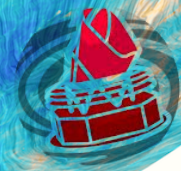


Studies of statistical properties of the Planck CMB maps

Paweł Bielewicz



NARODOWE
CENTRUM
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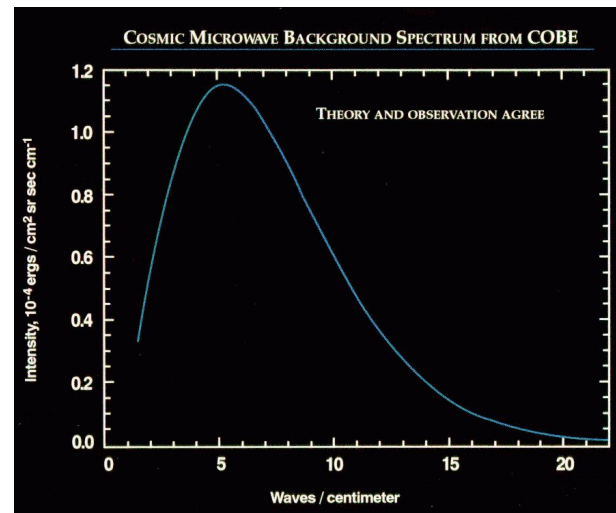
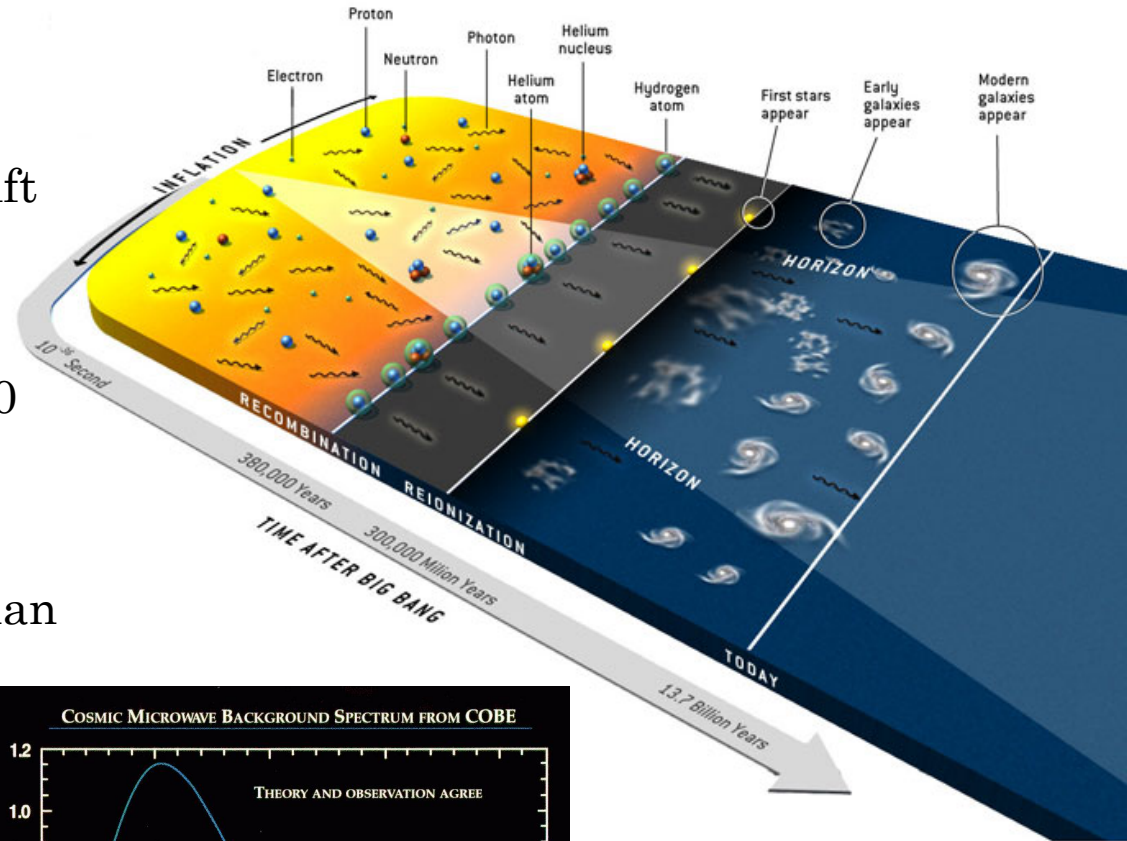
planck



- CMB and the Planck satellite
- Testing foreground-cleaned Planck CMB maps
- Testing statistical isotropy and Gaussianity of the Planck CMB maps
- Summary



- Thermal radiation coming from early epochs of the Universe
- Blackbody power spectrum with temperature $T = 2.7$ K currently
- Decoupled from baryonic matter at redshift $z = 1100$ ($\sim 380\,000$ years after Big Bang)
- Anisotropy of order $\frac{\Delta T}{T_0} \approx 10^{-5}$ shows distribution of baryonic matter at $z = 1100$ and scales comparable to the size of the observable Universe
- Inflationary models predict nearly Gaussian fluctuations with statistically isotropic distribution in the sky



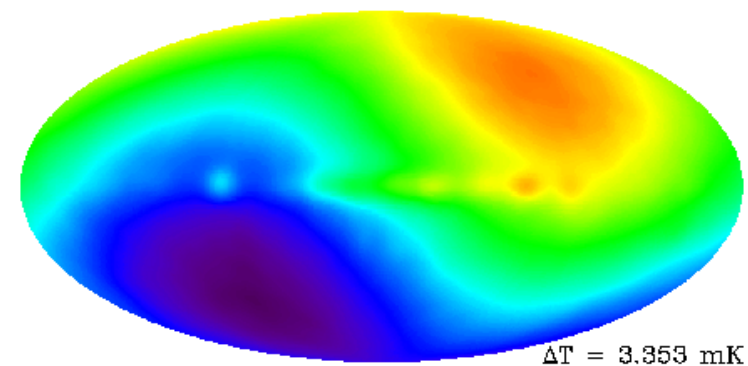
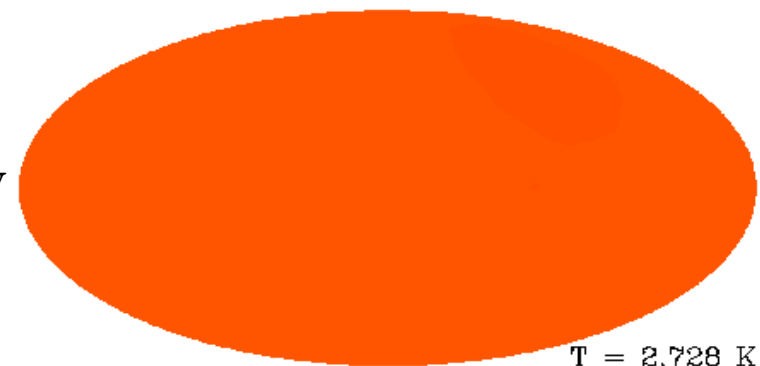


- Penzias & Wilson (1965): discovery of CMB (monopole $T_0=2.7$ K)

 $T = 2.728$ K

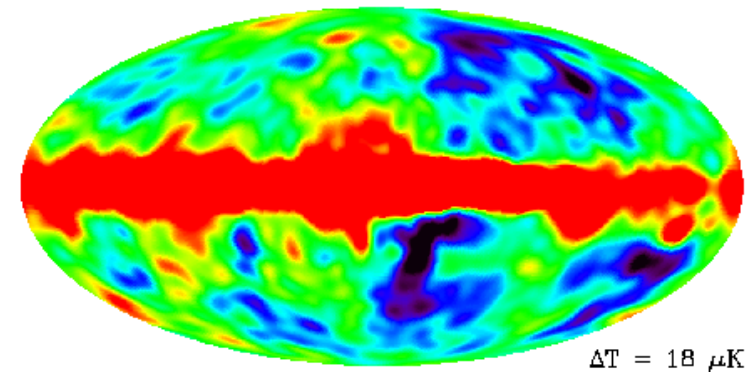
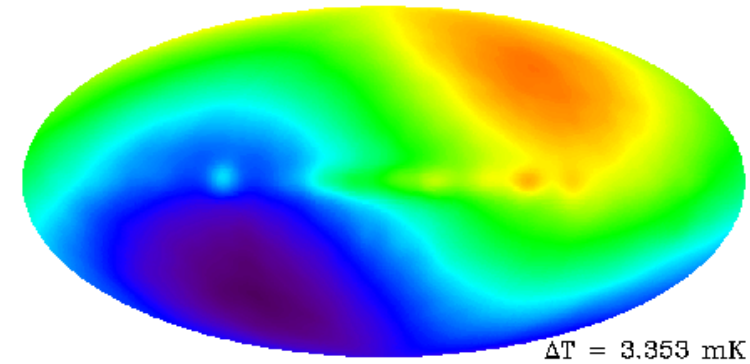
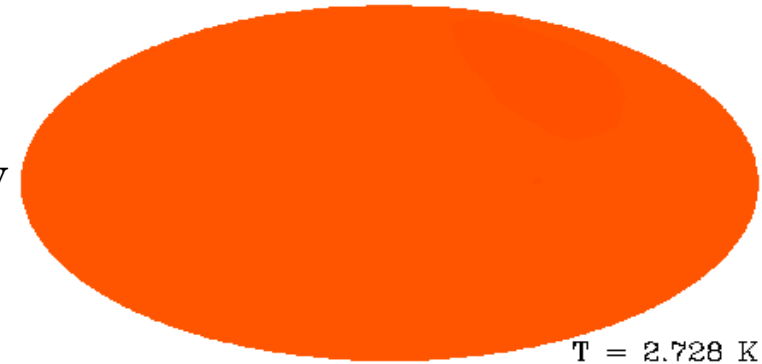


- Penzias & Wilson (1965): discovery of CMB (monopole)
 $T_0 = 2.7$ K
- Henry (1971), Corey & Wilkinson (1976): dipole anisotropy
 $\frac{\Delta T}{T_0} \approx 10^{-3}$ due to Earth motion with respect to CMB rest
frame ($v = 370$ km/s), $(l, b) = (264^\circ, 48^\circ)$



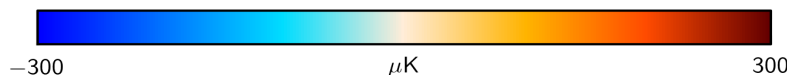
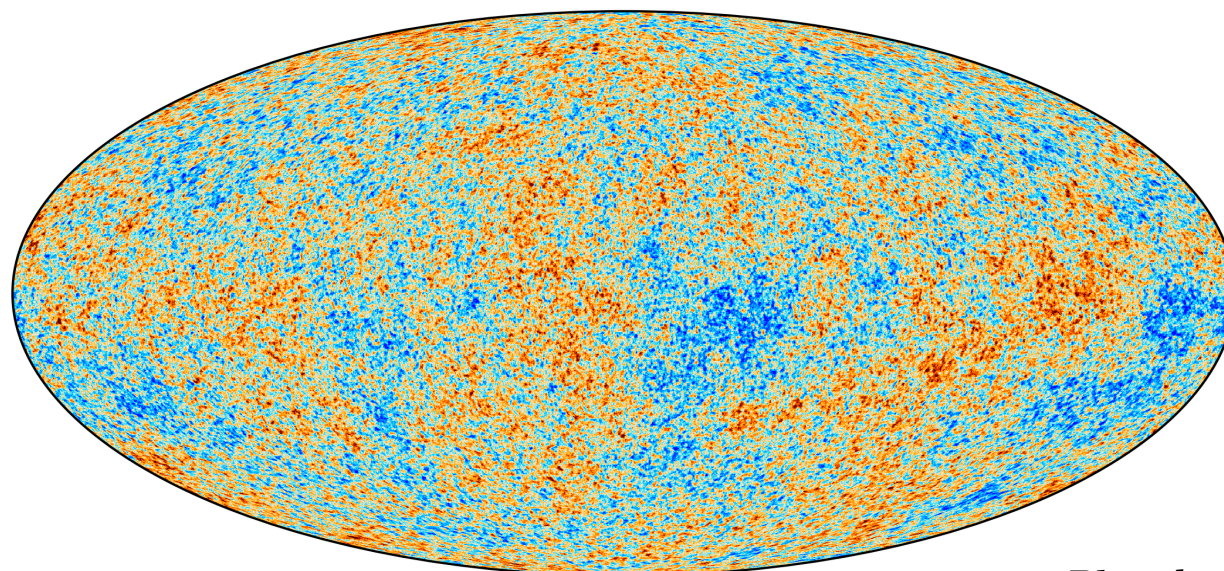
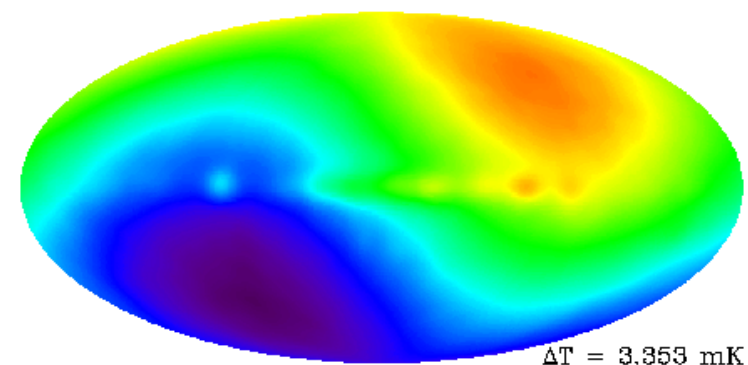
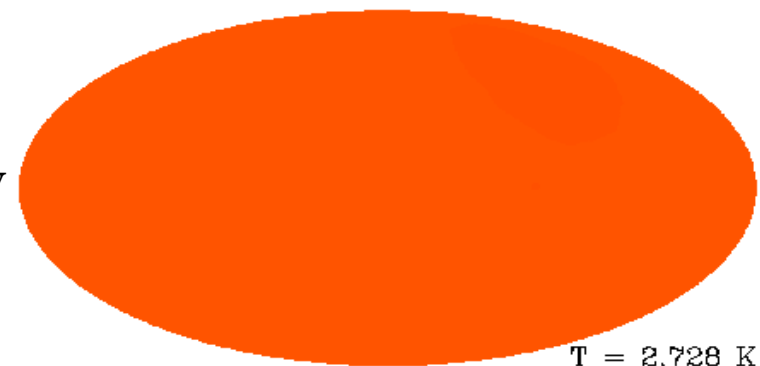


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- COBE satellite (1992): blackbody spectrum, primordial anisotropy $\frac{\Delta T}{T_0} \approx 10^{-5}$

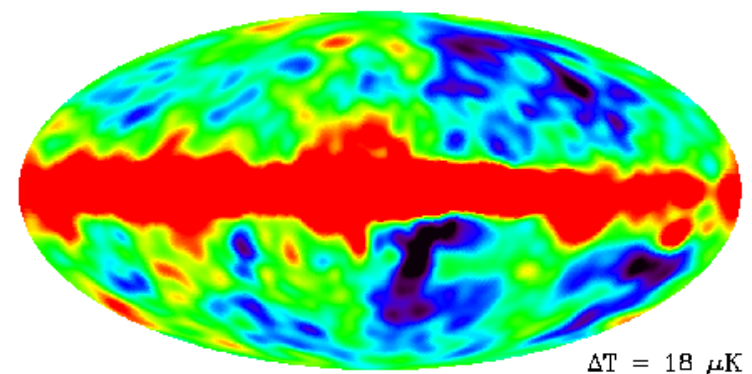




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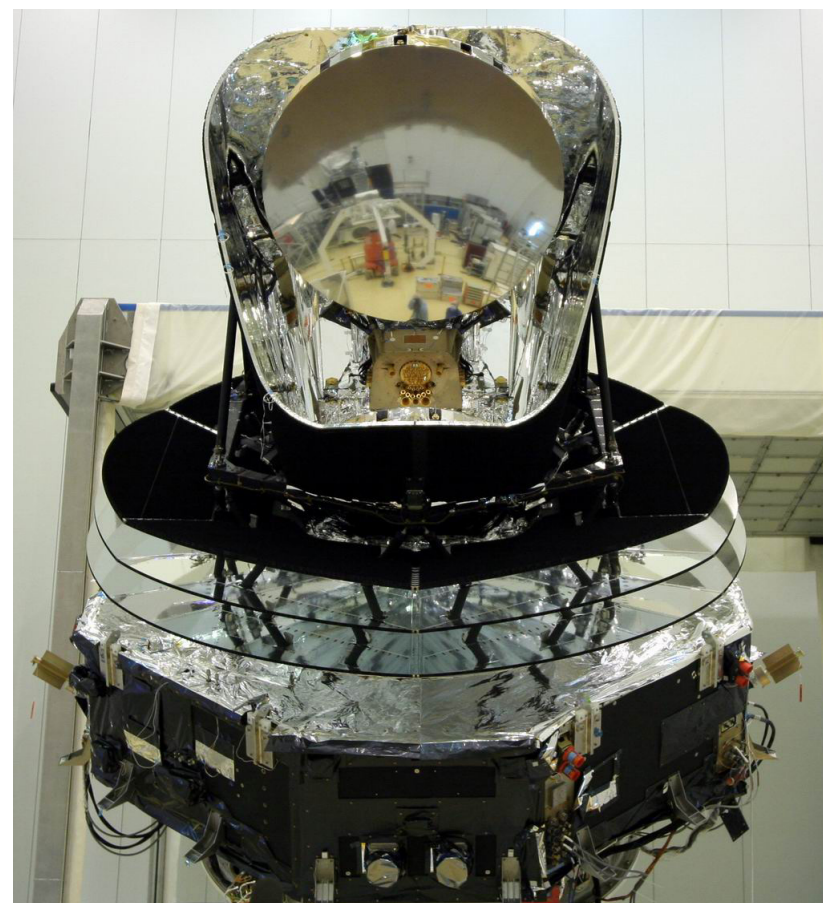


Planck



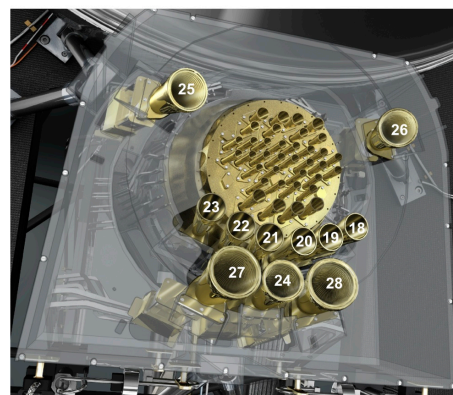
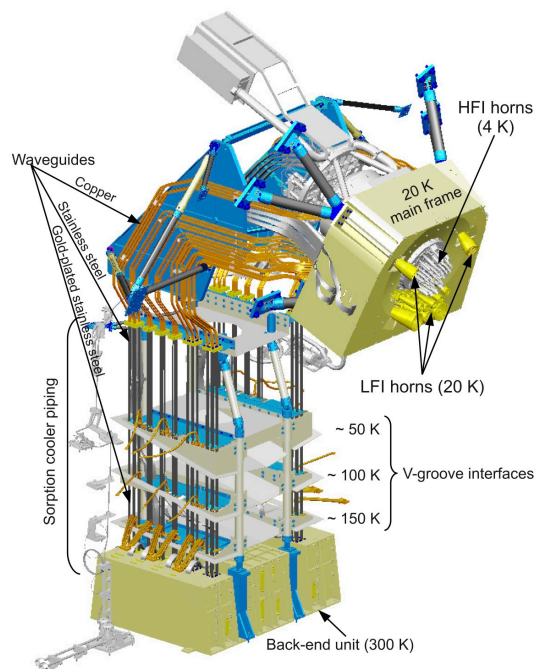
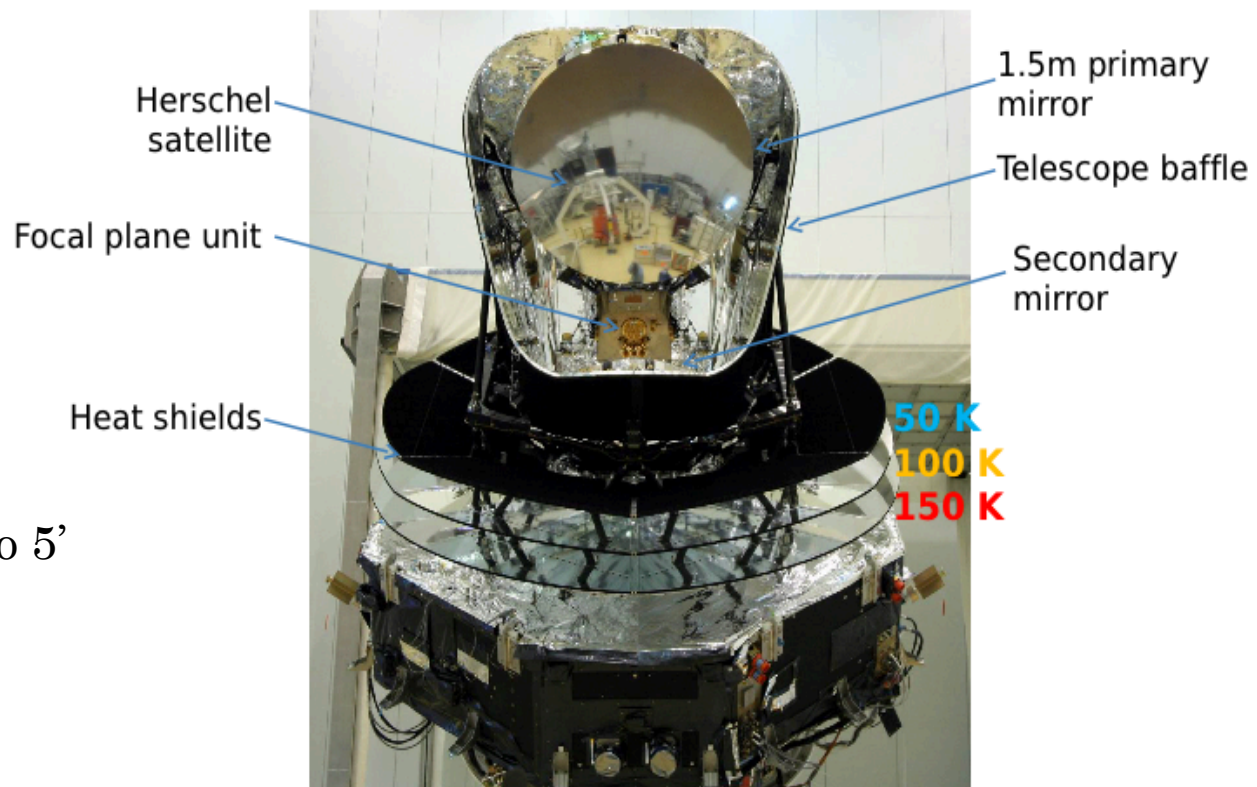


- Planck is an ESA satellite mission designed to perform the „final” measurement of the Cosmic Microwave Background (CMB) temperature fluctuations in the region where the primary contribution is dominant. It was also designed to measure to high accuracy polarization of the CMB anisotropies

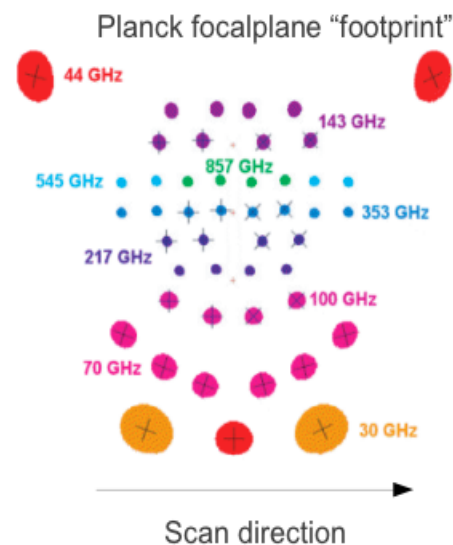




- Two instruments on board:
 - Low Frequency Instrument (LFI)
 - High Frequency Instrument (HFI)
- Wide frequency coverage with nine channels from 30 to 857 GHz
- Full sky coverage
- Angular resolution from 33' down to 5'
- High sensitivity

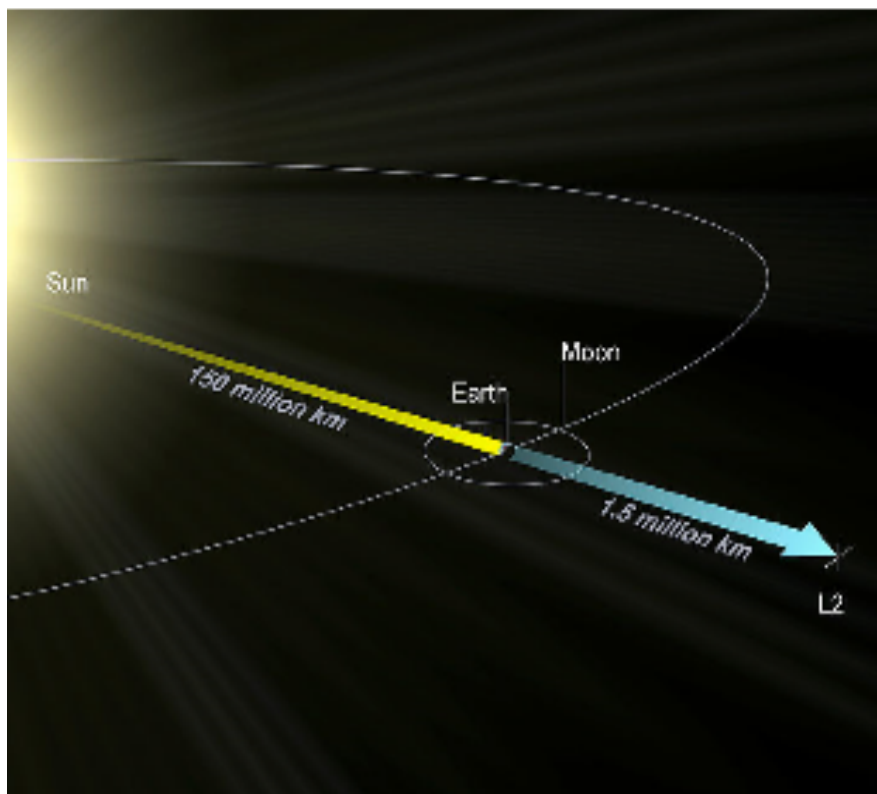


70 GHz: LFI-18 through LFI-23
 44 GHz: LFI-24, LFI-25, LFI-26
 30 GHz: LFI-27, LFI-28



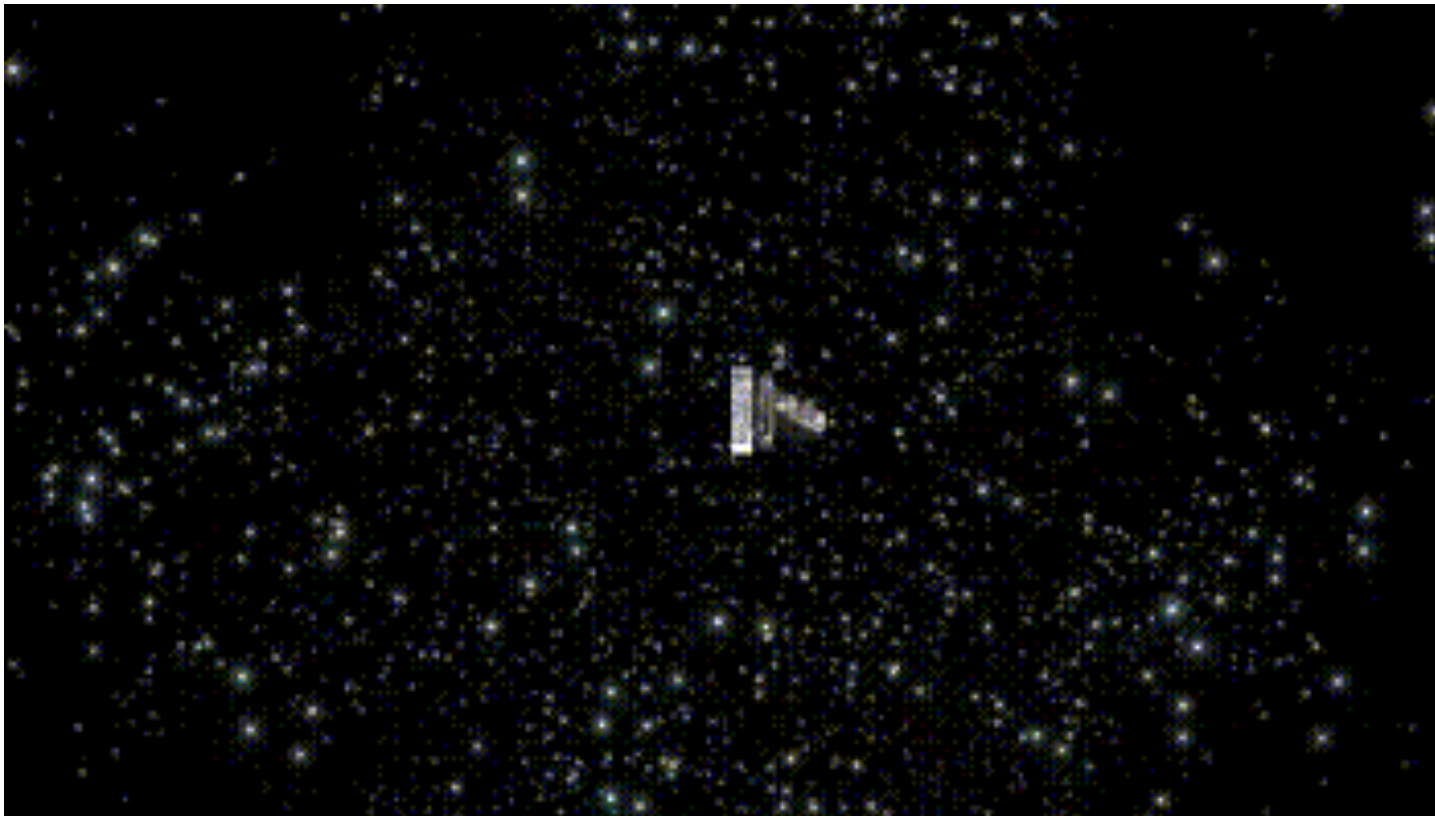


- Launched with the Herschel satellite on 14th May 2009 from Kourou (French Guiana)
- Observation point at the second Lagrange point of the Earth-Sun system (L2)



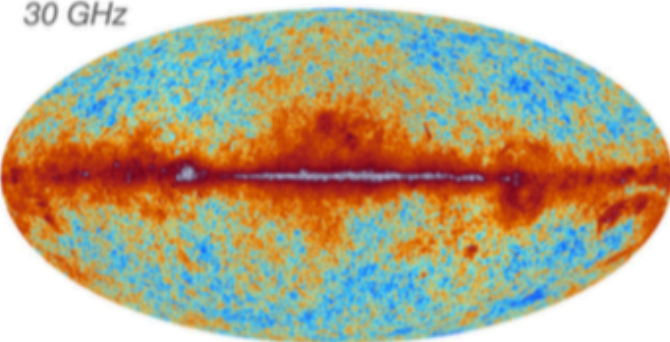


- A map is builded up from series of rings – spinning at 1 rpm
- Repointing of the telescope by 2' every ~ 40 min
- Slow modulation of the spin axis for full sky coverage
- One survey of the sky every six months

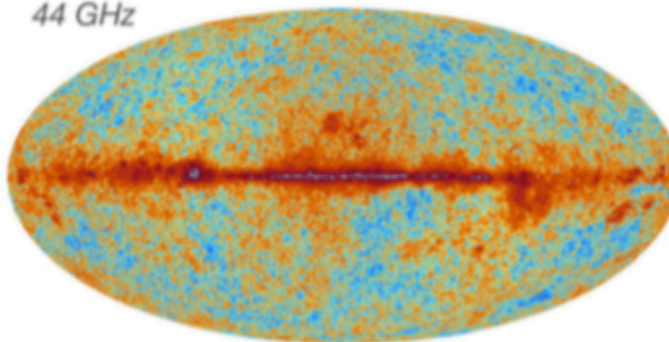




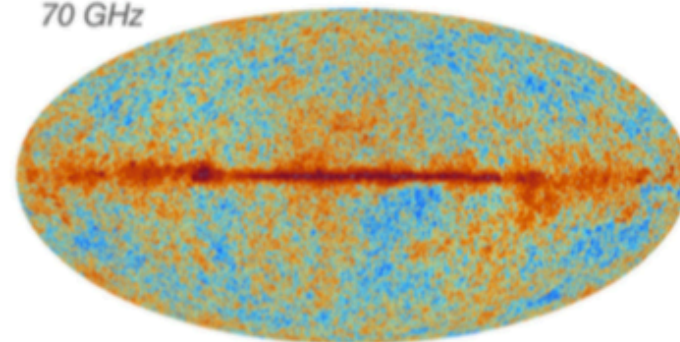
30 GHz



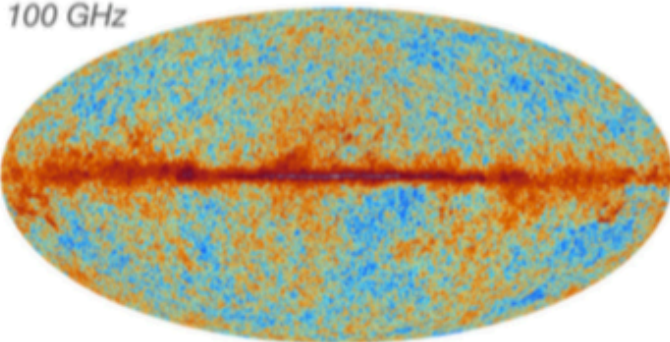
44 GHz



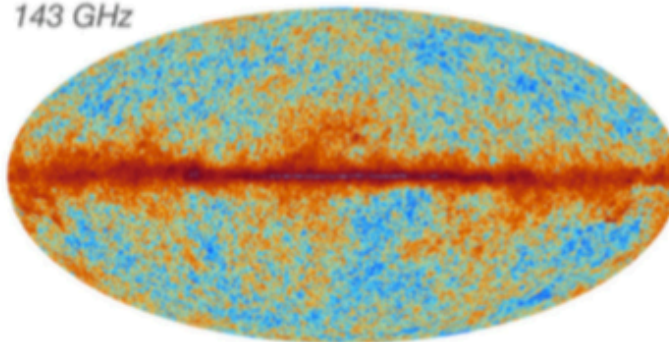
70 GHz



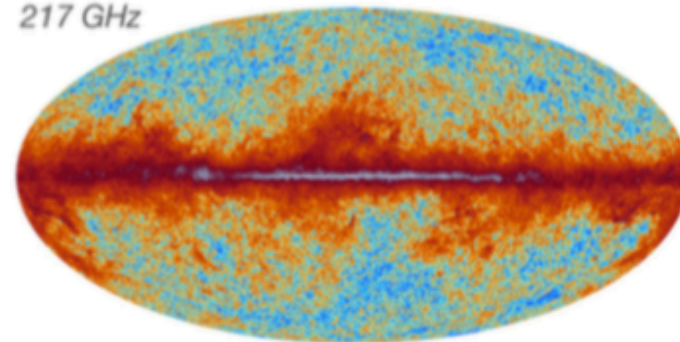
100 GHz



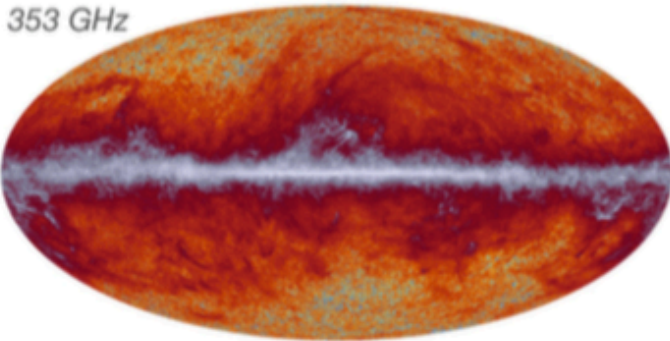
143 GHz



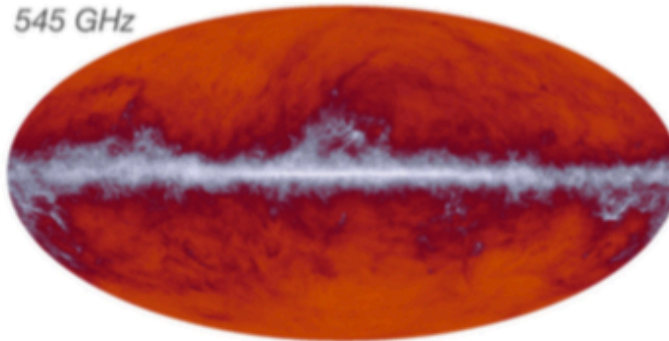
217 GHz



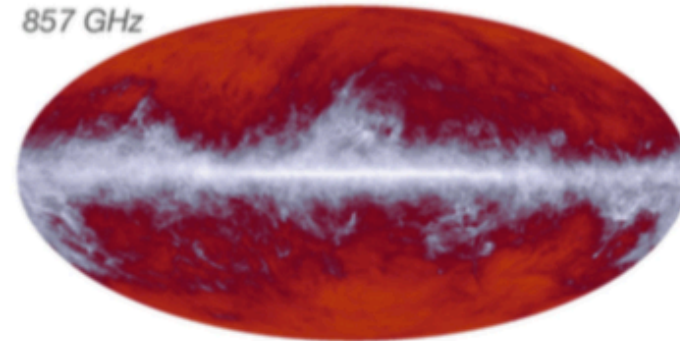
353 GHz



545 GHz



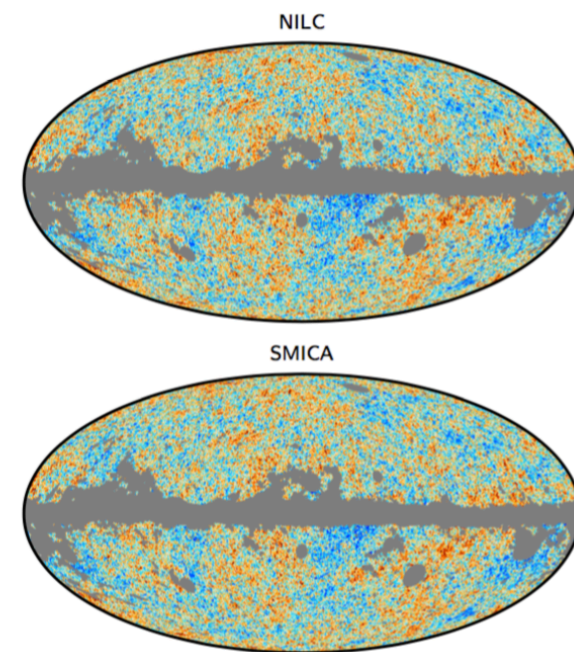
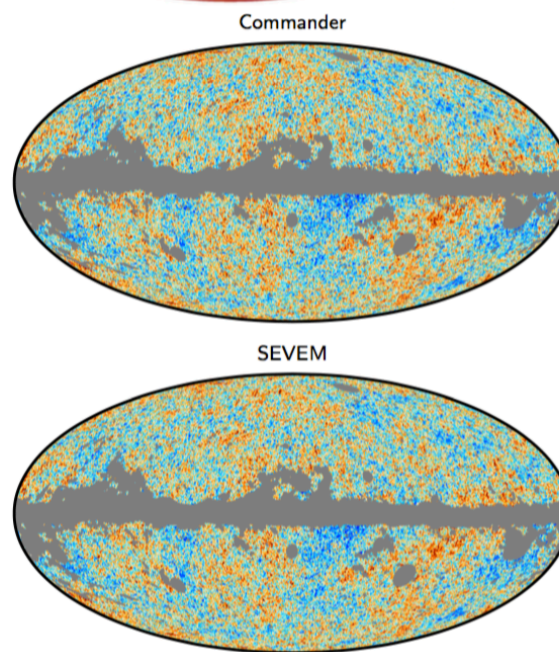
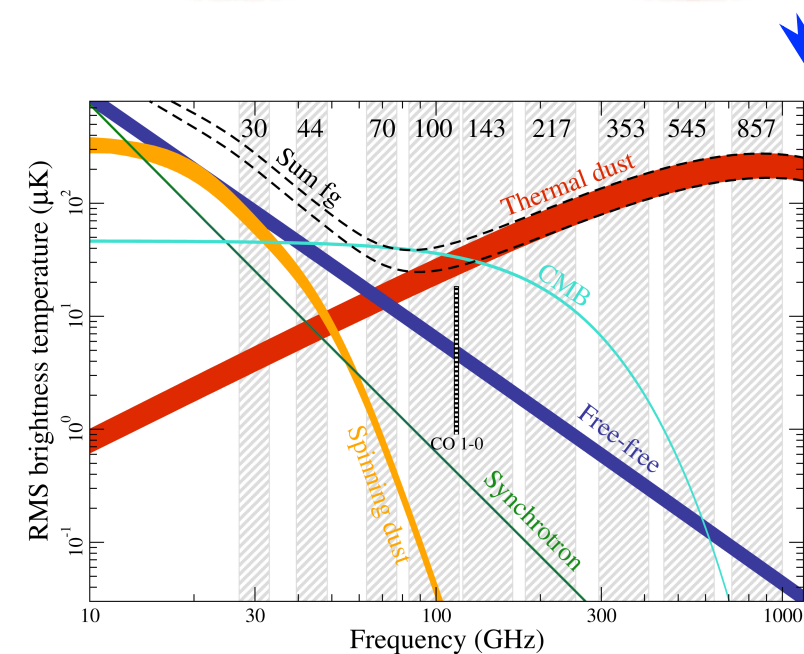
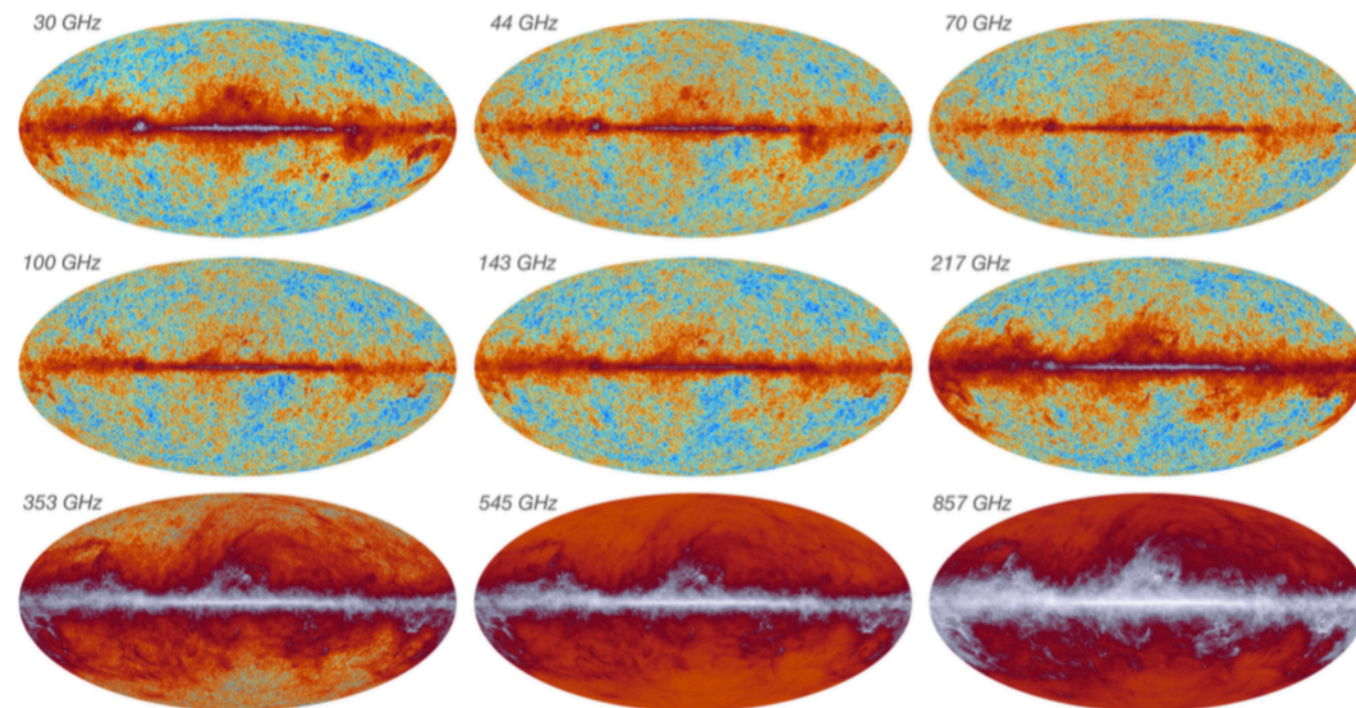
857 GHz





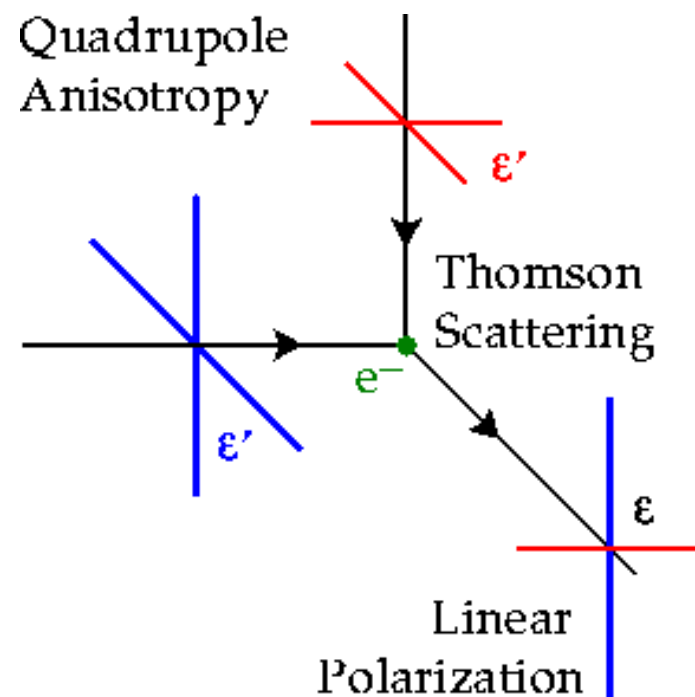
Cleaning CMB temperature maps

- Maps cleaned with 4 component separation methods



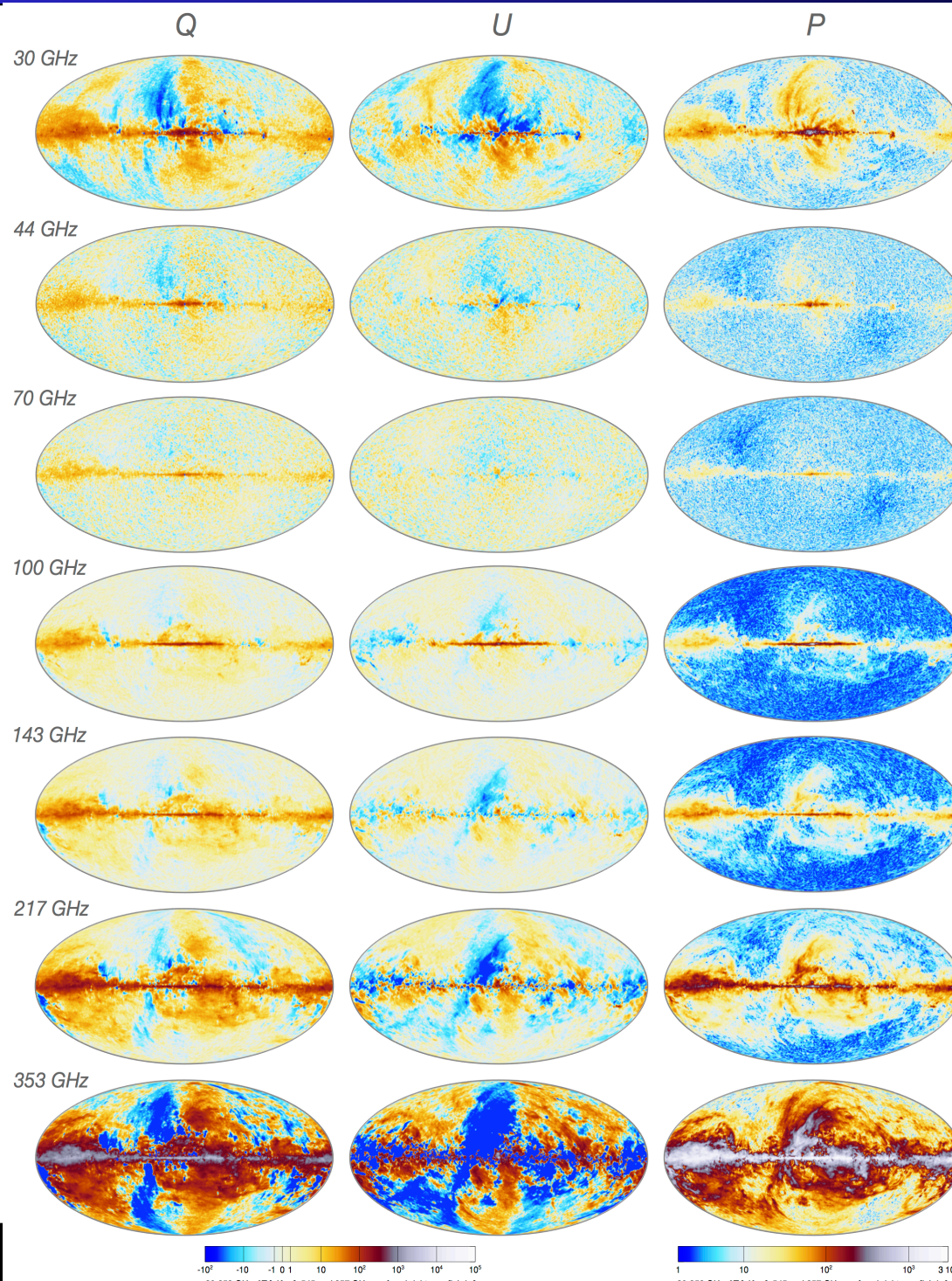


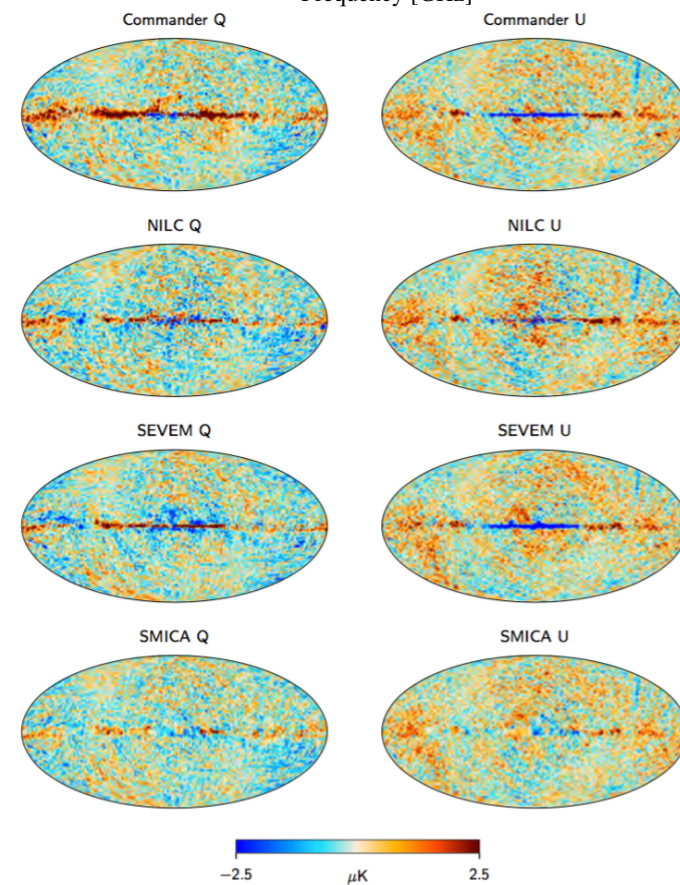
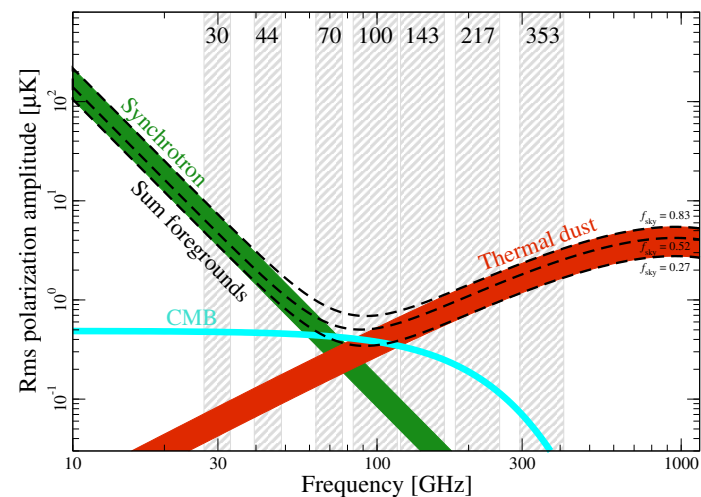
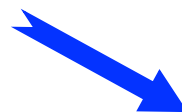
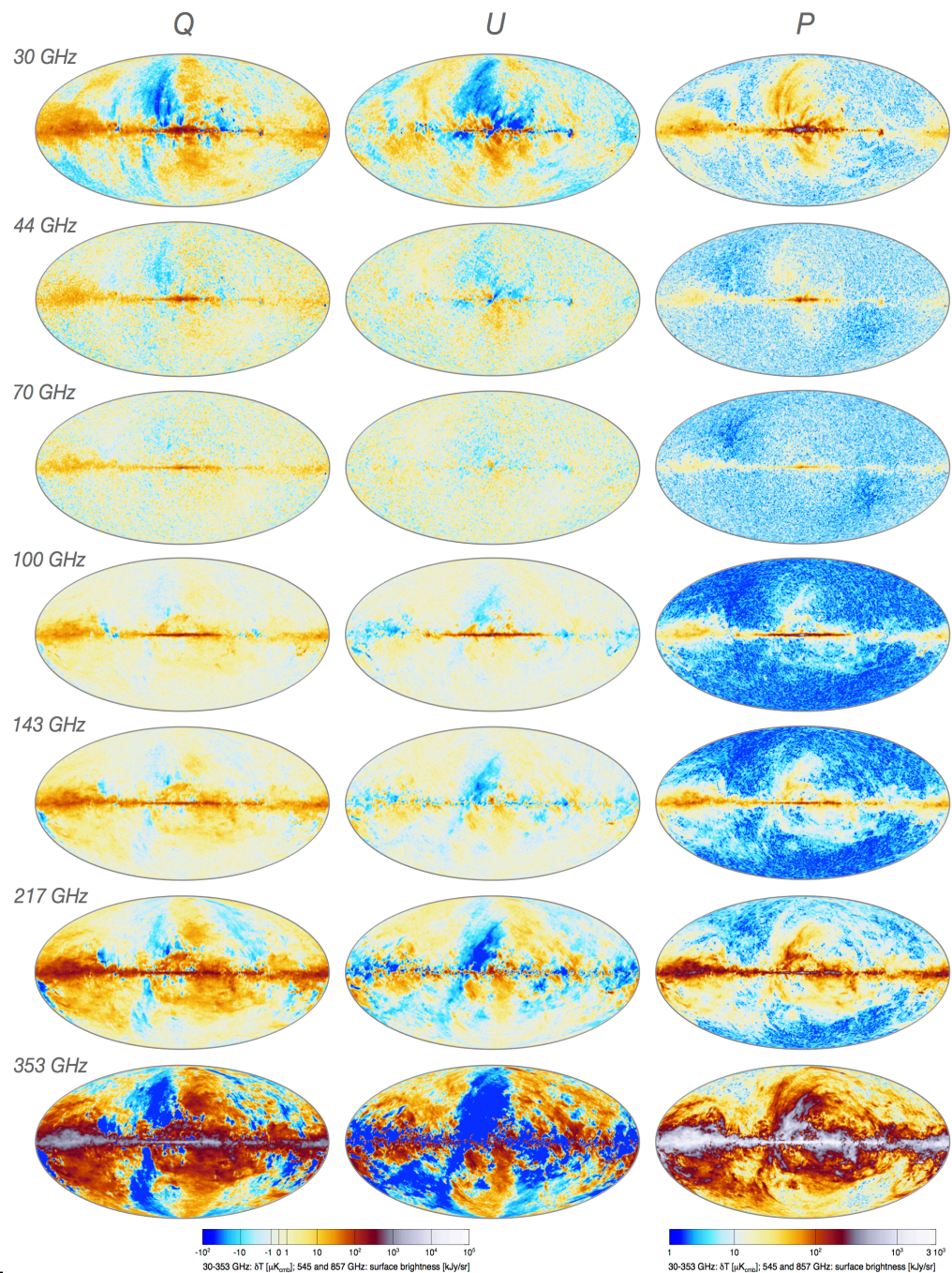
- CMB is polarised owing to **Thomson scattering** of photons at last scattering (or after reionisation)





CMB polarisation maps

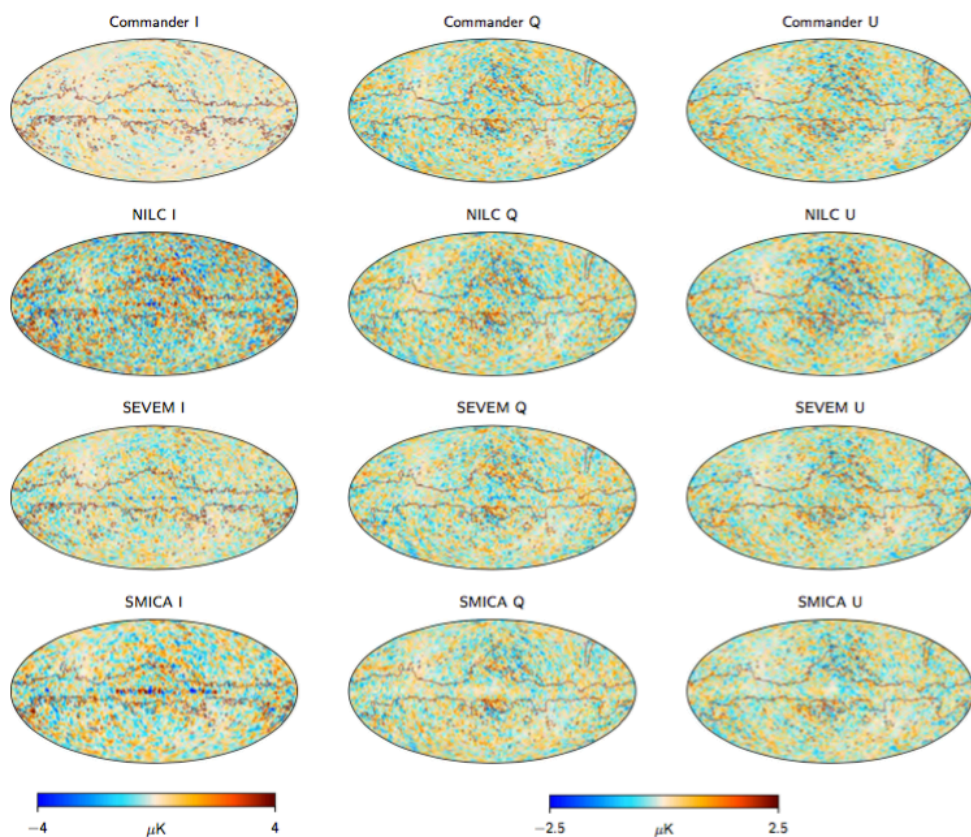




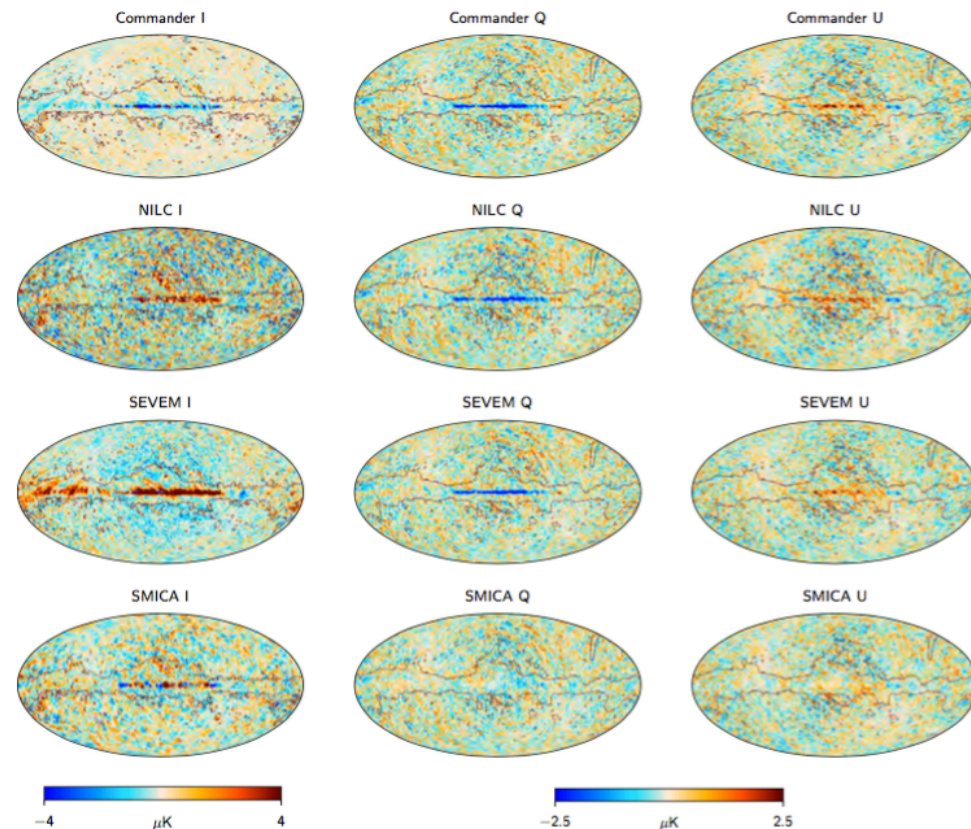


- Noise estimation based on half-difference maps:
 - odd-even half-difference (OEHD) maps: data divided according to odd and even ring numbers
 - half-mission half-difference (HMHD) maps: data divided according to observation years

OEHD maps



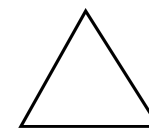
HMHD maps





- Computation of the real-space **2-point**, **pseudo-collapsed** and **equilateral 3-point correlation functions**

$$\hat{C}_N(\theta_1, \dots, \theta_{2N-3}) = \frac{\sum_i (w_1^i \cdots w_N^i) (X_1^i \cdots X_N^i)}{\sum_i w_1^i \cdots w_N^i}$$



where $X \in \{\Delta T, Q, U\}$ and $w_1^i, \dots, w_N^i$ are set to 1 or 0 for included or excluded pixels

- χ^2 and p-values estimated based on 1000 simulations of the half-difference maps

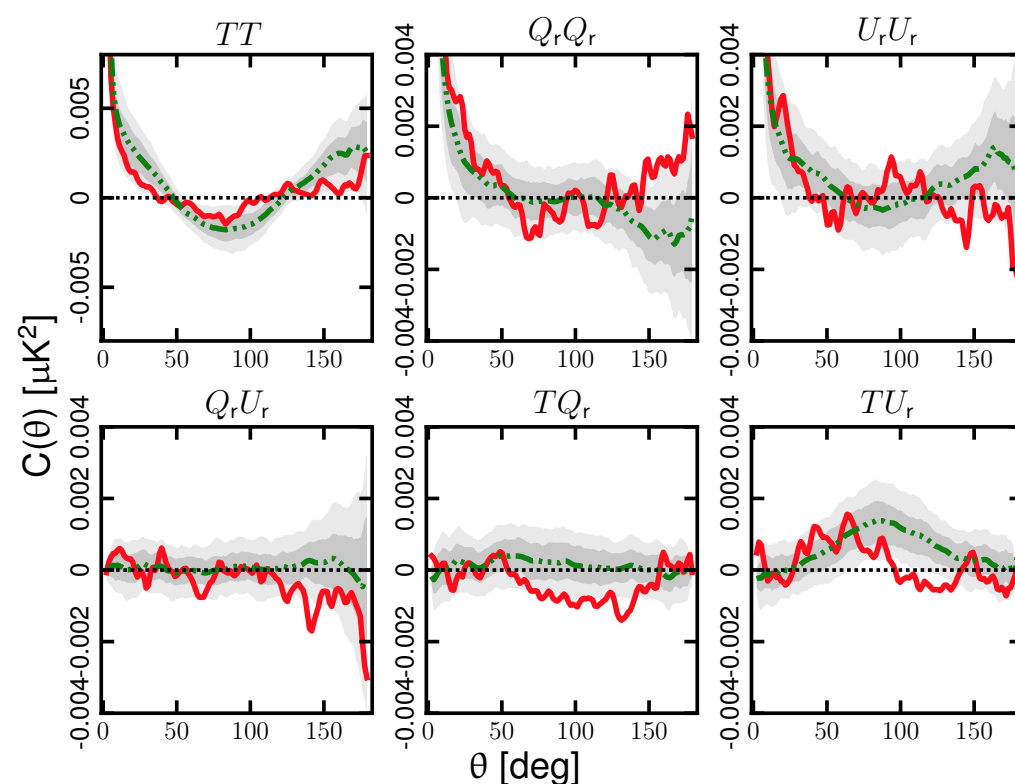
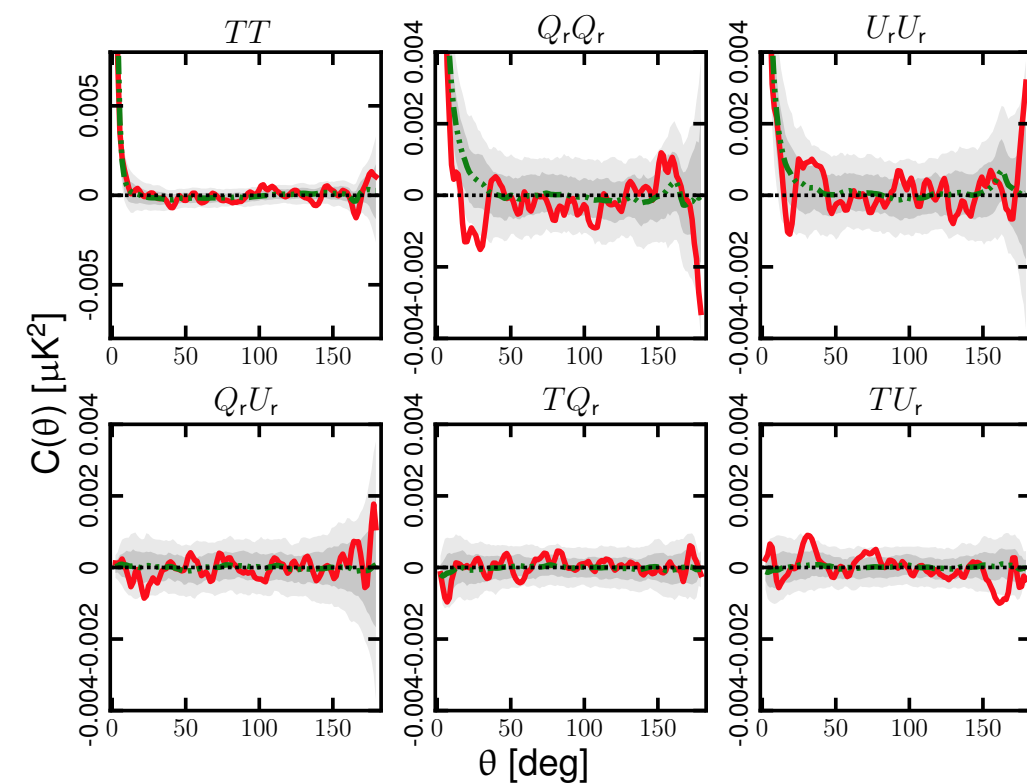


- 2-point correlation functions
- No statistically significant deviations from simulations

Red – data
Green – mean
for simulations

OEHD

HMHD





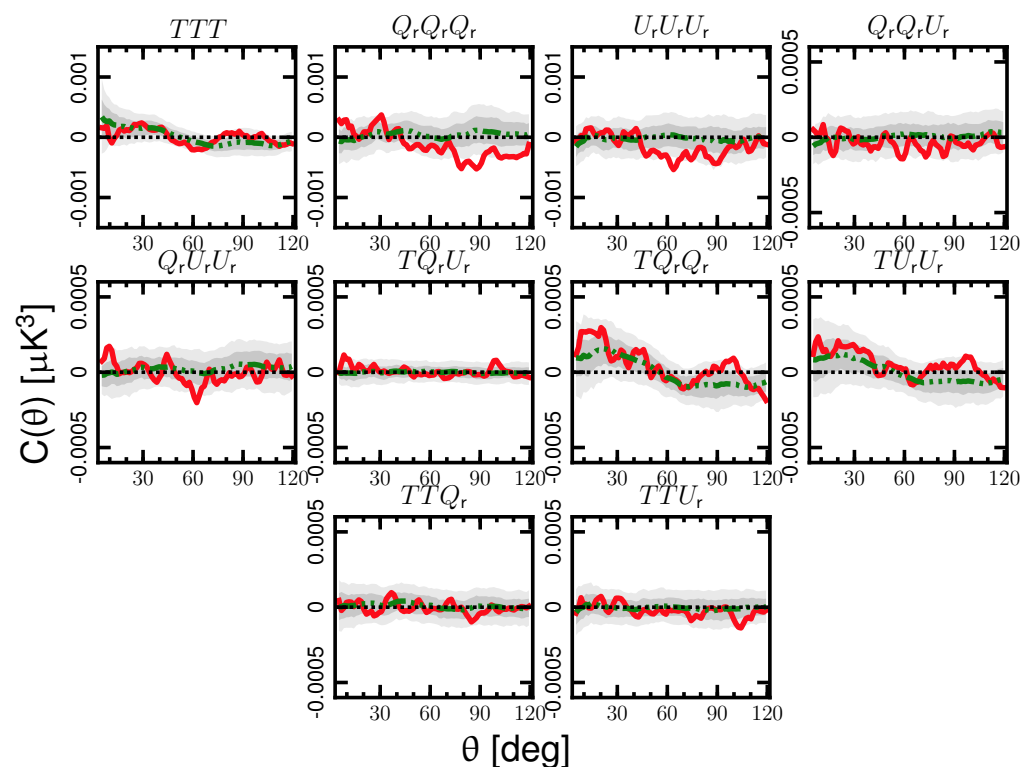
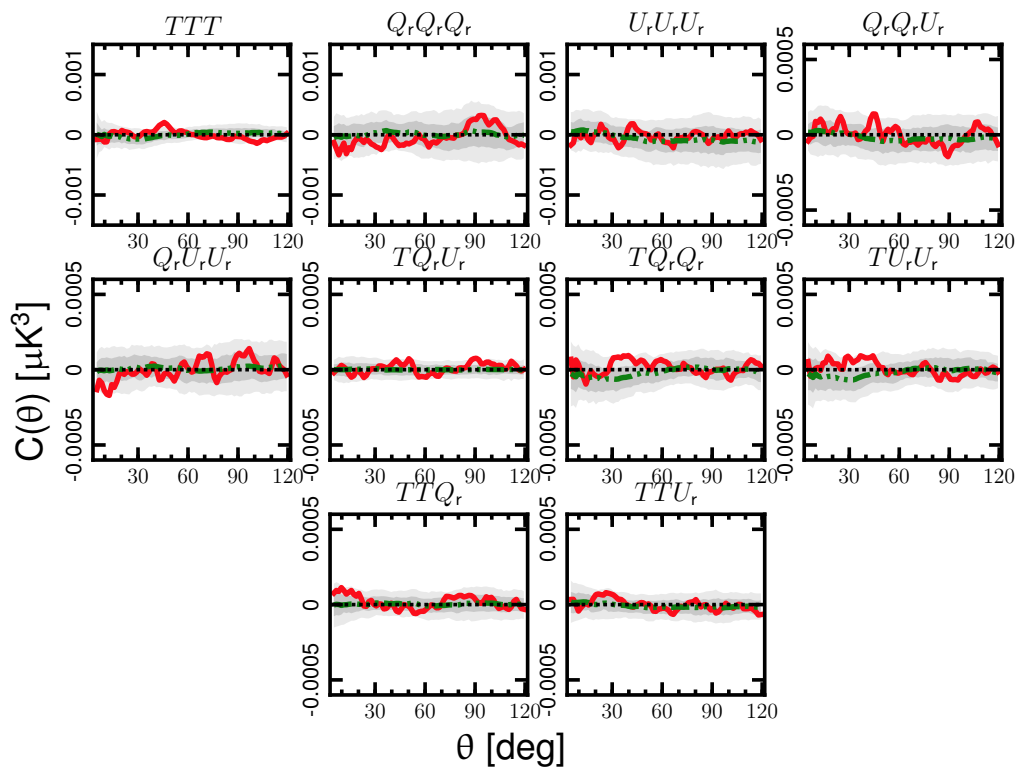
- Pseudo-collapsed 3-point correlation functions
- No statistically significant deviations from simulations



Red – data
Green – mean
for simulations

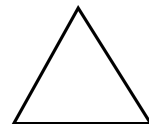
OEHD

HMHD





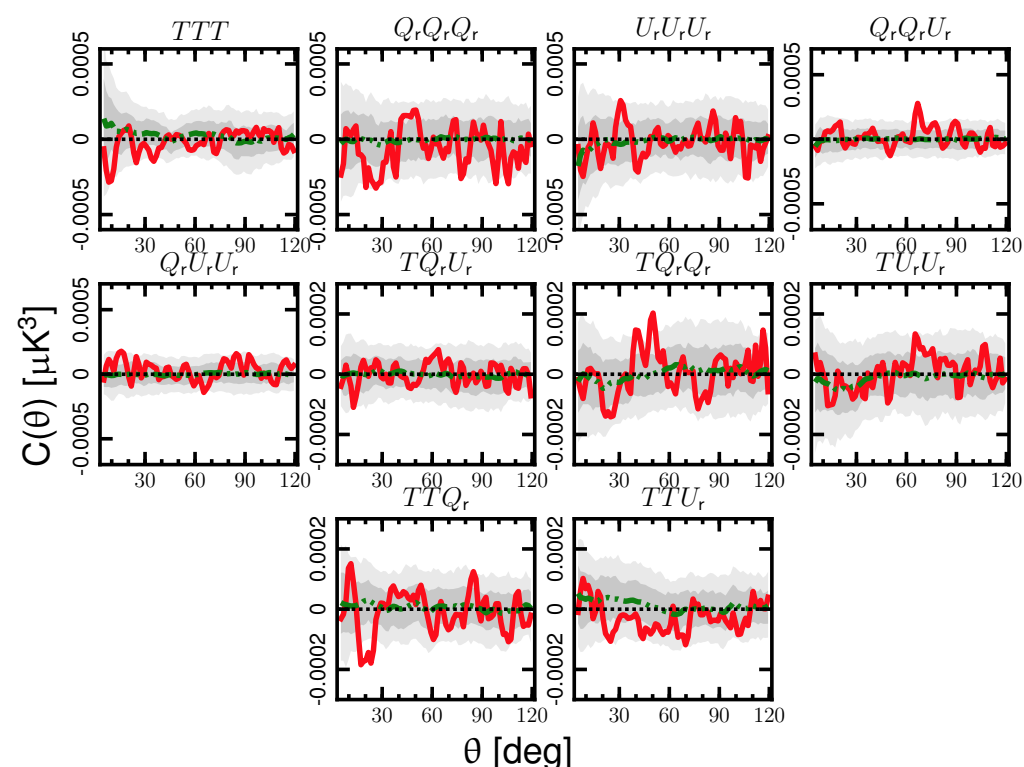
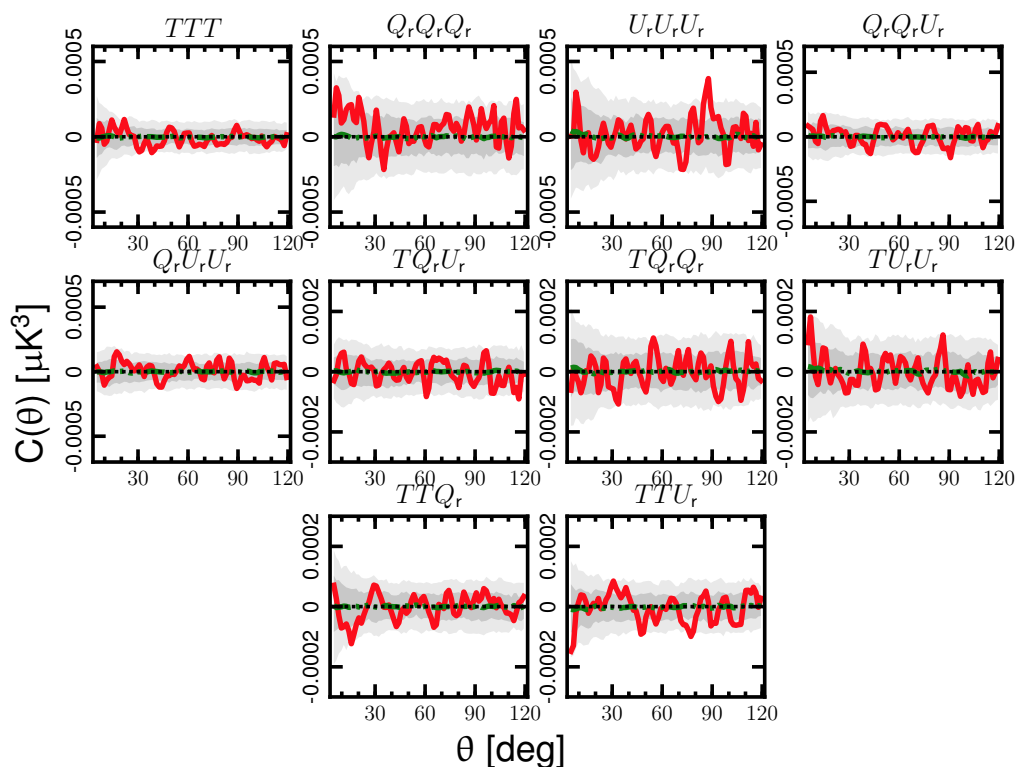
- Equilateral 3-point correlation functions
- No statistically significant deviations from simulations



Red – data
Green – mean
for simulations

OEHD

HMHD

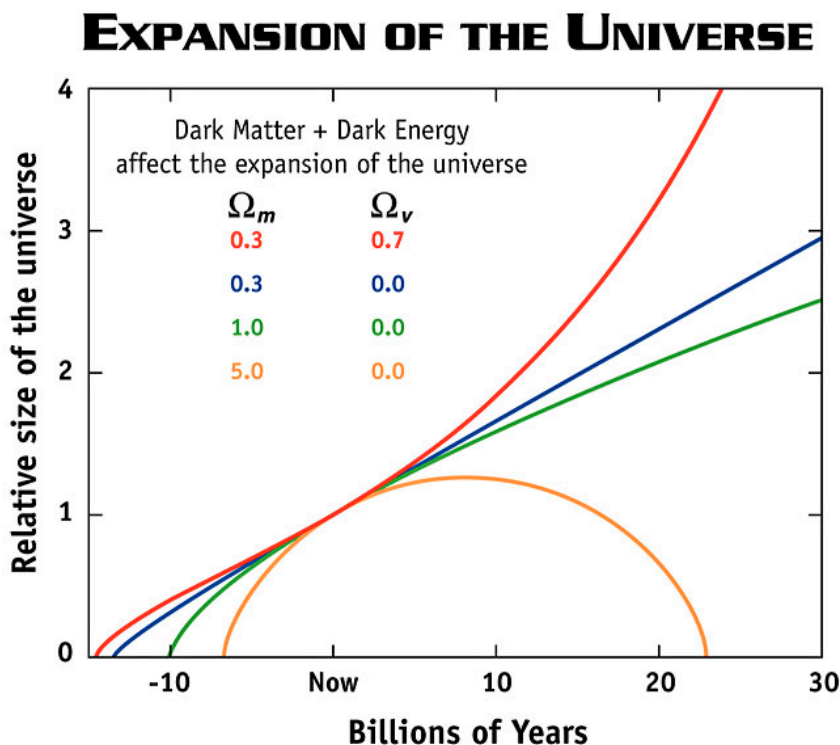
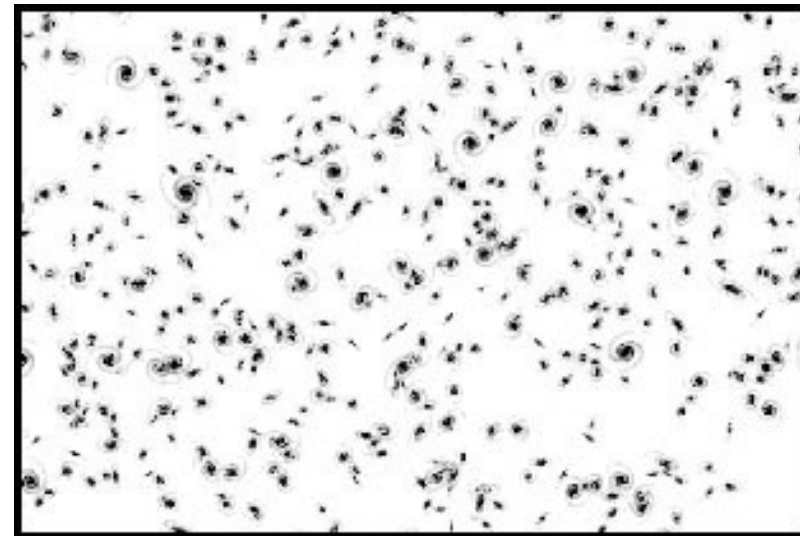




- Isotropy and homogeneity (cosmological principle) are fundamental assumptions underlying the standard Friedman-Robertson-Walker (FRW) model

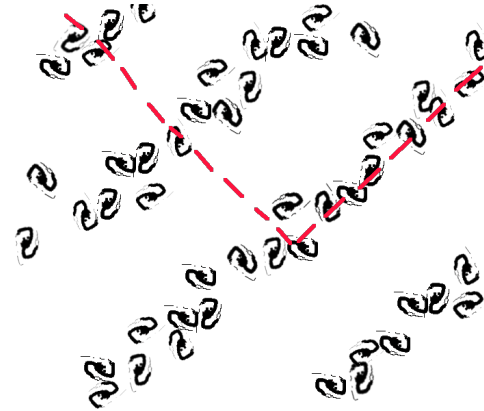
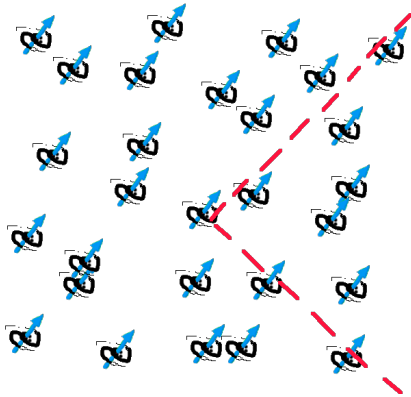
$$ds^2 = c^2 dt^2 - a^2(t) \left(\frac{dr^2}{1 - kr^2} + r^2 (d\vartheta^2 + \sin^2 \vartheta d\varphi^2) \right)$$

- Statistical isotropy and homogeneity of perturbations around the FRW metric

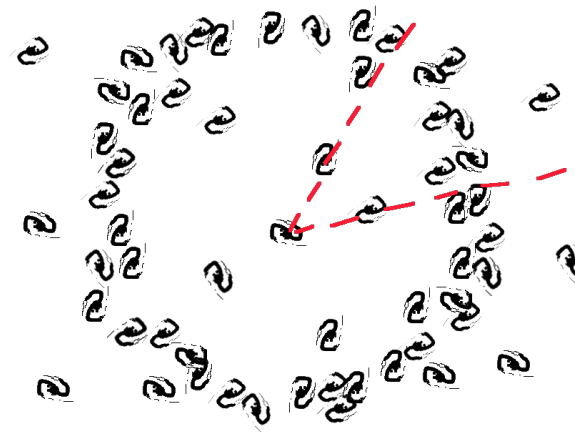
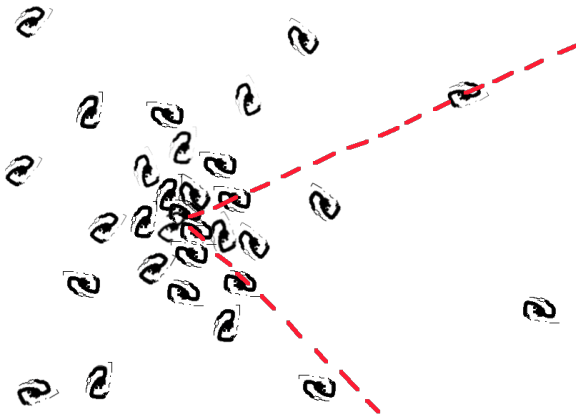




- Homogeneous but non-isotropic universe (with preferred direction)



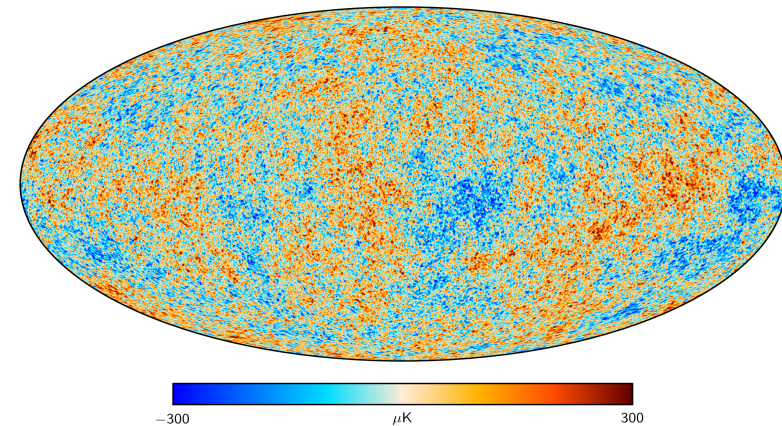
- Isotropic but inhomogeneous universe





- Isotropy confirmed by observations (CMB)
- Ehlers, Geren, Sachs theorem (1968) (Clarkson & Maartens 2010, Stoeger, Maartens, Ellis 1995):

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



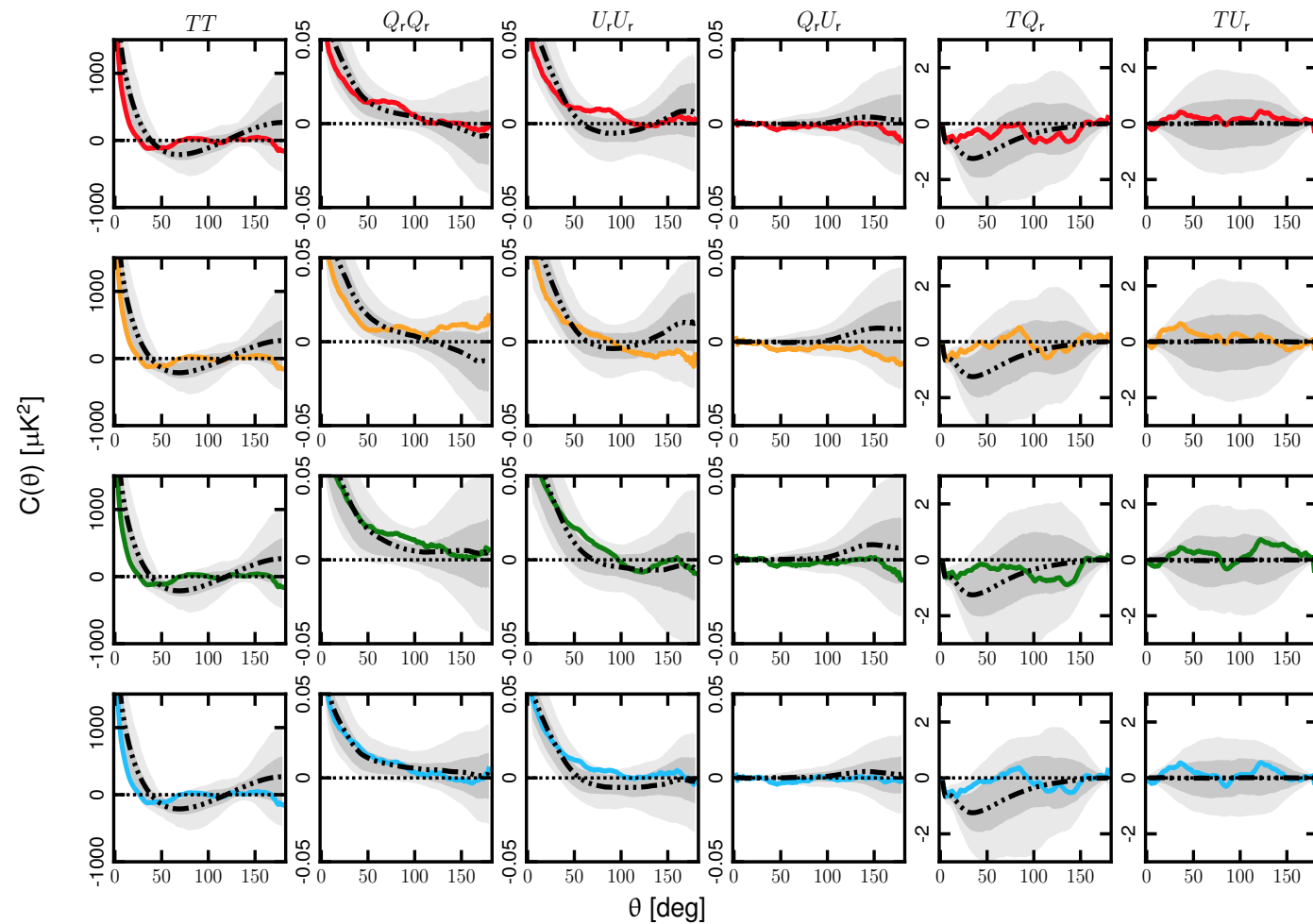


Before Planck few reports on breakdown of statistical isotropy of CMB at large angular scales:

- Lack of correlation at large scales
- Hemispherical asymmetry
- Quadrupole-octopole alignment
- Power spectrum asymmetry
- Power spectrum deficit for large scales
- Point-parity asymmetry
- The cold spot
- ...



- 2-point correlation functions of CMB maps





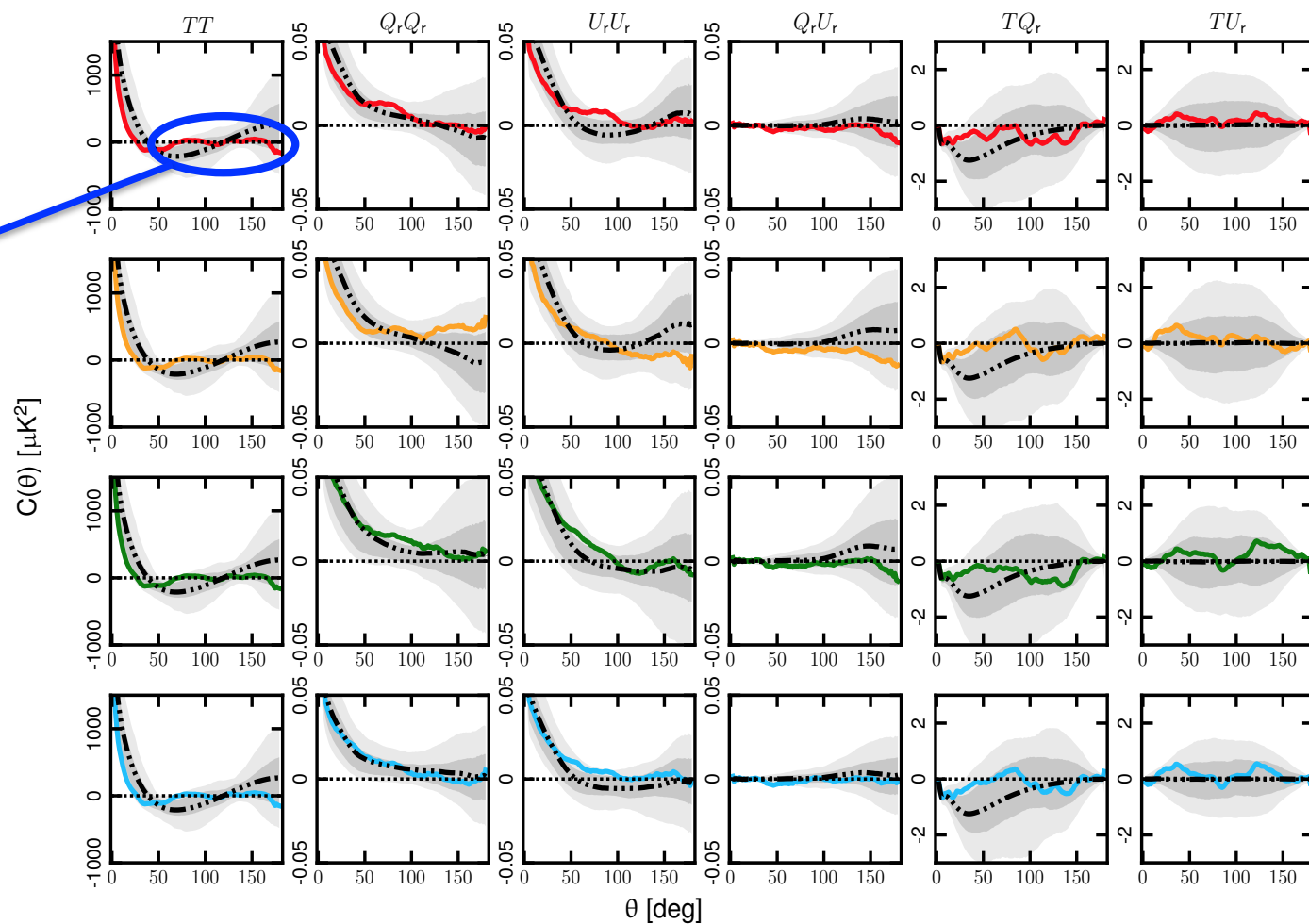
- 2-point correlation functions of CMB maps
- Lack of correlation at large scales

$$S^{XY}(\theta_1, \theta_2) = \int_{\cos\theta_2}^{\cos\theta_1} [\hat{C}_2^{XY}(\theta)]^2 d(\cos\theta)$$

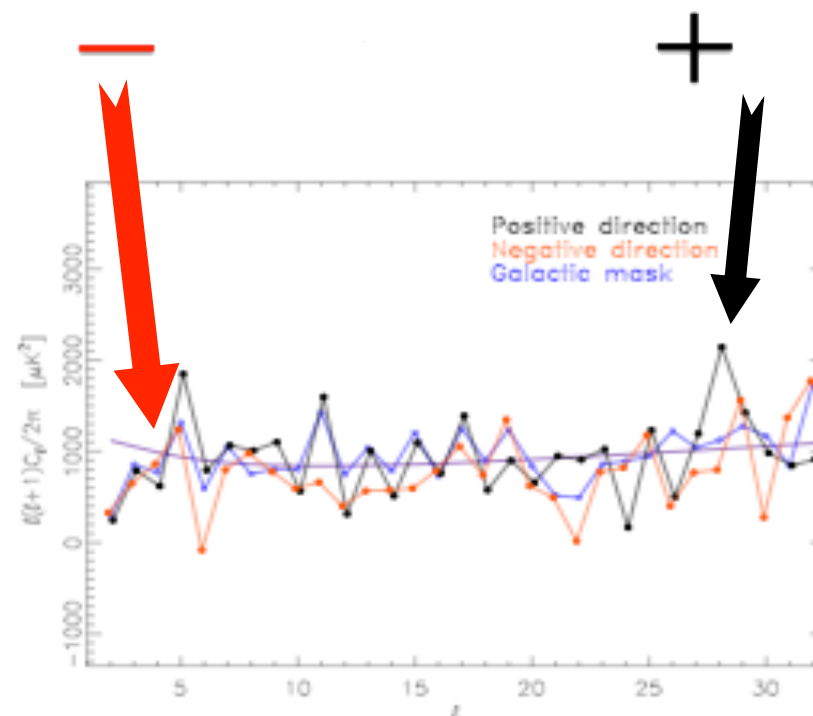
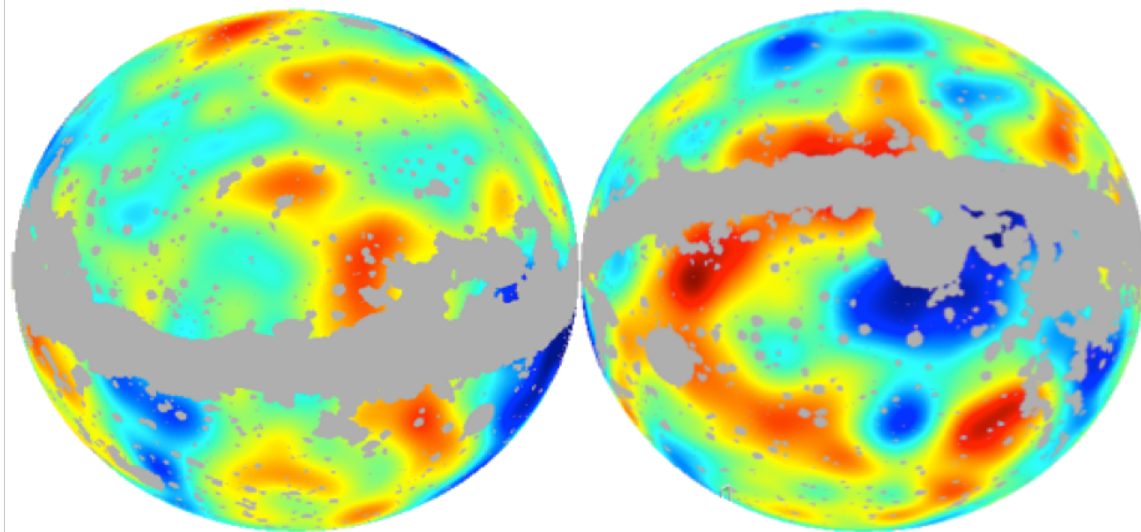
Table 13. Global p -value for the $S^{XY}(\theta, 180^\circ)$ statistic for the *Planck* fiducial Λ CDM model at most as large as the observed values of the statistic for the *Planck* 2018 CMB maps with resolution parameter $N_{\text{side}} = 64$.

Statistic	Probability [%]			
	Comm.	NILC	SEVEM	SMICA
TT	98.8	98.8	98.8	99.0
TT (no quadr.) ..	85.5	86.2	85.7	87.2
$Q_r Q_r$	94.2	57.1	74.5	85.7
$U_r U_r$	89.6	60.3	82.1	85.2
$T Q_r$	80.0	84.8	95.8	87.0
$T U_r$	71.0	82.9	34.6	88.0
$Q_r U_r$	72.5	48.7	87.3	97.1

Notes. The second row shows results for each temperature map after removing the corresponding best-fit quadrupole. In this table high probabilities would correspond to anomalously low $S^{XY}(\theta, 180^\circ)$ values.



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



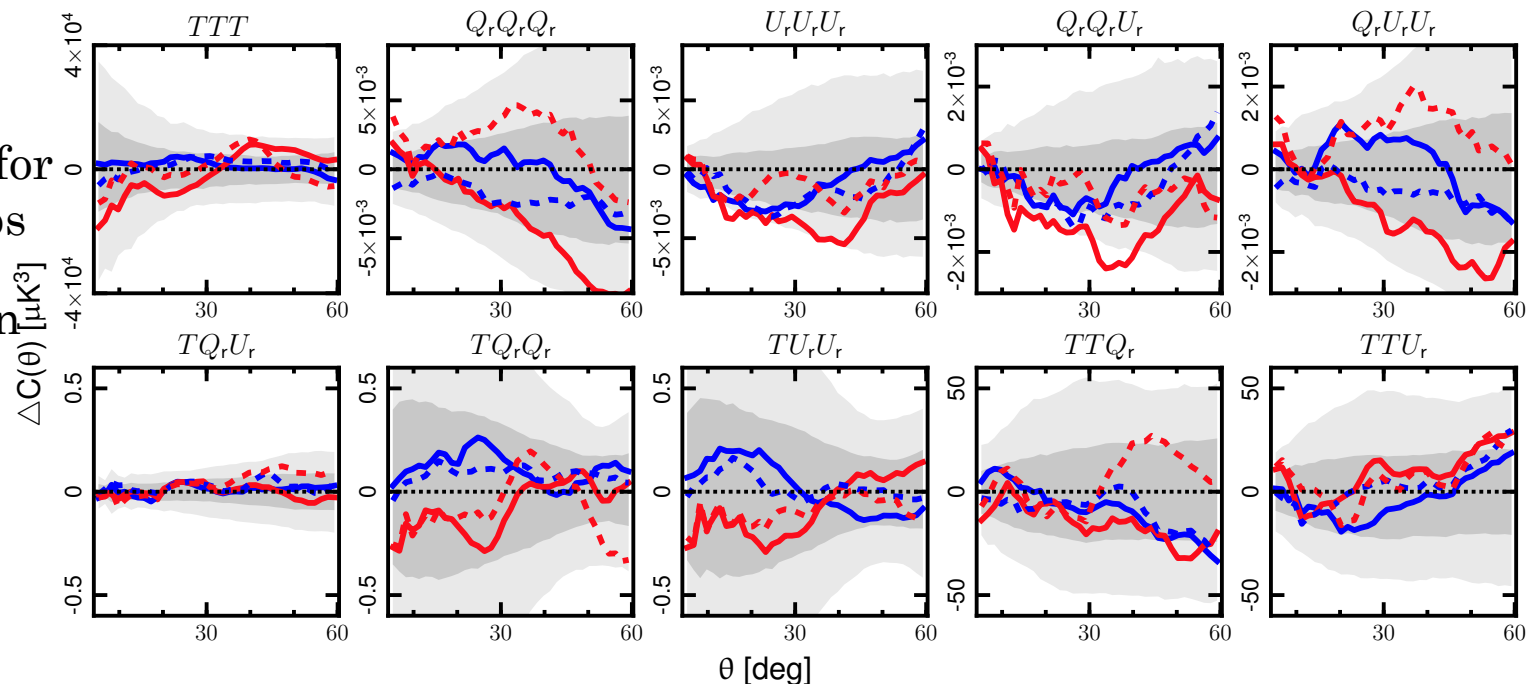


planck

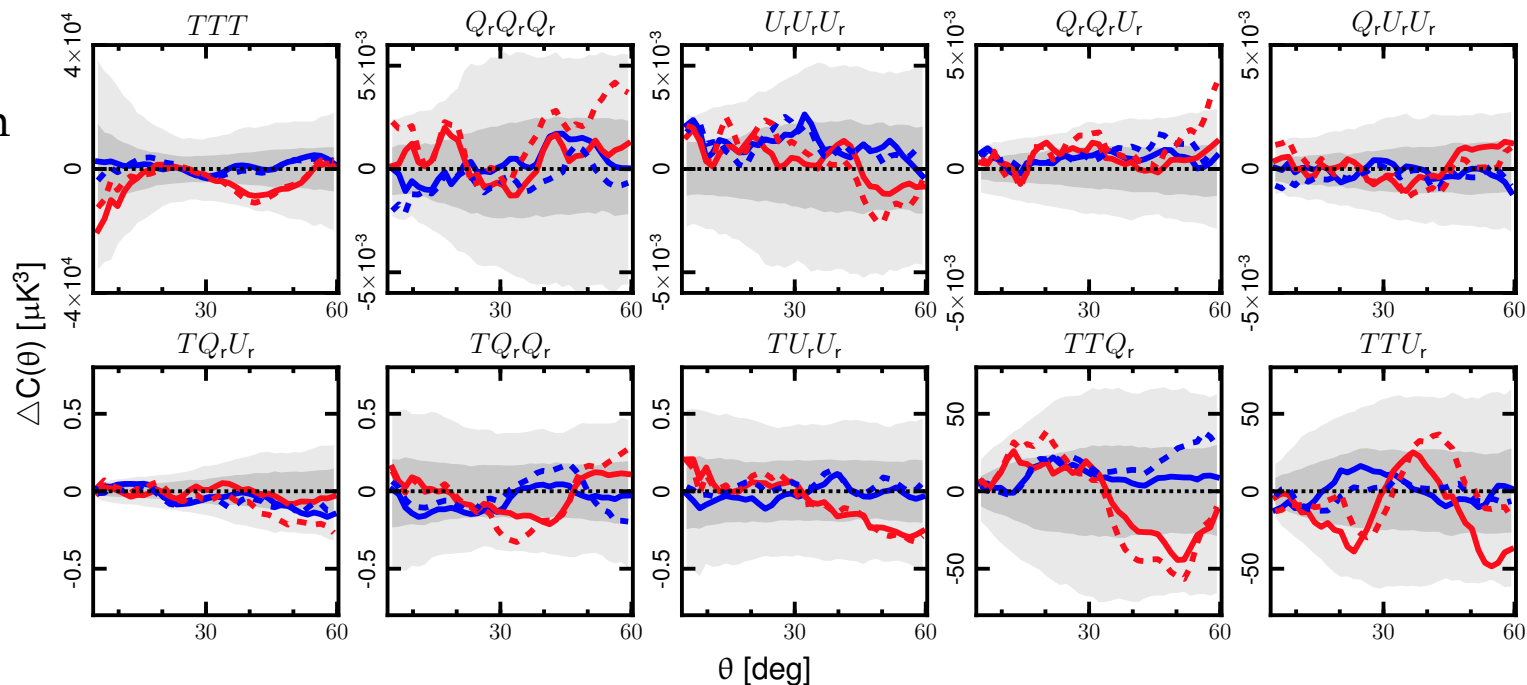
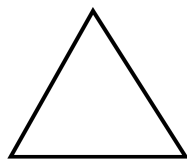
Hemispherical asymmetry – CMB polarisation

- No statistically significant deviations between hemispheres for CMB polarisation maps

Pseudo-coll. 3-pt function

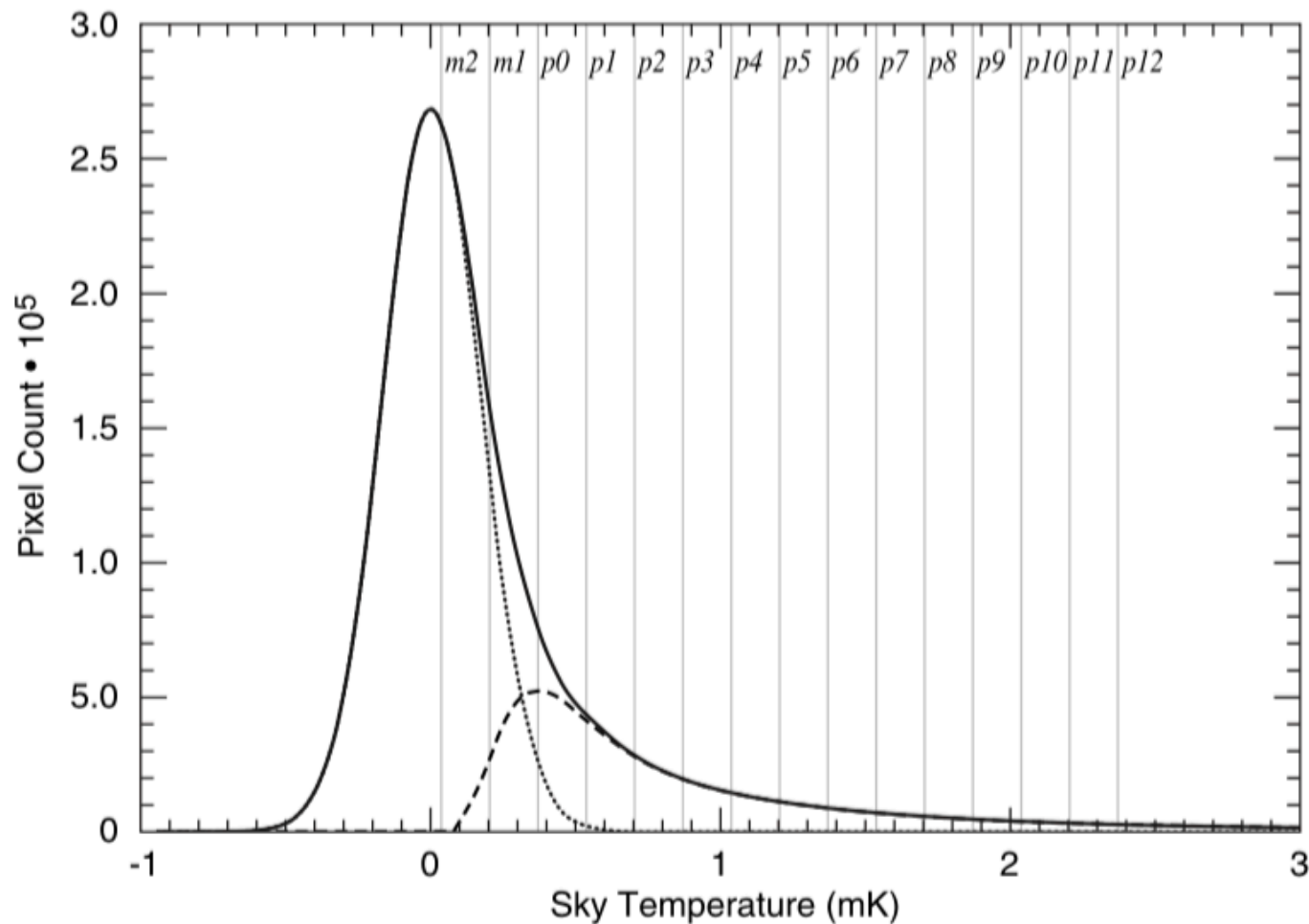


Equilateral 3-pt function





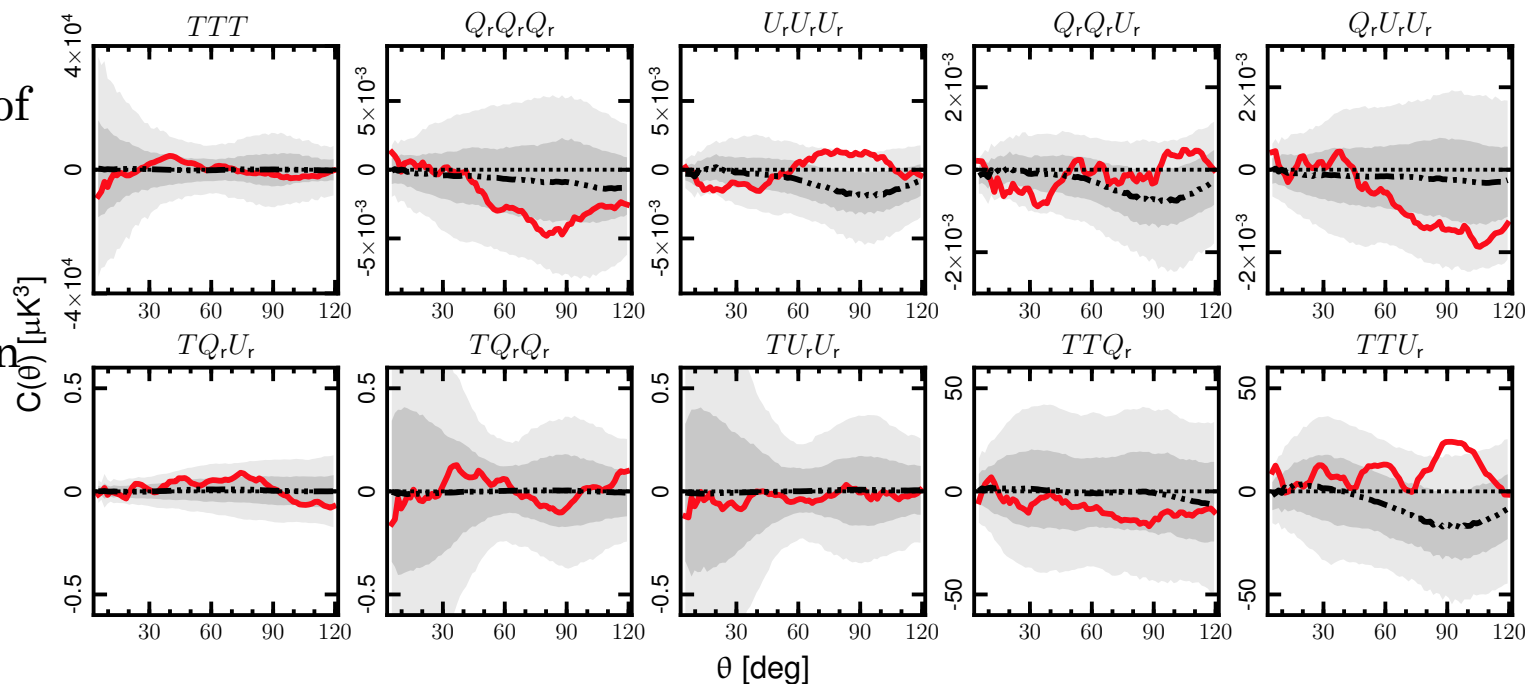
- Foreground-cleaned CMB maps should be Gaussian
- Non-Gaussianity may indicate on residuals of Galactic foreground emission



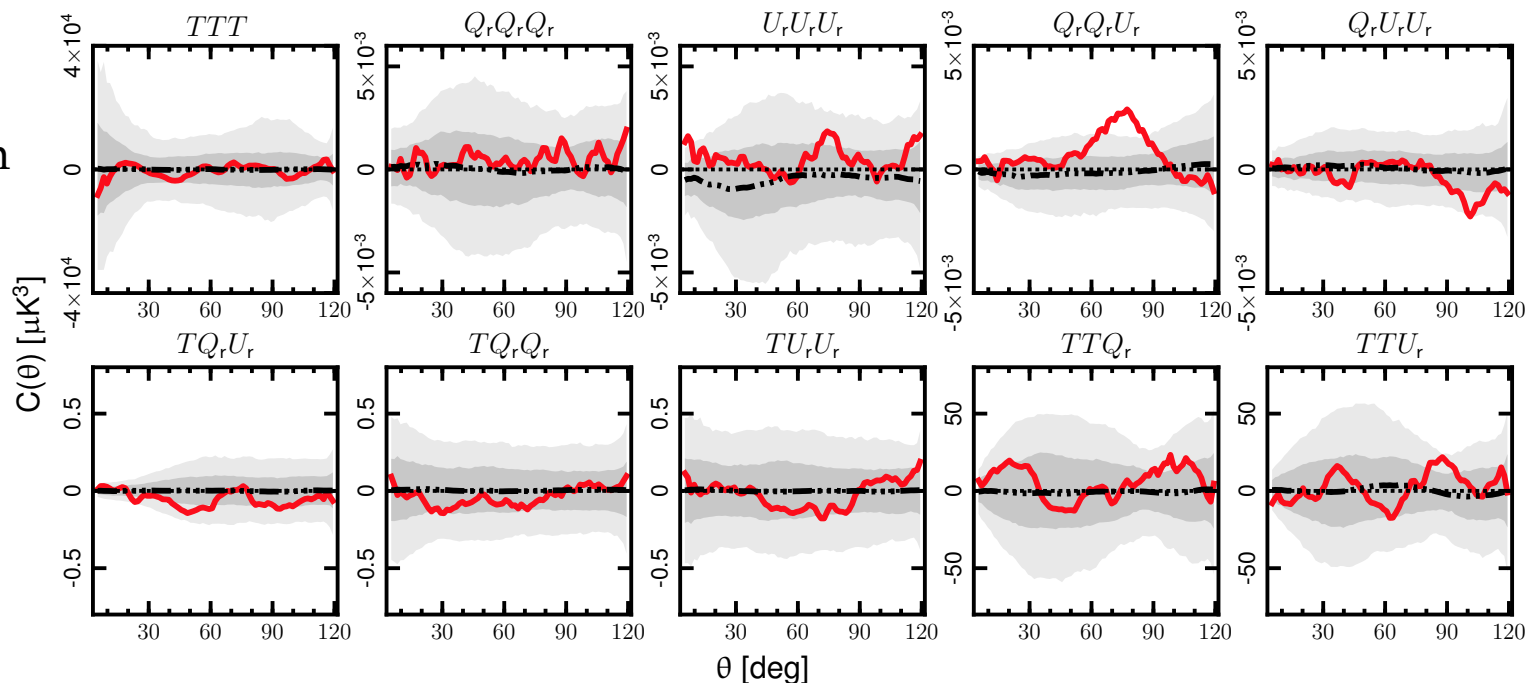
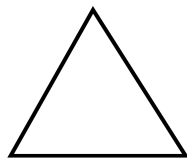


- No statistically significant deviations of the CMB maps from Gaussianity

Pseudo-coll. 3-pt function



Equilateral 3-pt function





- Real-space N-point correlation functions is a useful tool for testing statistical isotropy and Gaussianity of the CMB maps
- No statistically significant deviations between estimated Planck CMB noise maps and simulations
- Lack of large-scale correlations and hemispherical asymmetry not observed for the Planck CMB polarisation data
- No statistically significant deviation of the Planck CMB maps from Gaussianity at large angular scales
- In future possible improvement of constraints on statistical isotropy with forthcoming data (CMB polarisation measurements, galaxy and radio surveys, supernovae, etc.)