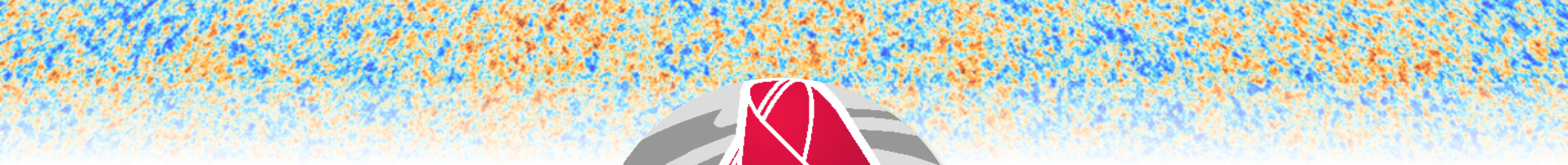


Planck observations of CMB polarisation

Matthieu TRISTRAM

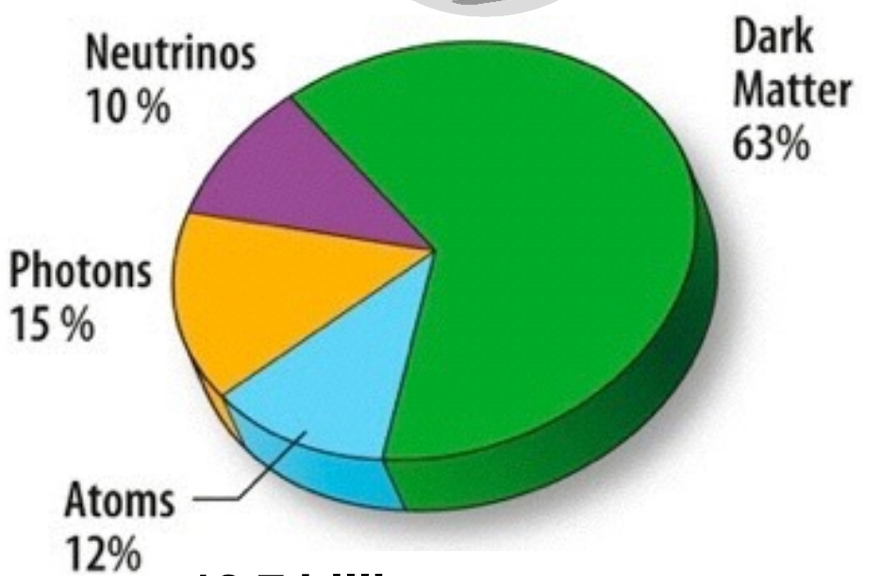
IN2P3 - CNRS

cosmology

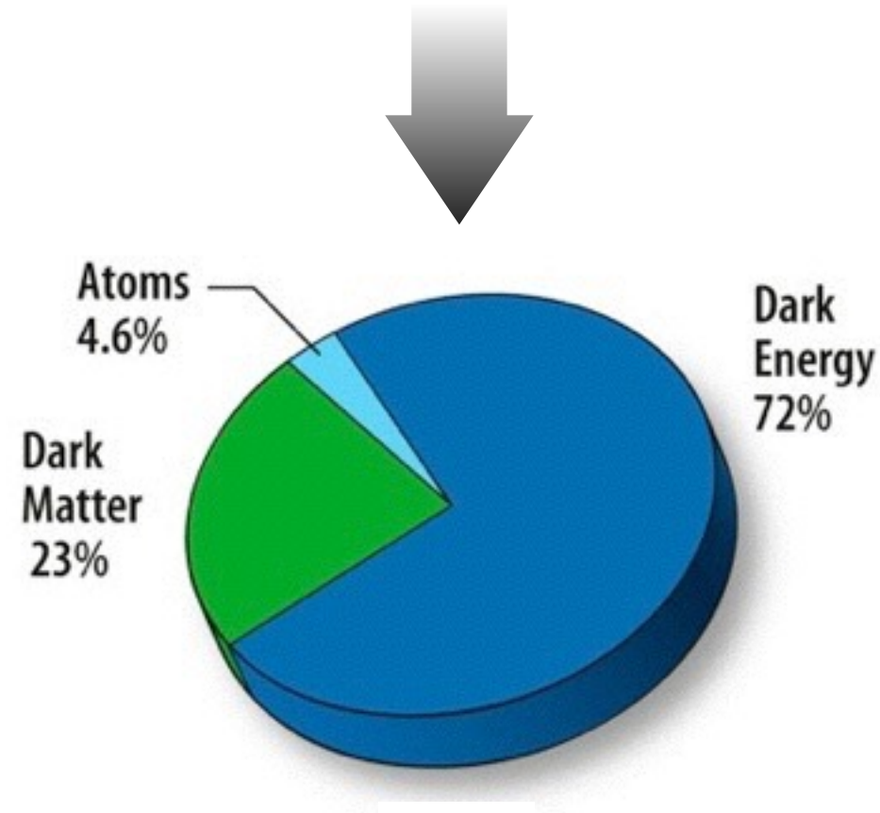
- **questions :**
  - How old is the Universe ?
  - What's its composition ?
  - How could we describe its evolution ?

- **that leads to more questions :**
  - What is dark matter ?
  - What is Dark Energy ?
  - …

- **informations :**
  - study matter distribution at different time during Univers evolution

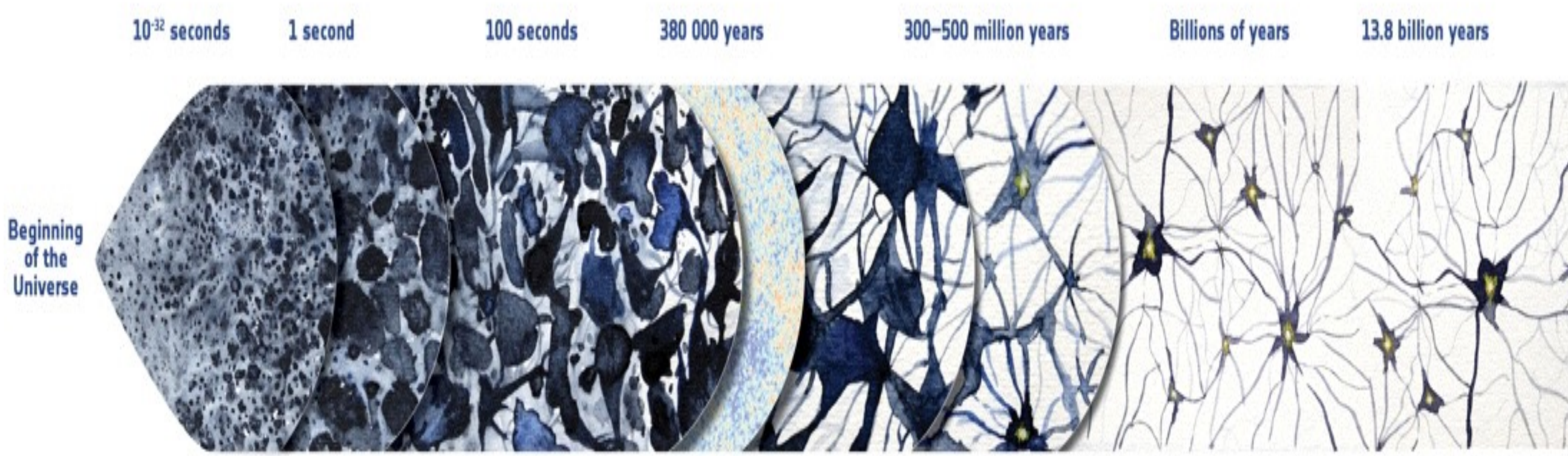


13.7 billions years ago



today

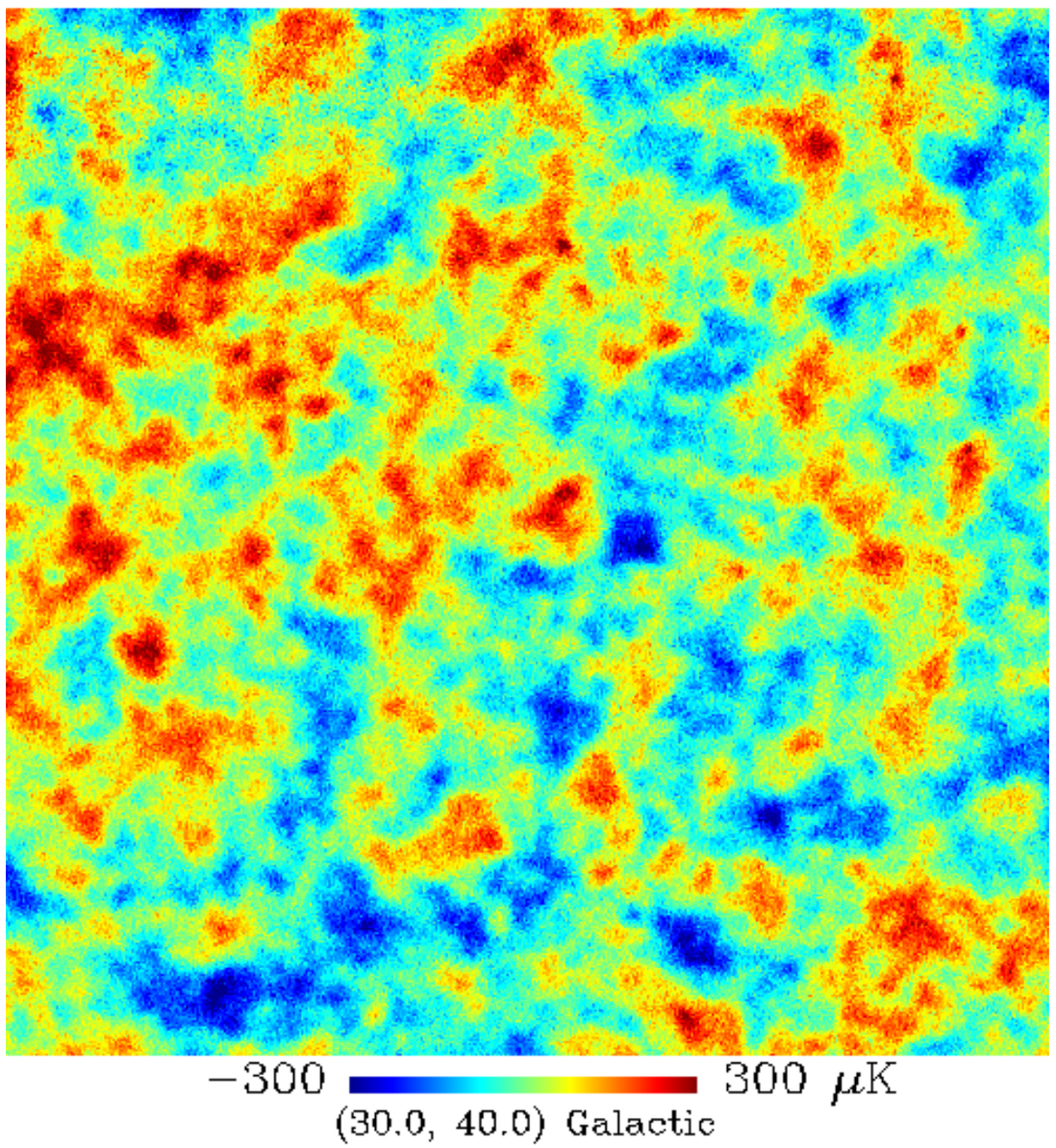
Big-Bang model



CMB anisotropies

match the matter distribution in the Universe at very early times

zoom $10 \times 10°$



- **Gaussian variable correlated in real space**
- **decorrelated in Fourier domain**

$$c(\theta) = \langle T(\hat{n}) \times T(\hat{n}+\theta) \rangle = \sum_{\ell} C_\ell (2\ell+1) P_\ell(cos\theta)$$

- **encodes information on the primordial fluctuations**

angular power spectrum

toy-model

- **causal physics**

$$\theta_H \simeq 1.2^\circ$$

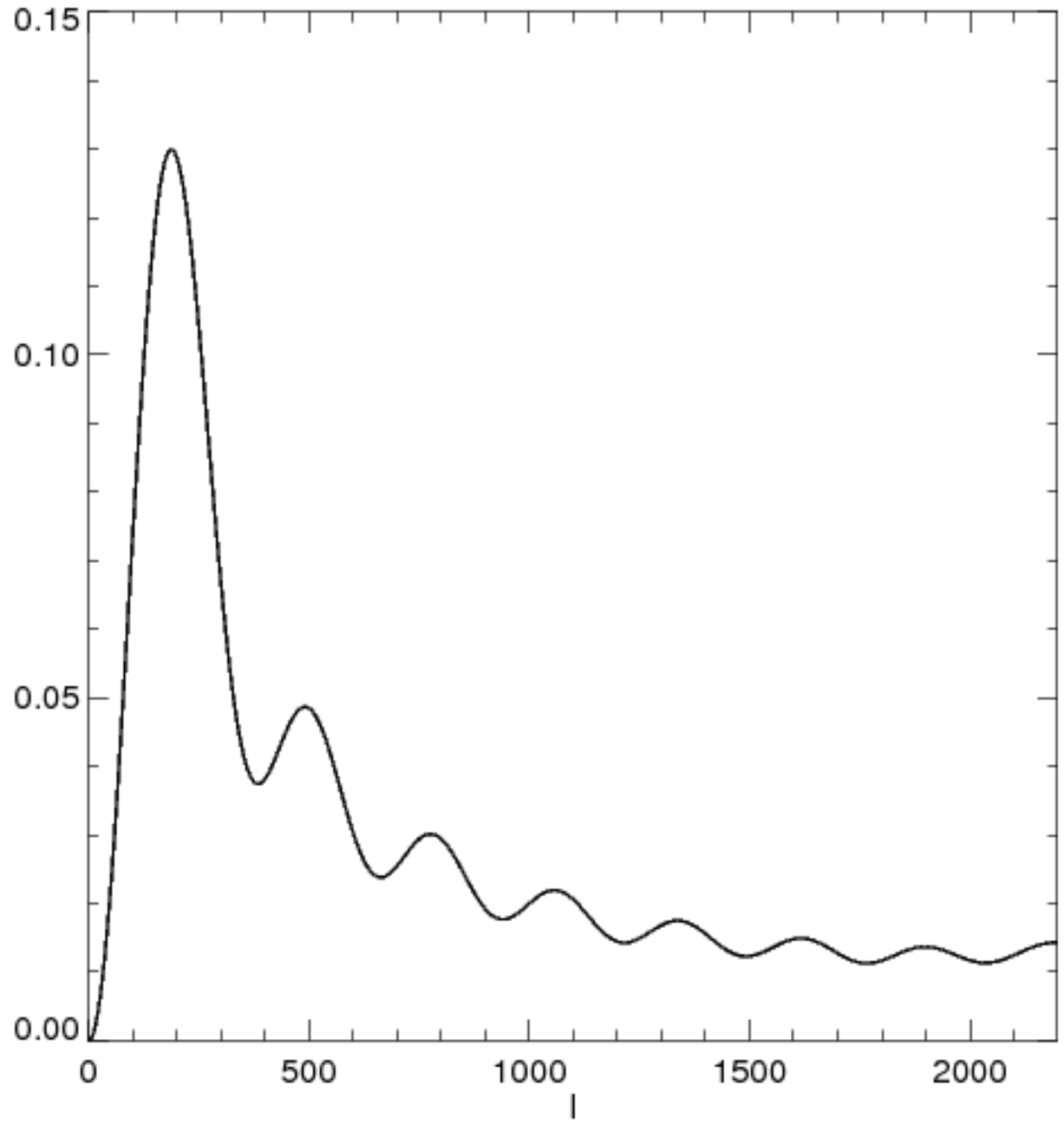
- **auto-correlation**

$$c(\theta) = \begin{cases} (\theta - \theta_H)^2 & \theta < \theta_H \\ 0 & \theta > \theta_H \end{cases}$$

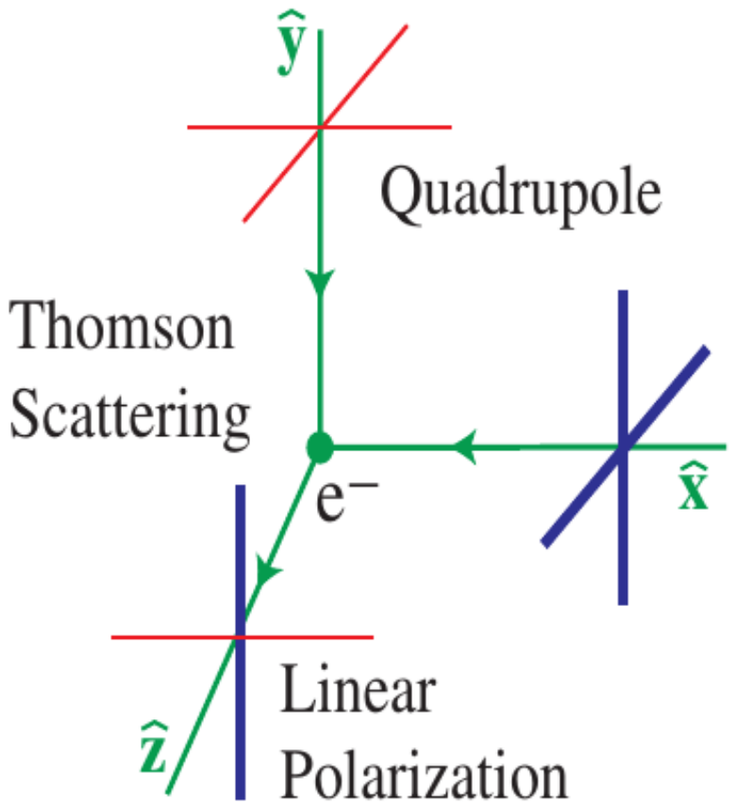
- **on the sphere**

$$\ell(\ell+1)C_\ell \simeq (1 - \frac{\sin \ell\theta_H}{\ell\theta_H}) \otimes sphere$$

$$\ell = 220 \leftrightarrow \theta \simeq 1.2^\circ$$



CMB polarisation

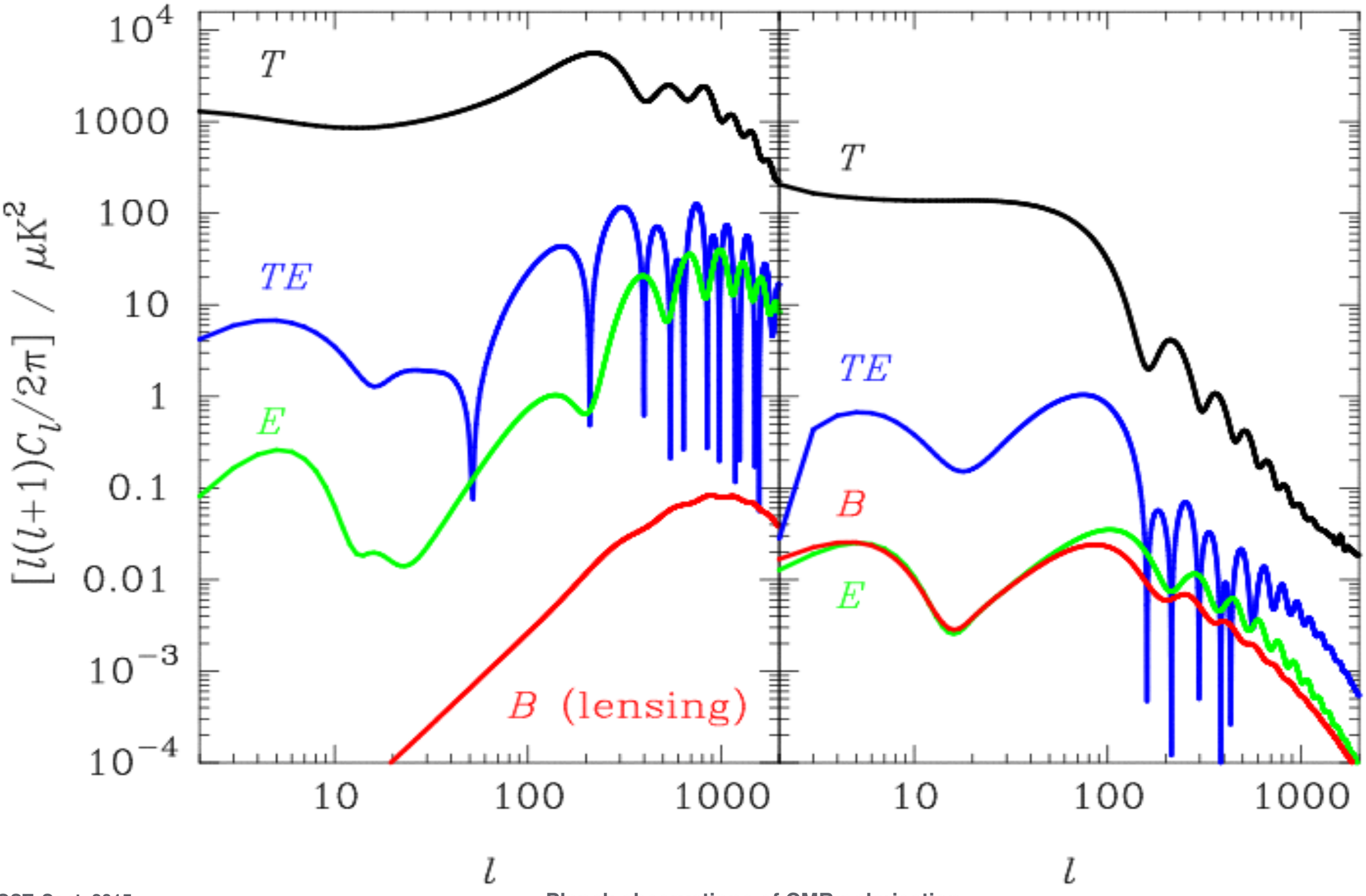


- **Thomson scattering on electrons at recombination**
  - quadrupolar anisotropy ⇒ linear polarisation
  - no circular polarisation

- **Q and U Stokes parameters maps**

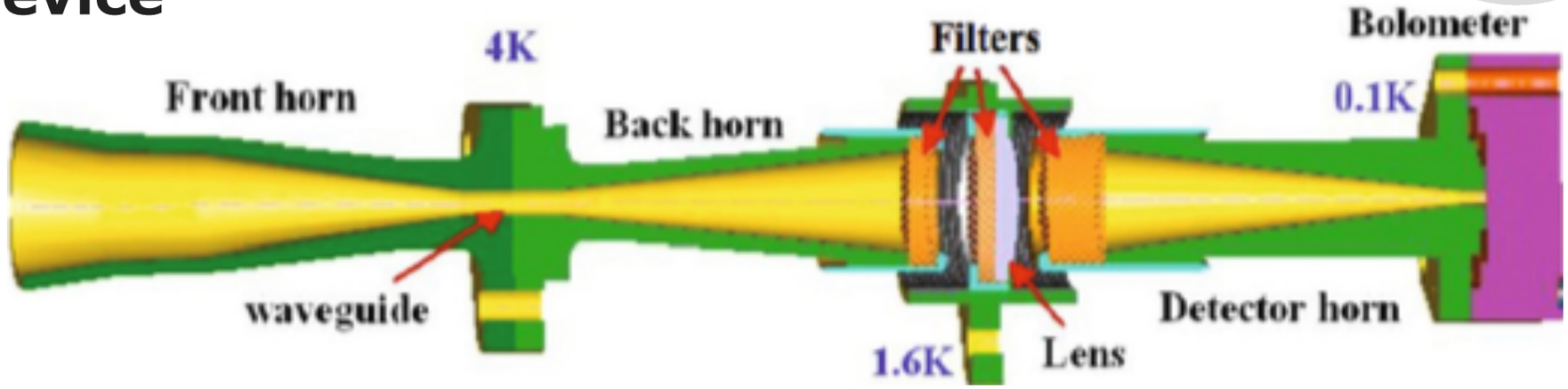
- **E,B modes in harmonic domain**
  - analogy with Electro-Magnetic fields

Cosmological model

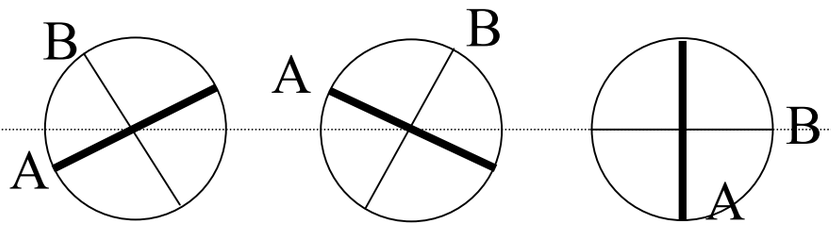


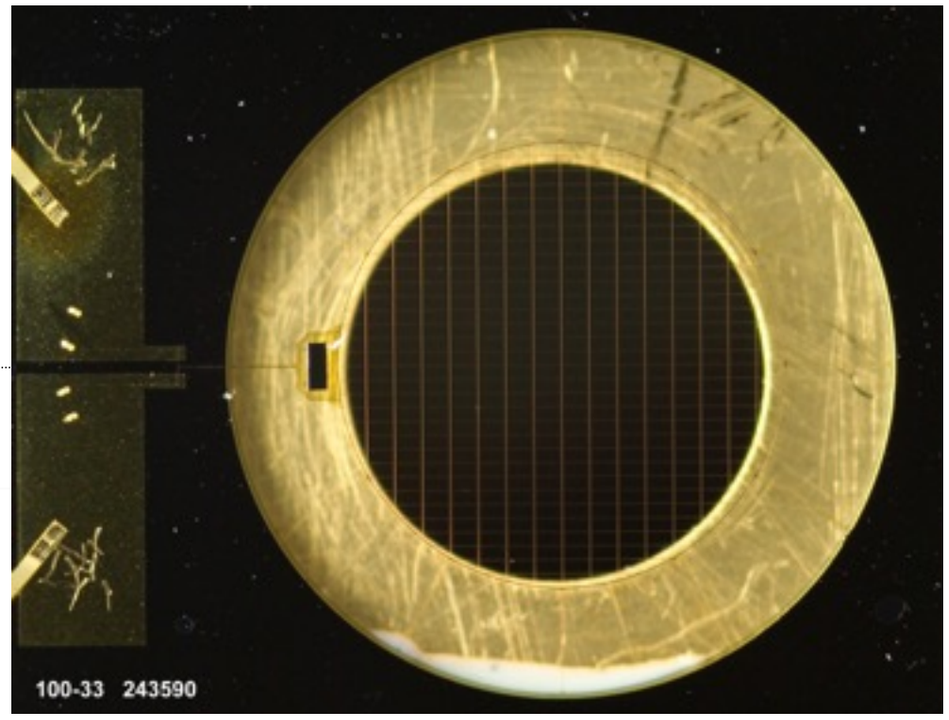
Planck polarised detectors

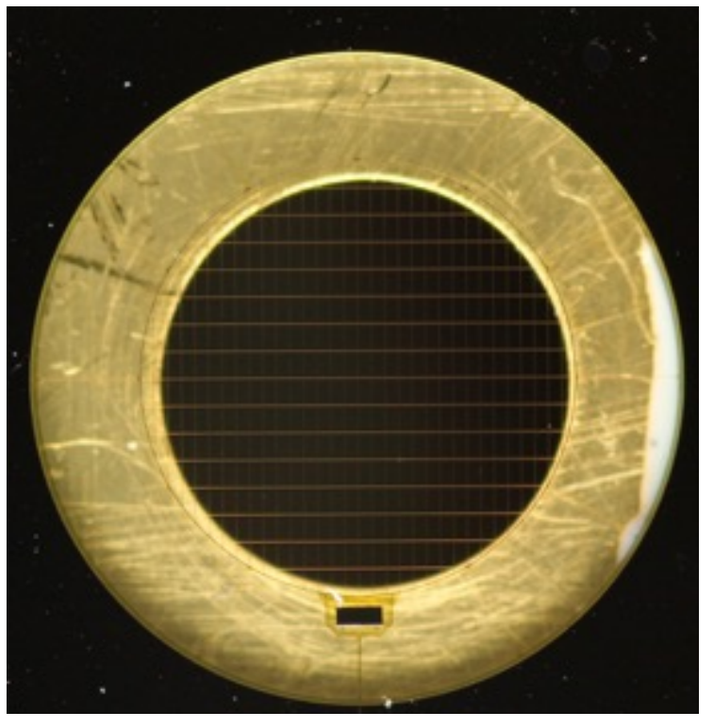
- **optical device**



- **Bolometers**







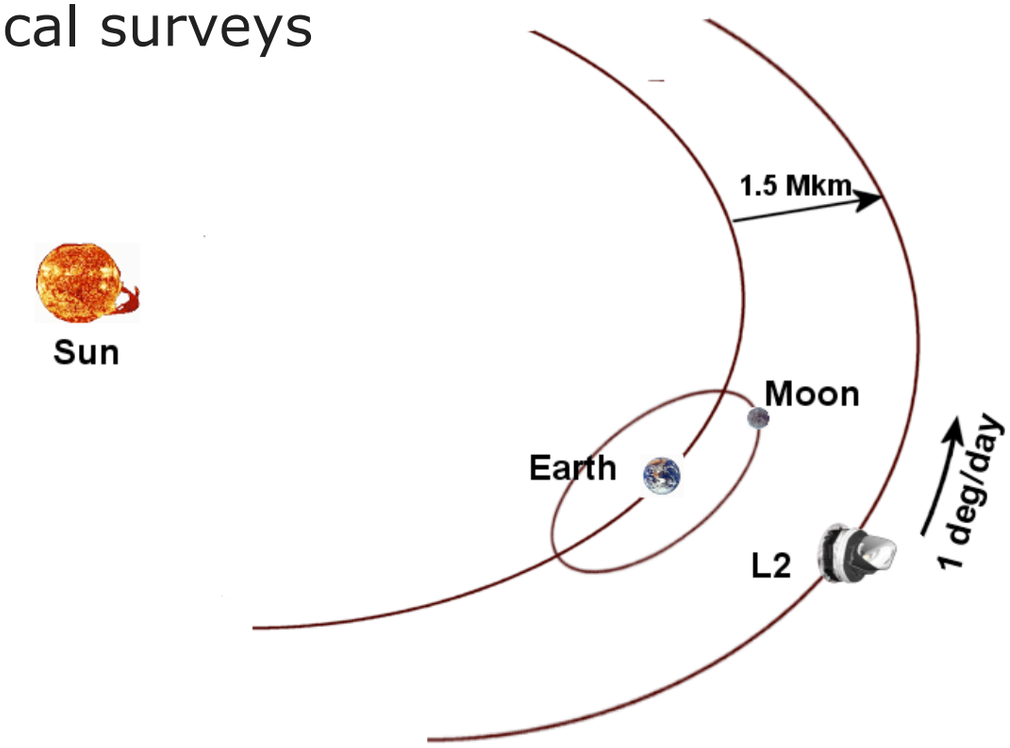
$$m_t = I(\vec{n}) + \rho\Big[Q(\vec{n}).cos(2\psi) + U(\vec{n}).sin(2\psi)\Big]$$

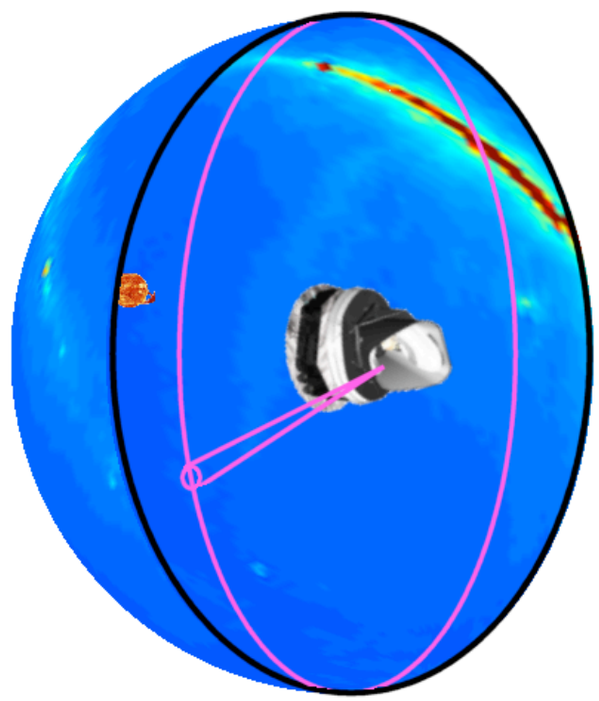
Polarisation measurement

- **we need different angles to measure I,Q,U**

$$m_t = I(\vec{n}) + \rho\Big[Q(\vec{n}).cos(2\psi) + U(\vec{n}).sin(2\psi)\Big]$$

- **Planck scanning strategy is such that we have**
  - one orientation of the focal plane / sky pixel / survey
  - 2 pairs of identical surveys

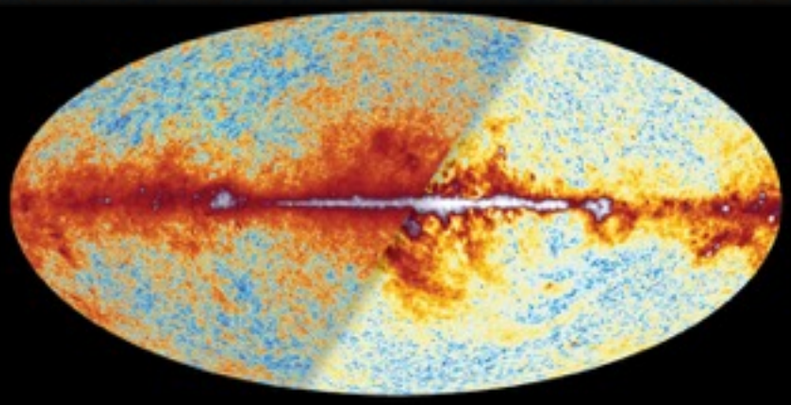




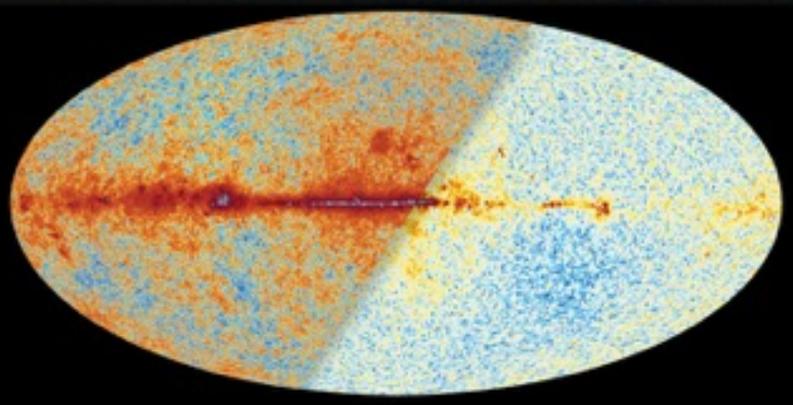
- **we combine detectors at 90deg**
  - need to have very precise inter-calibration to avoid I,Q,U mixing
  - Intensity signal is ~100 to 1000 times larger than polarisation

the sky as seen by Planck

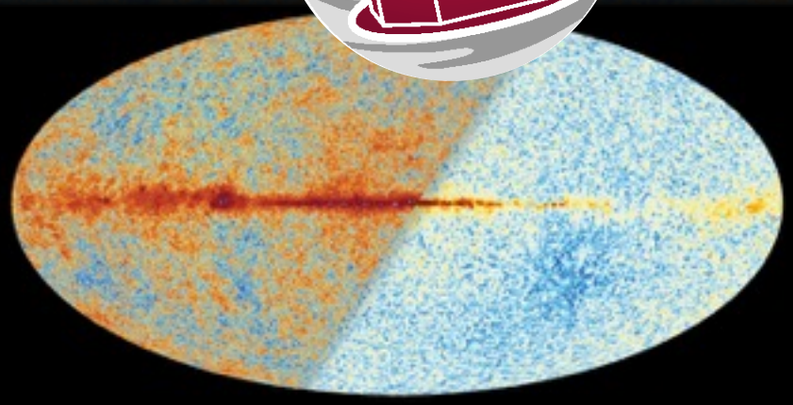
planck



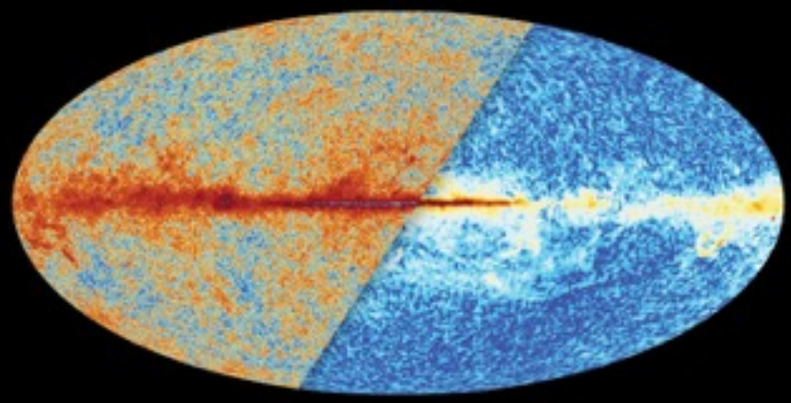
30 GHz



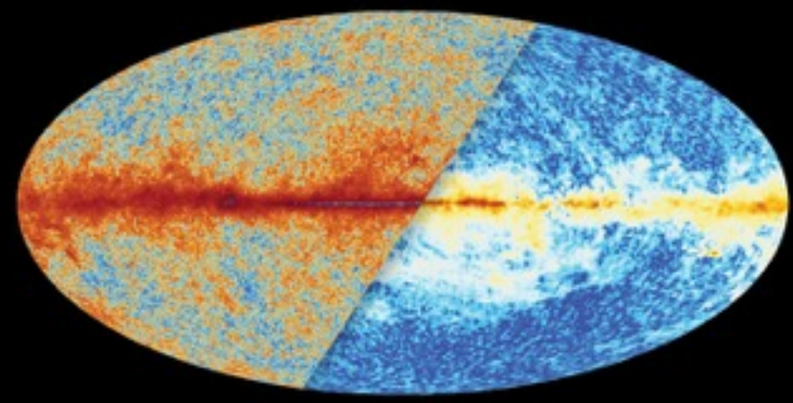
44 GHz



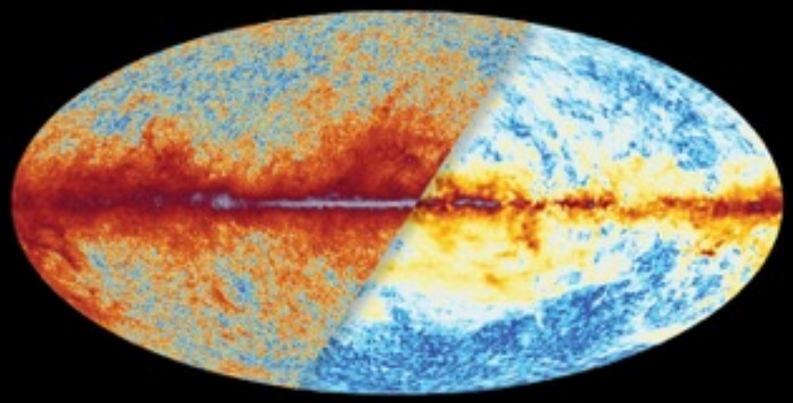
70 GHz



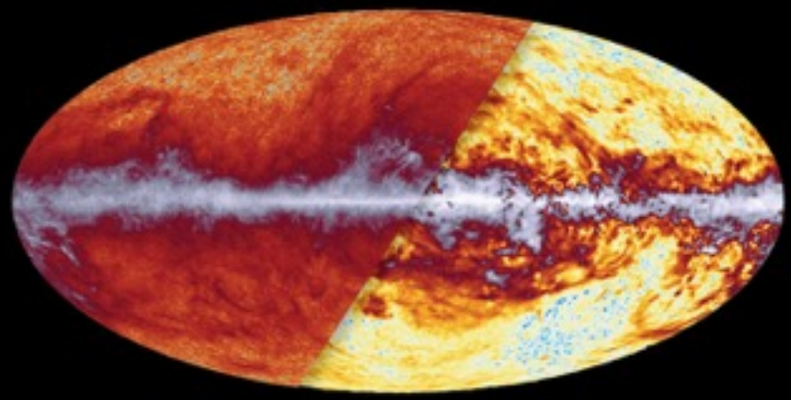
100 GHz



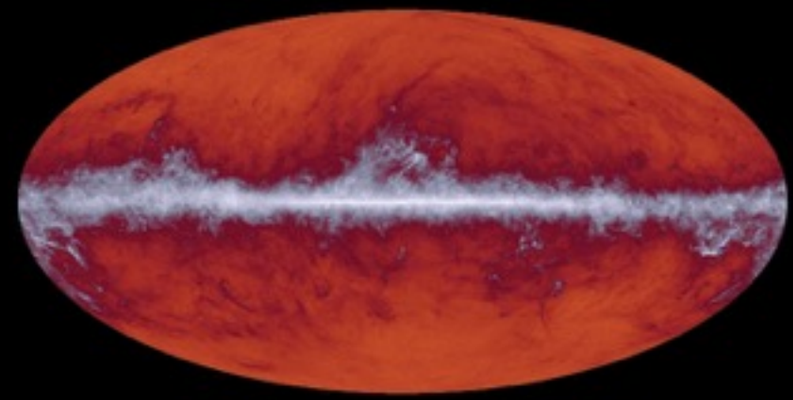
143 GHz



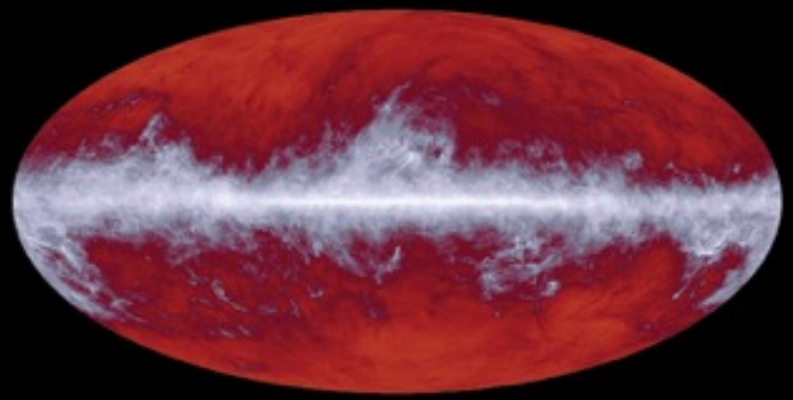
217 GHz



353 GHz



545 GHz



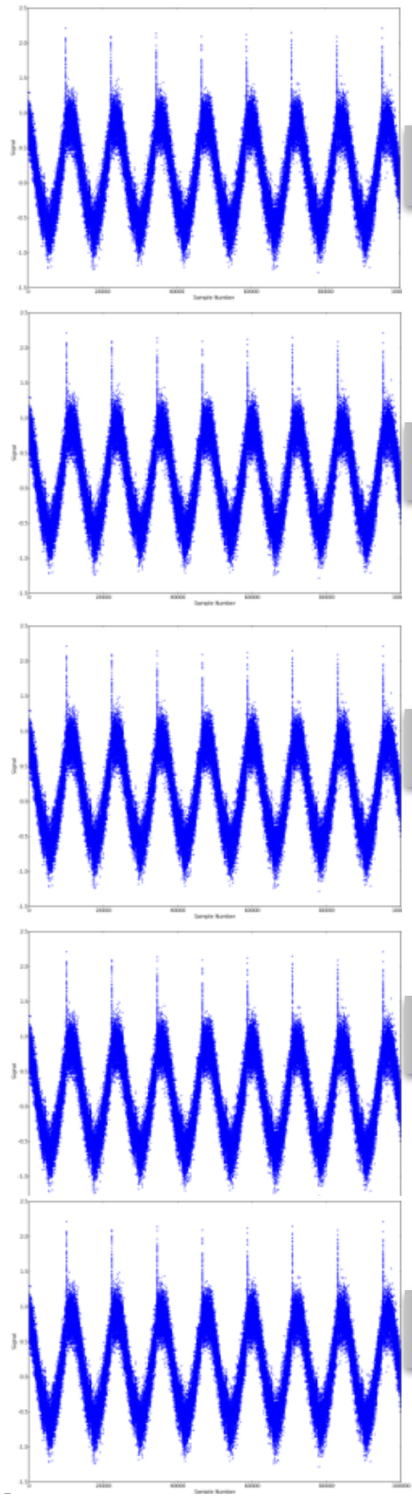
857 GHz

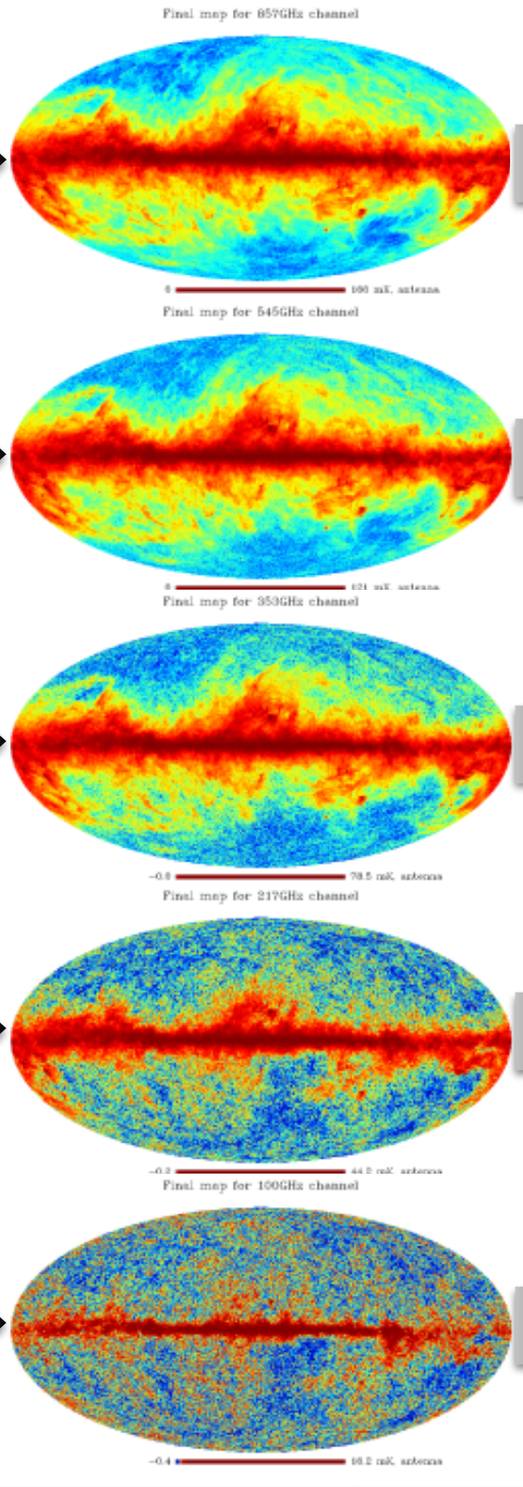
CMB data treatment

data

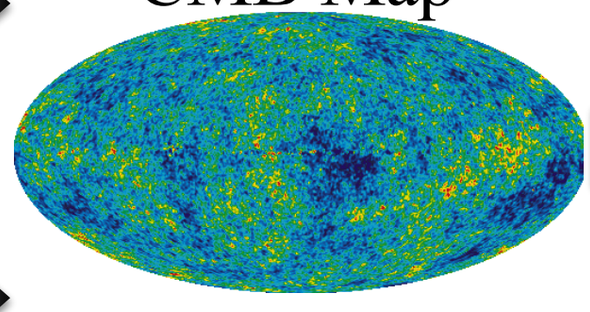
8 frequency maps

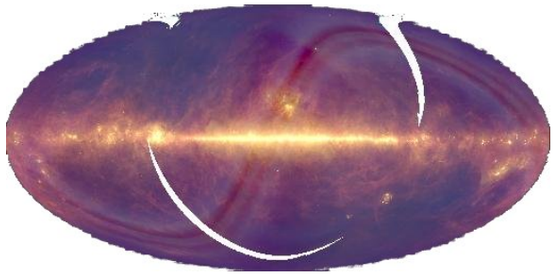
components maps

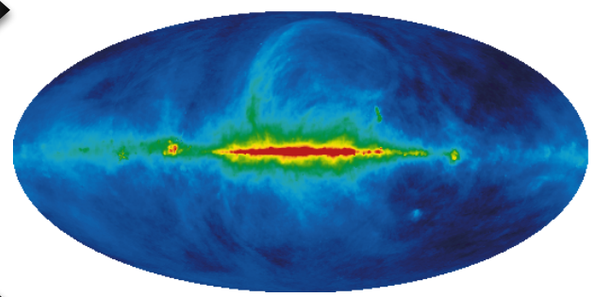




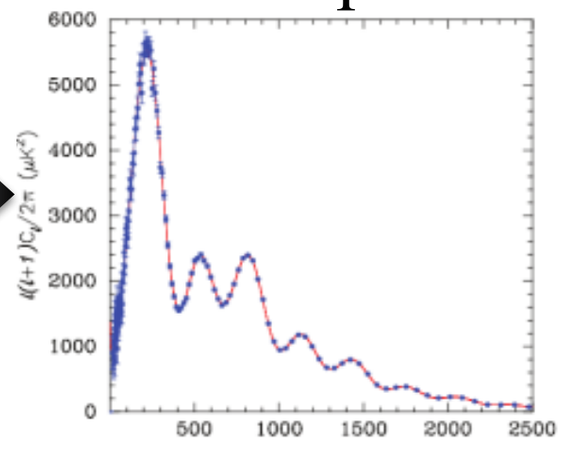
CMB Map

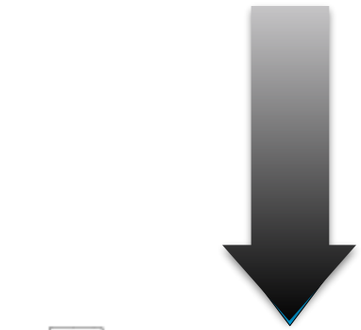




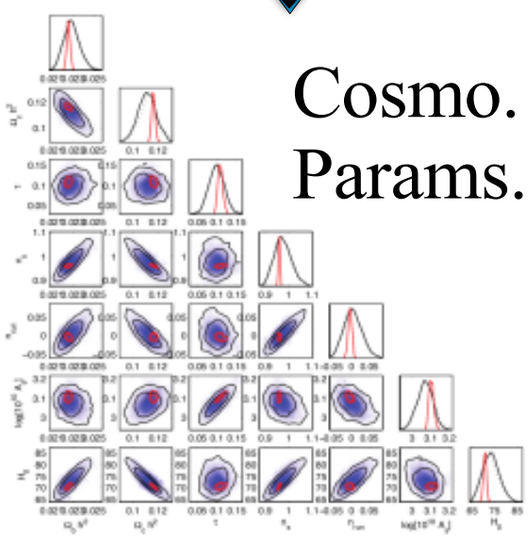


CMB Spectra





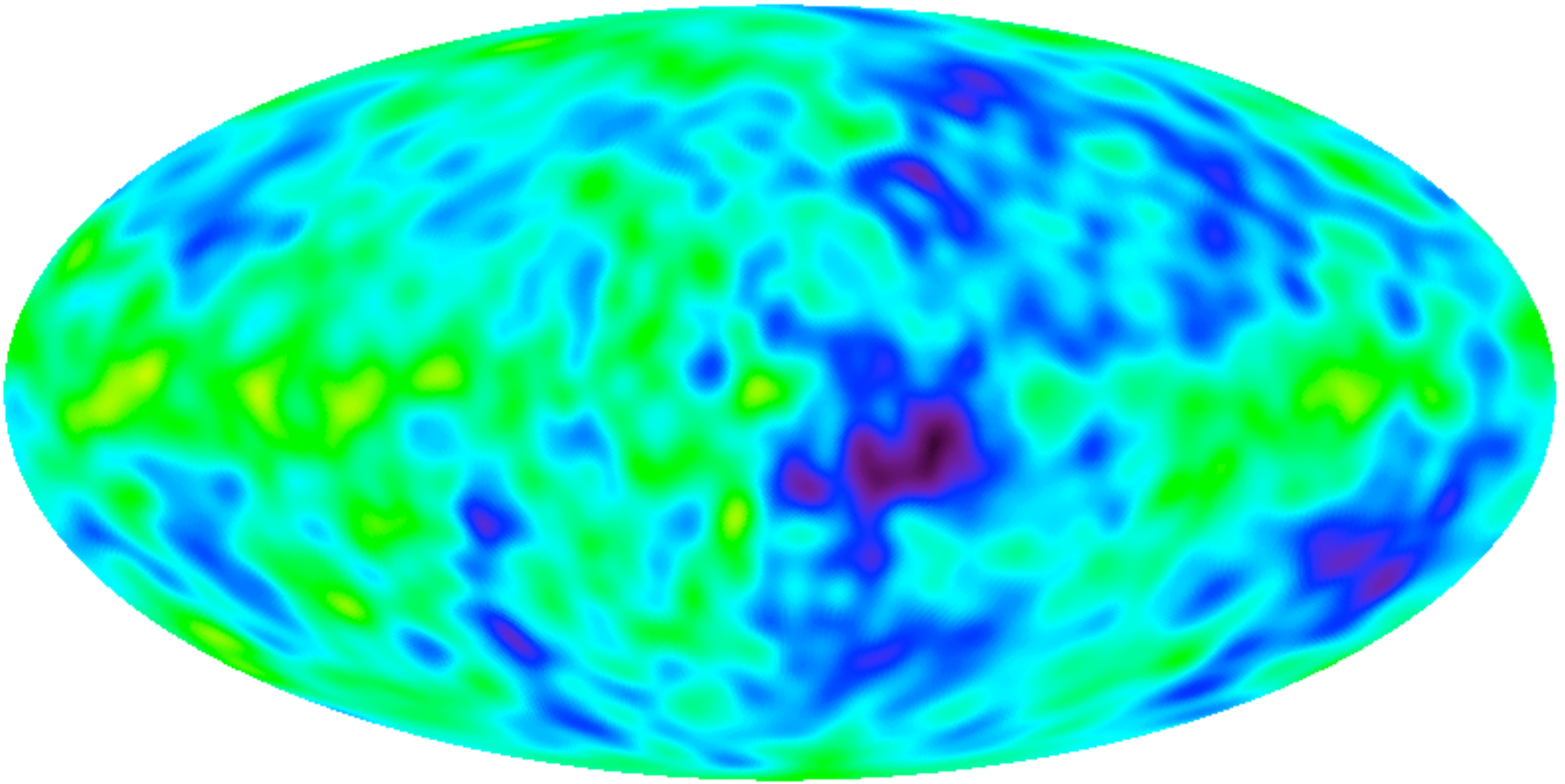
Cosmo. Params.



COBE

planck

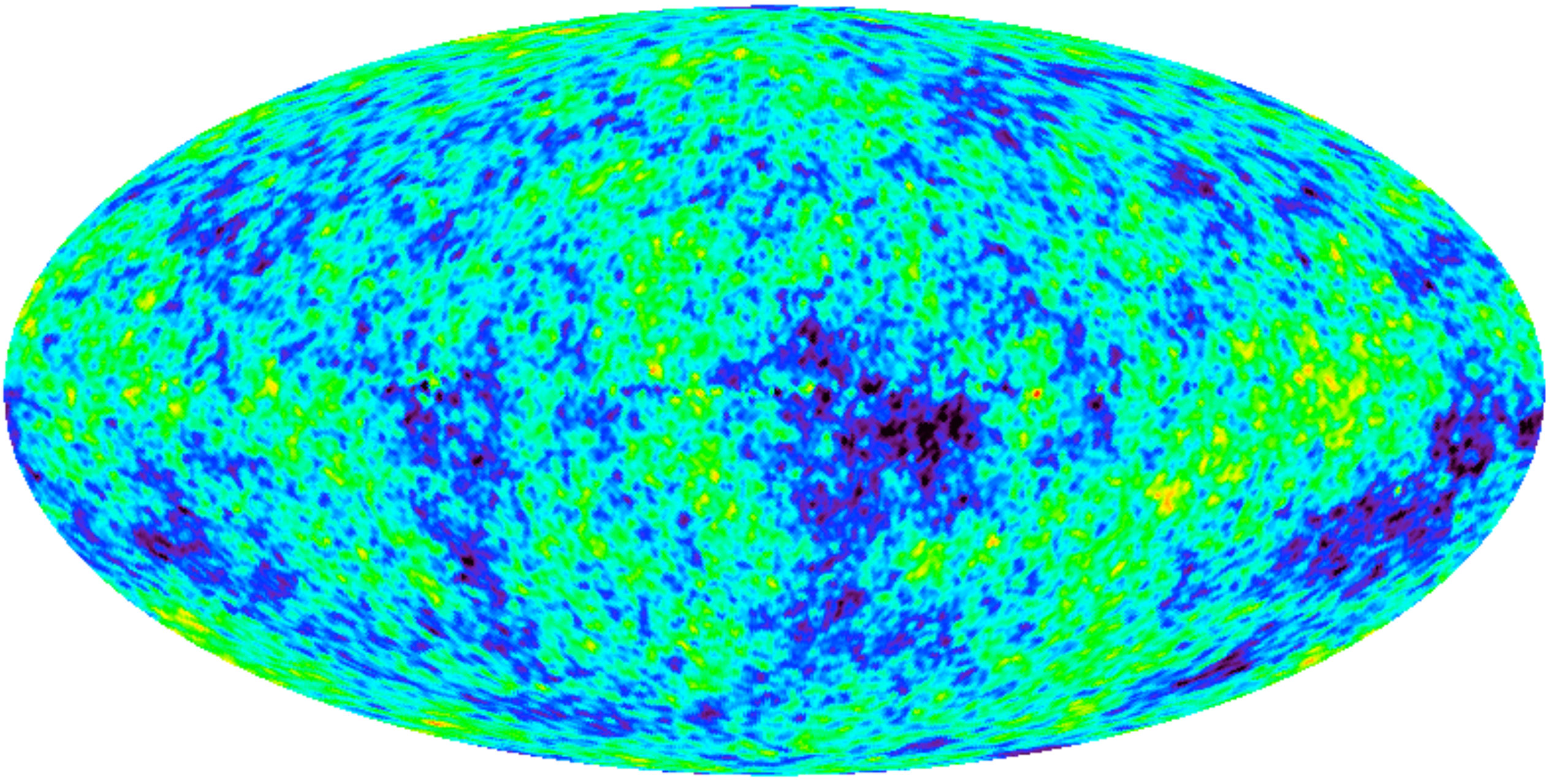
1993



WMAP

planck

2003



Planck

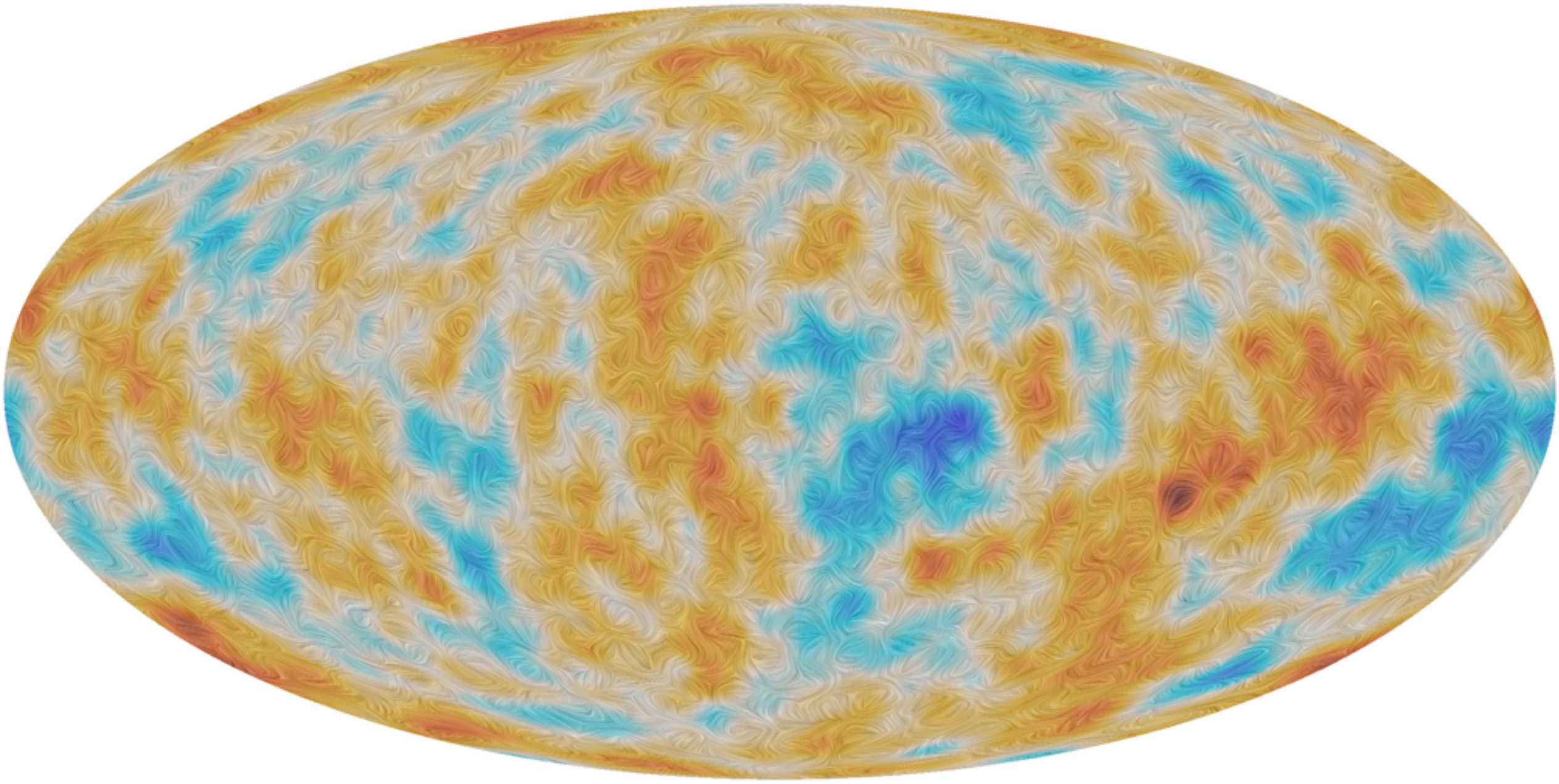
planck

2013

Planck

planck

2015

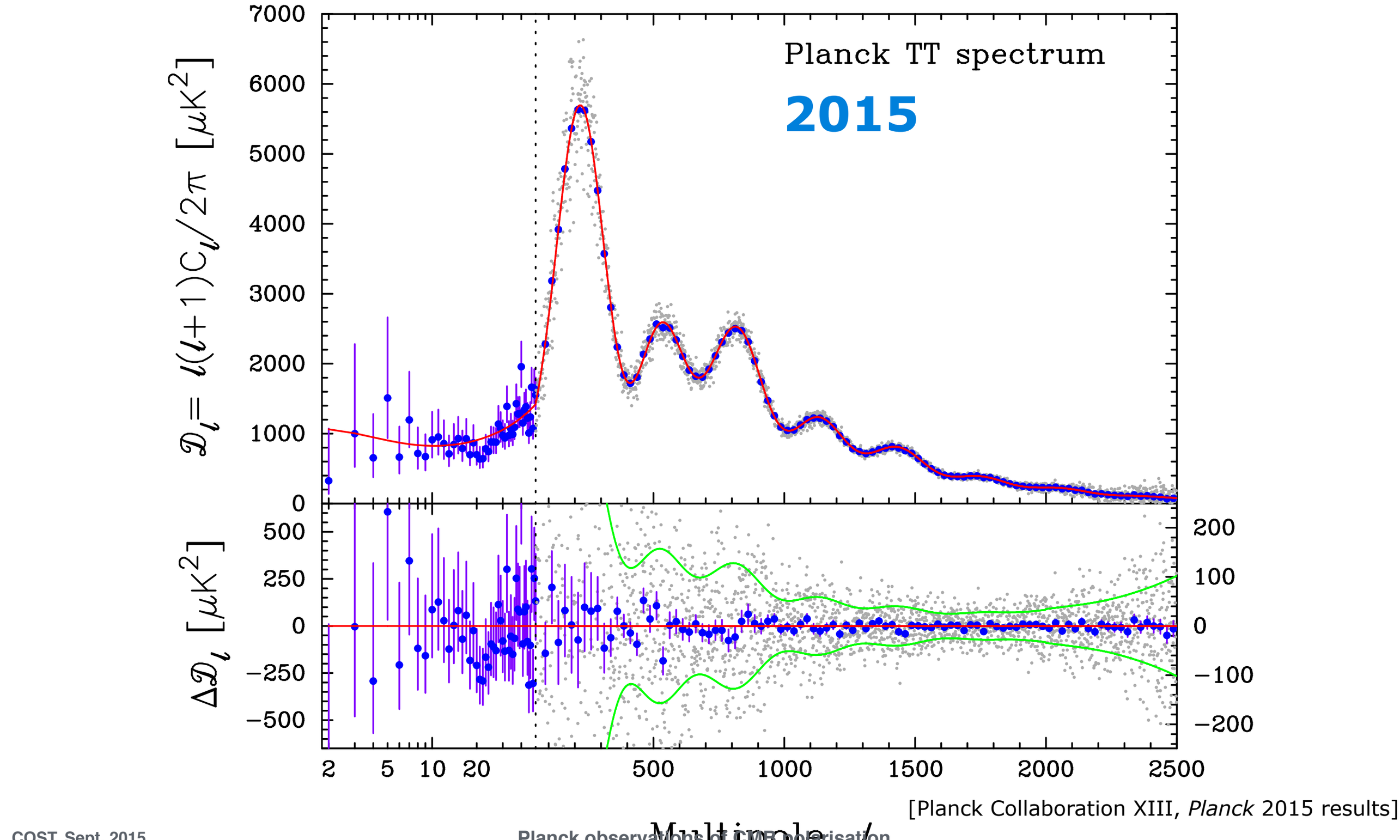


polarization

COST, Sept. 2015

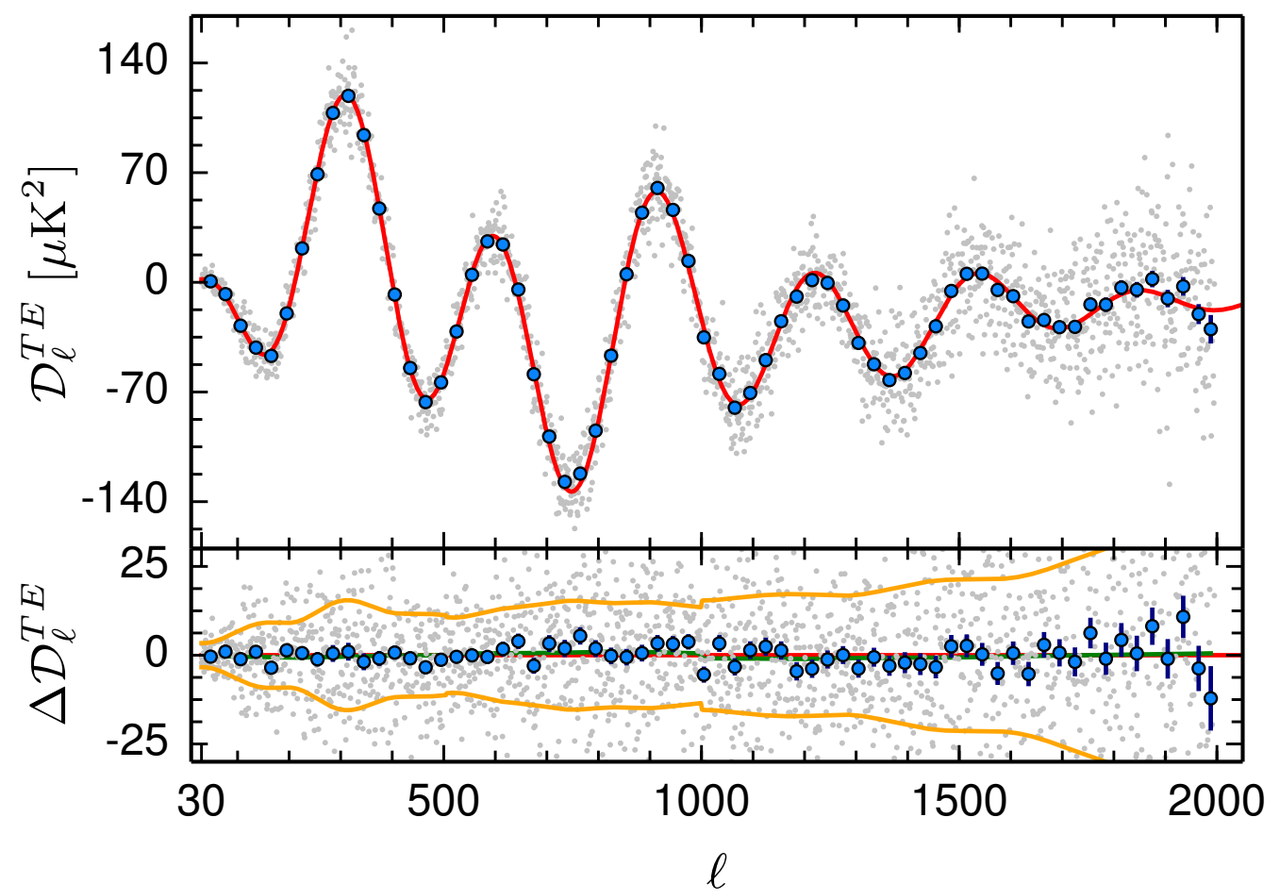
Planck observations of CMB polarisation

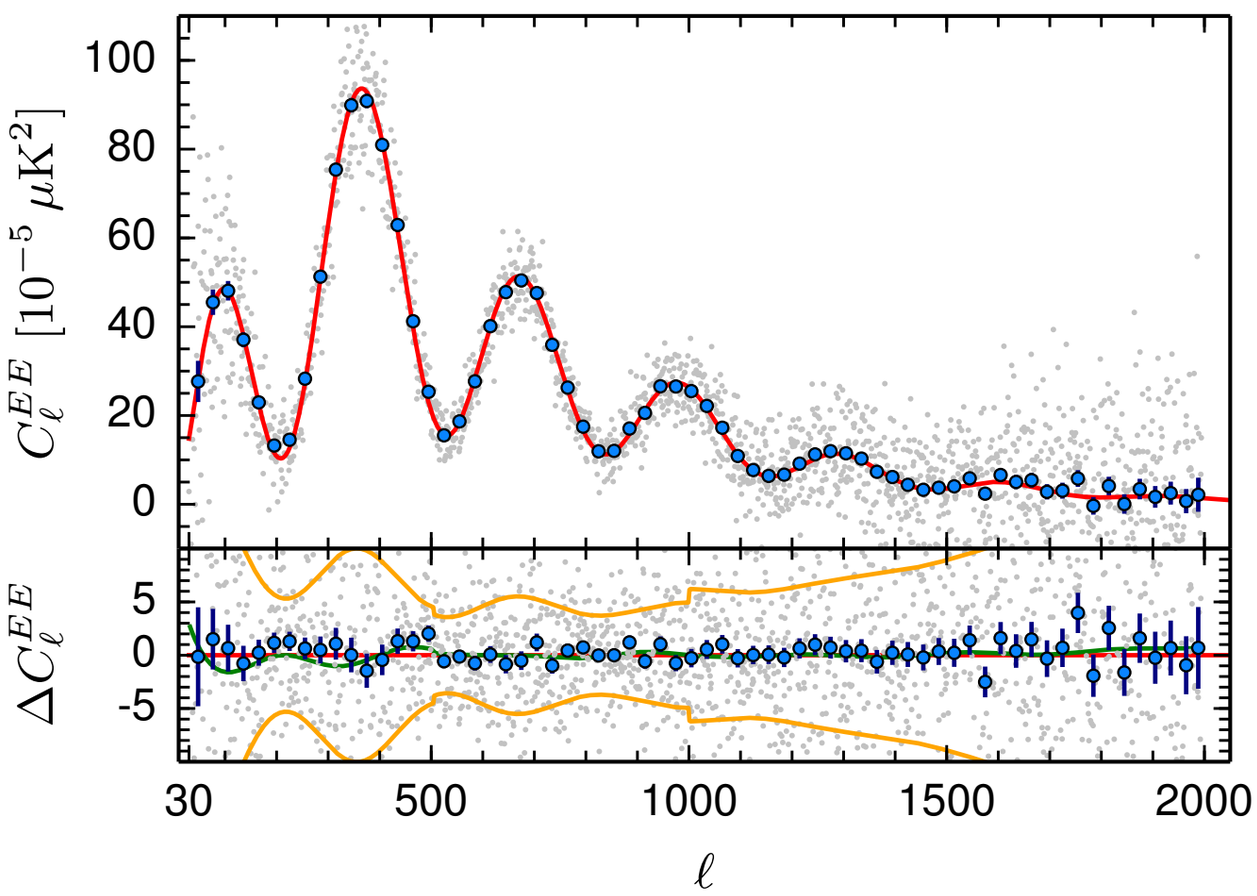
temperature power spectrum



[Planck Collaboration XIII, *Planck* 2015 results]

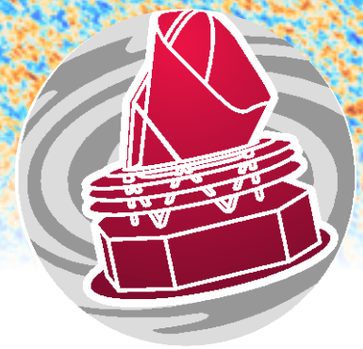
polarized power spectrum





[Planck Collaboration XIII, *Planck* 2015 results]

Cosmological standard model (ΛCDM)

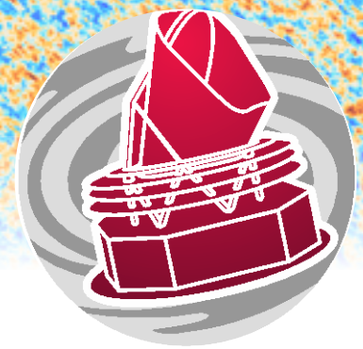


- **6 minimal parameters**
  - 2 for the primordial matter spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

  - 1 expansion rate H_0
  - 2 parameters for densities Ω_b Ω_c
  - reionization optical depth τ

ΛCDM results

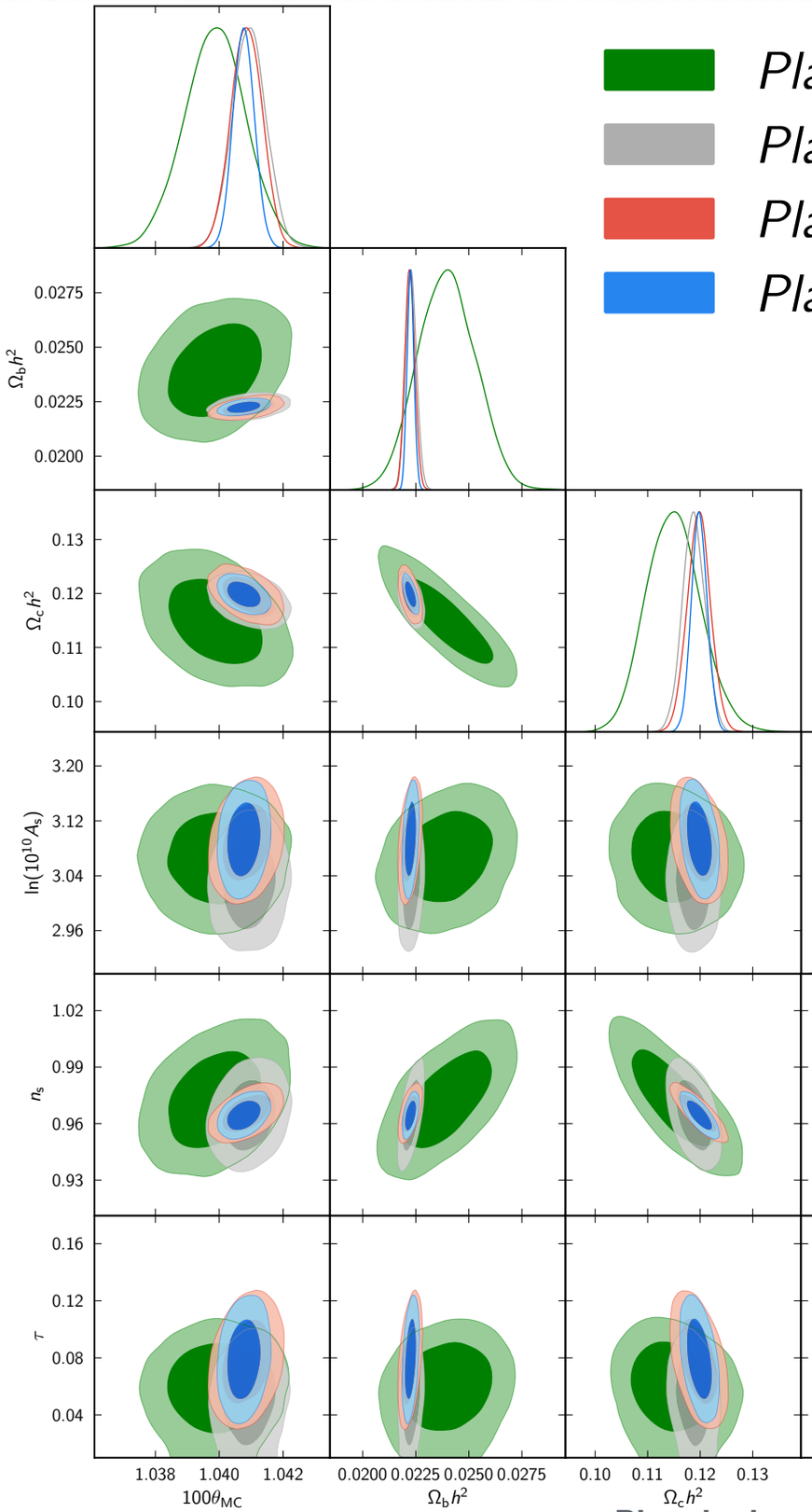


[Planck Collaboration XIII, *Planck* 2015 results]

	WMAP	Planck 2013	Planck 2015
Ω_b	0.0462 ± 0.0010	0.0487 ± 0.0006	0.04916 ± 0.0003
Ω_c	0.2322 ± 0.0092	0.2647 ± 0.0059	0.2647 ± 0.0033
H_0	70.0 ± 2.2	67.3 ± 1.2	67.27 ± 0.66
n_s	0.972 ± 0.013	0.960 ± 0.007	0.964 ± 0.005
$10^9\ A_s$	2.189 ± 0.090	2.196 ± 0.060	2.207 ± 0.074
τ	0.089 ± 0.014	0.089 ± 0.014	0.078 ± 0.019
Ω_Λ	0.721 ± 0.025	0.685 ± 0.018	0.684 ± 0.009
Ω_m	0.279 ± 0.023	0.315 ± 0.018	0.316 ± 0.009

- **almost factor 2 on error bars wrt WMAP**
- **Planck very stable between 2013 and 2015**
- **almost factor 2 in 2015 when adding polarization**

CMB results



Planck EE+lowP

Planck TE+lowP

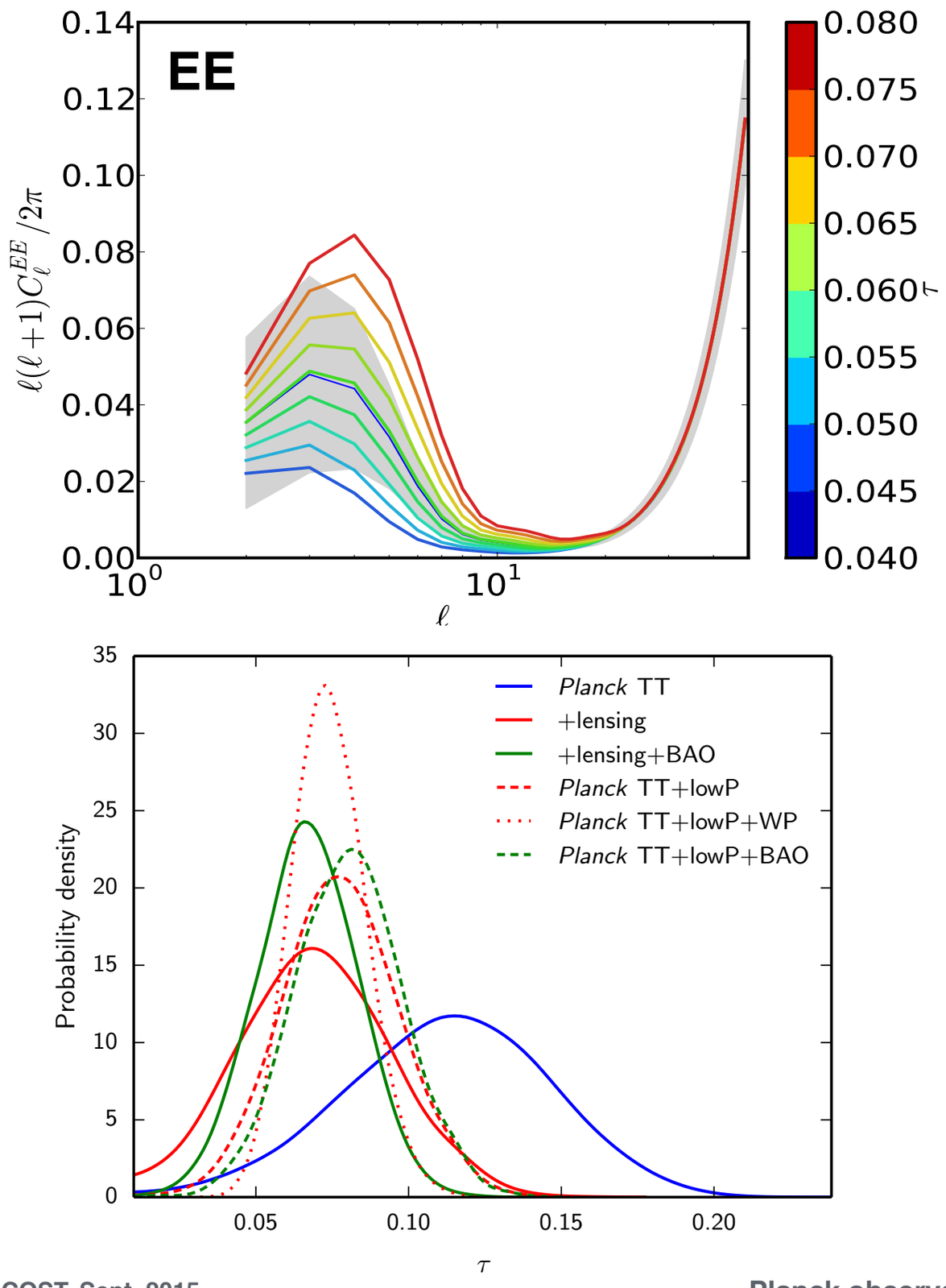
Planck TT+lowP

Planck TT,TE,EE+lowP

polarization spectra are generally highly consistent with TT spectra

[Planck Collaboration XIII, *Planck* 2015 results]

reionisation optical depth



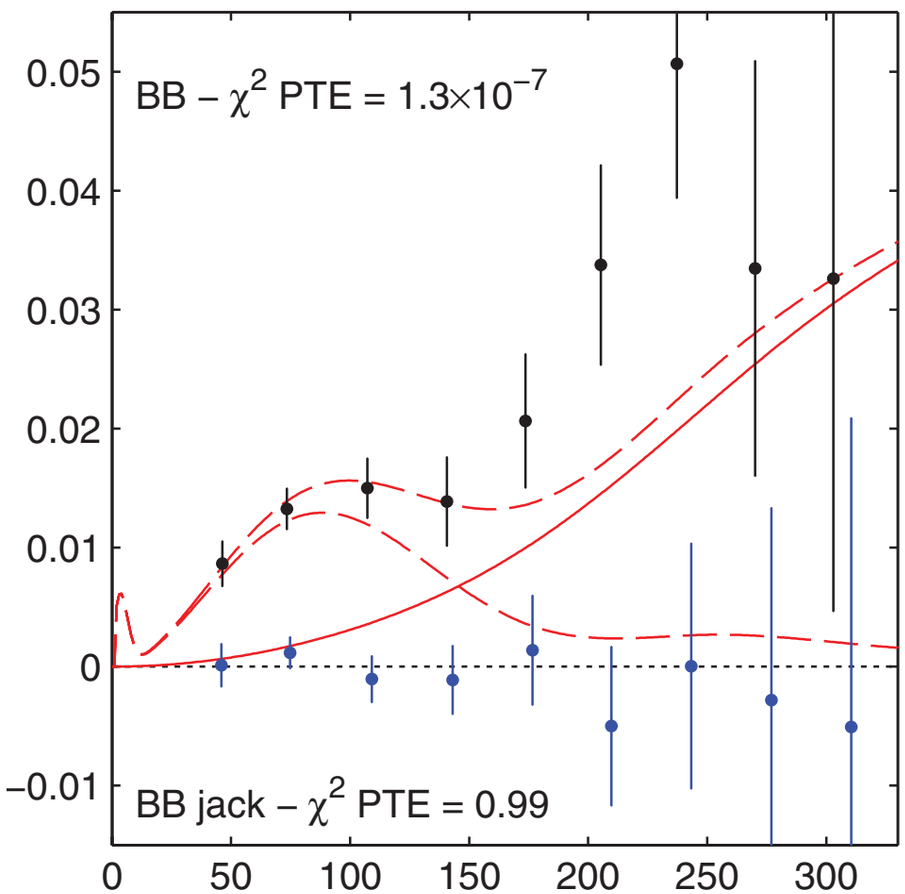
From CMB data:

1. **WMAP 9yr**
   - τ = 0.089 ± 0.014
2. **Planck 2013**
   - τ = 0.089 ± 0.014 (TT with WP)
   - τ = 0.075 ± 0.013 (TT with Planck dust)
3. **Planck 2015**
   - τ = 0.078 ± 0.019 (TT + lowP)
   - τ = 0.066 ± 0.016 (TT + lowP + lensing)
   - τ = 0.067 ± 0.016 (TT + lensing + BAO)
4. **Planck HFI polarisation EE low-l**
   - decreasing trend continues…

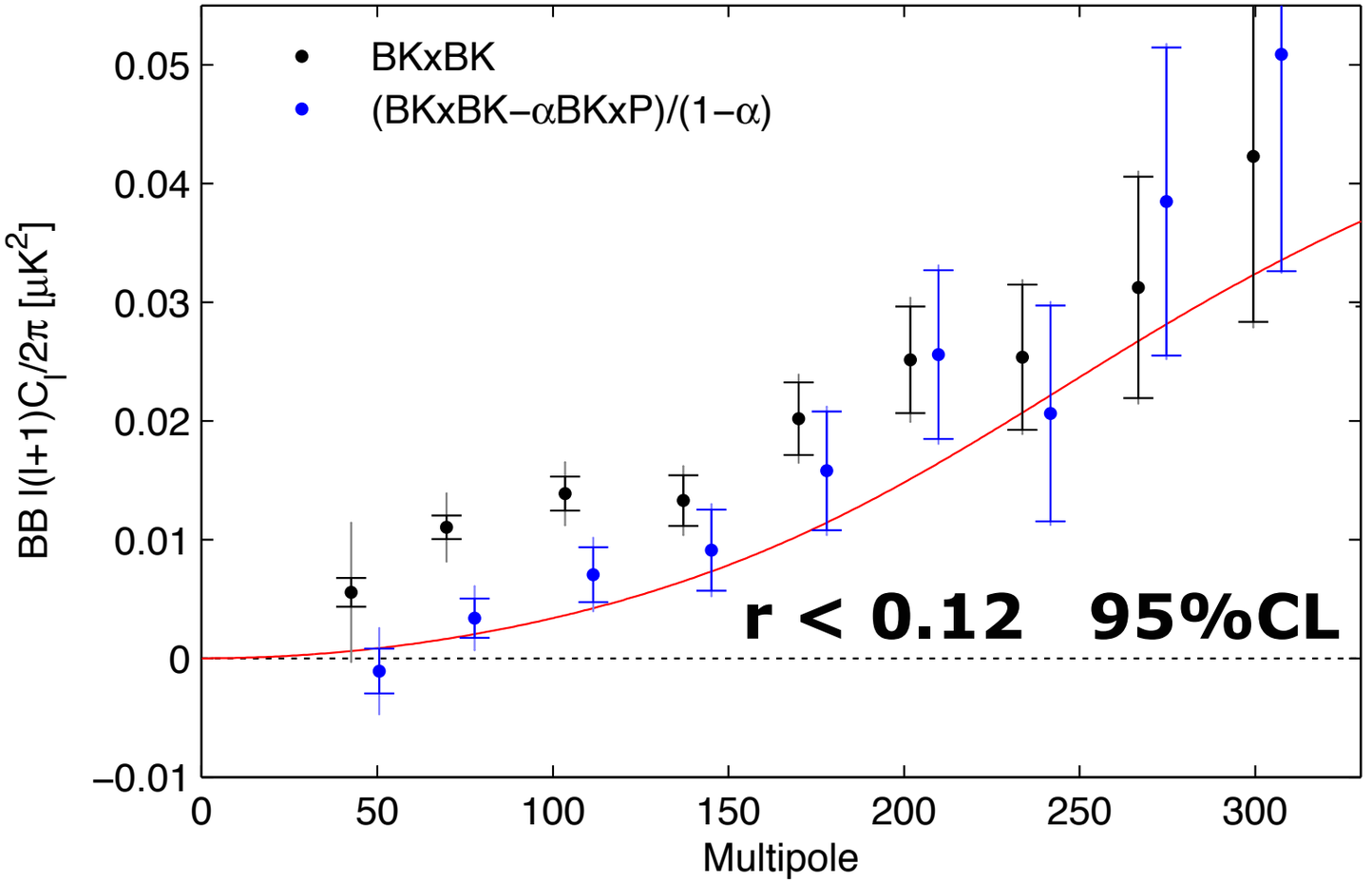
[Planck Collaboration XIII, *Planck* 2015 results]

primordial gravitational waves

- **March 2014**
  BICEP2 claimed 5σ detection of primordial B-modes with r=0.2 **[PRL 112, 241101 (2014)]**
- **September 2014** **[Planck Intermediate XXX, arXiv:1409.5738 (2014)]**
  Planck showed that BICEP2 results are compatible with polarized dust emission
- **January 2015** **[arXiv:1502.00612 (2015)]**
  joint analysis Planck-BICEP2/Keck shows no primordial signal, give upper-limit



[BICEP2 collaboration, PRL 112, 241101 (2014)]



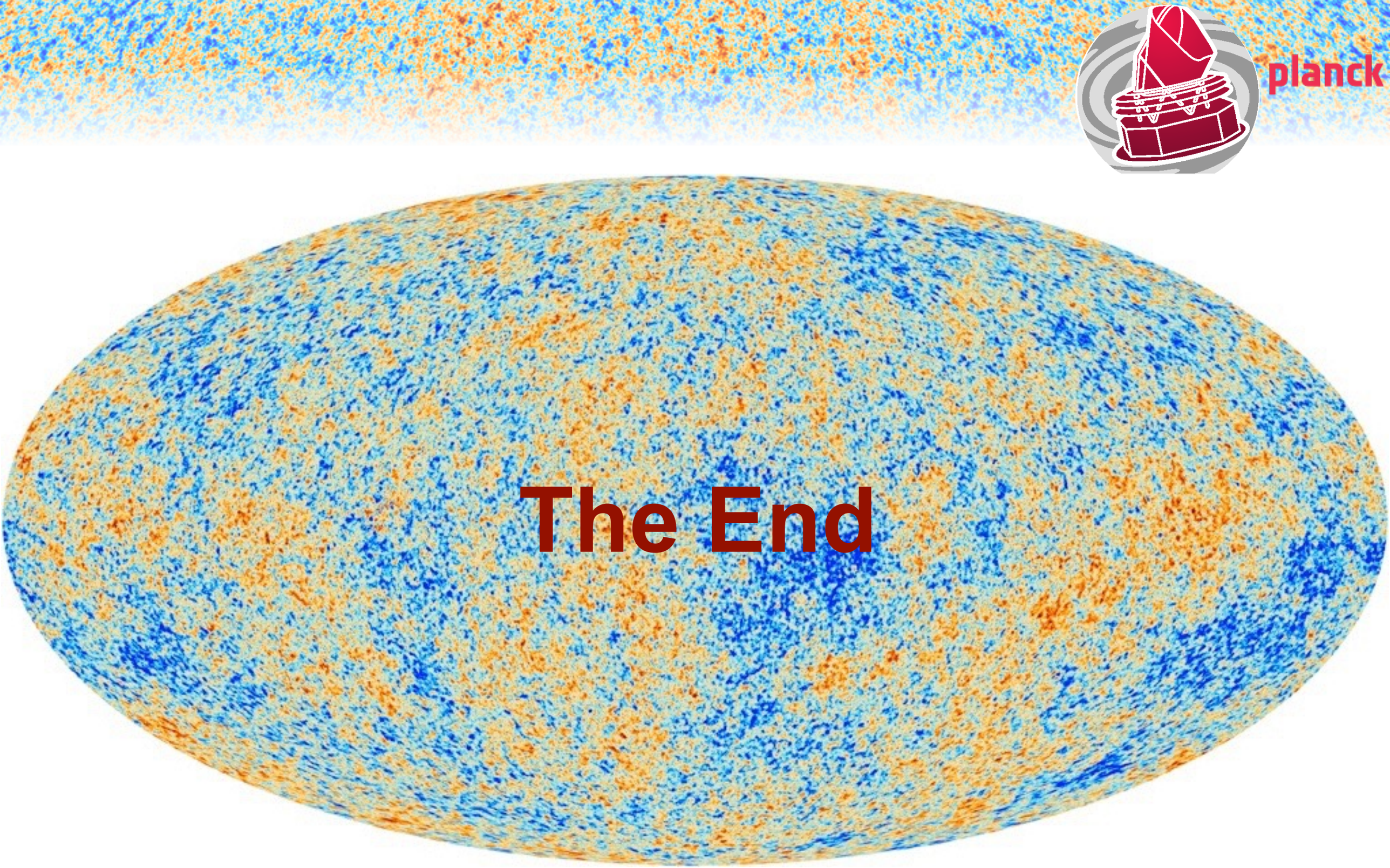
[BICEP2/Keck - Planck collaborations, arXiv:1502.00612 (2015)]

conclusions

- **2015 Planck constraints now include polarization.**
- **As in 2013 ΛCDM model continues to be a good fit to the Planck data, including polarization.**
- **No convincing evidence for any simple extensions.**
- **Specific polarisation effect:**
  - Reionization optical depth seems lower than expected which disfavor large abundances of star-forming galaxies beyond z=15
  - Planck constraints on gravitational waves
    - r<0.12 95% CL with BICEP2/Keck (direct measurement)

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.


planck
The End