CMB anomalies

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ASI/COSMOS meeting
Area della Ricerca di Bologna - 20 Jan 2017

Outline

- instant review of the CMB anomalies.
- focus on the lack of power. What are the features that make this anomaly important?
- what to do in the near future in this field.

Introduction

- what is a CMB anomaly?

- It is a feature of the temperature (pol in future) CMB anisotropy pattern which is “far” from what expected in the standard ΛCDM scenario. Of course the evaluation of the distance between what observed and what expected is crucial. This has to be done avoiding “a-posteriori” estimators which would artificially tend to increase the statistical significance of the considered anomaly.

Instant review

- **power anomalies**:
  - ★lack of power at large angular scales: lack of correlation in the two-point correlation function of CMB anisotropies/low variance (they might hint to pre-inflationary era). All these are related one another.
  - ★even-odd asymmetry
- **directional anomalies**: Typically (not always) they test the cosmological principle (CP). The assumption that we are not occupying a special place in the universe make the testing of the CP a test of isotropy.
  - ★preferred directions:
    - ✦hemispherical asymmetry
    - ✦mirror symmetry (non-trivial topology, NB: flatness does not imply R^3)
  - ★relative directions (alignments). Quadrupole-Octupole alignment.
- **local anomalies**: based on local pattern features
  - ★cold spot (local deviation in the kurtosis in wavelet domain)

What observed now in WMAP or Planck data are signatures at the level of 2.5/3σ CL.

Lack of power

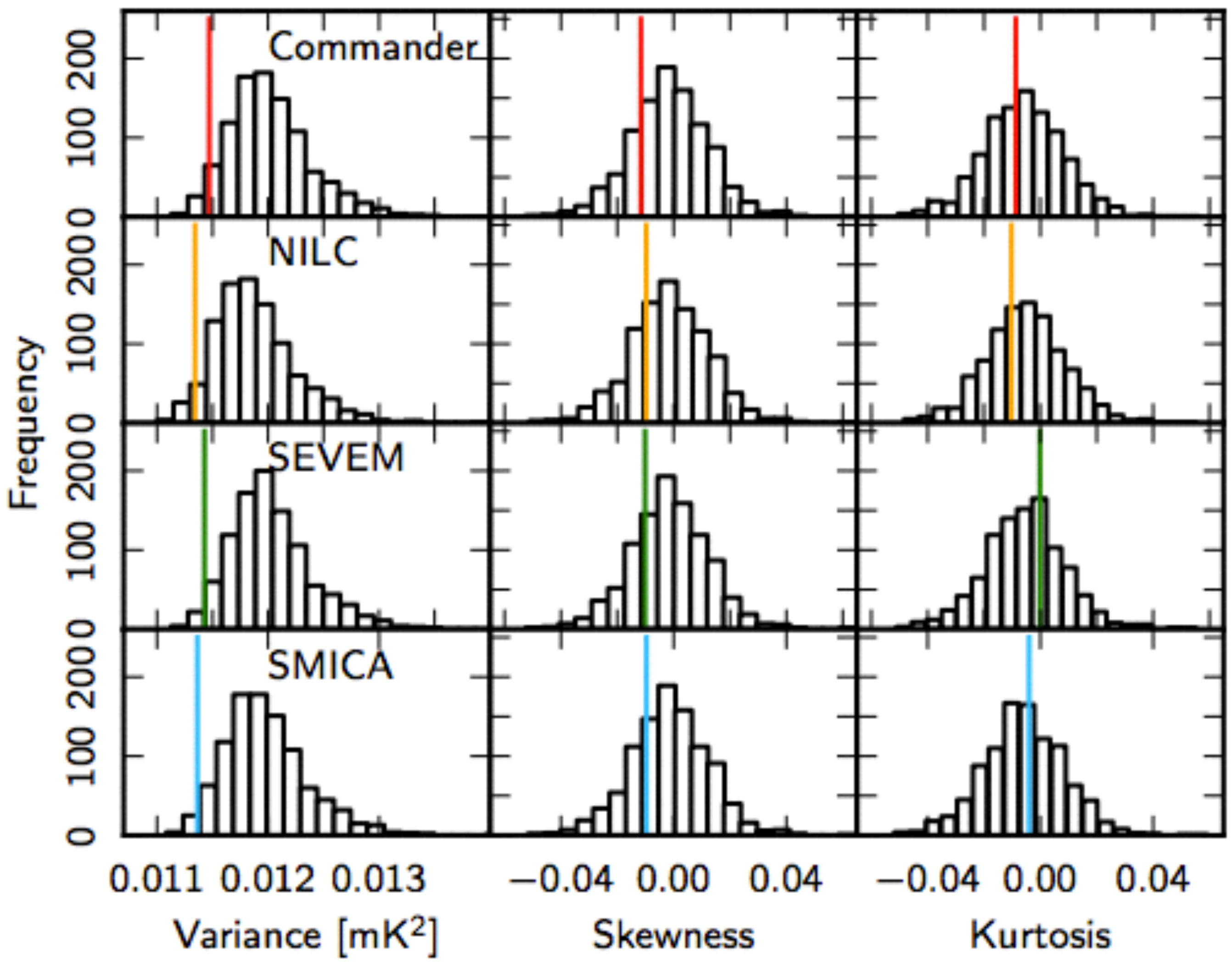


Fig. 1. Variance, skewness, and kurtosis for the four different component-separation methods – Commander (red), NILC (orange), SEVEM (green), and SMICA (blue) – compared to the distributions derived from 1000 Monte Carlo simulations.

Summary from Planck 2015 (Isotropy and Statistics paper)

nside=2048, fsky ~ 78%

lower-tail probabilities 3-1.5% (variance)

variance in pixel space

Lack of power

Table 12. Lower-tail probability for the variance, skewness, and kurtosis of the low resolution $N_{\rm side} = 16$ component-separated maps obtained with the common mask and two extended versions thereof.

Method	Probability [%] Variance	Skewness	Kurtosis
Common mask ($f_{\rm sky} = 58\%$)			
Commander	0.5	14.6	88.4
NILC	0.5	16.9	87.1
SEVEM	0.5	17.2	84.8
SMICA	0.5	16.6	82.7
$f_{\rm sky} = 48\%$			
Commander	0.1	29.4	65.0
NILC	0.1	29.6	60.8
SEVEM	0.1	29.4	62.4
SMICA	0.1	29.4	57.3
$f_{\rm sky} = 40\%$			
Commander	0.4	35.2	32.4
NILC	0.4	34.4	28.7
SEVEM	0.4	34.3	30.2
SMICA	0.4	33.8	25.5

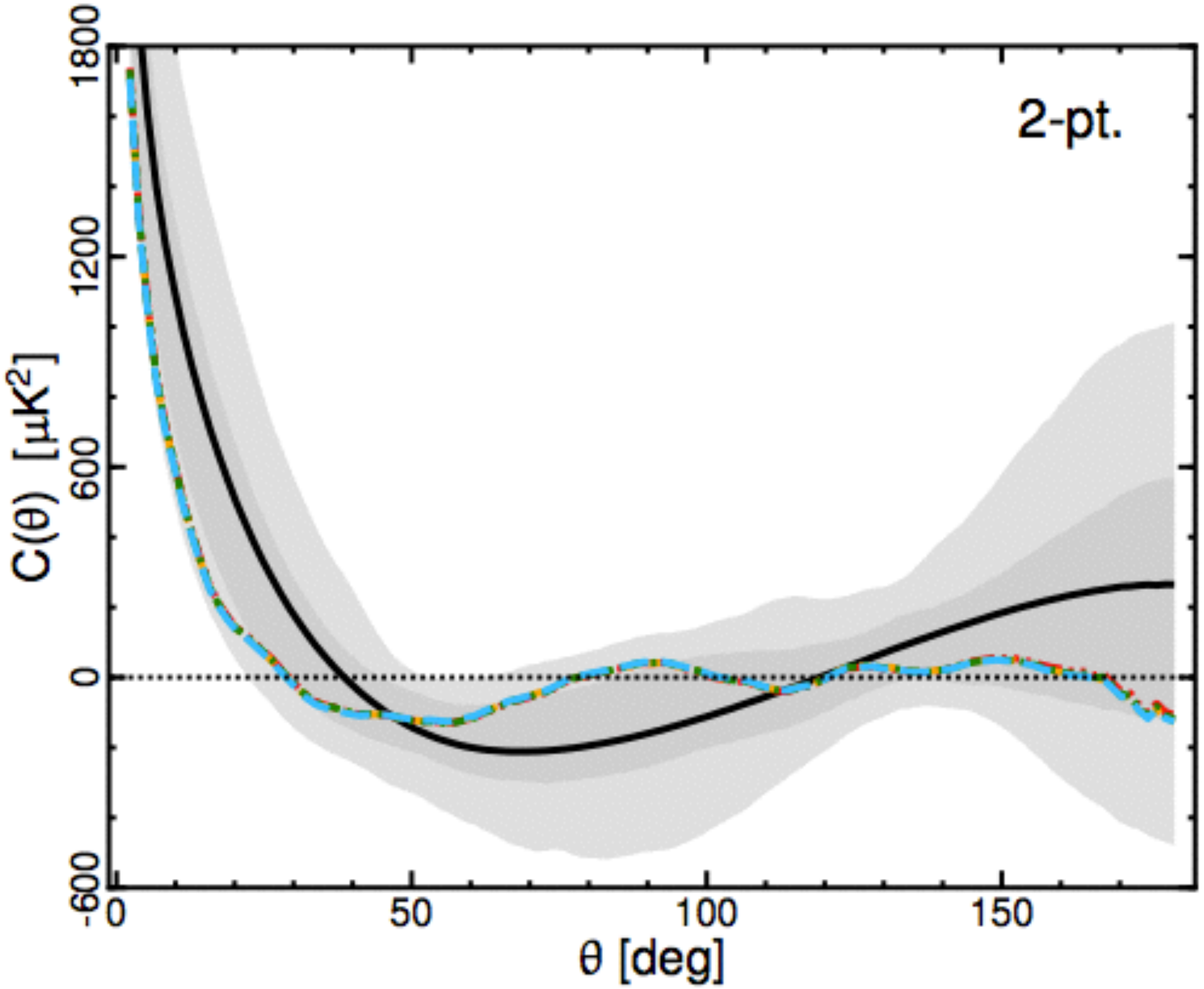
Summary from Planck 2015 (Isotropy and Statistics paper)

nside=16,
fsky ~ 58-40%

lower-tail probabilities 0.5-0.1% (variance)

variance in pixel space

Lack of power



Summary from Planck 2015 (Isotropy and Statistics paper)

lack of power can be seen as lack of correlation

nside=64,
fsky ~ 67%

2-pt corr. function in pixel space

Lack of power

$$S(x) = \int_{-1}^{x} \left[\hat{C}_2(\theta)\right]^2 \mathrm{d}(\cos\theta) ,$$

Table 13. Probabilities of obtaining values for the $S_{1/2}$ and χ_0^2 statistics for the *Planck* fiducial ΛCDM model at least as large as the observed values of the statistic for the *Planck* 2015 temperature CMB maps with resolution parameter $N_{\mathrm{side}} = 64$, estimated using the `Commander`, `NILC`, `SEVEM`, and `SMICA` maps.

Statistic	Probability [%]			
	`Comm.`	`NILC`	`SEVEM`	`SMICA`
$S_{1/2}$	99.5	99.6	99.5	99.6
$S(x)$ (global)	97.7	97.8	97.8	97.9
$\chi_0^2(\theta > 60°)$	98.1	98.8	98.1	98.4

Notes. We show also the corresponding estimation of the global p-value for the $S(x)$ statistic.

Summary from Planck 2015 (Isotropy and Statistics paper)

lack of power can be seen as lack of correlation

nside=64,
fsky ~ 67%

2-pt corr. function in pixel space

Lack of power

At large angular scale of the temperature CMB pattern shows less power wrt what expected (~2.5-3σ CL).

Of course this might be a **statistical fluke**. However it is very unlikely that it is due to artifacts/spurious effects:

- It is not natural to ascribe this effect to **foreground emissions** not fully removed: Galactic and cosmological emissions are expected to be uncorrelated. Therefore any residuals should *increase* rather than reduce the power. (note: I am not saying that there are no residuals. I am saying that residuals should push in the opposite direction wrt what observed)

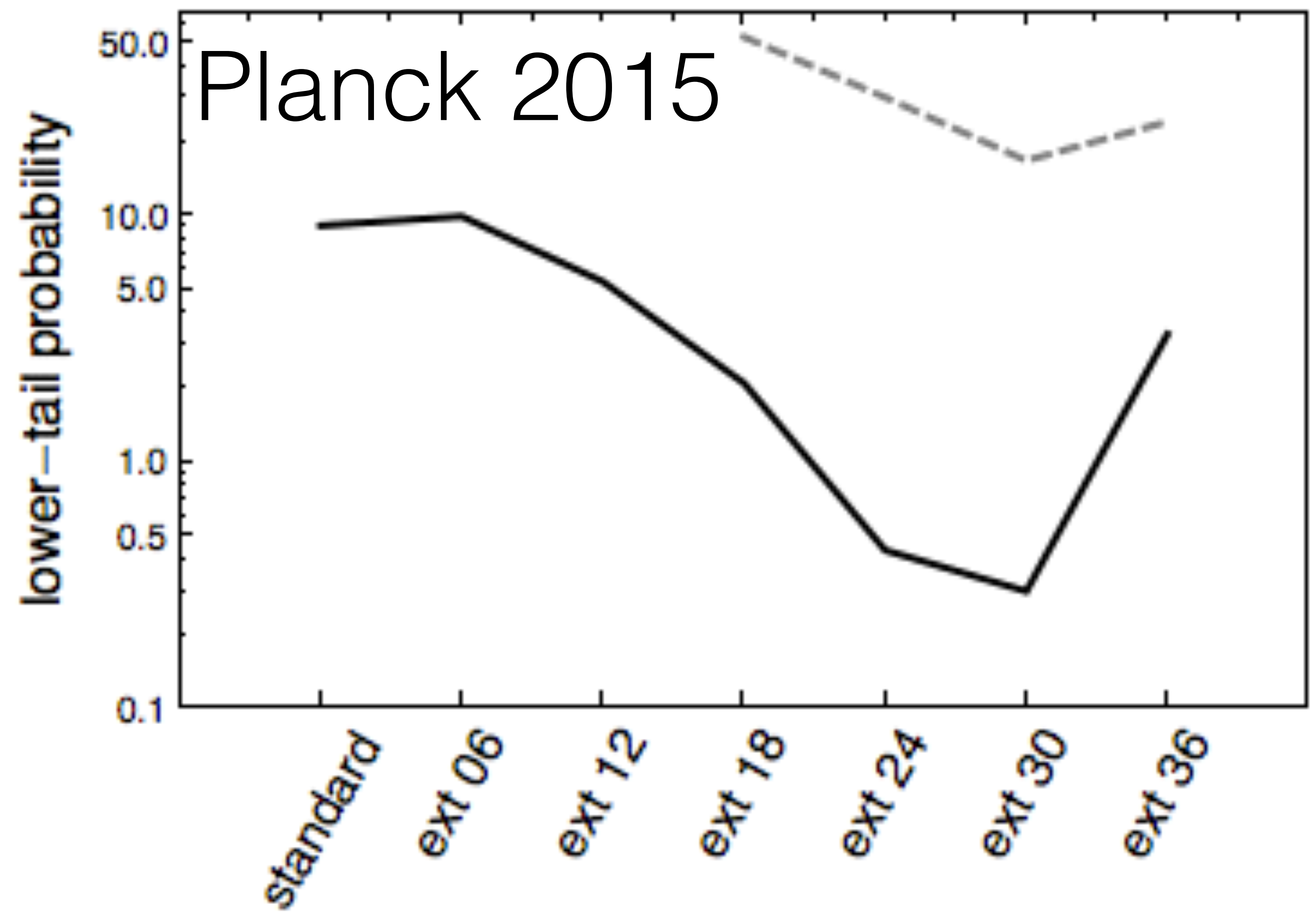
- It is not natural to ascribe this effect to **instrumental systematics**: two independent experiments (WMAP and Planck) observe the same features. Differences are dictated more by the reference ΛCDM model. (This is valid for all the anomalies)

Lack of power

Moreover there is a **particular behavior**:

Gruppuso et al. (in prep.)

The significance of this anomaly gets stronger when the Galactic mask is increased. This is really a remarkable fact since the exclusion of regions close to the Galactic plane is in principle a very conservative choice.



% 94 84 71 59 49 39 31

The CMB pattern at large angular scale seems to behave statistically differently depending on the Galactic latitude considered

variance in harmonic space nside=16

What’s next/some considerations

A) Such a behavior of the **lack of power** seems to tell that most of the temperature large-scale power is localized around the Galactic mask.

1. Look for other test that might highlight the fact that low and high Galactic latitude pattern behave very differently from a statistical point of view.

2. How much likely is that most of the power happens to be “close” to the Galactic plane?

3. Look for spurious effect that might increase the power around the Galactic plane.

What's next/some considerations

B) **There are many anomalies** but none of them individually reaches the 5σ detection level (which is threshold that is adopted in particle physics). It appears hard to believe that we live in such a rare realization of ΛCDM that have all of these features by chance, *unless they have a common origin*.

1. Find sets of independent anomalies when analyzed in ΛCDM. This is only partially done in literature (e.g. the lack of correlation implies the low variance but not the quadrupole-octupole alignment).

What's next/some considerations

C) Up to now **polarization** is not taken into account yet.

1. Include polarization data to perform a joint (T+P) analysis to increase statistical significance in a data-driven way.

2. Any given model for CMB temperature anomalies has predictions for polarization that can be tested.

What's next/some considerations

D) None of the known **foregrounds** is proven to cause CMB anomalies. Such anomalies have more or less the same statistical significance in four different foreground cleaning pipelines of Planck and in the corresponding WMAP pipeline.

1. however new information about local astrophysical emissions (zodiacal emissions, spinning dust,…) will help in understanding their impact on these CMB features.

Back-up

What's next/some considerations

E) **Instrumental systematic** effects of course might be considered as well. However such anomalies have more or less the same statistical significance for two independent experiments (Planck and WMAP)

1. anyway it cannot be completely excluded a case of instrumental features shared by the two experiments which impact on these findings.

Origin of the lack of power

It is natural to connect this anomaly to early departures of the inflaton from the slow-roll phase. Therefore such anomaly might hint at a pre-inflationary scenario before slow-roll.

At large angular scale the CMB power is governed by two effects: ordinary Sachs-Wolfe effect (sensitive to the early universe physics) and integrated Sachs-Wolfe effect (which accounts for the late evolution of the universe). Therefore S_1/2 estimator is coming from an early (SW), a late (ISW) and a cross-correlation term between early and late contribution. It is possible to show that

1. to obtain the value which is observed from a random realization of ΛCDM model it must happen that

   early contribution must be somewhat suppressed and that late and cross terms should cancel by chance.

2. if a physical mechanism (like a fast-roll evolution of the inflaton) makes the early contribution very low wrt the late contribution, i.e. ISW term, is not capable to screen it.

Copi, O'Dwyer and Starkman (MNRAS, 2016)

What’s next/some considerations

- Suppose there is a cosmological origin for the anomalies

1. a pre-inflationary era can explain the lack of power at large scales. Statistical significance might be important if only the region at high latitude is considered.

2. dipolar models (breaking of isotropy) can explain the hemispherical asymmetry. Multi-field inflation models could in principle accommodate this.

3. non trivial topology can in principle explain lack of correlation and alignments while preserving isotropic and homogeneous geometry

In short these cosmological explanations could explain one anomaly (but not all) and in general they are not statistically significant

Quadrupole-Octupole alignment

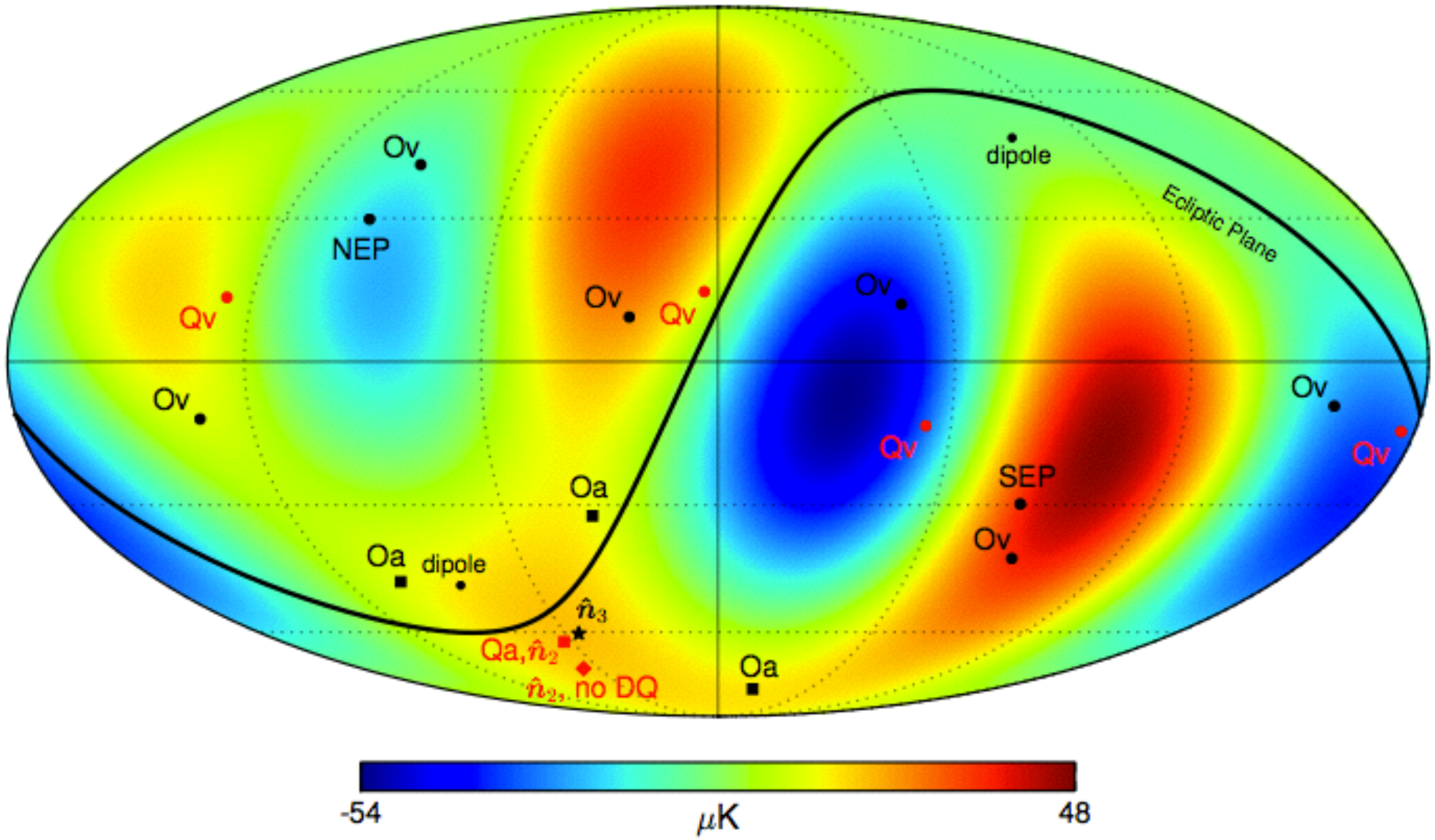


Figure 4. The combined quadrupole-octopole map from the Planck 2013 release [33]. The multipole vectors (v) of the quadrupole (red) and for the octopole (black), as well as their corresponding area vectors (a) are shown. The effect of the correction for the kinetic quadrupole is shown as well, but just for the angular momentum vector $\hat{n}_2$, which moves towards the corresponding octopole angular momentum vector after correction for the understood kinematic effects.

Cold spot

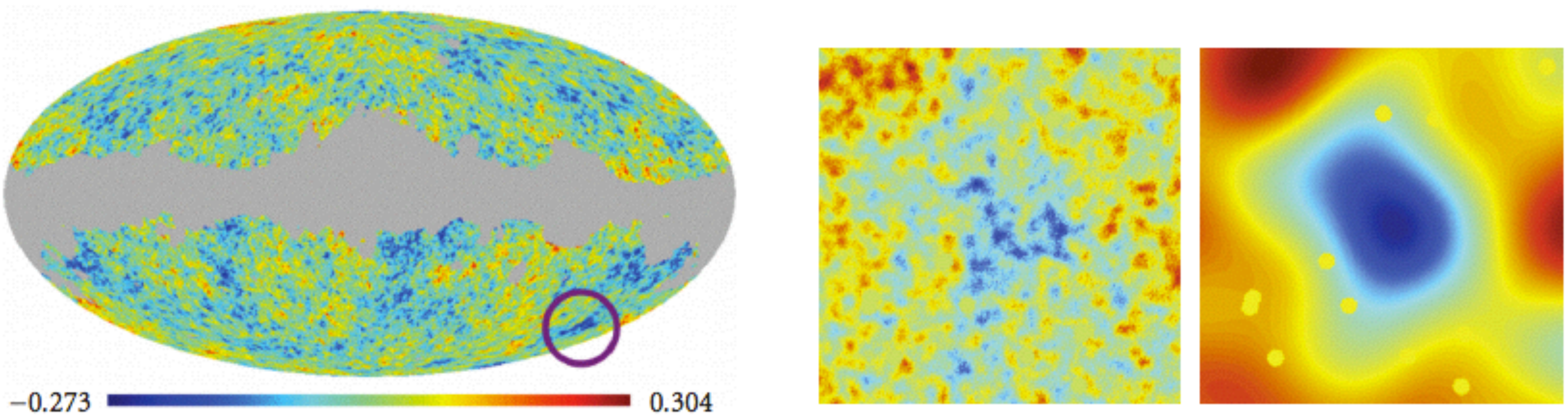


Figure 8. Cold spot in WMAP 7th year temperature maps. Left panel shows the map with the circle. Middle panel is the more detailed picture of the spot, while the right panel is the wavelet-filtered version of the middle panel (wavelet size $R = 250'$). The small spots in the right panel are regions of known point sources that have been masked). All figures are adopted from the review in Ref. [80].

Definitions

The skewness, γ, and kurtosis, κ, of a random variable, X, are defined as

$$\gamma(X) = \frac{\langle X - \langle X \rangle \rangle^3}{(\sigma^2(X))^{3/2}}, \quad (4)$$

$$\kappa(X) = \frac{\langle X - \langle X \rangle \rangle^4}{(\sigma^2(X))^2} - 3, \quad (5)$$

where σ^2, the variance is:

$$\sigma^2(X) = \langle X^2 \rangle - \langle X \rangle^2. \quad (6)$$

Component Sep methods

Two algorithms are based on **model fitting**

Commander. It works in pixel domain.
Fits parametrized model of CMB and foregrounds to the data.

SMICA. It works in harmonic domain.
Fits model of CMB considering auto and cross spectra.

and two on **minimization of variance**

NILC. It works in Needlet domain.

SEVEM. It works in pixel domain.
Clean CMB channels with internal templates and combines maps to provide a single CMB map.