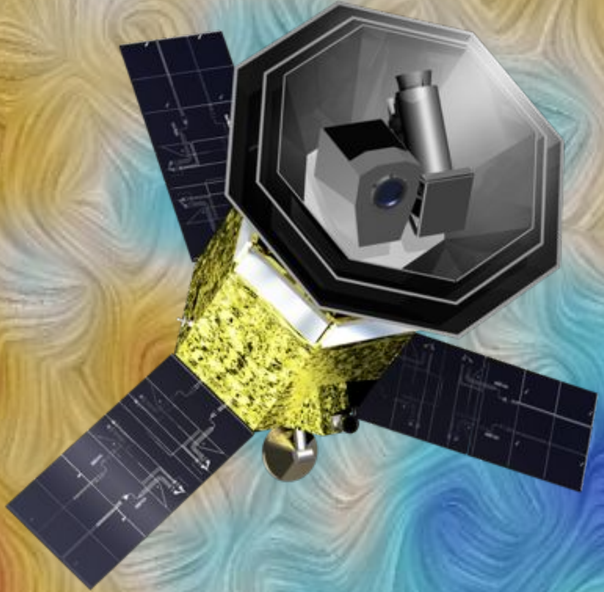
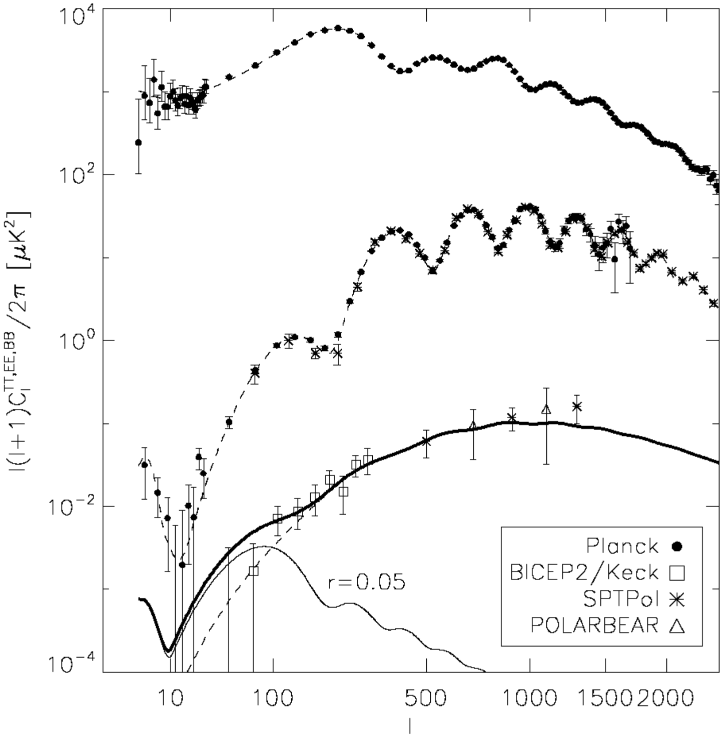
Anomalies in the CMB



LiteBIRD Day / A.J. Banday / 2024-05-13

“State-of-the-Art” Anisotropy Power Spectrum



6-parameter cosmological model (LCDM) an excellent fit to the data.

Gaussianity and Isotropy?

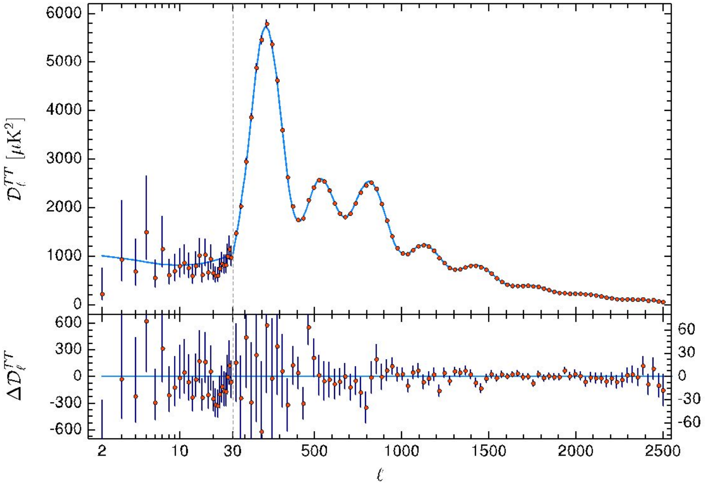
WMAP and *Planck* have found evidence of statistical anomalies in the temperature anisotropies that individually have modest levels of significance.

The simplest explanation for the anomalies is that they are statistical flukes, caused by unusual patterns in the temperature anisotropies arising in the standard cosmological model.

Alternatively they may be providing hints of new physics.

Since no further information is available in temperature, new *independent* probes are required. This can be provided by maps of the CMB polarisation.

Lack of large angular-scale power



Planck 2018 temperature anisotropy compared to the best-fit LCDM model with 6 parameters, plus residuals.

A dip is observed at l ~ 20 and more generally a deficit in power for l < 30.

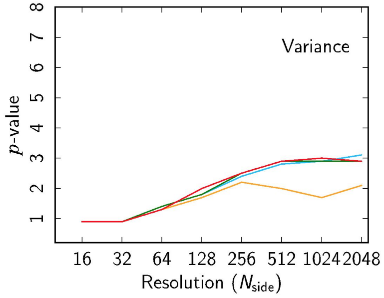
Significance is modest ~ 2σ

Is this a statistical fluke, over-subtracted foregrounds, or evidence of new physics?

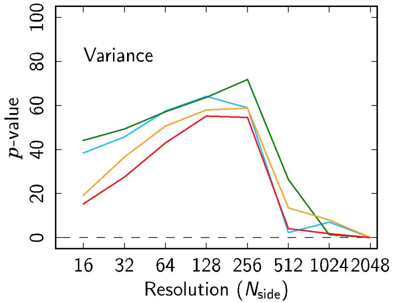
A corresponding low pixel variance is seen for low-resolution temperature maps with a probability of ~ 1%.

There is a trend to lower towards lower variance in polarization, but low signal-to-noise limits interpretation.

Temperature



Polarization

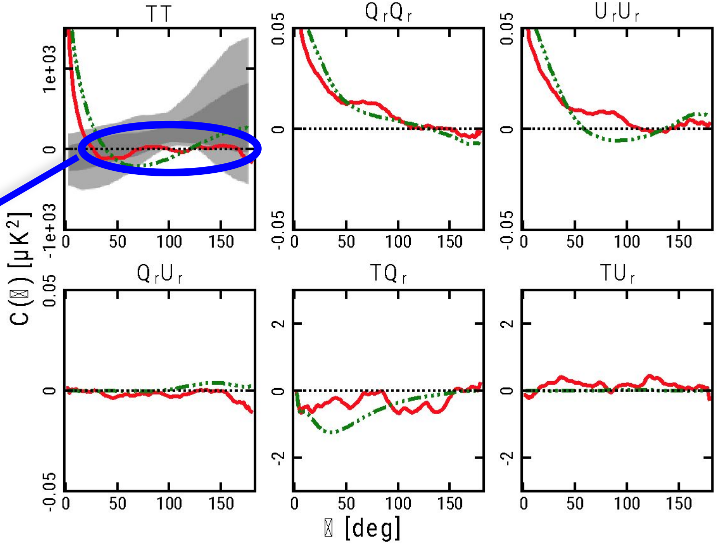


Lack of large-angle correlations

$$S^{XY}(\theta_1,\theta_2) = \int_{\cos\theta_2}^{\cos\theta_1} \left[\hat{C}_2^{XY}(\theta)\right]^2 \, d(\cos\theta)$$

Table 12. Probabilities of obtaining values for the $S_{1/2}^{XY}$ statistic for the *Planck* fiducial ΛCDM model at least as large as the observed values of the statistic for the *Planck* 2018 CMB maps with resolution parameter $N_{\rm side} = 64$, estimated using the `Commander`, `NILC`, `SEVEM`, and `SMICA` maps. The second row shows results for each temperature map after removing the corresponding best-fit quadrupole.

Statistic	Probability [%]			
	`Comm.`	`NILC`	`SEVEM`	`SMICA`
TT	>99.9	>99.9	>99.9	>99.9
TT (no quadr.) . .	96.0	96.1	96.1	96.2
Q_rQ_r	42.8	50.5	30.3	57.0
U_rU_r	74.5	71.7	68.9	89.0
TQ_r	83.5	94.0	74.6	94.8
TU_r	94.5	97.8	79.1	88.6
Q_rU_r	88.8	59.7	94.4	97.7



- Consistency of the N-point functions between data and simulations for T, Q and U maps
- No statistically significant deviation of the CMB map from Gaussianity
- Lack of large-angle correlations in the case of the CMB temperature maps
- No anomalous correlations at large-angles in the case of the CMB polarization maps

Alignments at low-*l*

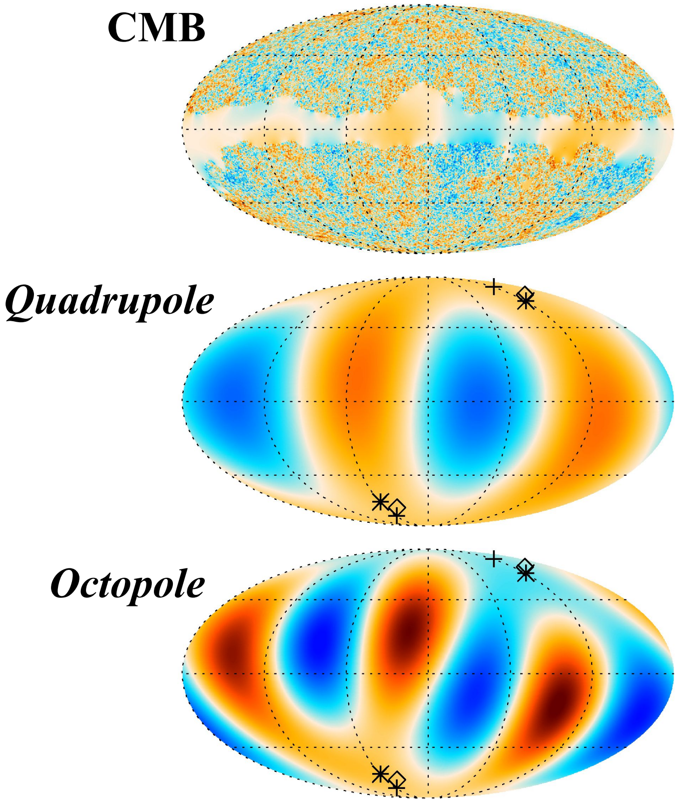
In the standard LCDM model, anisotropies have random phases.

The orientations and shapes of the multipole moments are uncorrelated.

$$\sum_m m^2 |a_{\ell m}(\boldsymbol{n})|^2$$

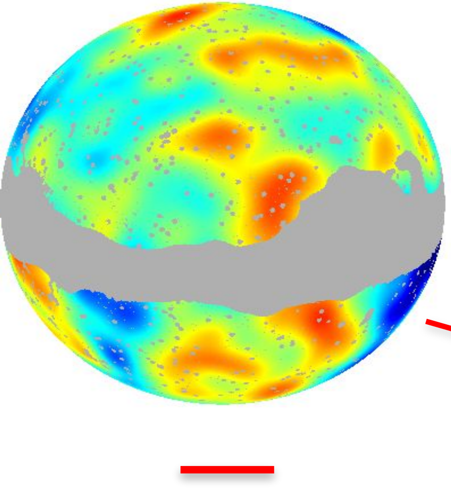
This can be tested using the Angular momentum dispersion and finding the plane that maximizes this quantity.

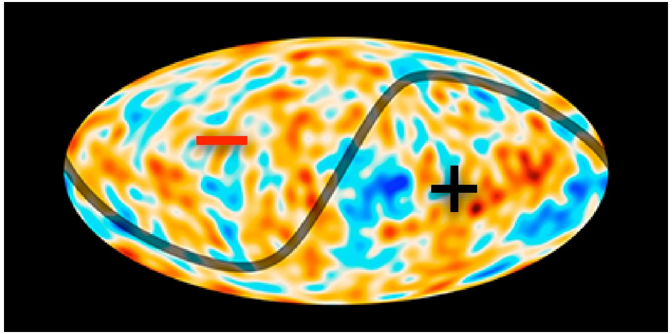
Analyses of both WMAP and Planck find
- the octopole is unexpectedly planar (dominated by $m = \pm l$)
- the quadrupole and octopole planes are aligned with each other

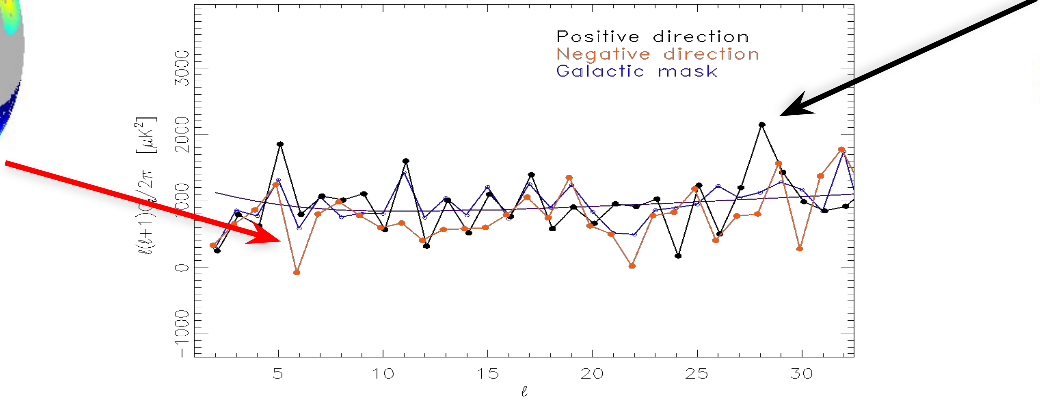


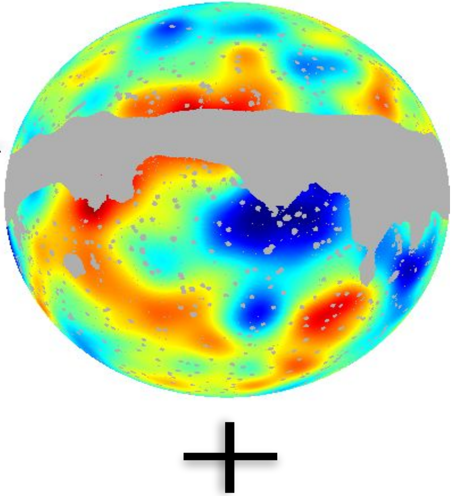
Power asymmetry

Planck results 2013. XXIII. A&A, 571, A23, 2014









Variance asymmetry

We estimate a dipole component in the distribution of the variance measured within discs of various radii in the map.

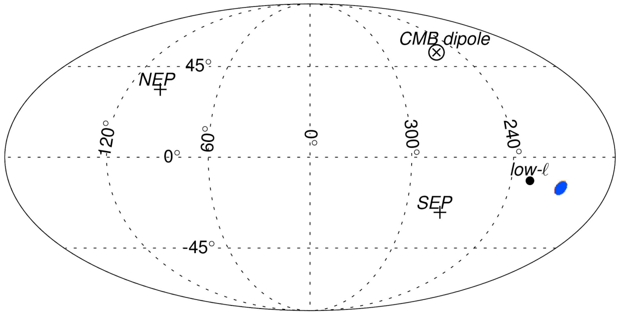
Evidence is seen for a significant asymmetry (p<0.1%) in the variance distributions, with a dipole amplitude of ~6%.

The significance is not unambiguously reproduced in the polarization analysis.

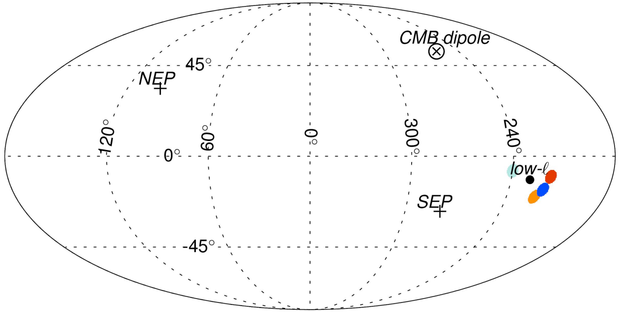
However, the preferred directions found for the E-mode polarization data, are intriguingly close to those determined for the temperature data.

Data	p-value [%]	(l, b) [deg]	Alignment with T: $\cos\alpha$[a]	Alignment with T: p-value [%]
Commander	0.7	(217, −10)	0.99	0.9
NILC	5.8	(222, −19)	0.97	1.9
SEVEM	0.4	(240, −7)	0.86	6.9
SMICA	5.5	(219, −16)	0.99	0.9

[a] α is the separation angle between the preferred directions computed for the temperature and E-mode polarization data.



T



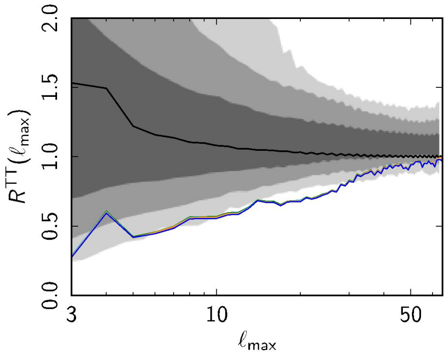
E

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 is observed in the *Planck* and WMAP data. For the analysis of *Planck* 2018 temperature data, we define:

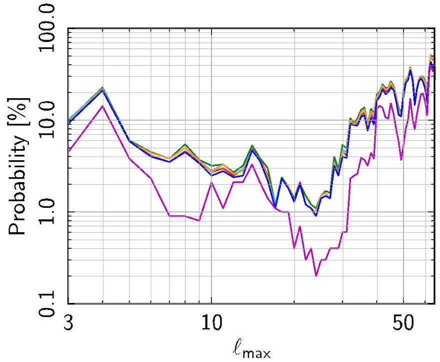
$$C^{\mathrm{TT}}_{+,-} = \frac{1}{\ell^{+,-}_{\mathrm{tot}}} \sum_{\ell=2,\ell_{\max}}^{+,-} \frac{\ell(\ell+1)}{2\pi} C^{\mathrm{TT}}_{\ell}$$

$$R^{\mathrm{TT}}(\ell_{\max}) = \frac{C^{\mathrm{TT}}_{+}(\ell_{\max})}{C^{\mathrm{TT}}_{-}(\ell_{\max})}$$



Results from *Planck* 2018 data show evidence of an odd point-parity preference, with a lower-tail probability of ~1% over the range of multipoles l_{max} = 20-30.

Including *a posteriori* corrections reduces the probability to ~1.6%.

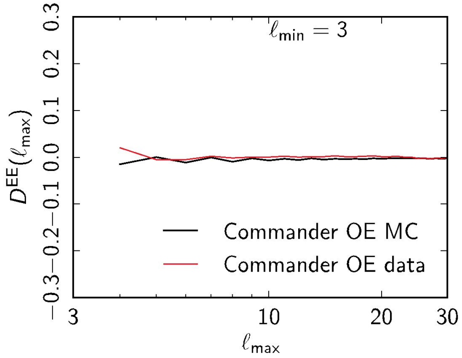


Point-parity asymmetry

For the analysis of the polarization data, we use a modified estimator to avoid problems with the low signal-to-noise power spectrum estimates.

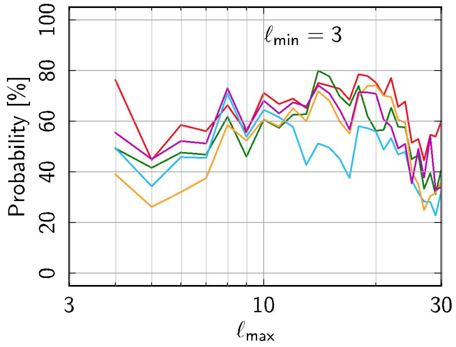
$$D^X(\ell_{\max}) = C_+^X(\ell_{\max}) - C_-^X(\ell_{\max})$$

l = 2 modes are also omitted since they are affected by residual systematic effects.



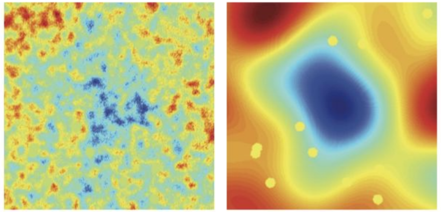
No anomalous lower-tail probability is found.

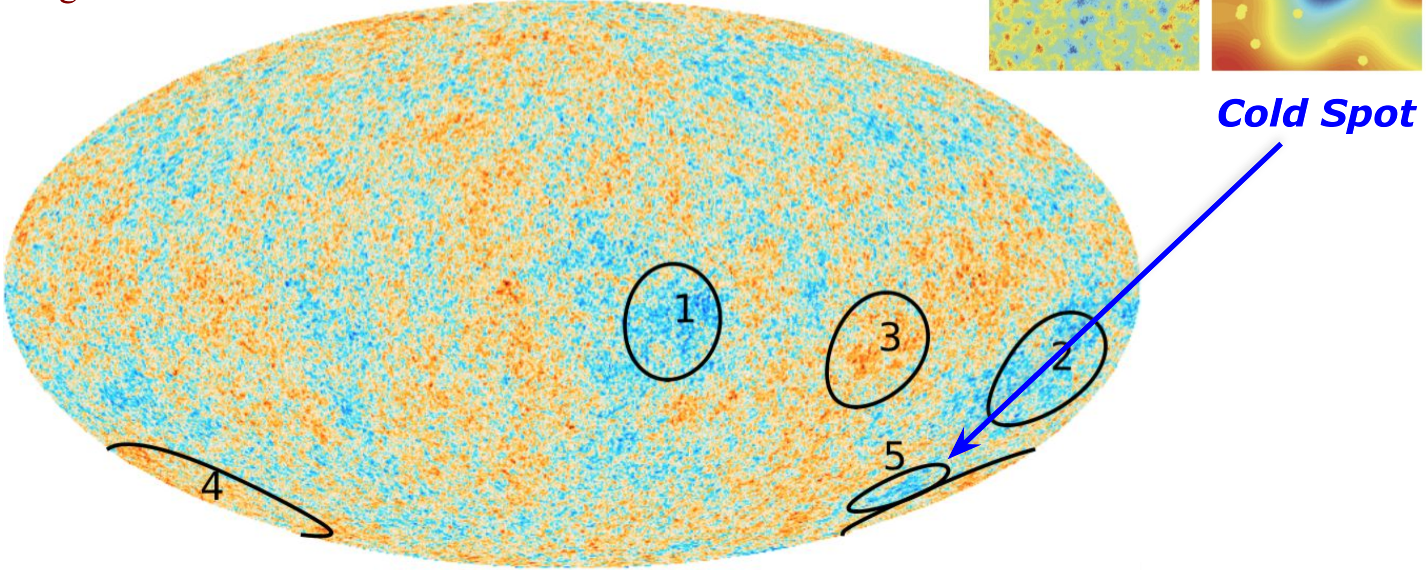
The low signal-to-noise of the *Planck* polarization data over these scales is a limiting factor in the analysis.



The *Cold Spot* and other large-scale peaks

The *Cold Spot* is an anomalous CMB feature of large area and a negative amplitude, and a large kurtosis at scales of around 5 deg.



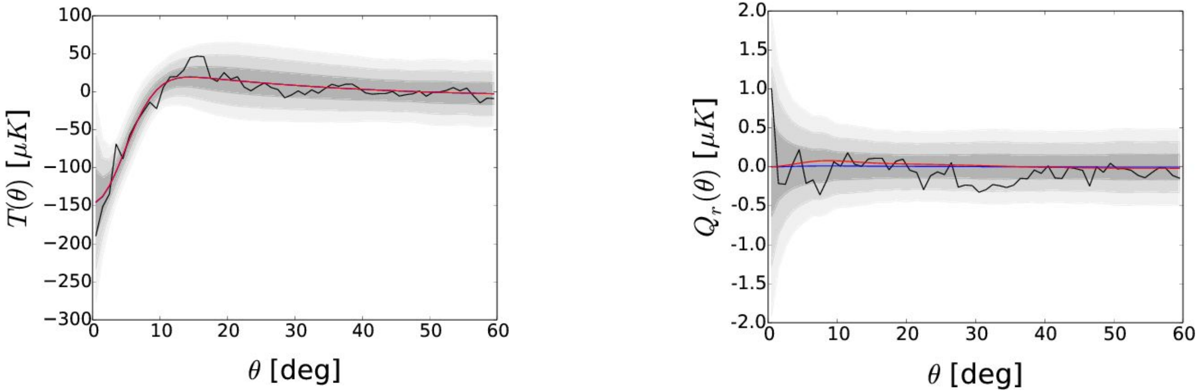


Besides the *Cold Spot* we have also investigated the multipolar profiles of four more large-scale peaks, which have been previously identified anomalous features at very large scales (at 10 deg).

The *Cold Spot* and other large-scale peaks

We compute radial profiles, $T_0(\vartheta)$ and $Q_{r,0}(\vartheta)$ for the *Cold Spot*, then fit the observed profiles to the theoretical profiles.

A free normalization parameter A=1 would imply a perfect agreement with ΛCDM. A value close to 0 would be an indication of lack of polarization wrt. LCDM.



In temperature, the peak profiles are in agreement with ΛCDM, whereas for polarization, the noise is too large to obtain a significant result.

Peak	Comm.	NILC	SEVEM	SMICA
Peak 1	-1.330 ± 1.102	-0.200 ± 1.146	0.164 ± 1.117	-0.034 ± 1.134
Peak 2	0.978 ± 1.088	1.523 ± 1.088	0.446 ± 1.124	0.791 ± 1.077
Peak 3	0.129 ± 1.261	0.090 ± 1.298	0.196 ± 1.270	-0.331 ± 1.311
Peak 4	0.691 ± 0.957	0.150 ± 1.011	1.981 ± 0.994	0.516 ± 0.927
Peak 5	-0.232 ± 0.951	-0.170 ± 1.035	0.152 ± 1.019	-0.598 ± 1.023

LiteBIRD and anomalies

LiteBIRD will improve on Planck studies by reducing potential contamination of the data by non-cosmological signals

- the scanning pattern has near ideal cross-linking properties to cancel systematic errors and optimize map making;
- the use of a rotating HWP allows for map making that does not rely on differencing measurements between different detectors, so that the map noise properties are close to the white noise limit, at least an order-of-magnitude better than *Planck*;
- broad frequency coverage from ~40 to ~400 GHz will allow removal of the Galactic foreground emission to high precision.

LiteBIRD will measure the CMB (temperature and) polarization anisotropy providing measurements of the E-mode polarization in the range $2 \leq l \leq 200$ at close to the cosmic variance limit.

The LitBIRD Isotropy and Statistics Working Group is currently studying such issues.

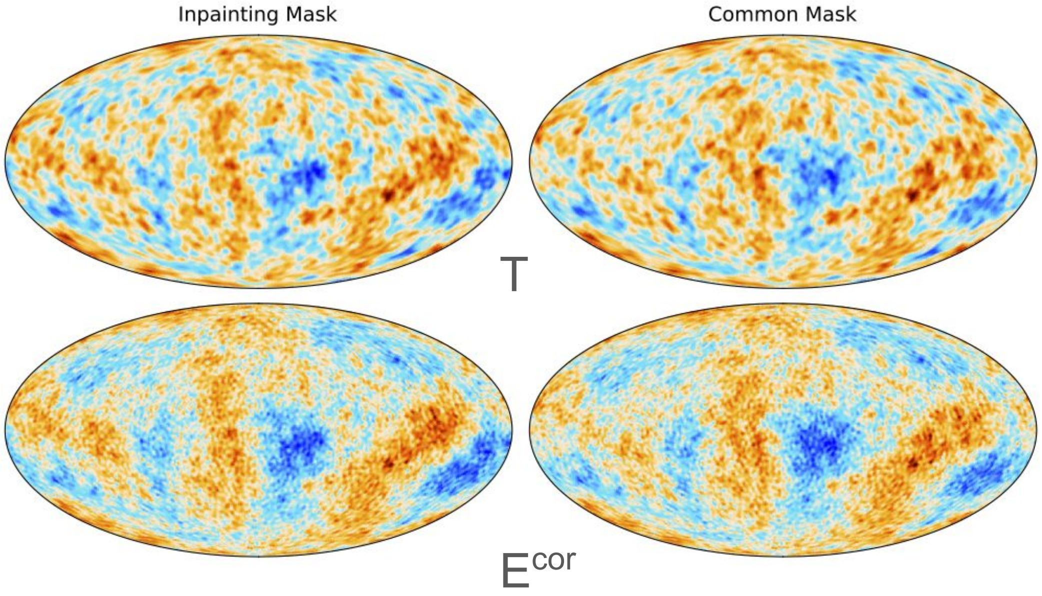
The lack of a unique model to explain all anomalies is problematic.

Current studies relate to specifically testing the *fluke hypothesis*.

Constrained Realisations

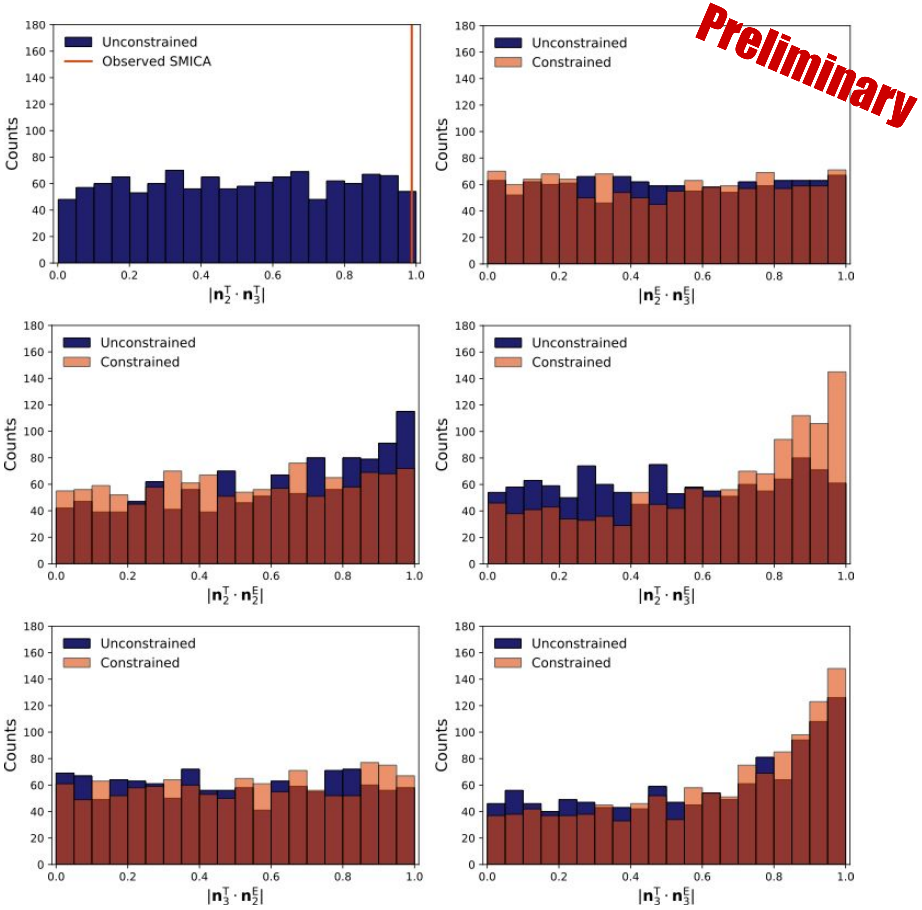
$$a_j^T = \sqrt{C_\ell^{TT}}\zeta_1,$$
$$a_j^E = \frac{C_\ell^{TE}}{\sqrt{C_\ell^{TT}}}\zeta_1 + \sqrt{C_\ell^{EE} - \frac{(C_\ell^{TE})^2}{C_\ell^{TT}}}\zeta_2,$$

$$a_j^E = \frac{C_\ell^{TE}}{C_\ell^{TT}}a_j^T + \sqrt{C_\ell^{EE} - \frac{(C_\ell^{TE})^2}{C_\ell^{TT}}}\zeta_2,$$



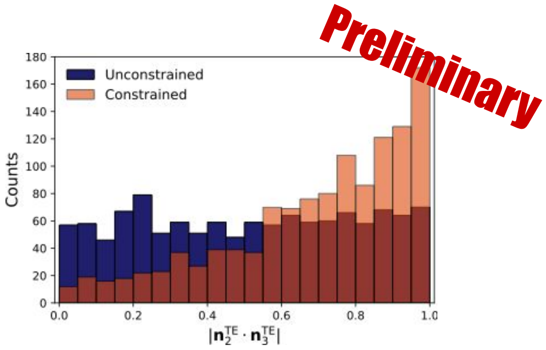
The E-mode signal includes a temperature correlated part. Constrained realisations fix this to the observed Planck sky (inpainted to avoid foreground residuals in the Galactic plane.

Alignment statistics with LiteBIRD



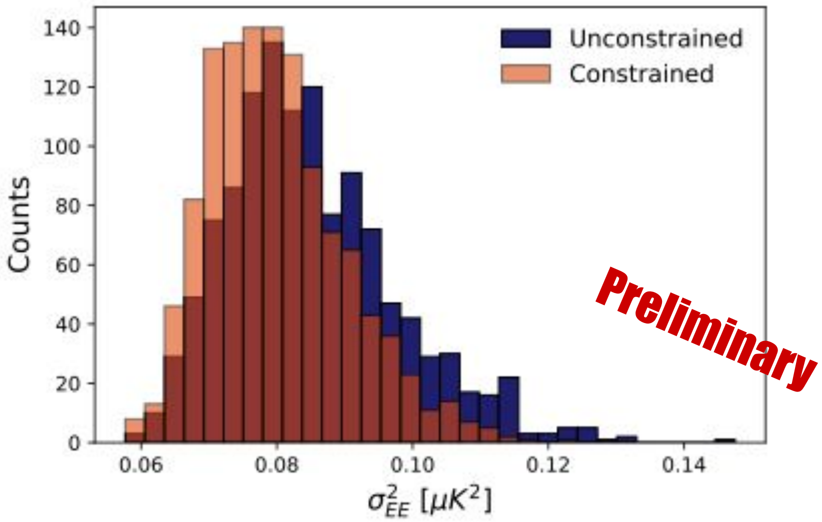
Generally, E-mode results cannot address the fluke hypothesis

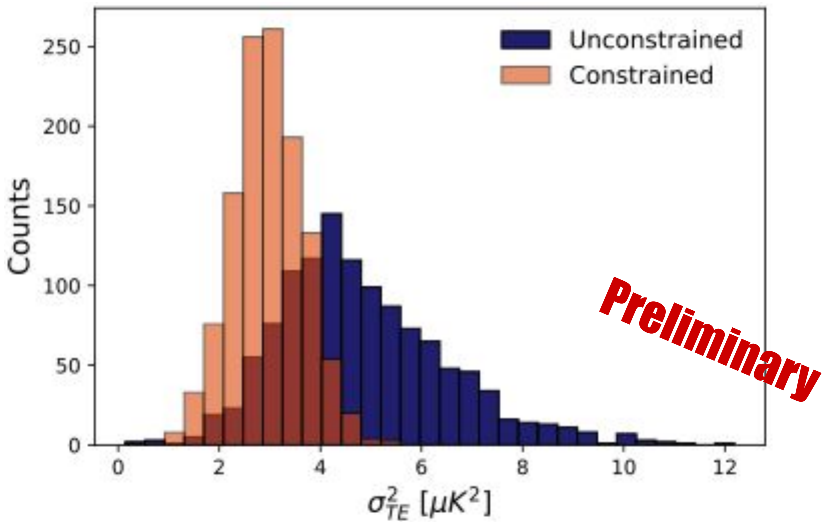
$$\sum_m m^2 |a^T_{\ell m}(\hat{n}) \cdot a^E_{\ell m}(\hat{n})|$$



Joint analysis of T and E most likely to test the origin of the temperature anomalies.

1-pdf statistics with LiteBIRD





Generally, our results indicate that E-mode results are not sensitive to the fluke hypothesis;
E-mode anomalies will directly indicate inconsistency with LCDM and new physics.

Otherwise, TE results can be informative about the fluke hypothesis;
if no anomalies are found, then it is likely that the temperature signatures arise from local sources rather than early Universe physics.

Harmonic analysis on the sphere

Temperature

$$T(\mathrm{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathrm{n}) d\Omega$$

$$a_{\ell m} = \sum_{i} T(\mathrm{n}_i) Y_{\ell m}(\mathrm{n}_i) d\Omega$$

Polarization

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{(\pm 2)} \;{}_{\pm 2}Y_{\ell m}(\hat{\boldsymbol{n}})$$

$$a_{\ell m}^{E} = -\frac{1}{2}\left(a_{\ell m}^{(2)} + a_{\ell m}^{(-2)}\right)$$

$$a_{\ell m}^{B} = \frac{i}{2}\left(a_{\ell m}^{(2)} - a_{\ell m}^{(-2)}\right)$$

$$E(\hat{\boldsymbol{n}}) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{E} Y_{\ell m}(\hat{\boldsymbol{n}})$$

$$B(\hat{\boldsymbol{n}}) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{B} Y_{\ell m}(\hat{\boldsymbol{n}})$$

Power spectrum

$$C_\ell = \frac{1}{2\ell + 1} \sum_{\ell m} |a_{\ell m}|^2$$