Planck isotropy and statistics

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Outline

- Isotropy and statistics tests
- Data and simulations used
- Tests of primordial Gaussianity
- CMB anomalies
- Conclusions

Isotropy and statistics

- Isotropy, i.e. the same properties in all directions, is a well known property of the CMB that motivates the cosmological principle. Due to its fundamental implications it is very relevant to quantify the degree of statistical isotropy of the CMB anisotropies at all scales.

- Primordial CMB fluctuations are predicted to be very close to Gaussian in the simplest inflationary scenarios. Any deviation from Gaussianity is thus a good indicator of the presence of foreground residuals and secondary anisotropies but also of physics beyond the standard cosmological model.

- At a more practical level, isotropy and Gaussianity are assumed in the derivation of the power spectra and the cosmological parameters.

Statistical tests

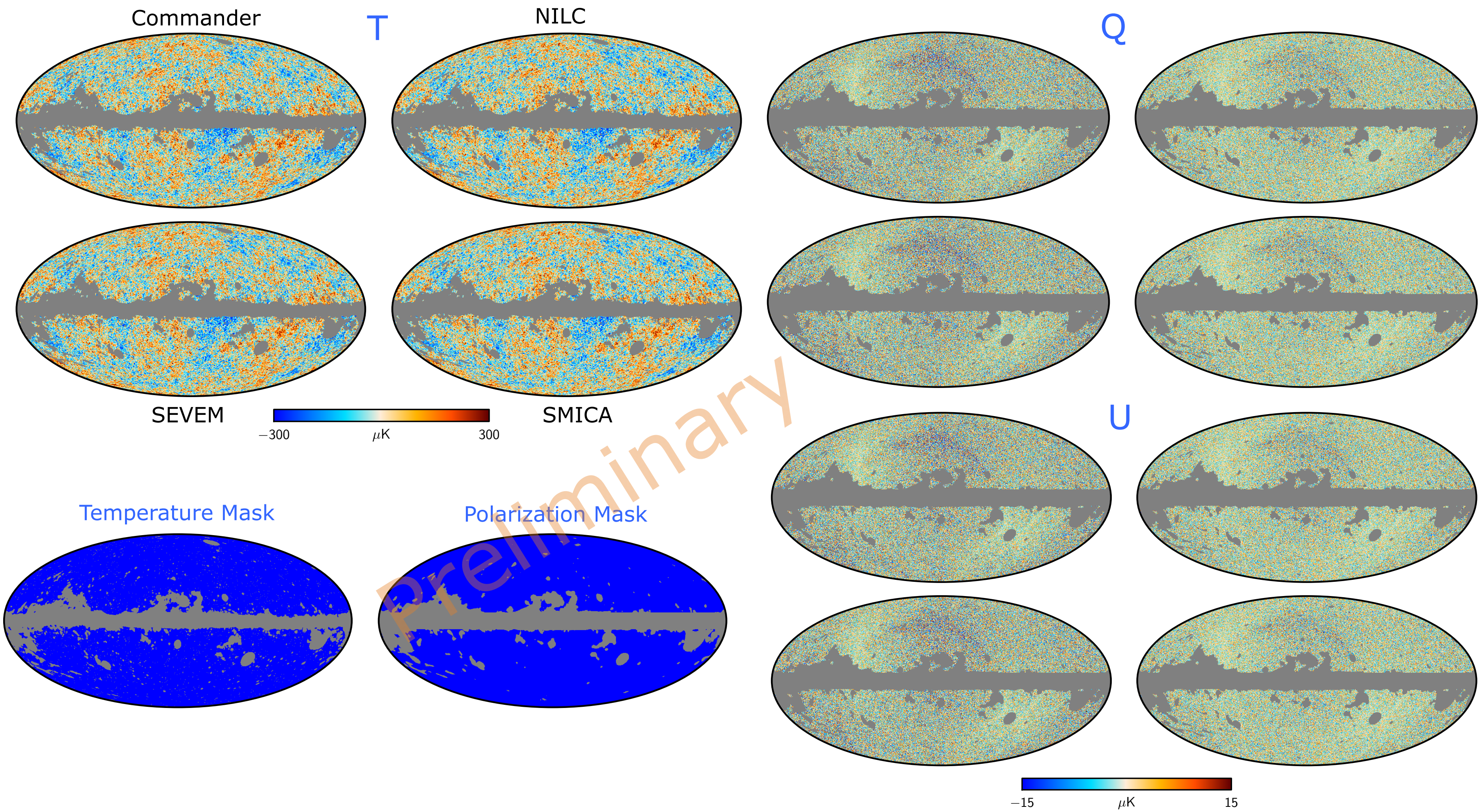
A battery of statistical tests have been applied to the temperature and polarization data:

- Variance, skewness and kurtosis
- N-pdf at low resolution
- N-point correlation functions
- Minkowski functionals
- Multiscale analysis
- Stacking

Data and simulations

- The Planck best-fit ΛCDM model is confronted to the Planck CMB maps extracted from four component separation methods: Commander, NILC, SEVEM and SMICA.
- The common mask is used to remove the contaminated pixels from the analysis.
- The Planck best fit model is represented by realistic (FFP8) Planck simulations that, in addition to the statistical properties of the CMB signal, also contain the most relevant characteristics of the observational process (e.g., beam, noise, Doppler boosting, lensing, …).
- 1000 (FFP8) simulations (only 200 used for NILC)

Temperature and polarization data



Variance, skewness and kurtosis

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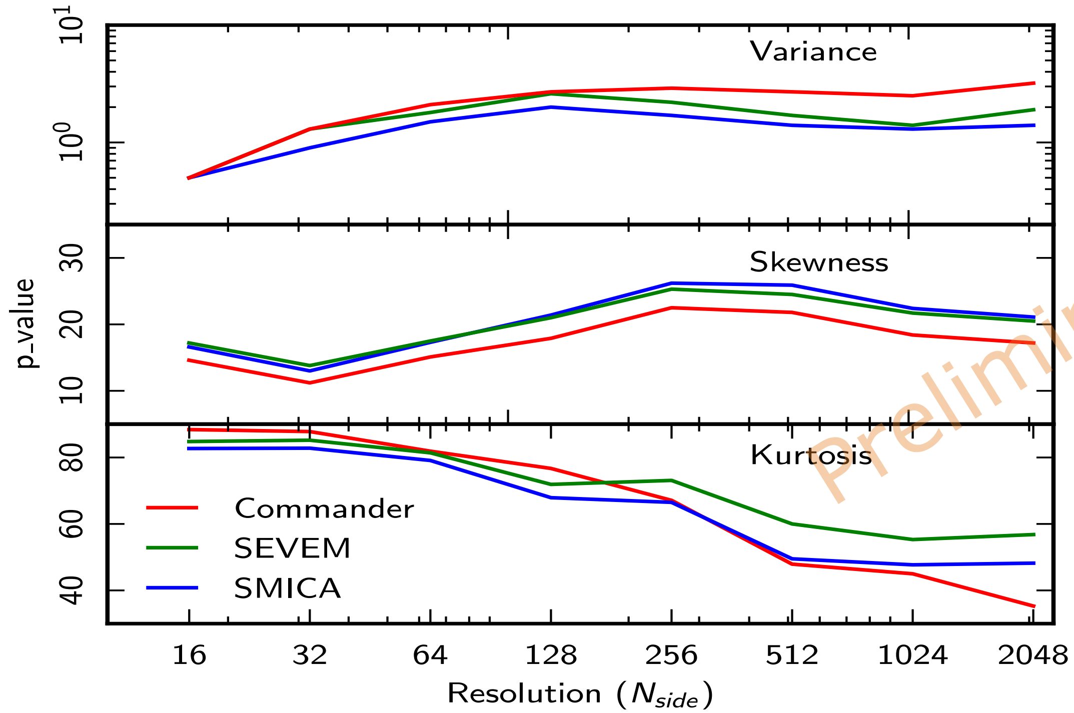
The variance of the CMB is estimated from the Planck maps and corresponding realistic simulations.
The higher order moments are calculated from the normalized data map.



Different frequencies (SEVEM, N_side=2048, %)

	Variance	Skewness	Kurtosis
100GHz	3.4	13.4	67.5
143GHz	2.4	16.9	61.2
217GHz	3.4	11.4	58.3

Different masks (N_side=16, %)

	Variance	Skewness	Kurtosis
	Common mask ($f_{sky} = 58\%$)		
Commander	0.5	14.6	88.4
SEVEM	0.5	17.2	84.8
SMICA	0.5	16.6	82.7
	$f_{sky} = 48\%$		
Commander	0.1	29.4	65.0
SEVEM	0.1	29.4	62.4
SMICA	0.1	29.4	57.3
	$f_{sky} = 40\%$		
Commander	0.4	35.2	32.4
SEVEM	0.4	34.3	30.2
SMICA	0.4	33.8	25.5

A significantly low variance is consistently found at different resolutions, component separations, frequencies and masks. The lowest probabilities are found at the lowest resolutions.
In agreement with Planck Collaboration XXIII (2014).

N-point correlation functions

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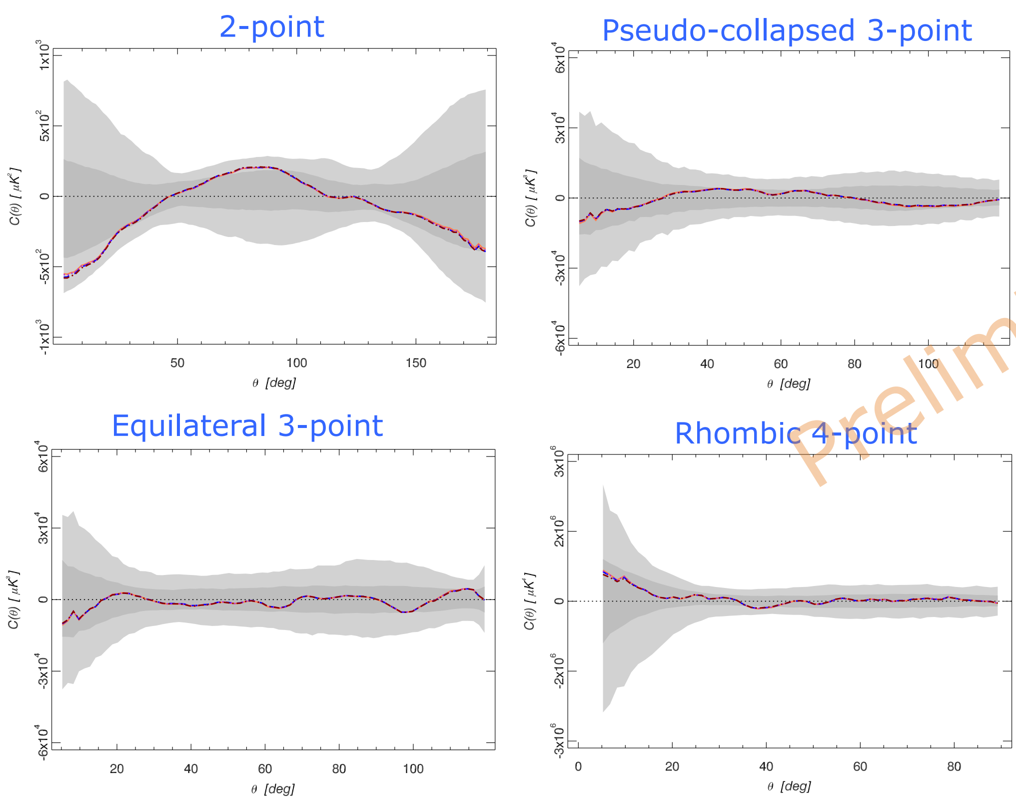
Difference with respect to the ΛCDM model



Function	Probability			
	Comm.	NILC	SEVEM	SMICA
Two-pt.	0.972	0.982	0.974	0.981
Pseudo-coll. three-pt.	0.921	0.922	0.918	0.922
Equil. three-pt.	0.740	0.769	0.758	0.790
Four-pt.	0.646	0.655	0.656	0.659

General agreement is found for the N-point correlation functions.
However, the 2-point function shows a relatively low χ^2 value indicating low correlations relative to the model (a similar behaviour to the one already seen in WMAP and Planck Collaboration XXIII 2014).

Minkowski Functionals

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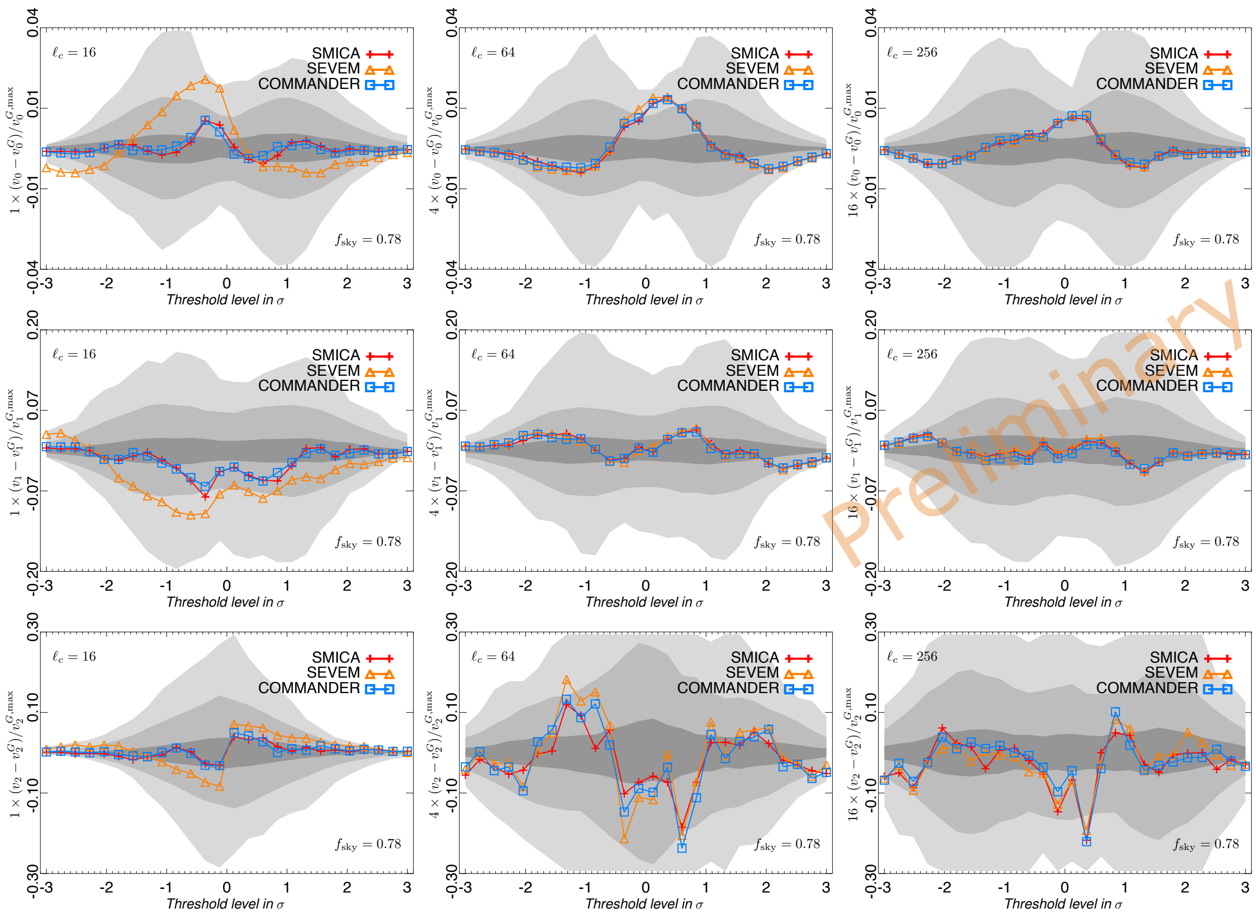
MFs in needlet space



MFs tell us about the morphological properties of the data.
There are three on 2D:

- v_0=area,
- v_1=perimeter
- v_2=genus.

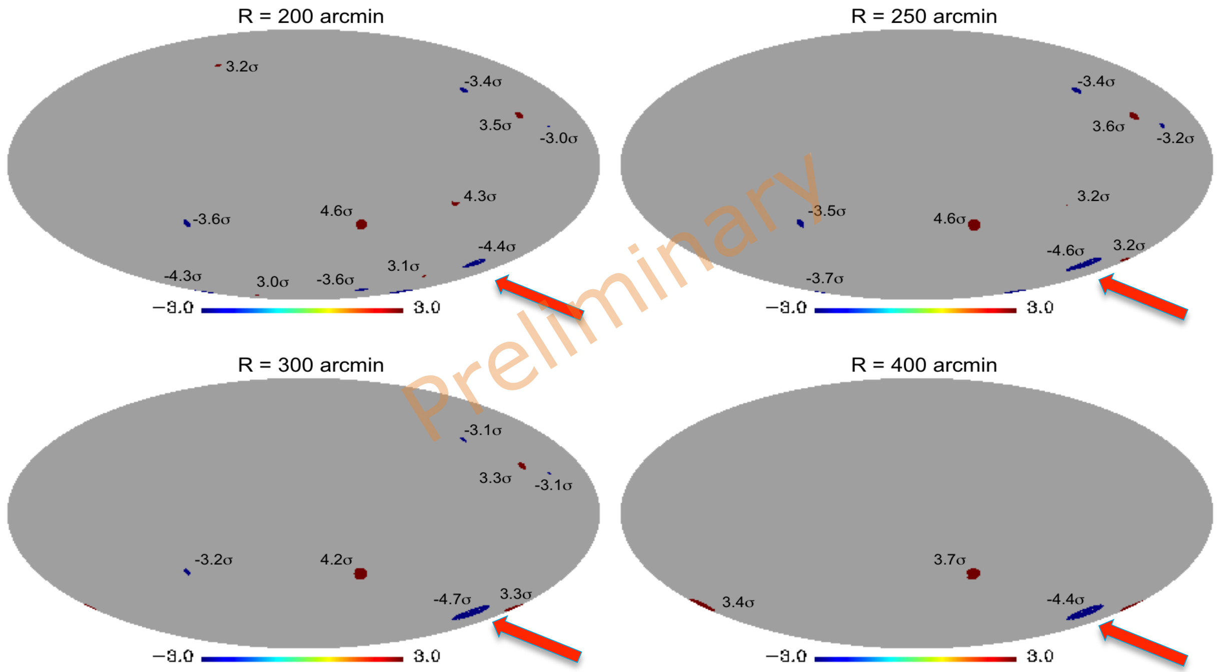
MFs are computed in real and needlet spaces. Needlet space allows a multiresolution analysis of MFs.

General consistency with Gaussianity is found. However, some differences among CS methods are seen for some MFs.

Multiscale analysis

A multiscale analysis is performed based on three different filters: the wavelet SMHW, the matched filter for a 2D-Gaussian profile GAUSS and the Savitzky-Golay kernel SSG84

Pixels above 3σ



p-values (%) of area above 4σ

SMHW/T-map		UTP			
Area	Scale [′]	Comm.	NILC	SEVEM	SMICA
Cold	200	3.8	6.5	3.7	3.8
	250	1.4	1.5	1.4	1.4
	300	0.4	0.5	0.4	0.4
	400	0.9	0.5	0.9	0.9
Hot	200	2.0	2.0	1.7	1.5
	250	2.4	2.0	2.1	2.0
	300	4.2	4.0	4.1	3.9
	400	N/A	N/A	N/A	N/A

GAUSS/T-map		UTP			
Area	Scale [′]	Comm.	NILC	SEVEM	SMICA
Cold	200	1.7	3.0	1.7	1.7
	250	1.2	2.0	1.2	1.2
	300	1.6	6.0	1.2	1.8
	400	N/A	N/A	N/A	N/A
Hot	200	2.9	6.0	2.8	2.6
	250	5.7	11.0	5.6	5.4
	300	N/A	N/A	N/A	N/A
	400	N/A	N/A	N/A	N/A

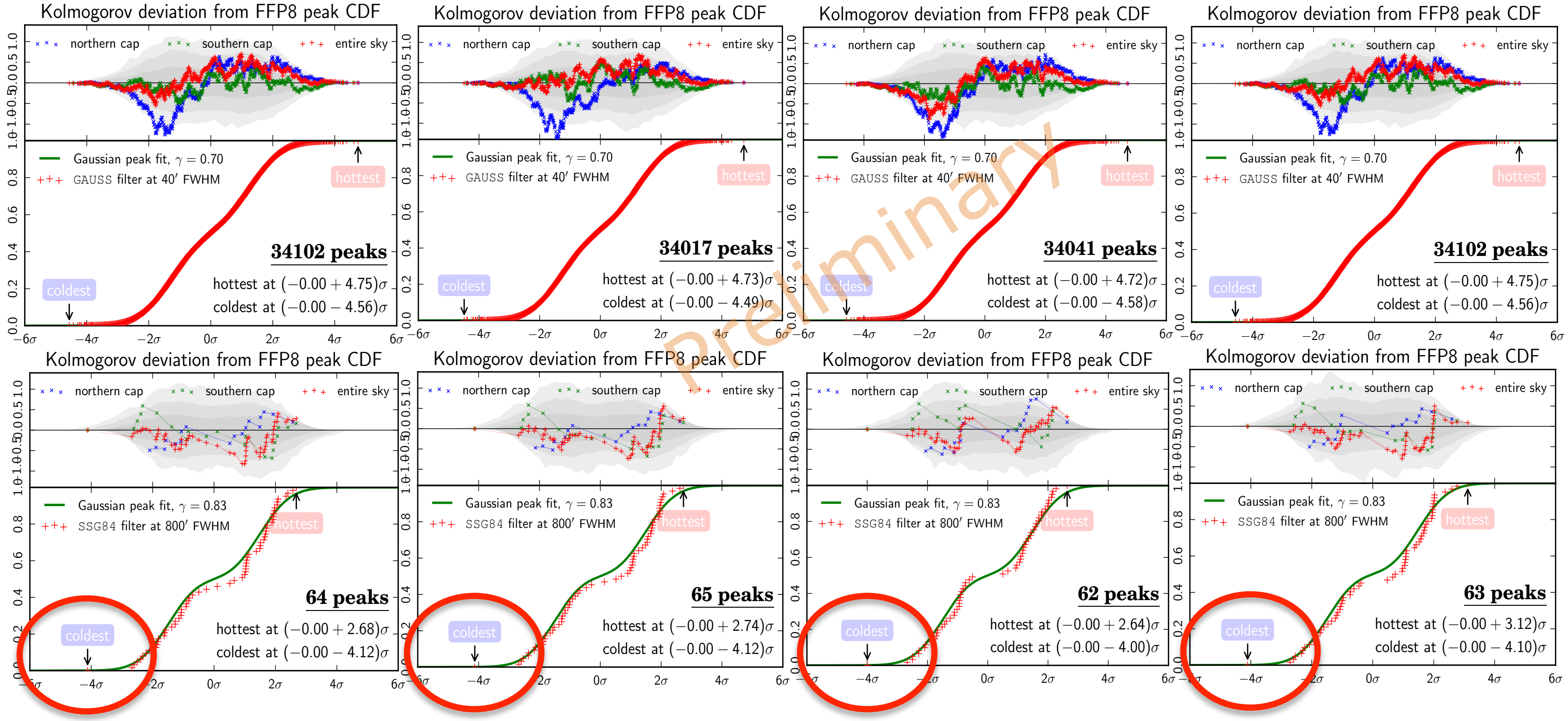
Similar results are obtained for other filters (GAUSS, SSG84).
The area is dominated by the Cold spot and shows a significantly low probability, as do the kurtosis and peak statisitics.
The results are similar to the ones for the first release (Planck Collaboration XXIII 2014).

Multiscale analysis

The statistics of peaks constitutes a powerful alternative test to search for non-Gaussian features.

Comparison of the peak CDF of temperature data and simulations

Commander NILC SEVEM SMICA



Percentage of peaks common to the 4 methods are above 90% for all scales.
The peak distributions are consistent with Gaussianity apart from the Cold Spot.

Stacking in polarization

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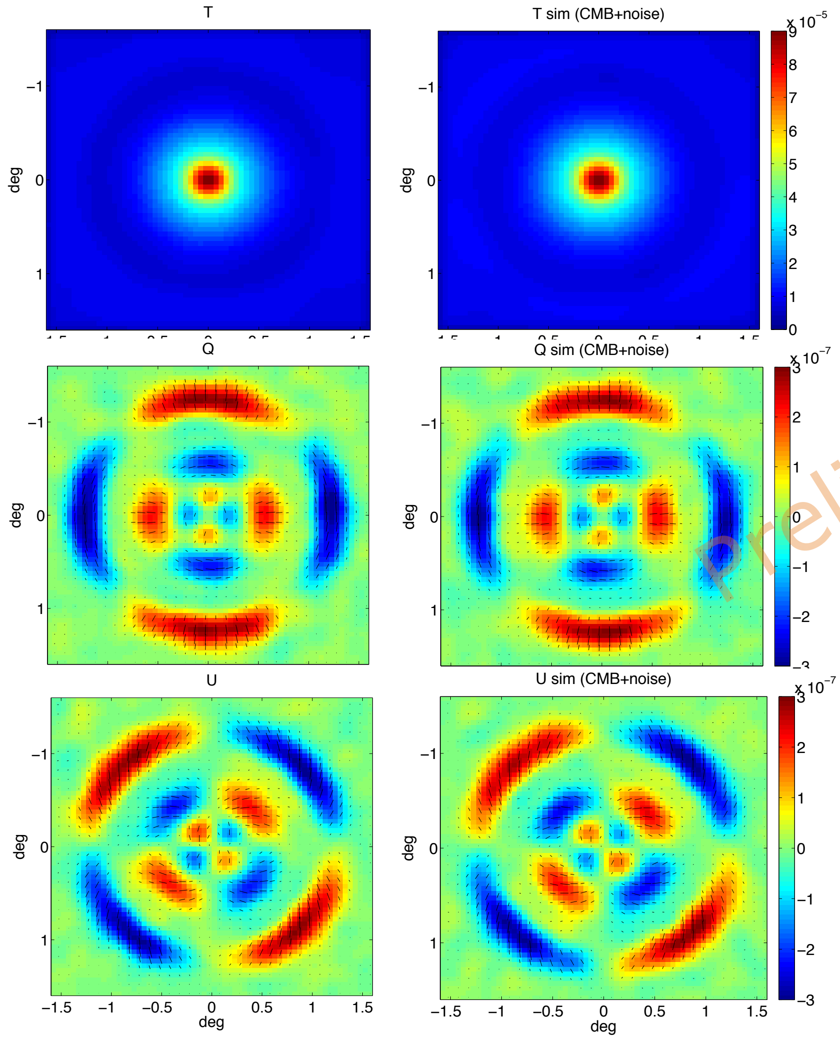
Commander | Simulation

T (>0σ)

Q

U



Stacking of polarization patches at temperature peak positions

Commander | Simulation

Qr

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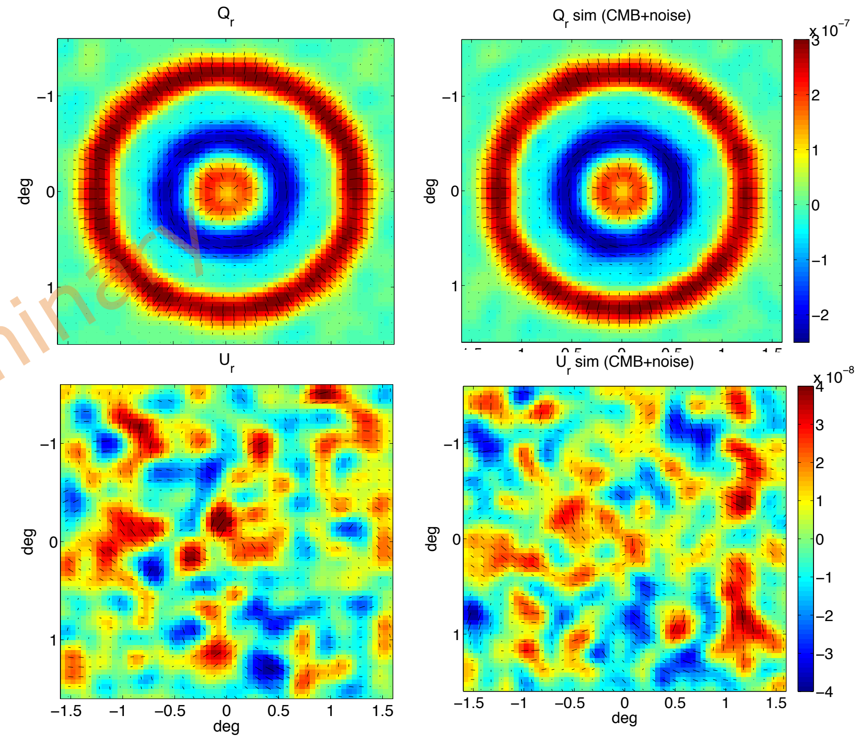


The stacking in polarization probes degree angular scales and shows good consistency with Gaussianity (for the generalized stacking see Z. Huang talk)

Anomalies

Some of the most relevant anomalies have been studied in the Planck full data:

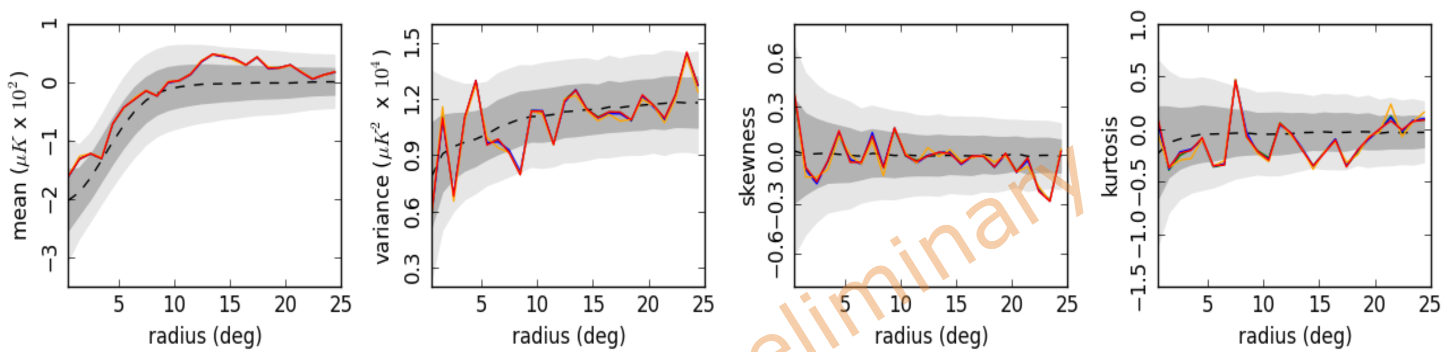
- Low variance: already reviewed
- Large scale asymmetries → See G. Polenta Talk
- The Cold Spot

The Cold Spot

First detected in the WMAP first year data (Vielva et al. 2004) and later confirmed by later WMAP and Planck releases.

In the previous slides the Cold Spot appeared as an anomalous feature in terms of kurtosis, area and peak statistics at scales above several degrees.

Here we focus on its internal structure that has also been recently considered in the literature.



Statistics	Commander	SEVEM	SMICA
Mean	1.5	1.7	1.3
Variance	26	26	30
Skewness	81	87	81
Kurtosis	60	57	64

The mean profile is anomalous whereas the higher order ones are compatible with Gaussianity.

In polarization the high-pass filtering of the map impedes us in probing the Cold Spot.
A forecast based on the unfiltered simulations and the CS noise levels provides an 8% discrimination significance (in agreement with Fernandez-Cobos et al. 2013)

The Cold Spot

Several possibilities have been proposed to explain its nature although none of them is very convincing:

- Statistical fluke of the LCDM model.
- Foreground contamination seems to be discarded (Cruz et al. 2006, Planck Collaboration XXIII 2014).
- The texture origin was originally proposed by Cruz et al. 2007. It was later re-examined by Feeney et al. 2012 for the whole sky finding no evidence but without ruling out this possibility.
- The void origin has been recently invoked based on a super void found by Szapudi et al. (2014) in the WISE-2MASS-Panstarrs galaxy catalogue and independently by Finelli et al. (2014) in WISE-2MASS. However the -150 μK amplitude first estimated by Finelli et al. 2014 using an LTB model has not been confirmed by any of the later works (Zibin 2014, Nadathur et al. 2014).
- Another possibility is the bubble collision considered in Feeney et al. 2013 who found no evidence for it but again not ruling it out.

Conclusions

- Tests of isotropy and Gaussianity provide the basis to support the assumptions made in the derivation of the power spectra and the cosmological parameters.
- In addition they also probe physics beyond the standard cosmological model.
- Planck data demonstrate good consistency with the Gaussianity assumption apart from the known anomalies of low variance and the Cold Spot.
- Polarization at degree angular scales has been probed by stacking at positions of hot/cold spots identified in temperature. The polarization profiles are consistent with the ΛCDM model.
- The anomalies are seen in the temperature full data set at similar levels as in the 2013 release. Due to the high-pass filtering in polarization most of the signal at the largest scales is removed.
- In addition to the significantly low probabilities found for the area, kurtosis and peak statistics, the temperature profile of the Cold Spot shows an anomalous behaviour.

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.