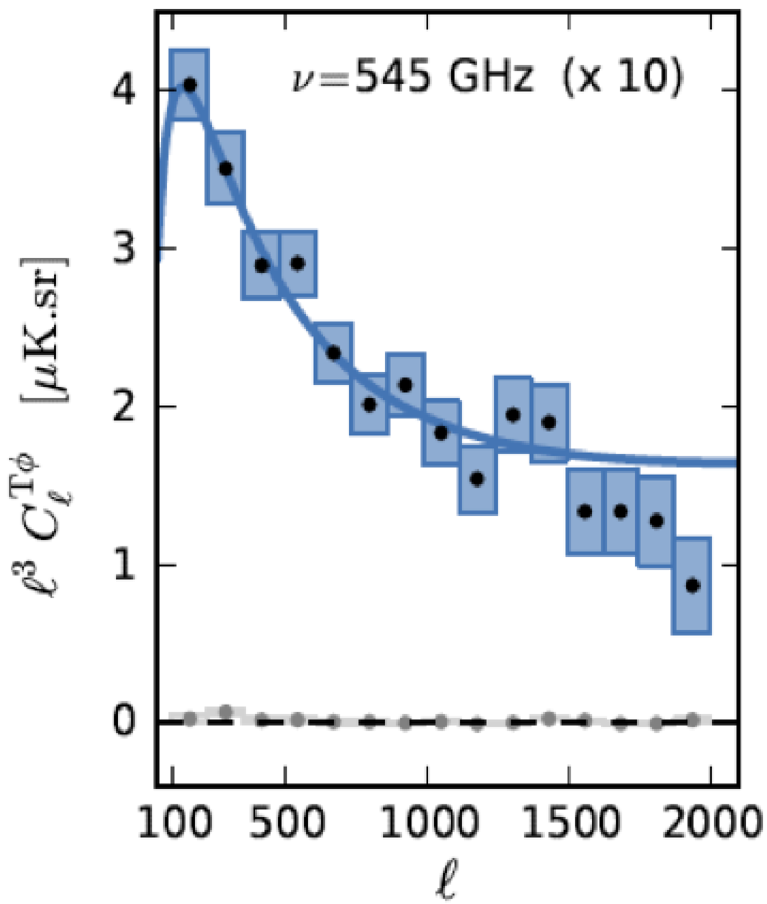
Planck results on DM in the visible Universe

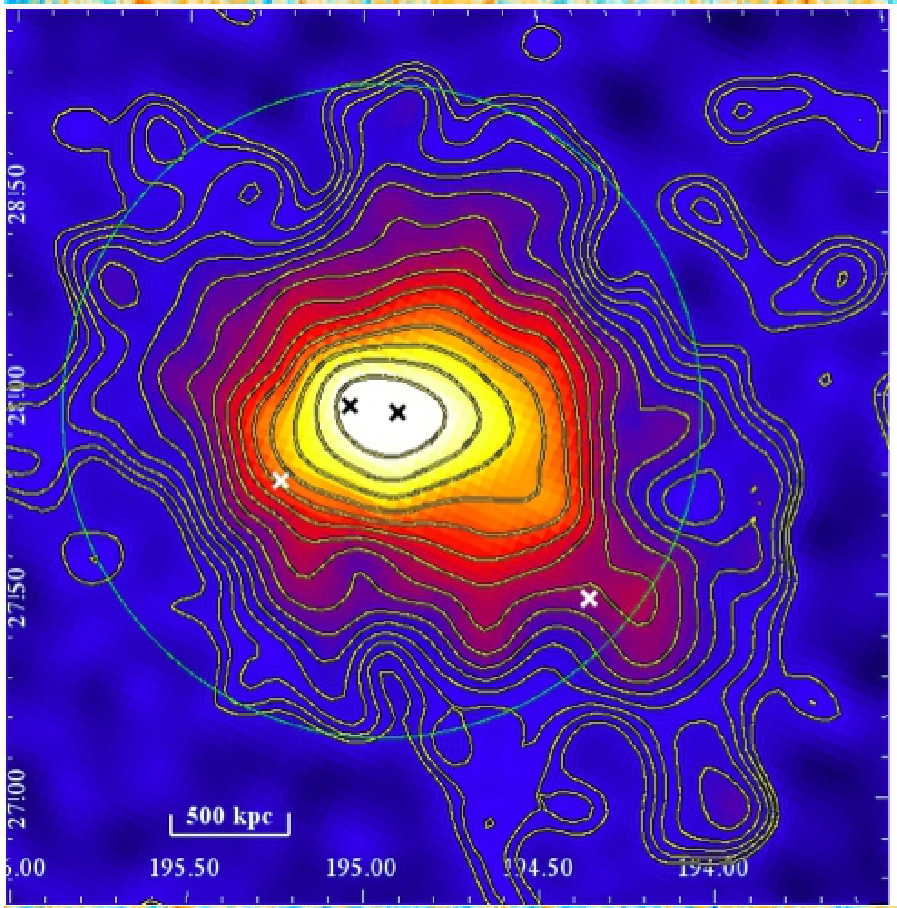
Stacking the Planck mass maps at the positions of peaks and troughs of Cosmic Infrared Background leads to a strong detection of the mass associated with these distant star forming galaxies. This is mostly Dark Matter,



Planck results on DM in the visible Universe

The Planck mass map correlates very strongly with the CIB maps. This is a direct detection of the total mass associated with galaxies at the time they were making most of their stars. During this epoch, the Universe went from 20% to 50% of its present age.



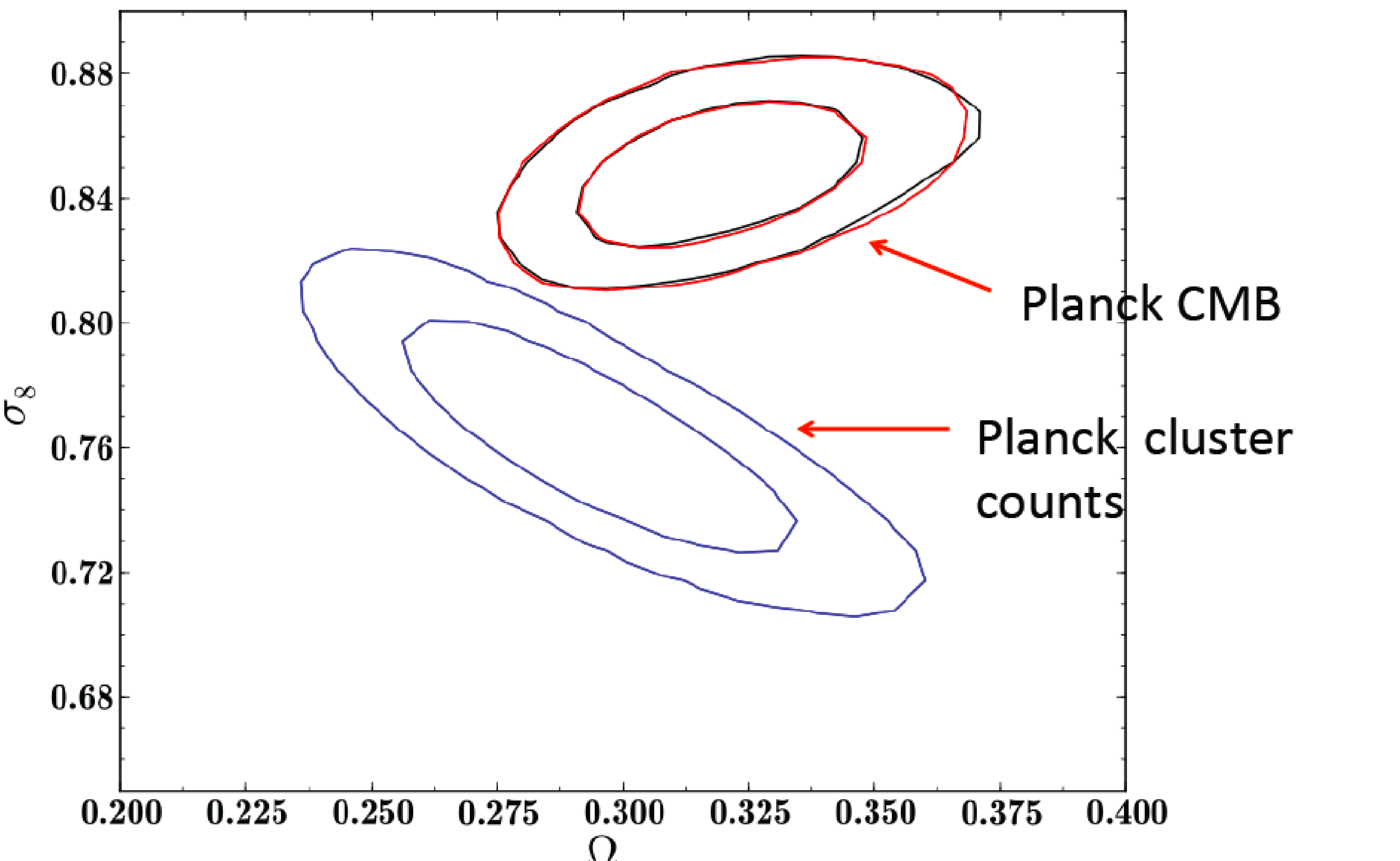


Planck not only allows us to explore the early universe by mapping the clouds at t~380,000 years which hide it from us, but also maps the ordinary and Dark Matter distributions throughout the visible universe in front of those clouds.

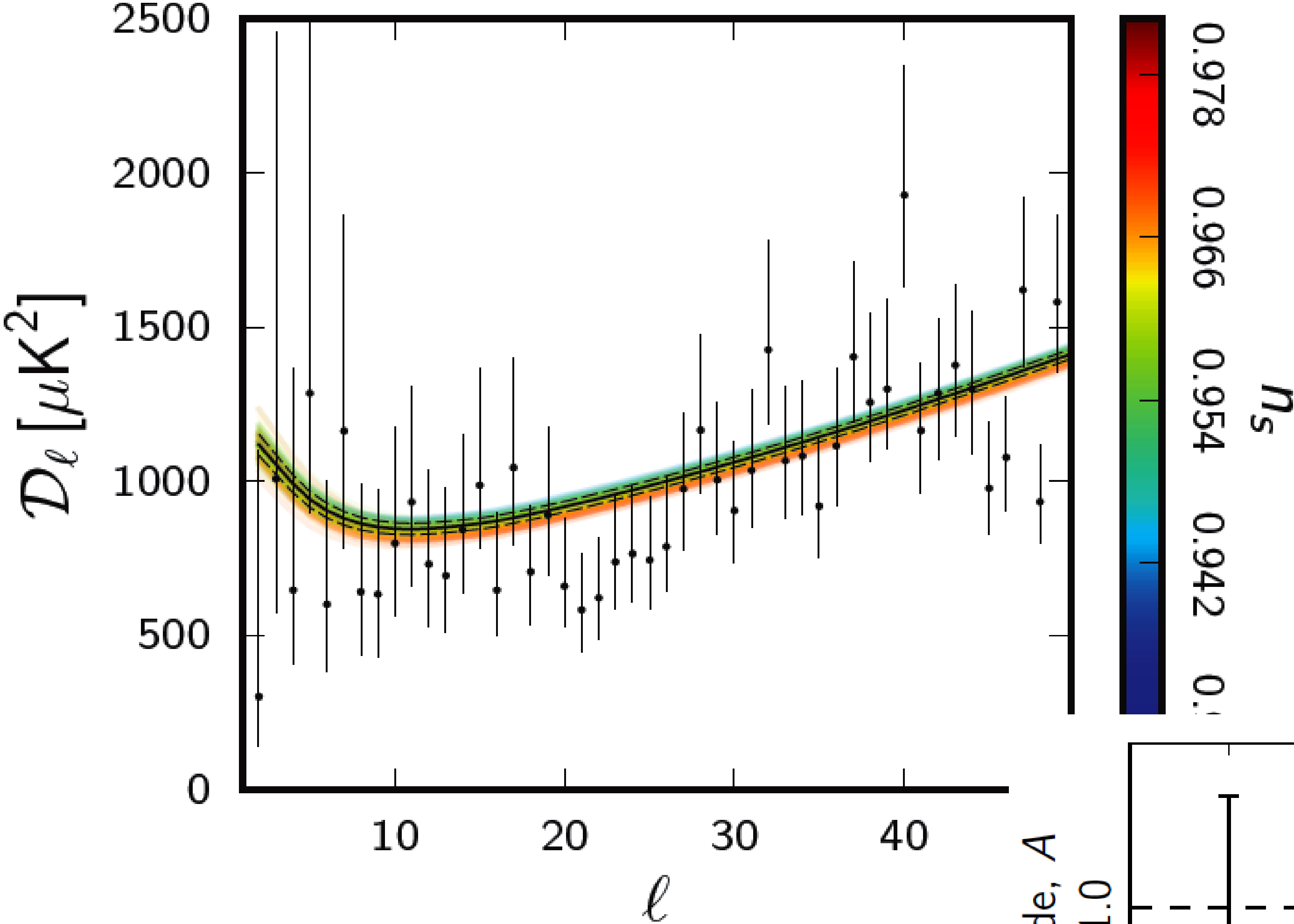
This brings us closer to understanding how today's universe emerged from the Big Bang

Some inconsistencies with ΛCDM

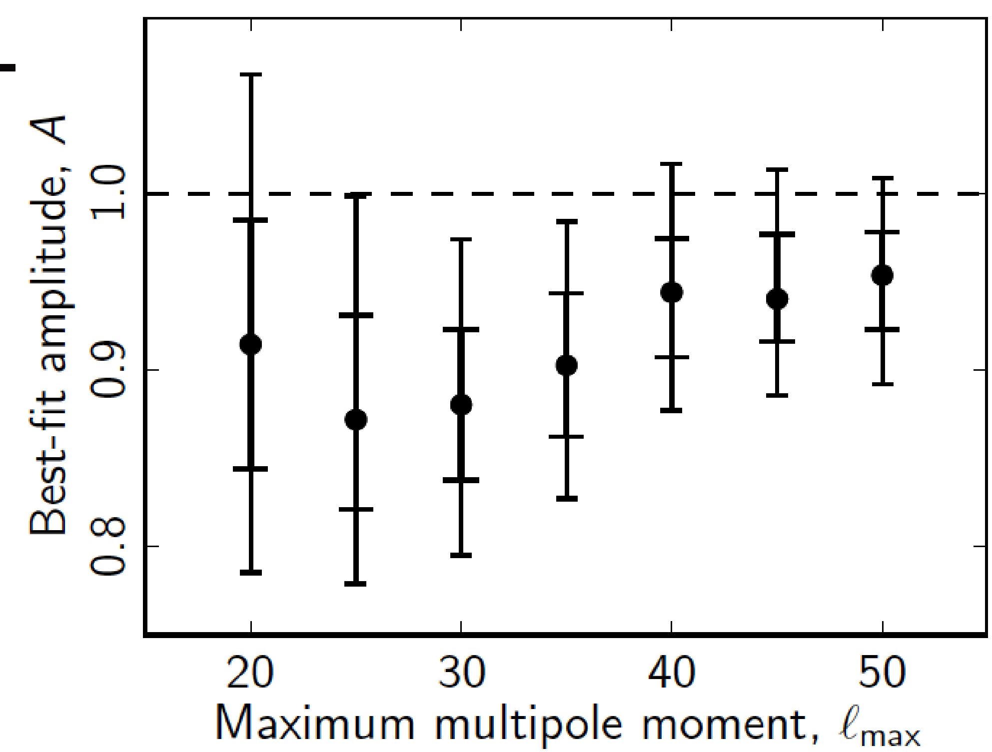
- "Anomalies" – as WMAP, including hemispherical power asymmetry, cold spot, low multipole alignments, `Bianchi' type large-scale anisotropy.
- "Favouritism" for a power-spectrum feature at $k \approx 0.1$ Mpc^{-1}.
- "Feature" model non-Gaussianity seen in modal estimator.
- Cluster count σ_8-Ω_m discrepancy with power spectrum parameters.
- Compton y map σ_8-Ω_m discrepancy with power spectrum parameters.
- ……………



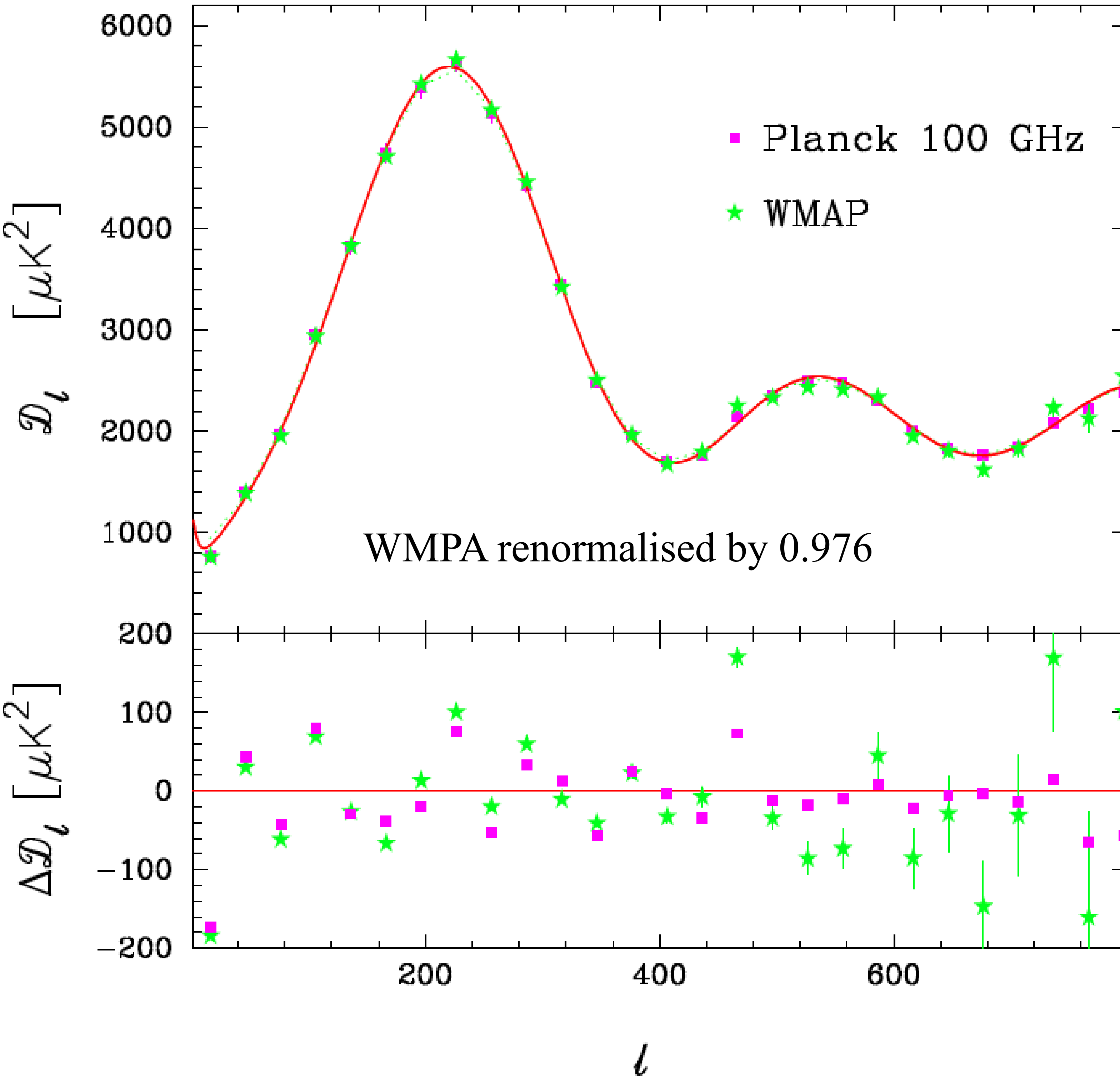
0.88
0.84
0.80
0.76
0.72
0.68
σ8
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400
Ω
Planck CMB
Planck cluster counts



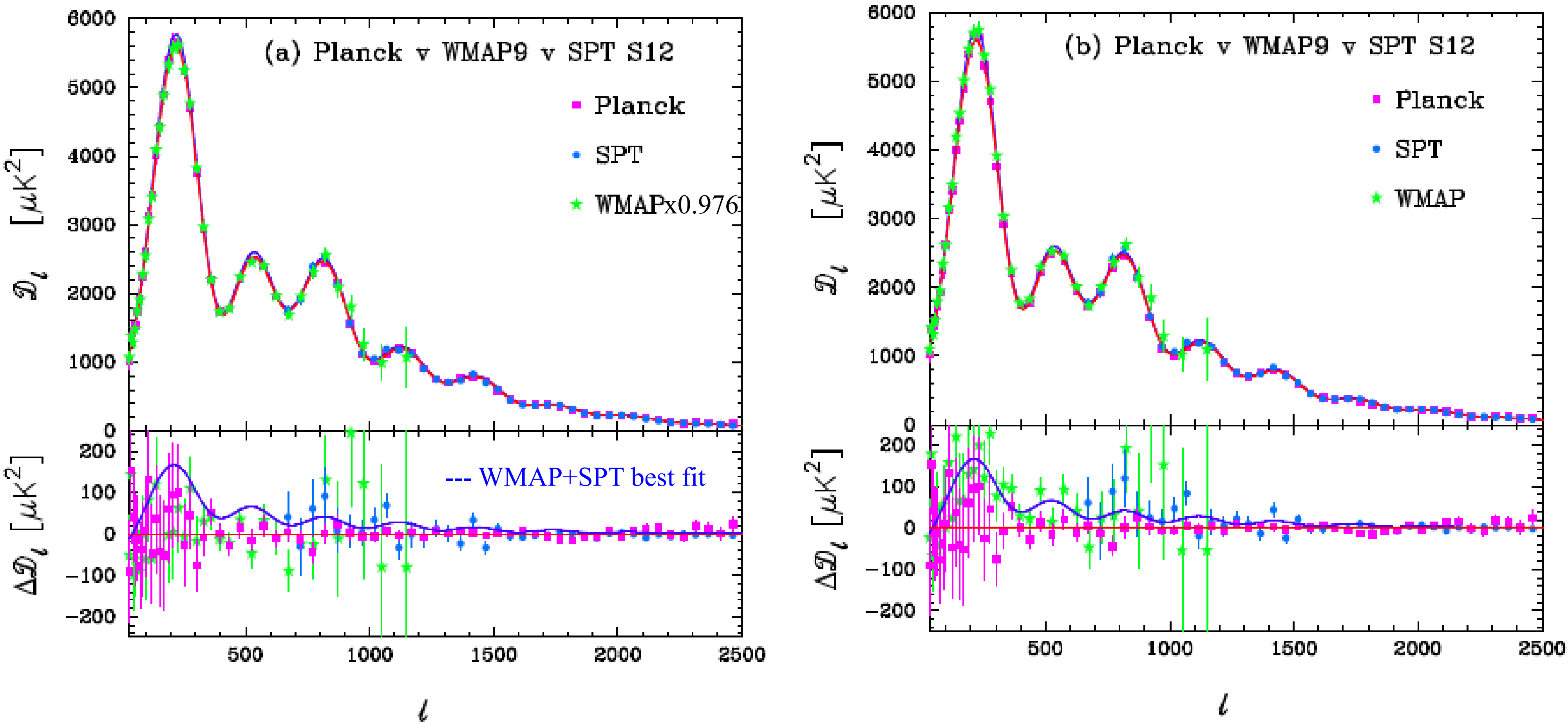
2500
2000
1500
1000
500
0
$\mathcal{D}_\ell\,[\mu K^2]$
10
20
30
40
ℓ
0.978
0.966
0.954
0.942
n_s



Best-fit amplitude, A
0.8
0.9
1.0
20
30
40
50
Maximum multipole moment, $\ell_{\max}$



6000
5000
4000
3000
2000
1000
200
100
0
−100
−200
200
400
600
$\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ
Planck 100 GHz
WMAP
WMPA renormalised by 0.976



(a) Planck v WMAP9 v SPT S12
Planck
SPT
WMAPx0.976
--- WMAP+SPT best fit
$\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ
(b) Planck v WMAP9 v SPT S12
Planck
SPT
WMAP
$\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ