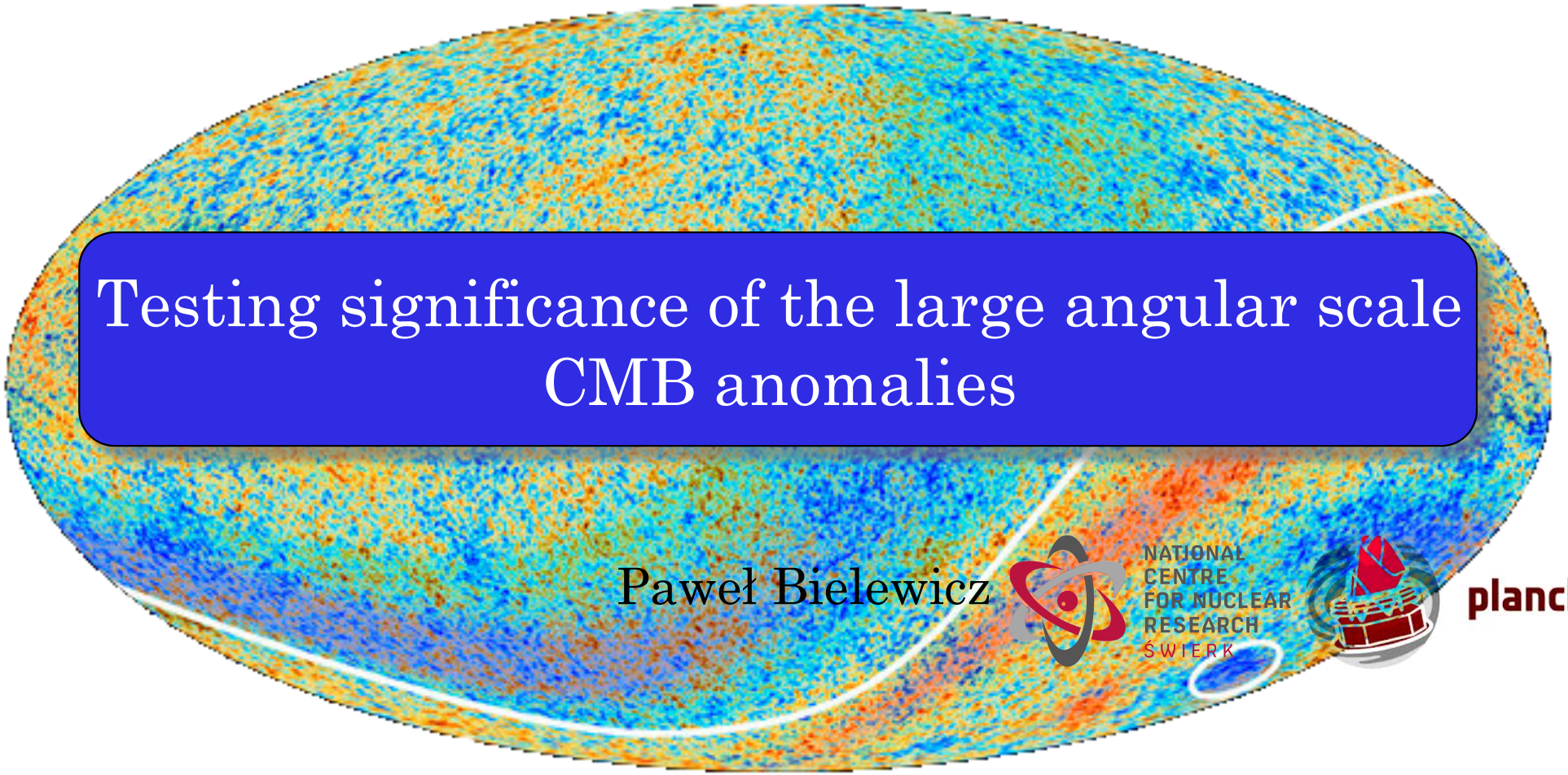


Testing significance of the large angular scale CMB anomalies

Paweł Bielewicz

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

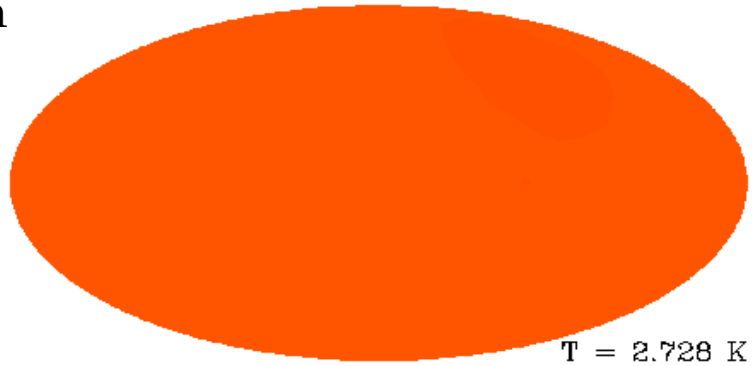
planck

based on „Planck 2018 results VII. Isotropy and statistics of the CMB”

Isotropy of the Universe

- Isotropy and homogeneity are fundamental assumptions in the standard Friedman-Robertson-Walker (FRW) model

$$ds^2 = c^2 dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2\left(d\vartheta^2 + \sin^2\vartheta\, d\varphi^2\right)\right)$$



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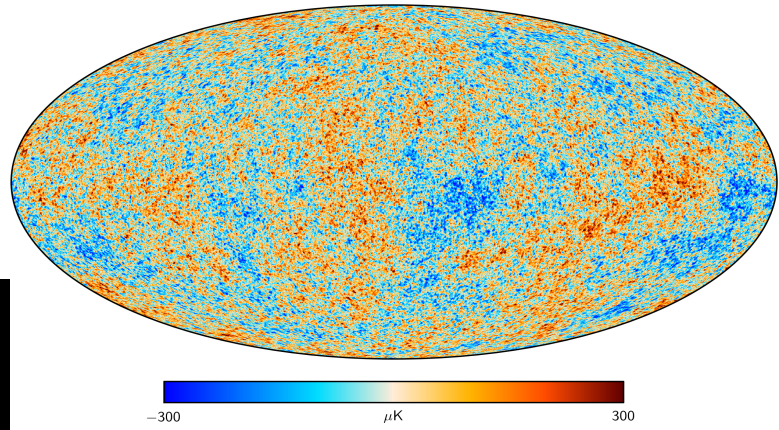
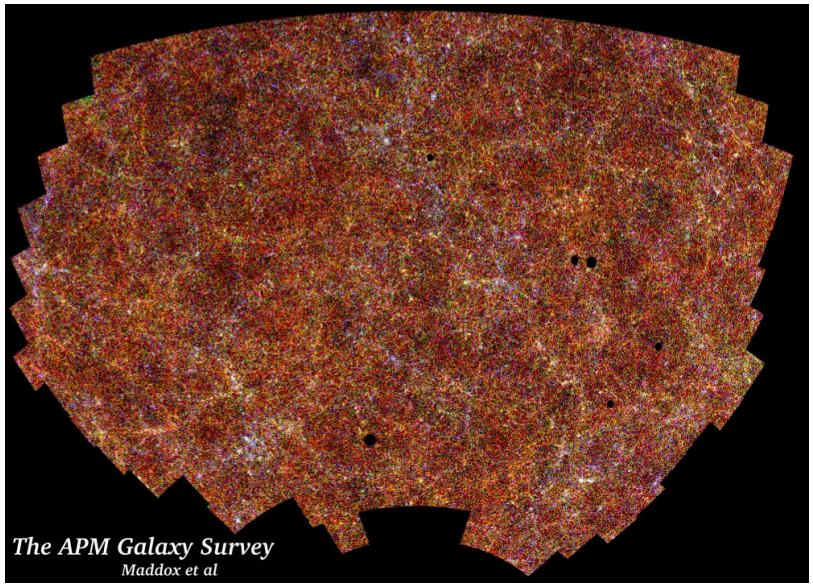
- Isotropy confirmed by observations (CMB, galaxy surveys)





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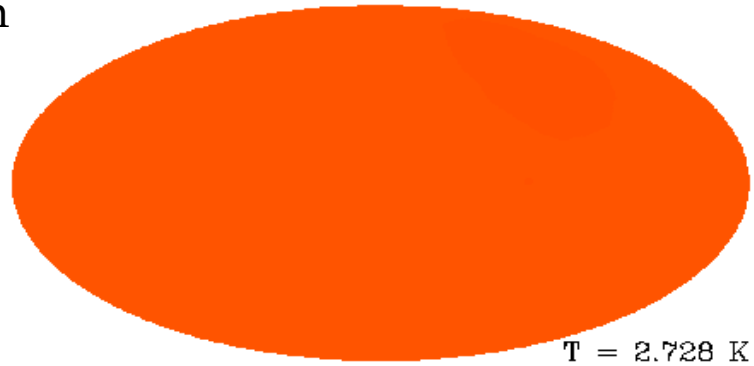

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- Homogeneity more difficult to test (obervations on past light cone, not spatial hypersurface)
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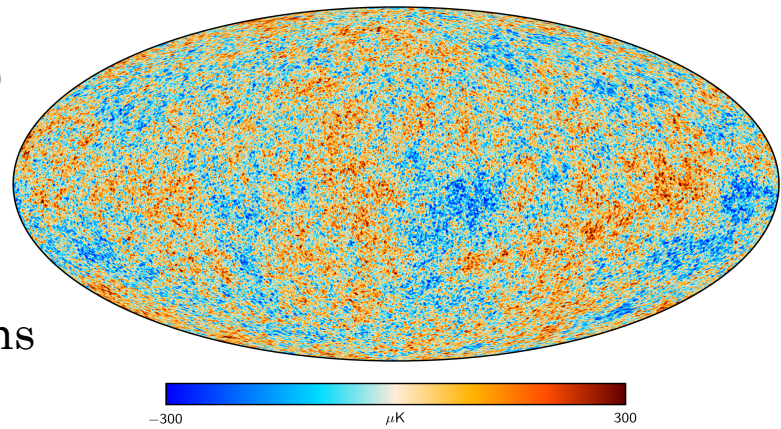

(statistical) isotropy + Copernican principle $\Longrightarrow$ (statistical) homogeneity

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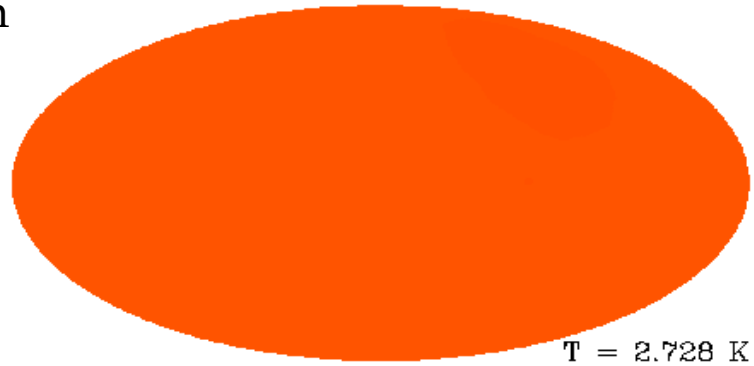

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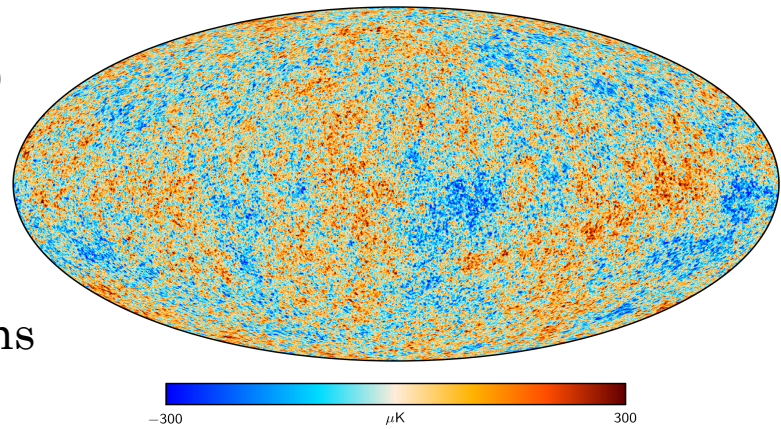

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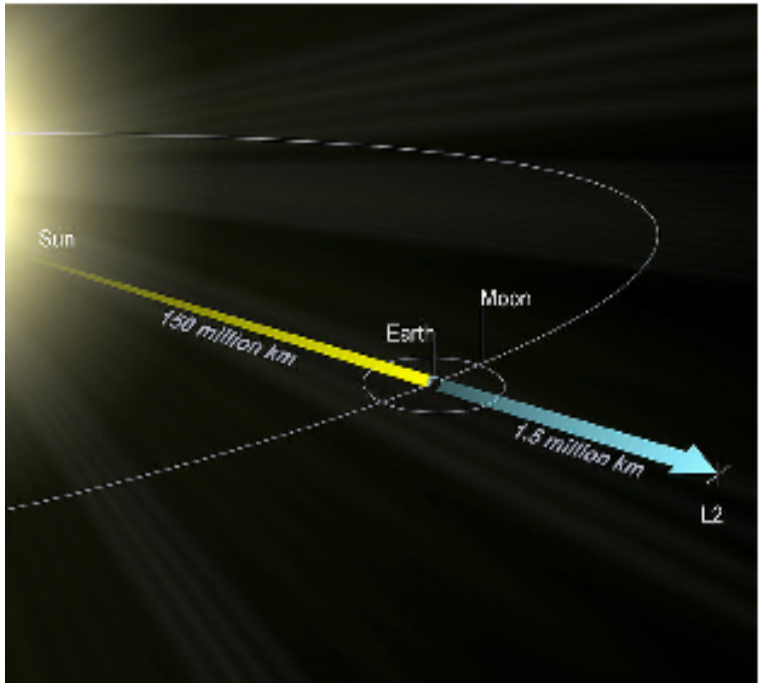
?

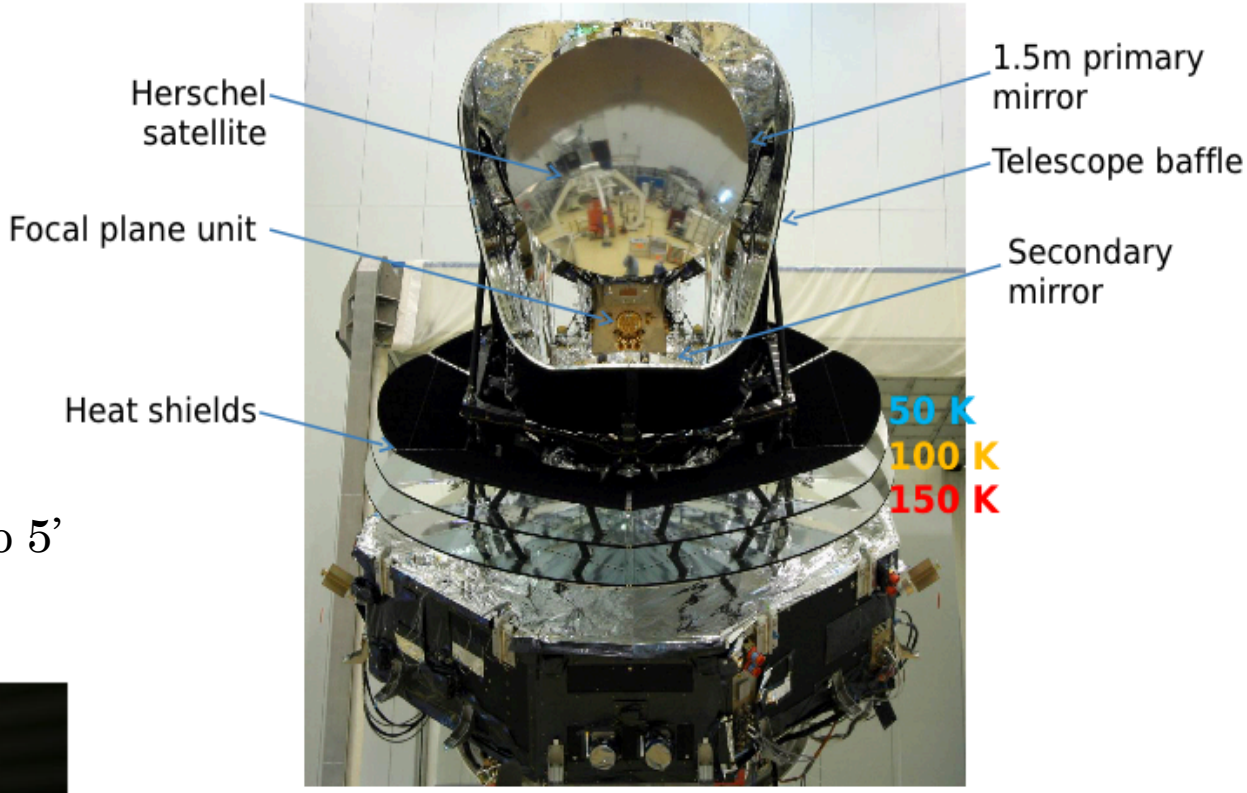
The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

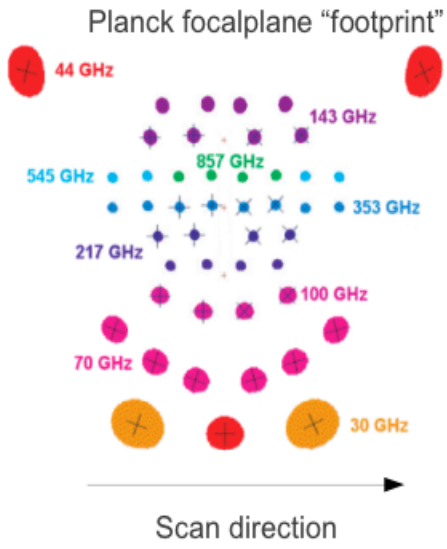
2019

Planck satellite

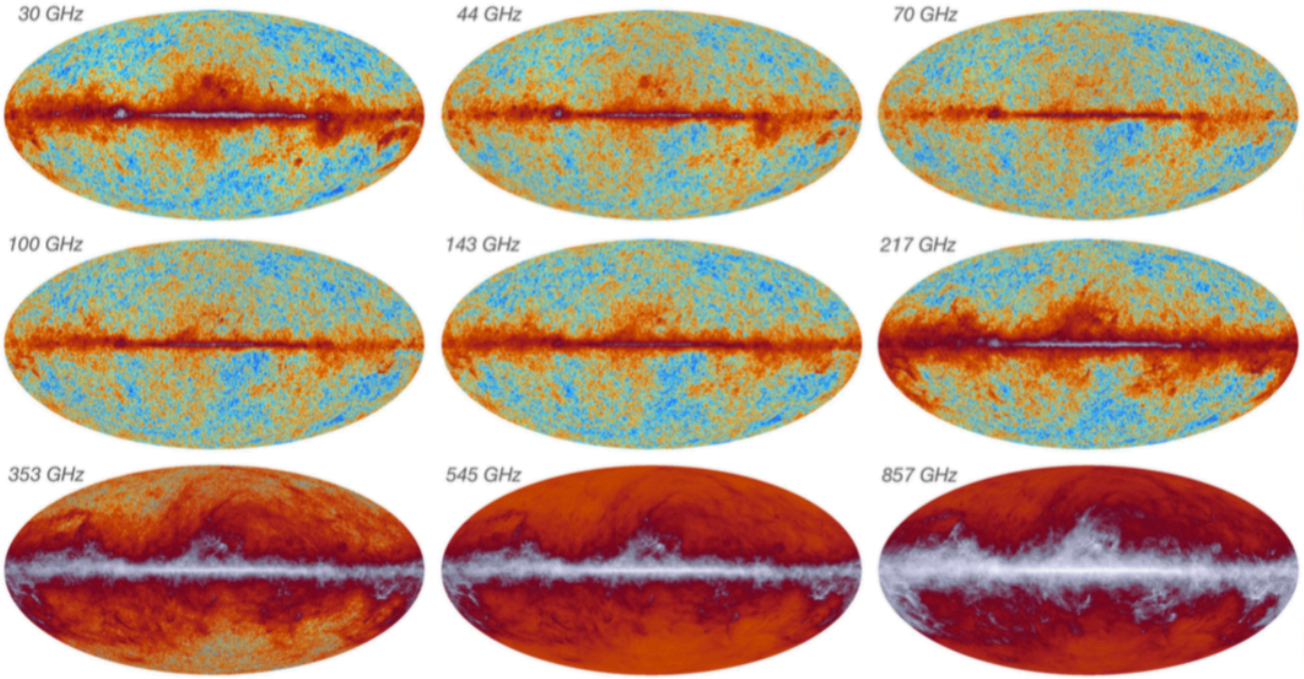
- Two instruments on board:
  - Low Frequency Instrument (LFI)
  - High Frequency Instrument (HFI)
- Wide frequency coverage with nine channels from 30 to 857 GHz
- Full sky coverage
- Angular resolution from 33’ down to 5’
- High sensitivity

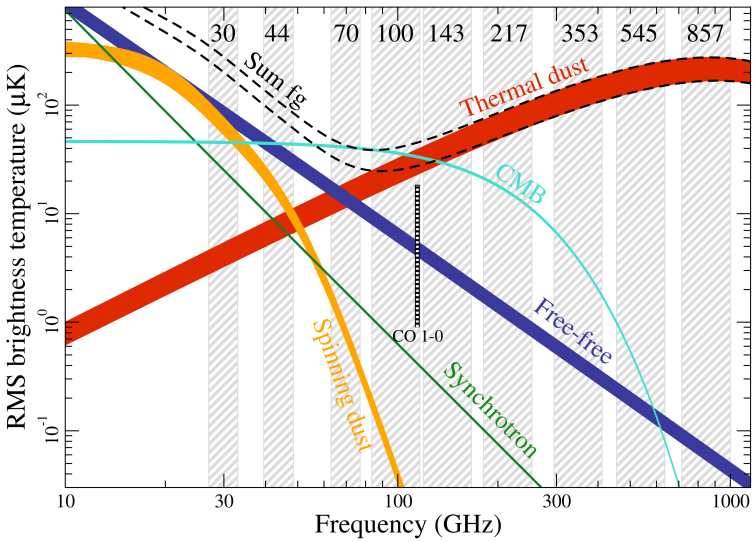


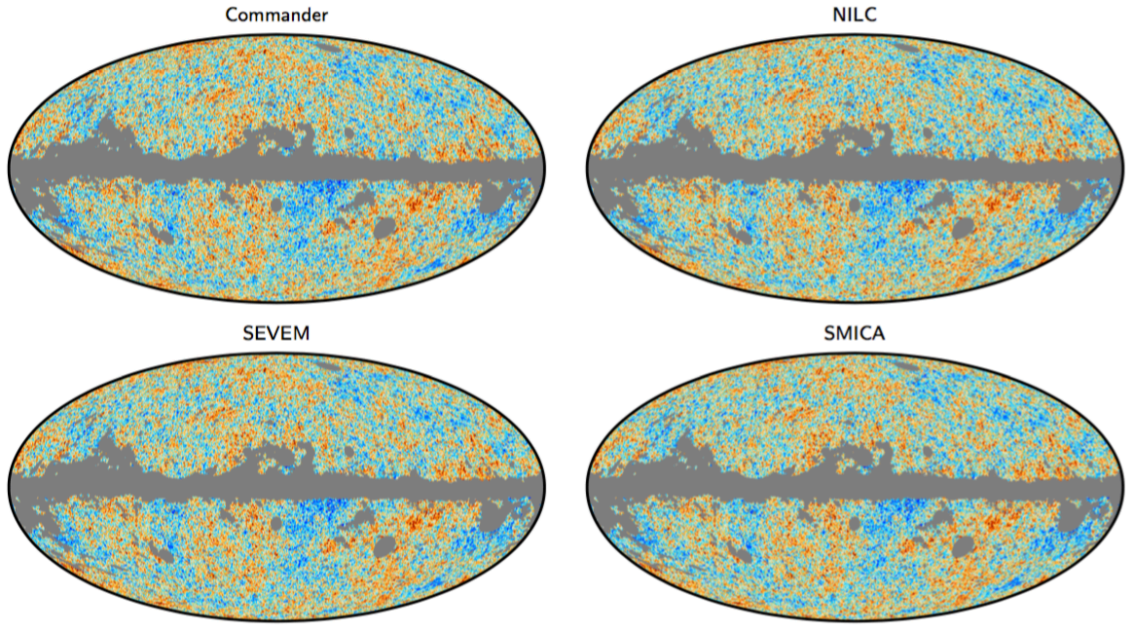




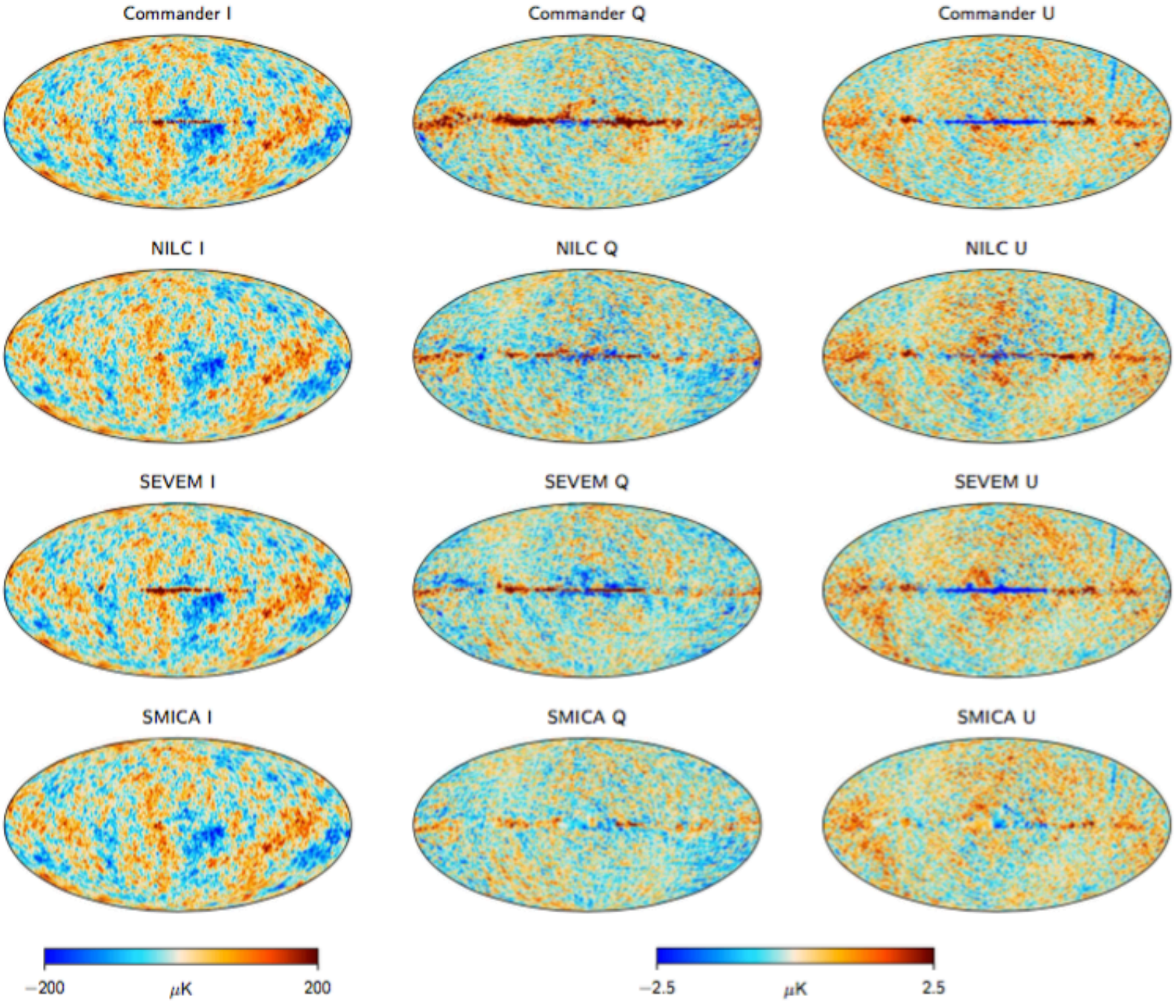
CMB temperature maps







Planck CMB maps



Large angular scale CMB anomalies

CMB anomalies tested by the Planck team for 2018 data release:

- Lack of correlation (lack of power) at large angular scales
- Point-parity asymmetry (preference for odd-parity modes in power spectrum)
- Hemispherical asymmetry for power spectrum and higher-order statistics
- Dipolar power asymmetry
- The Cold Spot and other large-scale peaks
- …

Large angular scale CMB anomalies

Possible explanations:

- Systematic effects (calibration, processing of data, ...) ? No
- Galactic foreground ? Rather not
- Local astrophysical origin ? Rather not

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Large angular scale CMB anomalies

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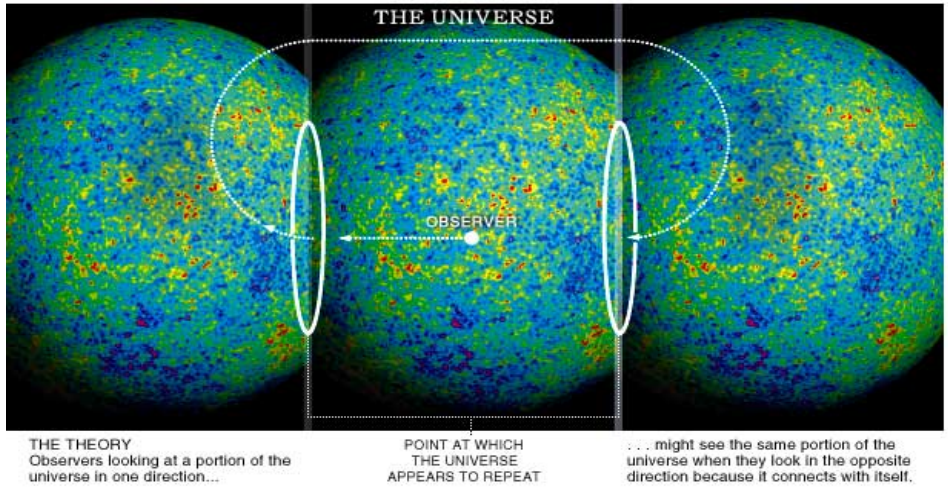
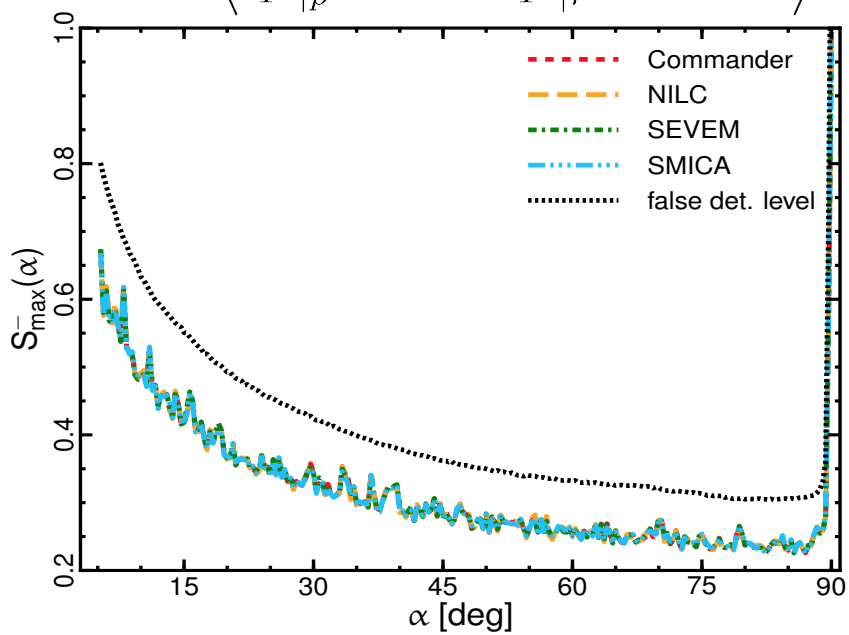
- Systematic effects (calibration, processing of data, ...) ? No
- Galactic foreground ? Rather not
- Local astrophysical origin ? Rather not
- Result of a posteriori inference (a.k.a. the multiplicity problem, look elsewhere effect) ? Maybe
- Cosmological origin ? Maybe
  - Bianchi VII_h models (no evidence if the Bianchi model parameters coupled to the cosmological ones)
  - Multi-connected topology
  - ...



$$S^{\pm}_{\max}(\alpha) = \max_{p,r,\beta} \frac{2\left\langle \frac{\delta T}{T}_{|p}(\alpha, \pm\phi)\, \frac{\delta T}{T}_{|r}(\alpha, \phi+\beta)\right\rangle}{\left\langle \frac{\delta T}{T}^{2}_{|p}(\alpha, \phi) + \frac{\delta T}{T}^{2}_{|r}(\alpha, \phi+\beta)\right\rangle},$$

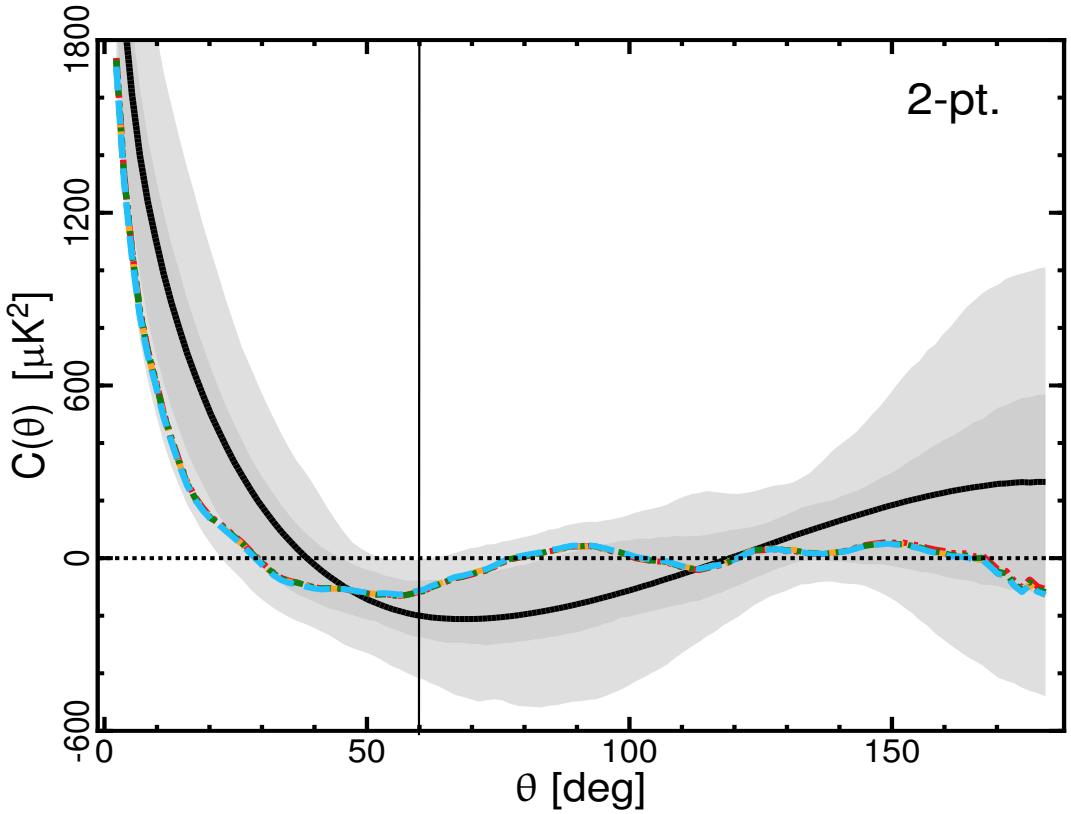


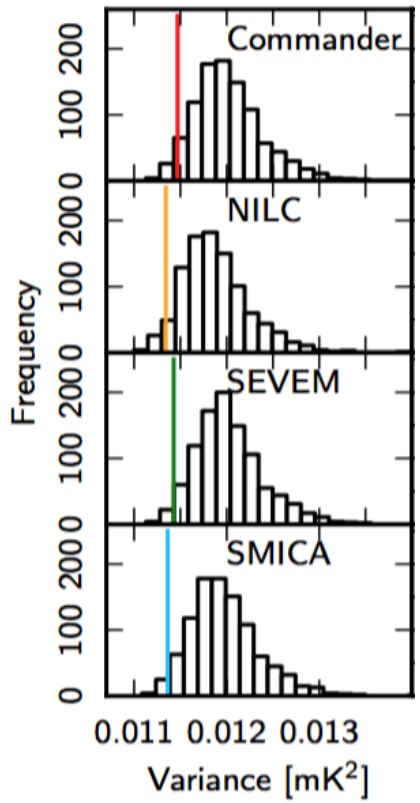
Planck 2015 results XVIII

Lack of large scale correlation (power)

- Lack of correlation for separation angles > 60° (~99.5 % CL)

$$S_{1/2} = \int_{-1}^{\cos(60^0)} C^2(\theta)\, d\cos\theta$$





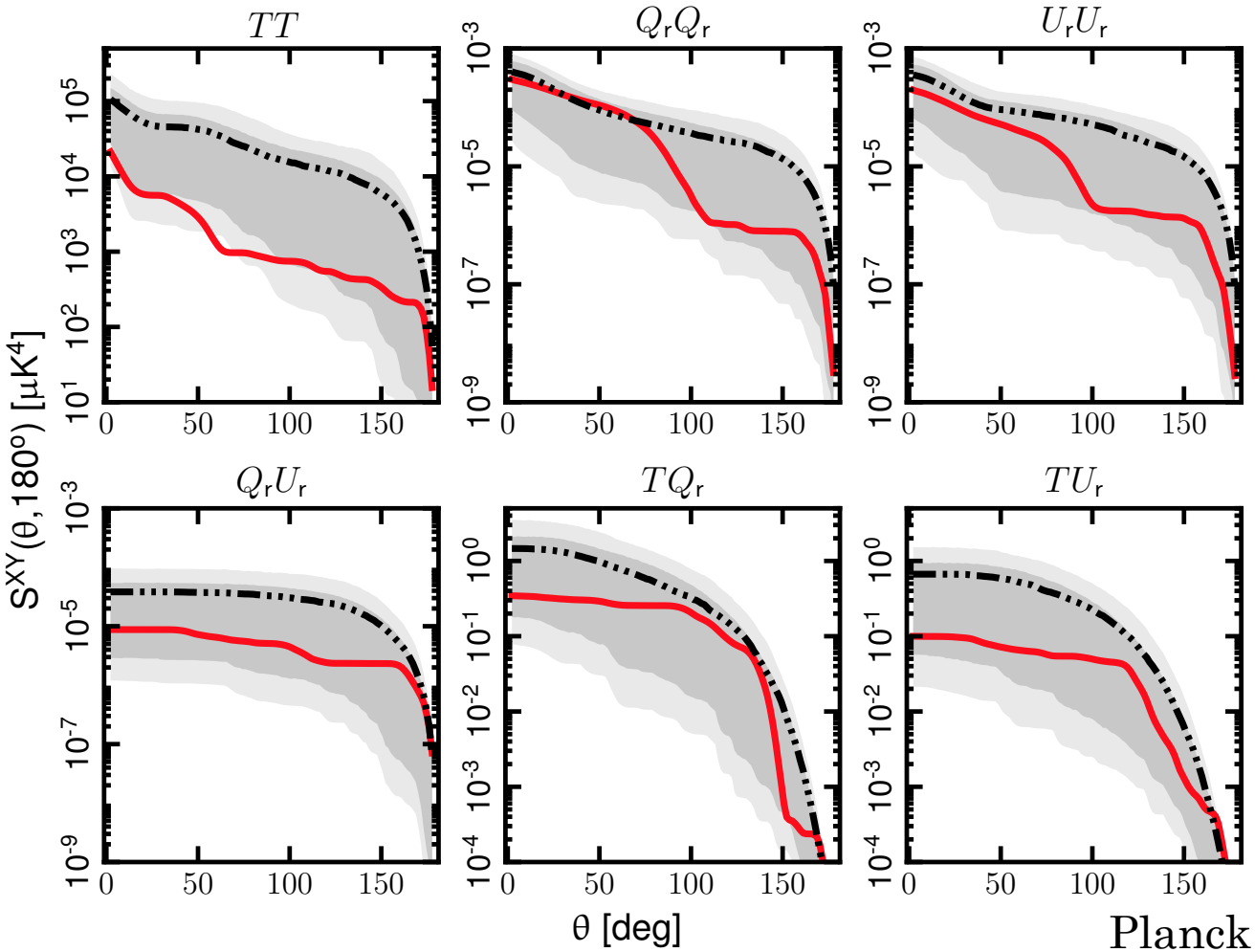
Planck 2015 results XVI

Lack of large scale correlation – polarisation maps

Testing lack of correlation:

- for other range of angular separation
- using Planck CMB polarisation maps

$$S^{XY}(\theta,180^\circ) = \int_{-1}^{\cos\theta} \left[C^{XY}(\theta')\right]^2 d\cos\theta' \quad X,Y \in \{T,Q,U\}$$



Planck 2018 results VII

Point-parity asymmetry

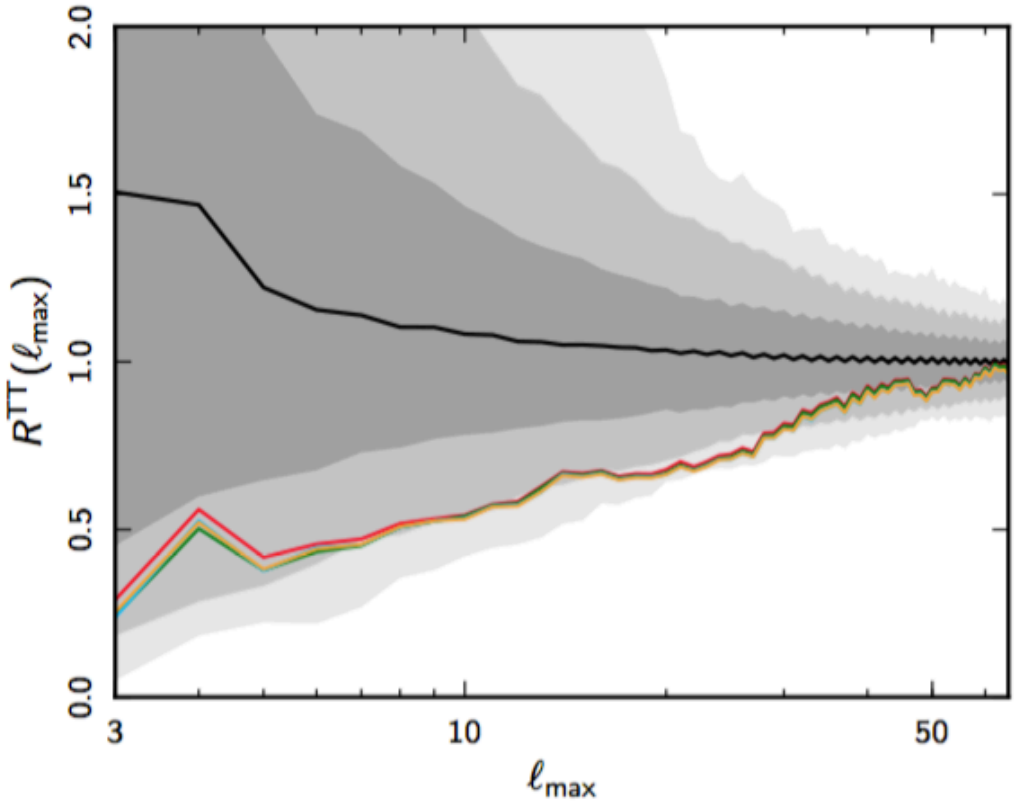
- CMB anisotropy map may be divided into parity-symmetric and parity-antisymmetric functions

$$T^{\pm}(\hat{\boldsymbol{n}}) = \frac{1}{2}[T(\hat{\boldsymbol{n}}) \pm T(-\hat{\boldsymbol{n}})]\,,$$

- Point-parity asymmetry (~98 % CL taking into account LEE)

$$R^{\mathrm{TT}}(\ell_{\mathrm{max}}) = \frac{D_{+}^{\mathrm{TT}}(\ell_{\mathrm{max}})}{D_{-}^{\mathrm{TT}}(\ell_{\mathrm{max}})},$$

$$D_{+,-}^{\mathrm{TT}} = \frac{1}{\ell_{\mathrm{tot}}^{+,-}} \sum_{\ell=2,\ell_{\mathrm{max}}}^{+,-} \frac{\ell(\ell+1)}{2\pi} C_{\ell}^{\mathrm{TT}},$$



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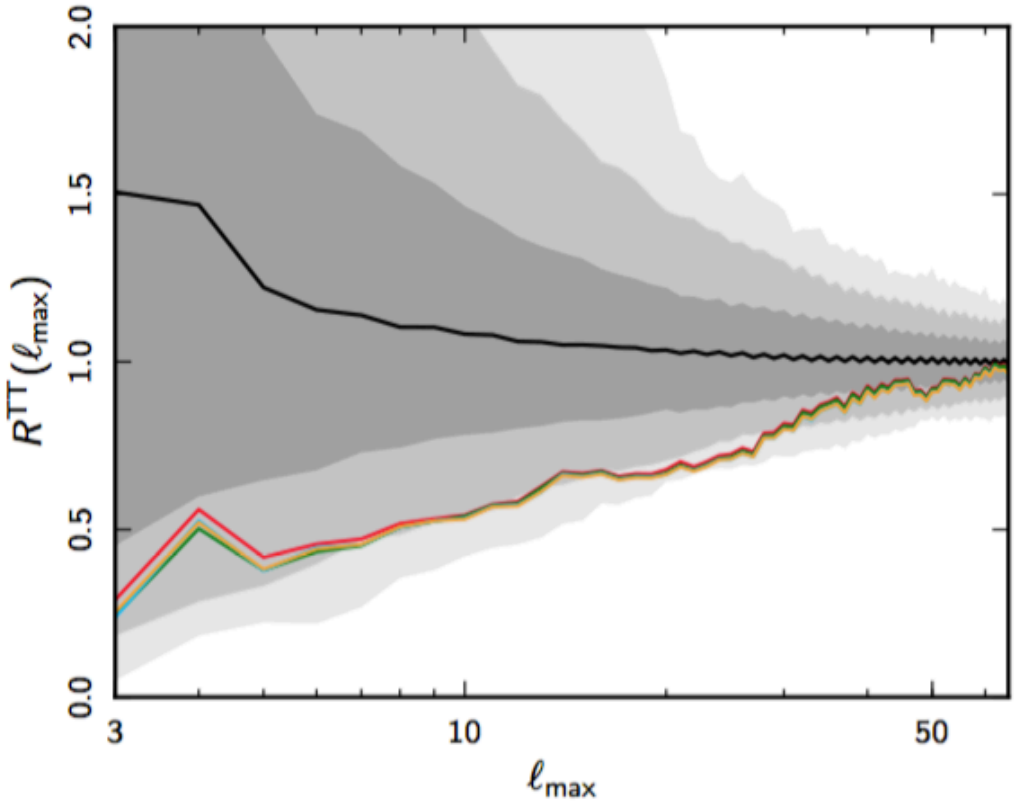
- Related with the 2-point correlation function at 180^0

$$C_2^{TT}(180^\circ) = \sum_{\ell=2}^{\infty} (-1)^{\ell} \frac{2\ell+1}{4\pi} C_{\ell}^{TT}$$



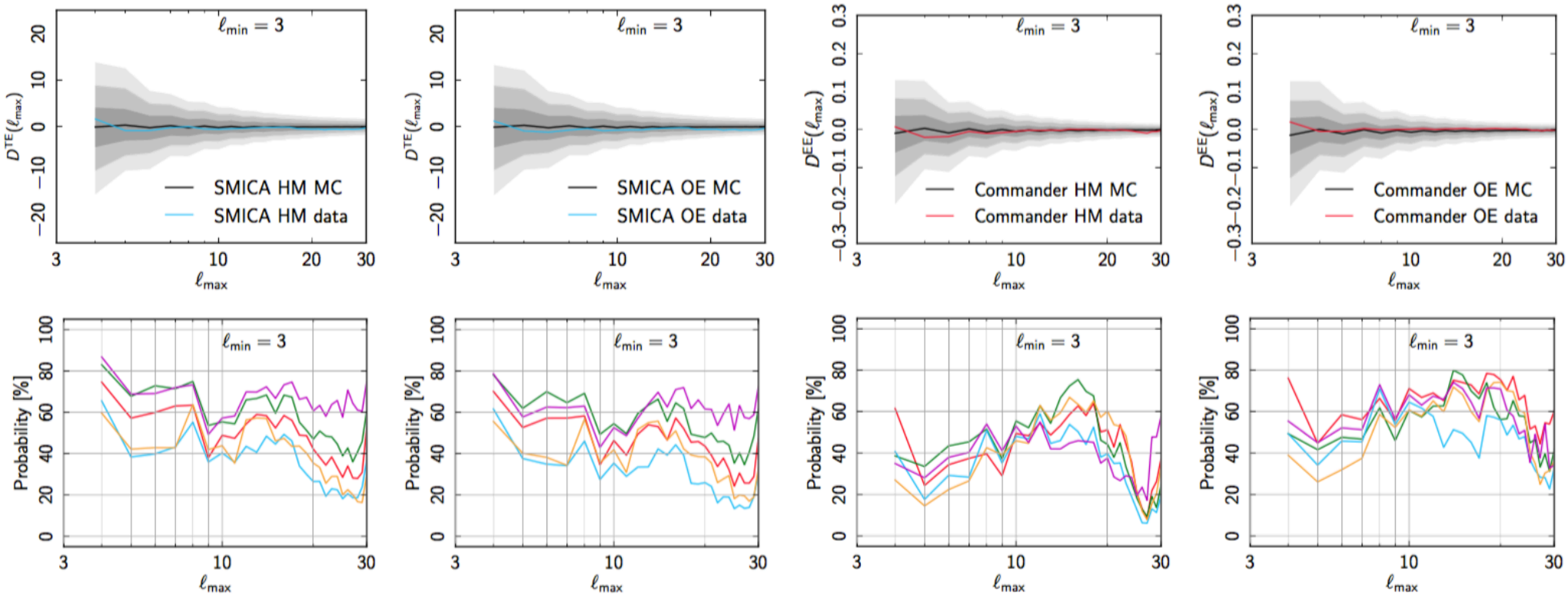
Planck 2015 results XVI

Point-parity asymmetry – CMB polarisation

- Testing point-parity with polarisation data

$$D^X(\ell_{\rm max}) = C_+^X(\ell_{\rm max}) - C_-^X(\ell_{\rm max})$$

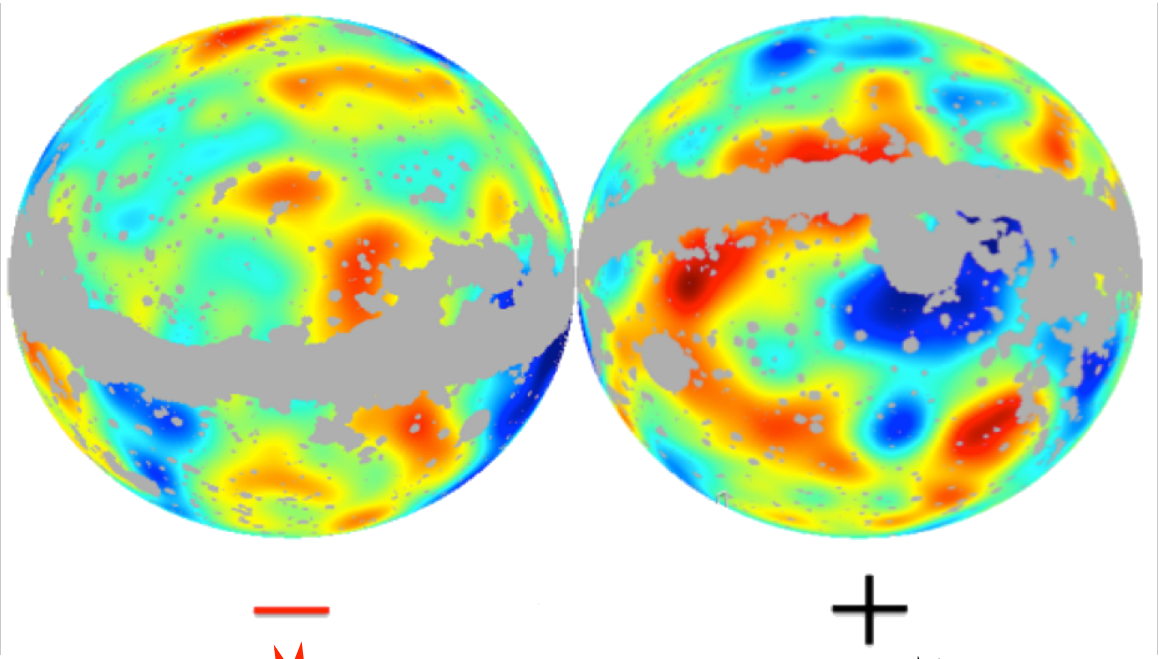
- No detection of anomalies for the Planck polarisation data
- Low signal-to-noise ratio is a limiting factor for the analysis

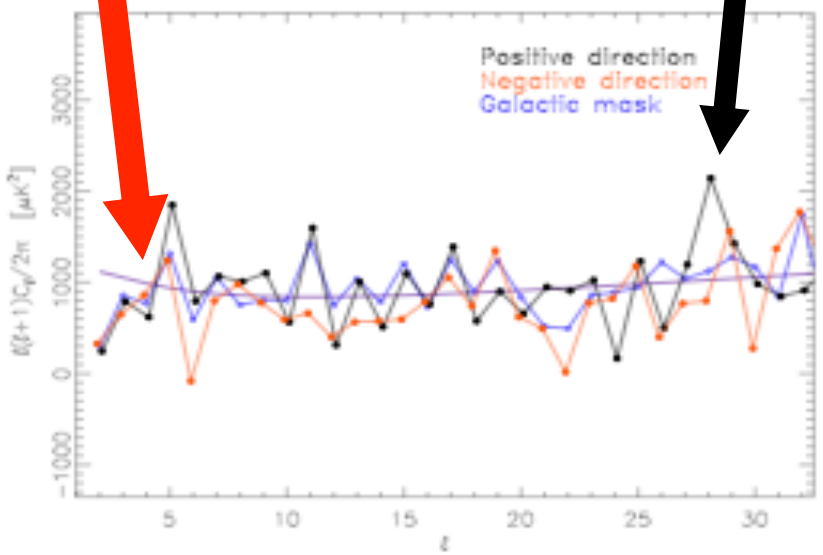


Planck 2018 results VII

Hemispherical asymmetry – temperature maps

- Hemispherical asymmetry (significant differences between power spectra and higher order statistics in opposite hemispheres) ~ 98.5 % CL
- Amplitude of ~6 %
- Direction of maximum asymmetry (l,b)~(225^0,-15^0) (near the ecliptic pole)





Planck 2013 results XXIII

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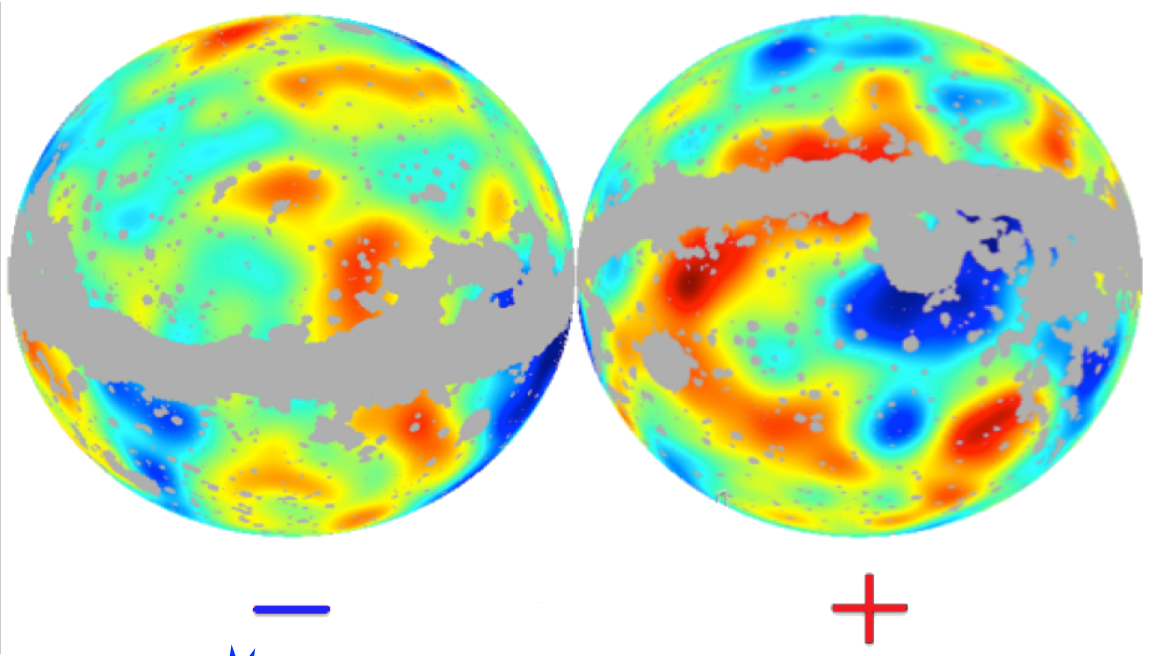
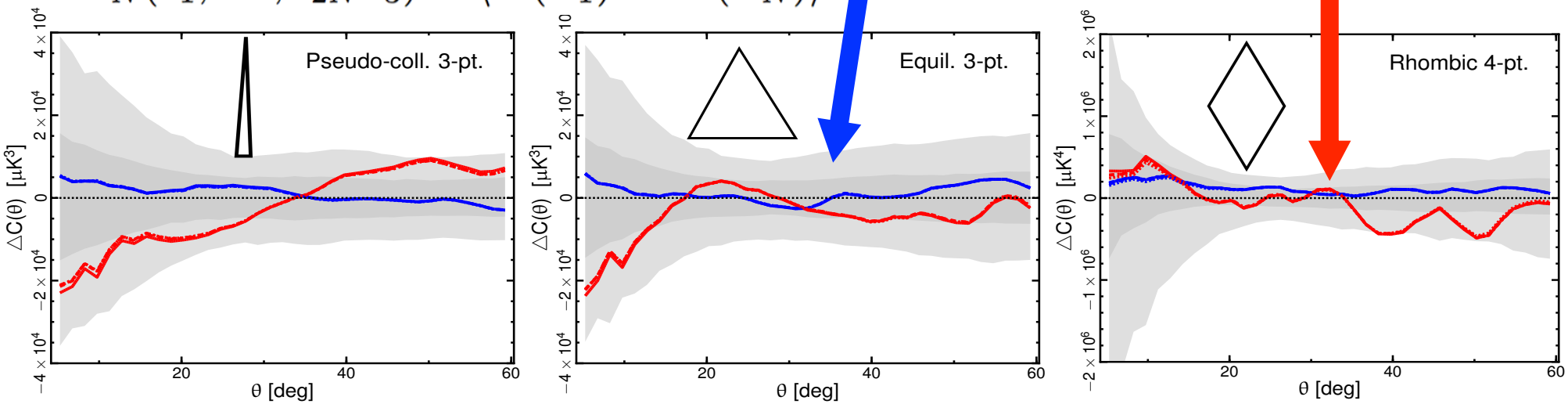


$$C_N(\theta_1,\ldots,\theta_{2N-3}) = \langle X(\hat{\boldsymbol{n}}_1)\cdots X(\hat{\boldsymbol{n}}_N)\rangle$$

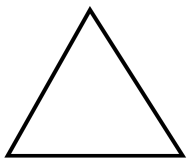


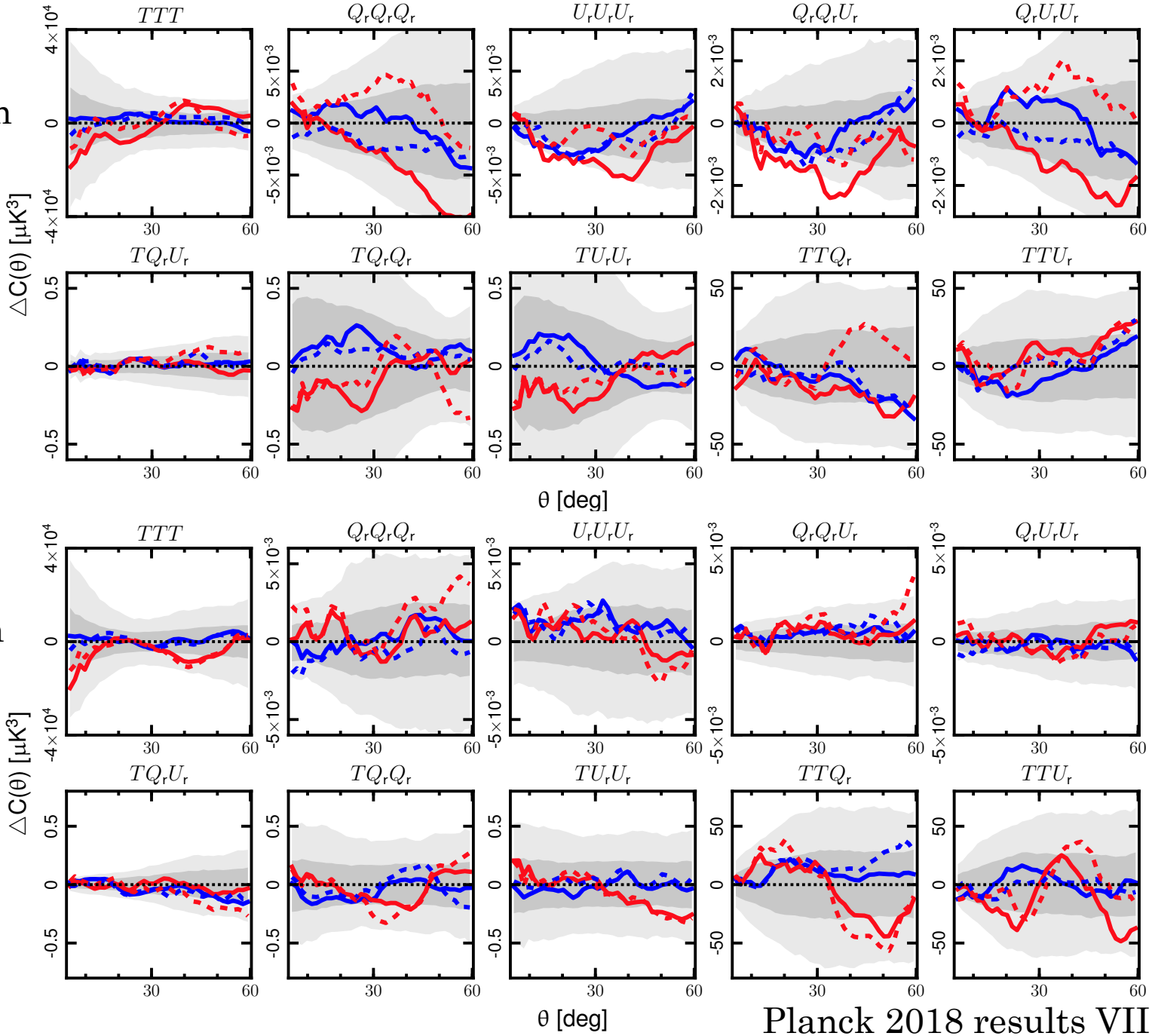
Planck 2015 results XVI

Hemispherical asymmetry – CMB polarisation

Pseudo-coll. 3-pt function

Equilateral 3-pt function



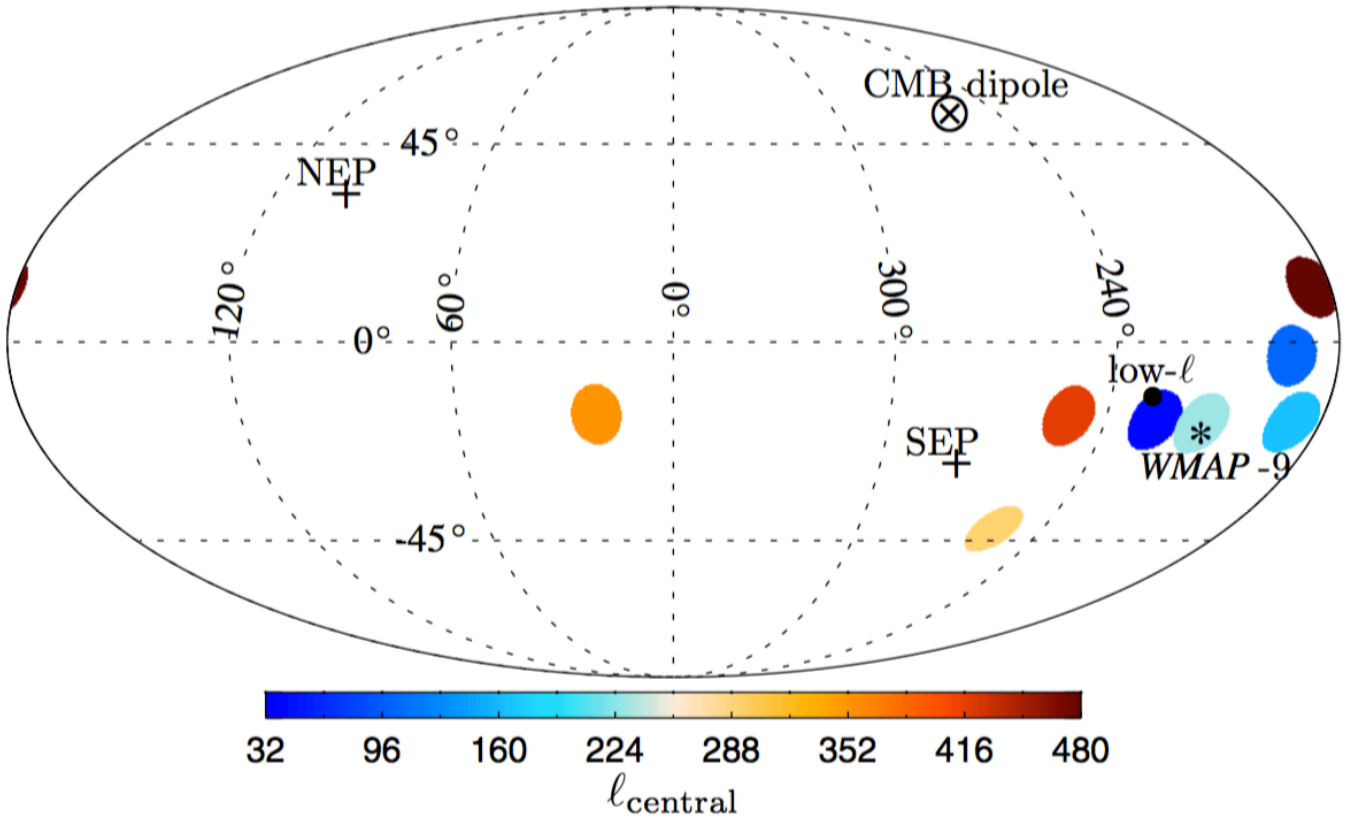


Planck 2018 results VII

Dipolar power asymmetry

- Dipolar modulation of CMB temperature map (amplitude of ~7% in the direction (l,b) = (221^0, -22^0), ~98% CL)

$$T(\hat{n}) = T_{iso}(\hat{n})\left(1 + A\,\hat{p}\cdot\hat{n}\right)$$



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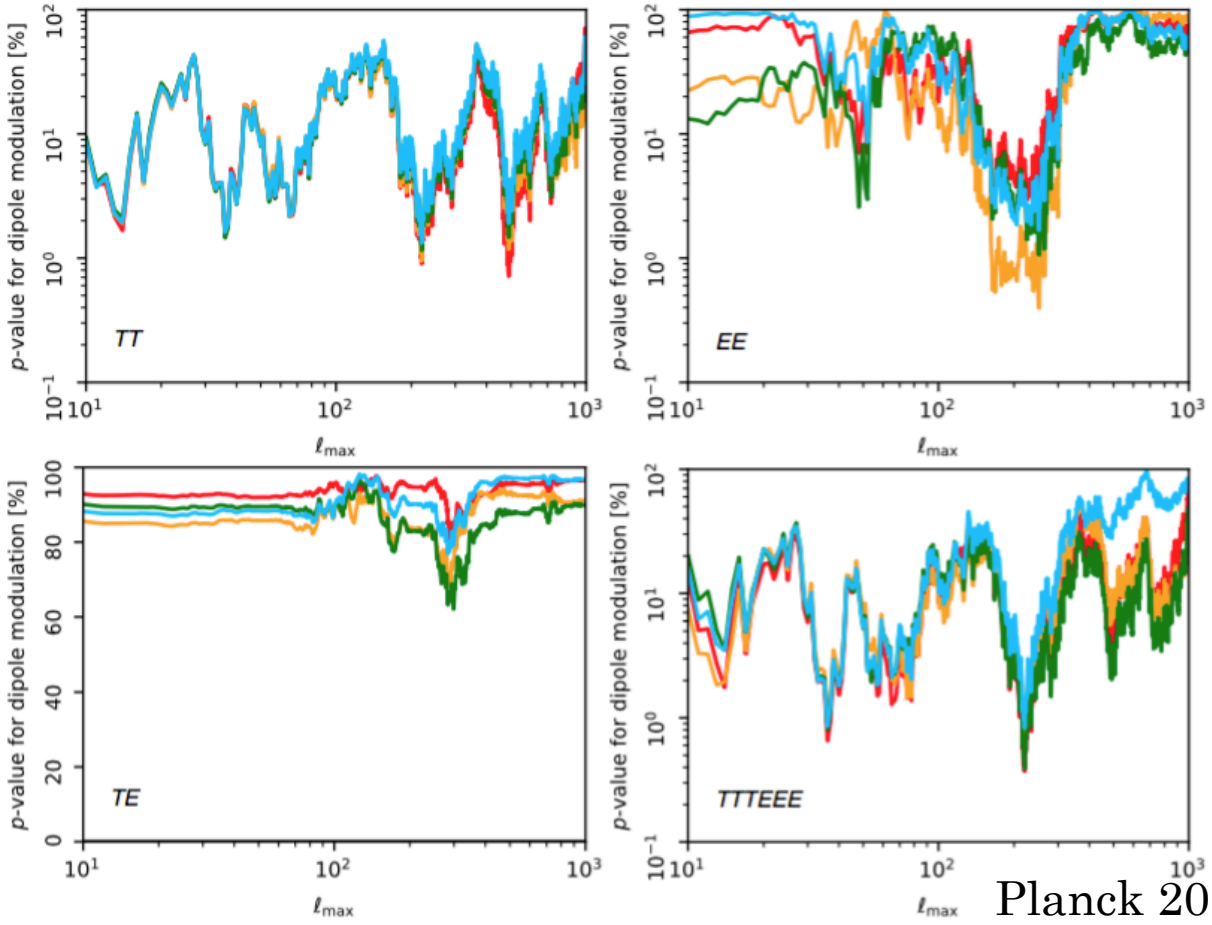
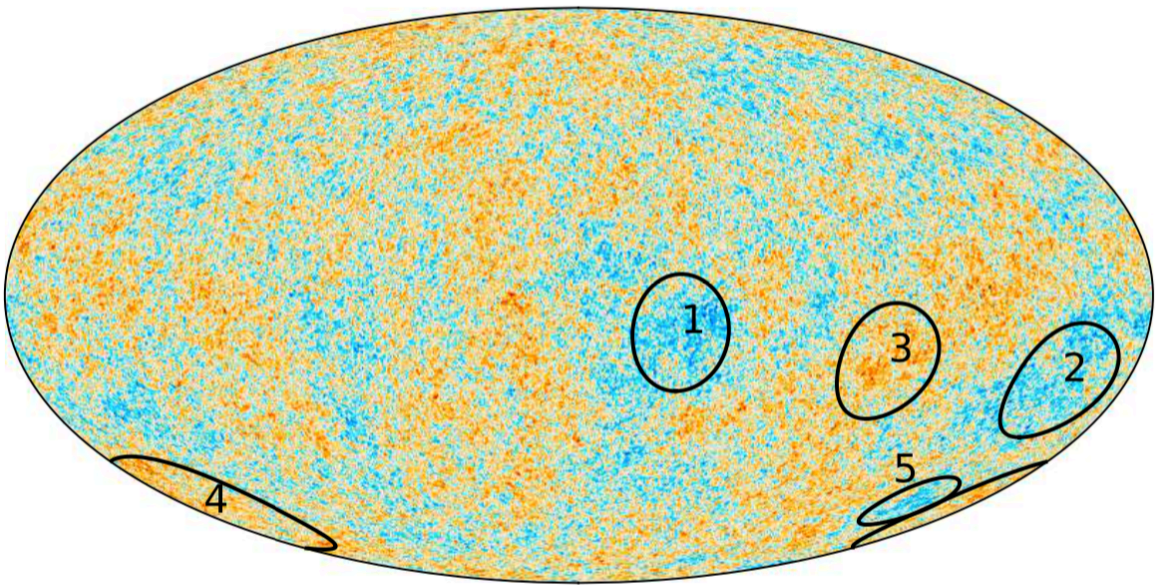
- No detection of asymmetry for the Planck polarisation data
- Sensitivity of the Planck polarisation data too low to confirm the temperature dipolar asymmetry

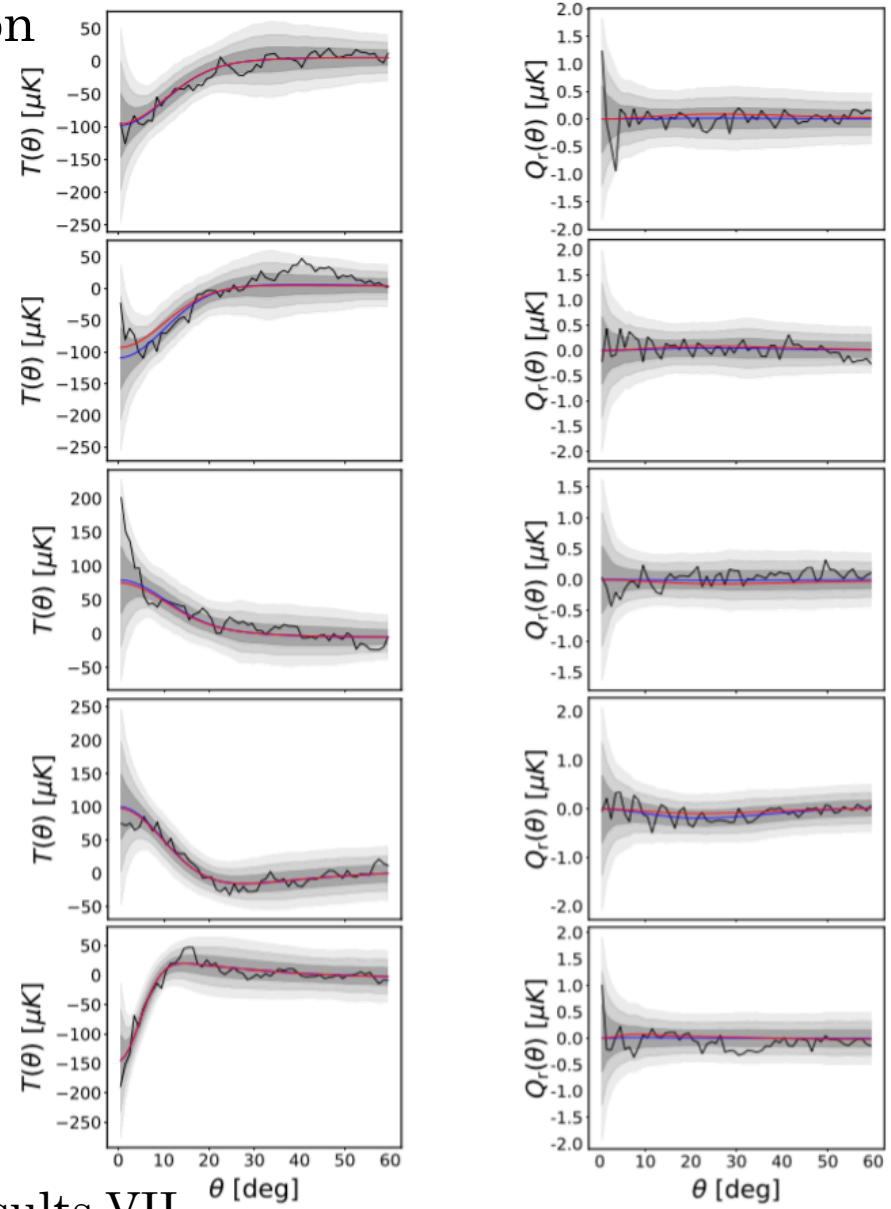


Planck 2018 results VII

The Cold Spot and other large scale peaks

- Peaks of size of order of 10^0 located in the southern Galactic hemisphere
- No detection of peaks in the Planck polarisation maps





Planck 2018 results VII

Summary

- Studies of the CMB anisotropy give opportunity to test the assumption of statistical isotropy of the Universe
- Observed large angular scales CMB anomalies do not provide conclusive proofs that anything nonstandard is going on, but may indicate places to look for interesting nonstandard phenomena on large scales
- Anomalies not observed for the Planck polarisation data
- Low signal-to-noise ratio of the Planck polarisation data is a limiting factor for the studies
- In future possible testing of the large-scale anomalies and statistical isotropy with polarisation data from satellite missions or CMB maps combined from few ground based CMB experiments (AliCPT + Advanced ACT + POLARBEAR, etc.)