Large-scale anomalies with *Planck*

Gianluca Polenta

ASI Science Data Center

on behalf of the Planck Collaboration

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.

Here, the current status of some of the CMB anomalies at large angular scales is presented in the light of *Planck* 2014 full mission data. Two other anomalies, the low variance and the cold spot, will be discussed in the next talk by E. Martinez Gonzalez.

Dataset and methodology

Results shown in this talk have been produced using *Planck* 2014 full mission intensity data. The analysis of polarization is in progress.

Frequency maps have been processed by 4 different component separation methods to obtain 4 CMB maps, in order to test the robustness of results wrt 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.

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

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

Power asymmetries at large angular scales

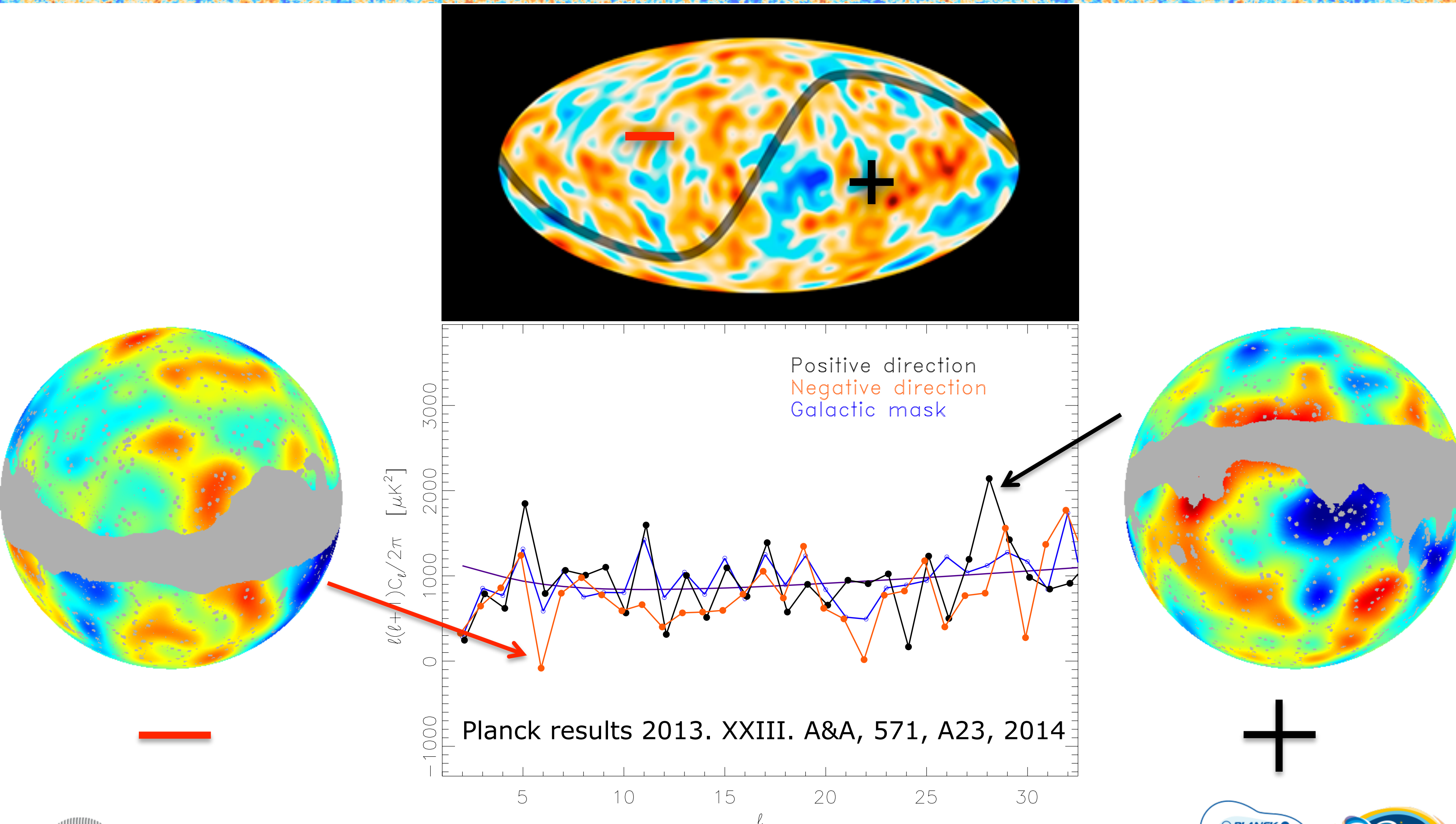
Intensity analysis showed significant differences between power on opposite hemispheres.

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.

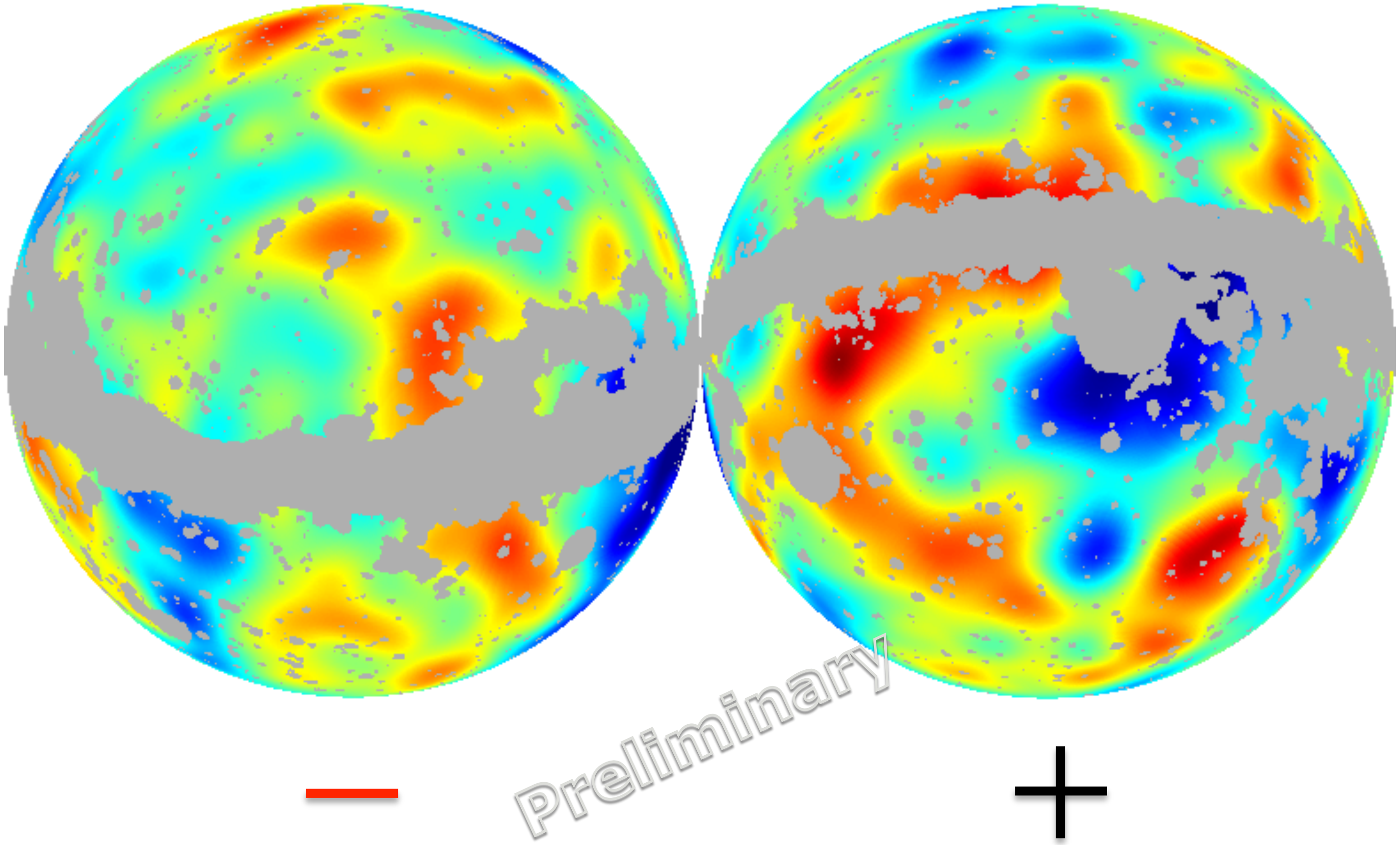
In short:

- Asymmetry clearly seen at large angular scales/low mulipoles
- 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* 2013 nominal mission data



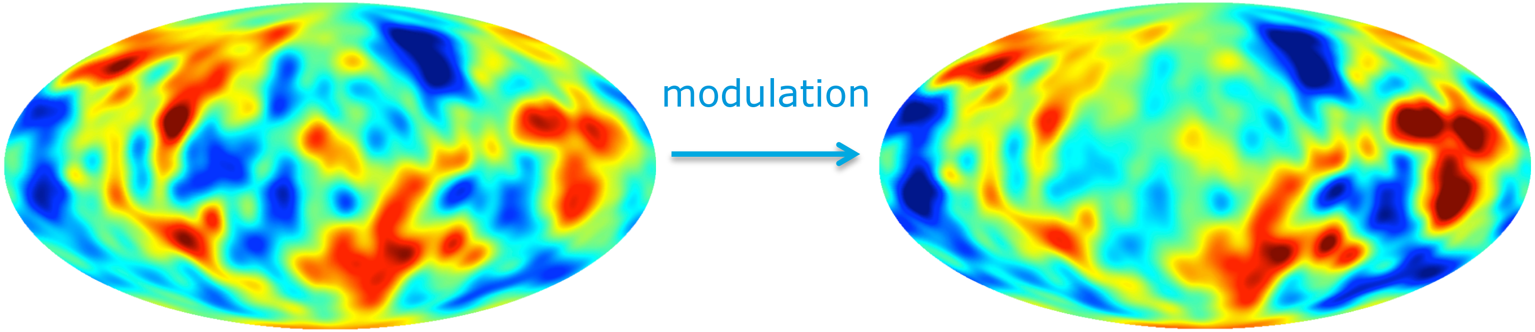
Power asymmetry in *Planck* 2014 full mission data



Features on 2014 full mission data are very similar to 2013 nominal mission data.

Dipolar power modulation

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



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

- Direct likelihood in pixel space
- Variance distribution 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: $d=Bs_{iso}+n$

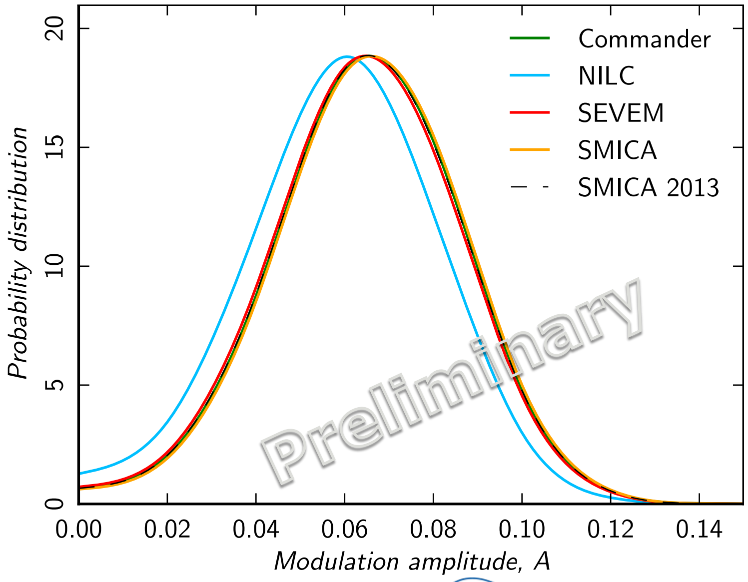
Dipolar power modulation is included by modifying the signal model as $d=BMs_{iso}+n$, where $M_{ij}=(1+\alpha\,\boldsymbol{p}\bullet\boldsymbol{n}_i)\delta_{ij}$ and α is the modulation amplitude.

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.

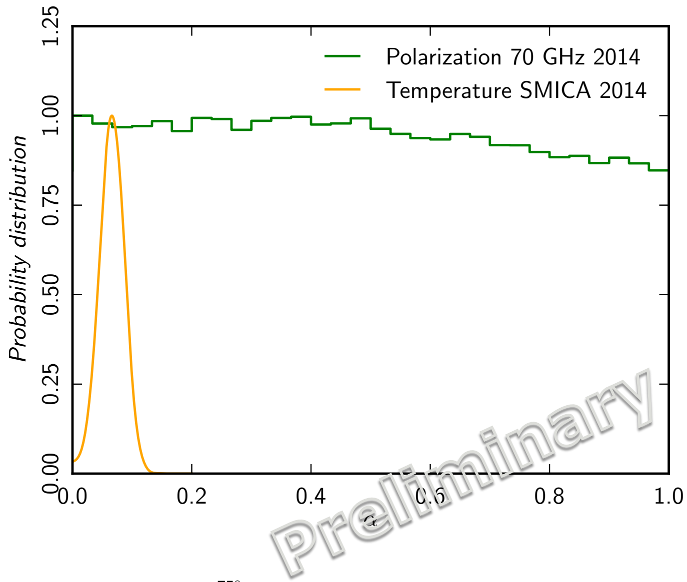


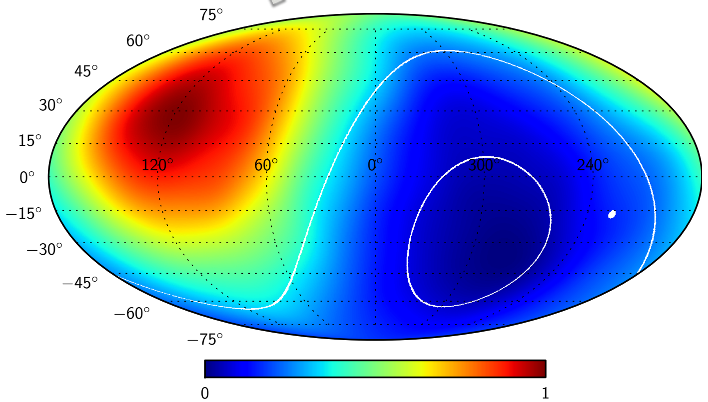
Dipolar power modulation: likelihood approach in polarization

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.



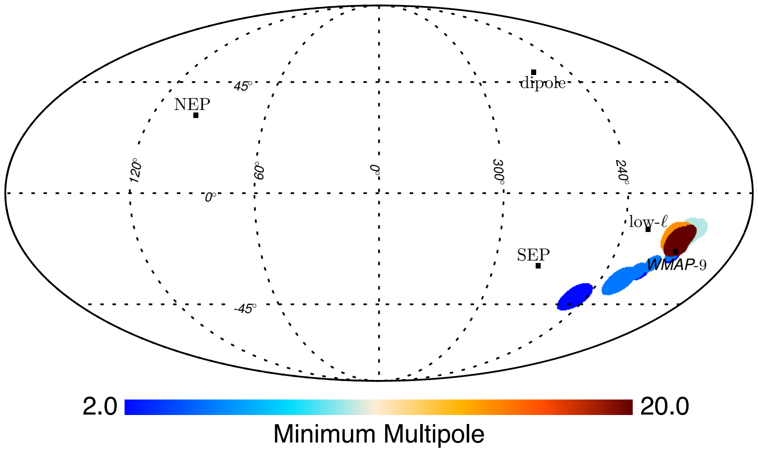


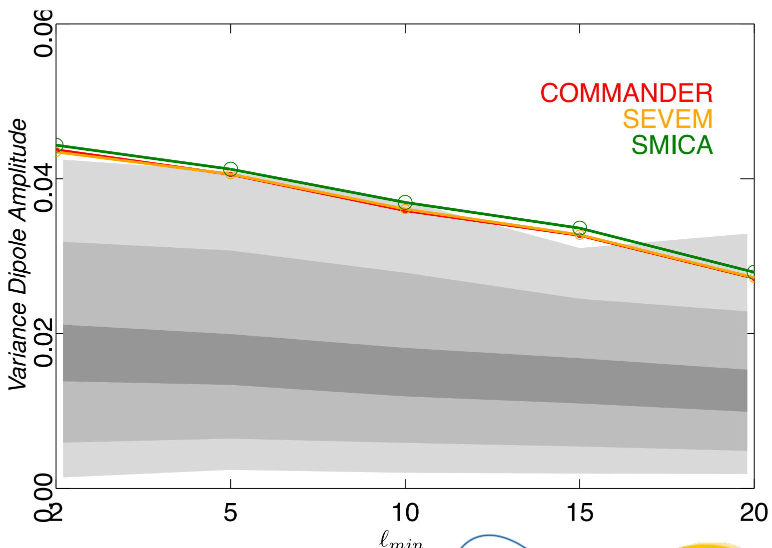
Variance asymmetry in pixel space

We use the local variance method described in Akrami et al 2014 to estimate a dipole component in the distribution of the power in the map.

Results obtained using *Planck* 2014 full mission data show evidence for a significant asymmetry in the variance distributions.

Direction and amplitude (~4%) are both close to the low-ℓ power asymmetry. This is an important consistency test as the two methods are basically probing the same range of angular scales in two different bases.

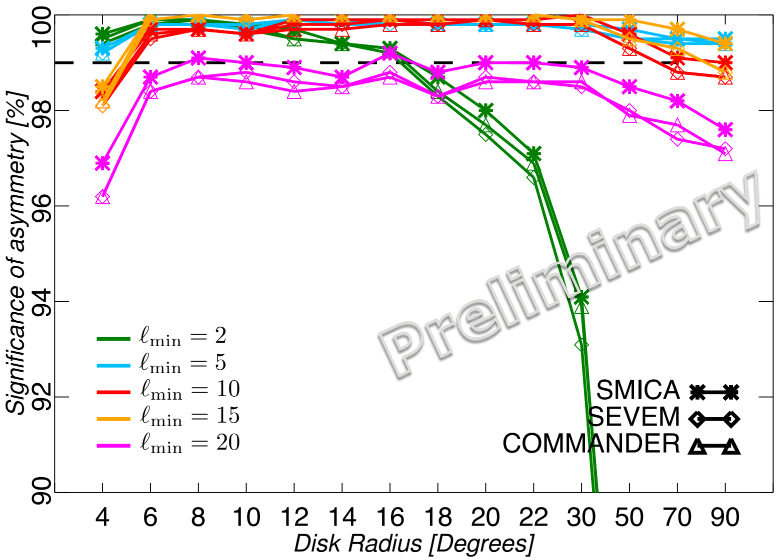




Variance asymmetry in pixel space

The significance of the detection drops at small disc radius as only a few pixels are used for each disc and the variance estimates are too noisy.

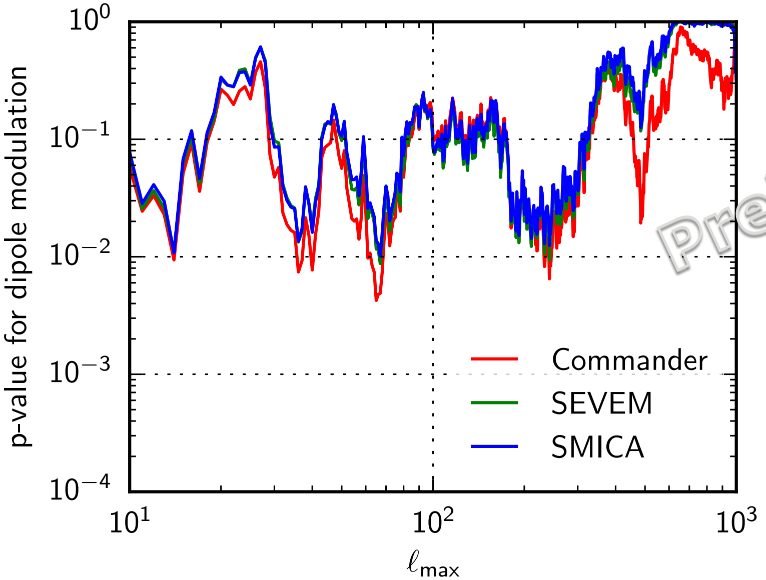
For large disc radius we probe the very large angular scales, i.e. the ones that are more affected by cosmic variance, thus reducing the significance of the detection (Fantaye 2014).

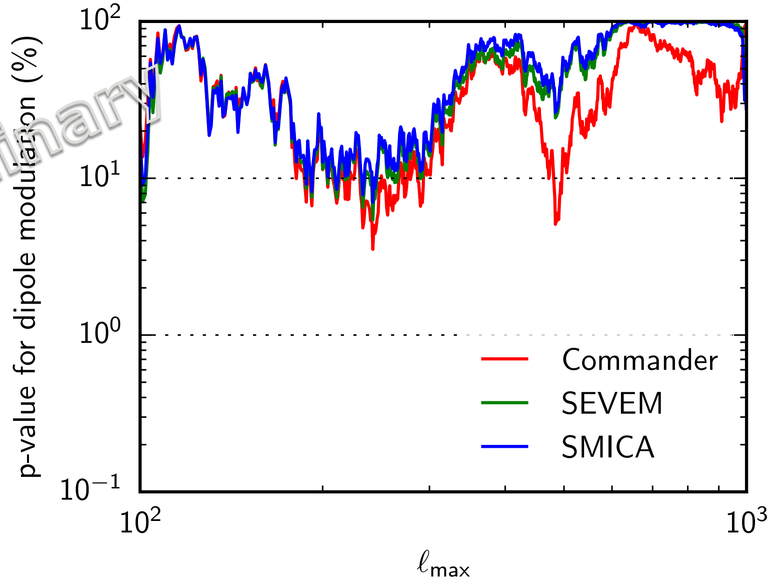


Hence, we apply a 4th order high-pass filter in harmonic space to study the dependence of the significance as a function of ℓ_{min}.

Filtering these modes clearly stabilizes the significance of the asymmetry. However, at the same time it also reduces the amount of signal, leading to a reduction of the amplitude that eventually reduces the significance for ℓ_{min}=20.

Dipolar power modulation: harmonic analysis





We use the harmonic QML estimator introduced in Moss et al 2011 (see also The Planck Collaboration, 2014, 571:A17-A27) to *Planck* intensity maps.

For ℓ_{min}=2 we found a ~3σ dipole modulation at ℓ_{max}~65 with a ~6.3% amplitude.

There is also evidence for modulations at ℓ_{max}~40, and ℓ_{max}~240.

However, the latter becomes much less significant when adopting ℓ_{min}=100, i.e. removing large angular scales.

Dipolar power modulation: harmonic analysis

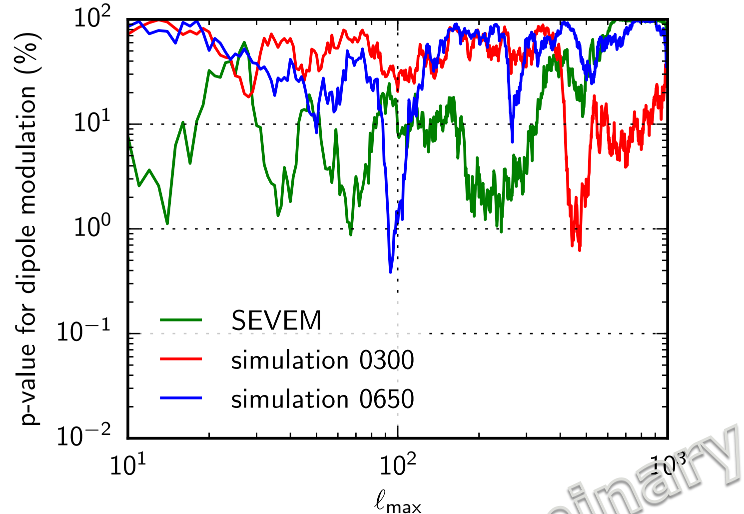
When analyzing (isotropic) simulations we found even more significant modulations, depending on the choice of ℓ_{max}.

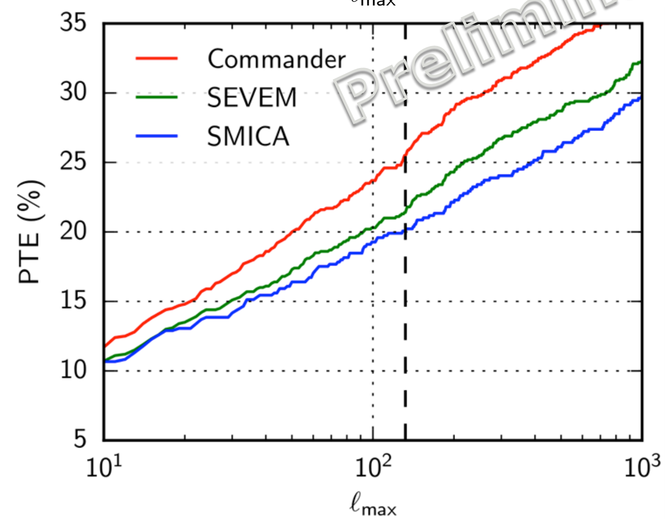
However, there is no *a priori* reason to adopt ℓ_{max}~65, and there is only the *a posteriori* observation that ℓ_{max}~65 provides the most significant detection.

Hence, we use simulations to derive the probability of finding a modulation as significant as in the *Planck* data as a function of ℓ_{max}.

This is known as *multiplicity of tests*, *a posteriori correction*, or *look-elsewhere effect*.

Accounting for this reduces the significance of the modulation to PTE~15-20% at ℓ_{max}~65.





Point-parity asymmetry

The CMB sky map is the sum of even and odd parity functions. A preference for more power in odd multipoles at large angular scales was observed in the *Planck* 2013 data. Similar results were found using WMAP data.

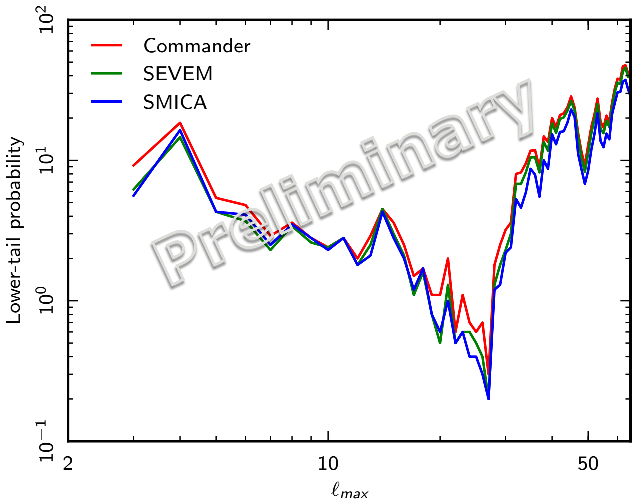
For the analysis of *Planck* 2014 data we define:

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

where power spectra are computed using a QML estimator (BolPol, Gruppuso et al 2011) on real data and simulations.

Results from *Planck* 2014 data show a clear detection of an odd point-parity preference, with a lower-tail probability of ~0.5% at ℓ_{max}=28 as derived from simulations.

However, *a posteriori correction* is not included.



Mirror-parity asymmetry

Last year we studied the properties of the *Planck* 2013 low-resolution map under reflection with respect to a plane. The results showed anomalous behavior with a anti-symmetry direction (*l*, *b*)=(264°, -17°).

For 2014 analysis we use again the S^+ (S^-) estimators defined in Finelli et al 2012

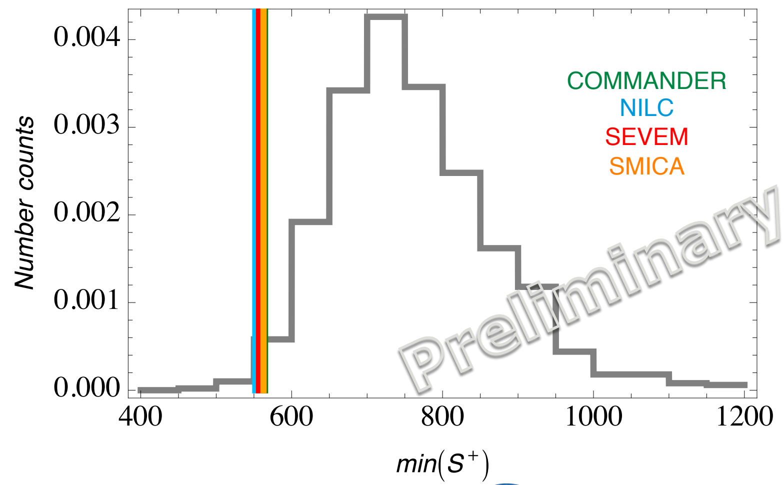
$$S^{\pm}(\mathbf{n_i}) = \frac{1}{N_{pix}} \sum_{j=1}^{N_{pix}} \left[\frac{1}{2} \left(\frac{\delta T}{T}(\mathbf{n_j}) \pm \frac{\delta T}{T}(\mathbf{n_k}) \right) \right]^2$$

where n_k is the reflection of n_j with respect to the plane defined by n_i.

Results from *Planck* 2014 data confirm the anomaly for S^+ in almost the same direction and significance as in 2013 analysis: (*l*, *b*)=(264°, -15°) - PTE=99.3%.

Here, simulations are analyzed varying n_i for all possible directions as an attempt to account for the *a posteriori correction*.

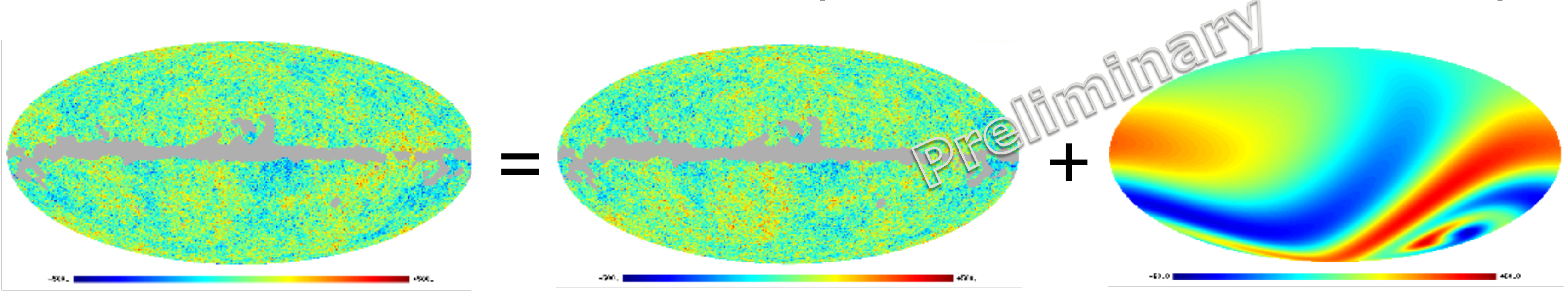
Two different map resolutions and smoothing have also been used.



The geometry of the Universe: Bianchi models

Homogeneous but anisotropic Bianchi cosmologies.

Large-scale ***intensity*** pattern of the CMB has a similar morphology to models in the Bianchi VII_h class (with linked shear and rotation).



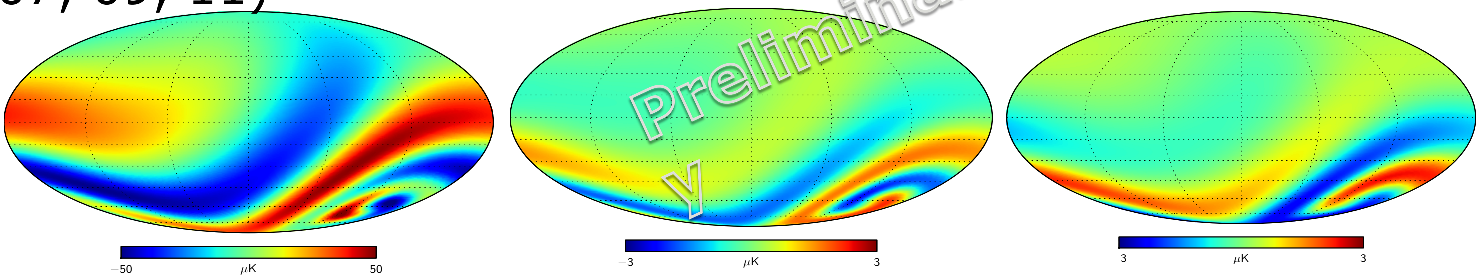
The parameters needed to match the template differ significantly from the standard cosmology — phenomenology, not physics (e.g., $\Omega_m=0.3\pm0.1$; $\Omega_\Lambda=0.3\pm0.2$).

Full Bayesian calculation (a la McEwen et al 2013): if we link Bianchi and cosmological parameters (as we should!) no evidence for Bianchi pattern, even in intensity: $(\omega/H)_0<7.6\times10^{-10}$ at 95%

Bianchi in polarization

How do we account for the strong similarity to the Bianchi pattern? Does it remain in polarization?

Models generically predict similar patterns in E and B (Pontzen et al, 2007, 09, 11)



Best-fit Bianchi intensity map	Corresponding *E*-mode map	Corresponding *B*-mode map

Intensity map remains a good fit, although it is pointing close to the cold spot.

For this model, the best-fit amplitude of the polarisation map is

$$A = -0.10 \pm 0.04$$

(cf. $A=1$ if the model is right)

Discussion and Conclusions

We searched for large scale anomalies in the *Planck* 2014 full mission data.

- Dipolar power modulation:
    - ~3σ detection of dipolar modulation with amplitude α~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.
- Point-parity asymmetry at ℓ=[20,30] is confirmed at >2σ significance as well as Mirror parity asymmetry. inclusion of *a posteriori correction* is in progress.

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

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. Polarization also strongly disfavours these models.

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.

esa

planck

cnes

agenzia spaziale italiana

NASA

cnrs

DTU Space National Space Institute

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Science & Technology Facilities Council

CSIC

National Research Council of Italy

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO ISTITUTO NAZIONALE DI ASTROFISICA ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA