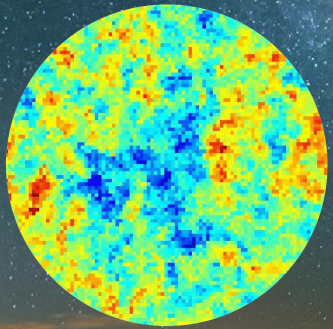
COSMOS meeting on
Astroparticle and Fundamental
Physics with the CMB

A revision of the CMB *Cold Spot*



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The original detection

A genuine CMB feature

A modern characterization

Possible explanations and additional probes

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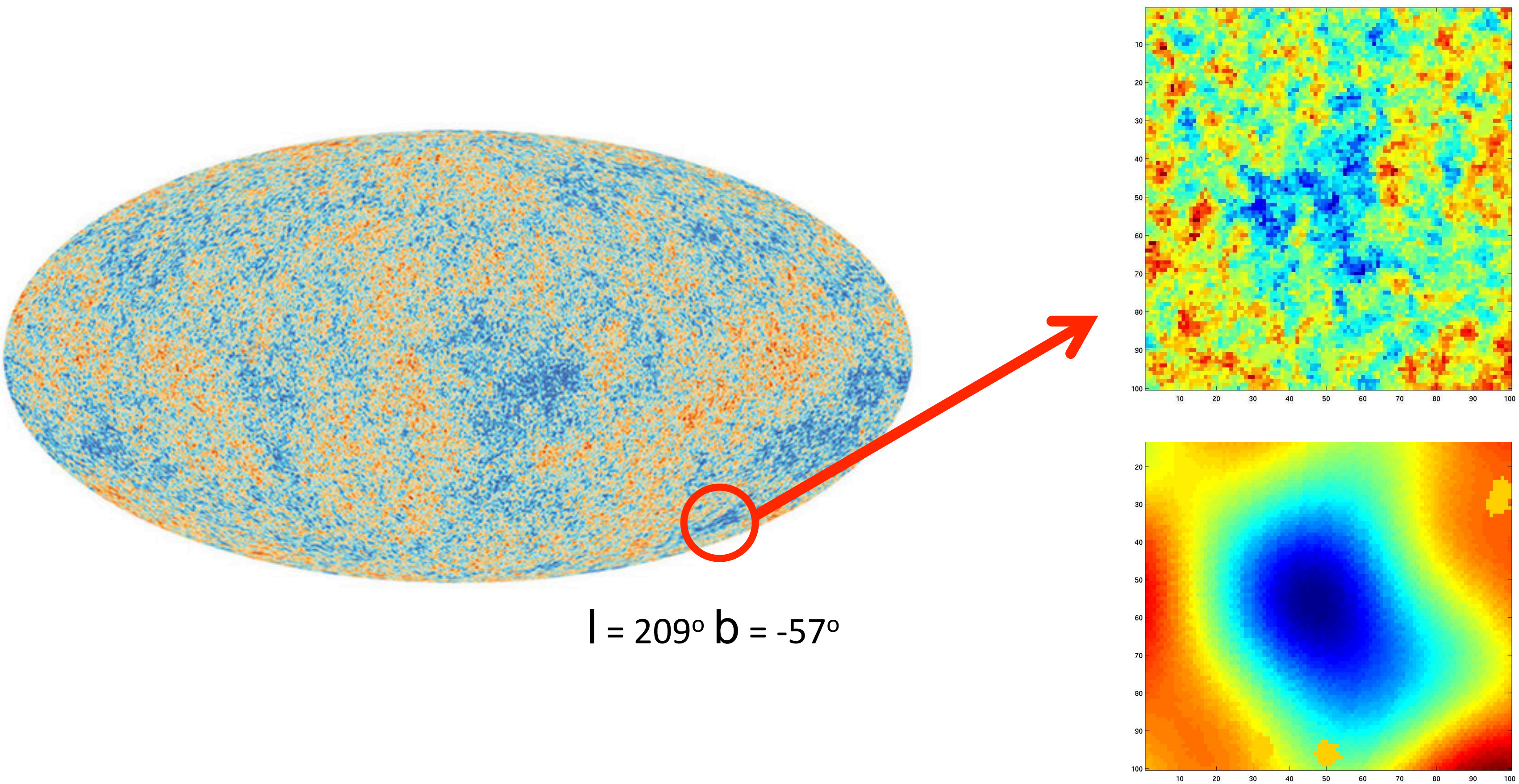
The original detection

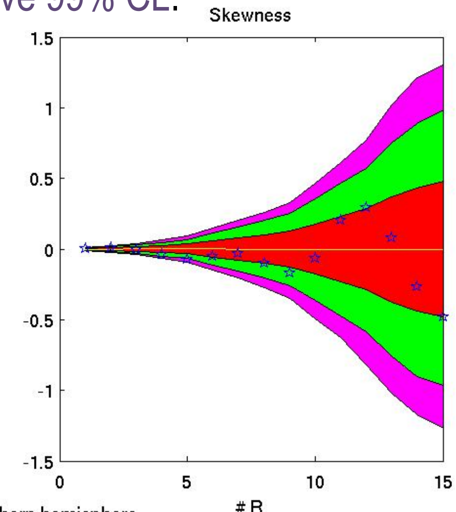
The **Cold Spot** is a very cold and large region in the sky located in the southern hemisphere, firstly detected in 2004 [Vielva et al. 2004] and identified as the most prominent feature contributing to a deviation of Gaussianity claimed by analyzing the WMAP data with the Spherical Mexican Hat Wavelet.

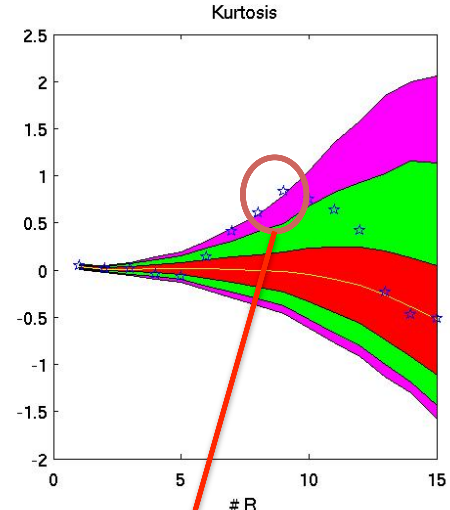


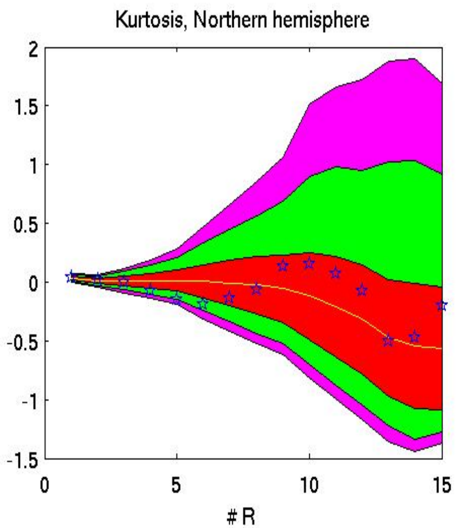
The original detection

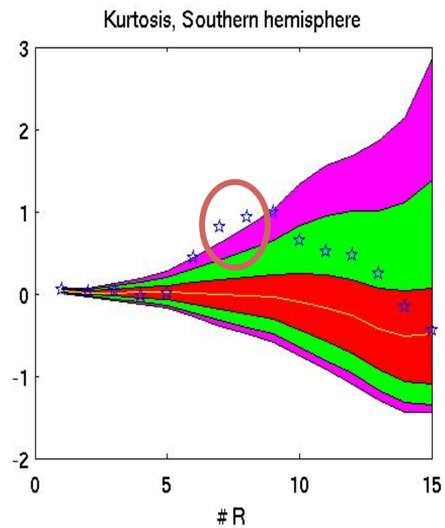
The **Cold Spot** was noticed during a global test of Gaussianity of WMAP data performed in wavelet space. In particular, the CMB map was analyzed at several scales and standard statistics were computed from the wavelet coefficients: the kurtosis deviates above 99% CL.

The NG deviation was localized at the Southern galactic hemisphere.





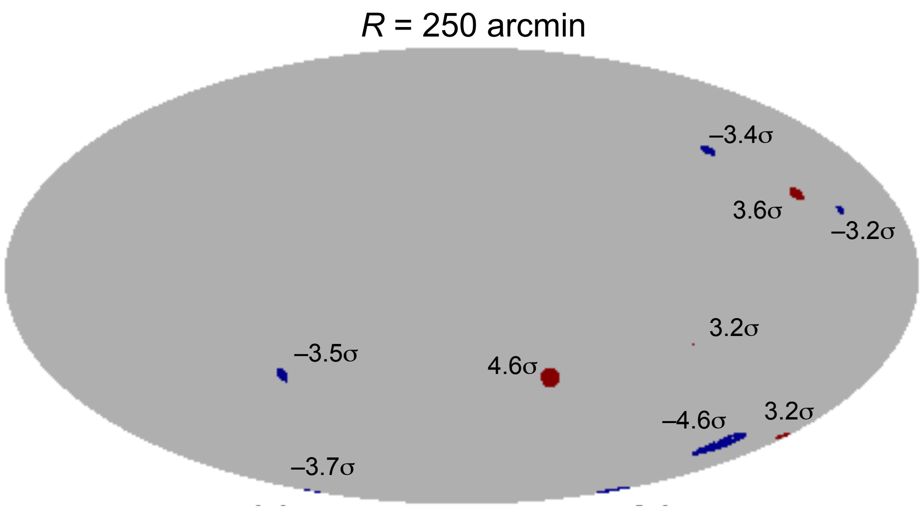




[Vielva et al. 2004]

This corresponds to R=250 and 300 arcmin

The original detection



[Cold and Hot spots above 3σ, for SMHW scale of 250 arcmin]

The **Cold Spot** appears as **the most prominent feature**.

Notice that the hot spot of 4.6σ was not seen in the original WMAP analysis because was covered by the mask. This is also the case for some other of the spots here represented.

[Planck Collaboration 2016, 594, 16]

Soon after the detection, several additional works confirmed the **Cold Spot**, by analyzing different statistics related to the Gaussianity and the isotropy of the CMB.

An incomplete census is: area of the SMHW coefficients above a given threshold [e.g., Cruz et al. 2005], the Higher-Criticism (also in SMHW space, [e.g., Cayón et al. 2005]), additional wavelets (as directional [e.g., McEwen et al. 2005], steerable [e.g., Wiaux et al. 2008] and needlets [Pietrobon et al. 2008]), scalar indices [e.g., Räth et al. 2007], and Kolmogorov stochasticity parameter [e.g., Gurzadyan et al. 2009].

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A genuine CMB feature

Clearly, once detected, the next step is to provide a **nature for the Cold Spot**. Perhaps, the two first obvious suspects were:

- Systematics
- Residual foregrounds

Already at the time of WMAP data, it was confirmed that the simulations were in reasonable agreement with the data. Example of these tests were:

- Compatible results when analyzing *maps from different detector combinations*
- Null signal when analyzing *map differences*
- Signal stable against *changes on the cosmological parameters*

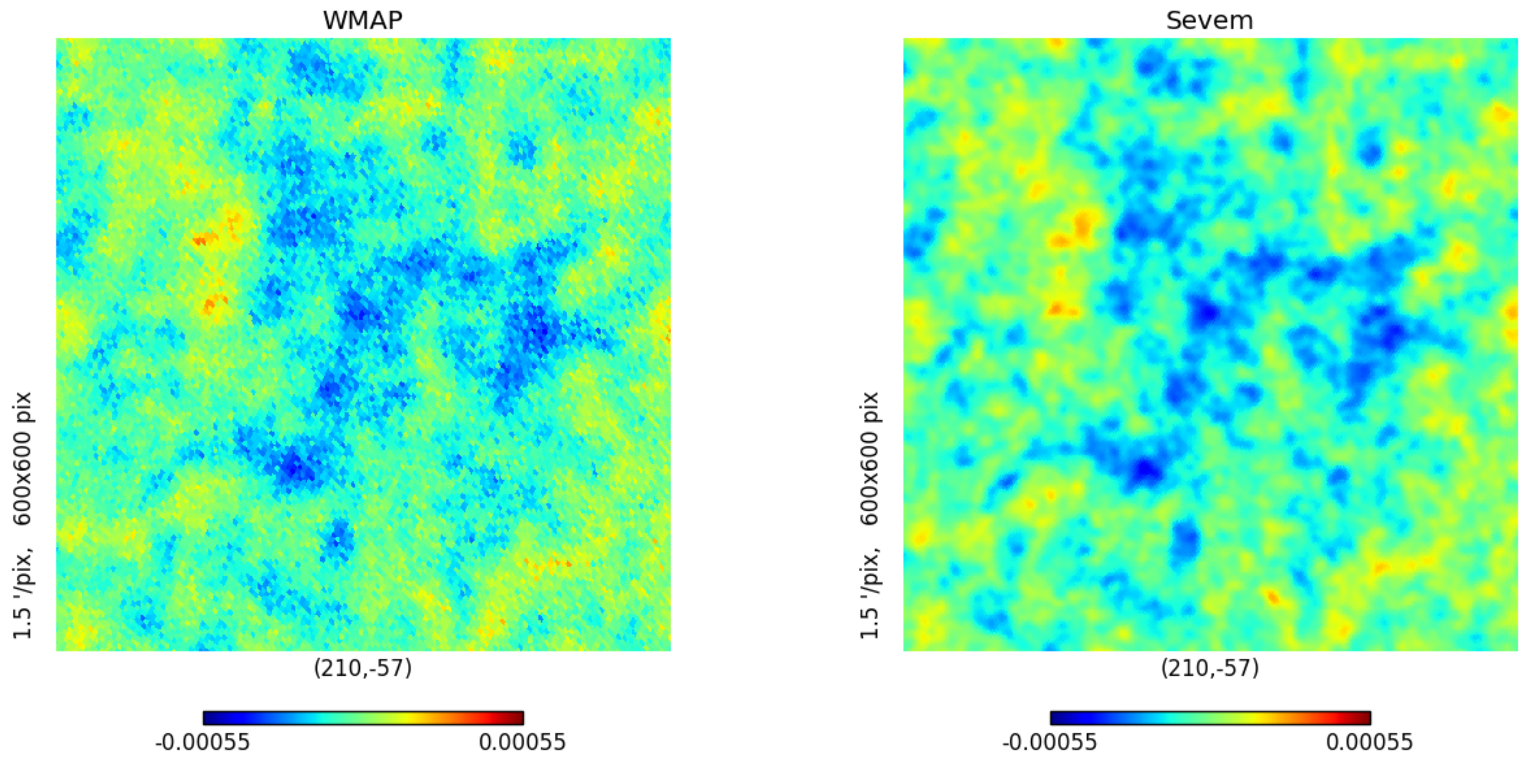
Also the foregrounds hypothesis was explored very much in detail:

- The estimate level of residual *galactic foregrounds* (even with generous margins) was shown to be *clearly below the CMB signal*.
- At the WMAP time, a clear possibility was a the *Sunyaev-Zeldovich effect* (providing a negative fluctuation for all the frequency range observed by WMAP, with an almost flat dependence). *But it was discarded through a Bayesian test* against the ΛCDM hypothesis.

A genuine CMB feature

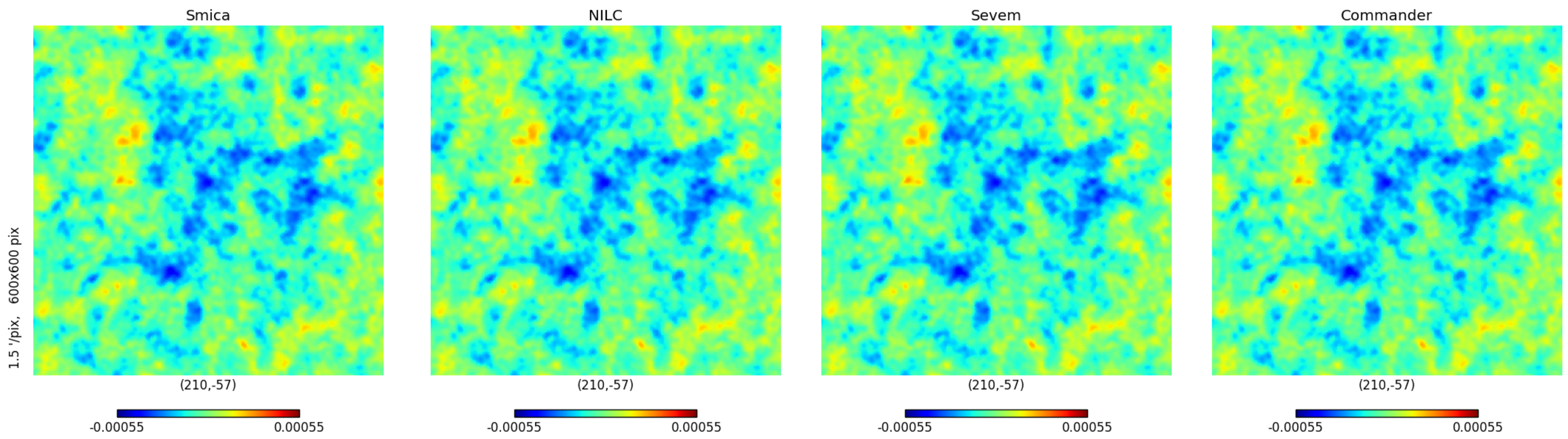
However, it was **the Planck data** what really helped us to confirm than the **Cold Spot** was a genuine CMB feature:

- **First**, **two different satellites observed the same signal** at roughly the same significance, discarding so the systematics hypothesis.



A genuine CMB feature

- **Second**, the larger frequency range of Planck, and the fact of having several clean CMB maps obtained under different assumptions with respect to the foregrounds, allowed us to:
  - Completely **discard the SZ hypothesis** (the **Cold Spot** also appears at 217GHz)
  - Establish that the anomalous signal **is frequency independent from 100 GHz to 217GHz**, doing its explanation in terms of galactic foregrounds very unlikely



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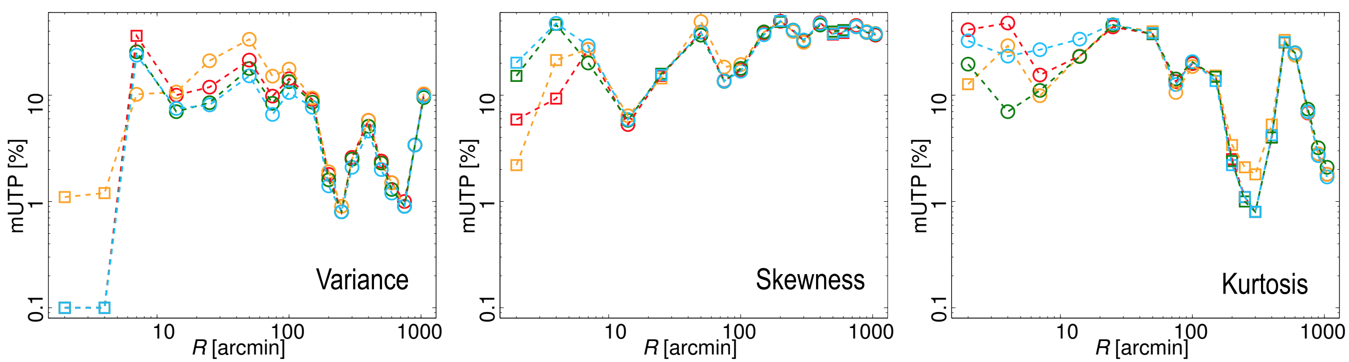
Modified upper-tail probability of the variance, skewness and kurtosis of the SMHW coefficients for the 4 Planck CMB maps (Commander, NILC, SEVEM and SMICA)

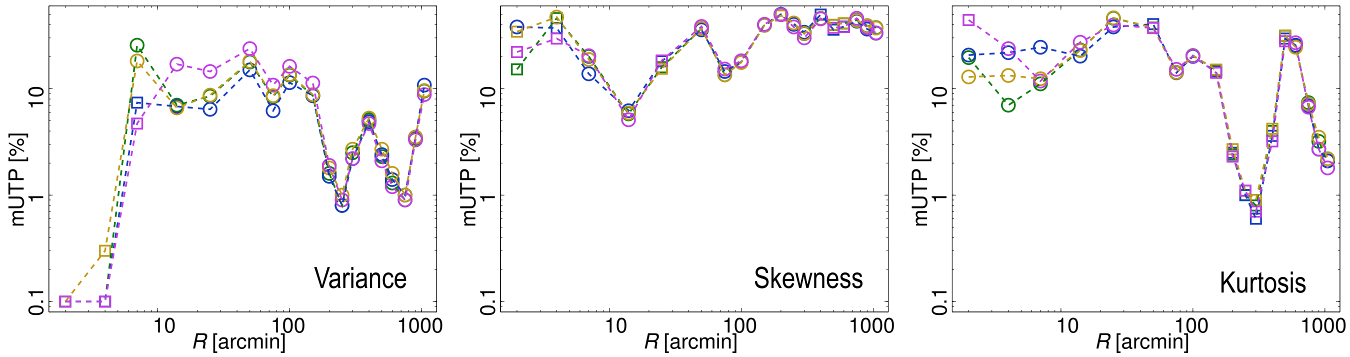
[Planck Collaboration 2016, 594, 16]

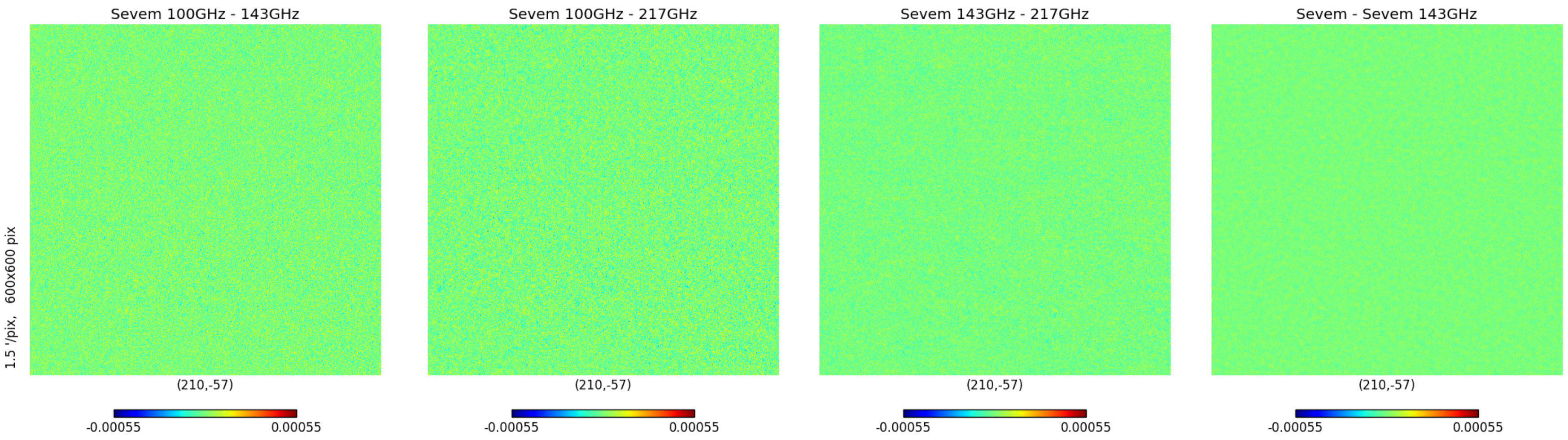


A genuine CMB feature

Modified upper-tail probability of the variance, skewness and kurtosis of the SMHW coefficients for three clean CMB maps from SEVEM: 100GHz, 143 GHz and 217GHz.

[Planck Collaboration 2016, 594, 16]





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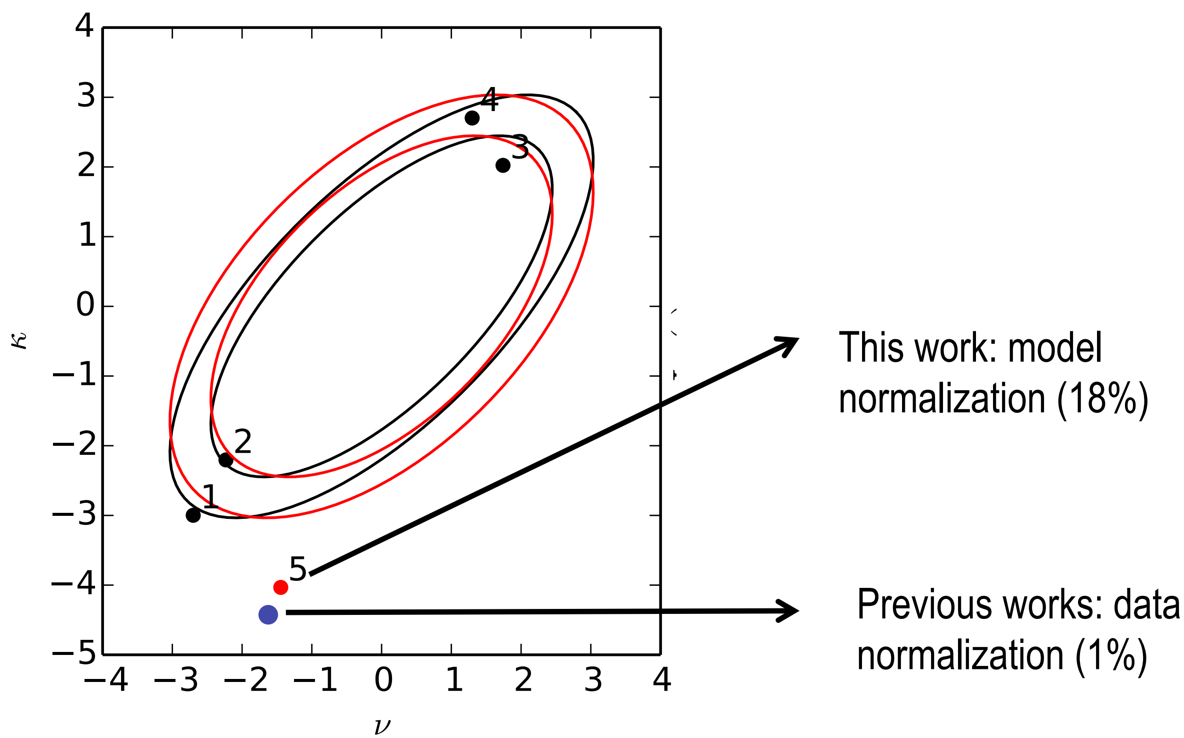
Possible explanations and additional probes

A recent work [Marcos-Caballero et al. 2017] has provided a **further insight** on the **Cold Spot**:

- First, providing a robust characterization in terms of the natural characteristics of a peak: **amplitude**, **curvature**, **gradient**, and **eccentricity** (defined in terms of the 0th, 1st and 2nd derivate)
- Second, showing its relation to another CMB anomaly: the low variance

The **curvature** (κ), estimated at a given angular resolution is totally equivalent to the **SMHW coefficient** at that scale.

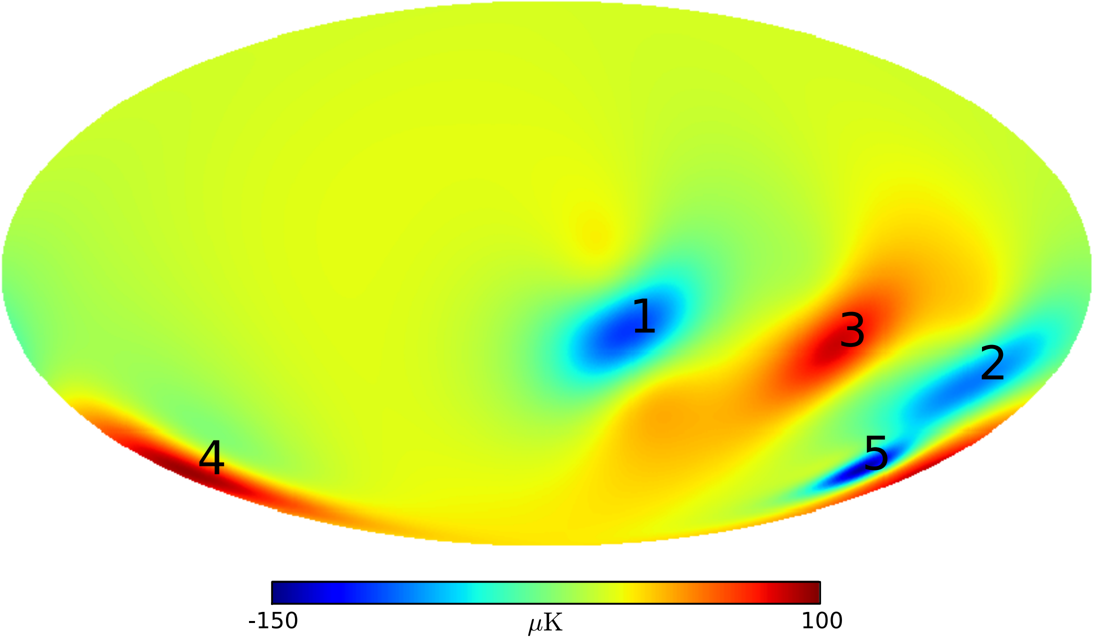


[Marcos-Caballero et al. 2017]

However [Marcos-Caballero et al. 2017] propose an alternative study of the peaks exploiting this geometrical quantities, in particular, in terms of the coefficients of the Fourier transform of the azimuthal angle around the peak:

$$T_m(\theta) = \frac{1}{2\pi}\int \mathrm{d}\phi\, T(\theta,\phi)\, e^{-im\phi}$$

Whereas $T_0(\theta)$ only depends on the amplitude and the curvature, $T_1(\theta)$ does it on the gradient and $T_2(\theta)$ on the eccentricity. This analysis was applied to the most prominent peaks localized in **Planck data**, four of them with a scale of 10º (peaks 1 to 4), and one with 5º (the **Cold Spot**).

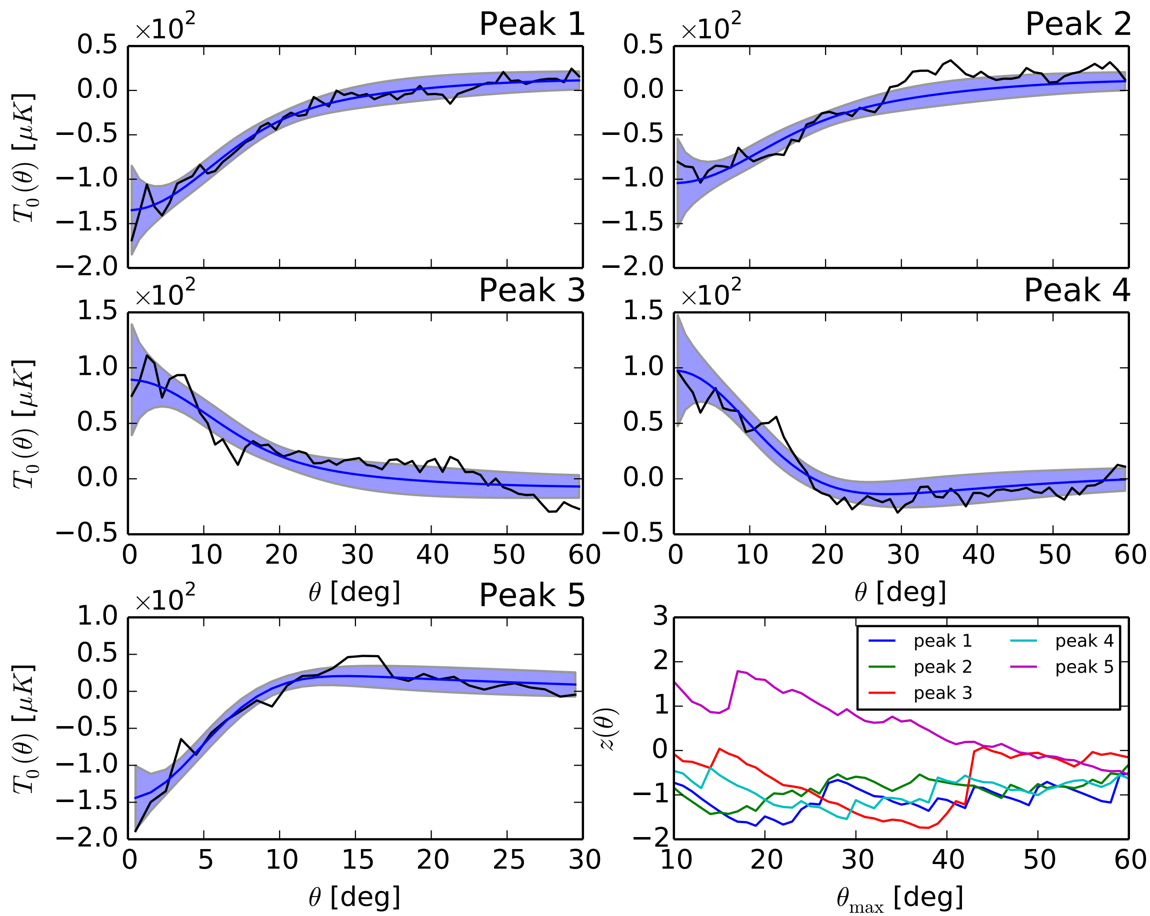


[Marcos-Caballero et al. 2017]

A modern characterization

When the values of the amplitude and curvature are the conditioned to those of the data, none of the peaks (including the **Cold Spot**) are anomalous.

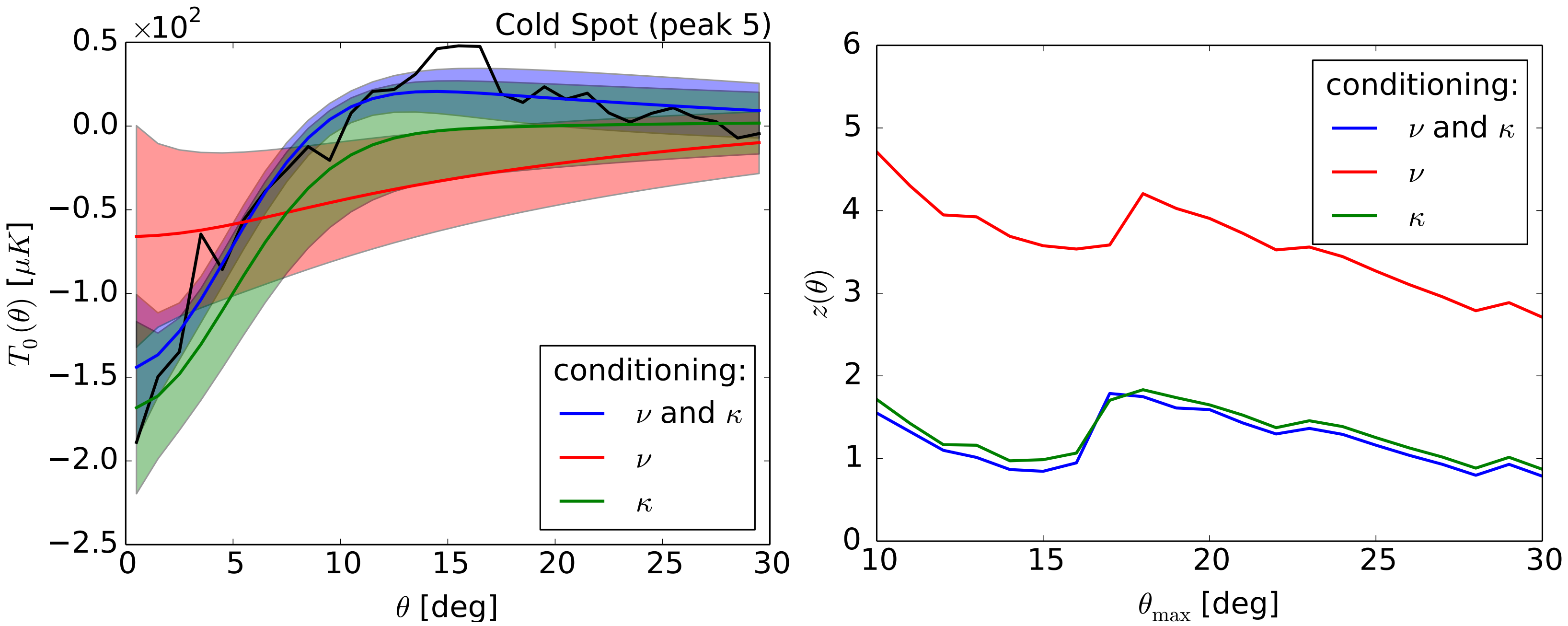
Similar results are obtained for the other profiles.



[Marcos-Caballero et al. 2017]

However, for the case of the **Cold Spot**, only when the amplitude is conditioned and the curvature is integrated out, then the **Cold Spot** show an excess above 3σ for all the θ_{max} explored.

Hence, the **Cold Spot** anomaly is caused by the large value of the curvature.



[Marcos-Caballero et al. 2017]

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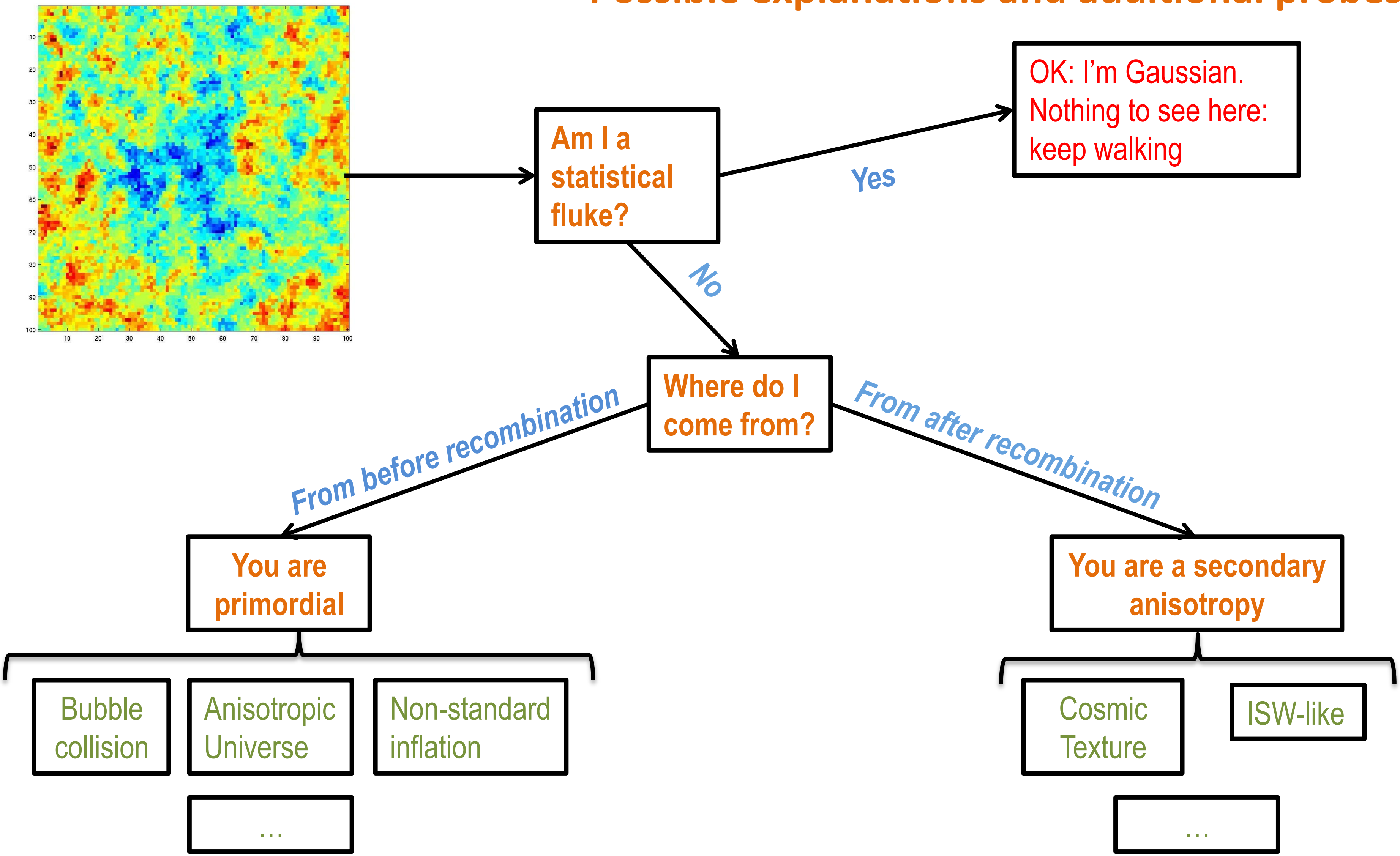
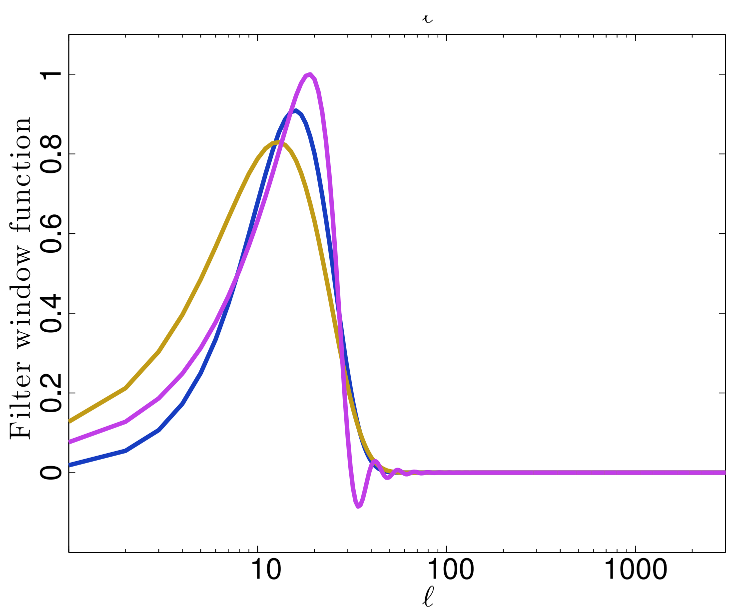
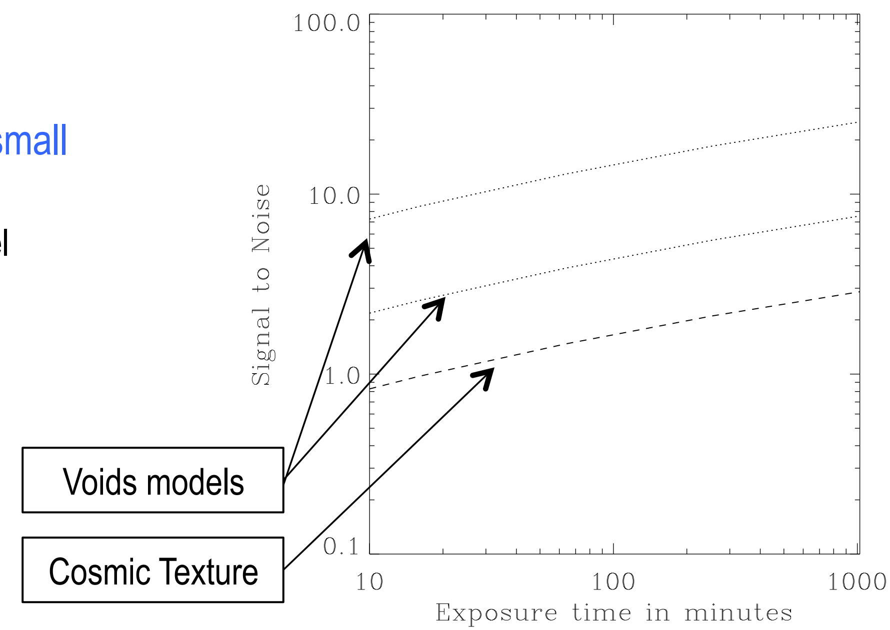


Possible explanations and additional probes

CMB temperature has provided already all the information that can be obtained form it. Only very small scales could still help to distinguish the secondary anisotropy nature via the CMB lensing [Das & Spergel 2008].



[Vielva 2007]



The CMB polarization from the Planck 2015 release was not enough to study in detail the Cold Spot.

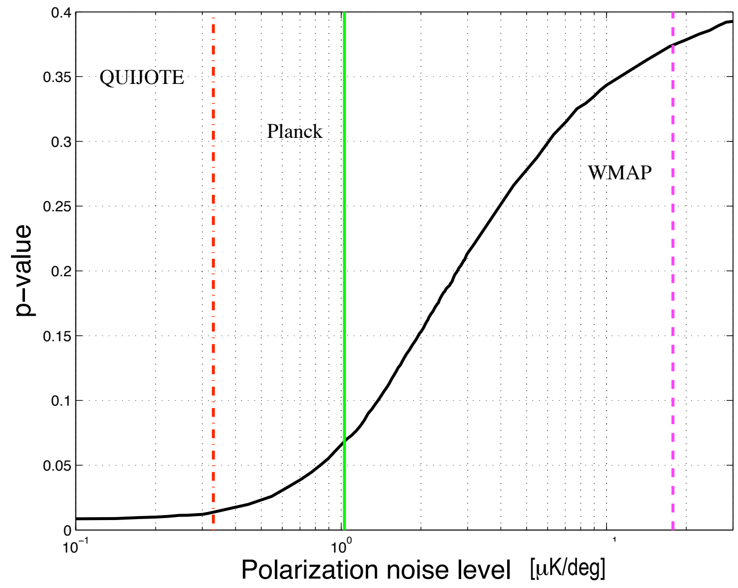
The signal was filtered for multipoles < 40. The SMHW filter (blue curve) at the scales of interest (~250 arcmin) cuts by itself all the multipoles above 40. Hence, no interesting signal was left.

Possible explanations and additional probes

The **Planck 2018 release will provide the best large-scale CMB polarization, for the next ~20 years**, at least.

Nevertheless, the signal-to-noise is too low, for instance, to distinguish between a primary or secondary anisotropy, or to distinguish among different sources for this secondary fluctuations.

[Vielva et al. 2011]

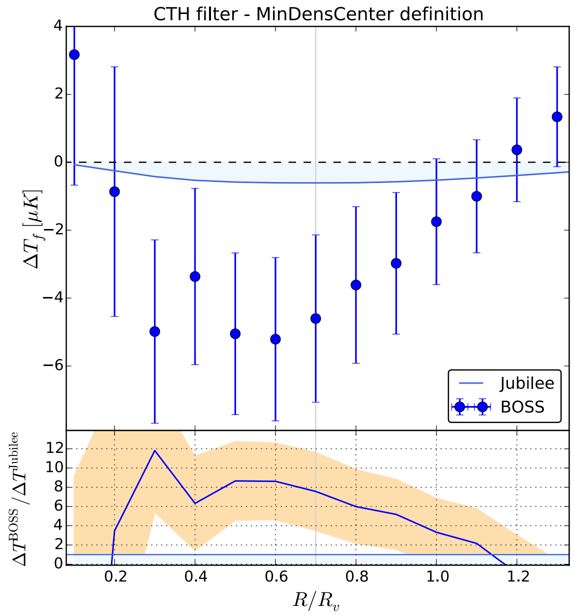


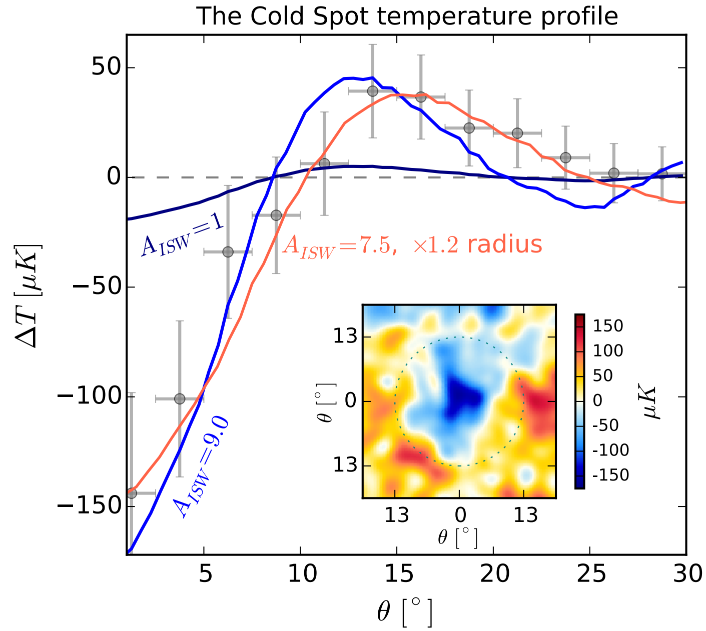
We will need missions like **LiteBIRD**, **CORE** or **PICO** to say the last word on the CMB side about the **Cold Spot**.

In addition, an hypothetical B-mode detection (at a reasonable level) could open a new window for probing primordial physics associated to the **Cold Spot**.

Possible explanations and additional probes

Probes of the LSS (galaxy surveys and 21cm) can still provide much more information, particularly if more evidences for tensions between CMB and LSS appears [e.g., Kovac 2018].





Anomalous ISW signal in Planck data, after stacking on the positions of supervoids form BOSS. An amplitude ~9 times larger than expected. Similar increase requested by **Cold Spot**, after choosing an already favorable model of the gravitational field.


Grazie!