Cosmological results from the Planck satellite

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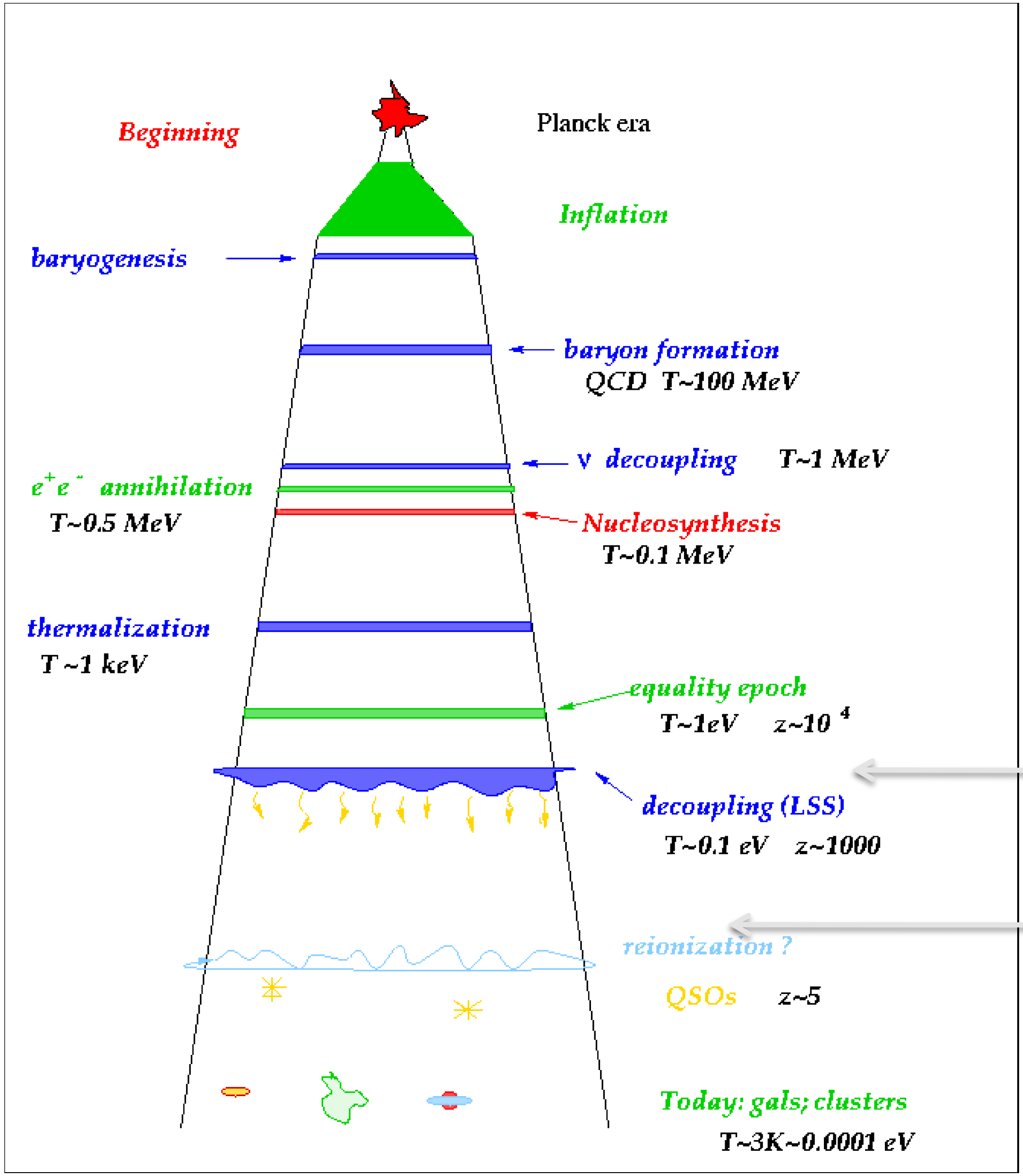
Strings 2013, Seoul

History of the Universe



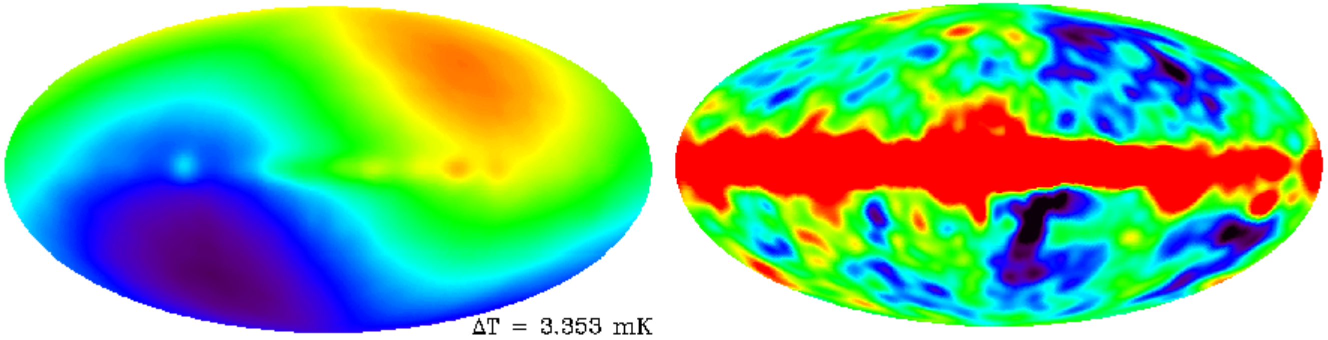
Cosmic Microwave Background emission, 300,000 years after B.B.

Dark ages

Cosmic Microwave Background

- Discovered by Penzias & Wilson (1964)

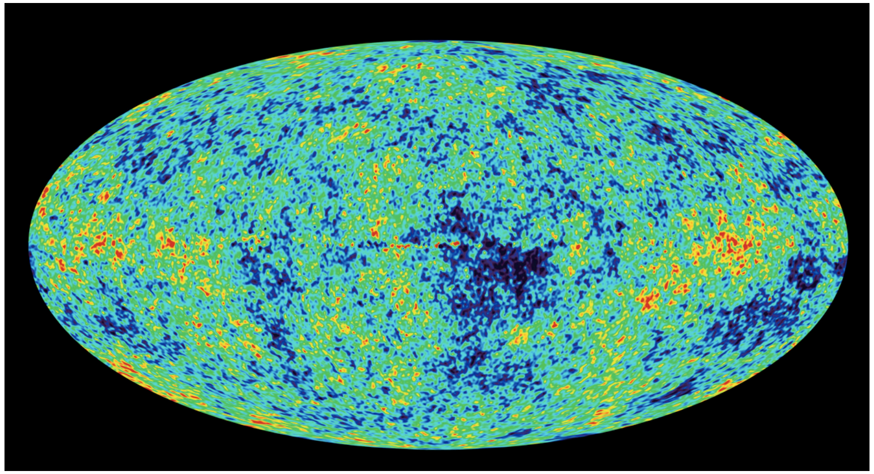
- Perfect Black Body spectrum (to the limit of the instruments) at 2.725 K measured by the COBE satellite



- Small temperature fluctuations ~ 100 μK

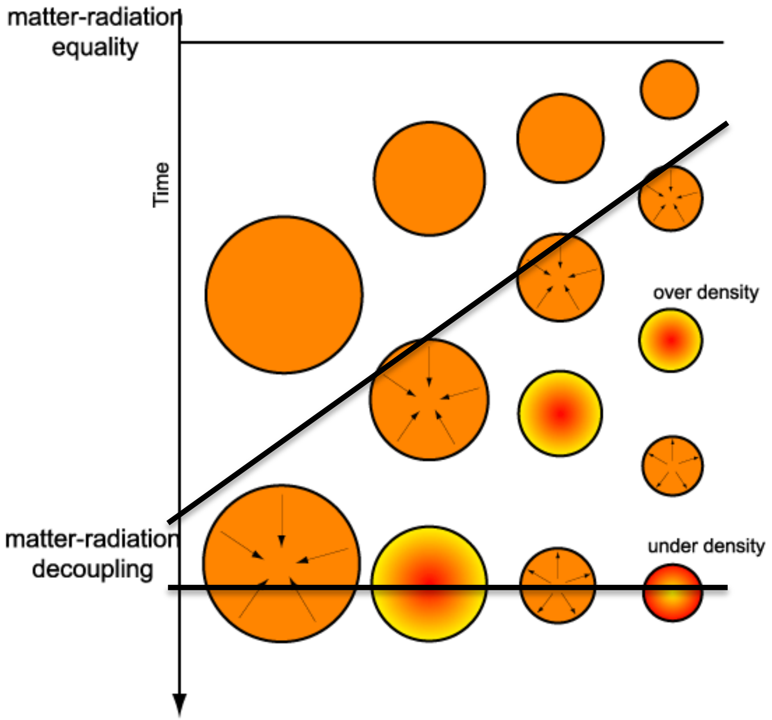
- Several ground-based and balloon experiments measured the CMB since.

WMAP satellite (2003) :



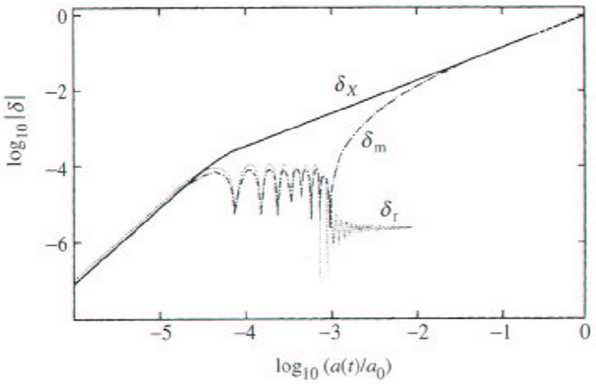
Origin of CMB fluctuations

- CMB fluctuations are the consequence of metric fluctuations (scalar and tensor) in the primordial Universe. In the standard picture, primordial fluctuations result from quantum fluctuations growing to cosmological scales during inflation.
- While the horizon grows, fluctuations are entering the horizon and start to oscillate under the effect of radiation pressure and gravitation.



Some scales are at their maxima after decoupling → Acoustic peaks

Dark matter fluctuations grow: no radiation pressure.

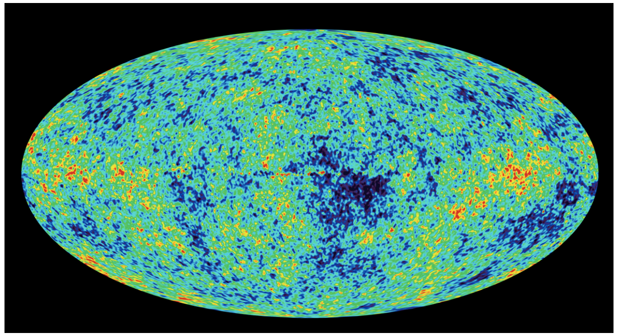


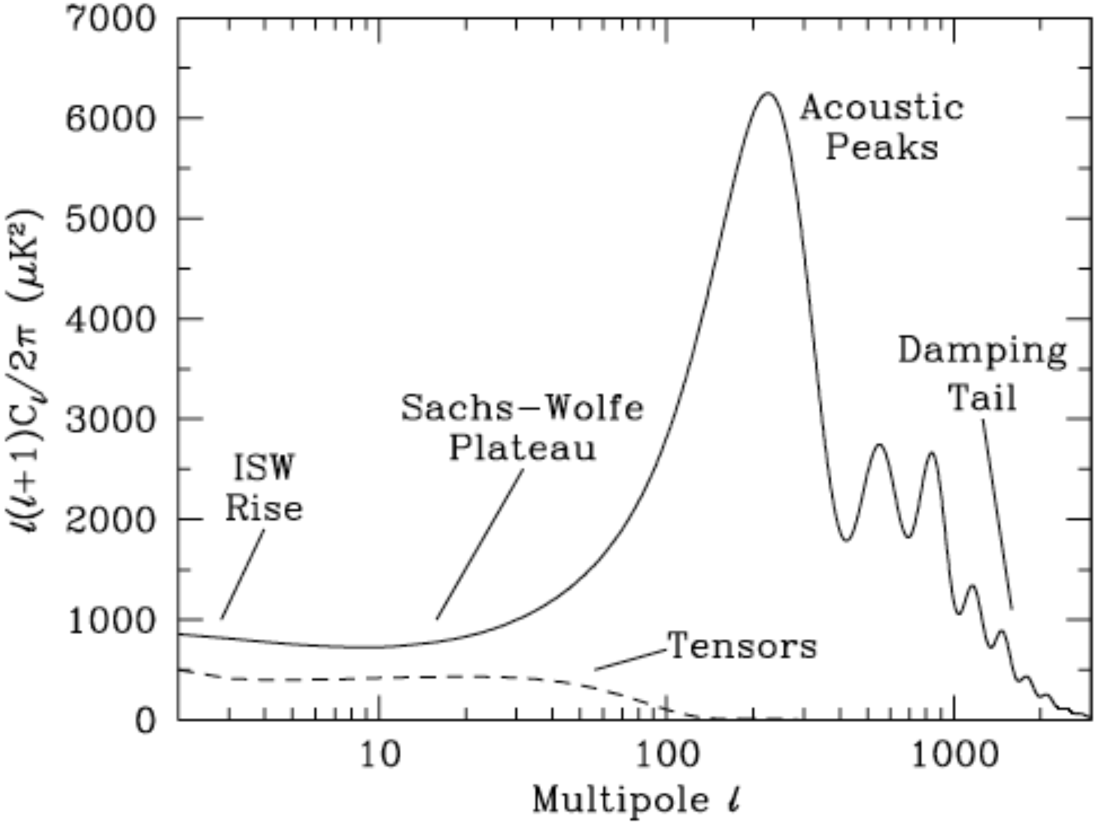
CMB Power spectrum

Spherical harmonics decomposition :

$$\frac{\delta T}{T} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell =< a_{\ell m} >$$





Gaussian fluctuations:
All physical information is contained in the power spectrum.

Spectrum depends on cosmological parameters

The Planck mission

Launched in May 2009

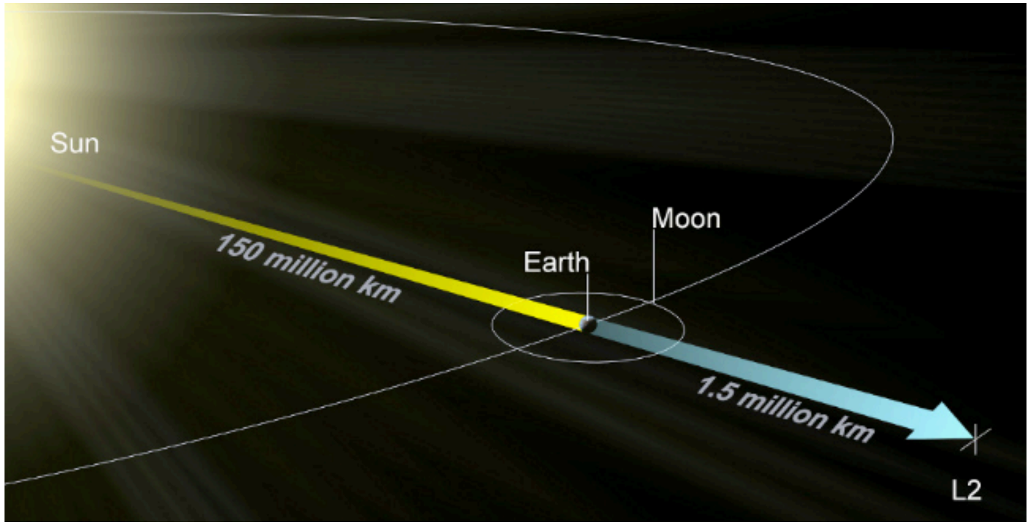
Orbiting at the Lagrange point L2

2.5 years of data acquisition

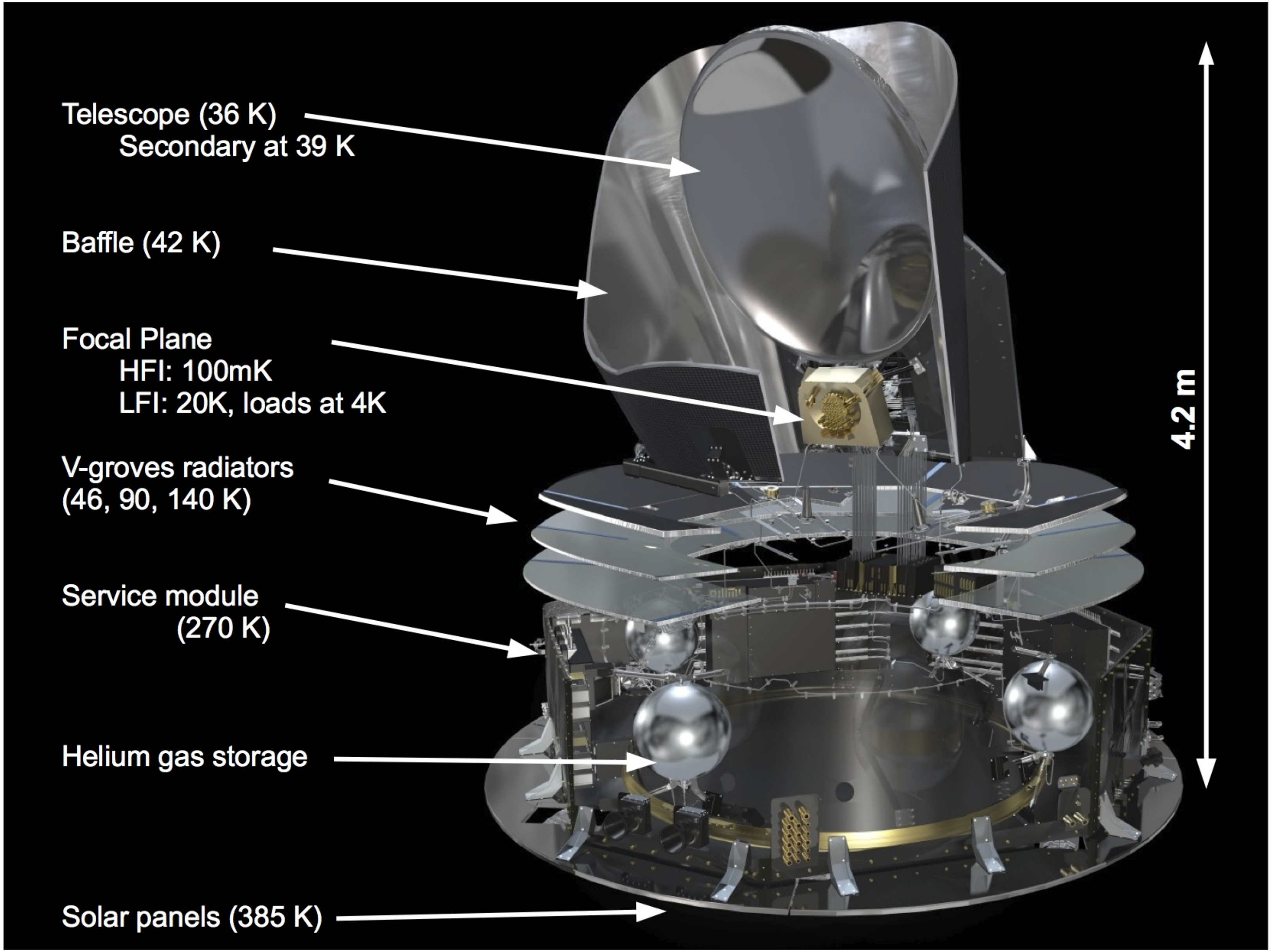
First cosmological results published last March!

600 scientists, 29 laboratories, 14 countries (Europe, USA, Canada)

Collaboration still analyzing the polarisation data



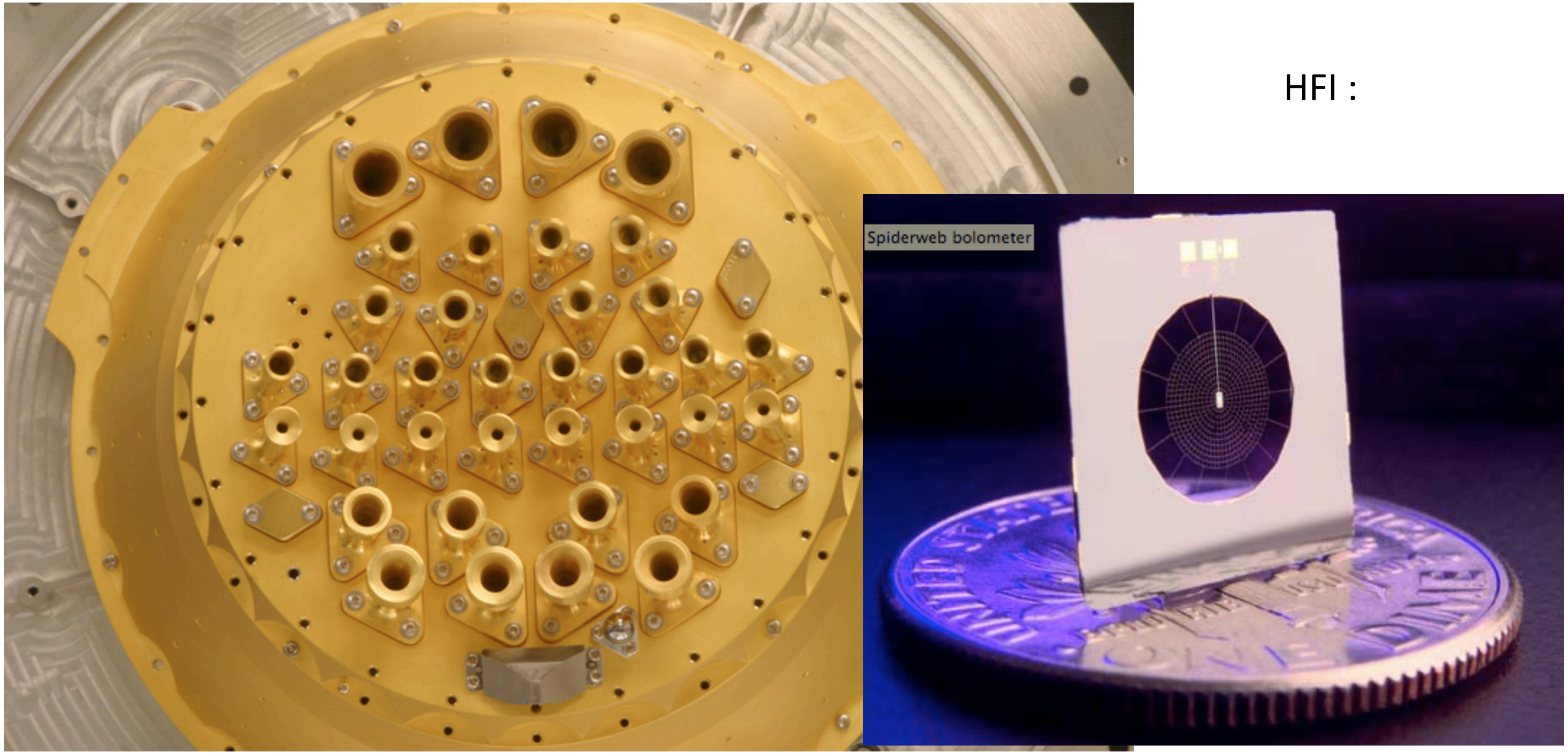
The Planck satellite



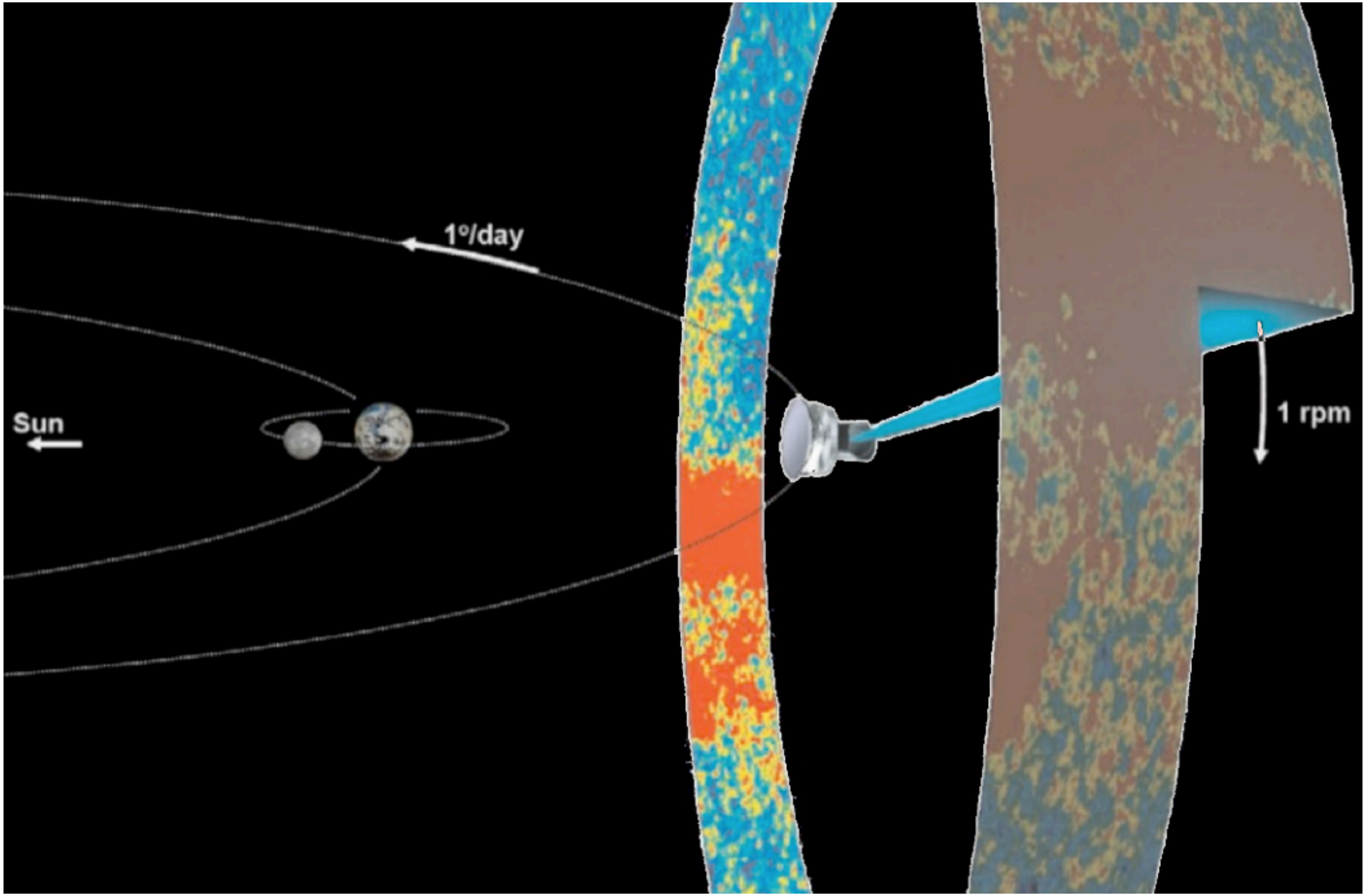
Planck detectors

- LFI instrument: HEMT antennas, 3 frequency bands between 33 and 70 GHz
- HFI instrument: bolometers cooled down to 100 mK, 6 frequency bands between 100 and 857 GHz

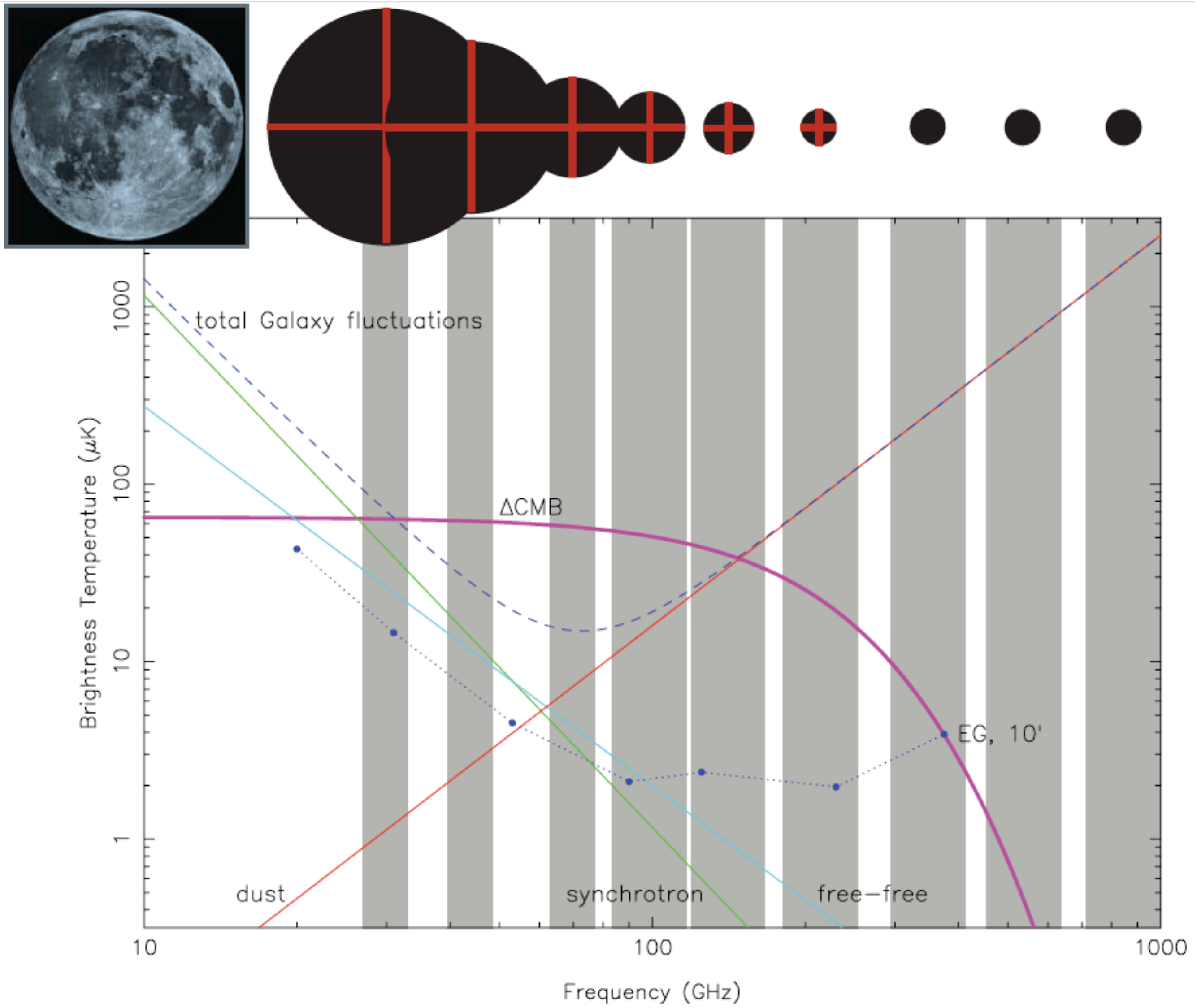
HFI :



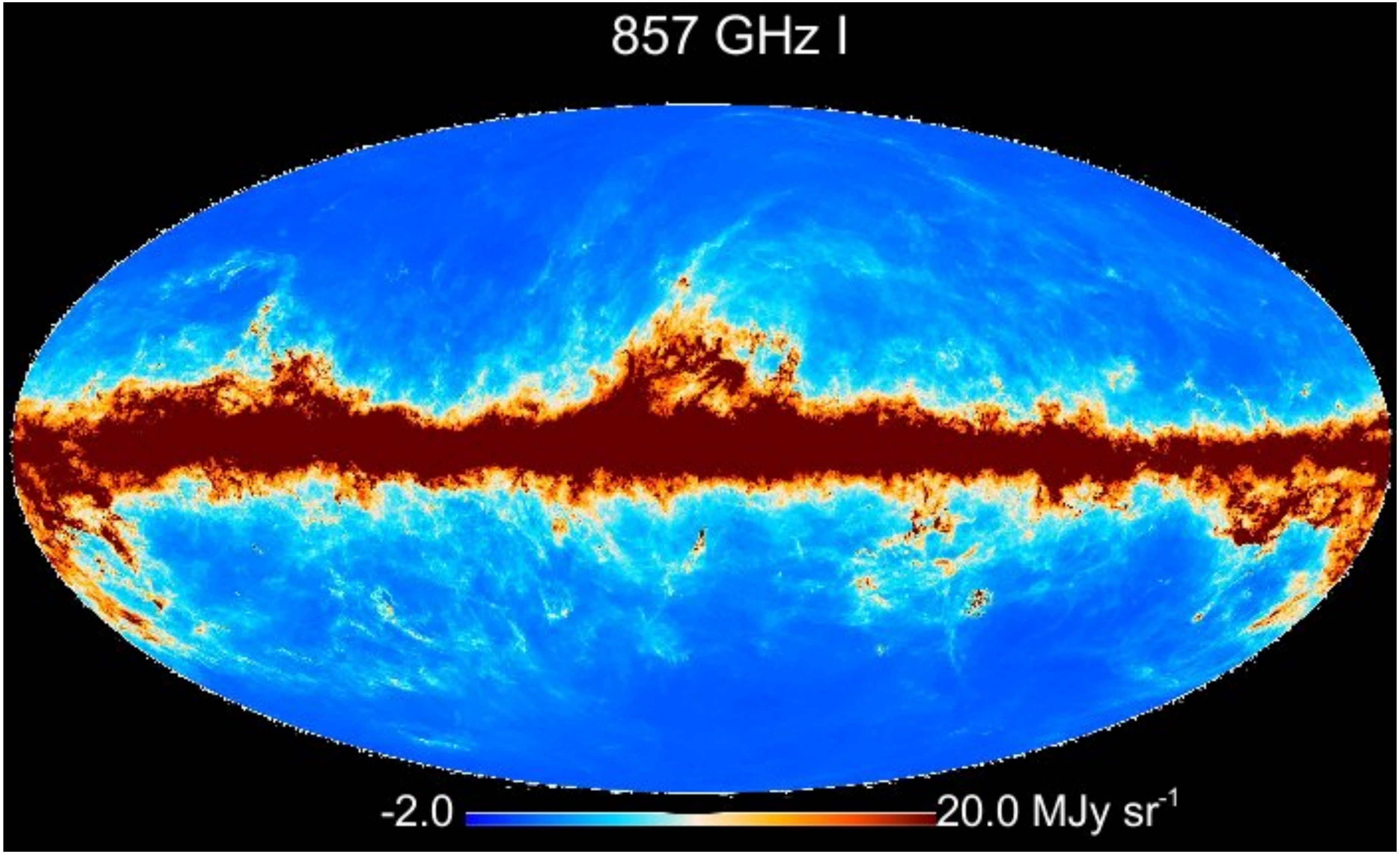
Observation strategy

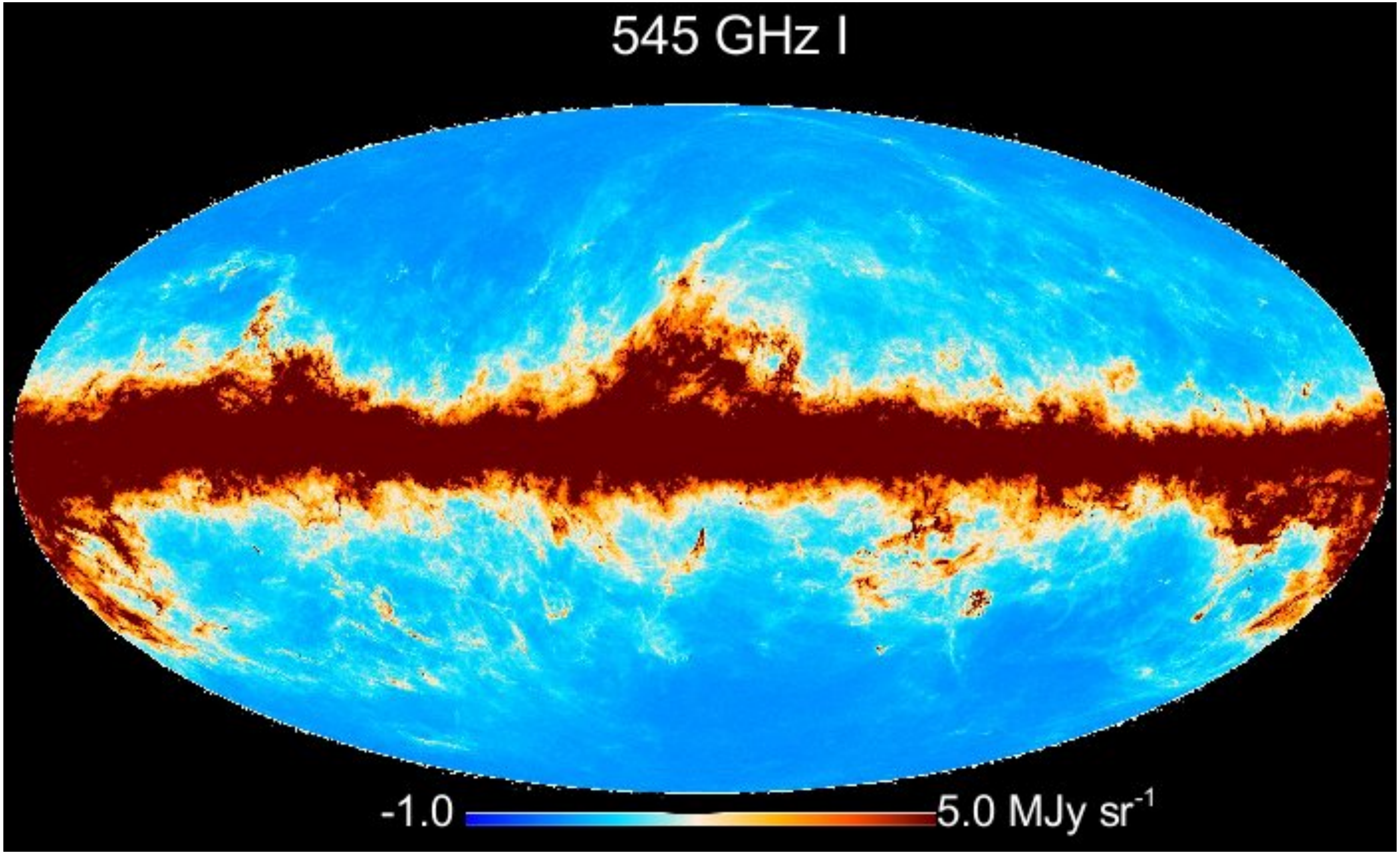


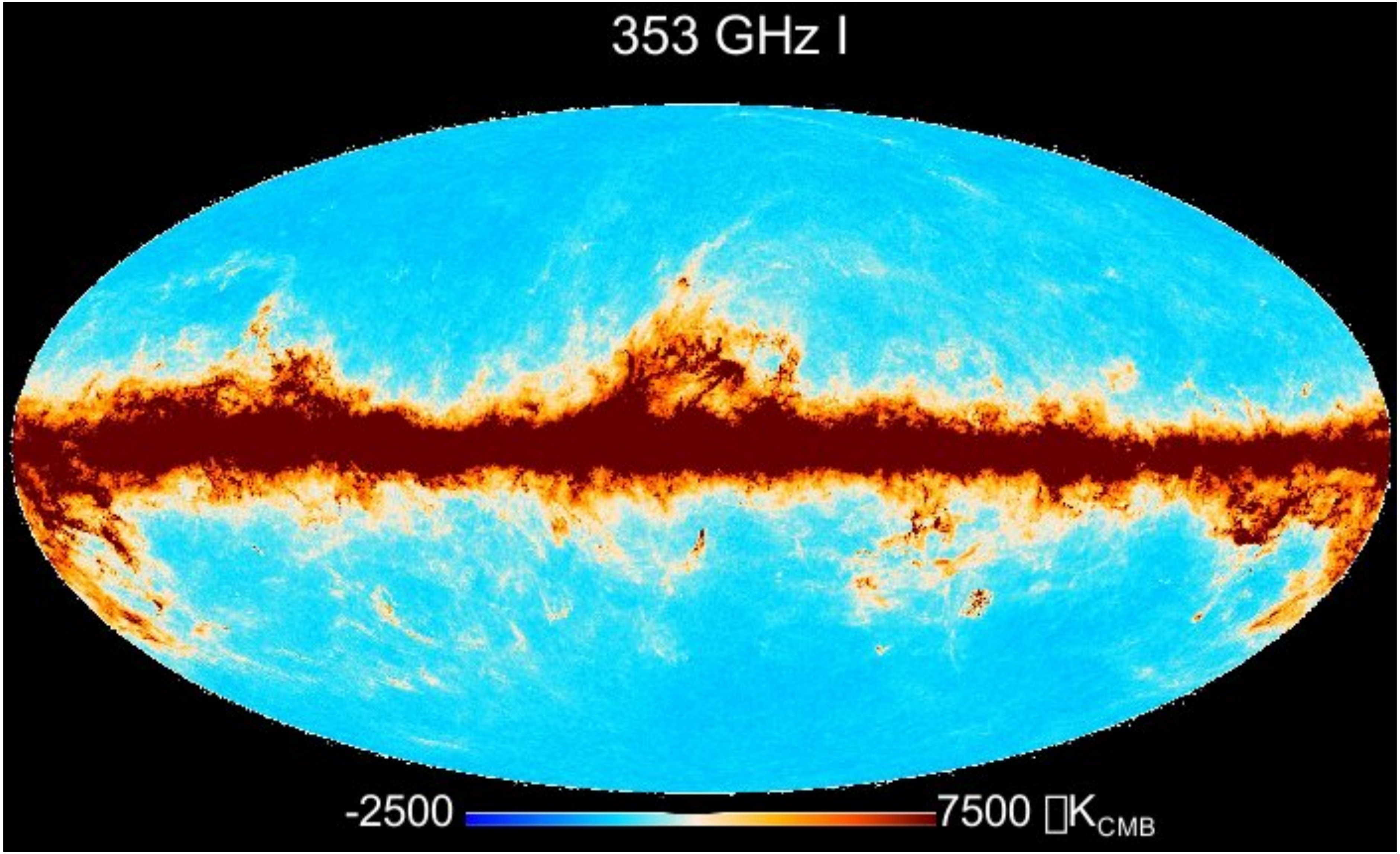
Observation frequencies

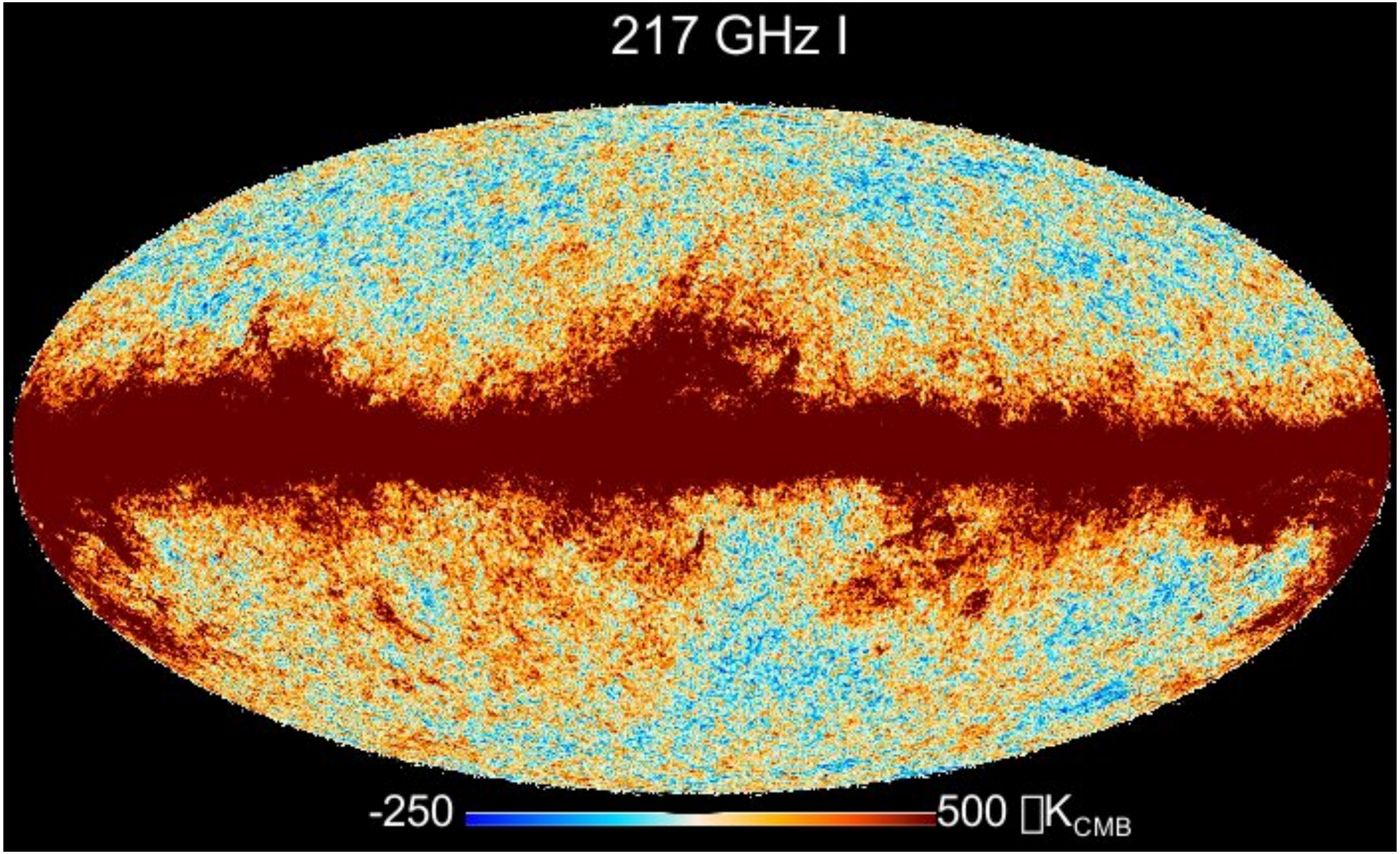


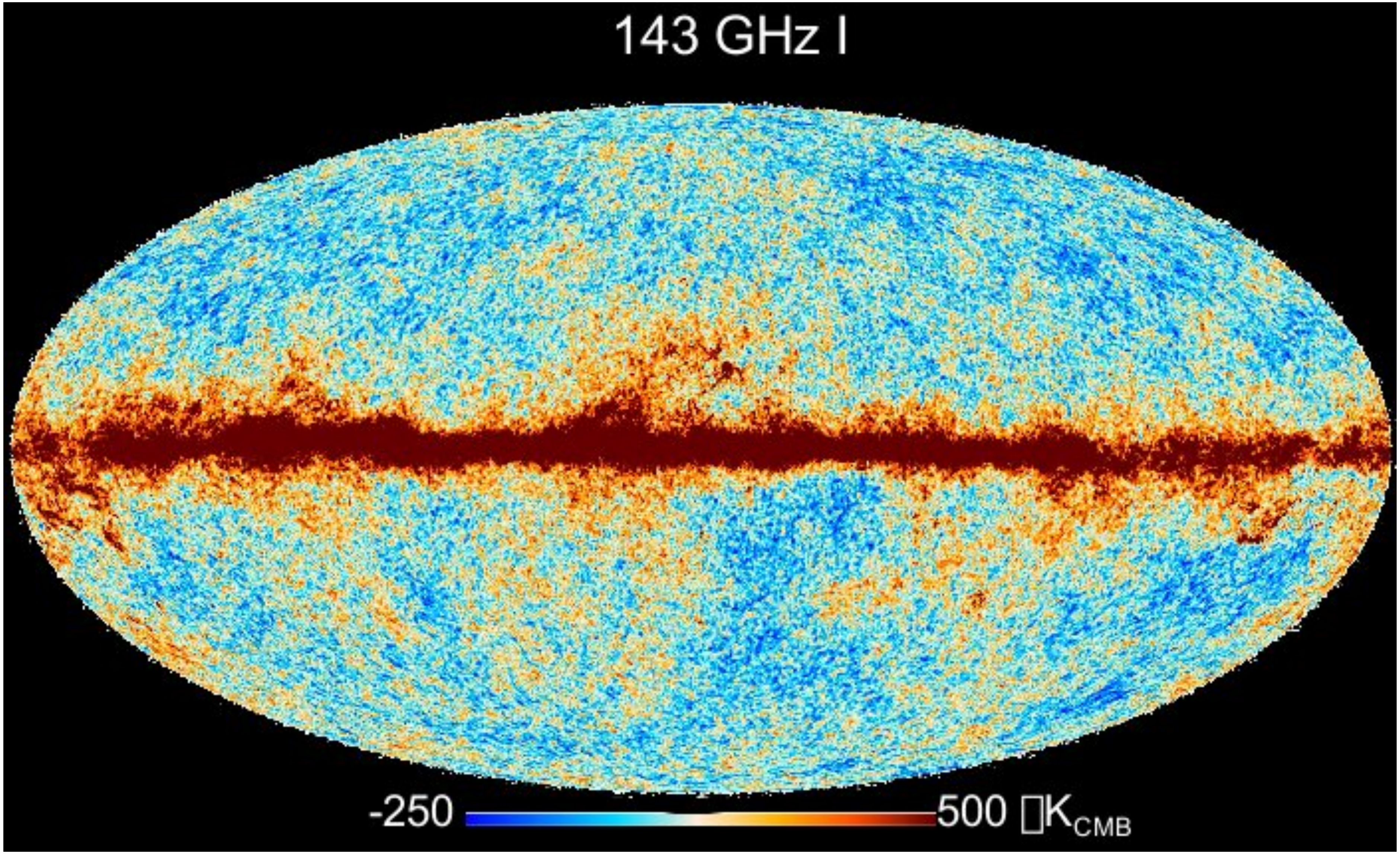
Multi-frequency observations allow a good subtraction of other astrophysical emissions

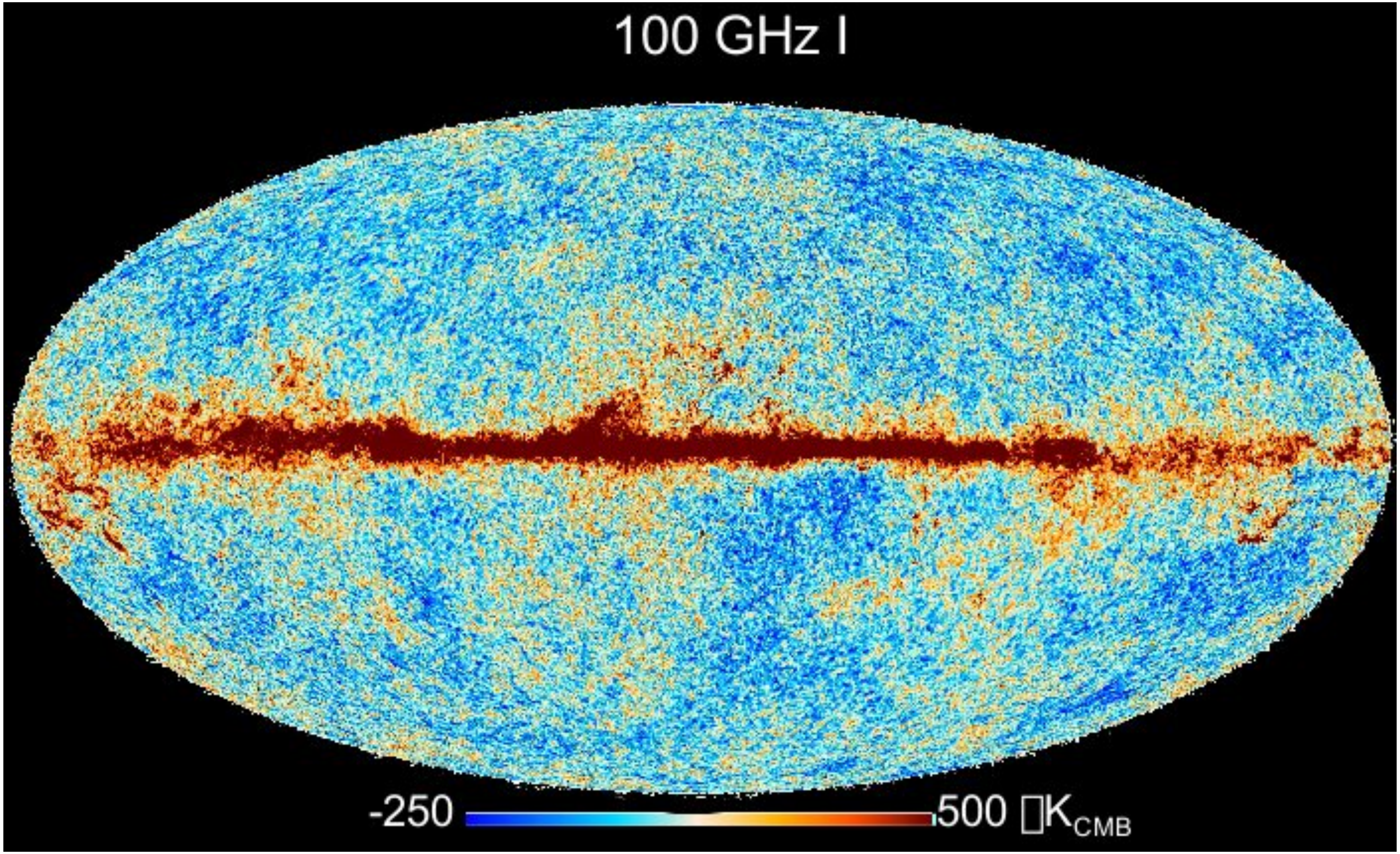

857 GHz I
-2.0
20.0 MJy sr^{-1}


545 GHz I
-1.0
5.0 MJy sr-1

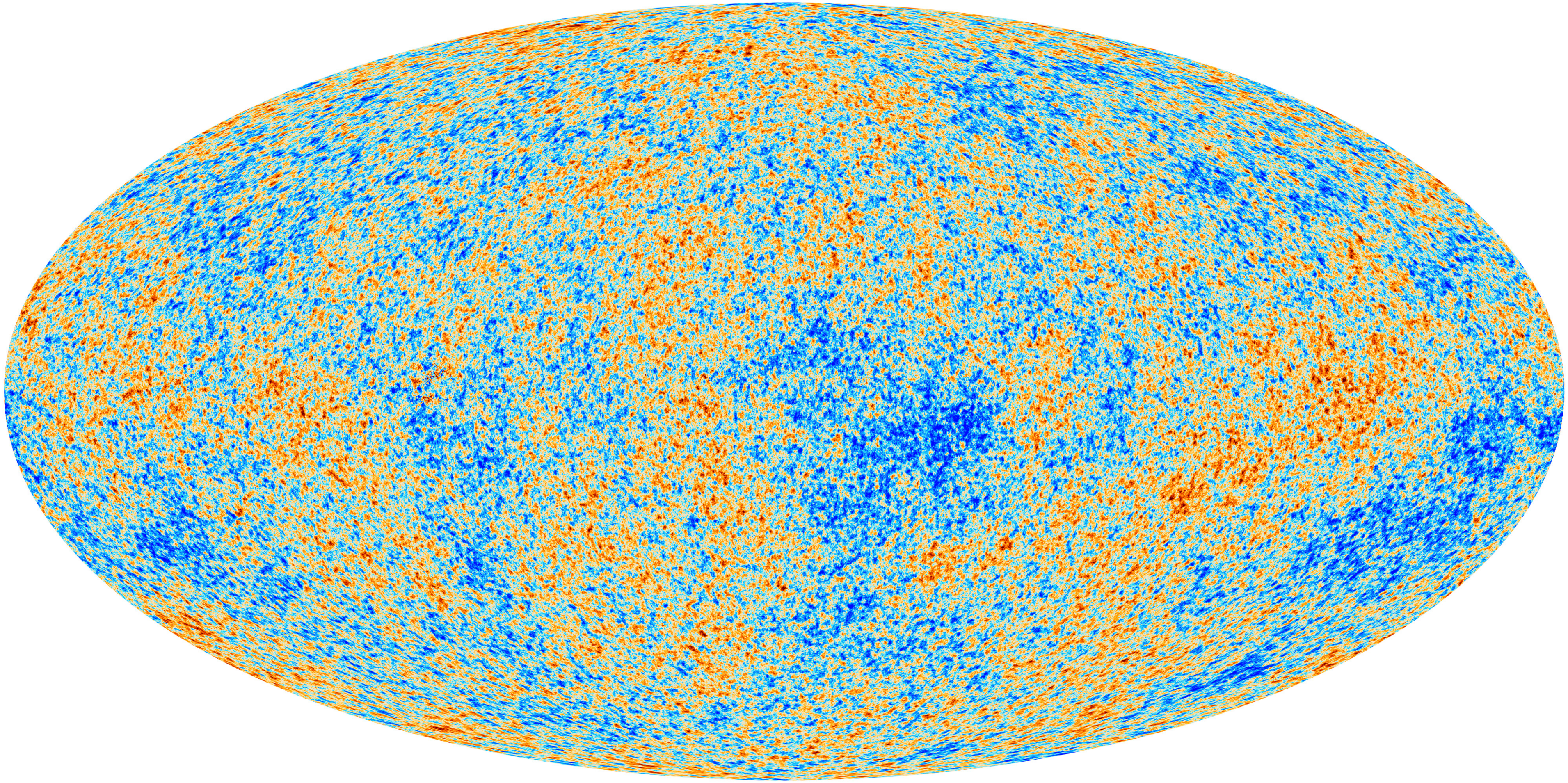

353 GHz I
-2500
7500 □KCMB

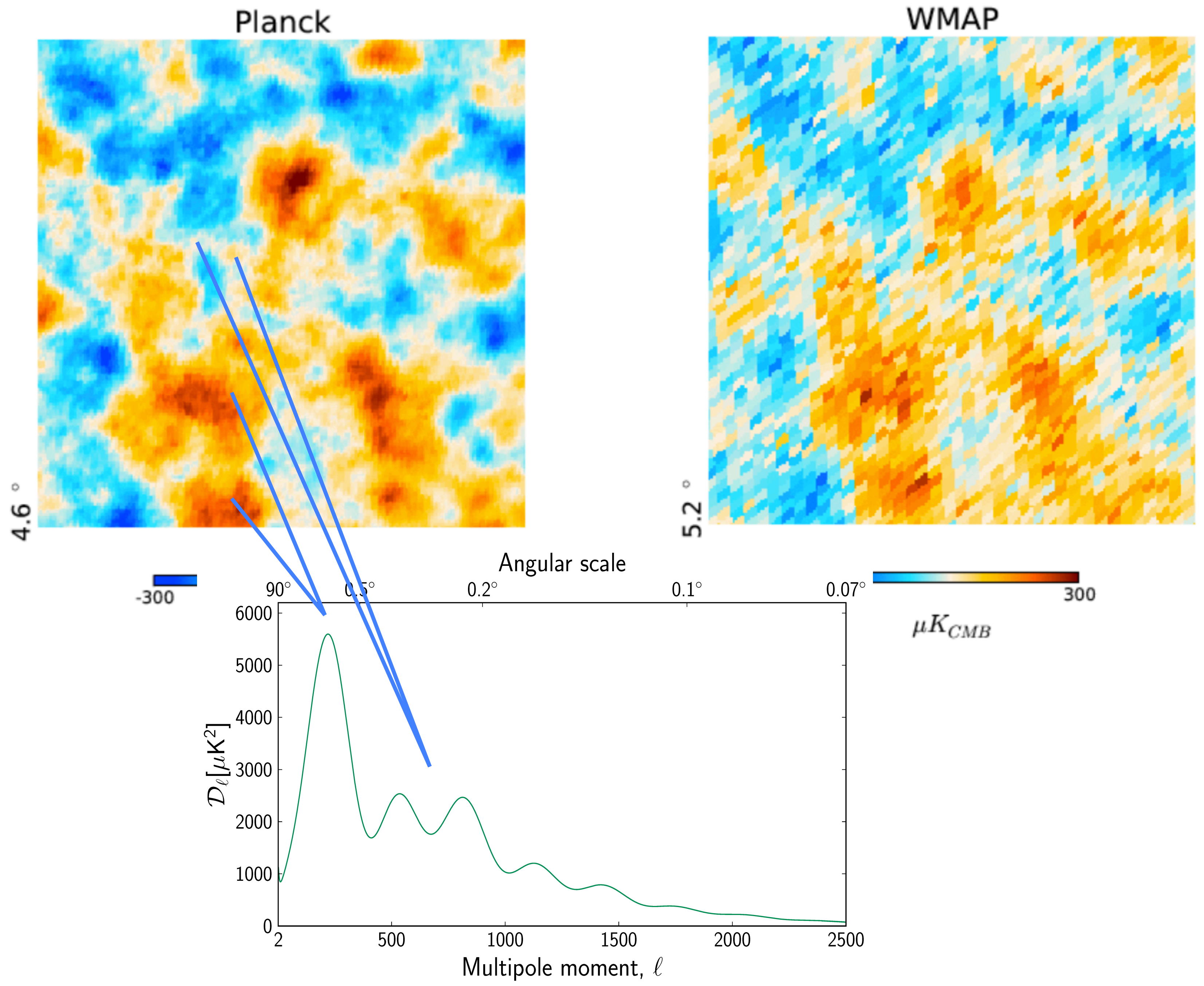

217 GHz I
-250
500 μK_CMB


143 GHz I
-250
500 □K$_{CMB}$

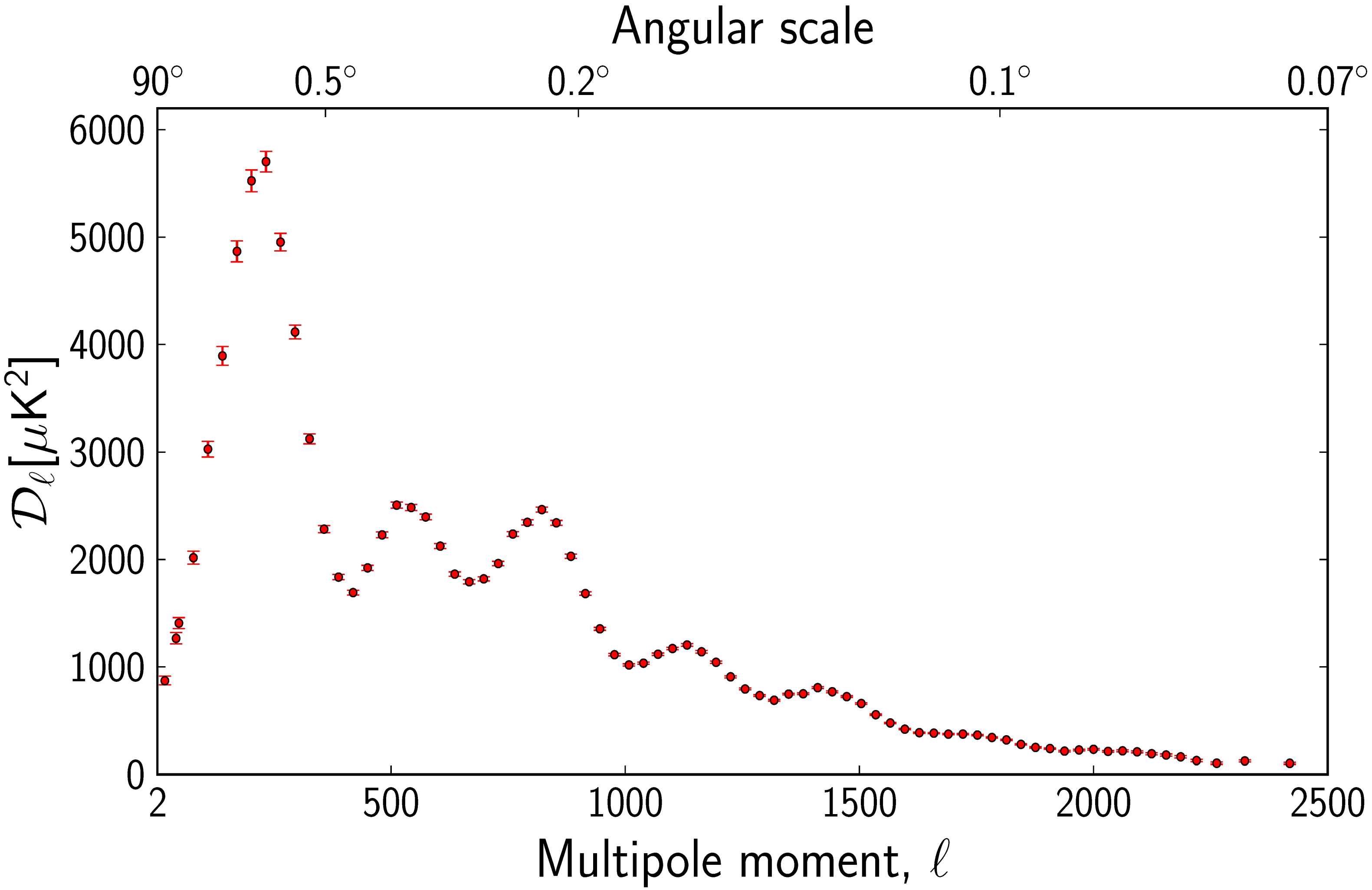

100 GHz I
-250
500 □K$_{CMB}$

CMB map mesured by Planck

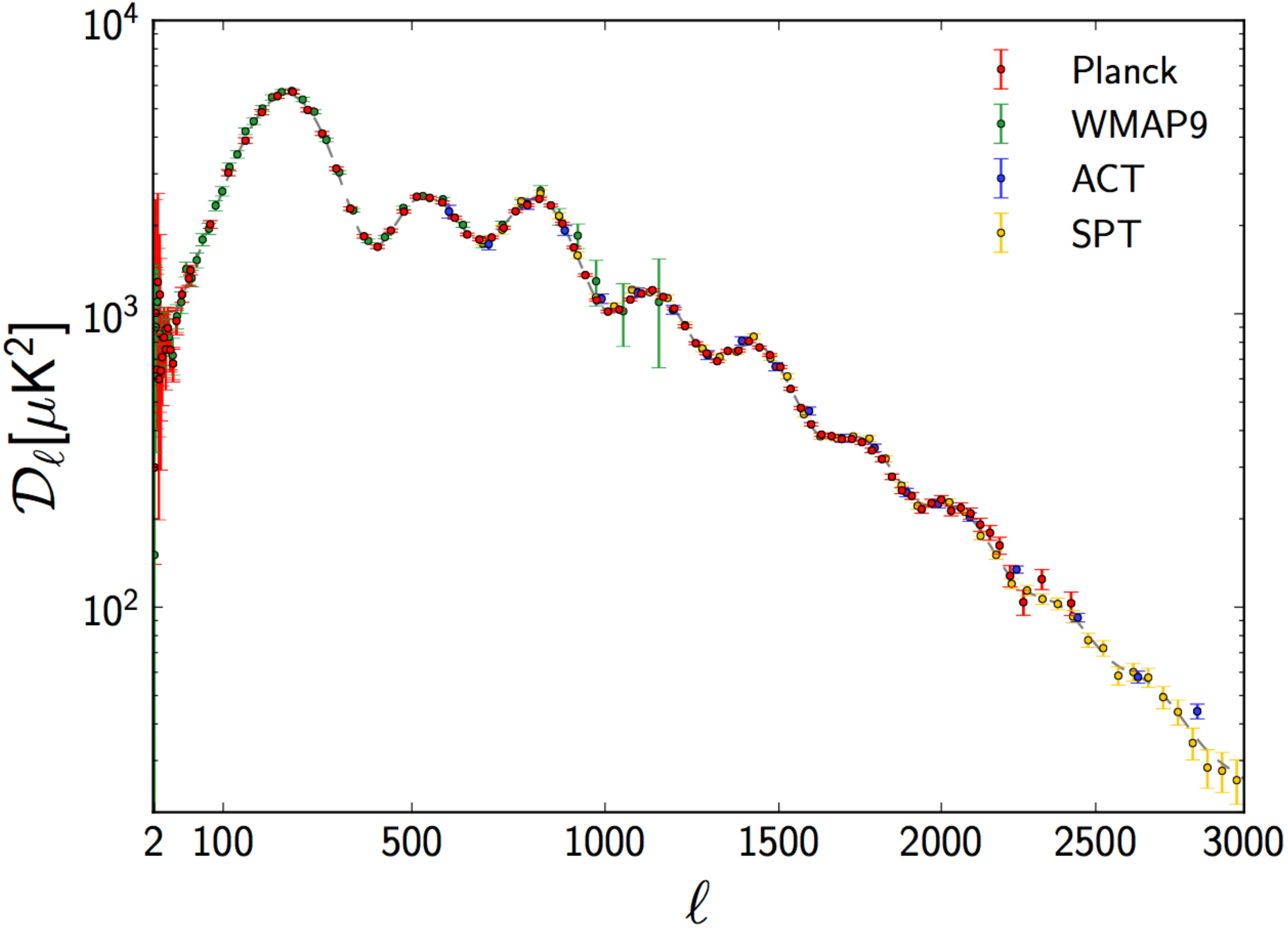



Planck
WMAP
4.6 °
5.2 °
-300
300
μK_{CMB}
Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ

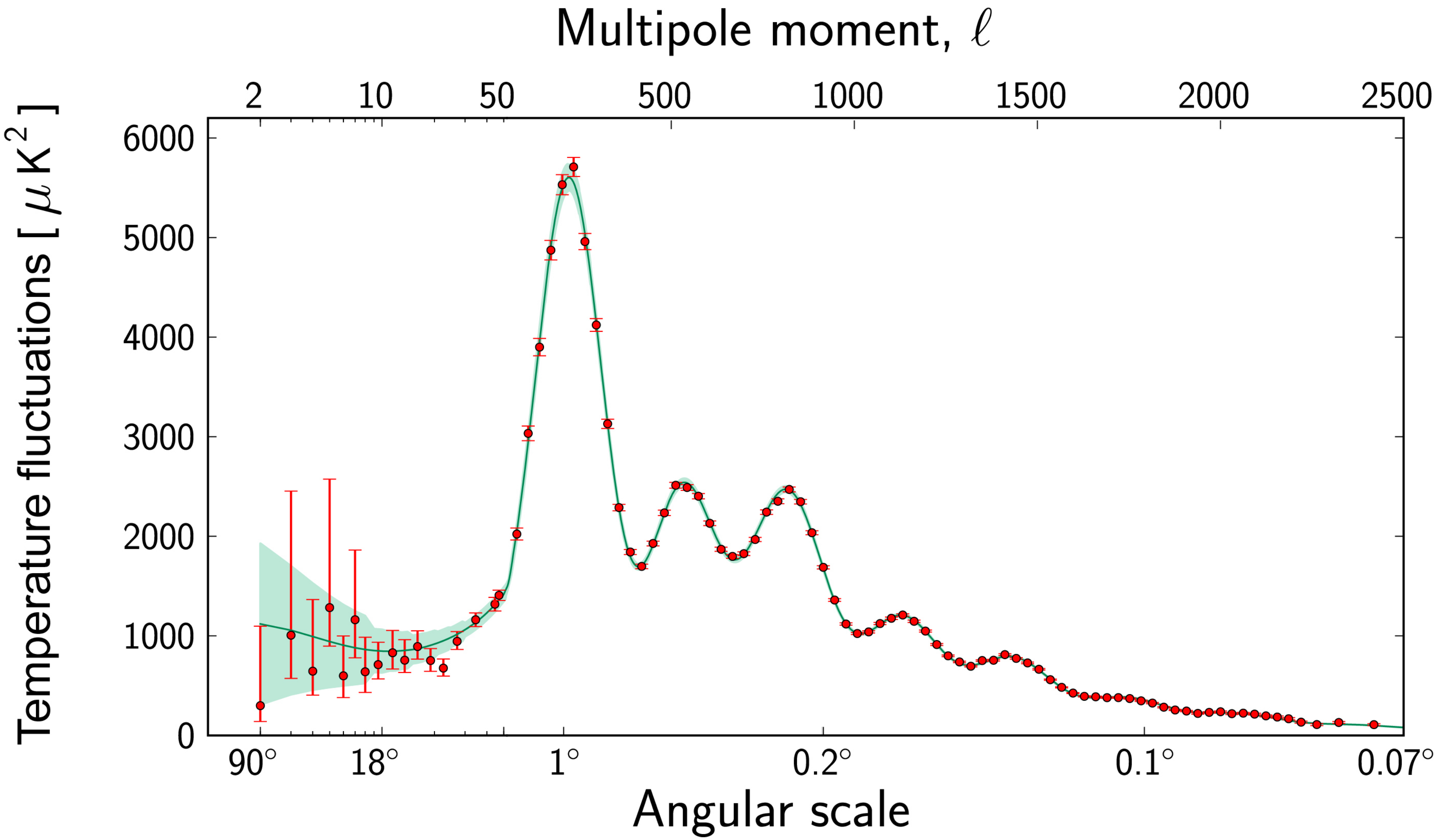
Angular power spectrum



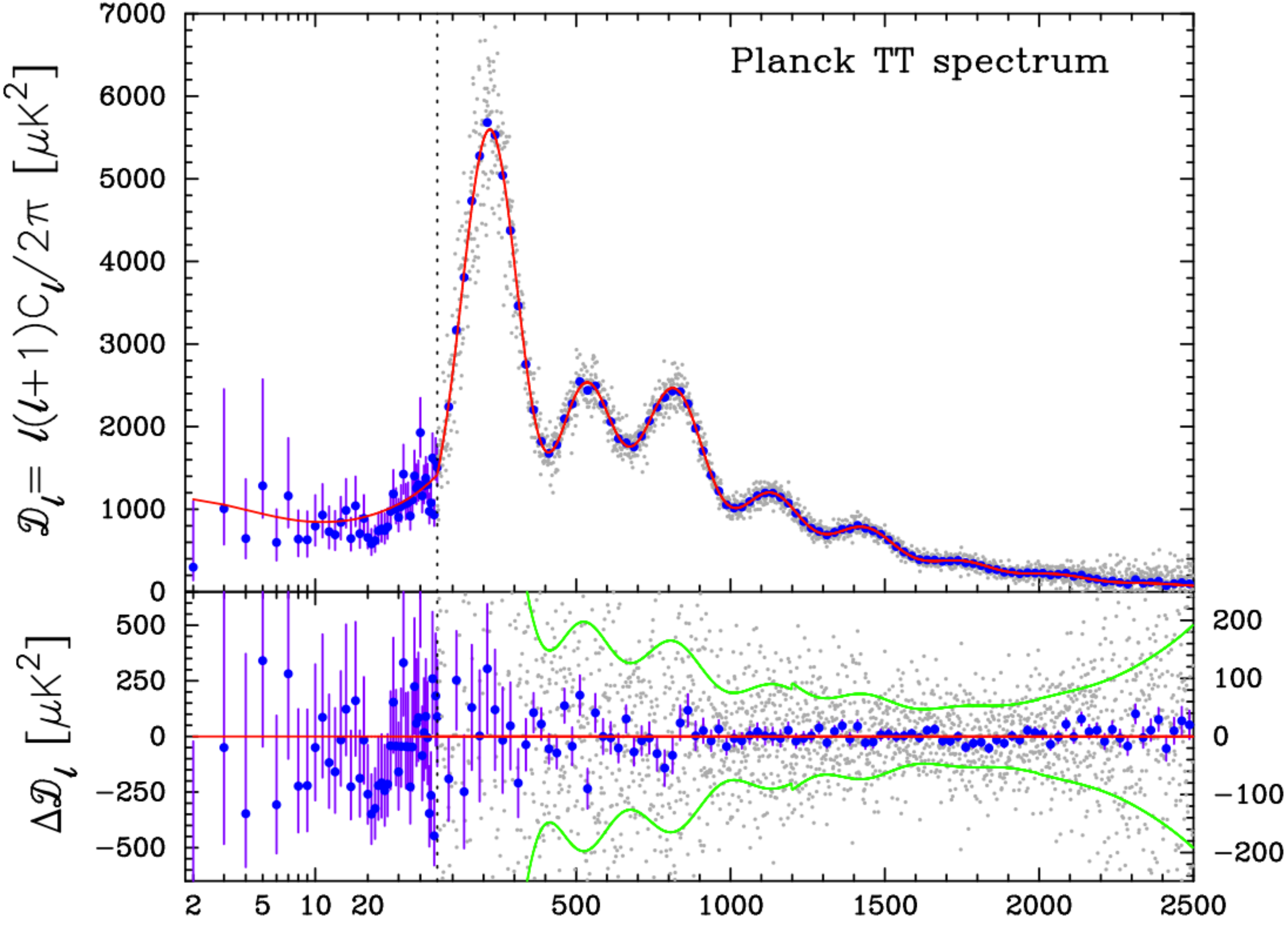
Comparison with other CMB experiments



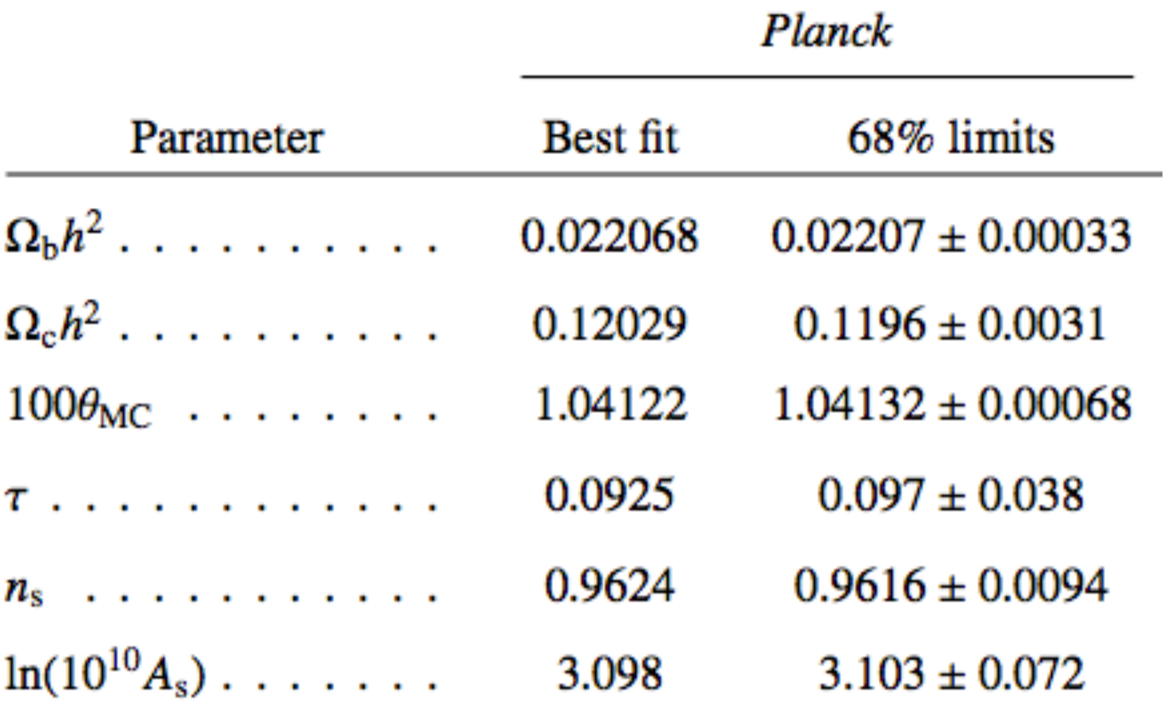
Best fit ΛCDM model



Remarquable fit with
only 6 parameters

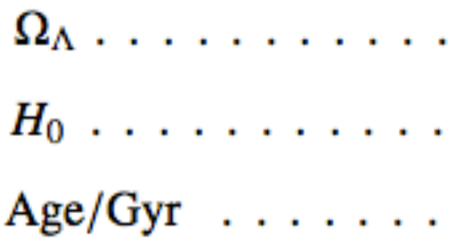

Planck TT spectrum
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

Cosmological parameters



	Planck		
Parameter	Best fit	68% limits	
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	Baryon density today
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	Dark matter density today
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	Acoustic horizon size at decoupling
τ	0.0925	0.097 ± 0.038	Reionization optical depth
n_s	0.9624	0.9616 ± 0.0094	Primordial scalar spectrum index
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	Primordial scalar spectrum ampl

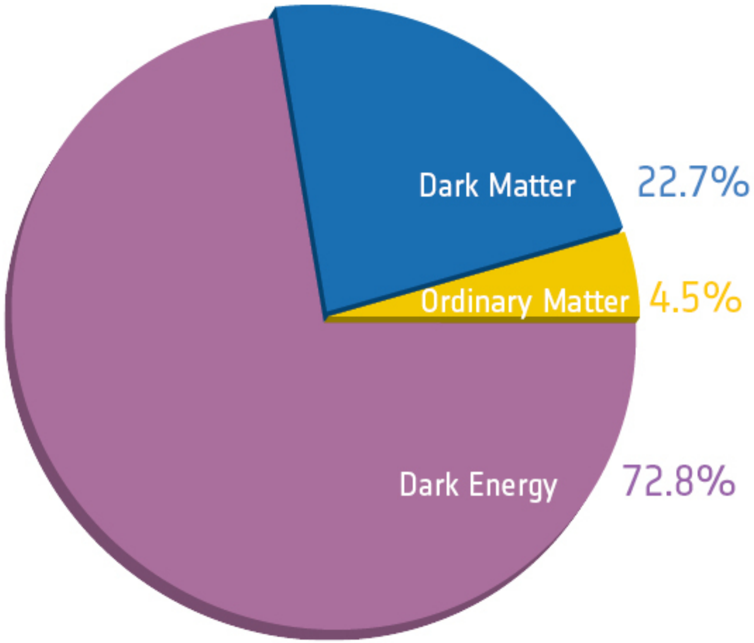
Derived parameters:



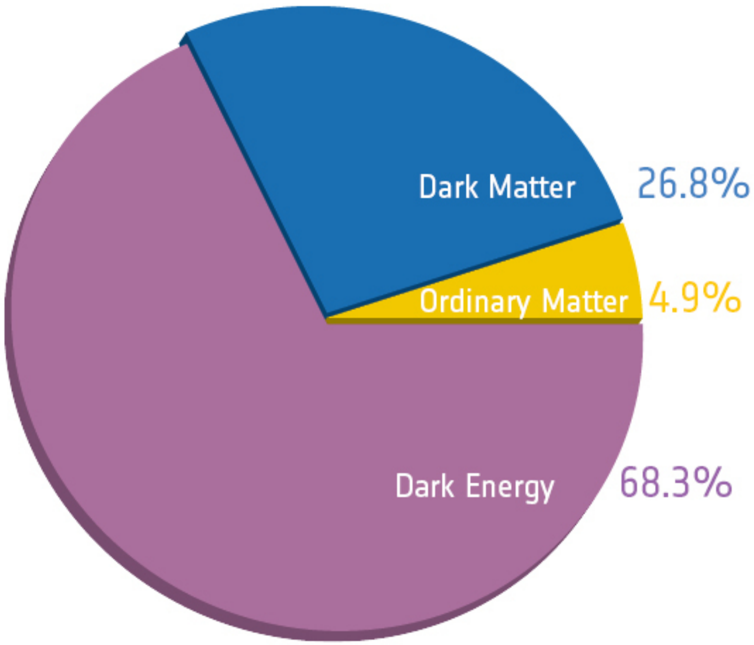
Ω_Λ	0.6825	0.686 ± 0.020	Dark energy density
H_0	67.11	67.4 ± 1.4	Hubble constant today
Age/Gyr	13.819	13.813 ± 0.058	Age of the Universe

⋮

Energy content of the Universe



Before Planck



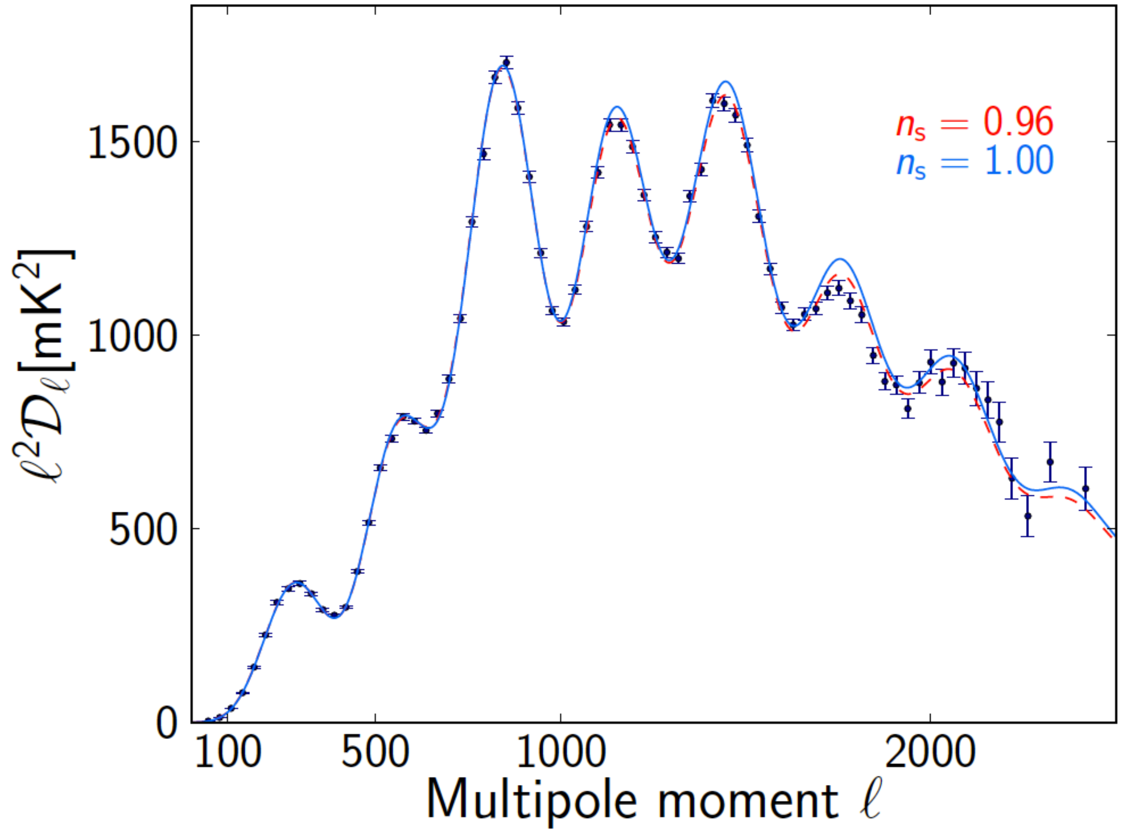
After Planck

Primordial power spectrum

Spectrum of primordial scalar fluctuations : $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$

$$n_s = 0.9608 \pm 0.0054$$

Scale invariant spectrum
excluded at 7 sigmas



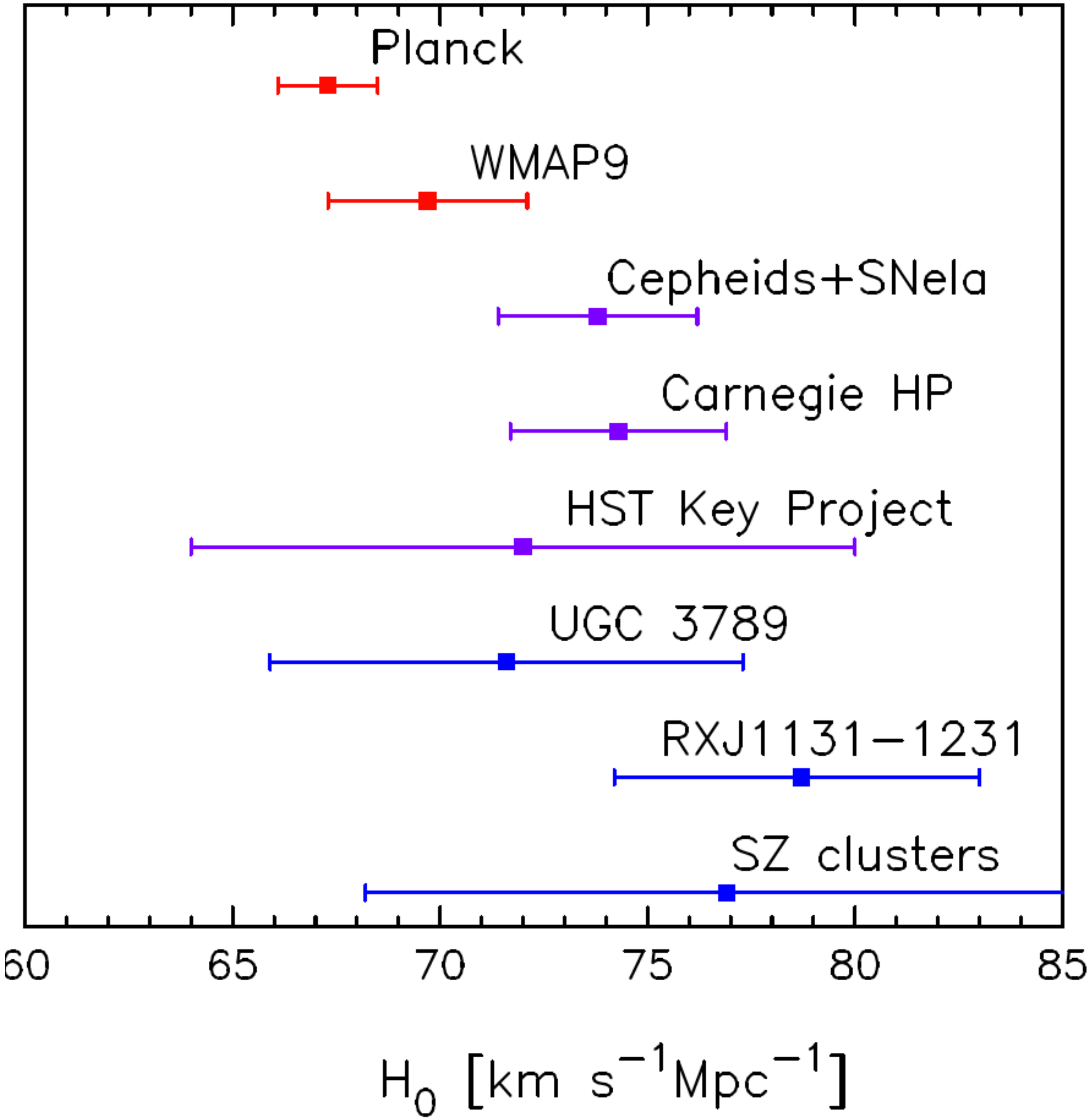
Hubble constant

Change…

$$H_0 = 67.3 \pm 1.2$$

2.5 sigmas tension between Planck and measurements of Cepheids + SNeIa

Indirect measurement with the CMB, but less sensitive to systematic effects.



Above the 6 parameter model

Neutrinos : $N_{eff} = 3.30 \pm 0.54$ et $\sum m_{\nu} < 0.23\, eV$ (95% limits)
including Baryonic oscillation measurements

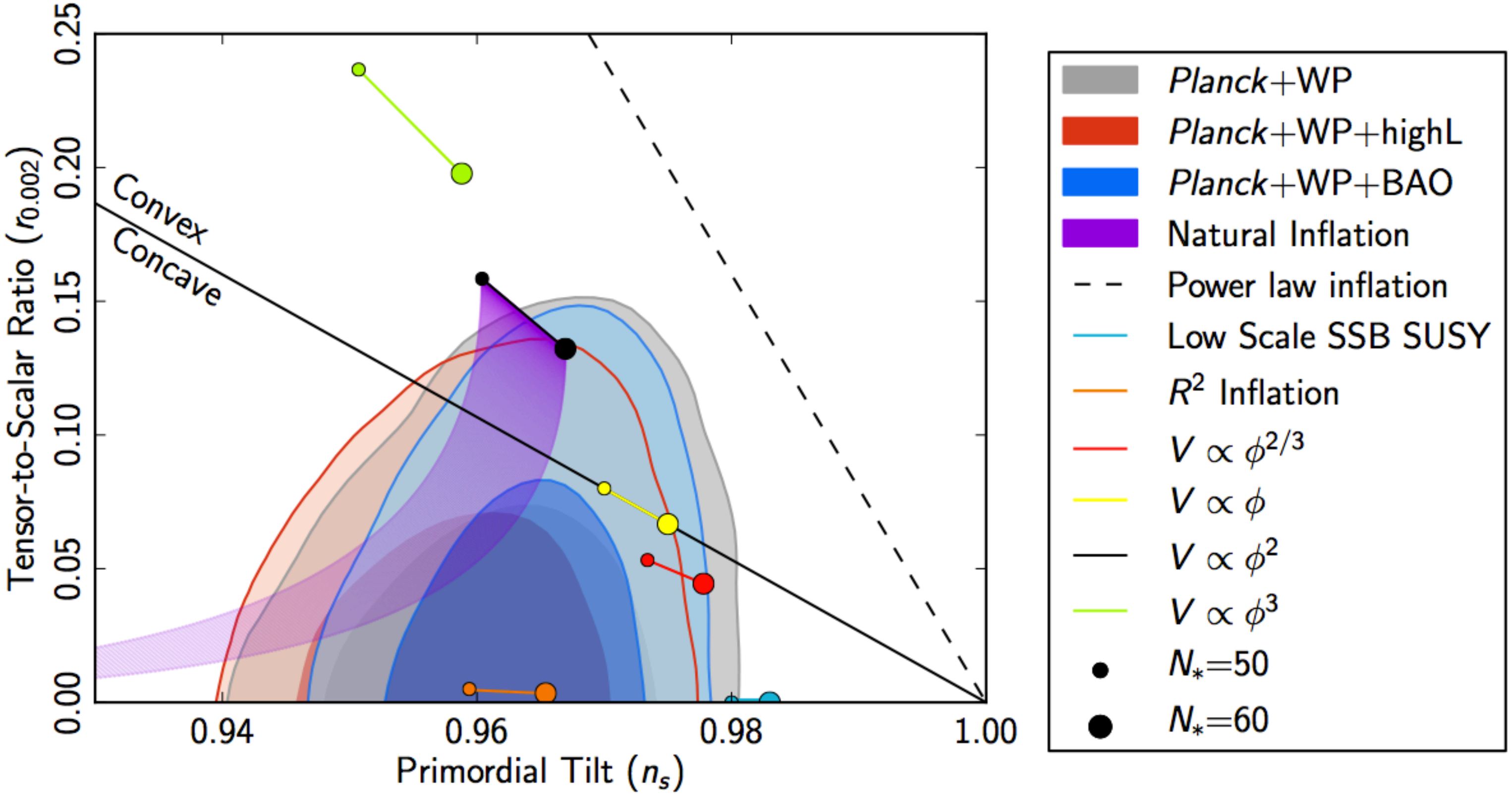
Dark energy dynamics : $w = -1.0109 \pm 0.24$ (95%)

Tensor modes : $r < 0.11$ (95%)

Running of spectral index : $dn_s / d\ln k = -0.014 \pm 0.017$ (95%)

No detections of: isocurvature modes, cosmic strings, no variations of fine structure constant…

Inflation



Some non-standard inflation models rejected,
But the simplest models are compatible with the data.

Non-gaussianity

Some inflation models can produce a significant level of non-gaussianity.

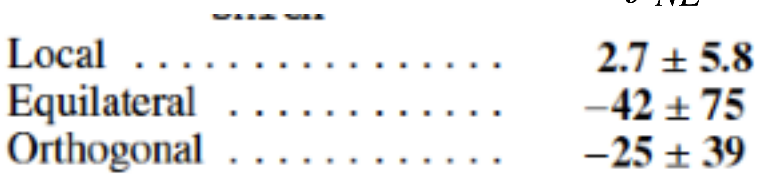
Parametric model for local non-gaussianity: $\Phi_{NG}(x) = \Phi_G(x) + f_{NL}\Phi_G(x)^2$

This can be constrained with the 3-pts correlation function in harmonic space.

$$< \Phi(k_1).\Phi(k_2).\Phi(k_3) >= f_{NL}\delta(k_1 + k_2 + k_3)F(k_1,k_2,k_3)$$

can be related to $< a_{l_1 m_1} .a_{l_2 m_2} .a_{l_3 m_3} >$

No detection of non-gaussianity in Planck CMB maps



	f_{NL}
Local	2.7 ± 5.8
Equilateral	−42 ± 75
Orthogonal	−25 ± 39

This is compatible with the simplest models of inflation

Anomalies

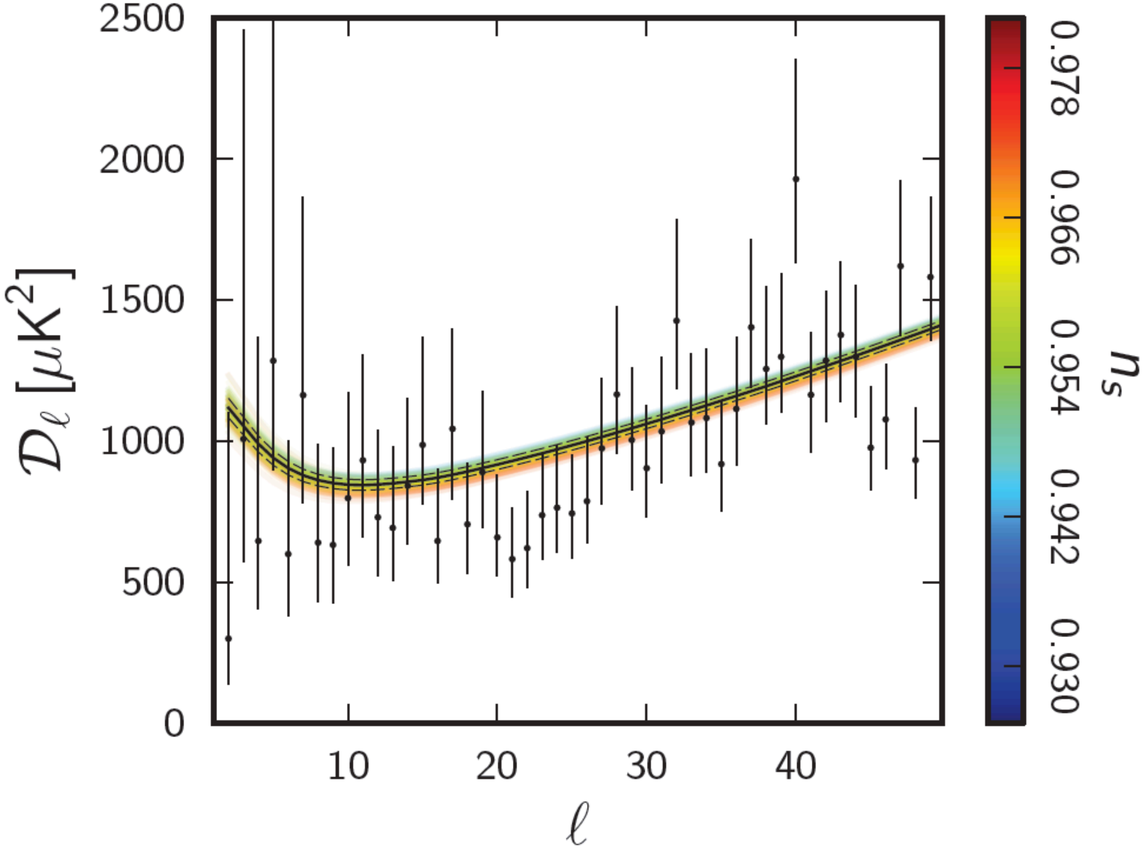
We observed strange behaviour at large scales.

Model predicts too much power as compared to data.

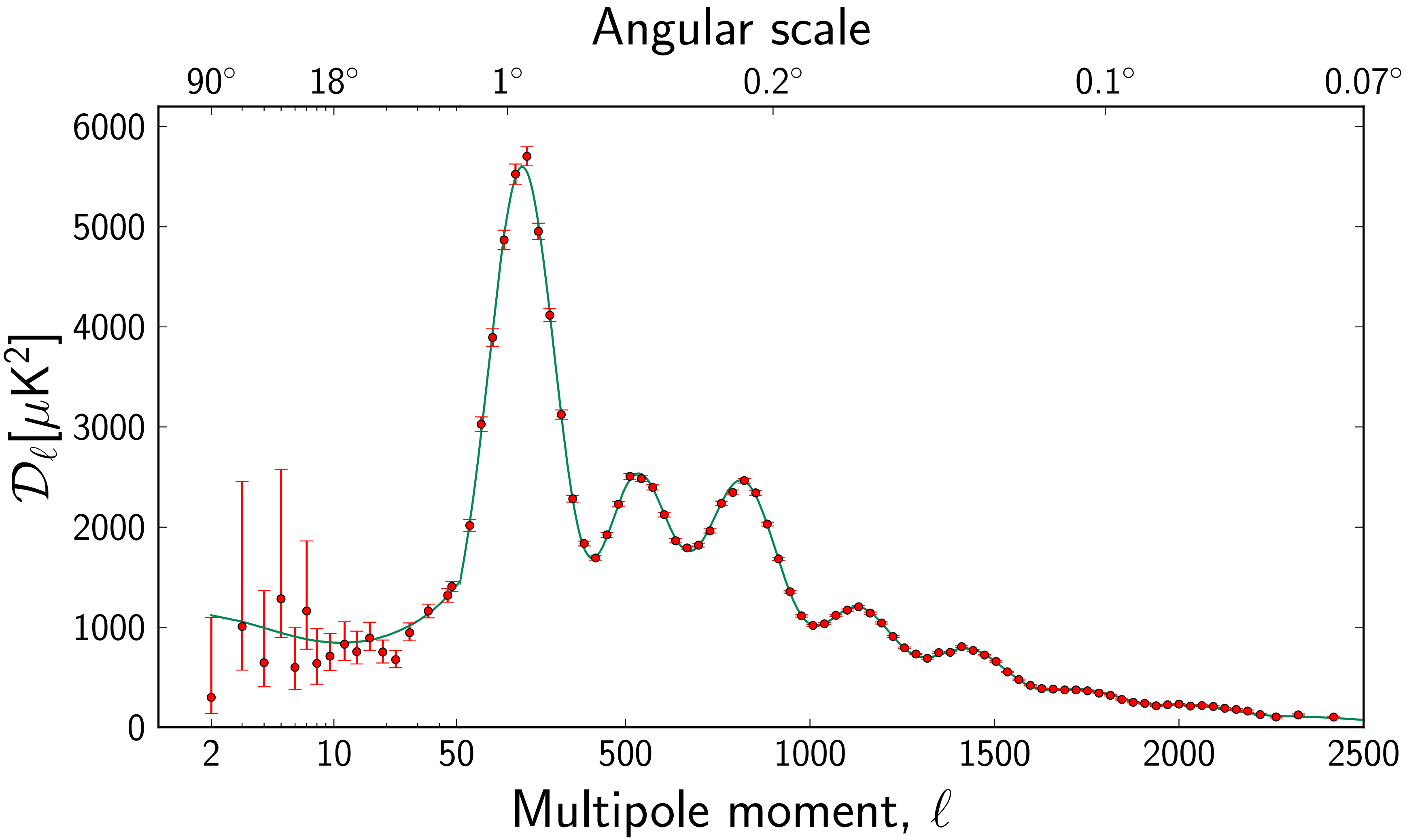
Effects appear below $\ell = 40$

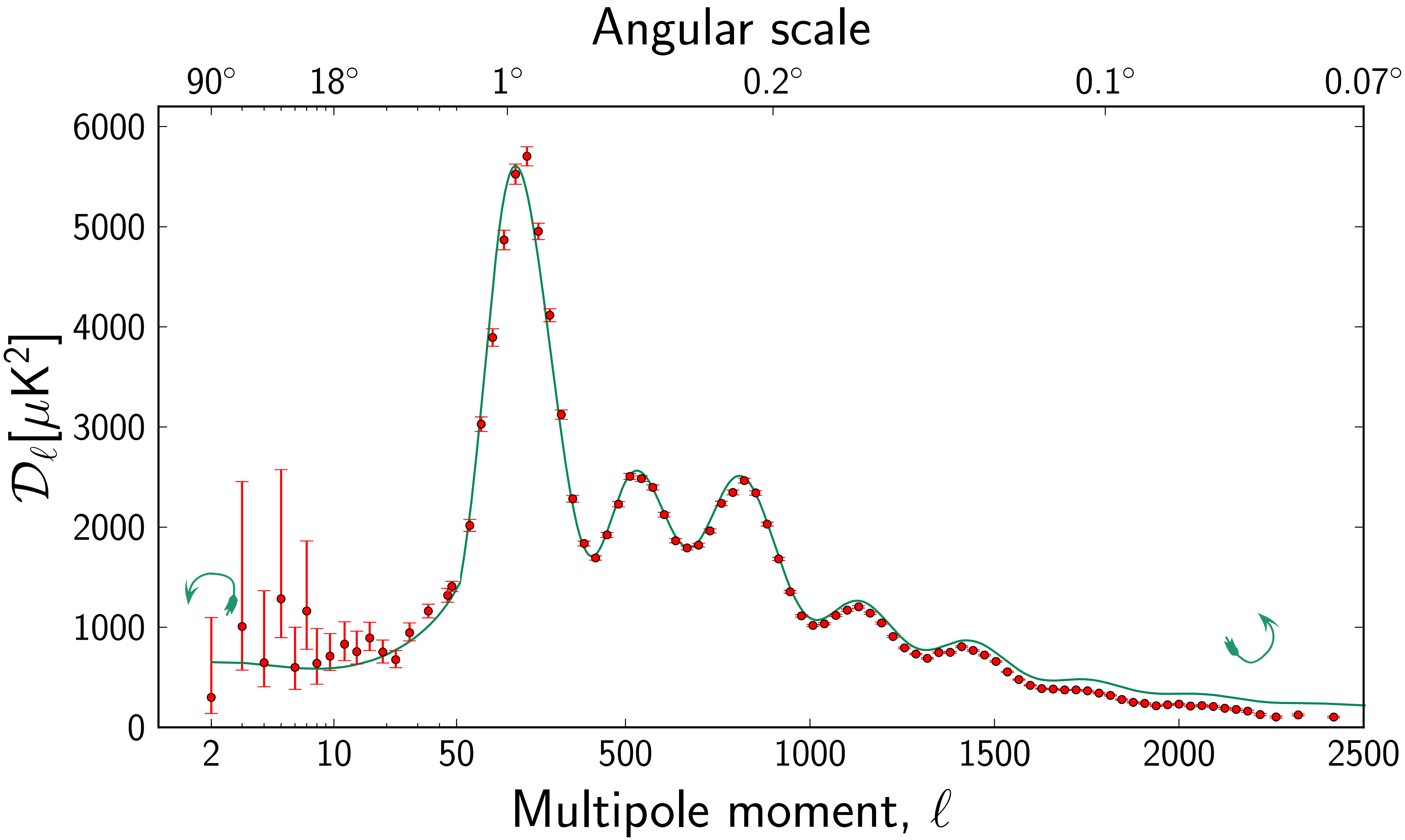
It intriguingly corresponds to the transition between modes inside and outside the horizon at decoupling.

But only a 2.5 sigma effect



Another anomaly is the low multipole alignment


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ


Angular scale
90°
18°
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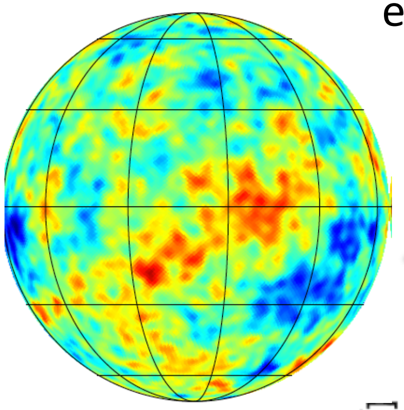
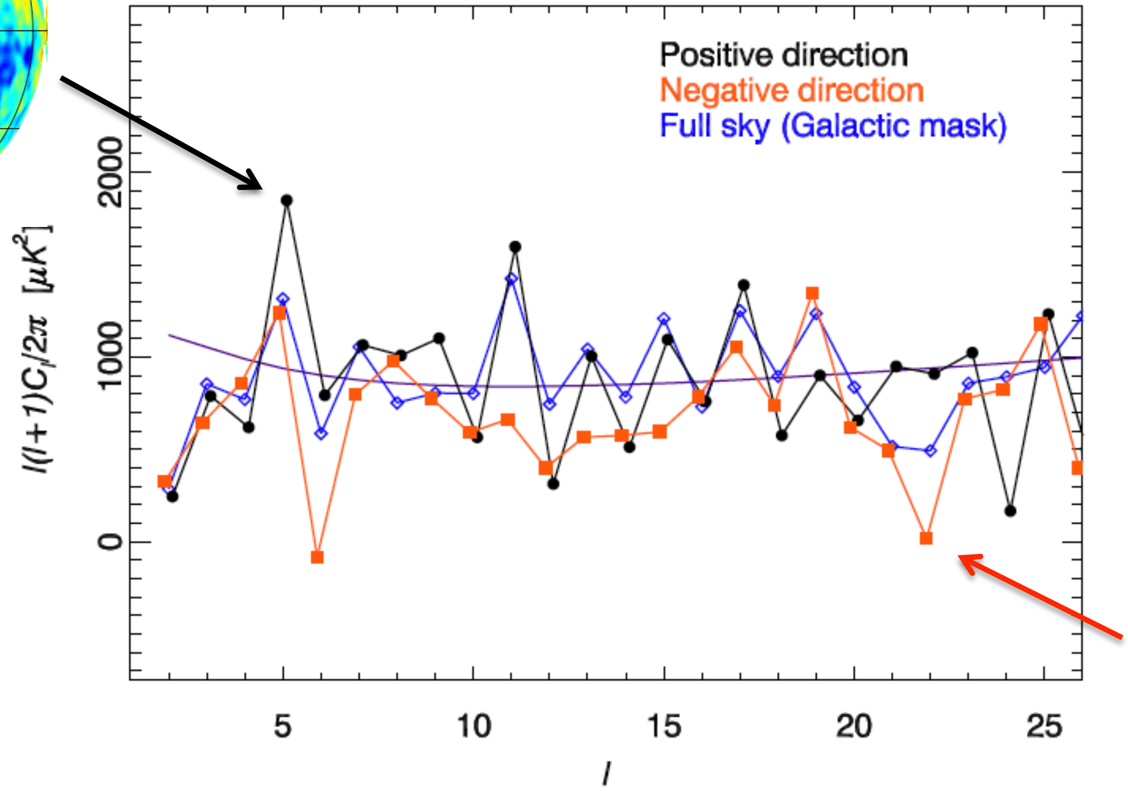
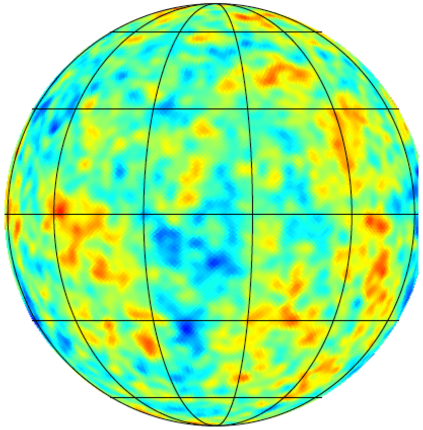
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

Difference two ecliptic hemispheres

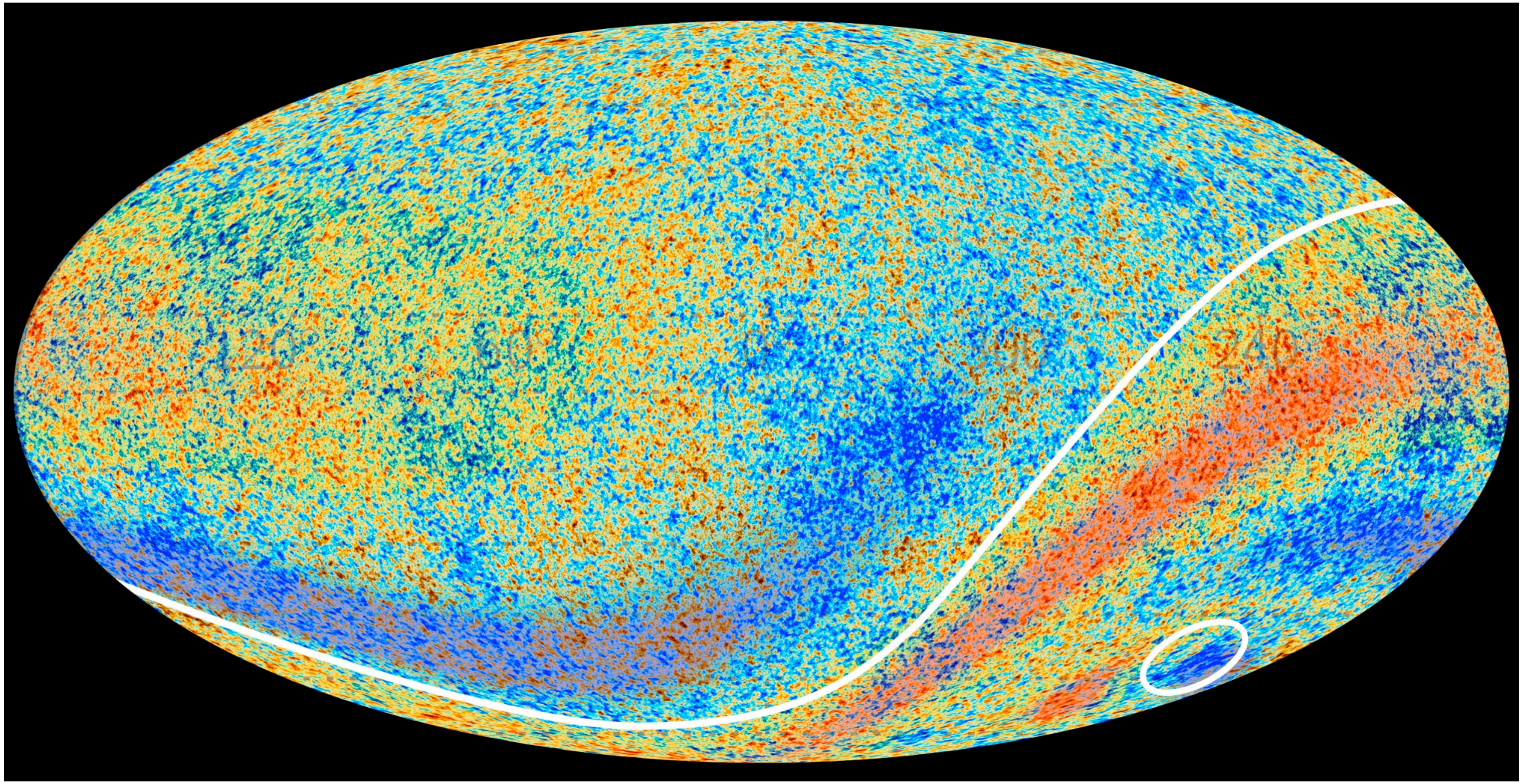
We also observe small difference of power at large scale between the two ecliptic hemisphere





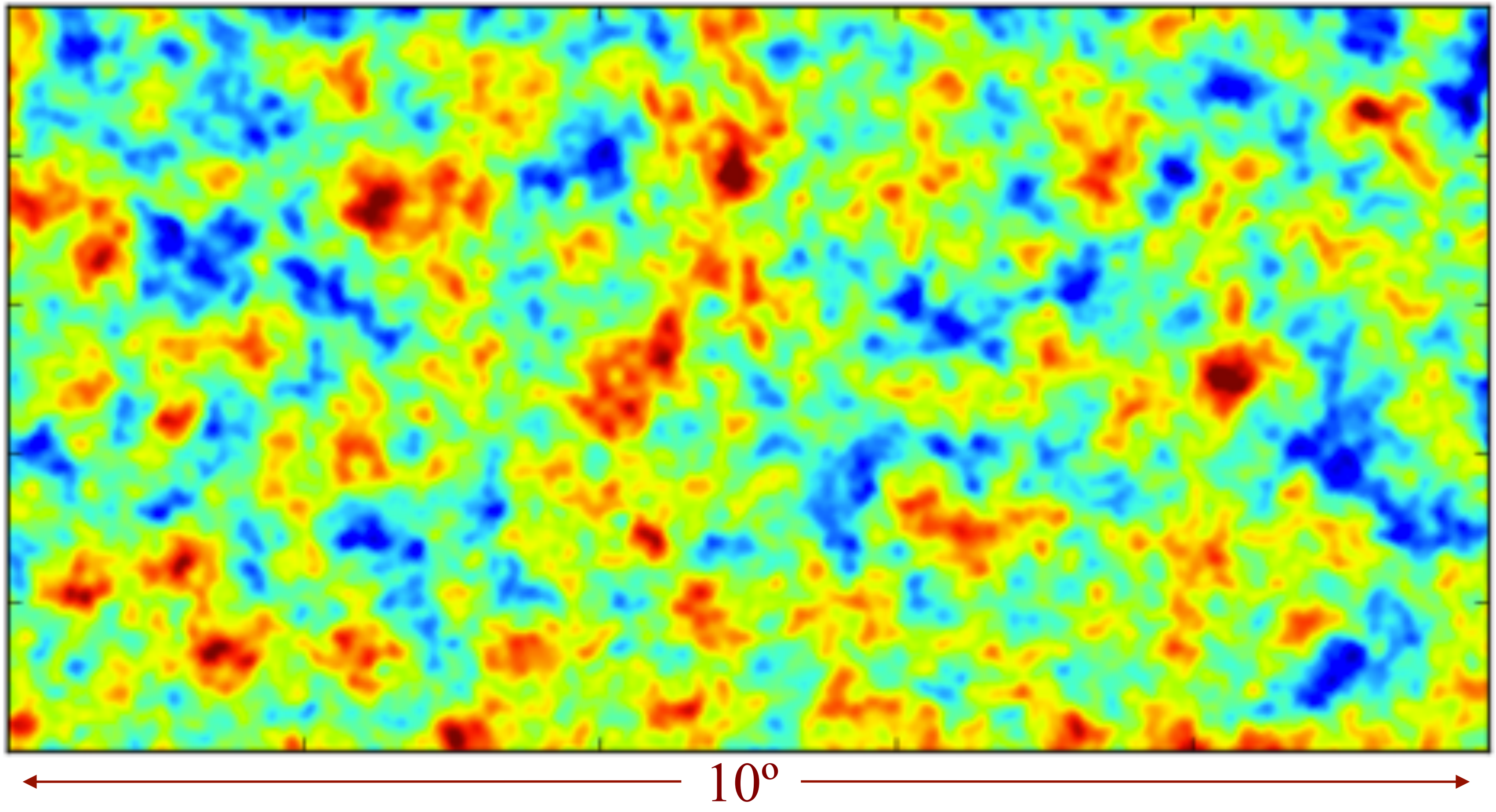


Bianchi VII model



Lensing effect on the CMB

Simulated CMB map before lensing



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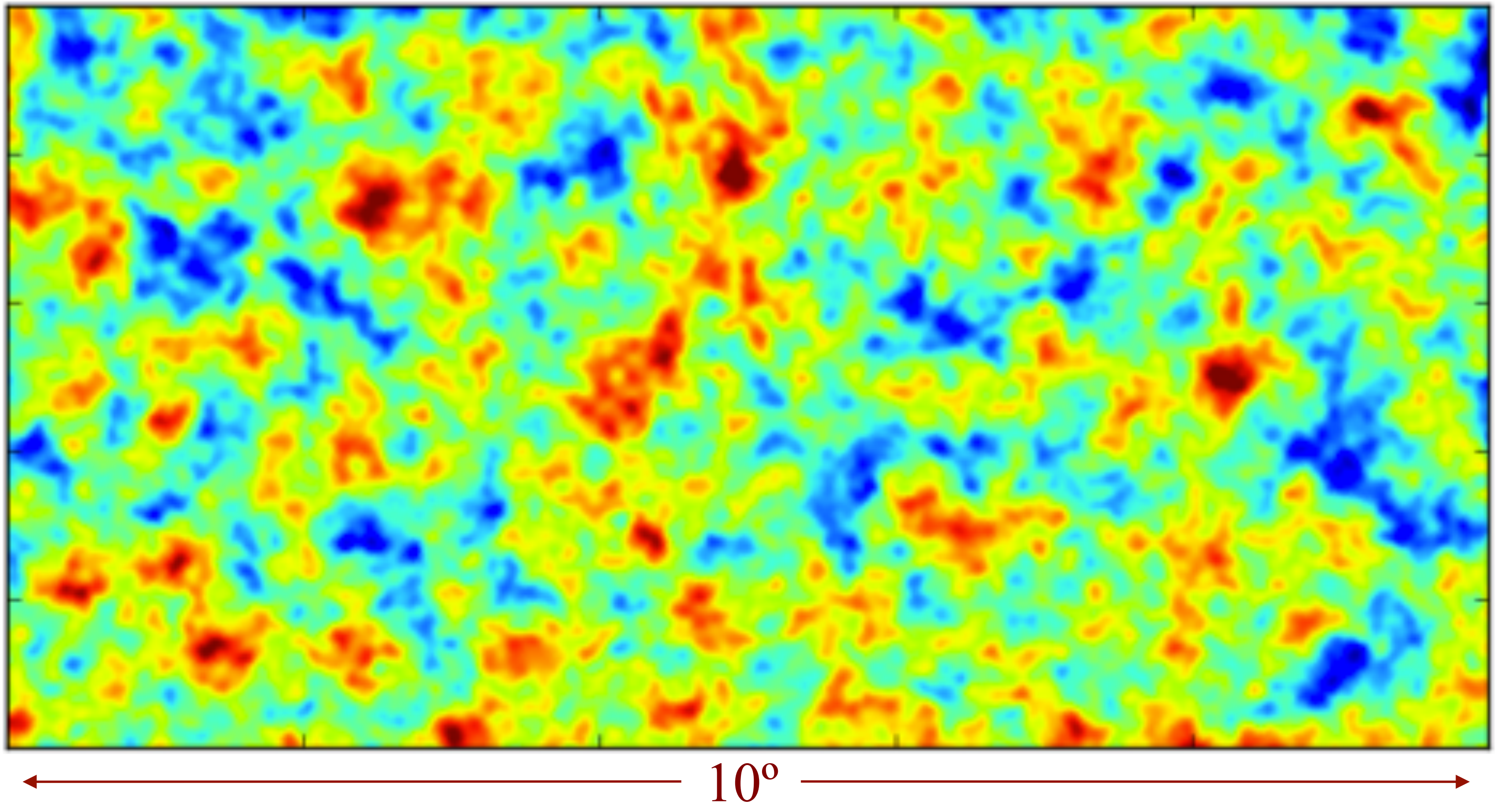
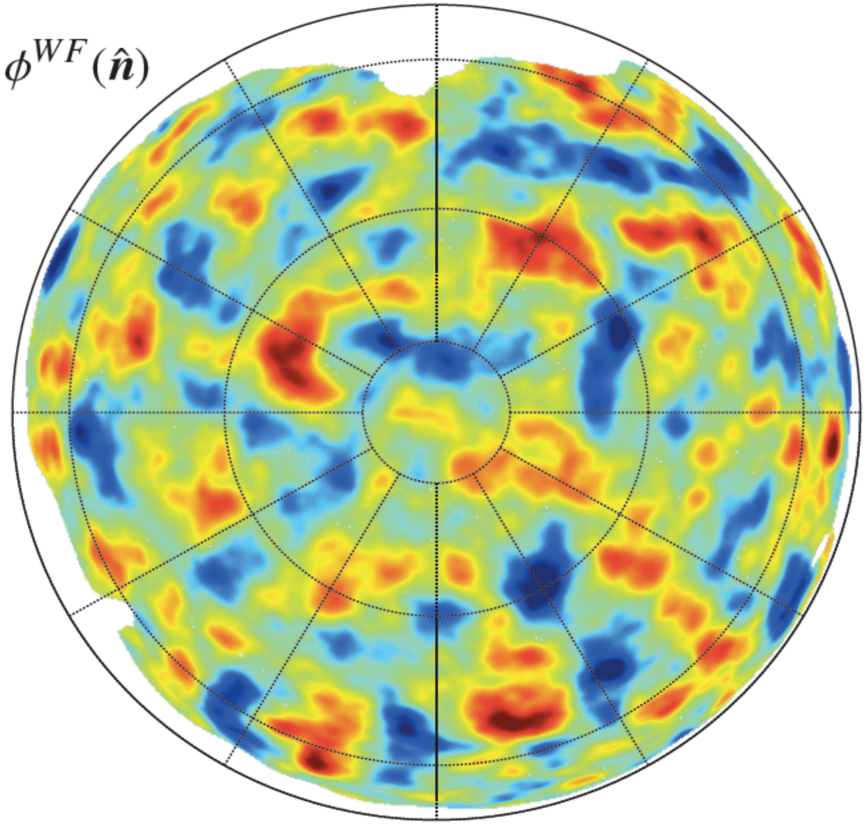
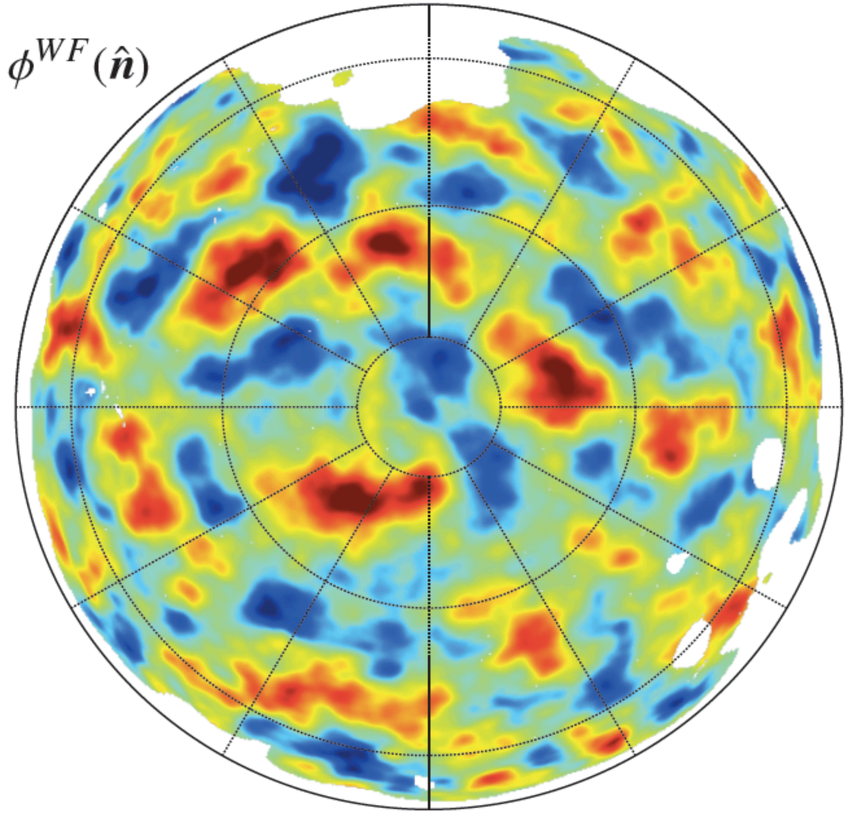


Dark matter distribution

Mass distribution in the Universe reconstructed from Planck maps,
85% dark matter, 15% ordinary matter

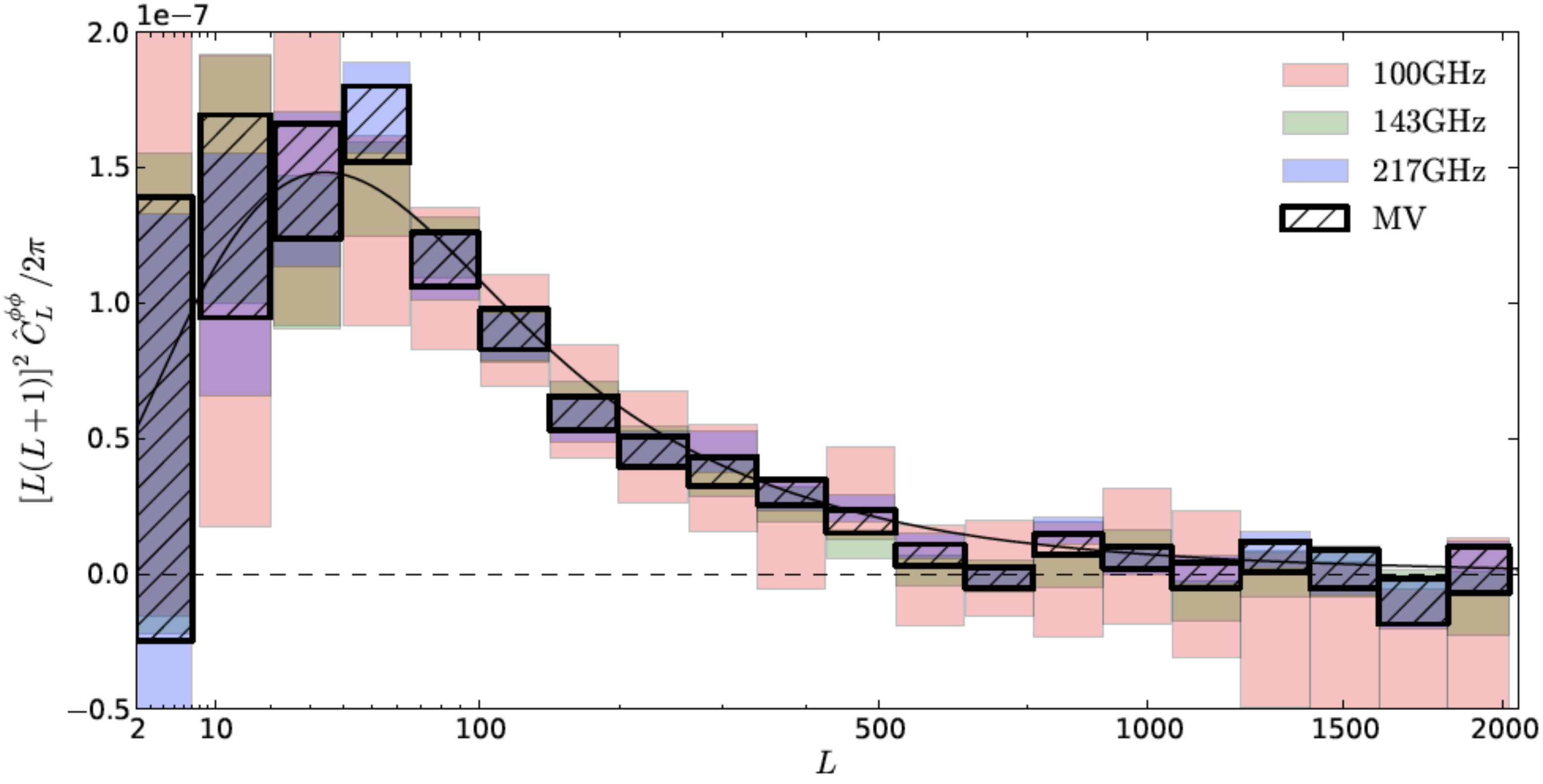


Galactic North



Galactic South

Power spectrum



Conclusion

- 29 papers published in March and more are coming!
- Six-parameter ΛCDM model is compatible with Planck data
- Scale invariant spectrum excluded at 7 sigmas
- H_0 lower than measured by other probes
- Simplest single field inflation model compatible with Planck data, given the value of n_s, a detection of B-modes (resulting from tensor perturbations) is possible with Planck.
- Polarisation data will be released in 2014.
- Important constraints on several fundamental parameters, e.g. m_ν
- Intriguing anomalies at large scales in the CMB
- Many other cosmological results from Planck data: lensing of the CMB by dark matter fluctuations on the path, Sunyaev Zeldovitch emission from clusters of galaxies, emission from distant sub-millimeter galaxies.
- Many astrophysical results, study of our galaxy