Isotropy and statistics results from Planck

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on behalf of the Planck Collaboration

IAU, Honolulu, Aug. 2015

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

Introduction

Planck 2013 results showed remarkably good consistency with ΛCDM predictions: the basic properties of CMB primary anisotropies are well described by a simple 6-parameter ΛCDM model.

Nevertheless, a number of interesting anomalies were reported in our previous work (Planck Collaboration, 2014, A&A 571, A23), some of which were already present in WMAP data.

Detection by different instruments strengthened the confidence of these detections as real sky signals.

The wide frequency coverage of *Planck* is fundamental to allow the separation of the CMB signal from foreground emissions, and therefore to possibly confirm the cosmological origin of such anomalies.

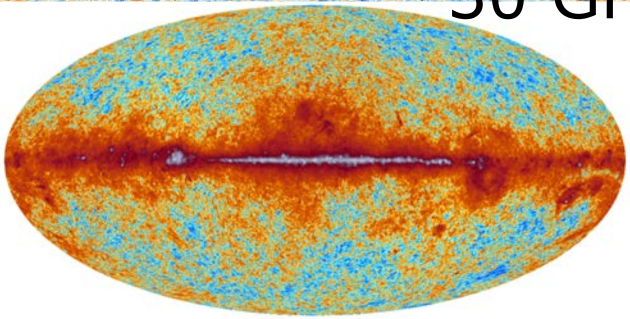
Dataset and methodology

- Results shown in this talk have been produced using *Planck* 2015 full mission intensity data. The analysis of polarization is in progress although we show some examples of interesting results.
- Frequency maps have been processed by 4 different component separation methods - Commander, NILC, SEVEM and SMICA - to obtain 4 CMB maps, in order to test the robustness of results w.r.t foreground cleaning.
- A common mask is used including both Galactic plane and point source masking. The corresponding f_{sky} is ~77% at full resolution and ~60% at low resolution.
- **Planck 2015 I&S paper – arXiv:1506.07135,**
  out on June 23, 2015

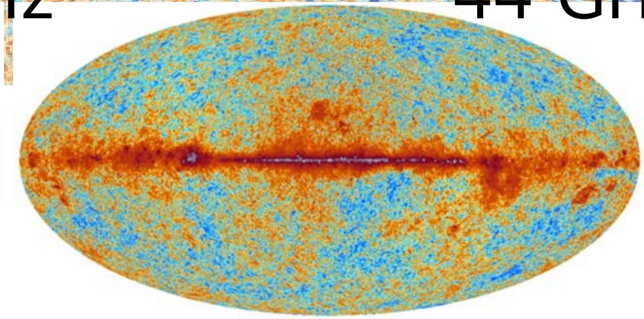
Planck 2015 Temperature Maps

Low Frequency Instrument:

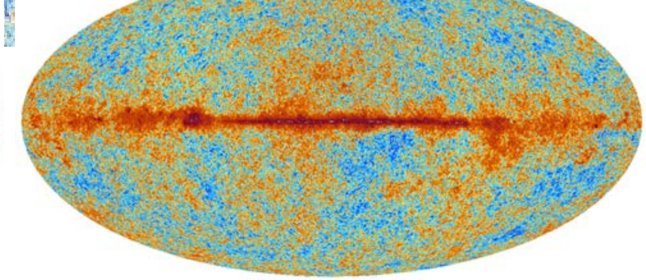
30 GHz



44 GHz

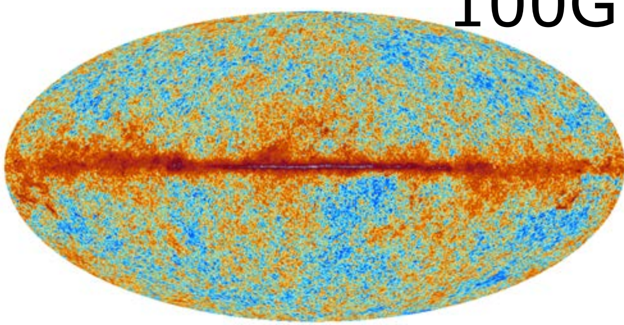


70 GHz

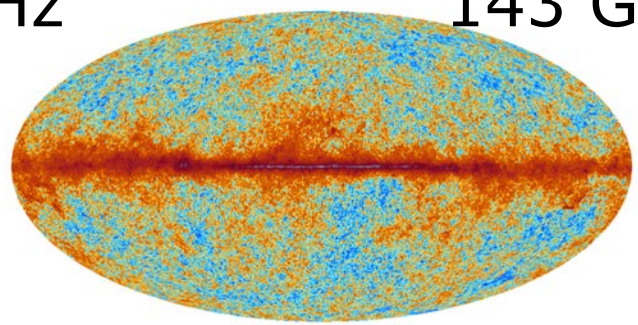


High Frequency Instrument:

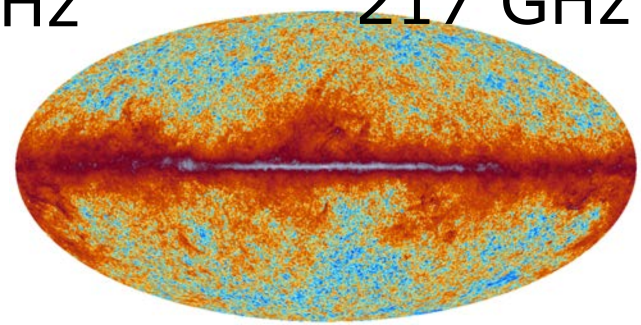
100GHz



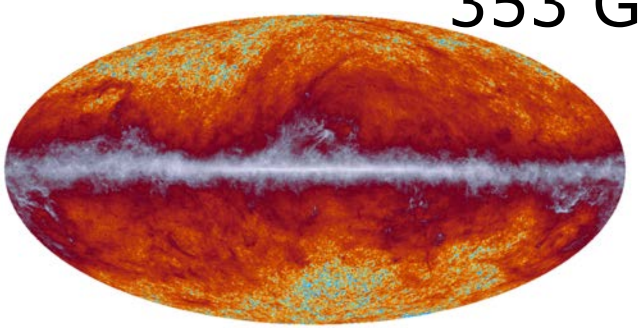
143 GHz



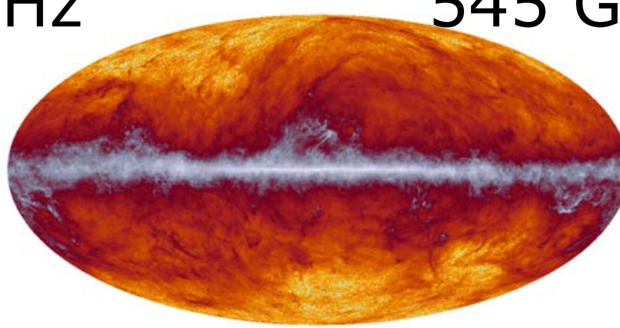
217 GHz



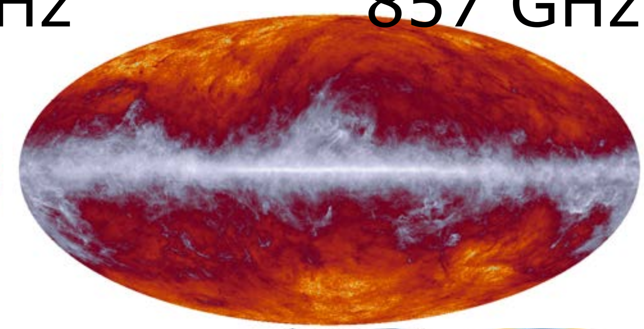
353 GHz

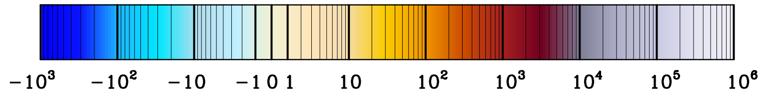


545 GHz

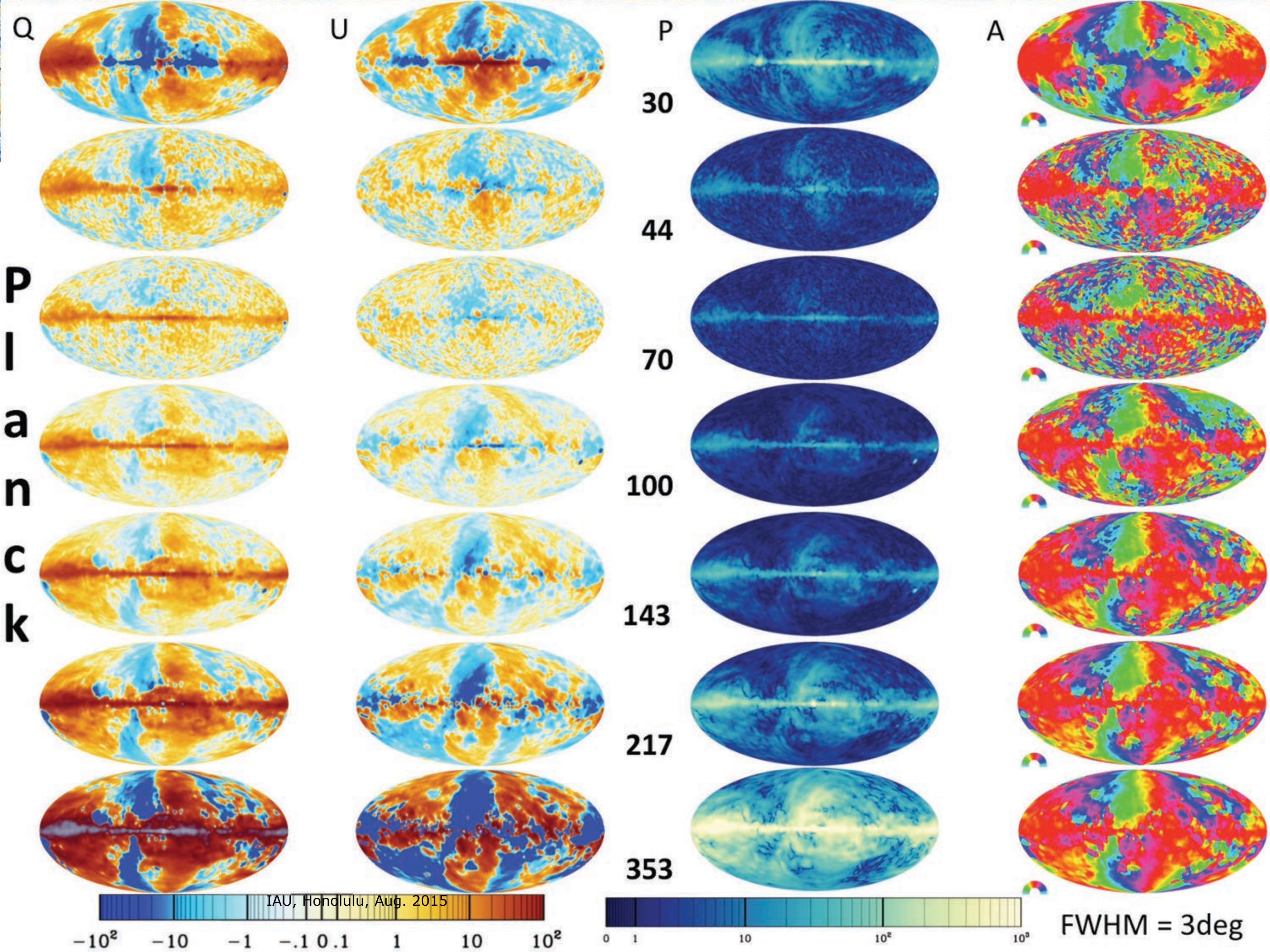


857 GHz





30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]


Q
U
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Planck
30
44
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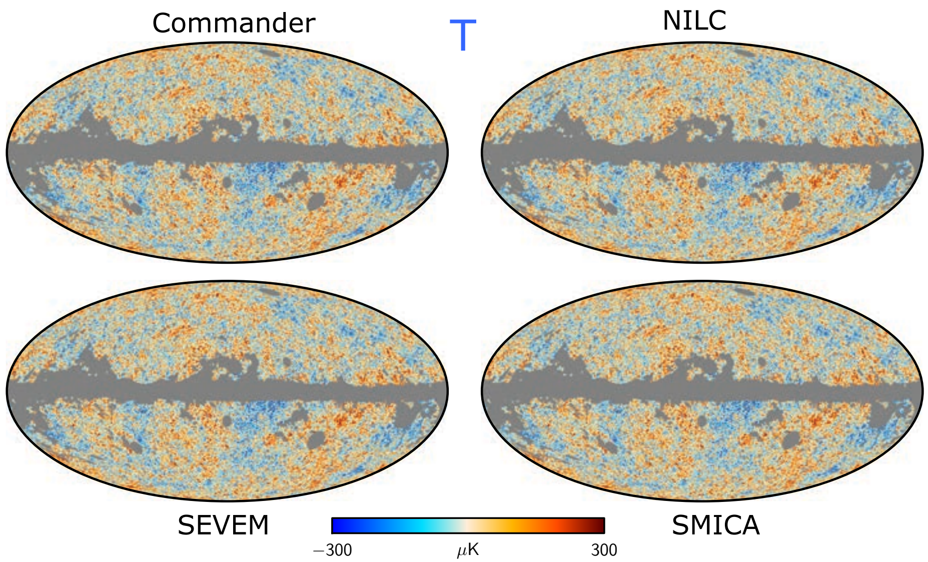
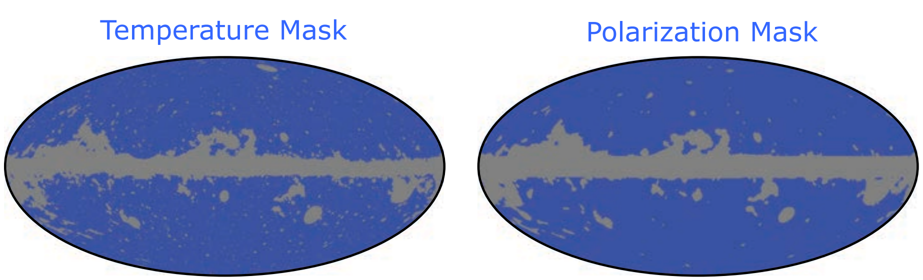
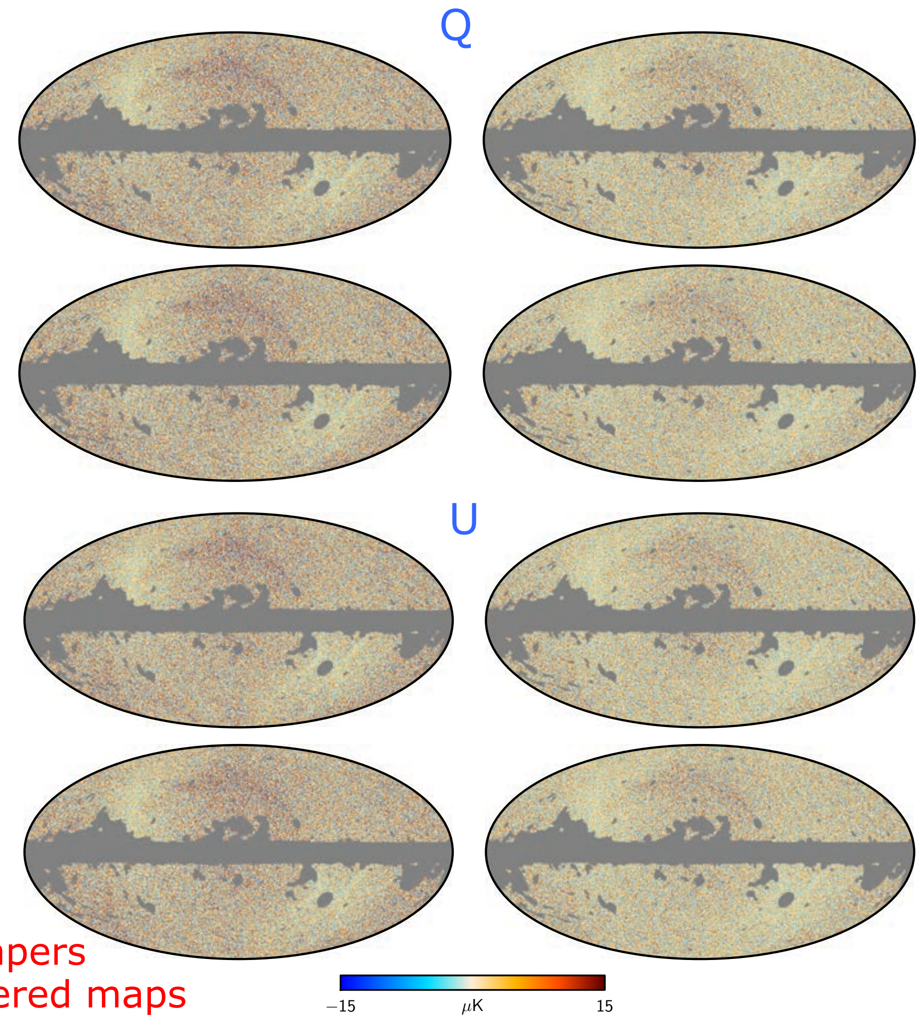
143
217
353
-10^2 -10 -1 $-.1$ 0 .1 1 10 10^2
0 1 10 10^2 10^3
FWHM = 3deg
IAU, Honolulu, Aug. 2015

Temperature and polarization data: post-component-separation CMB maps

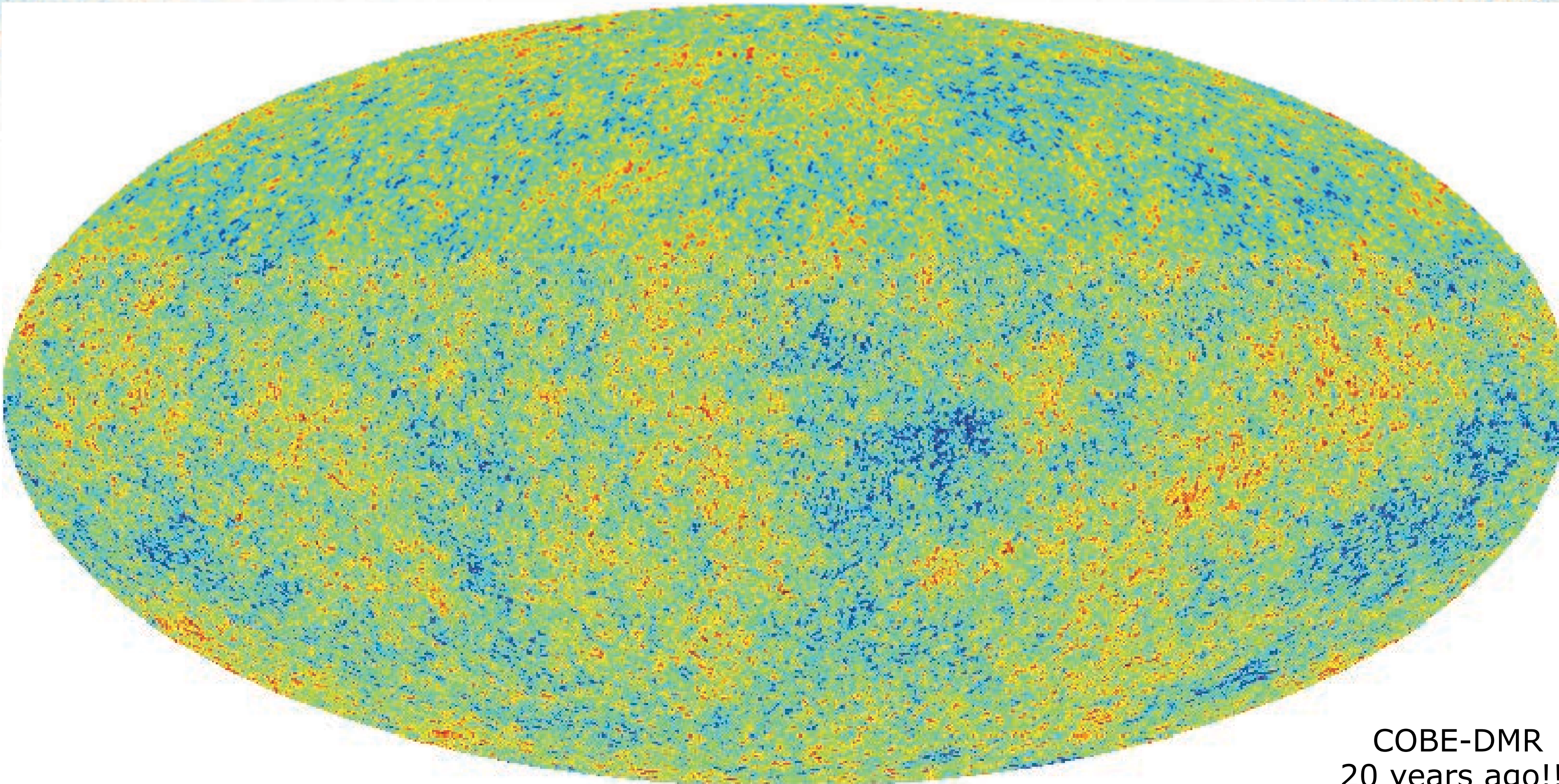




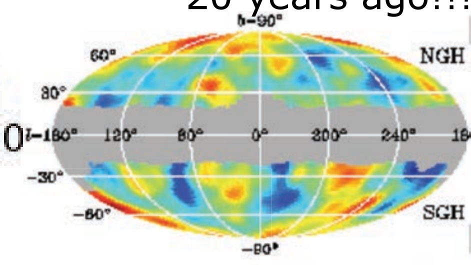


Polarization results in the CS and I&S 2015 papers
were presented for the spatially high-pass filtered maps

Legacy Product – nearly full sky Planck 2015 δT map



COBE-DMR
20 years ago!!!



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Simulations and methodology of statistical testing

- The Planck best-fit ΛCDM model is compared to the Planck CMB maps extracted from the four component separation methods.

- A companion set of realistic simulations (FFP8) has been produced and analyzed in the same way as the real data.

- The Planck best fit model is represented by these 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, …).

- In order to assess significance, we (generally) use the p-value, defined as the probability to obtain a value for a test statistic from a set of simulations as extreme as for the real data.

Statistical tests

There is no unique signature of non-Gaussianity. Therefore, a battery of statistical tests have been applied to the temperature data:

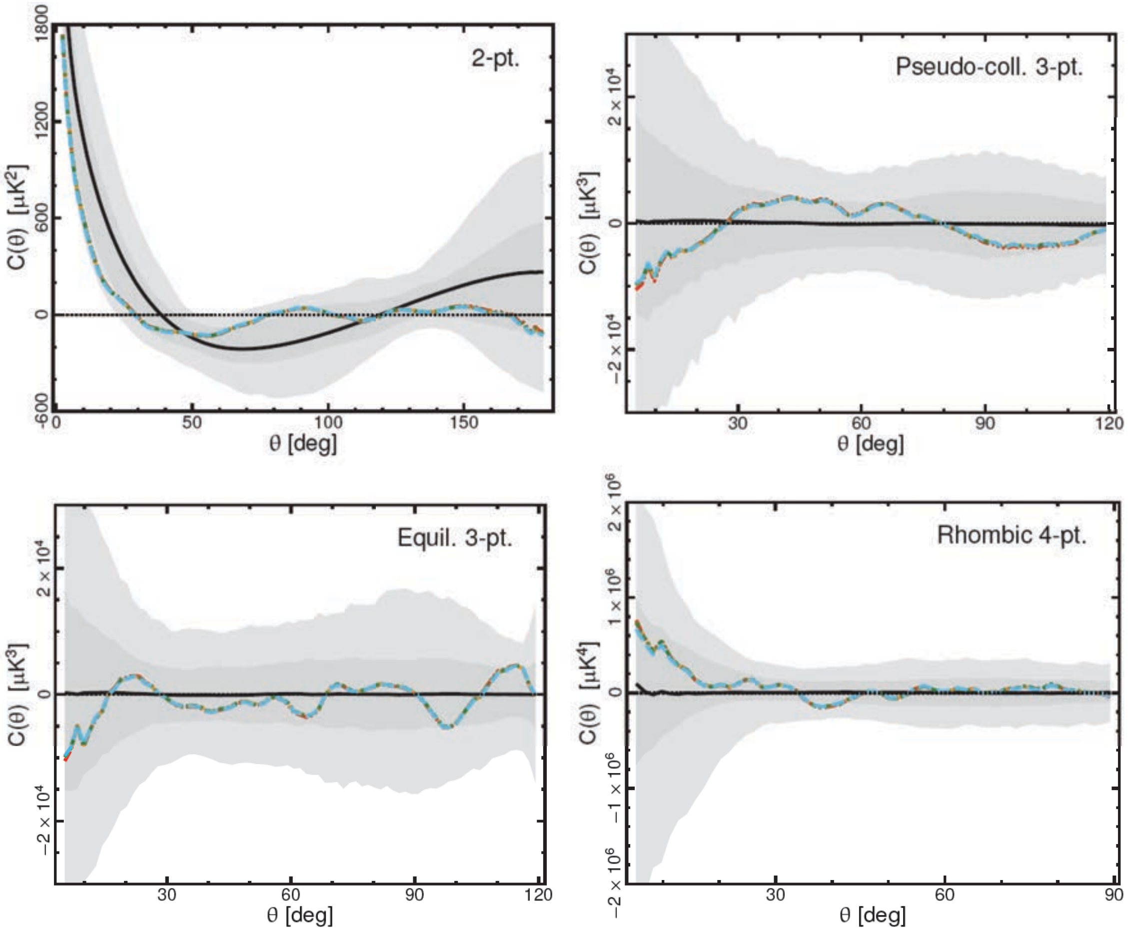
- Variance, skewness and kurtosis
- N-pdf at low resolution
- N-point correlation functions
- Minkowski functionals
- Multiscale analysis

These are 'descriptive' statistics. In the absence of a model, it can be hard to assign unambiguous significances ('Look-elsewhere effect' – more later).

For the polarization data, we perform a preliminary appraisal of the associated statistical properties using a Stacking technique.

N-point correlation functions

Comparison with the best fit ΛCDM model



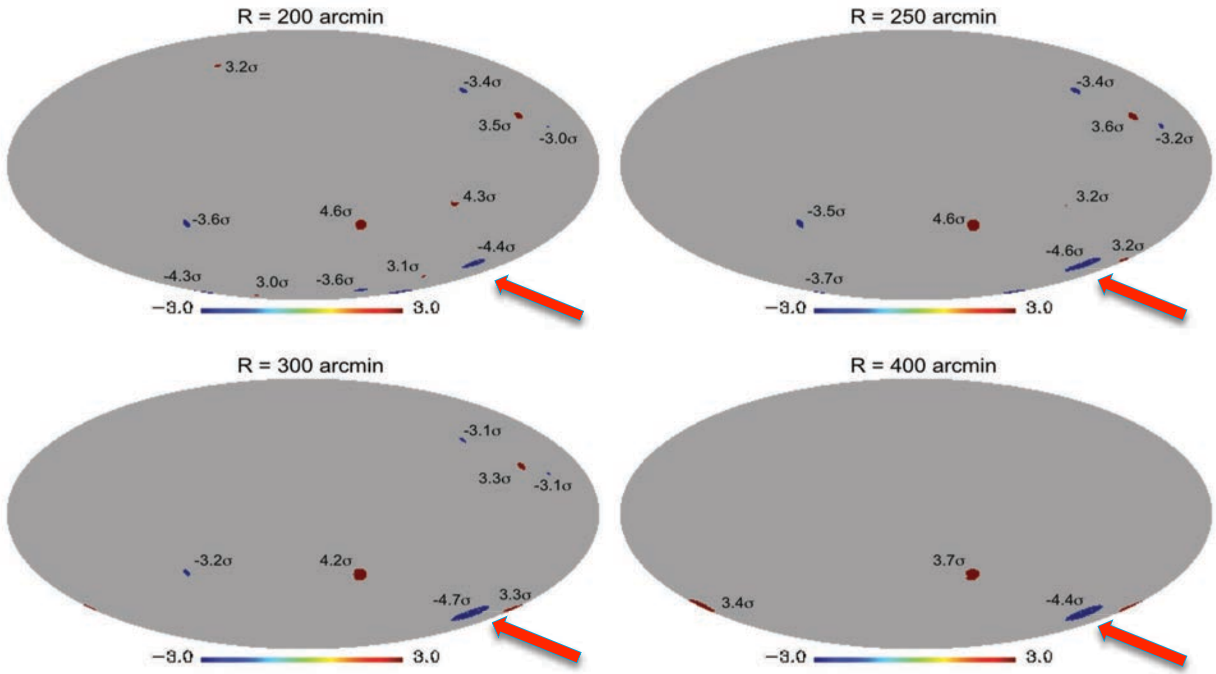
Function	Probability [%]			
	Comm.	NILC	SEVEM	SMICA
Two-pt.	97.2	98.9	97.4	98.1
Pseudo-coll. three-pt.	92.1	94.7	91.8	92.2
Equil. three-pt.	74.0	80.4	75.8	79.0
Four-pt.	64.6	70.9	65.6	65.9

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).

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

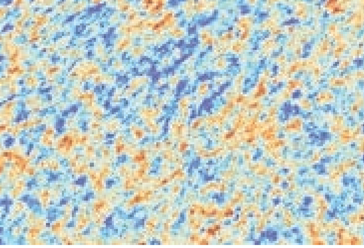
GAUSS/T-map		UTP			
Area	Scale [']	Comm.	NILC	SEVEM	SMICA
Cold	200	1.7	3.0	1.7	1.7
	250	1.2	2.0	1.2	1.2
	300	1.6	6.0	1.2	1.8
	400	N/A	N/A	N/A	N/A
Hot	200	2.9	6.0	2.8	2.6
	250	5.7	11.0	5.6	5.4
	300	N/A	N/A	N/A	N/A
	400	N/A	N/A	N/A	N/A

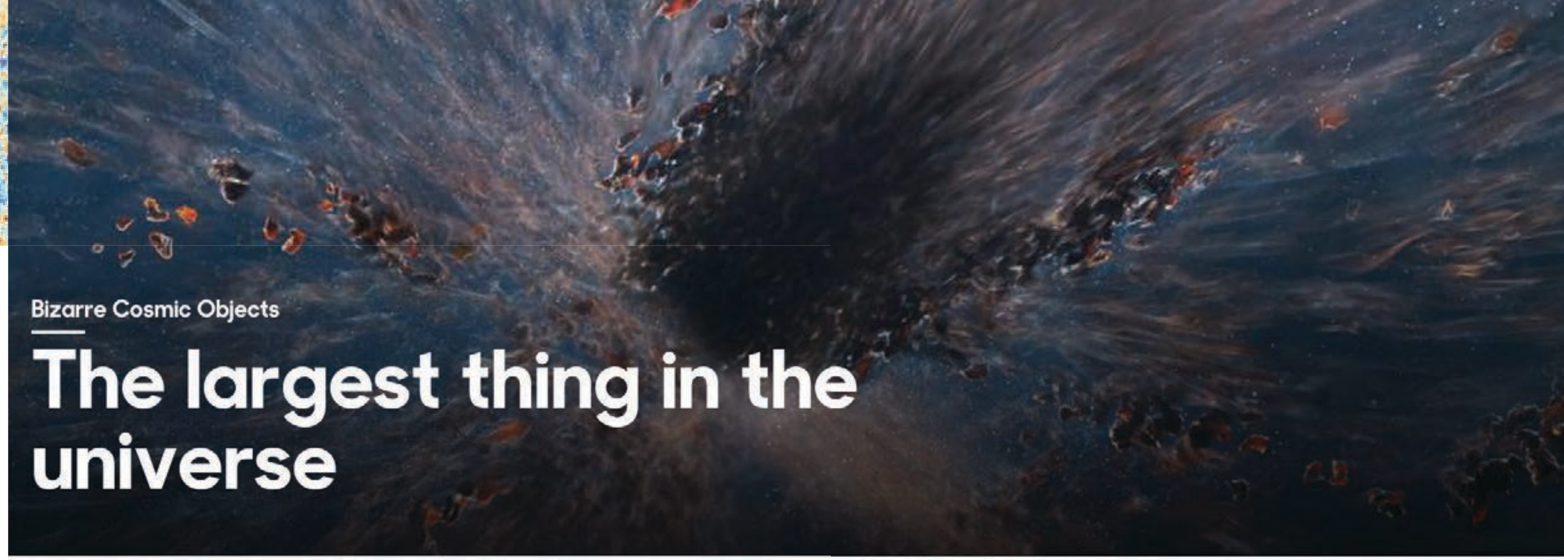
The area is dominated by the Cold spot and shows a significantly low probability, as do the kurtosis and peak statisitics.
The results are similar to the ones for the first release (Planck Collaboration XXIII 2014).

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.





Bizarre Cosmic Objects

The largest thing in the universe

In deep space lies a 'supervoid' that could be the biggest structure ever known

Presented by Marcus Woo

More than ten years ago, while taking the temperature of the universe, astronomers found something odd. They discovered that a patch of sky, spanning the width of 20 moons, was unusually cold.

The Cold Spot and the Supervoid

(Szapudi et al.)

But for now, the mystery of the cold spot continues. **"We just don't know the end of the story," Frenk says. "I don't think anybody knows."**
- BBC Science, June 23, 2015

Summary

- Tests of isotropy and Gaussianity provide the basis to support the assumptions made in the derivation of the power spectra and the cosmological parameters.

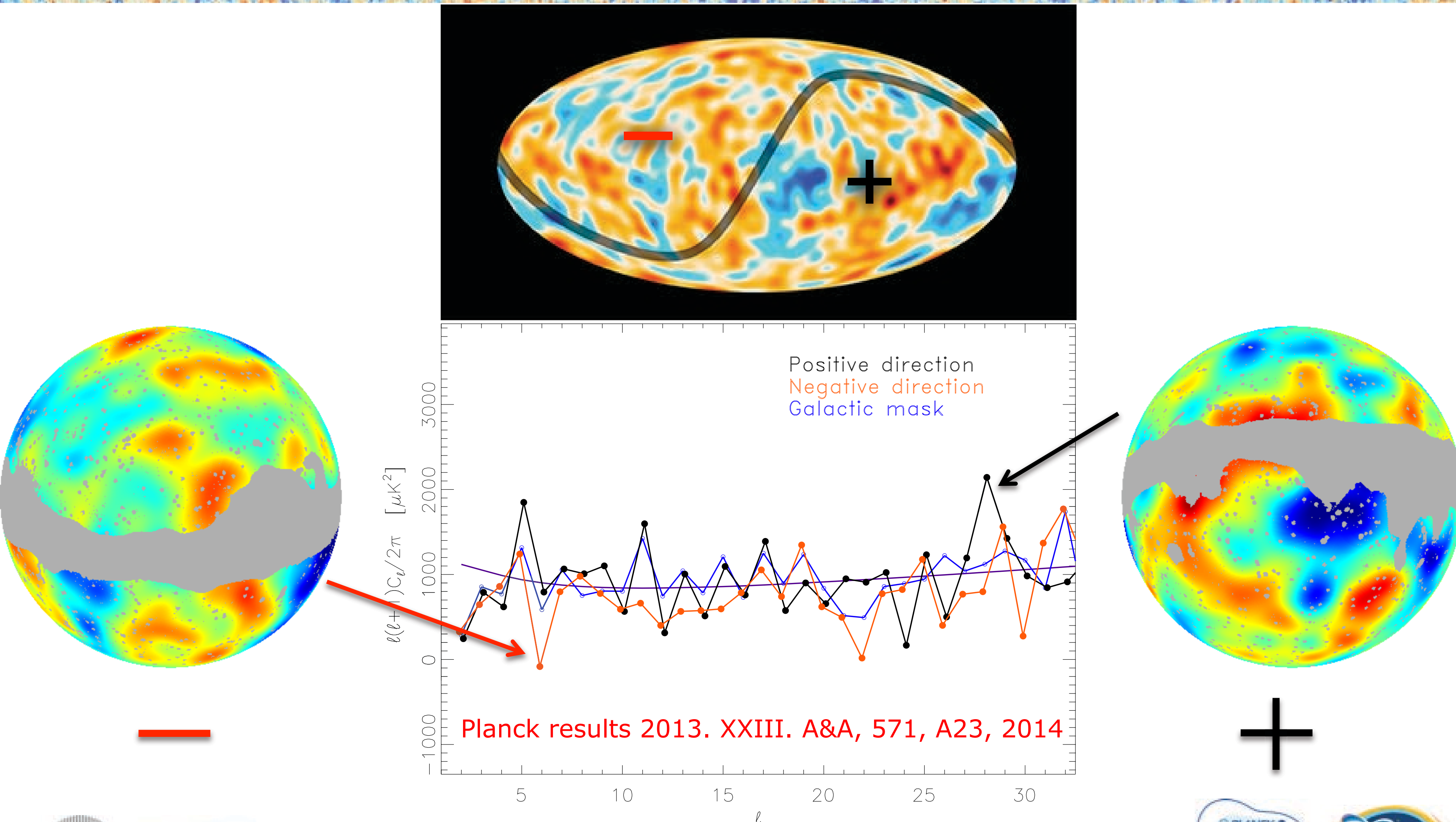
- In addition they also probe physics beyond the standard cosmological model.

- 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.

- 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.

Power asymmetry in *Planck* 2013 nominal mission data



Power asymmetries at large angular scales

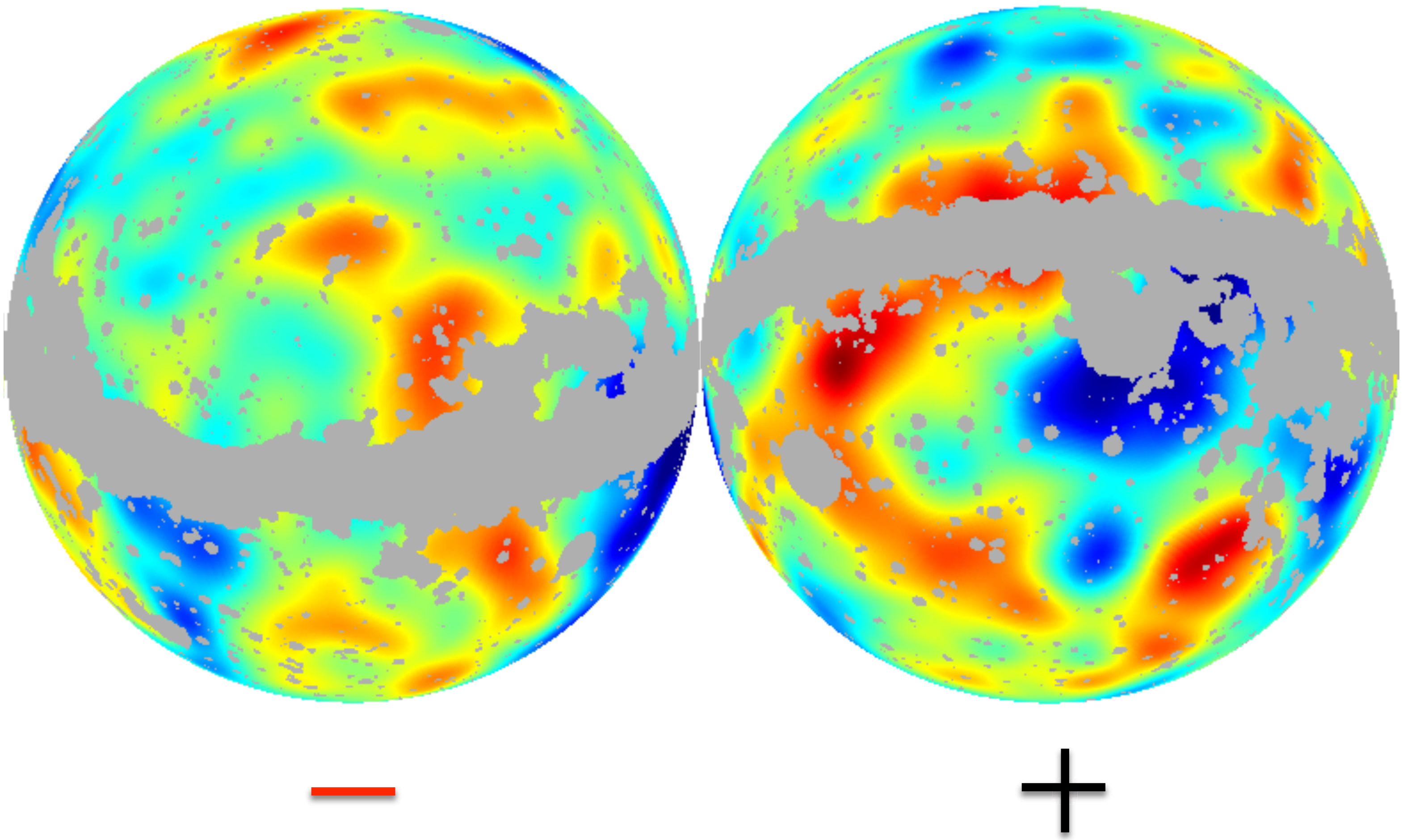
Intensity analysis showed significant differences between power on opposite hemispheres.

This effect is present in both WMAP and *Planck* 2013 data, and it has been the subject of more than 200 papers using independent approaches.

In short:

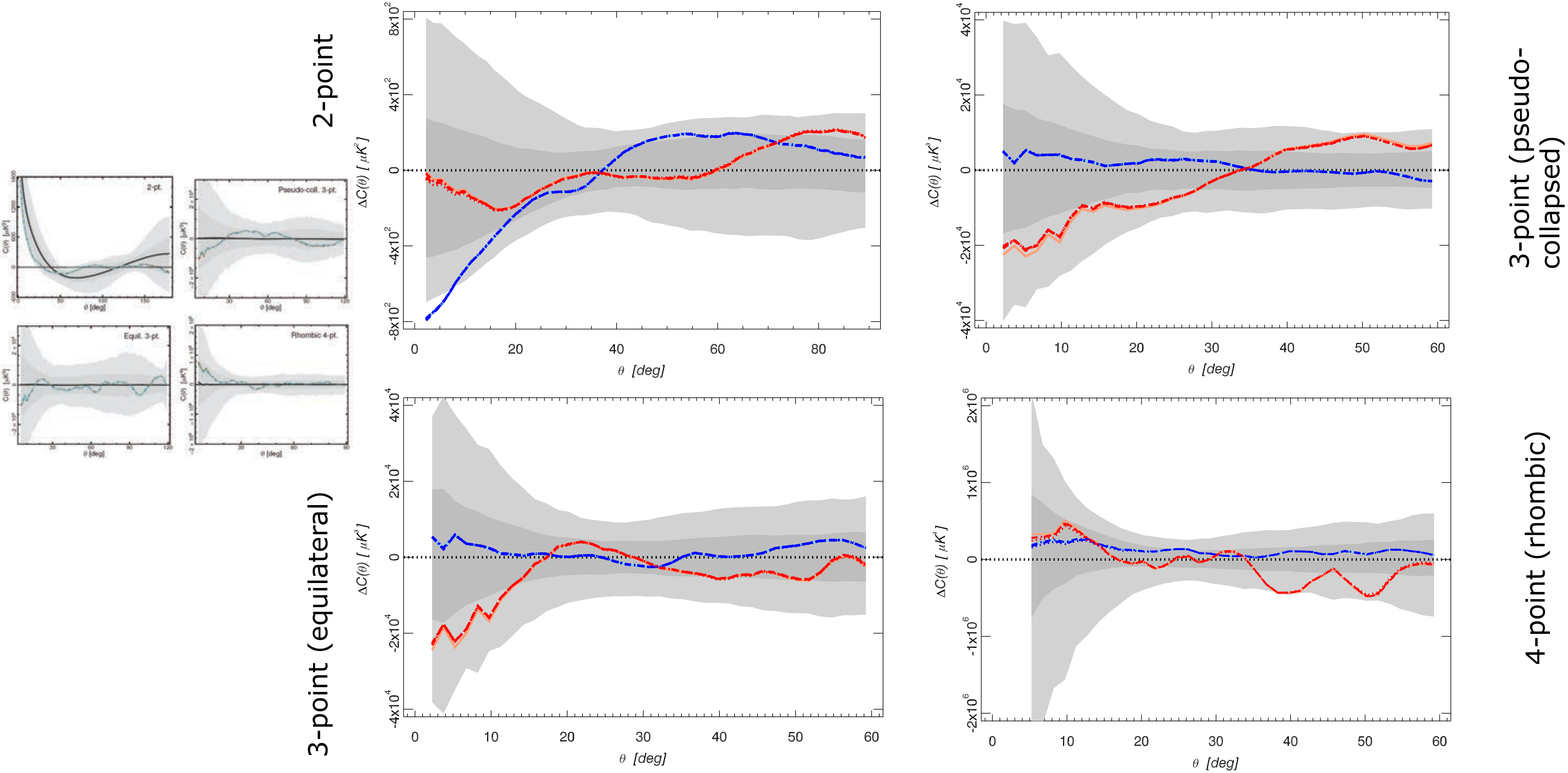
- Asymmetry clearly seen at large angular scales/low multipoles
- Amplitude of ~6%
- Direction of max *(l, b)*~(225°, -15°)
- The asymmetry axis is roughly near the Ecliptic plane, so some analyses have also focused on northern/southern Ecliptic hemispheres.

Power asymmetry in *Planck* 2015 full mission data



Features in 2015 full mission data are very similar to 2013 nominal mission data.

Hemispherical asymmetry

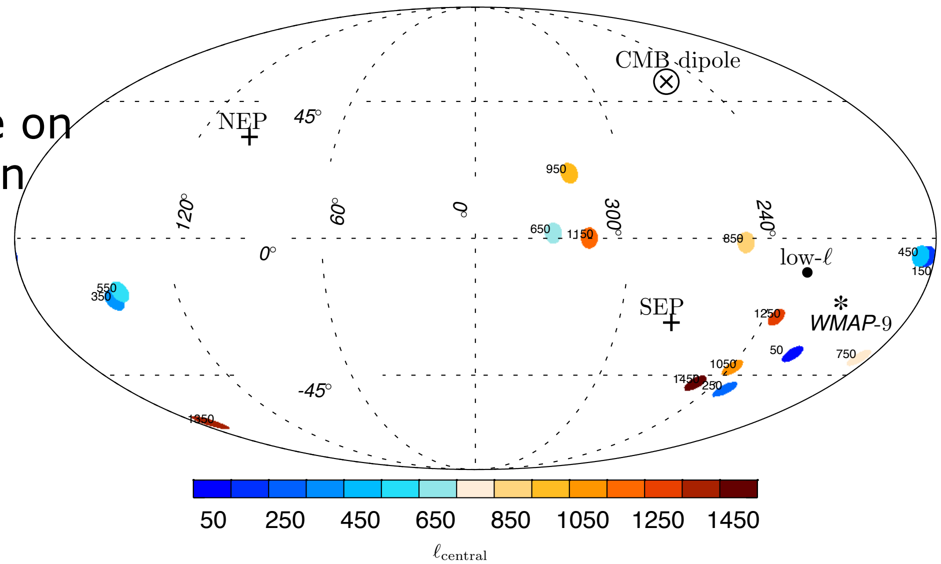


Remarkable asymmetry of power in ecliptic hemispheres!

Power Asymmetry

As a *model-independent* test of power asymmetry:

- estimate the power spectrum amplitude on 12 non-overlapping patches of the sky in ℓ–bins of 16 multipoles
- fit a dipole to the spatial distribution of power
- construct a measure of the alignment between these directions (Rayleigh statistic)
- compute the significance (p-value) by comparison to a suite of simulations.

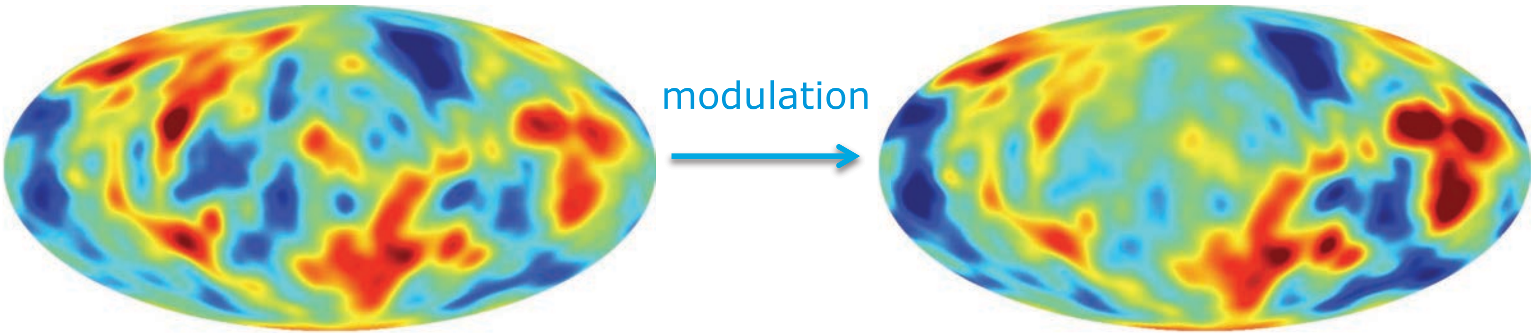


Evidence for the close correlation and alignment of directions on different angular scales presents a clear signature of power asymmetry, since in the standard model, these directions should all be independent random variables.

The advantage of this purely directional analysis is that it focuses on a central concept for tests of deviation from isotropy – whether there is a preferred direction.

Dipolar power modulation

This is a modulation of the sky signal by an ℓ=1 mode. It is equivalent to $\ell,\ell\pm1$ coupling.



There are several ways to look for this effect. Here, we present results for:

- Direct likelihood in pixel space
- Harmonic space estimators

It is important to use different estimators because they are sensitive to different potential systematic effects. Moreover, they can probe different region of the parameter space, thus reducing the impact of the "*a posteriori correction*".

Dipolar power modulation: likelihood approach

Signal in a given pixel is usually assumed as the sum of (isotropic) CMB signal s_{iso} convolved with the angular response of the instrument B plus instrumental noise n: $d=Bs_{iso}+n$

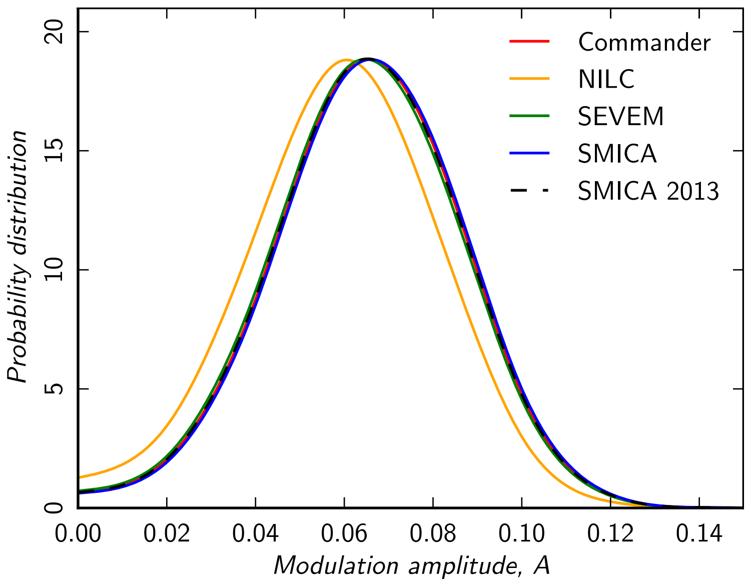
Dipolar power modulation is included by modifying the signal model as $d=BMs_{iso}+n$, where $M_{ij}=(1+\alpha\, \boldsymbol{p}\bullet\boldsymbol{n}_i)\delta_{ij}$ and α is the modulation amplitude.

The likelihood function in pixel space including α and $\boldsymbol{p}$ can be written as:

$$\mathcal{L}(\alpha,\hat{p},C_\ell) \propto \frac{e^{-\frac{1}{2}\mathbf{d}^t(\mathbf{BMSM}^t\mathbf{B}^t+\mathbf{N})^{-1}\mathbf{d}}}{\sqrt{|\mathbf{BMSM}^t\mathbf{B}^t+\mathbf{N}|}}$$

Using *Planck* 2014 data we found a ~3σ detection of α~6.5%.

This is consistent with 2013 findings, and is almost independent from the component separation method adopted.



Summary

- Dipolar power modulation:
  - $\sim 3\sigma$ detection of dipolar modulation with amplitude $\alpha \sim 6.3\%$ in the direction (l, b)~(225°, -20°)
  - Although the significance drops when accounting for the *a posteriori correction*, this feature if clearly of interest and should continue to promote investigations into theoretical models.

- Power asymmetry extends to higher *l.*

- Point-parity asymmetry at $\ell=[20,30]$ is confirmed at $>2\sigma$ significance as well as Mirror parity asymmetry.

- Bianchi VII_h models seem to reproduce features in the intensity map. However, when coupling with standard cosmological parameter estimation there is no evidence for Bianchi pattern.

What can polarization still add?

Polarization can provide valuable information, and a full analysis of *Planck* polarization maps is in progress.

It will be important to determine in more detail whether there are any peculiarities in the CMB polarization, and if so, whether they are related to existing features in the CMB temperature field.

The absence of any corresponding features in polarization might imply that the source of the temperature anomalies could be due to a secondary effect such as the integrated Sachs-Wolfe (ISW) effect, or alternative scenarios in which the anomalies arise from physical processes that do not correlate with the temperature, e.g., texture or defect models.

There also remains the possibility that anomalies may be found in the polarization data that are unrelated to existing features in the temperature measurements.

Important discriminator for Data-driven models (e.g. Dipole Modulation).

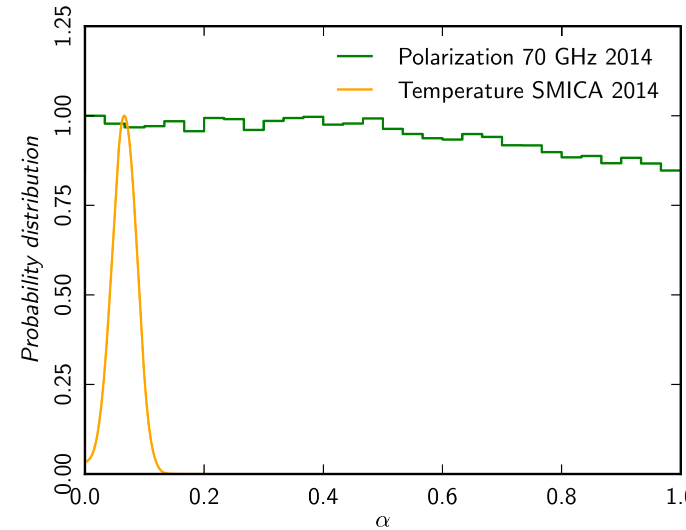
Some studies of large scale CMB polarization were performed using the high-pass filtered maps.
BUT:
"Due to an internal mixup, however, the unfiltered polarized sky maps ended up in PLA instead of the high-pass-filtered ones. This was discovered in July 2015, and the high-pass filtered maps at 100, 143, and 217 GHz were added to the PLA. **The unfiltered maps have been left in place to avoid confusion, but warnings about their unsuitability for science have been added.**"

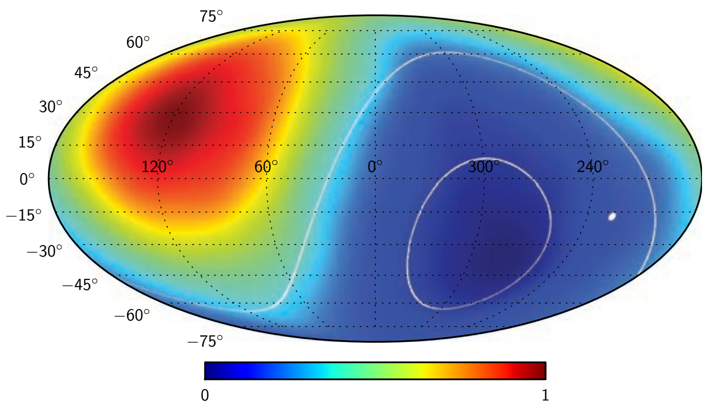
Dipolar power modulation: likelihood approach in polarization

We apply the same procedure on the polarization data included in the *Planck* likelihood, which is based on the *Planck* 70GHz channel cleaned using *Planck* 30 and 353GHz maps as synchrotron and dust templates.

Polarization doesn't show hints for dipolar modulation. However, S/N is much lower than for intensity, and only 47% of the sky is used.

At the same time, foreground residuals would show up as a power asymmetry towards the Galactic center. We see no evidence for this when looking at the constraints on the dipole modulation direction, confirming that foreground residuals are well below the noise.





2016

Expectation of delivery of significantly improved raw, and component separated polarization maps.

Completion of the I&S analysis of these maps.

Hope to reach then the definitive legacy status of both the temperature and polarization data from Planck, and improve our understanding of whether

the CMB anomaly story was ephemeral, or

that it is indeed just "the end of the beginning…"*

* verte

* From M. Kamionkowski's review talk at CMB@50 in Princeton, June 2015

(as he was musing on the standing and prospects for gaining improved understanding of the early universe in the context of Single Field Slow-Roll inflationary models …)

With or without B modes, many unanswered questions!!

1. What set the initial conditions for SFSR?
2. What is the identity of the inflaton?
3. How did the inflaton homogeneity required to begin inflation come about?
4. How does the flatness of the potential required for inflation arise?
5. Is there a completely different paradigm to explain measurements?

Closing

- SFSR inflation provides simple mathematical model for a_{lm}s
- B modes are obvious next test for paradigm
- Scenario leaves many unanswered questions
- No single "obvious" beyond-SFSR model
  - Must therefore leave no stone unturned
- Must be vigilant in exploring/entertaining alternative models for a_{lm}s

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.