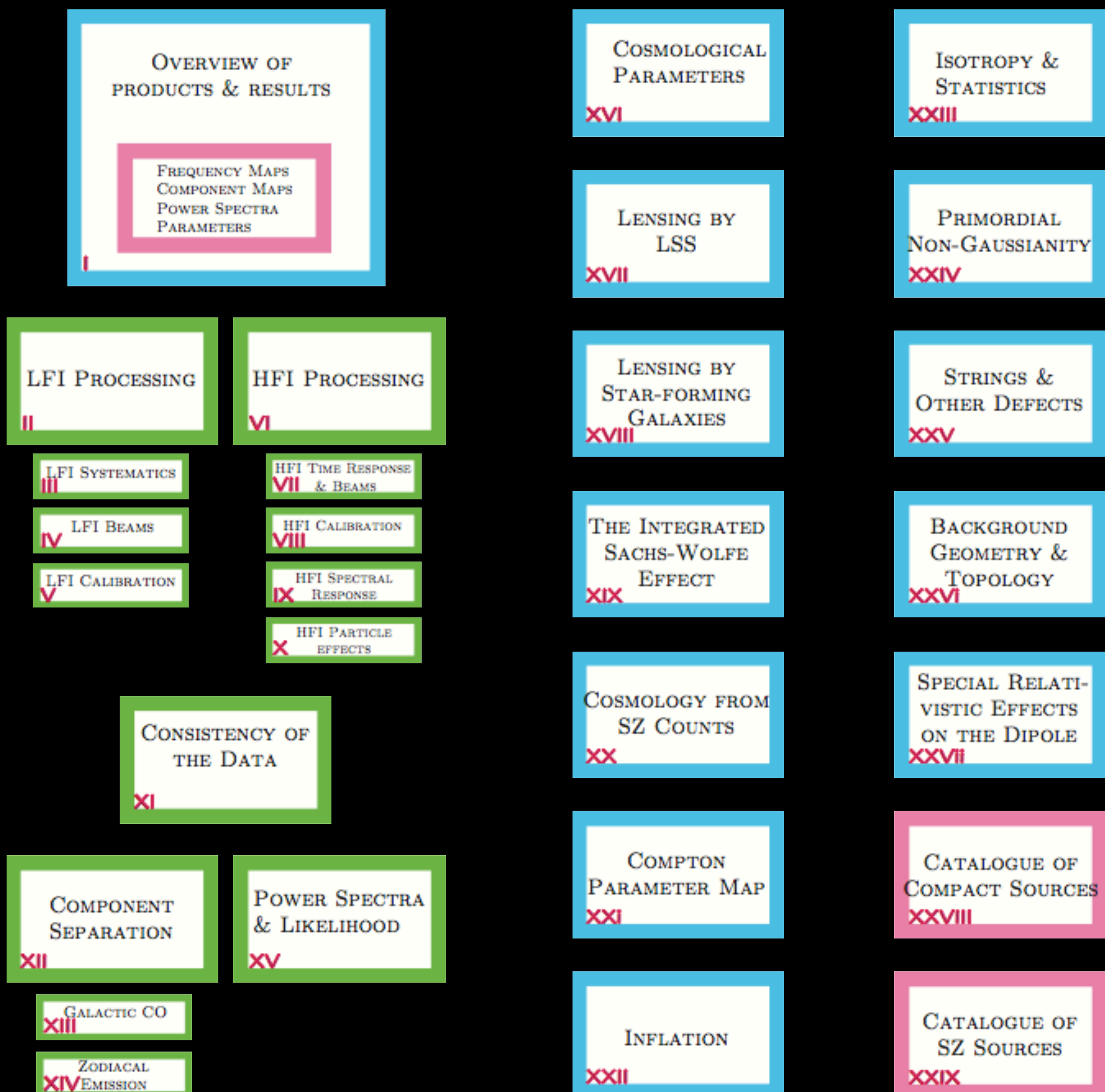
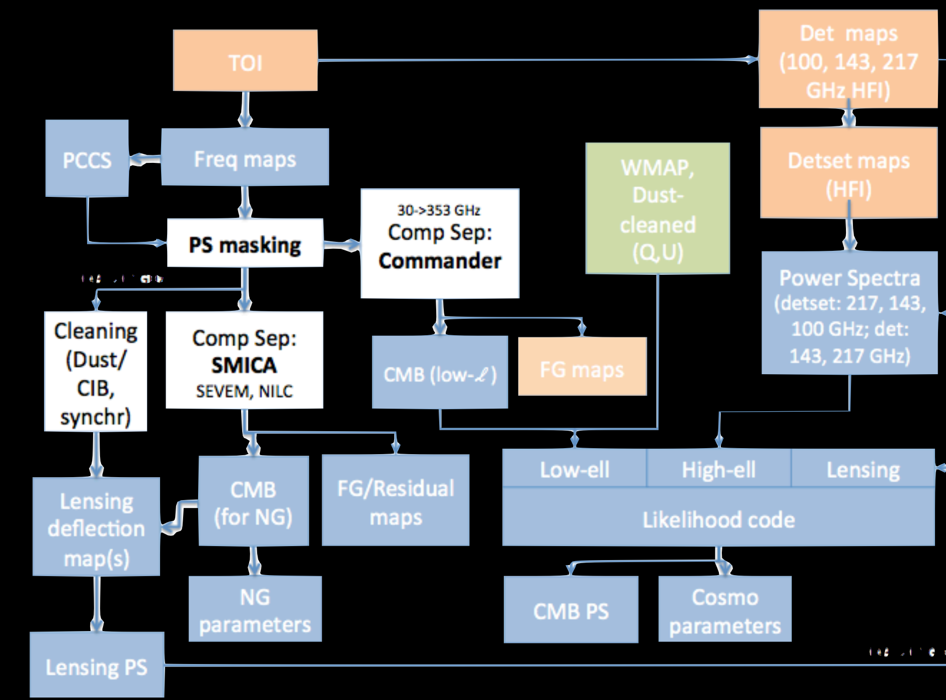
First cosmological results from Planck

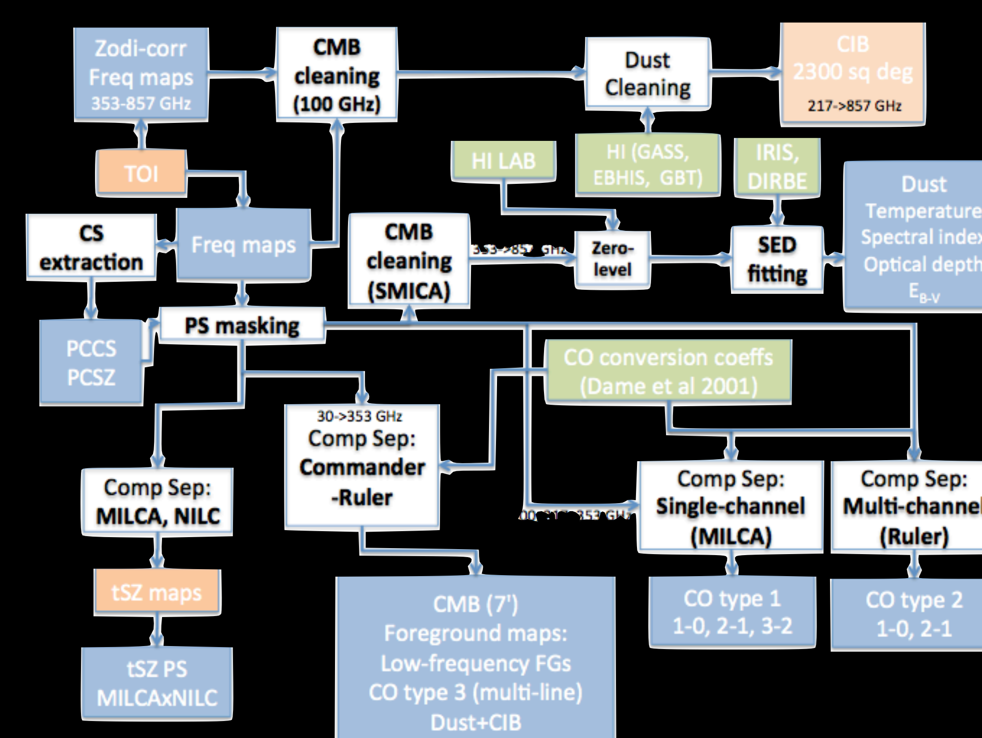
Cyrille Rosset - APC
EPS 2013

Planck 2013 publications



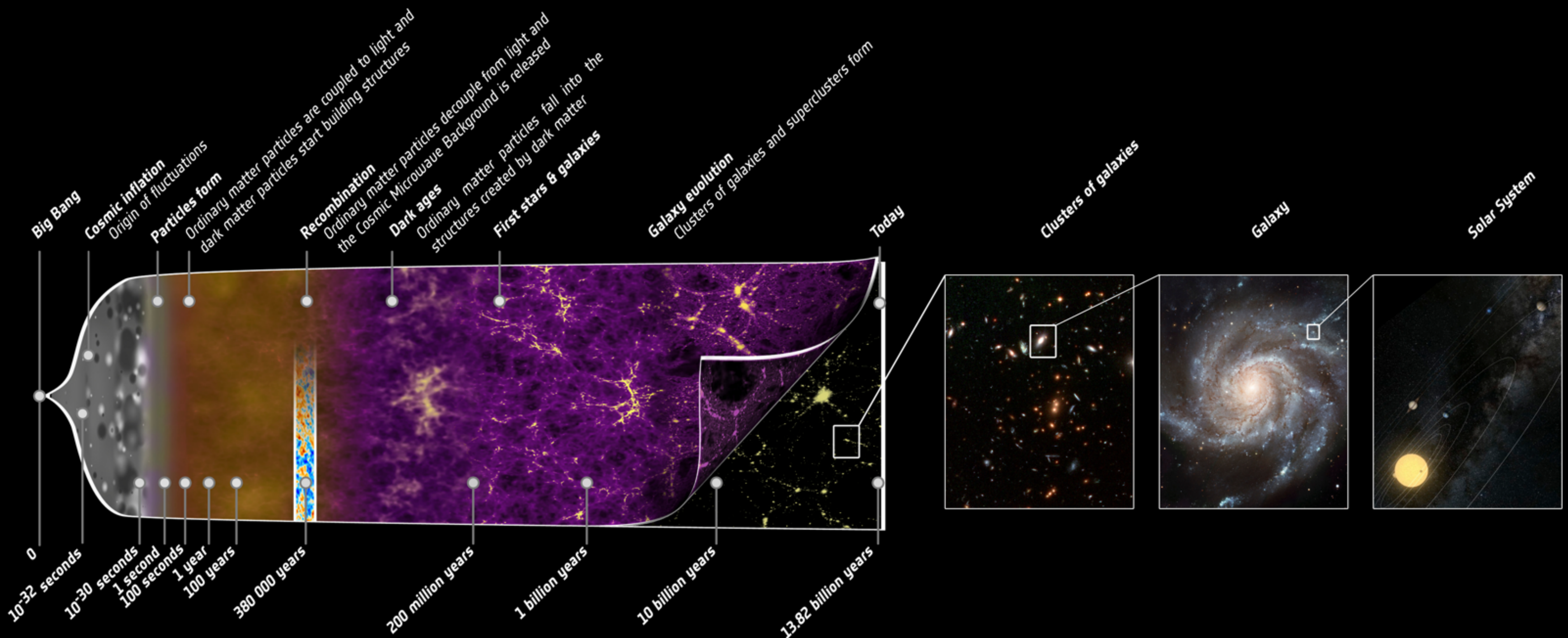


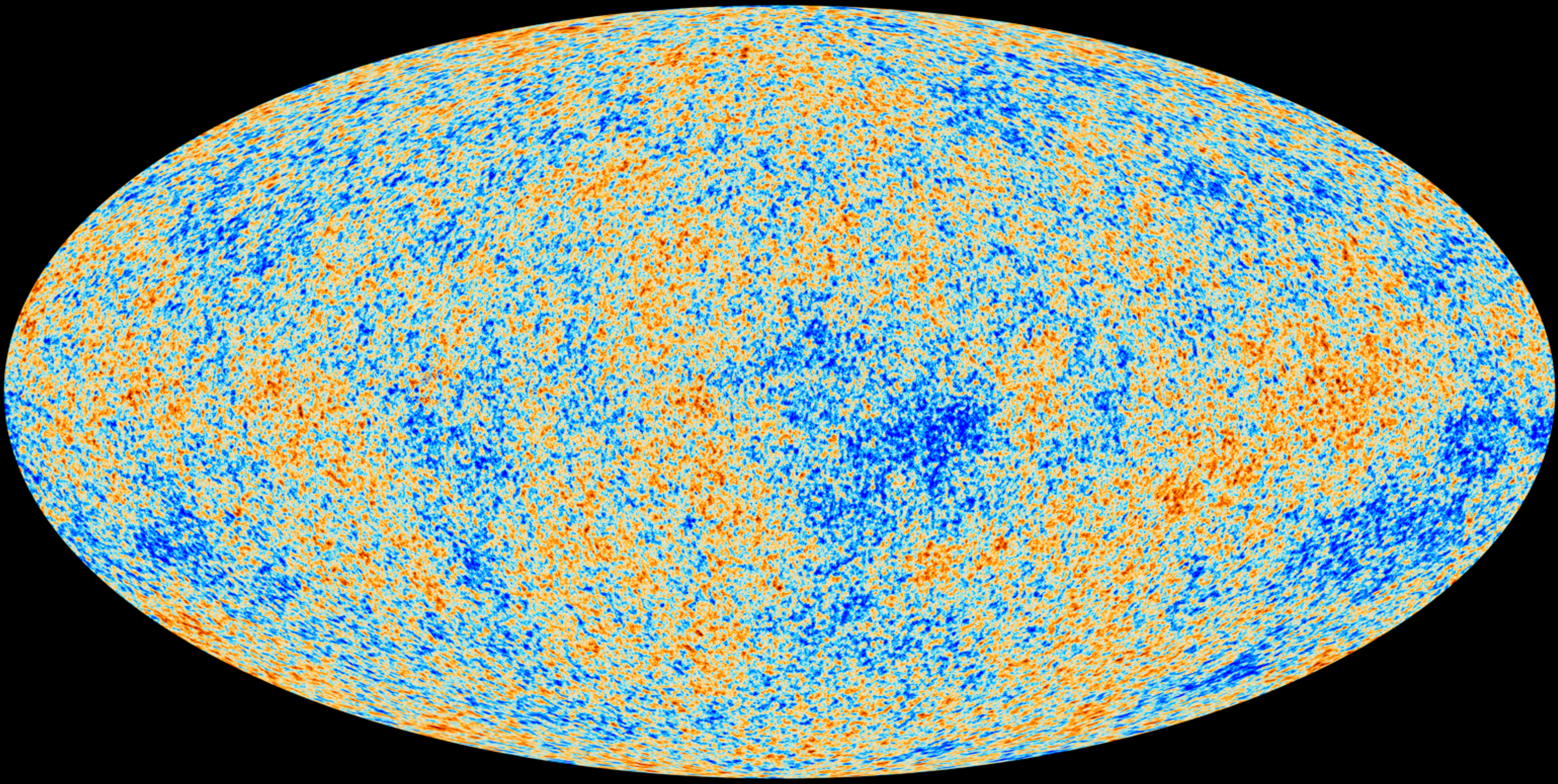
http://www.sciops.esa.int/index.php?page=Planck_Legacy_Archive&project=planck



> 1000 pages

History of Universe

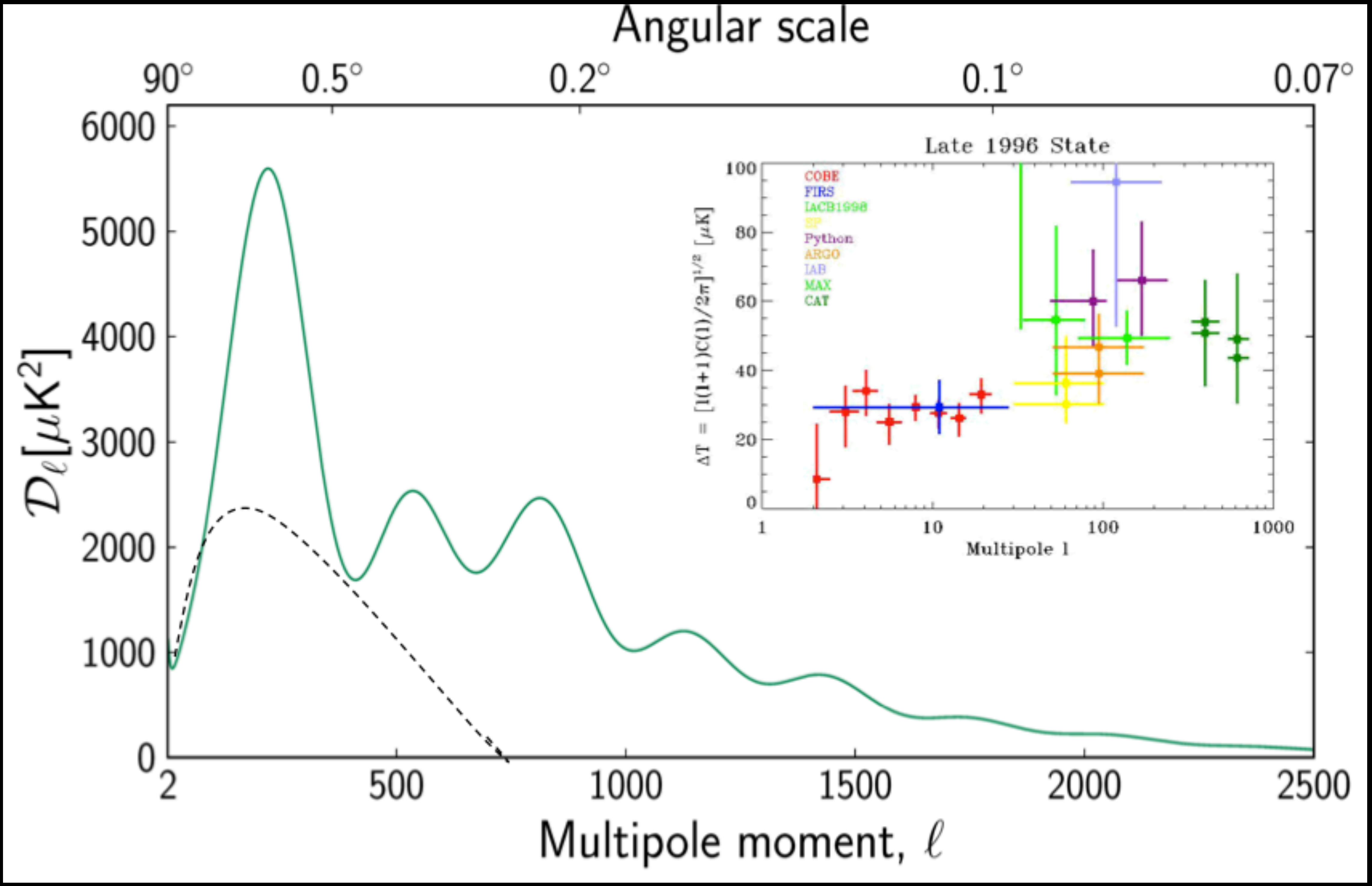




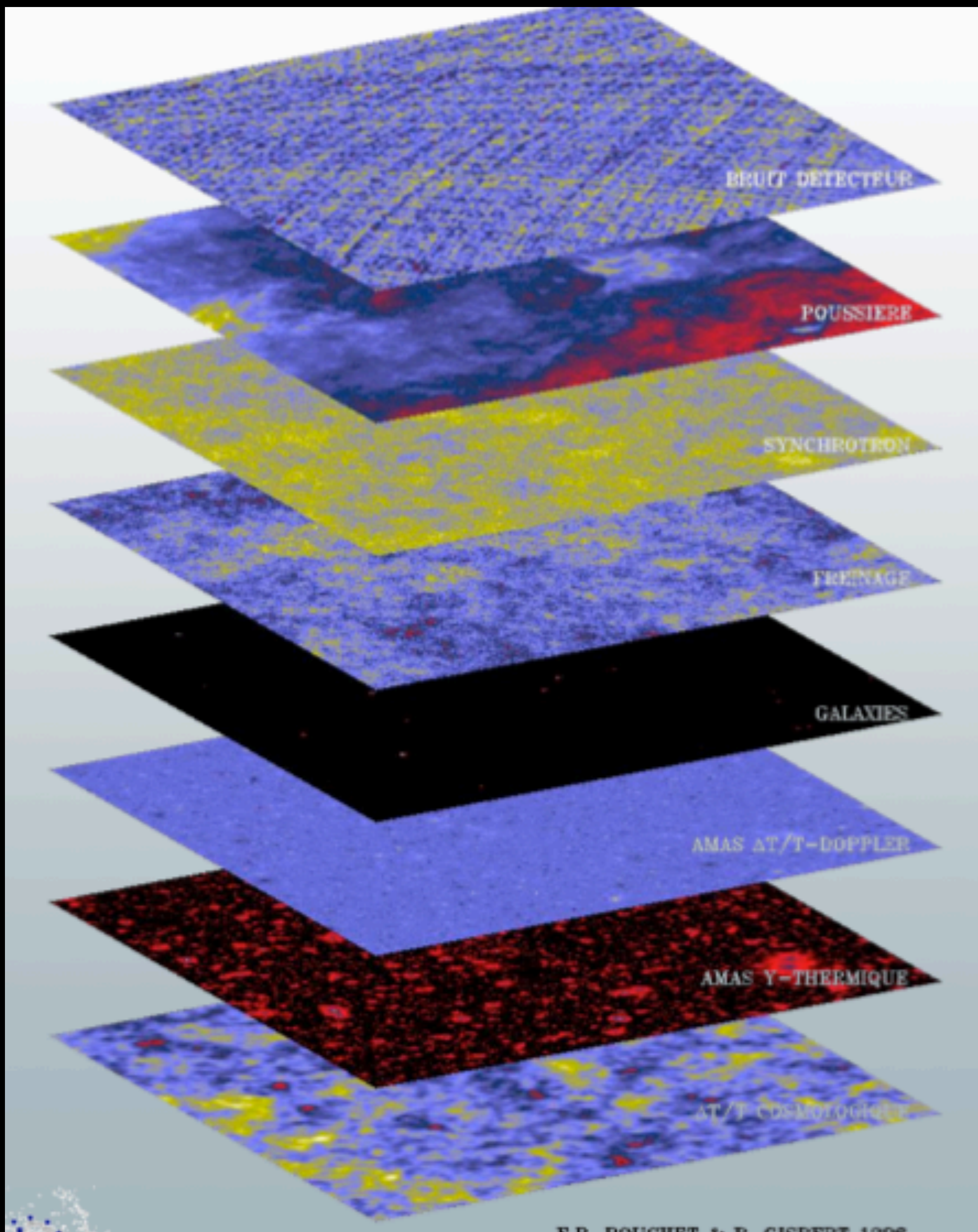
The Planck challenge

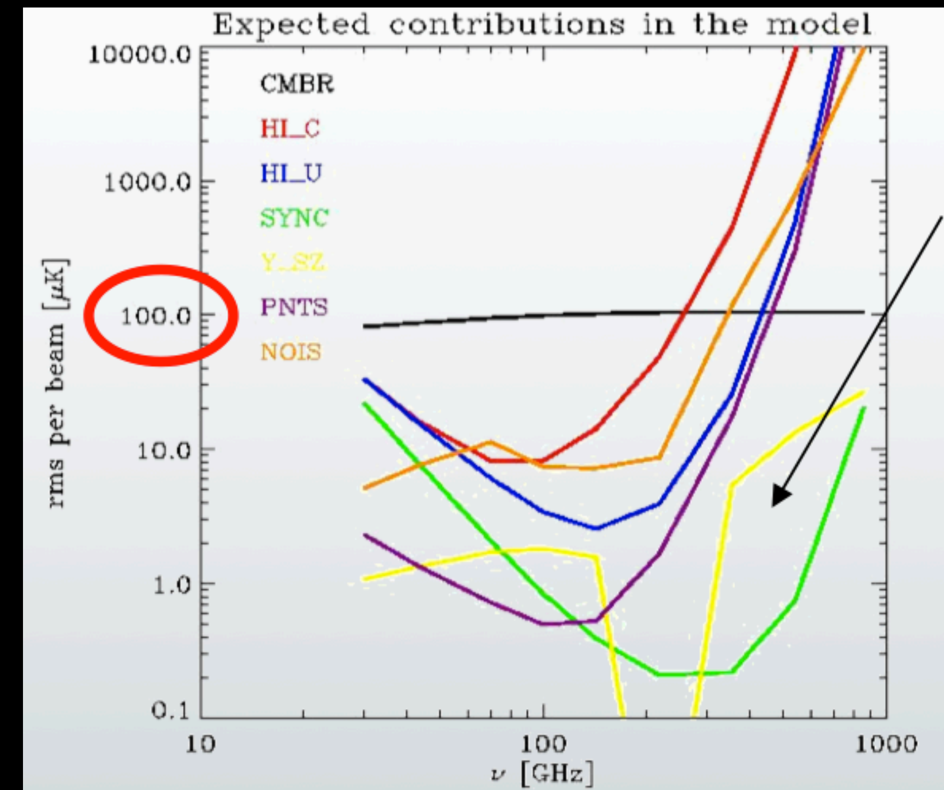
- To perform the "ultimate" measurement of the Cosmic Microwave Background (CMB) temperature anisotropies, needed:
  - full sky coverage and angular resolution, to survey all scales at which the CMB primary anisotropies contain information (~5')
  - sensitivity, essentially limited by ability to remove the astrophysical foregrounds
    - enough sensitivity within large frequency range [30 GHz, 1 THz] (~CMB photon noise limited for ~1 year in CMB primary window)
- Get the best performances possible on the polarization with the technology available
- ESA selection in 1996   (after ~ 3 year study)
- NB: with the Ariane 501 failure delaying us by several years (2003 ➡ 2007) and WMAP then flying well before us, polarization measurements became more and more a major goal

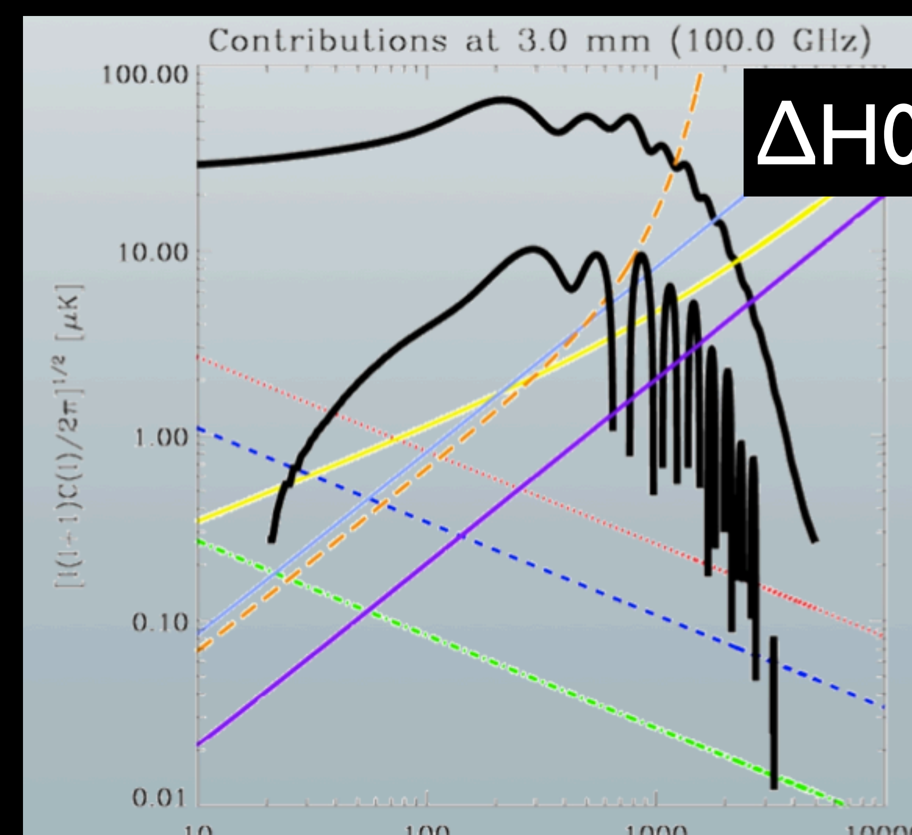
The target at selection time



Foregrounds







ΔH0 = 2%

Performance goals

Telescope	1.5 m (proj. aperture) aplanatic; shared focal plane; system emissivity 1%								
	Viewing direction offset 85° from spin axis; Field of View 8°								
Instrument	LFI			HFI					
Center Freq. (GHz)	30	44	70	100	143	217	353	545	857
Detector Technology	HEMT LNA arrays			Bolometer arrays					
Detector Temperature	~20 K			0.1 K					
Cooling Requirements	H_2 sorption cooler			H_2 sorption + 4 K J-T stage + Dilution cooler					
Number of Unpol. Detectors	0	0	0	0	4	4	4	4	4
Number of Linearly Polarised Detectors	4	6	12	8	8	8	8	0	0
Angular Resolution (FWHM, arcmin)	33	24	14	9.5	7.1	5	5	5	5
Bandwidth (GHz)	6	8.8	14	33	47	72	116	180	283
Average $\Delta T/T_I$* per pixel#	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
Average $\Delta T/T_{U,Q}$* per pixel#	2.8	3.9	6.7	4.0	4.2	9.8	29.8		

* Sensitivity (1σ) to intensity (Stokes I) fluctuations observed on the sky, in thermodynamic temperature ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

\# A pixel is a square whose side is the FWHM extent of the beam.

* Sensitivity (1σ) to polarised intensity (Stokes U and Q) fluctuations observed on the sky, in thermodynamic temperature ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

Planck breakthroughs

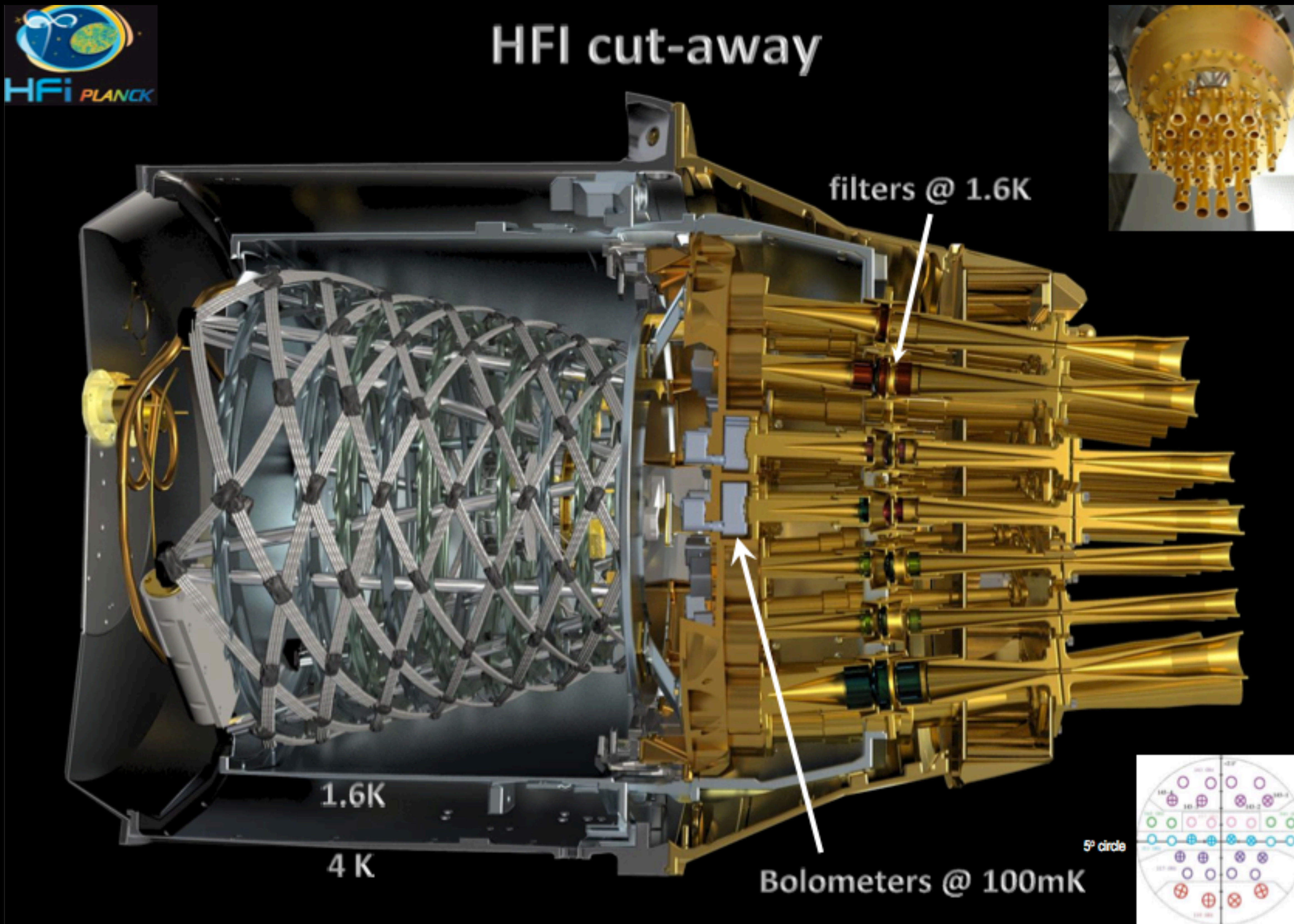
- Technological performance never achieved in space before :
  - sensitive and fast bolometers for HFI
    - NEP < 2.10^{-17} W/Hz$^{1/2}$, time constant ~ 5 ms (requires cooling at 100 mK)
    - low noise electronics : 6 nV/Hz$^{1/2}$, from 10 mHz to 100 Hz
    - excellent temperature stability from 10 mHz to 100 Hz
      - < 10 μK/Hz$^{1/2}$ for 4 K box
      - < 30 μK/Hz$^{1/2}$ for 1.6 K filter plate
      - < 20 nK//Hz$^{1/2}$ for 100 mK detector plate
  - low noise HEMT amplifier for LFI

Planck breakthroughs

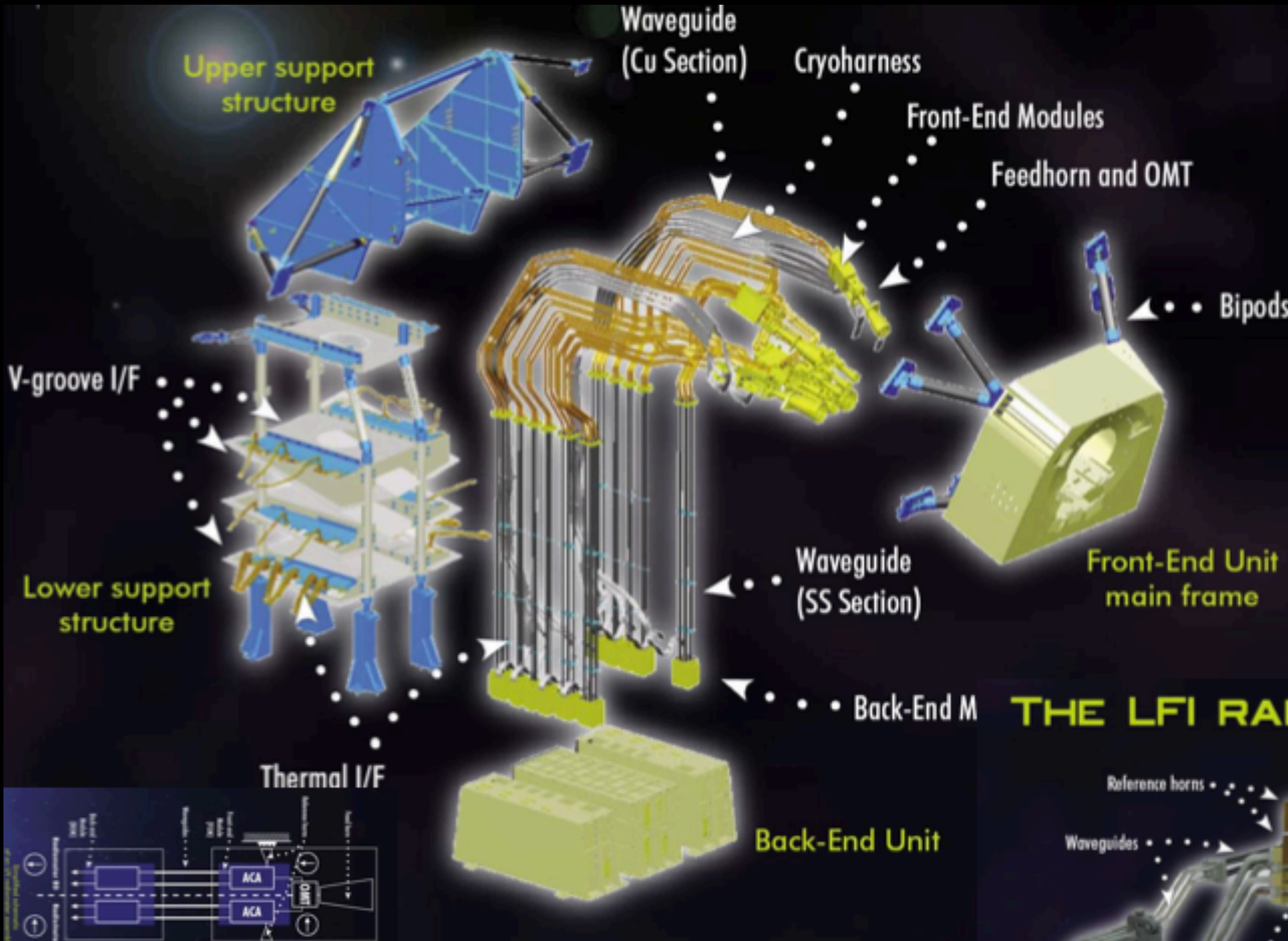
- Low emissivity, very low side lobes telescope
- minimum warm surface in front of detectors
- complex cryogenic cooling chain : 50 K (passive) + 20K, 4K, 0.1K active coolers
  - 20K for LFI
  - 4K, 1.6K and 100mK for HFI
  - Thermal architecture optimised to damp thermal fluctuations
- Integration of 3 complex chains - electronic, optics, cryogenics

Planck satellite

High Frequency Instrument

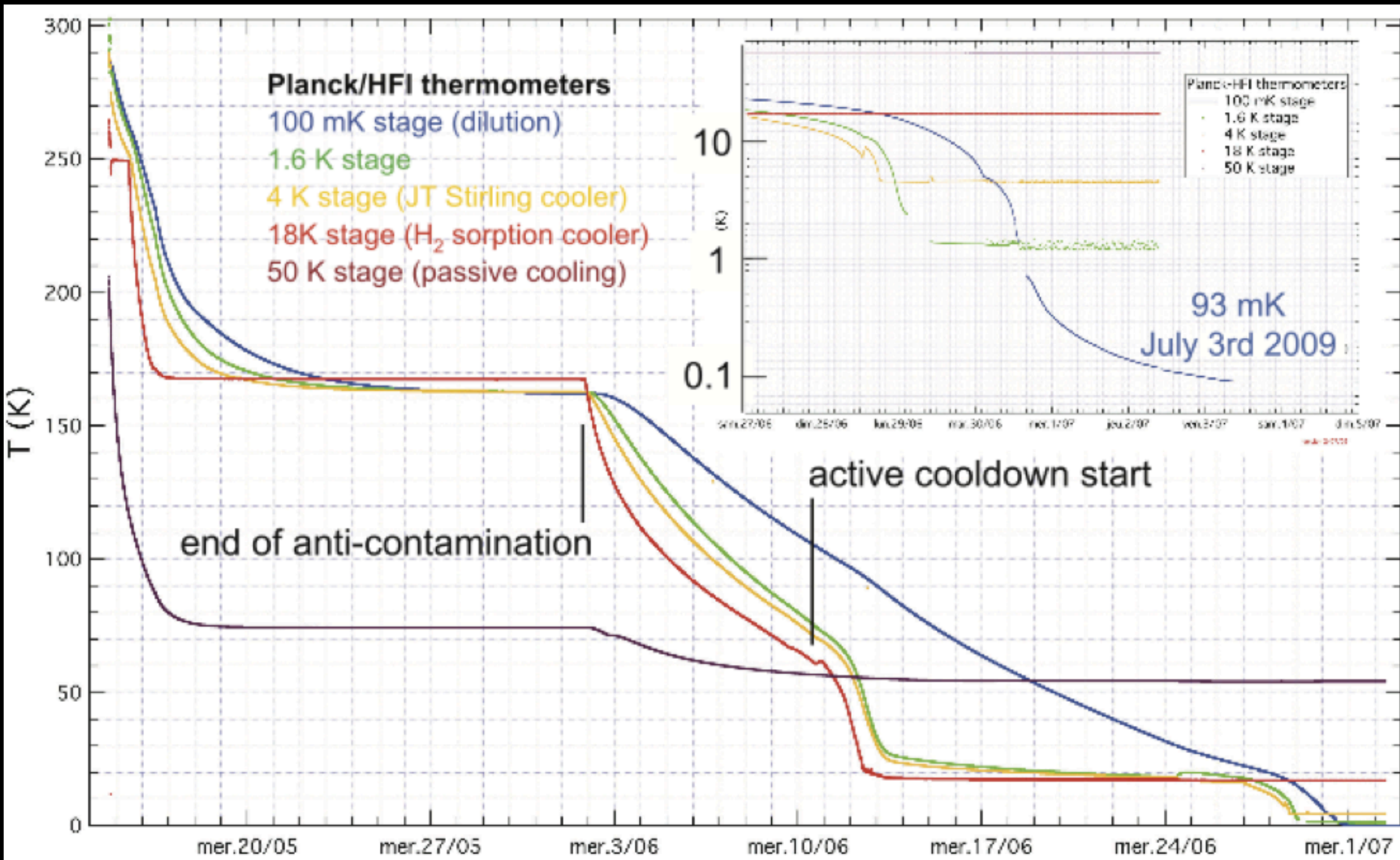


Low Frequency Instrument



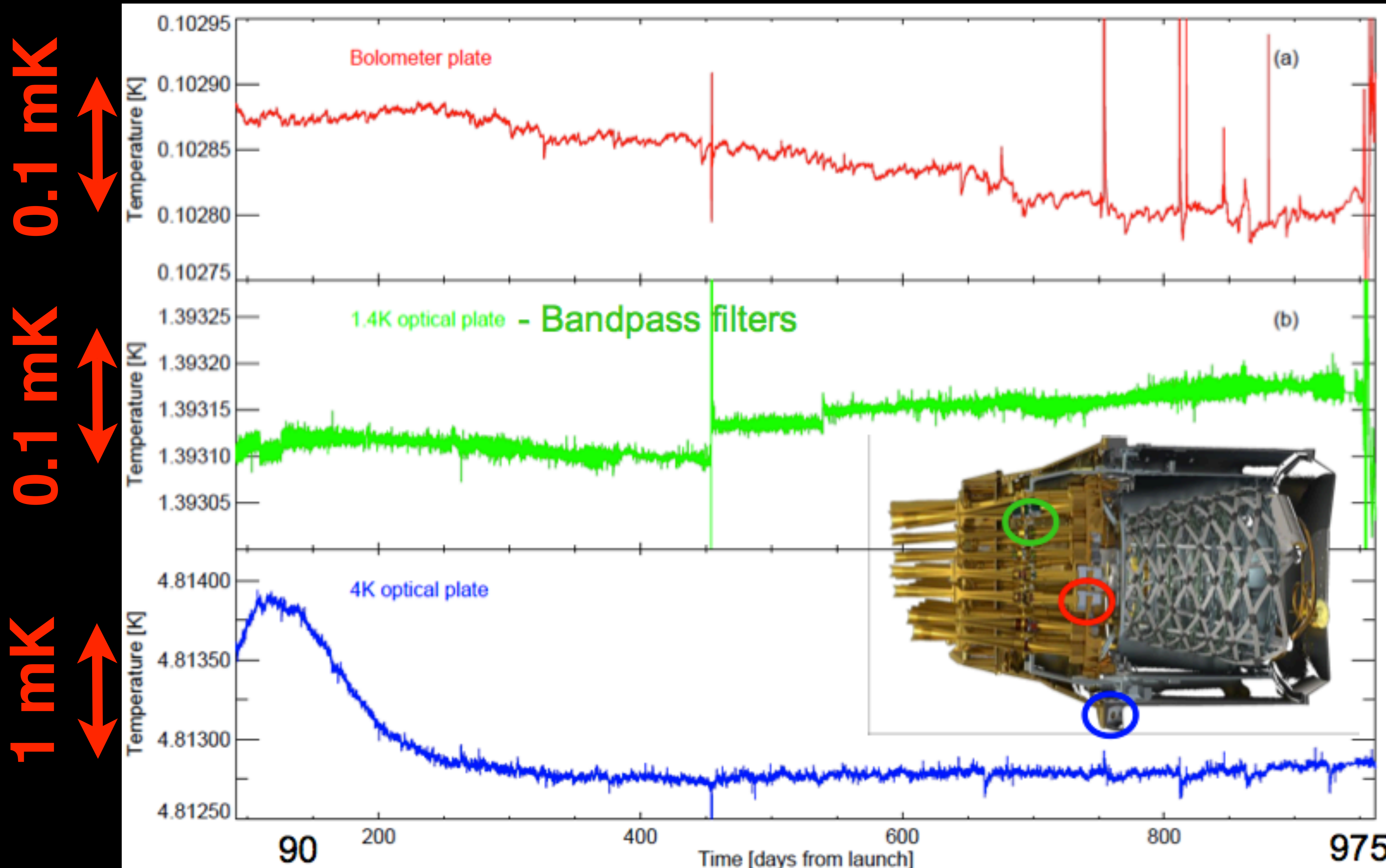
Launch on 14th May 2009

Cooling



Planck/HFI thermometers
100 mK stage (dilution)
1.6 K stage
4 K stage (JT Stirling cooler)
18K stage (H_2 sorption cooler)
50 K stage (passive cooling)
end of anti-contamination
active cooldown start
T (K)
300
250
200
150
100
50
0
mer.20/05
mer.27/05
mer.3/06
mer.10/06
mer.17/06
mer.24/06
mer.1/07
10
1
0.1
93 mK
July 3rd 2009

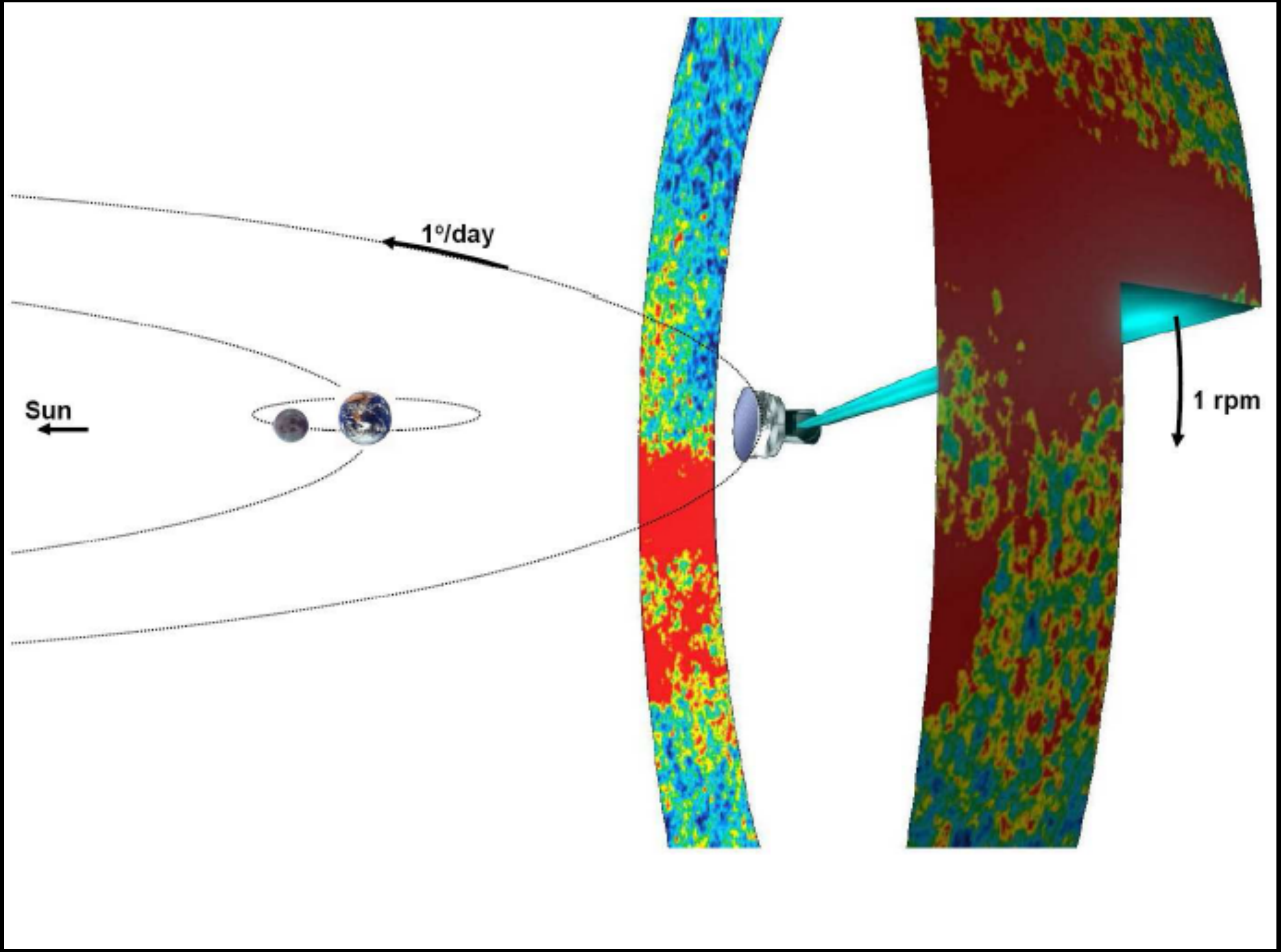
Temperature stability



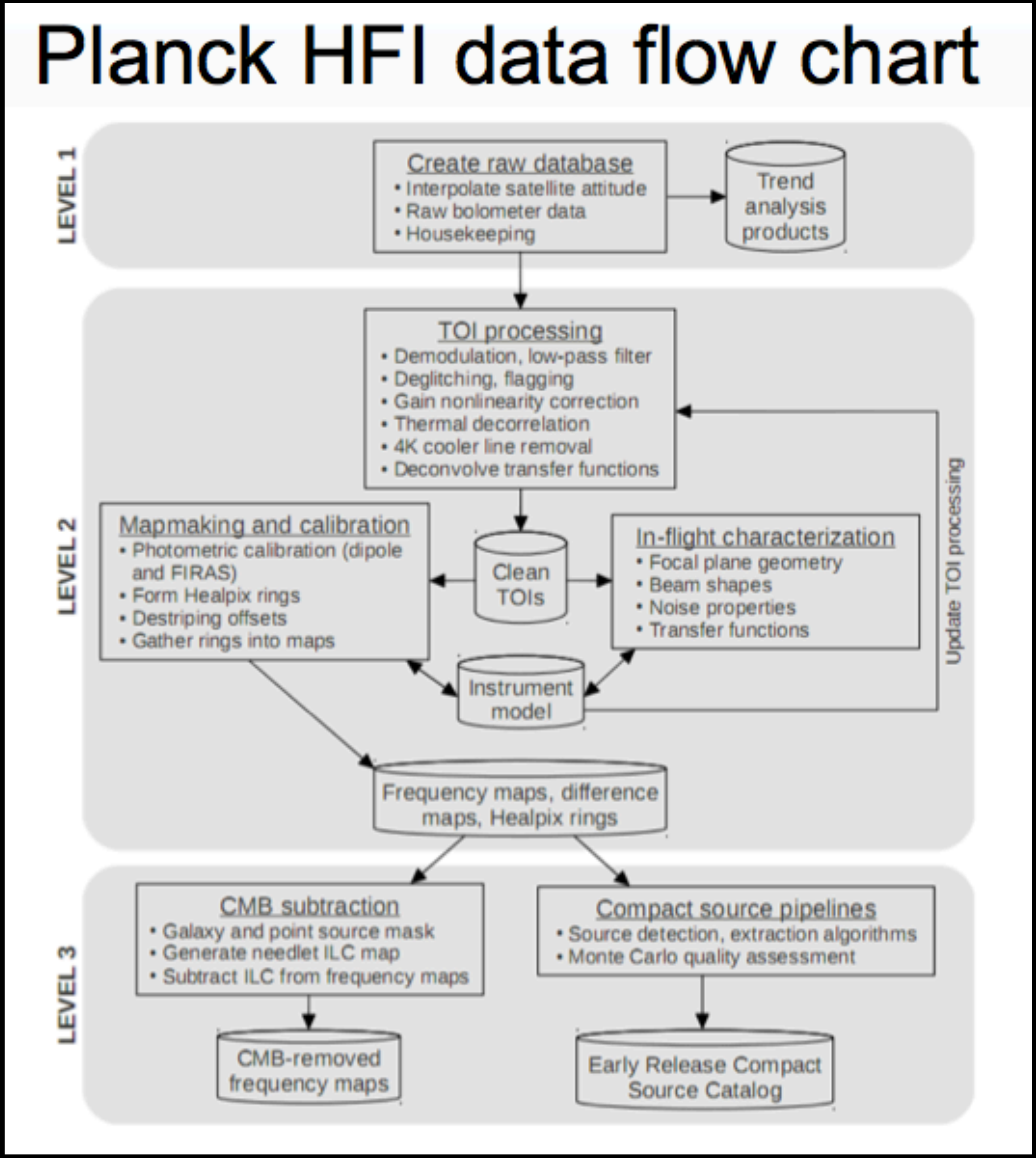
Short Log book

- Start of survey on August 13th 2009, instruments very stable
- No major problem till the end of life of HFI (January 2012)
- Expected sensitivies achieved in flight: HFI reaches or exceeds its goals
- June 2010: first full sky maps obtained with 10 months of data. Planck early results in January 2011
- November 2010: nominal mission completed (15.5 months), the sky has been seen twice by all detectors
  - public data delivery in 21st March 2012 with 28 “Planck early results” papers
- January 12th 2012 : all HFI data acquired. 5 surveys (twice the nominal duration). Next data delivery in mid-2014.

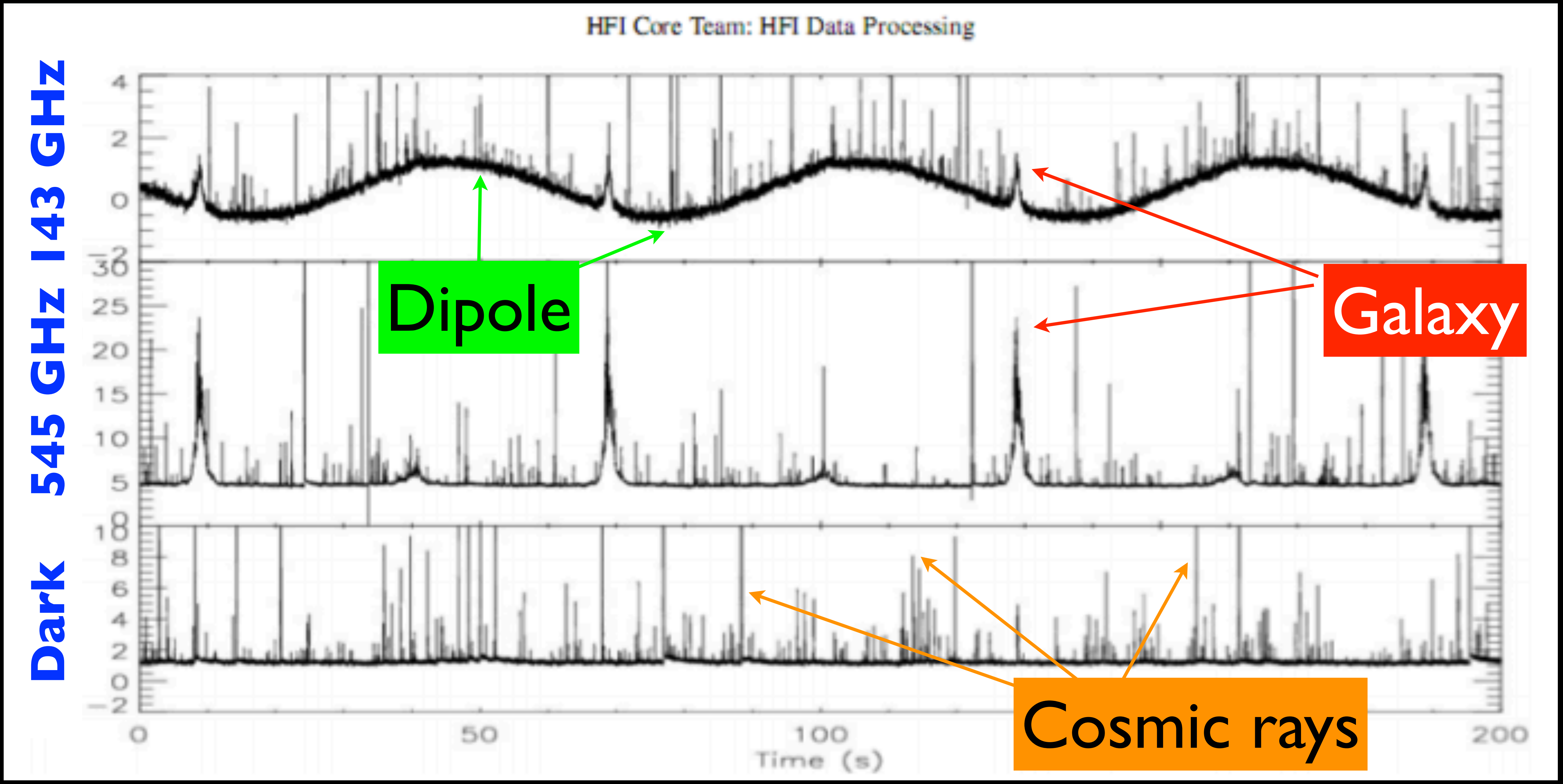
Scanning strategy



Data processing



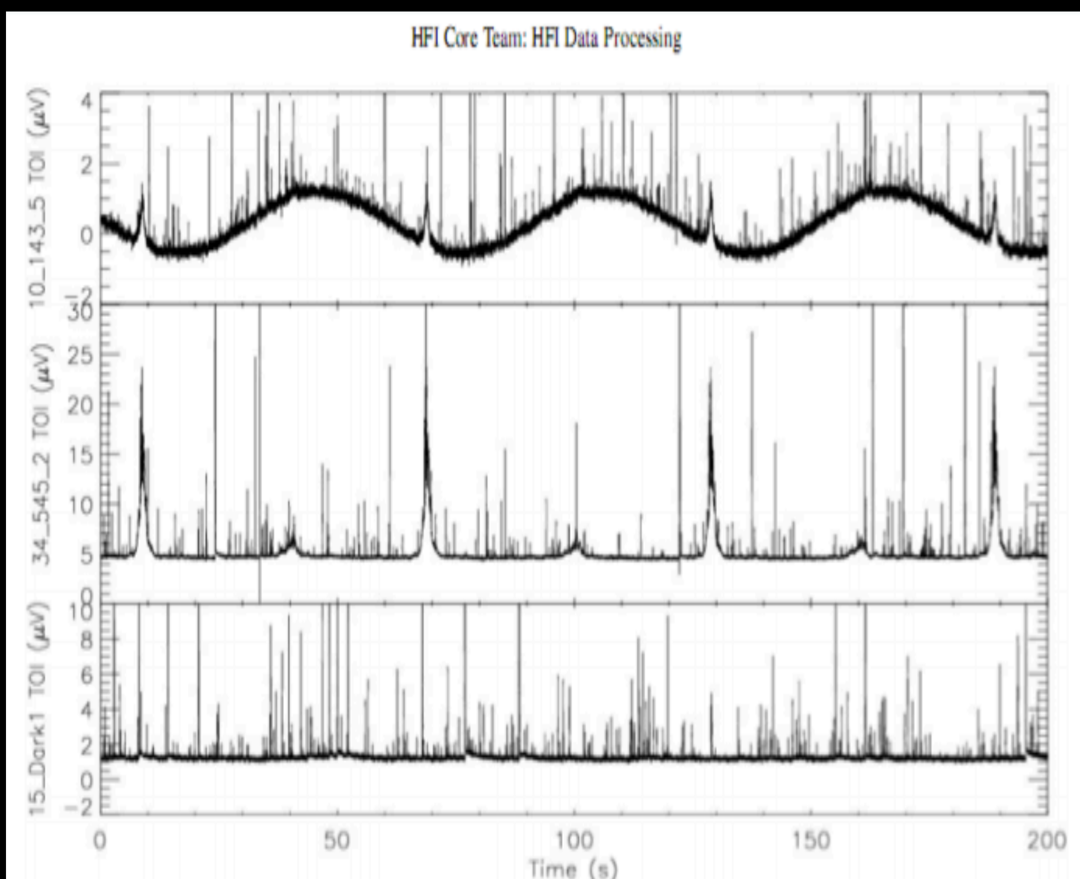
HFI raw detector signal

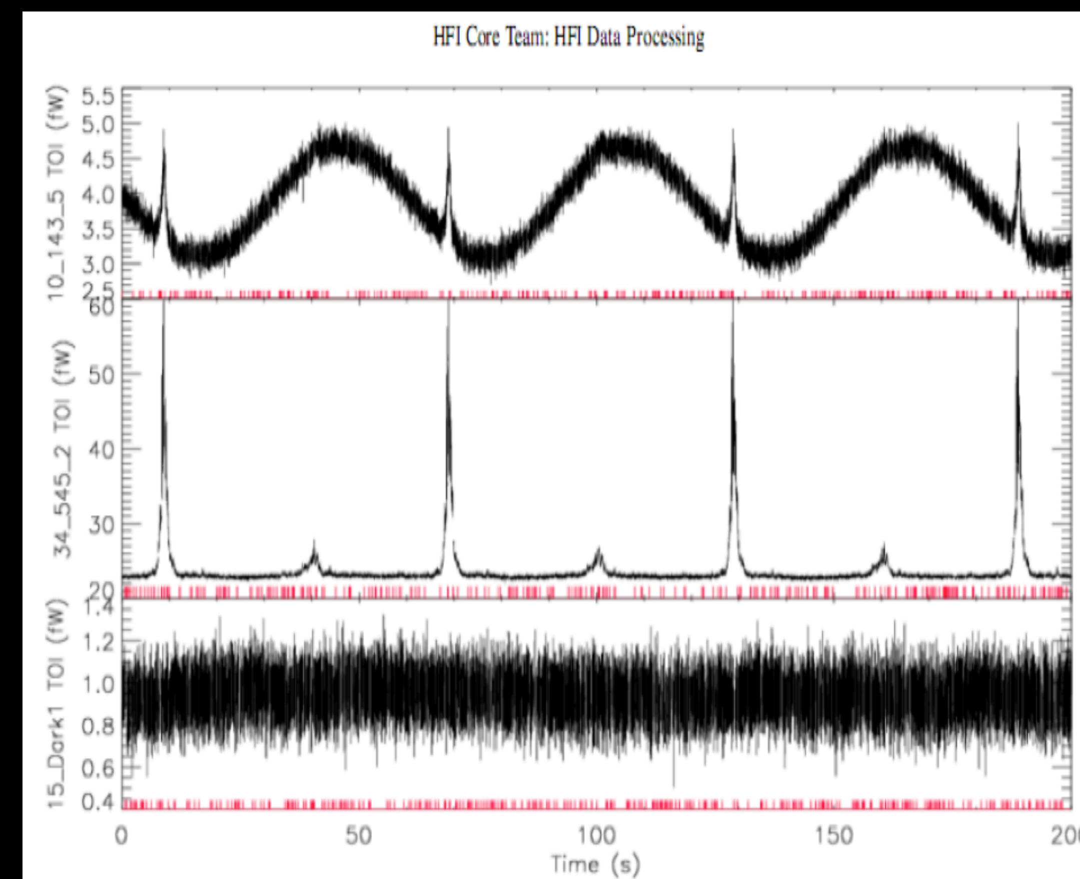


3 min of demodulated raw data

Cleaning data

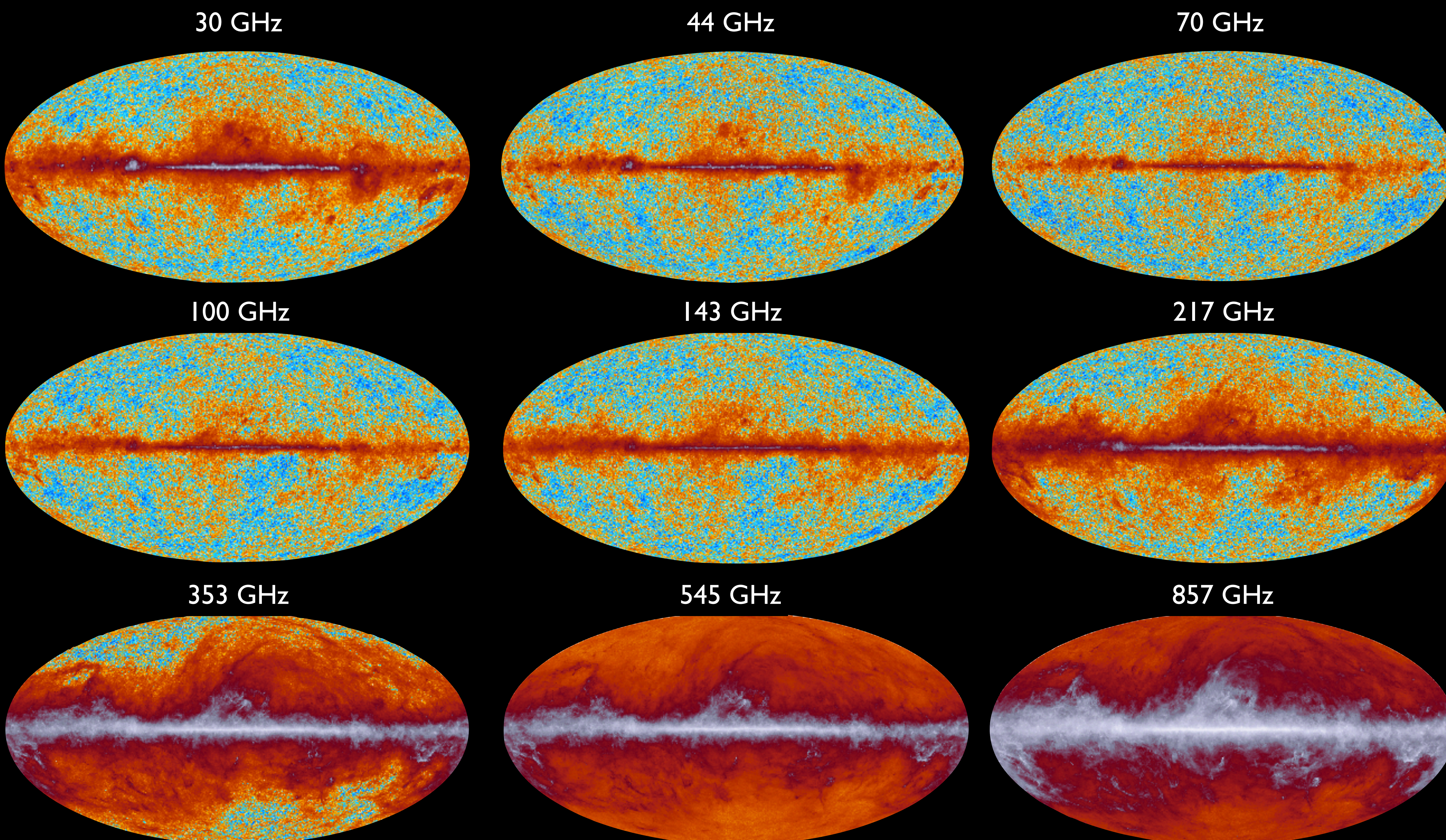
More glitches than expected :
use of redundancy to remove them



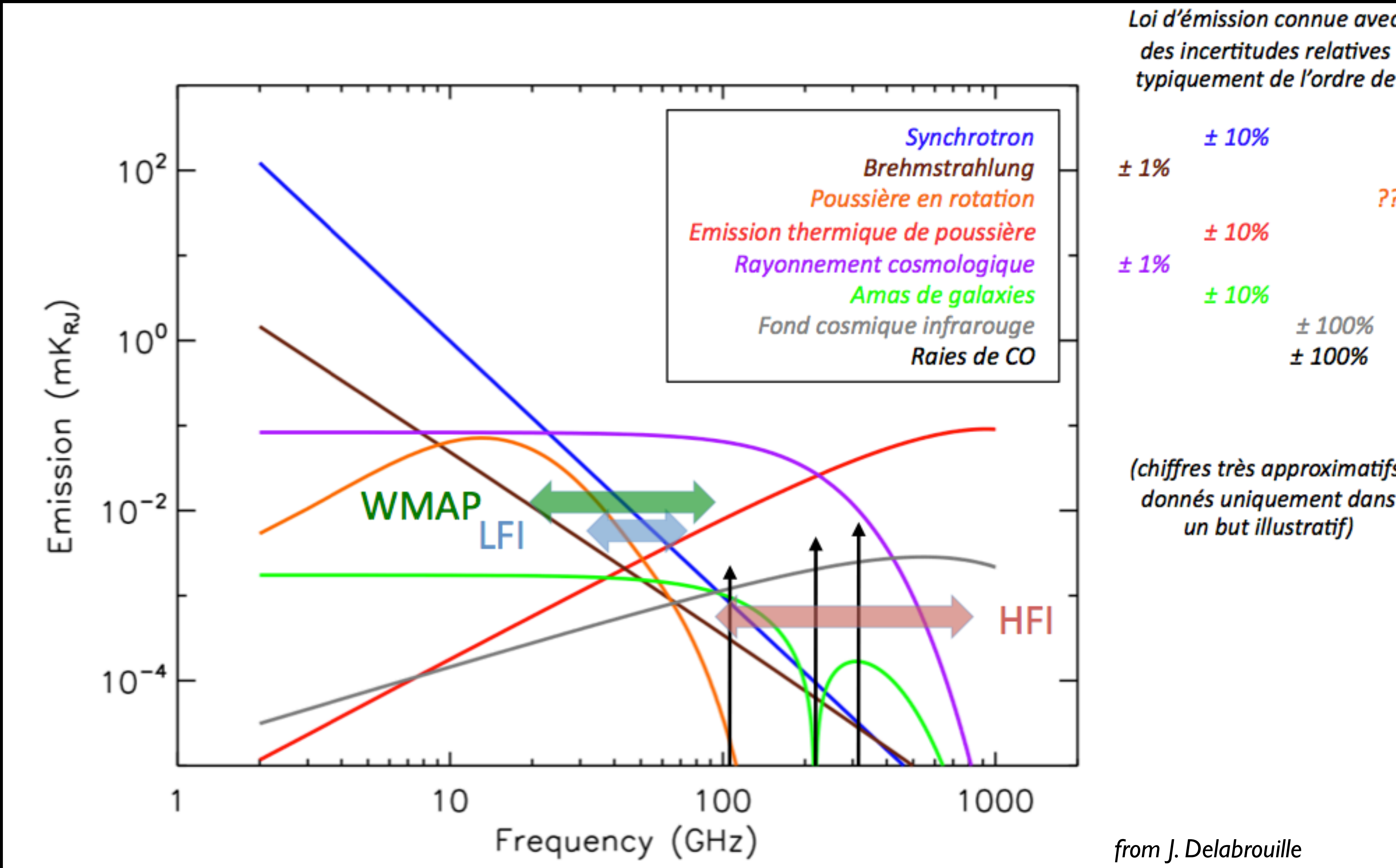


From μV to fW (calibration)

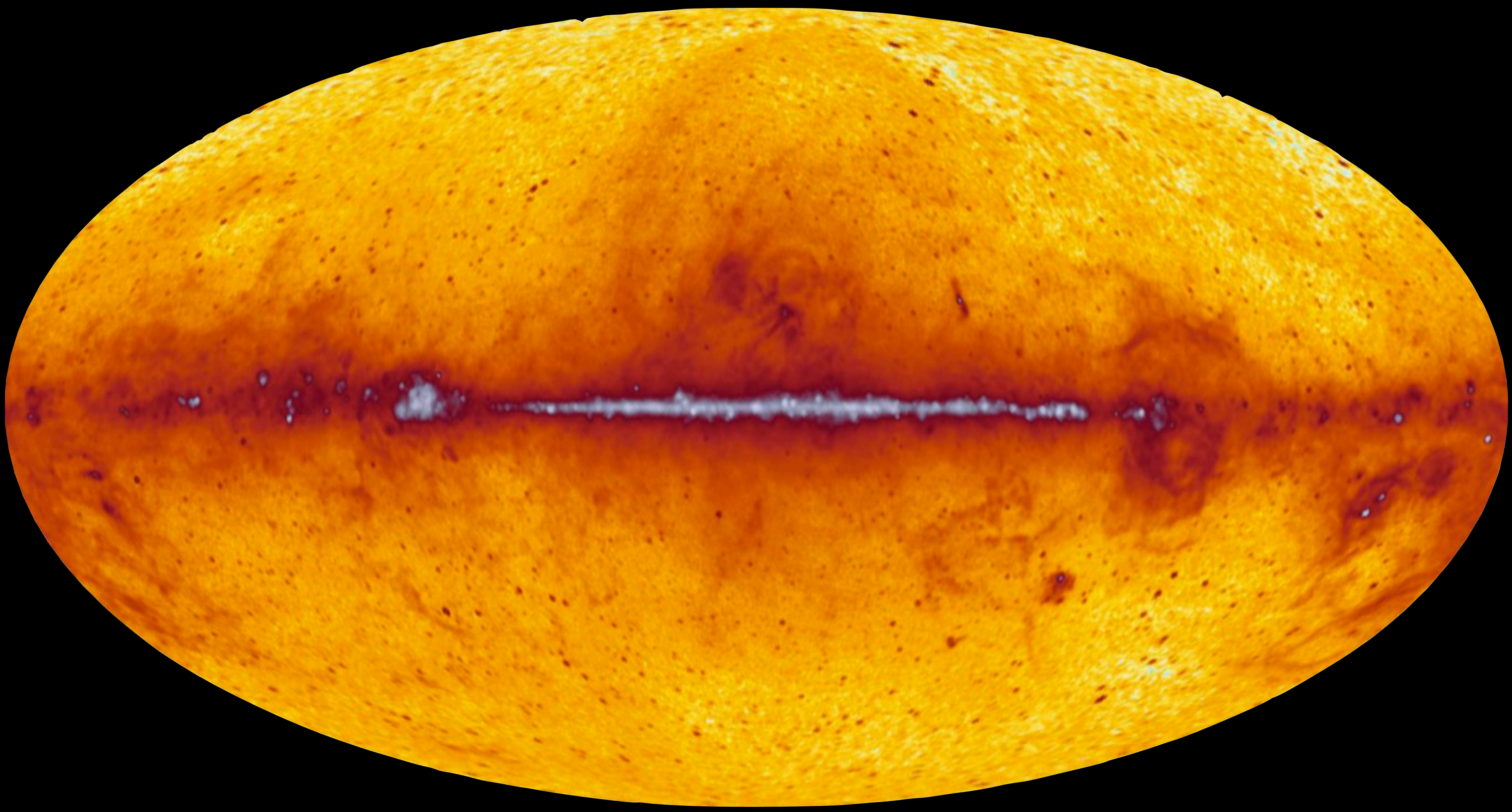
Sky as seen by Planck



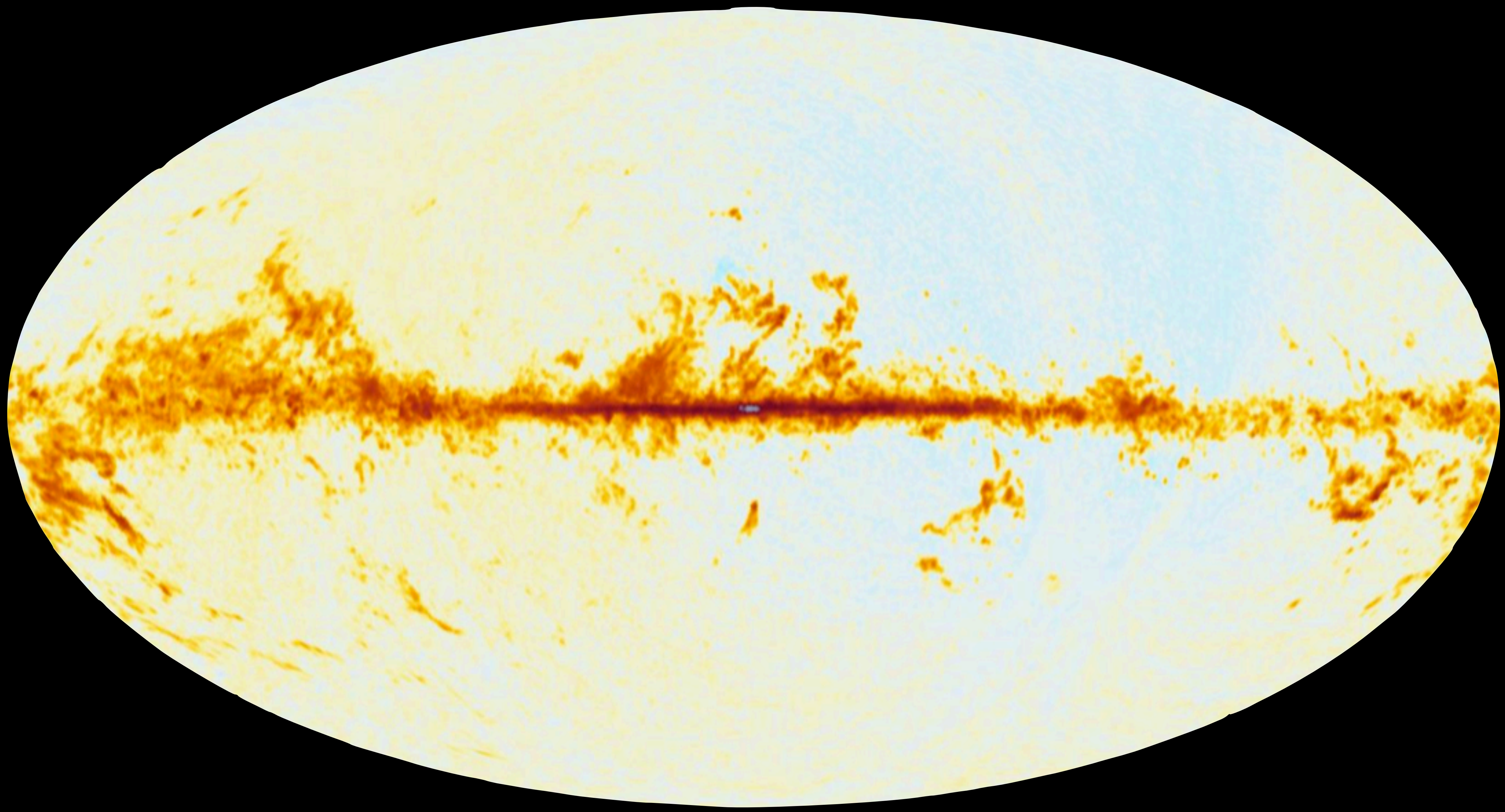
Foreground components



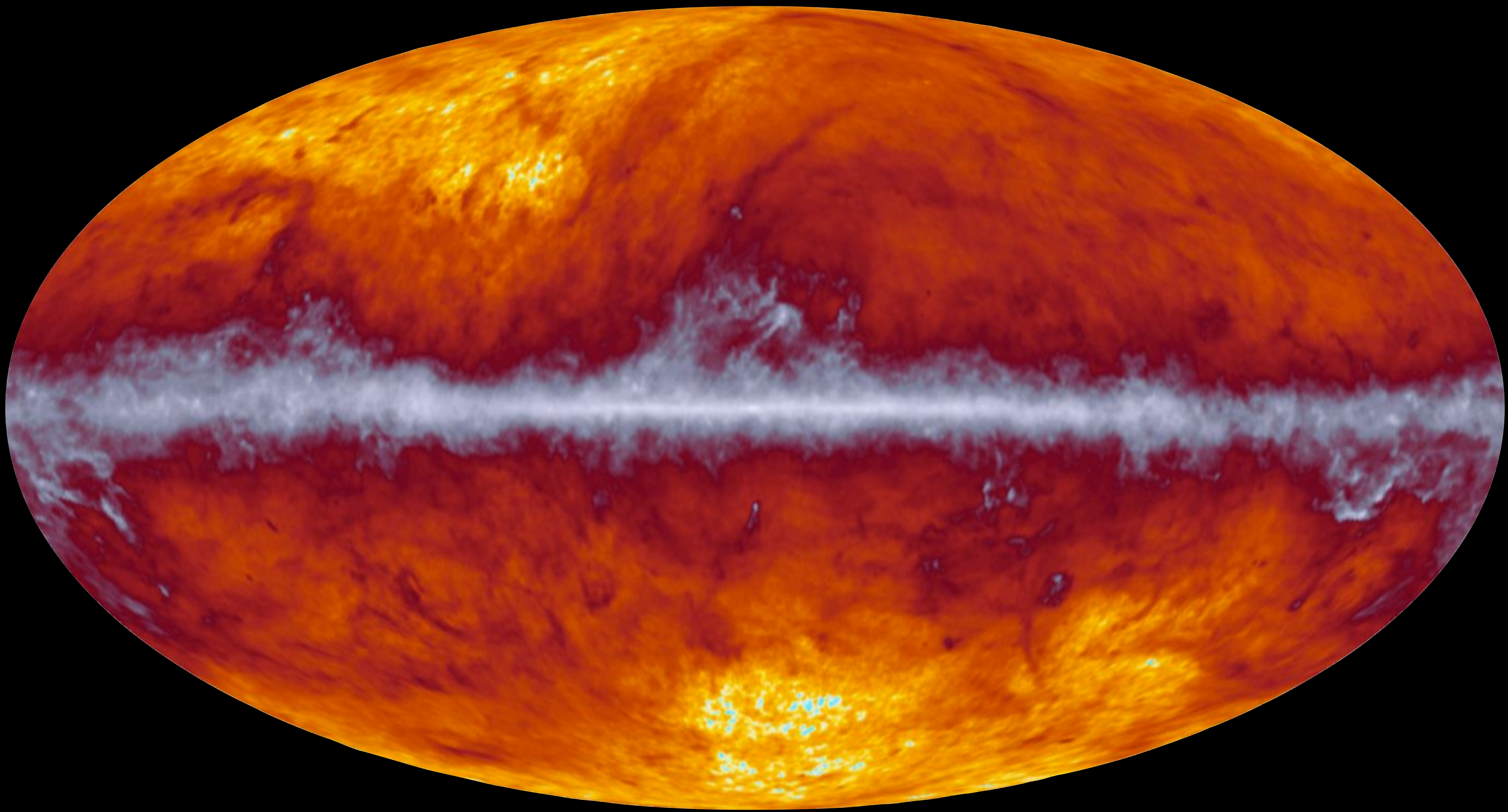
Low frequency emission



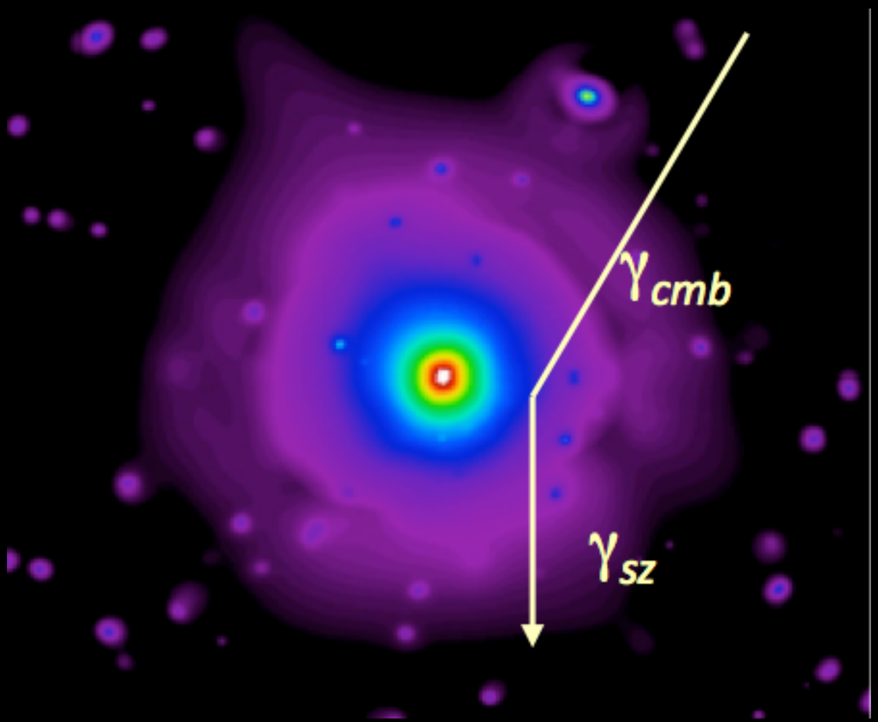
Reconstructed CO map

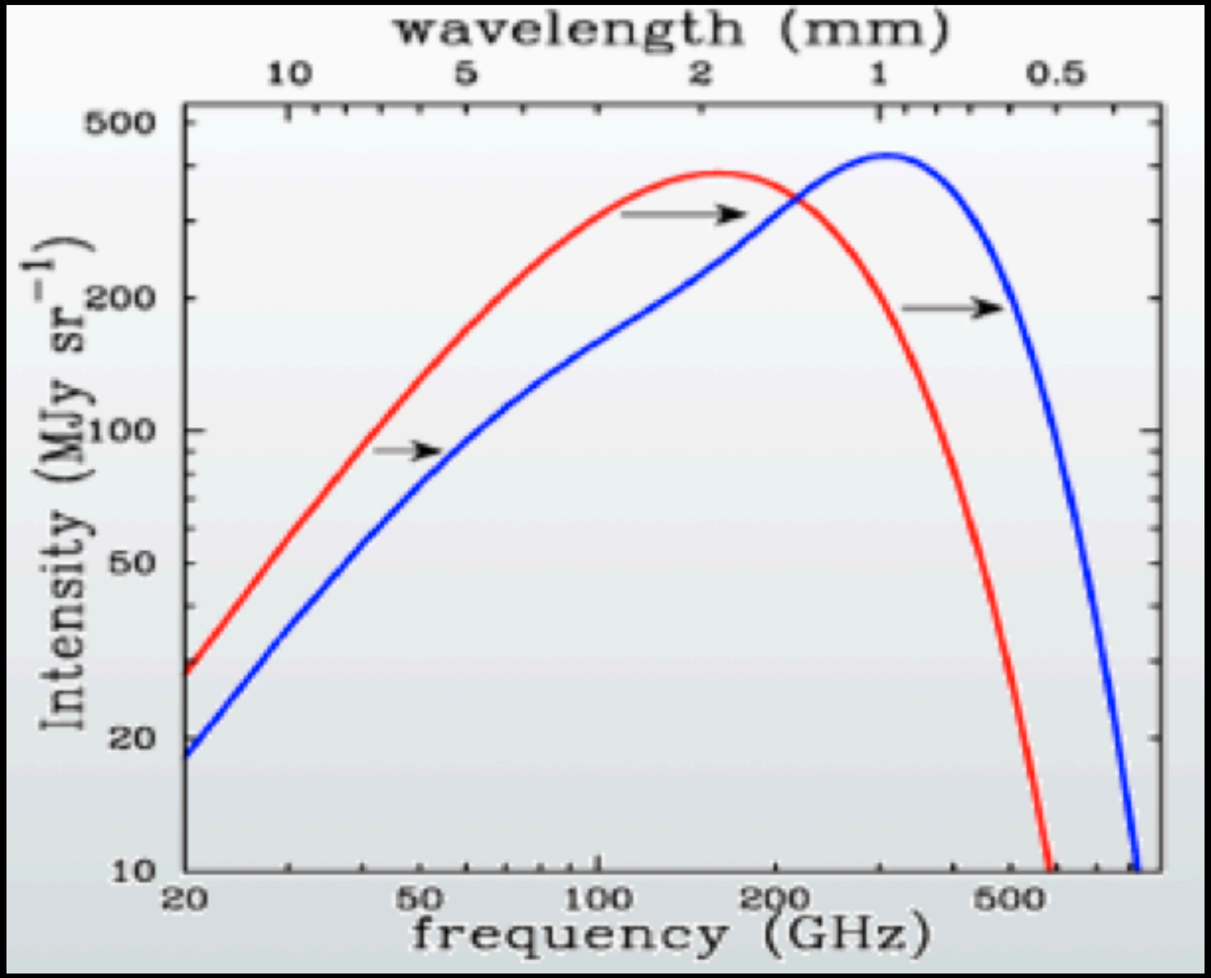


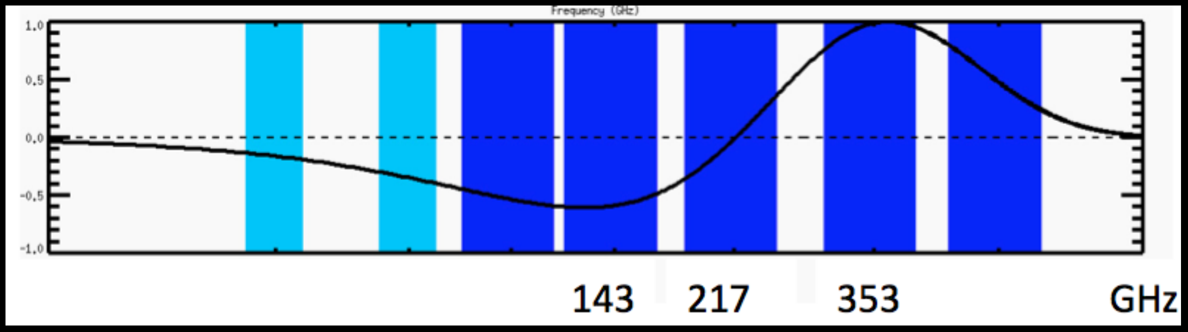
Dust emission



Sunyaev-Zeldovich effect

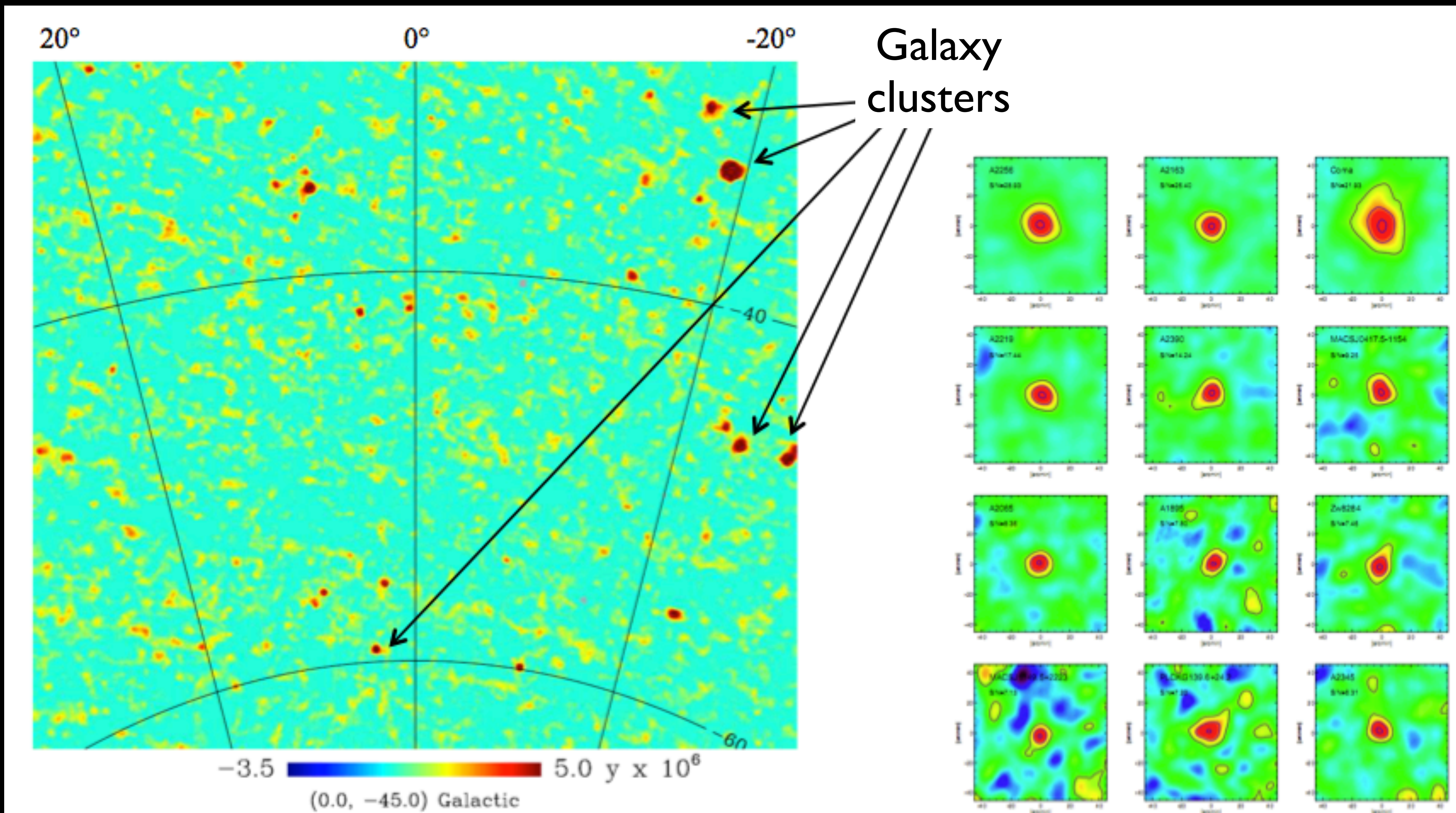




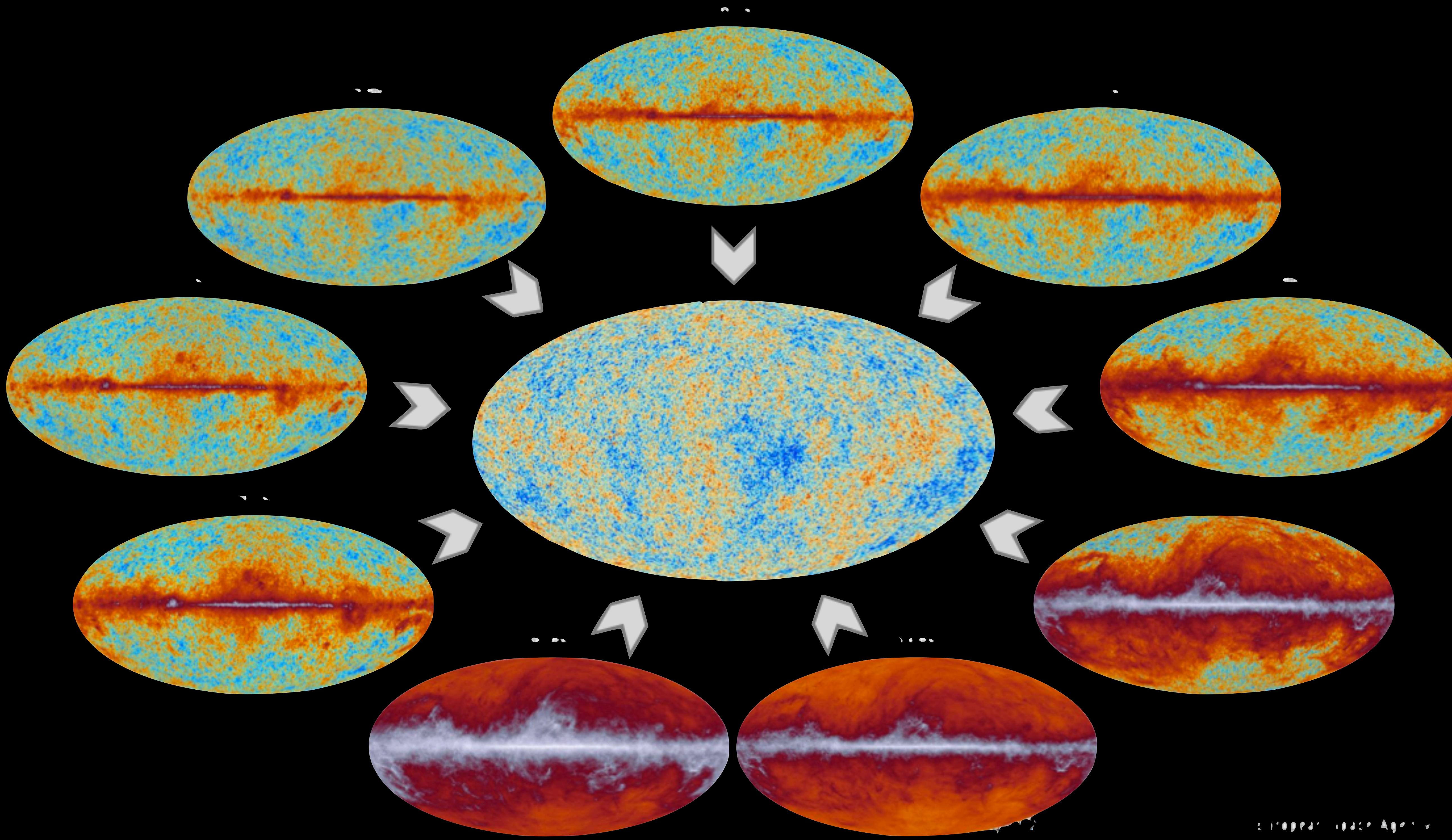


- Inverse Compton interaction between CMB photons and hot gas in clusters (~millions of K)
- Can be detected at high redshift
- Allow estimation of mass of clusters
- Gas fraction (M_{gaz}/M_{tot}) : linked to the universal ratio Ω_b/Ω_m

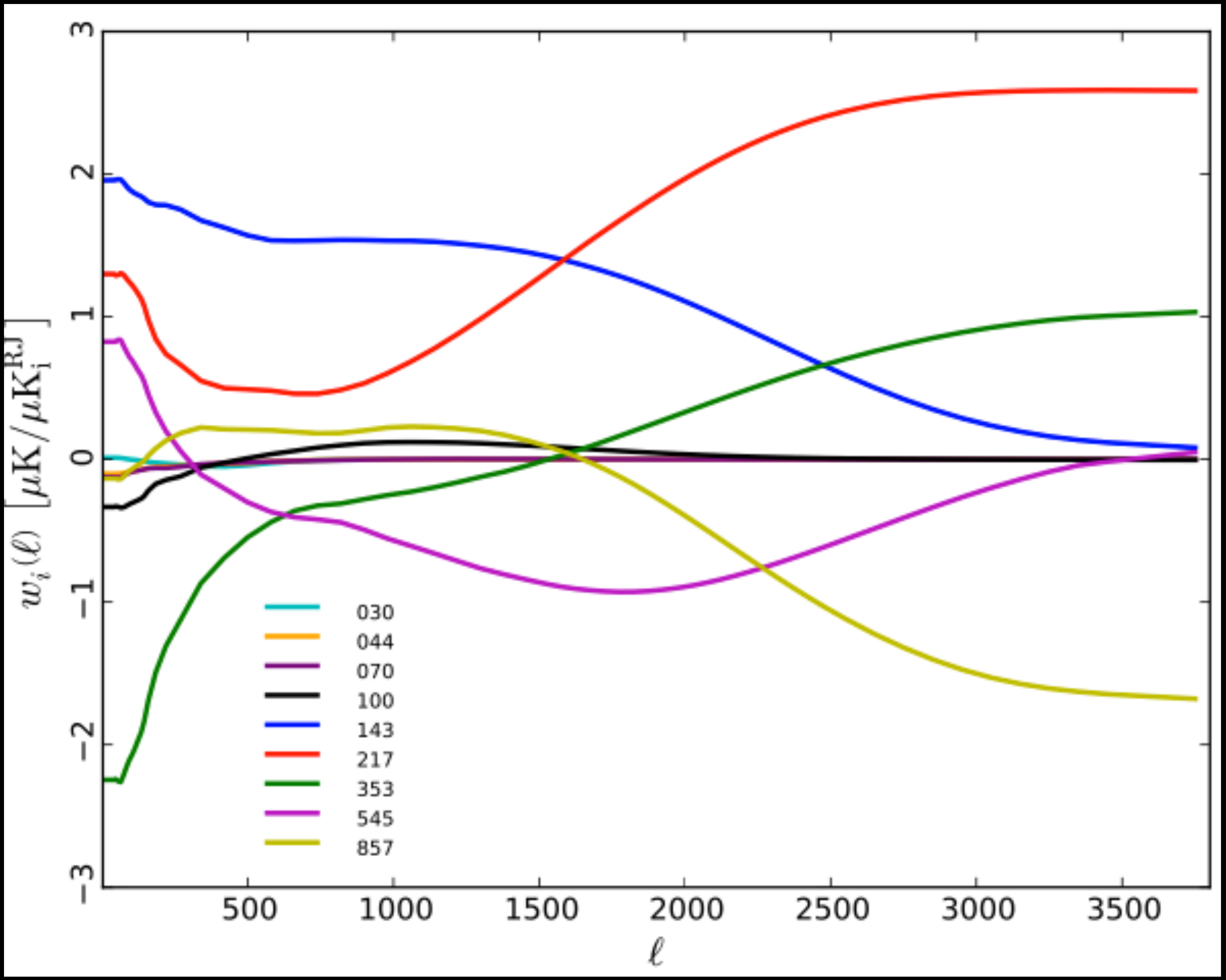
SZ sources


20°
0°
-20°
Galaxy clusters
-40
-60
−3.5
5.0 y x 10^6
(0.0, −45.0) Galactic
A2256
A2163
Coma
A2219
A2390
A2065
Zw8284
A2345

Cleaning the background

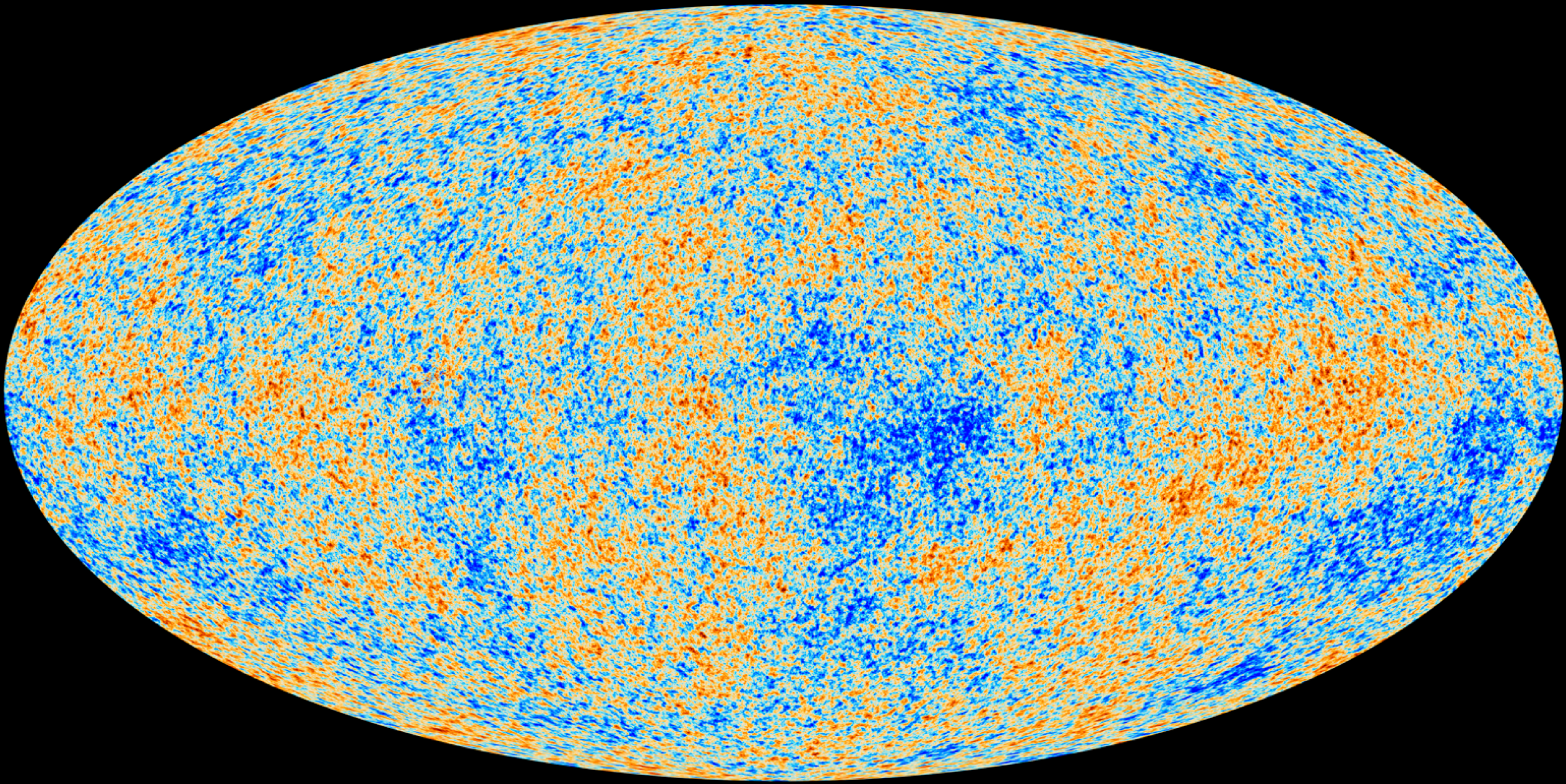


Cleaning the background

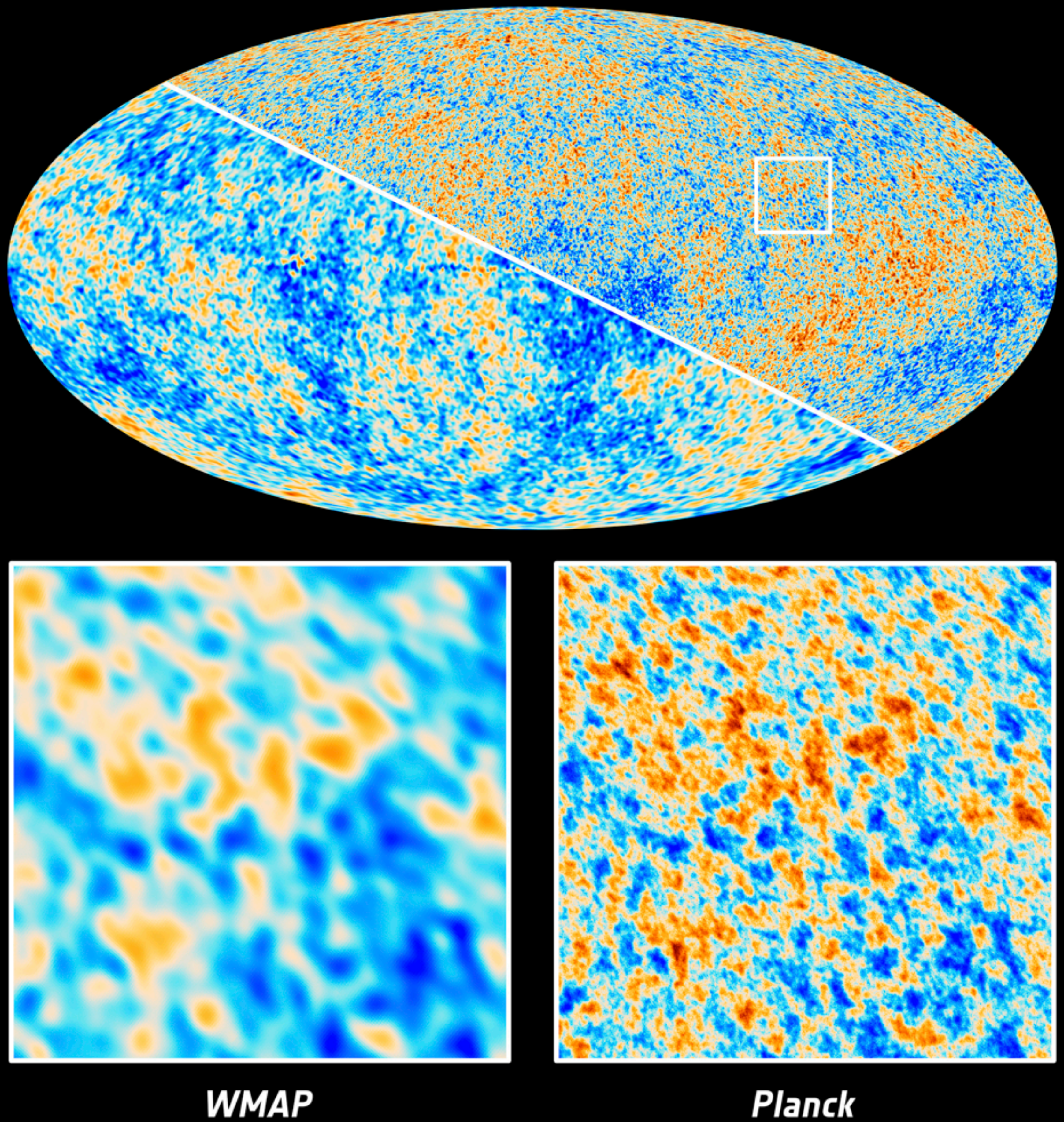


Contribution of each frequency channel on the final CMB map, depending on angular scale

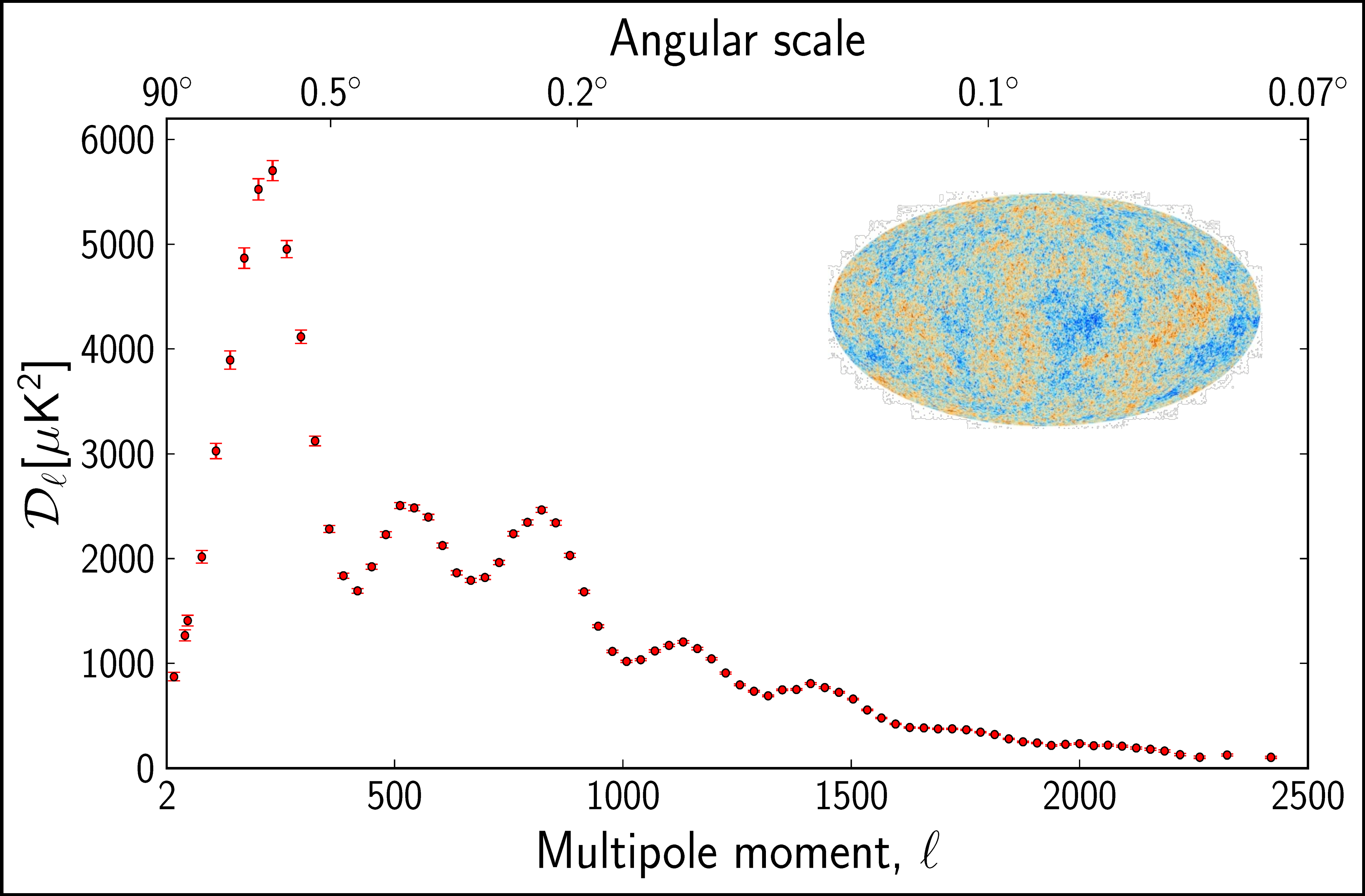
Final CMB map from Planck



The Cosmic Microwave Background as seen by Planck and WMAP



Angular power spectrum of CMB



Likelihood methodology

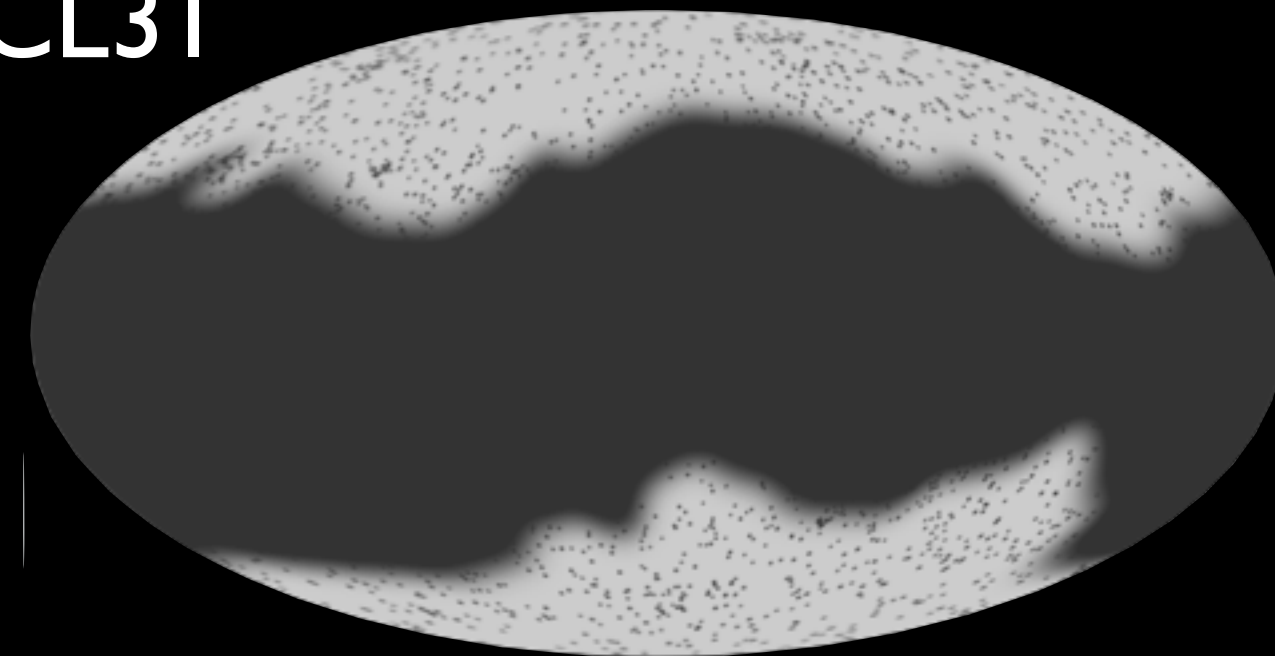
- Goal : provide P(Cl | Planck data)
- Hybrid multi-frequency likelihood approach:
  - Large scales (LL) : Gaussian likelihood on maps
  - Small scales (HL): Gaussian likelihood approximation on spectra
- Foregrounds residuals:
  - LL: parametrised at map level
  - HL: parametrised at the spectra level
- Validation:
  - Data selection
  - Null tests
  - Simulations

Data selection for HL

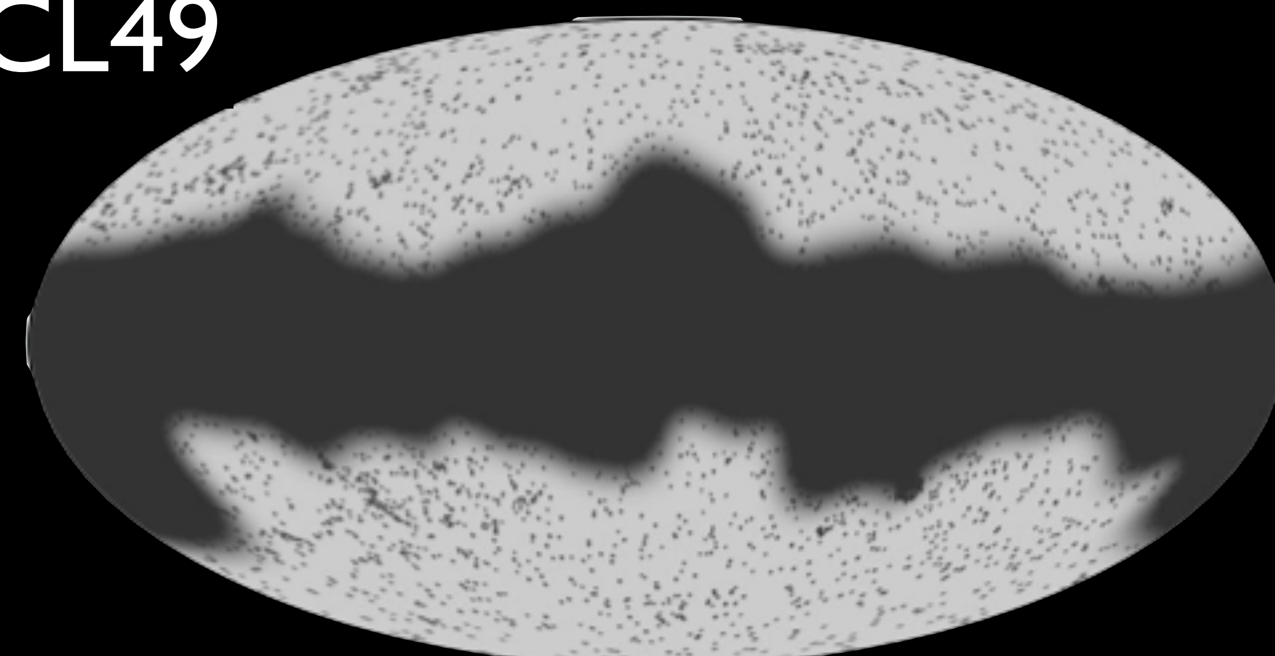
- Minimise foreground impacts
  - spatially
  - in multipole space
  - keeping low cosmic variance
- Galaxy : 353 GHz thresholding
- Sources : 100-353 GHz catalog
- Maps : keep easiest to model and most informative ones

Spectrum	Multipole range	Mask
100×100	50 – 1200	CL49
143×143	50 – 2000	CL31
143×217	500 – 2500	CL31
217×217	500 – 2500	CL31
Combined	50 – 2500	CL31/49

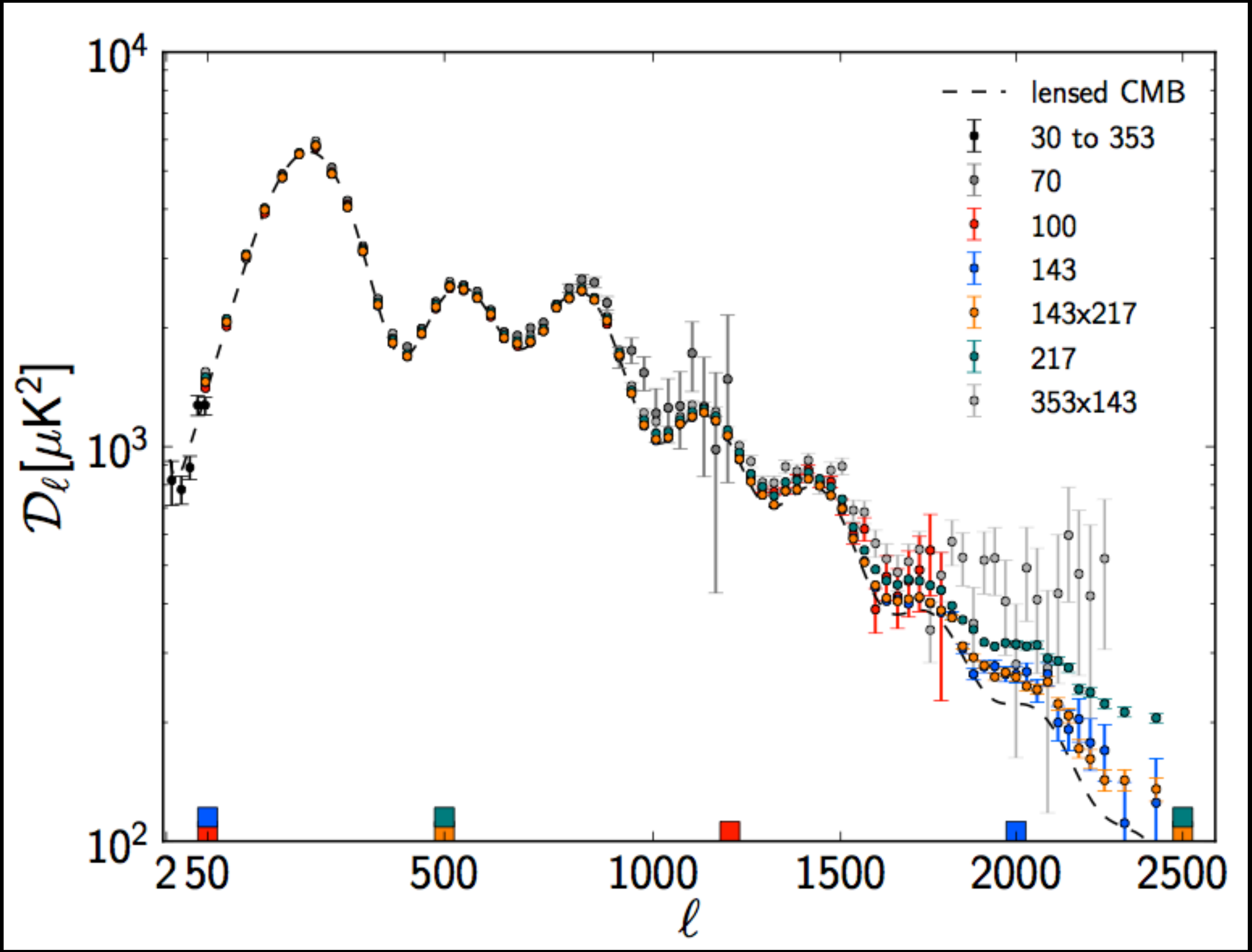
CL31



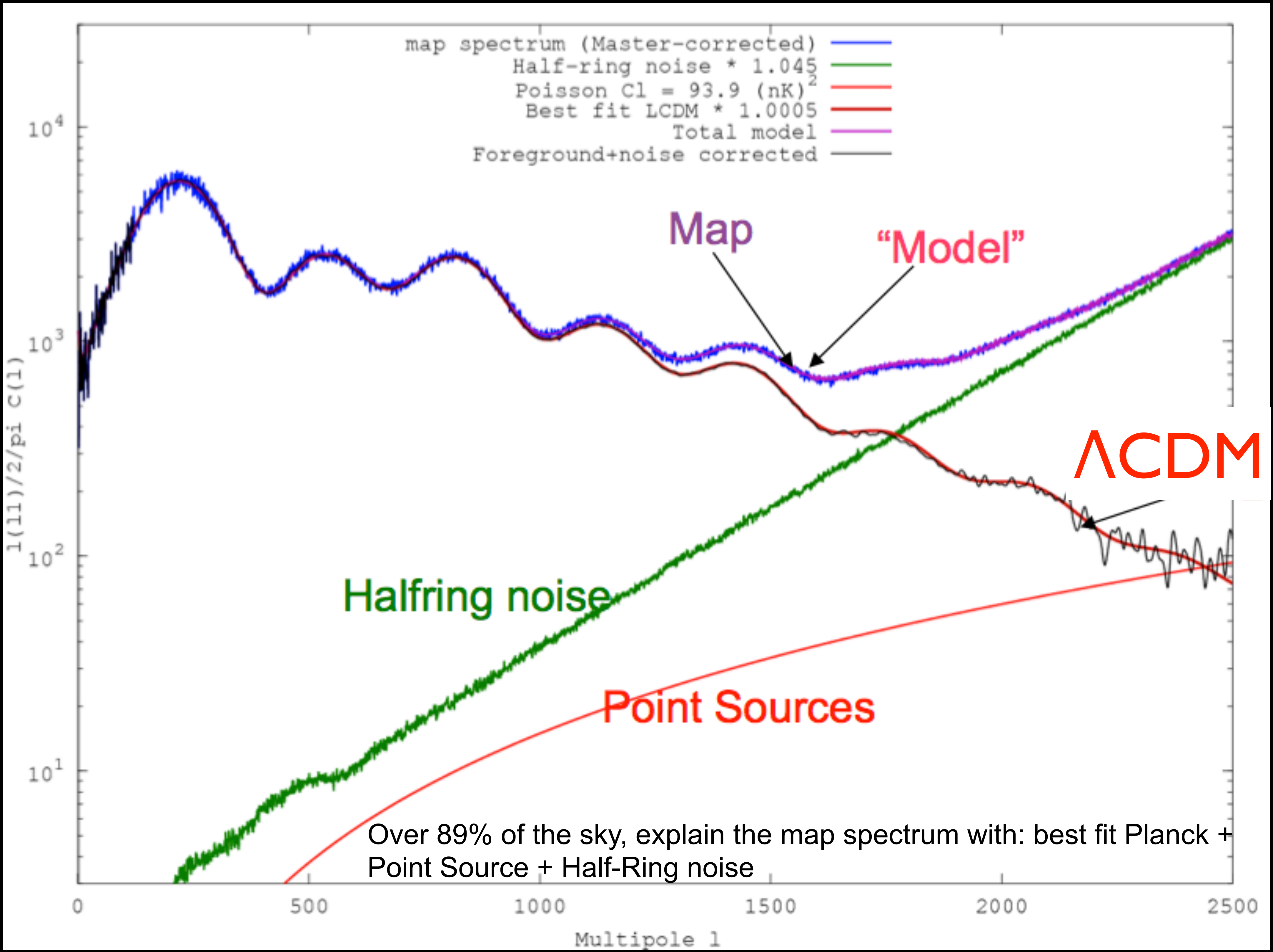
CL49



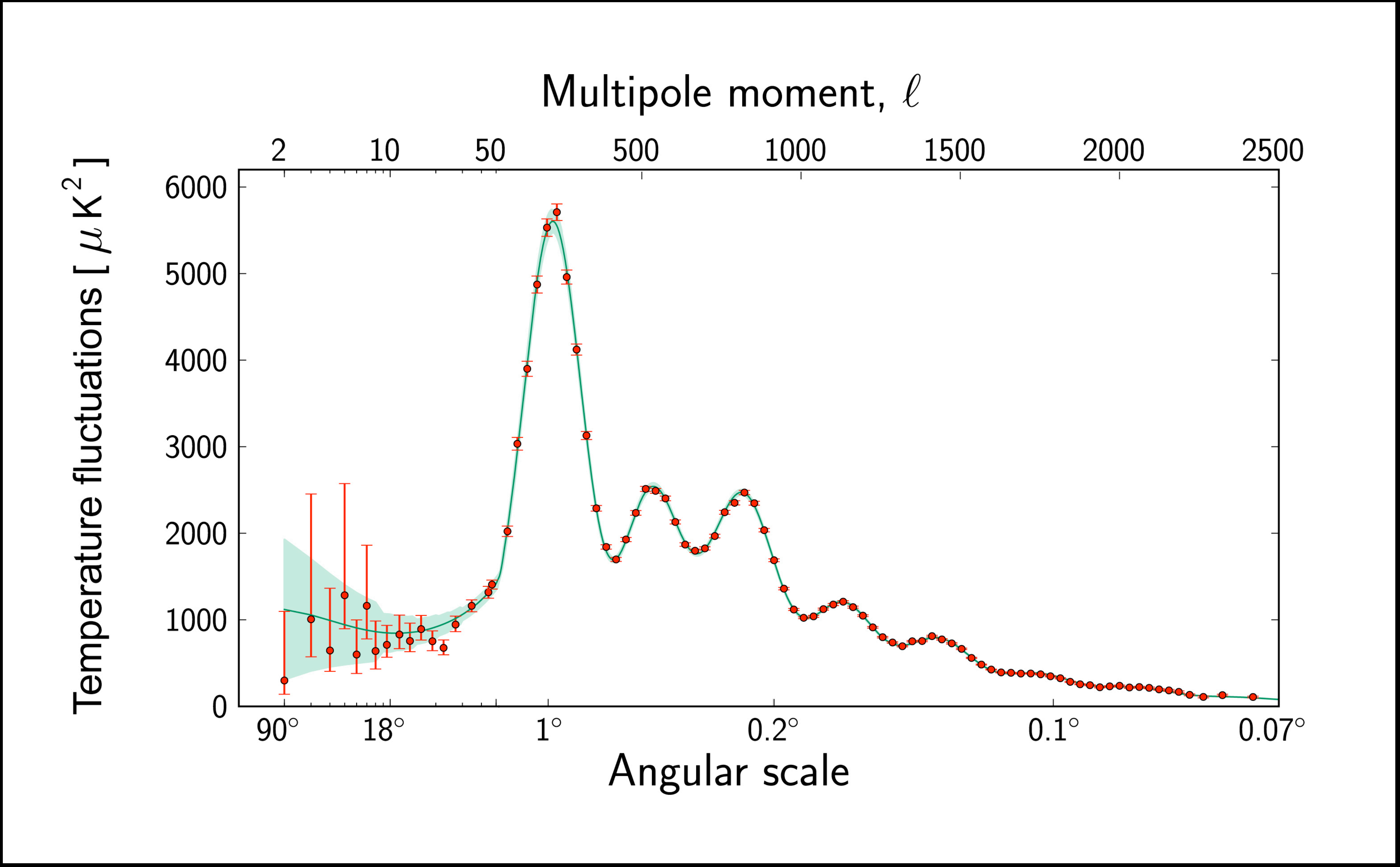
Planck power spectra



Including foreground modelling



Data vs theory

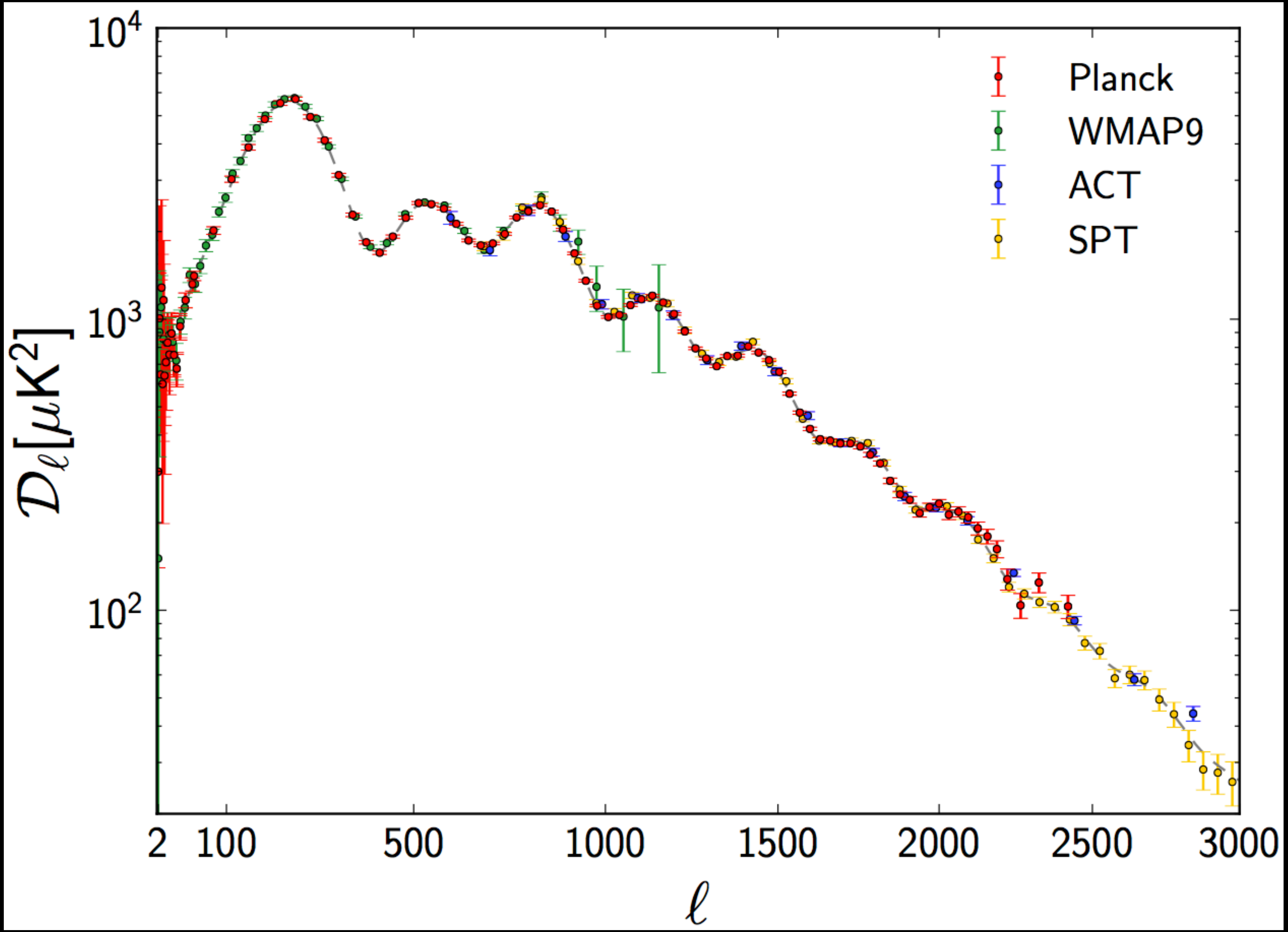


Cosmological parameters

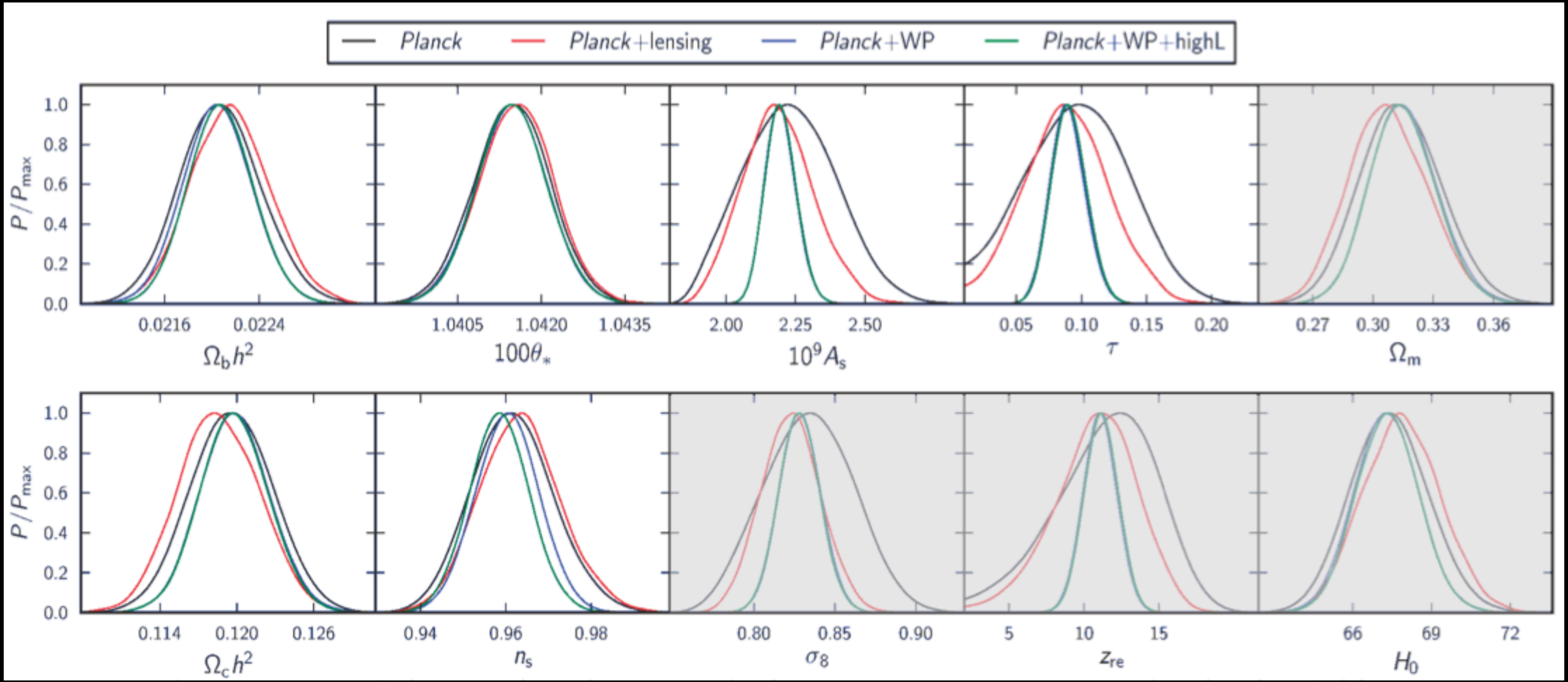
Parameter	*Planck*+lensing Best fit	*Planck*+lensing 68% limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

- Using only Planck
    - Sound horizon is measured by position of the peaks with a precision of 0.07 %
    - Exact scale invariance is excluded at ~4σ

Comparison with other experiments



Cosmological parameters with combined data



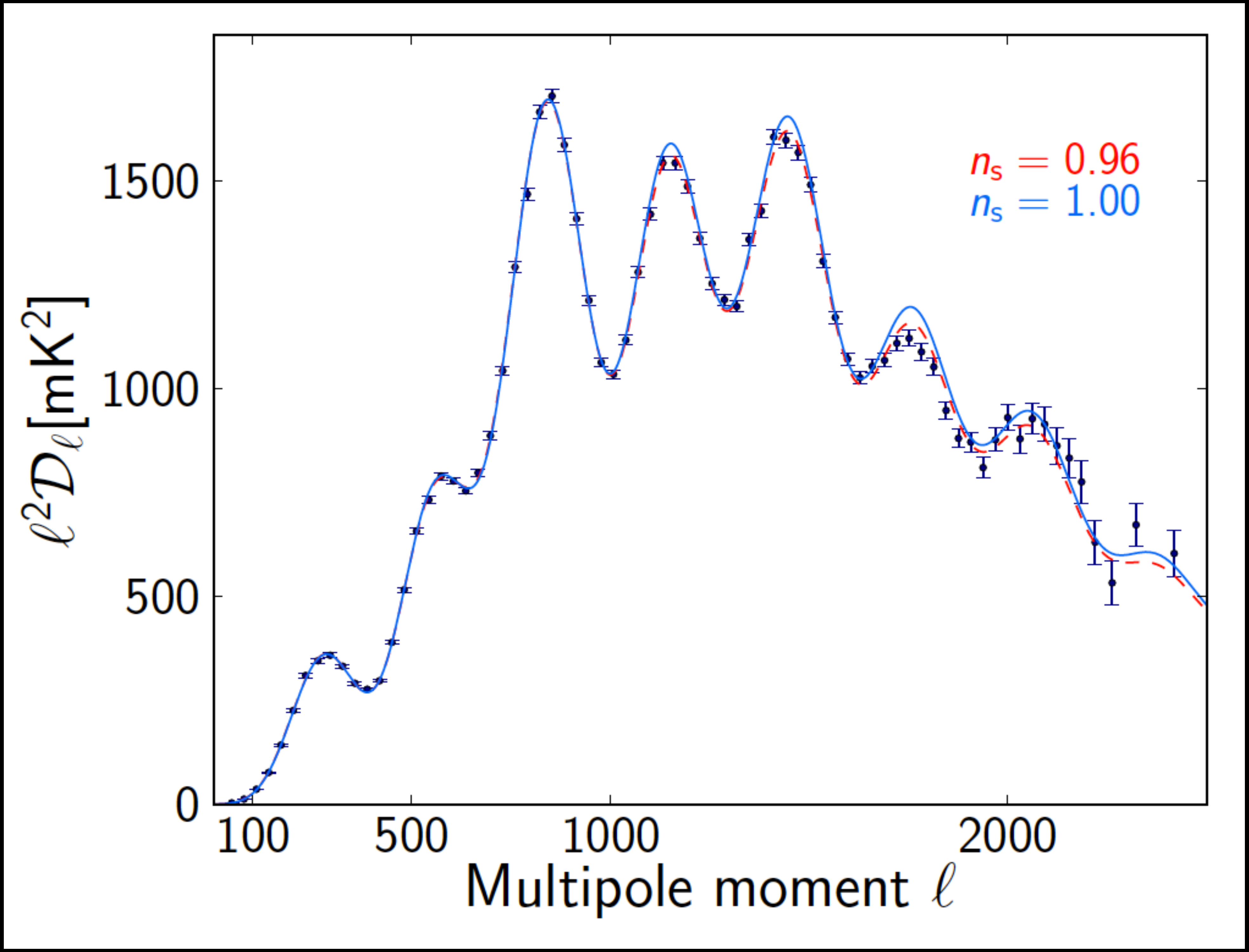
WMAP polarized data helps constraining reionization.
Using other experiments high-l data makes little difference.

Cosmological parameters

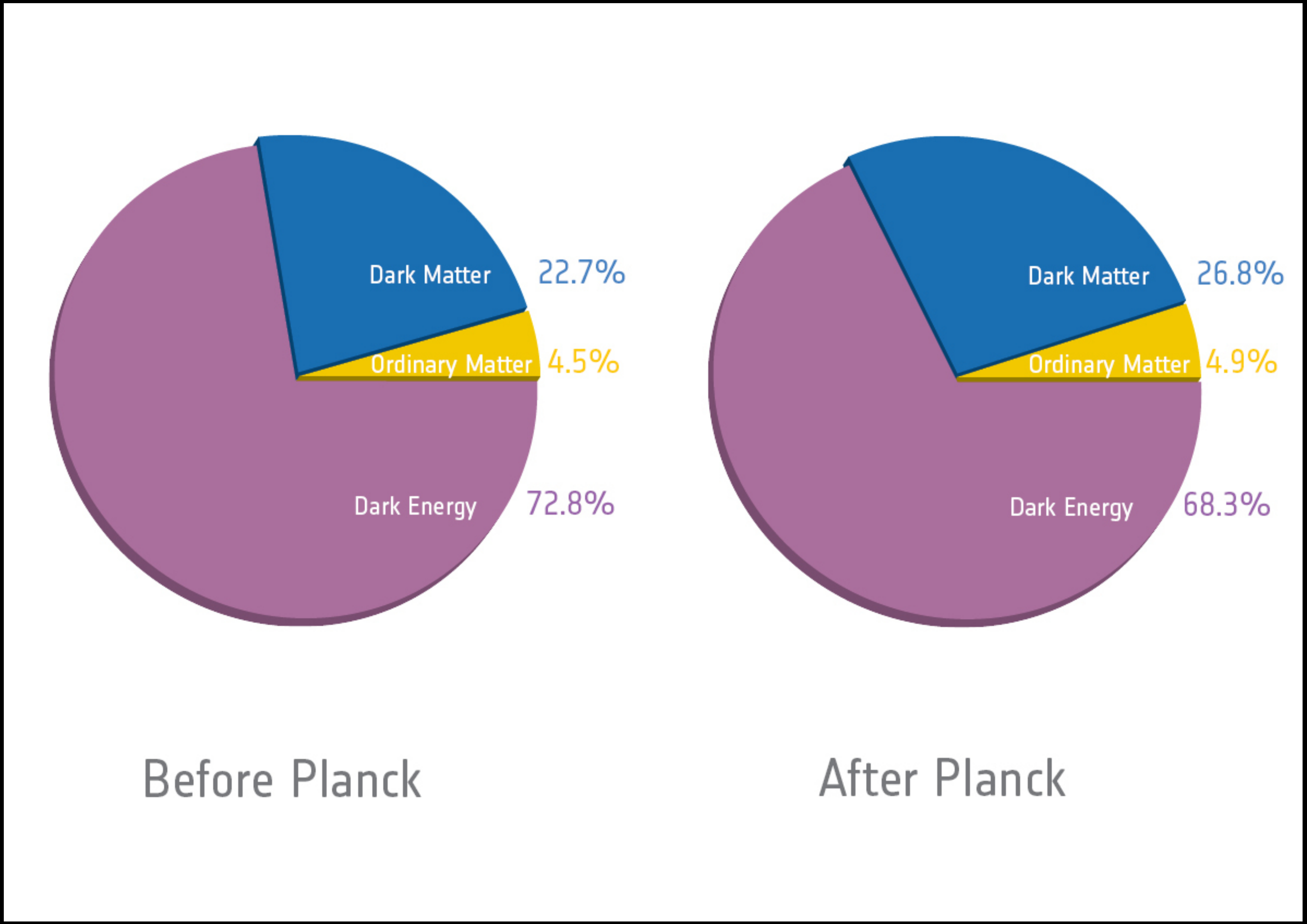
Parameter	*Planck* (CMB+lensing)		*Planck*+WP+highL+BAO	
	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025

Using other data, the sound horizon is measured with 0.05% precision and the exact scale invariance is excluded at more than 7σ (as predicted by inflaction models)

Constraint on primordial spectrum

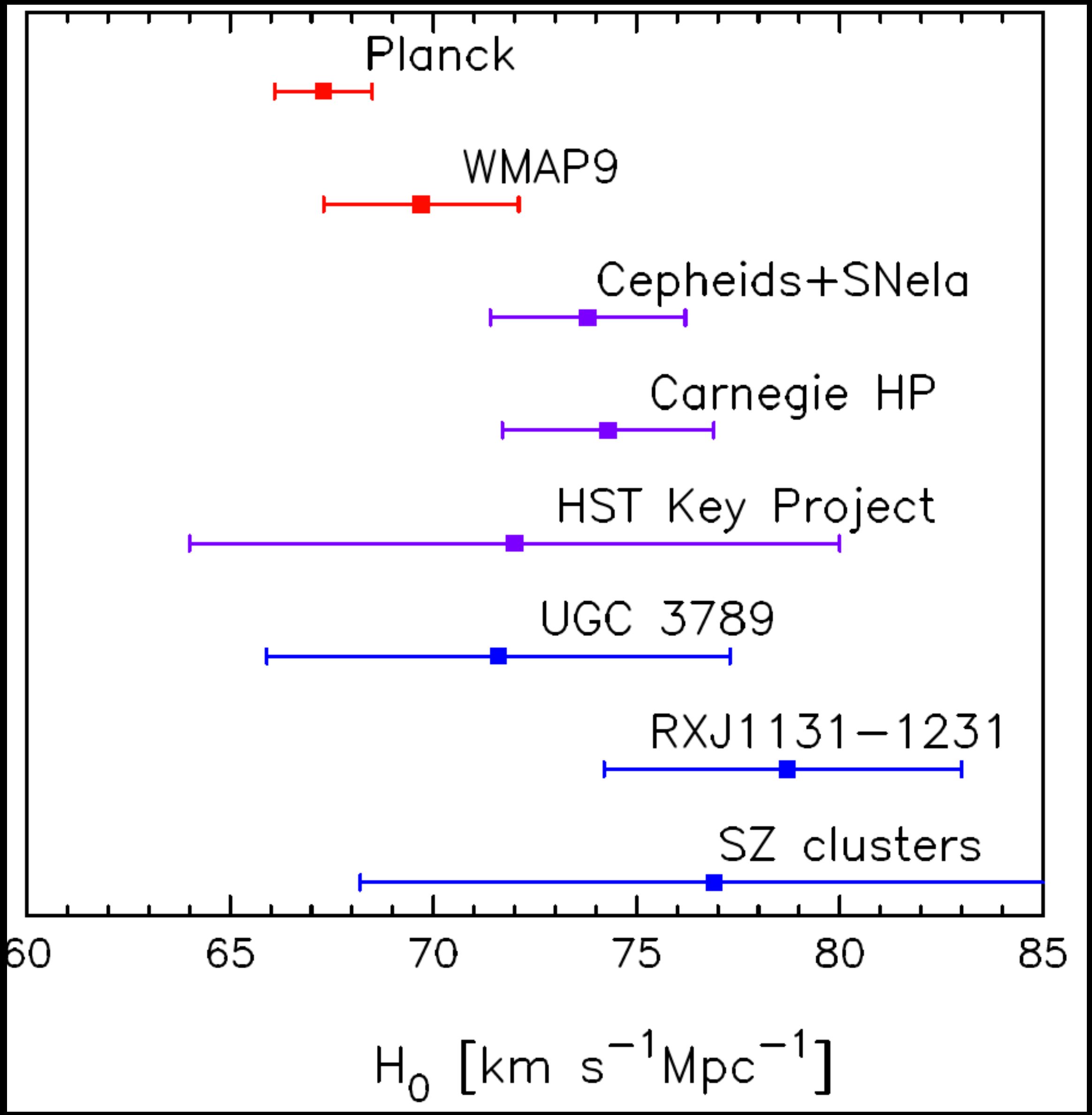


Content of the Universe

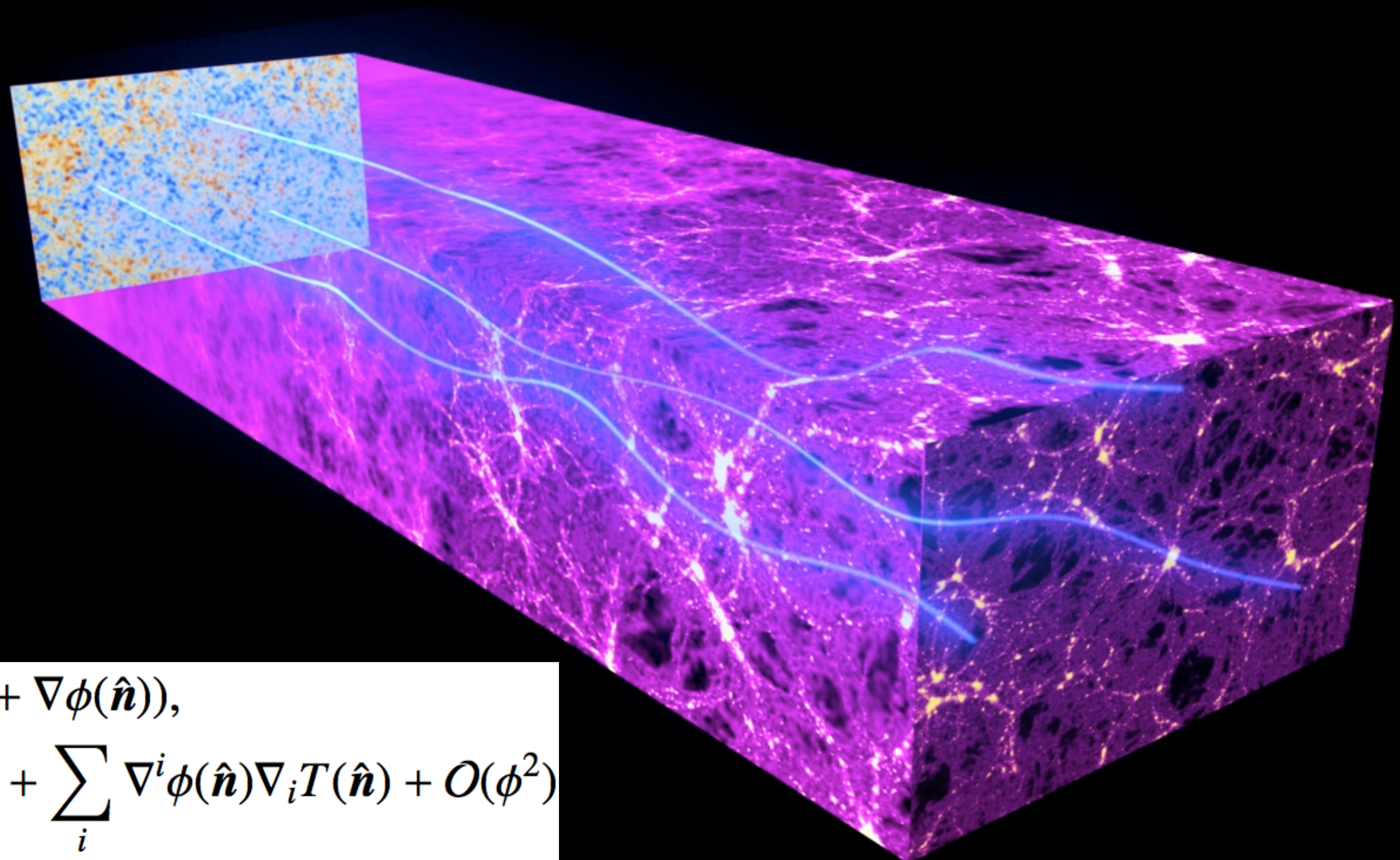


Expansion rate (Hubble constant)

- H0 is modified :
  - H0 = 67.3 ± 1.2
- Tension at 2.5σ between Planck and Cepheids or SNIa measurements



Gravitational lensing

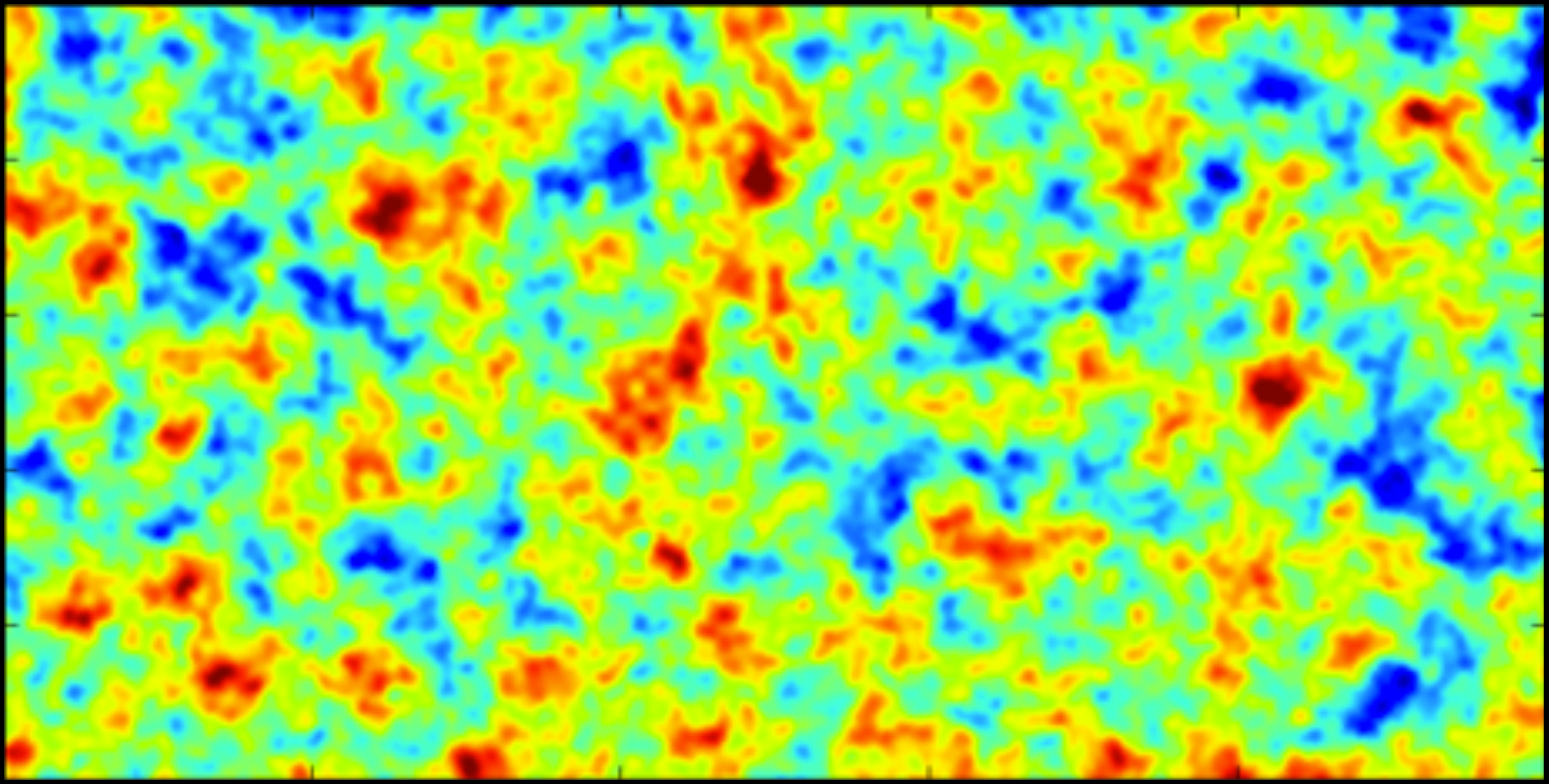


$$T(\hat{\boldsymbol{n}}) = T^{\mathrm{unl}}(\hat{\boldsymbol{n}} + \nabla\phi(\hat{\boldsymbol{n}})),$$
$$= T^{\mathrm{unl}}(\hat{\boldsymbol{n}}) + \sum_i \nabla^i\phi(\hat{\boldsymbol{n}})\nabla_i T(\hat{\boldsymbol{n}}) + O(\phi^2)$$

Gravitation bends the path of light through matter between last scattering surface and us.
This lensing effect distorts the CMB map.

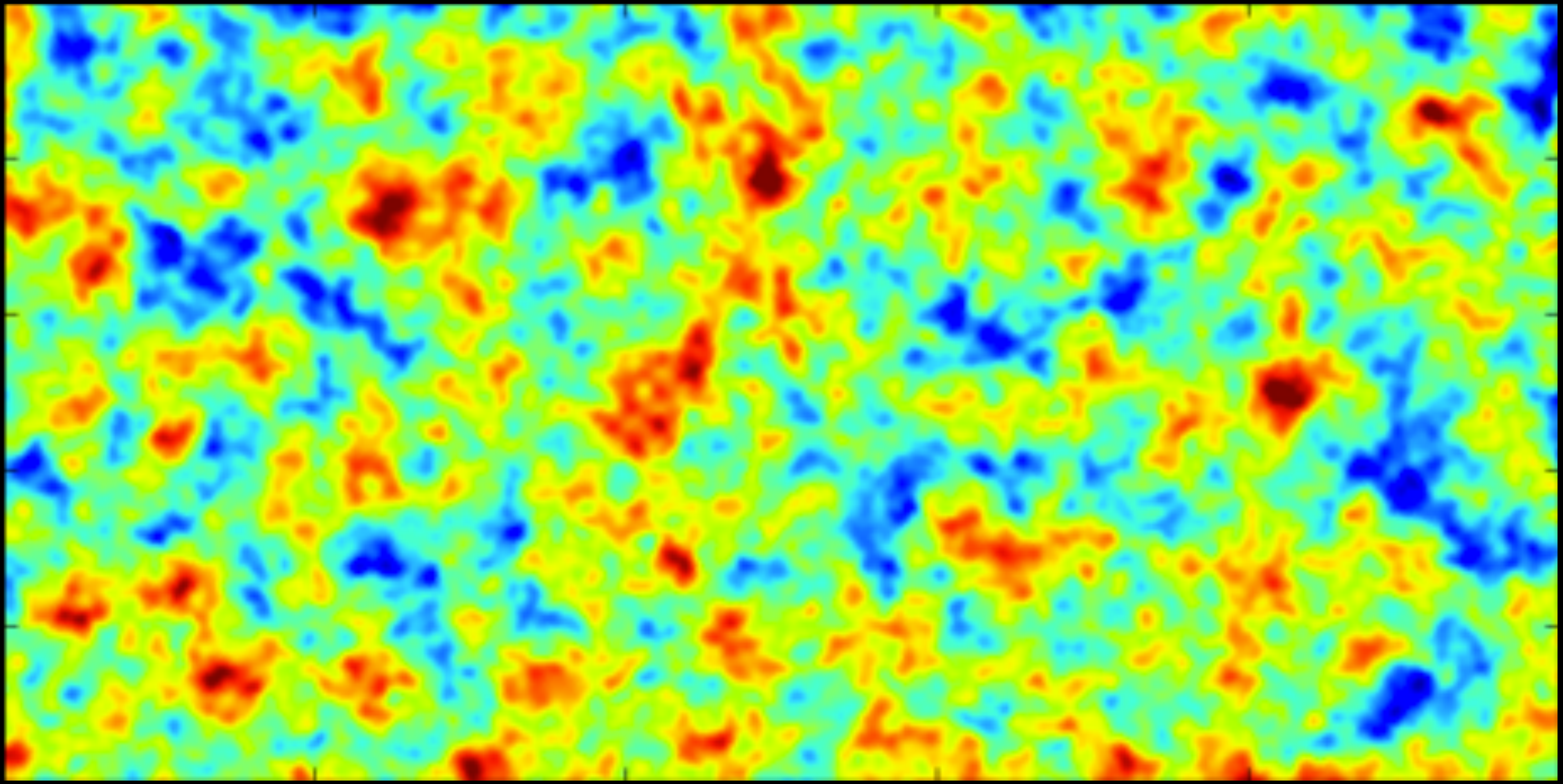
Lensing simulation

Map before gravitational lensing



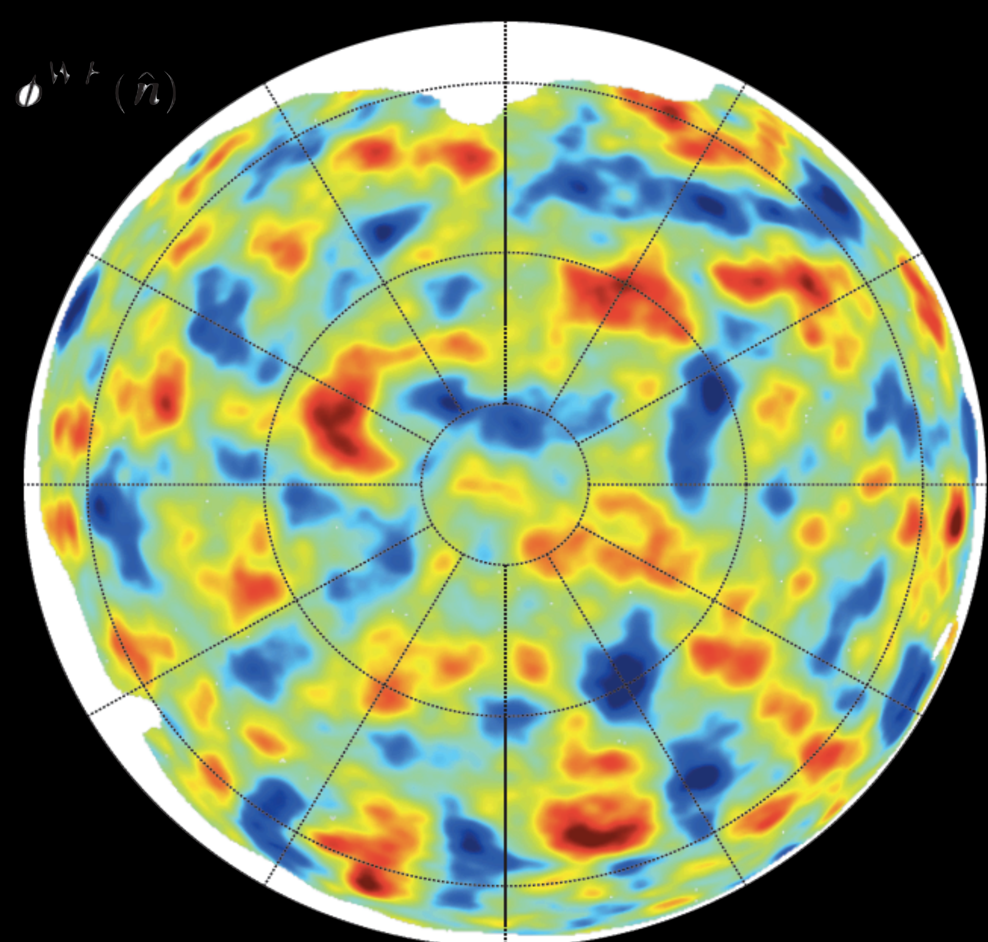
Lensing simulation

Map after gravitational lensing

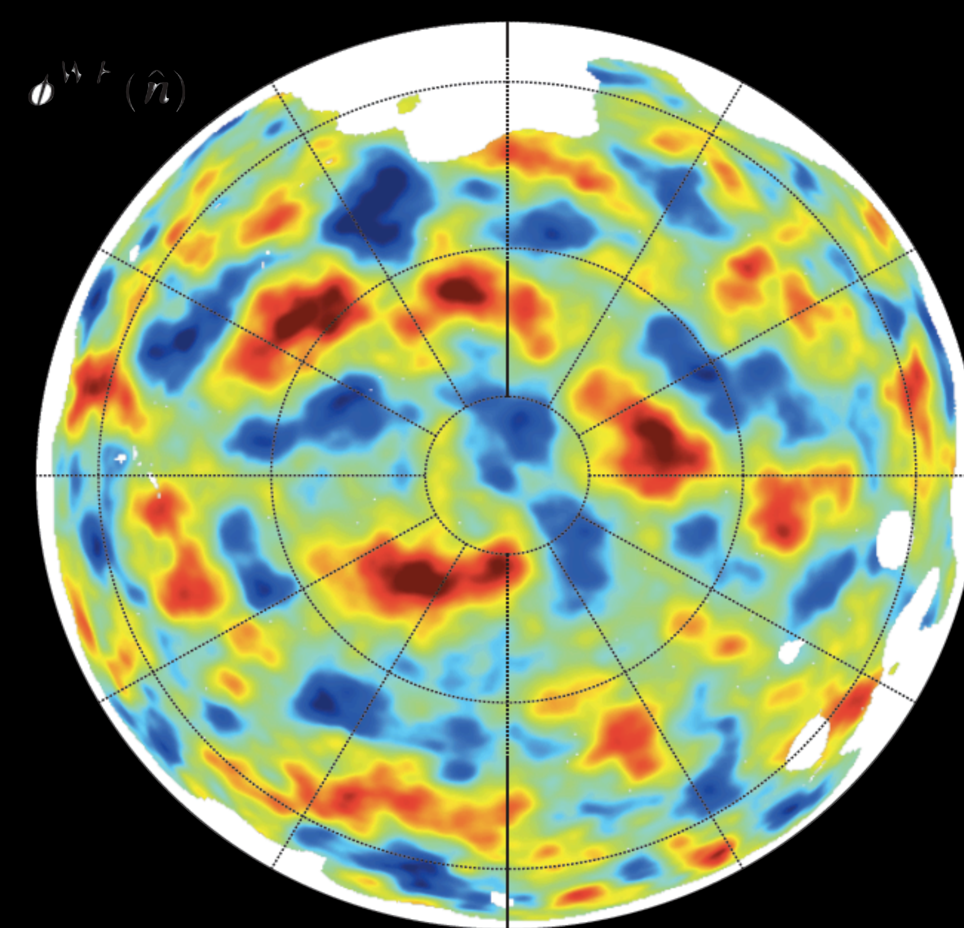


Reconstructed mass map

- Distribution of matter (dark + baryon) reconstructed from gravitational lensing effect

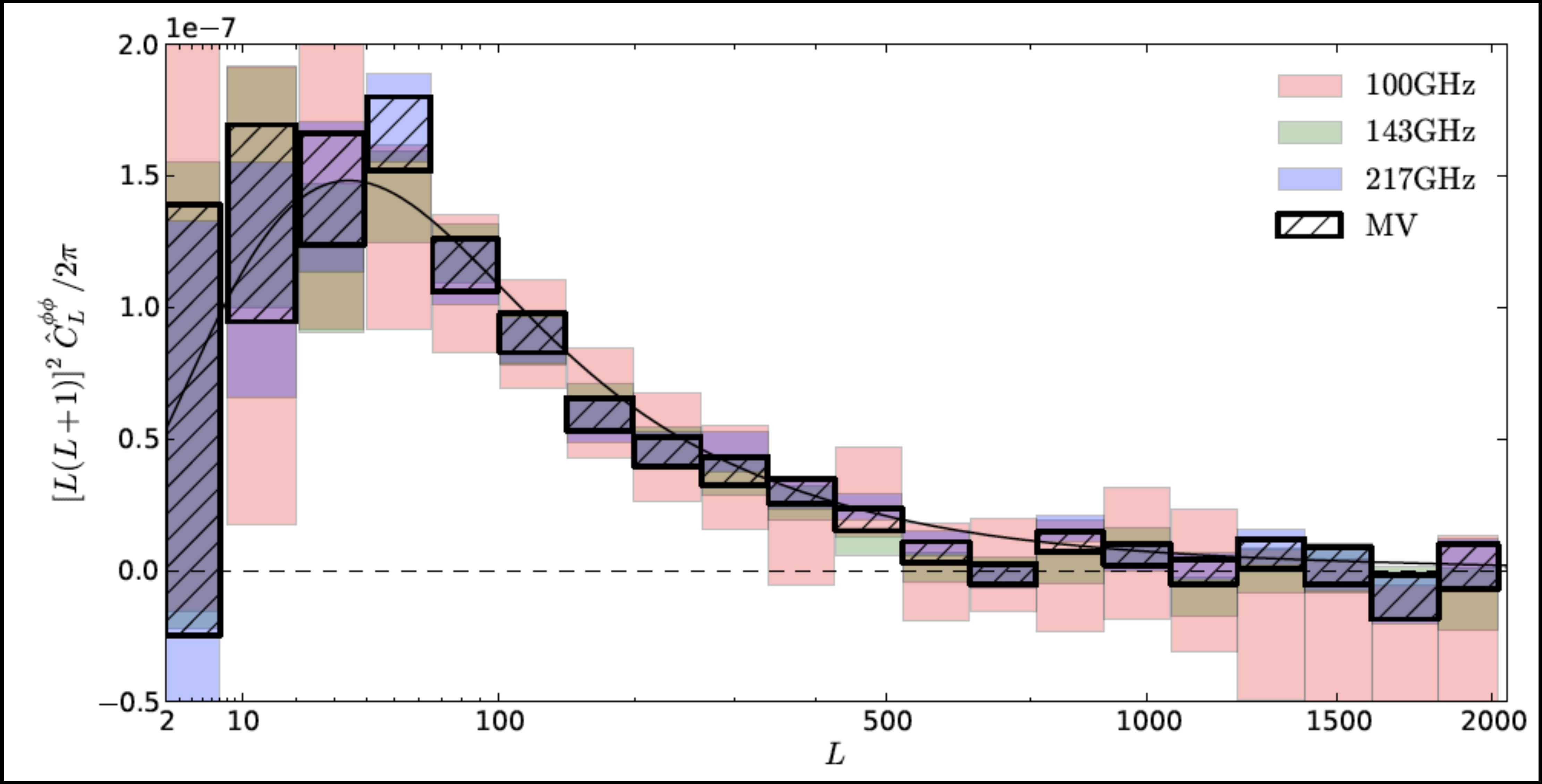


North galactic hemisphere



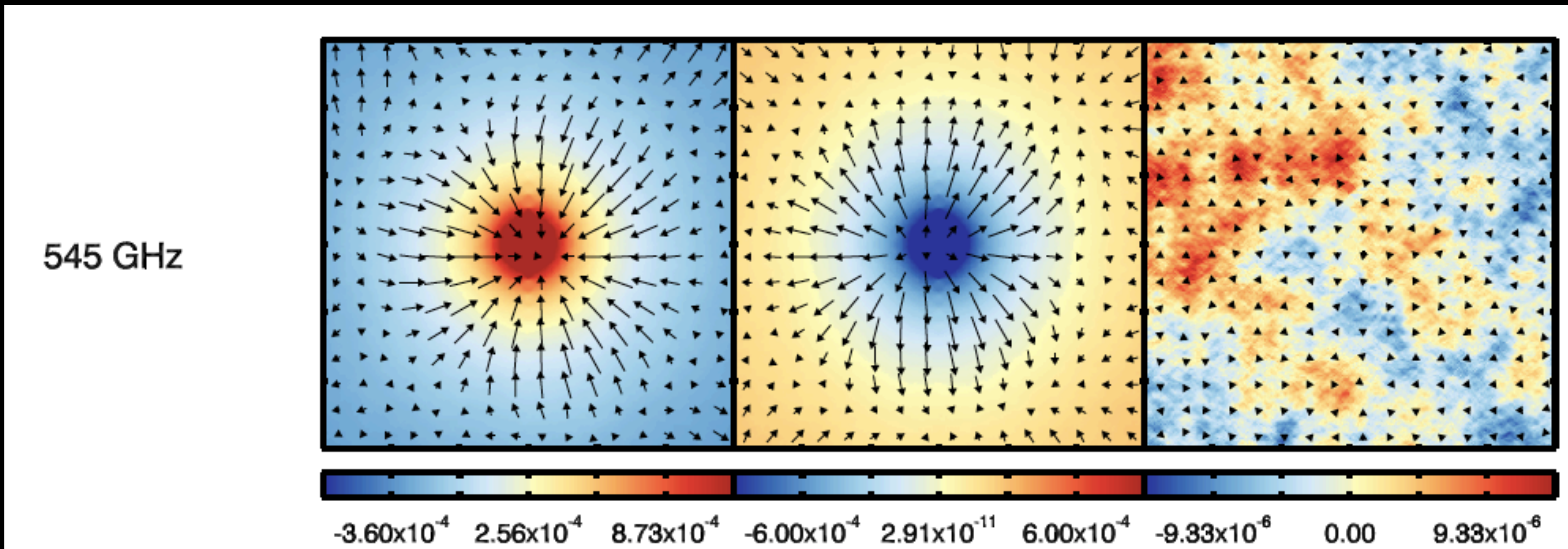
South galactic hemisphere

Power spectrum of lensing potential



The black line is the prediction using cosmological parameters from CMB alone

Correlation with distant galaxies

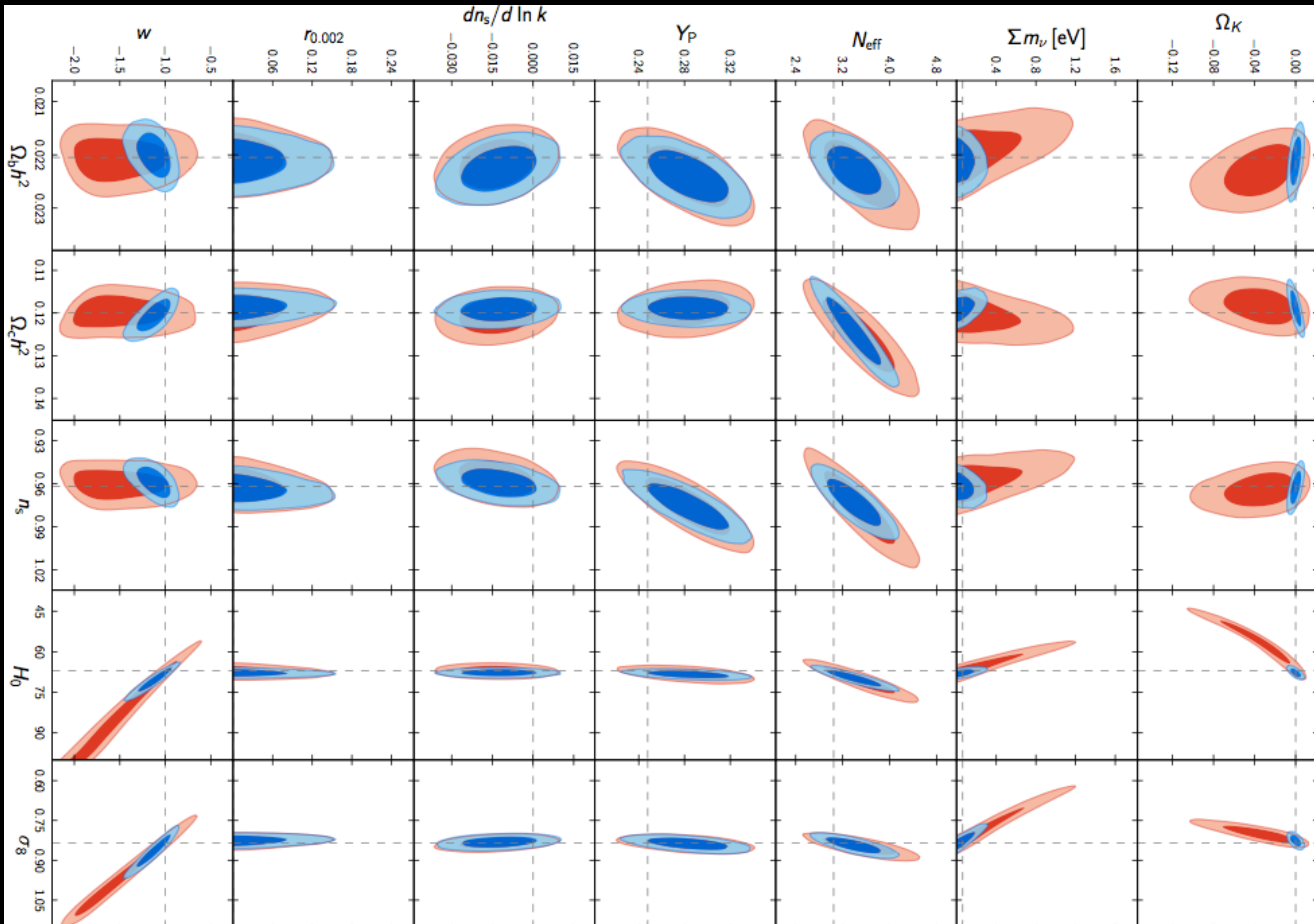


Arrows show the lensing distortion.
From left to right : stacking on maximum of CIB, on minimum and random stacking.

Extension of the model

- Test extension by adding one parameter at a time
  - Spatial curvature
  - Neutrinos properties (total mass, number of effective neutrinos)
  - Curvature of the primordial spectral index
  - Primordial tensor fluctuations (gravitational waves)
- No detection of any of these

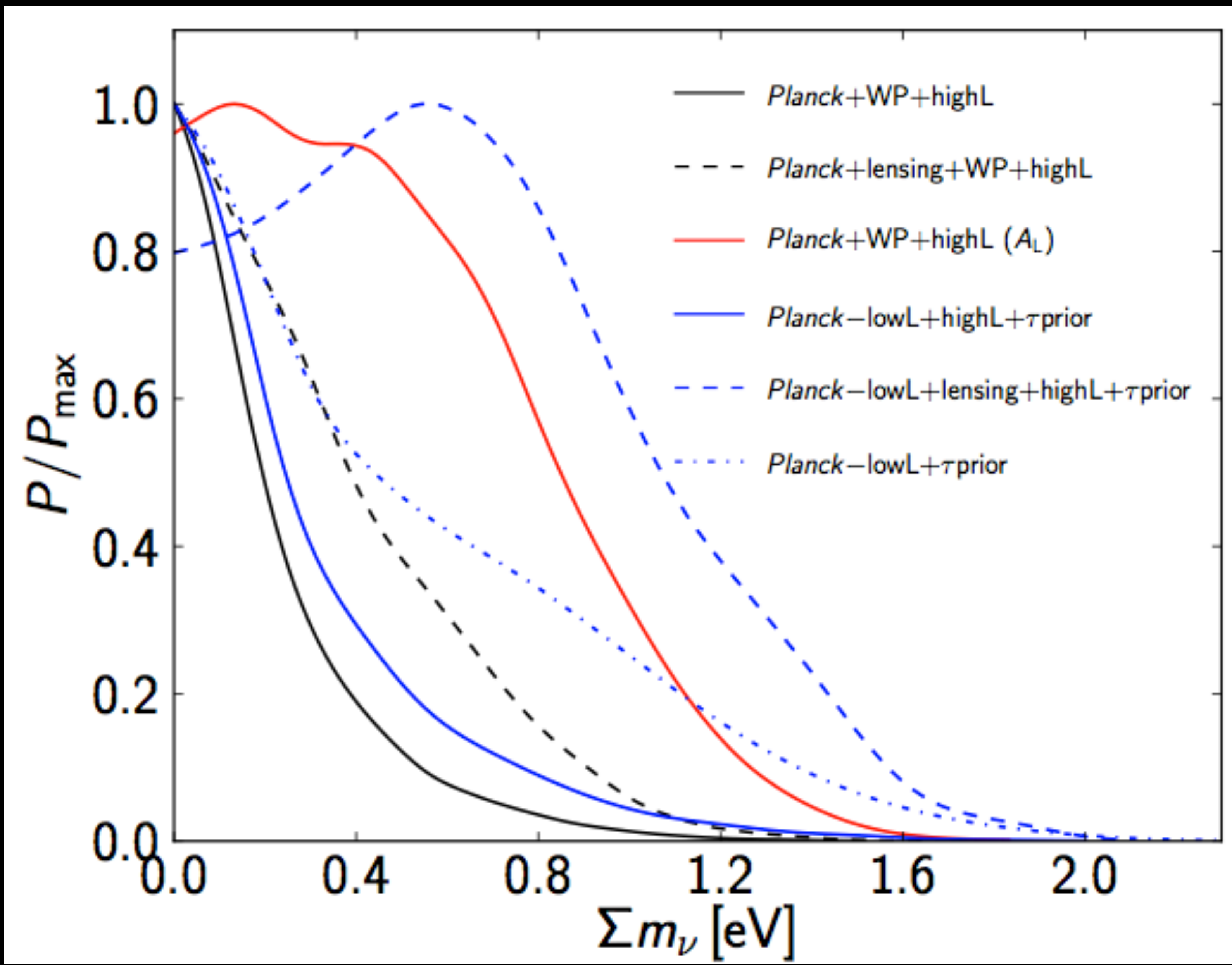
Grid of models



Planck +WP

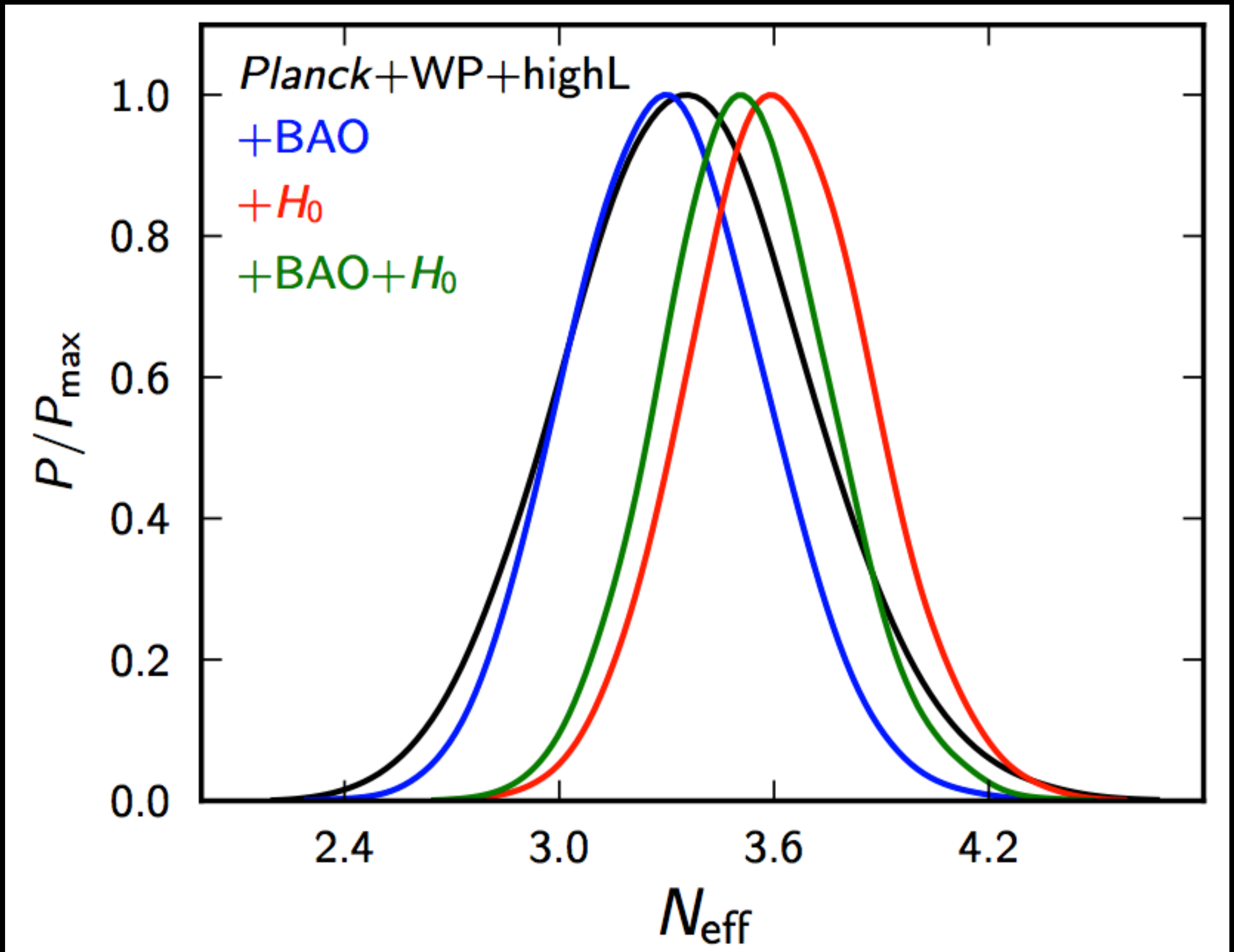
Planck +WP +BAO

Constraints on neutrinos



- Planck constrains neutrinos mass through their effect via lensing
- Removing this constraint weakens the limit:
  - $\Sigma m_\nu < 0.23$ eV
  - becomes $\Sigma m_\nu < 1.08$ eV

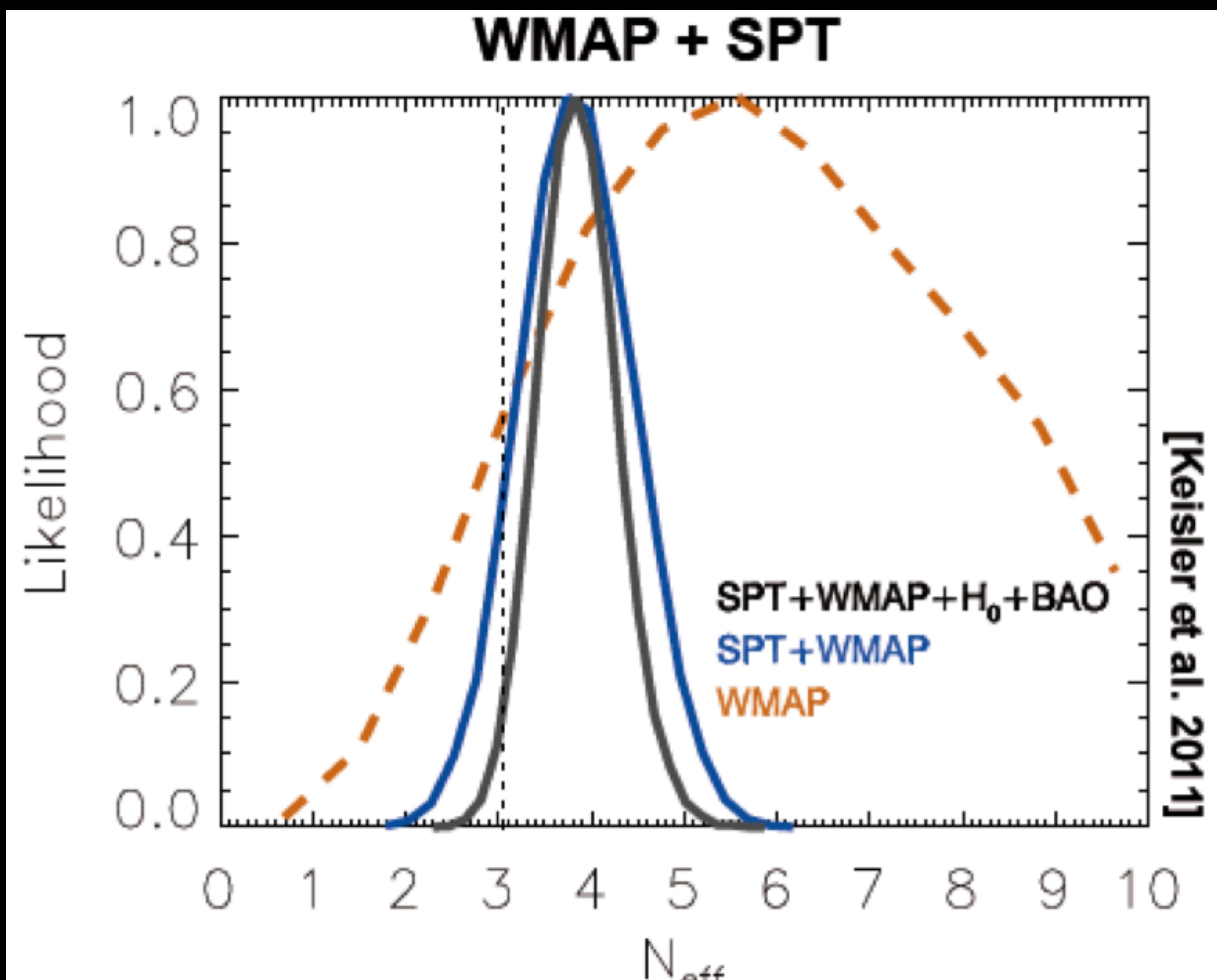
Number of neutrinos



- No evidence for additional neutrino-like relativistic particle beyonf the three families of neutrinos of the standard model
- Neff = 3.3 ± 0.27
- Note:
  - H0 pushes Neff high

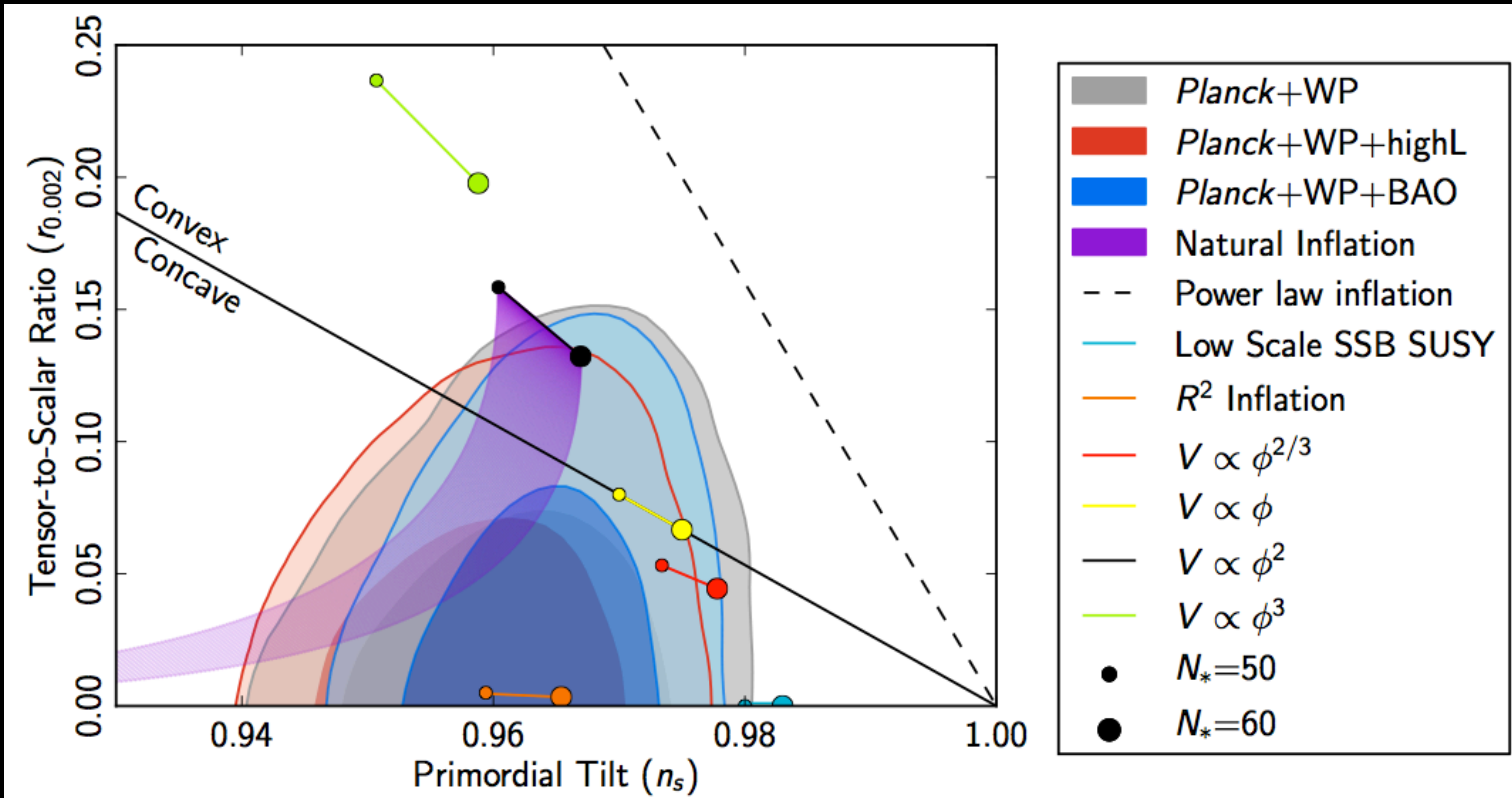
Number of neutrinos

Parameter	*WMAP* 9	+eCMB	+eCMB+BAO	+eCMB+BAO+H_0
Number of relativistic species[b]				
$N_{\rm eff}$	> 1.7 (95% CL)	3.89 ± 0.67	3.55 ± 0.60	3.84 ± 0.40



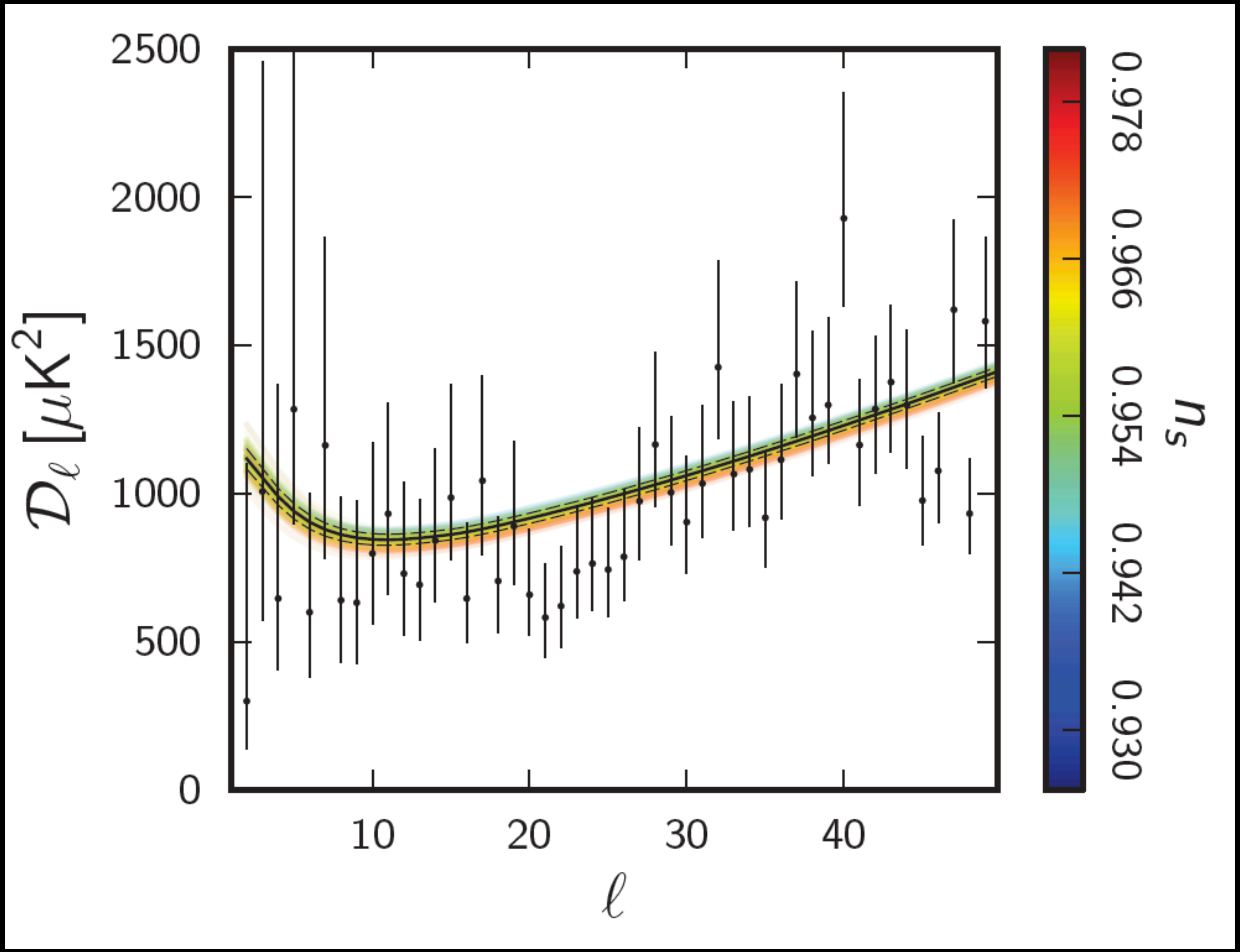
- WMAP-9 data were in favor of a fourth family of neutrinos... (Bennett et al, 2013)

Constraints on inflation



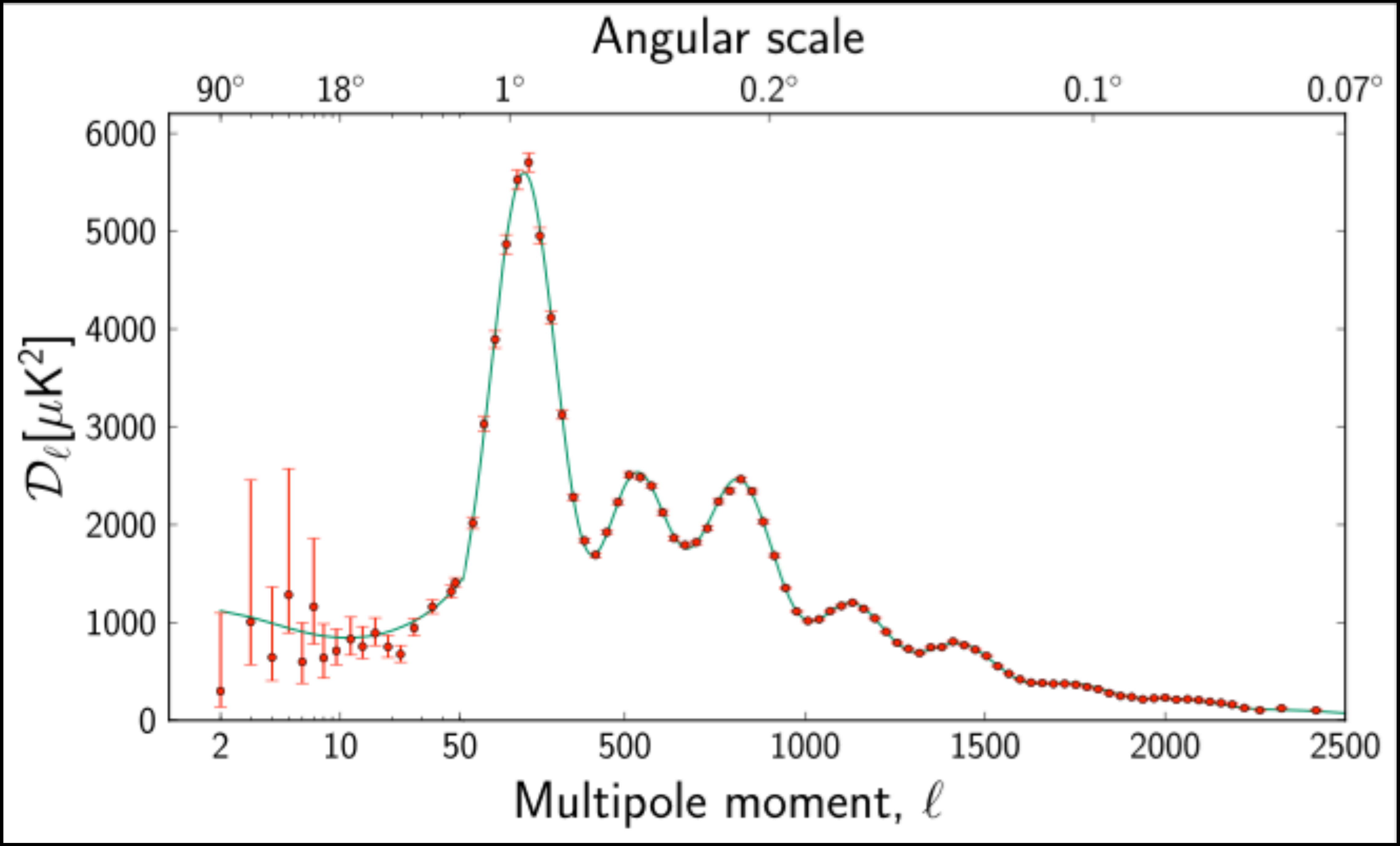
- Exponential potential, monomial potential of degree n>2, simplest hybrid model (SB SUSY) do not fit well the data

Large scale anomaly

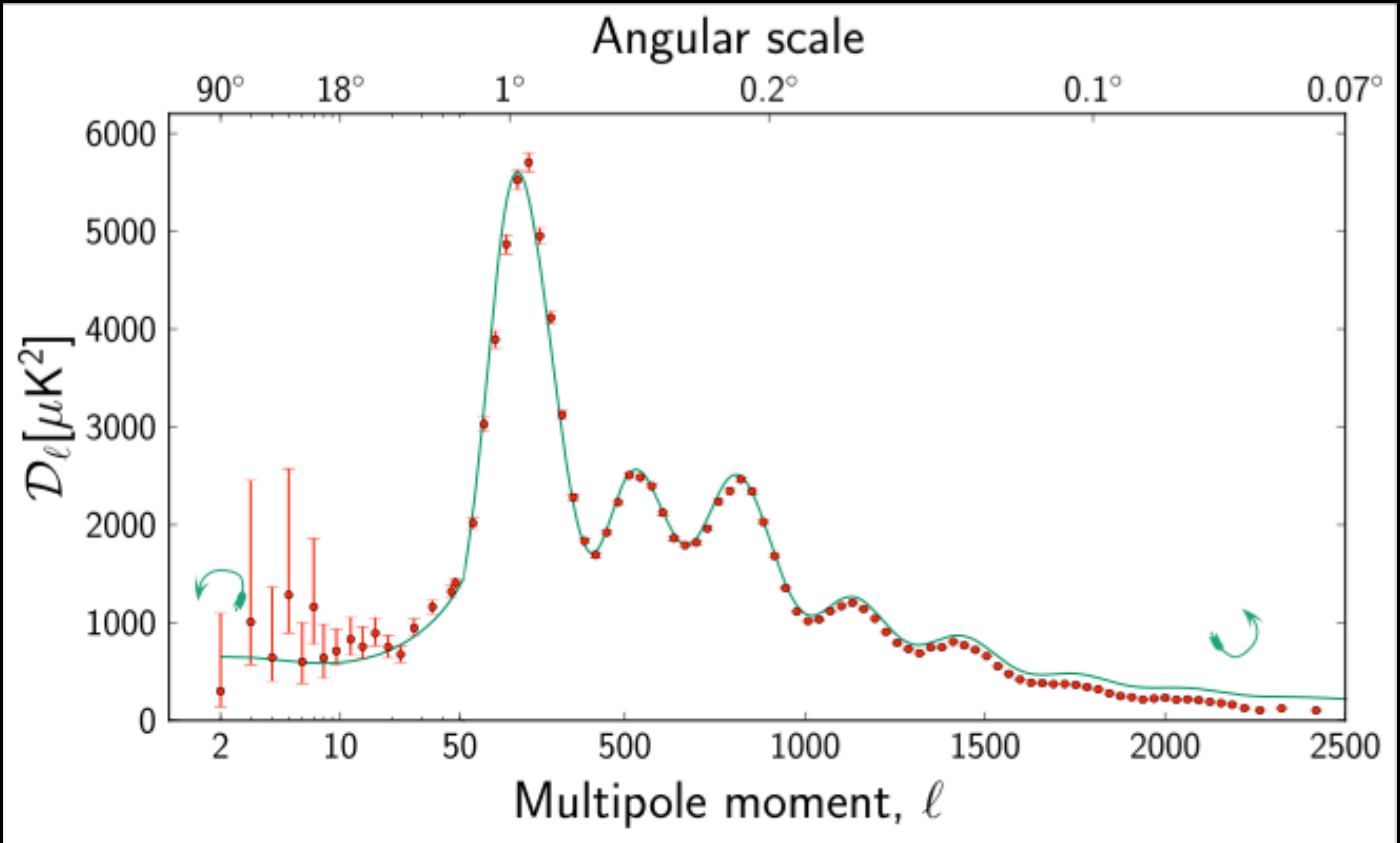


- The first 30 modes measured are lower than expected from the model
- Probability of 1% to happen...

Large scale anomaly

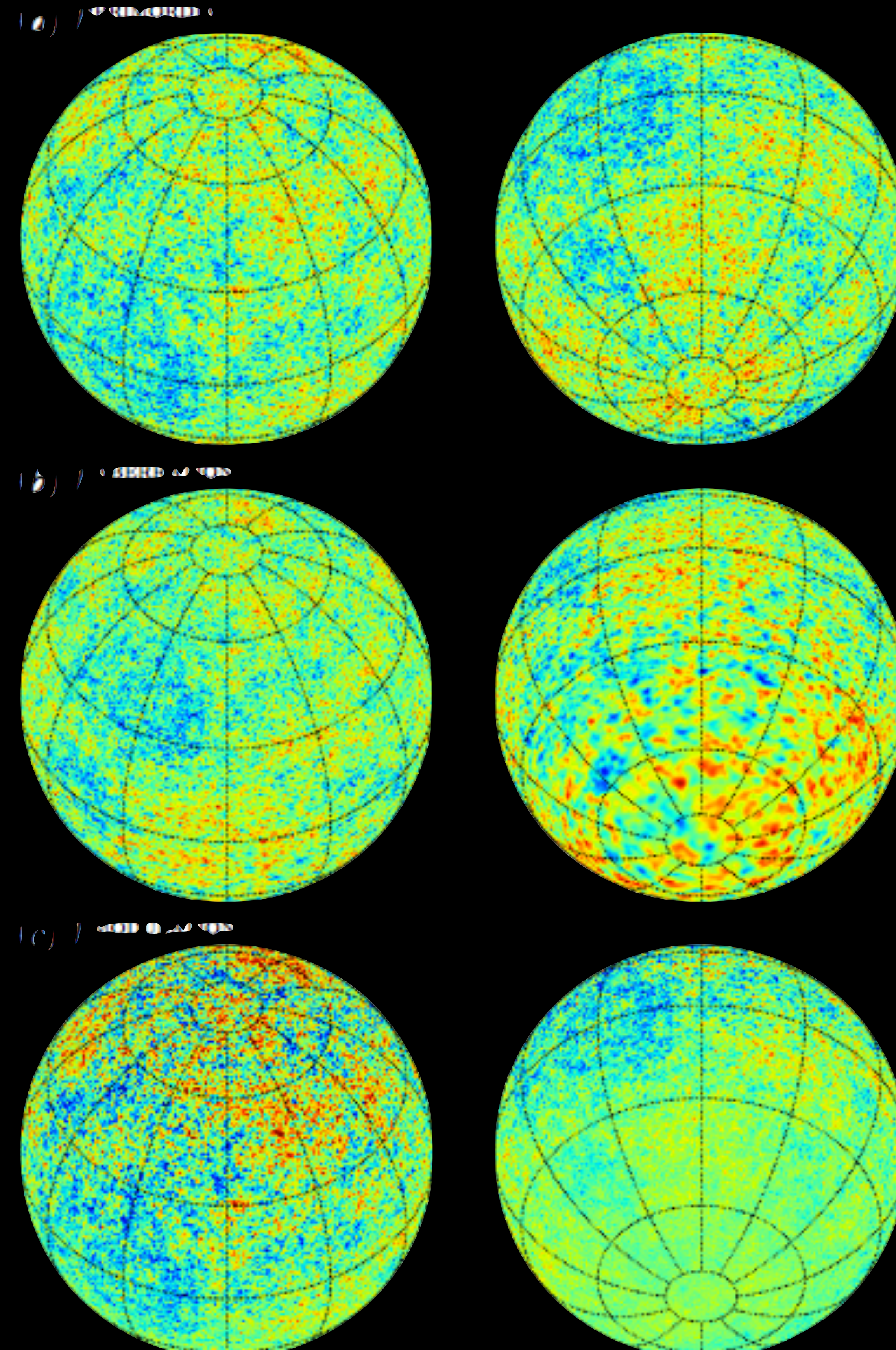


Large scale anomaly



Aberration

- Optical effect due to our movement with respect to the CMB
- Induces distortion of the measured CMB map (exagerated on the plot beside):
  - spots are smaller in direction of earth motion
  - dipolar amplitude modulation
- Can measure our speed wrt CMB independently of the dipole (ℓ=1 term in power spectrum)
- v = 384 ± 78 (stat) ± 115 (syst) $km.s^{-1}$
- (v_dipole = 368 ± 2 $km.s^{-1}$)

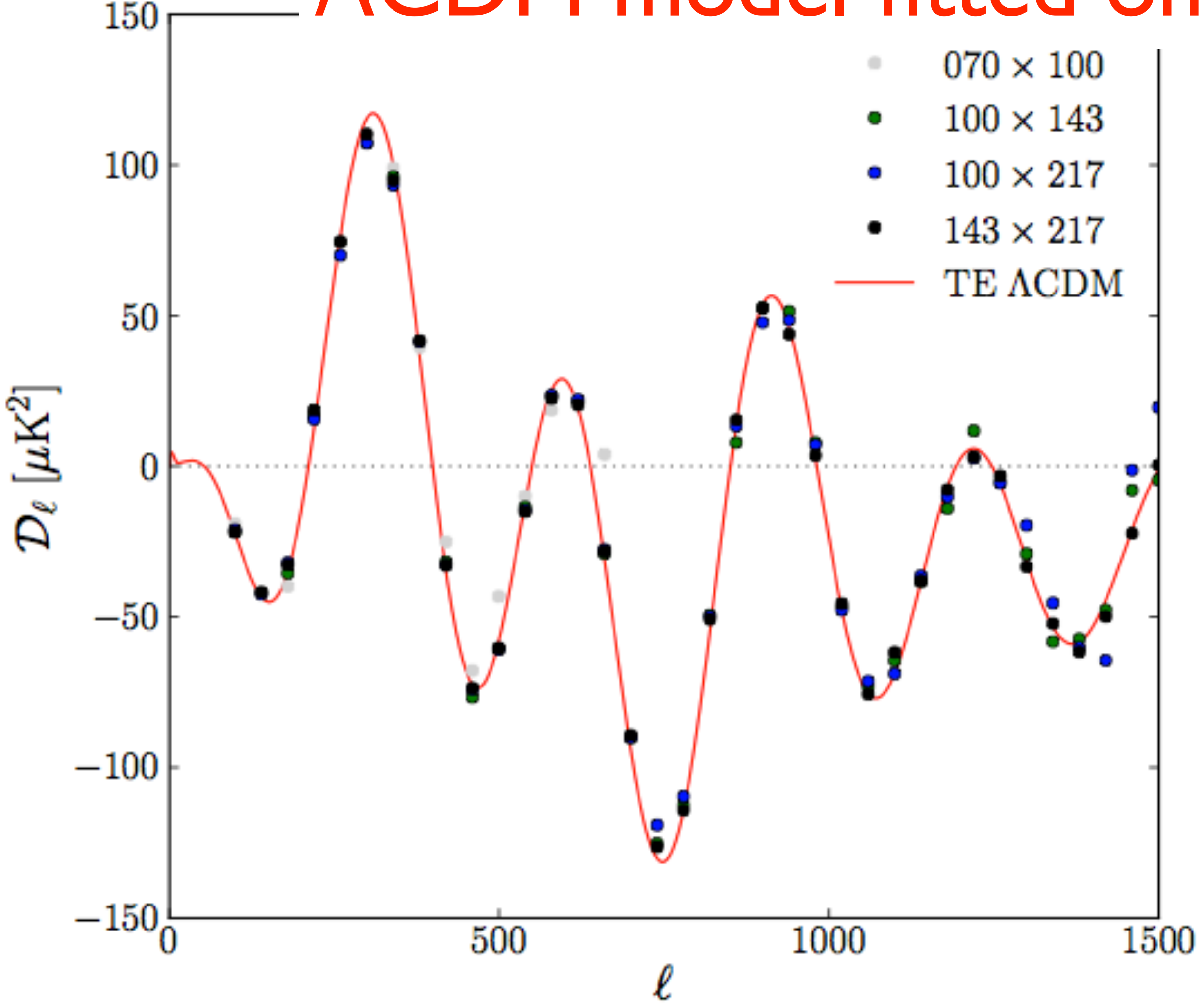


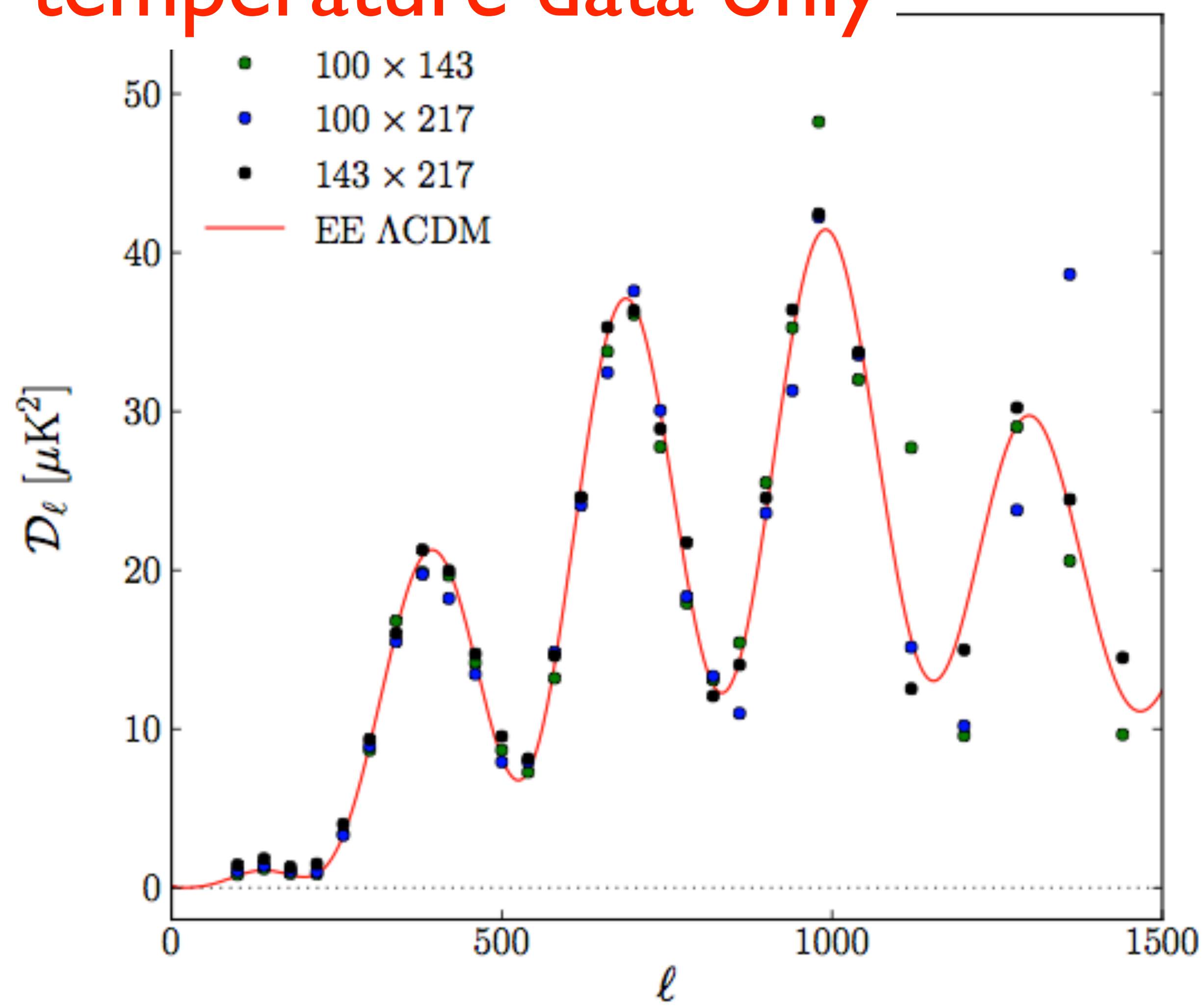
Conclusion

- Planck instruments and scanning strategy allows wide range of consistency tests
- Gives confidence in the robustness of the measurements
- Excellent agreement of T power spectrum with ΛCDM and simplest inflationary models
- Improved precision on cosmological parameters:
  - H0 value slighlty shifted, increase of Ωm and decrease of ΩΛ
  - No evidence of additional family of neutrinos: Neff = 3.3 ± 0.27
  - Limits on total mass of neutrinos: $\Sigma m_\nu < 0.23$ eV
  - No evidence for running spectral index
  - No detection of non-gaussianity, but stricter constraints
- Exponential potential, monomial potential of degree n>2, simplest hybrid model (SB SUSY) do not fit well the data
- Next data release (mid-2014) will include improvements in the analysis (better understanding of the instruments) and polarization

Polarization spectra

ΛCDM model fitted on temperature data only





Polarization stacking