Is the large-angle CMB anomalous?

Dragan Huterer
Physics Department
University of Michigan

[On sabbatical at MPA and Excellence Cluster, Jan-Aug 2015]

based mostly on work with
Copi, Schwarz & Starkman (2004-2014)

review in
Planck Collaboration: Planck 2013 results. XII. Component separation

Fig. 1: Foreground-cleaned CMB maps derived by Commander-Ruler, NILC, SEVEM and SMICA. Note that the SMICA map has been filled in smoothly inside a 3% Galactic mask.

Less is known about the AME spectrum, but spinning dust models with a spectrum peaking at frequencies below 20 GHz (in brightness temperature units) adequately describe current observations. Above the peak, the spectrum appears consistent with a power-law (e.g., Banday et al. 2003; Davies et al. 2006; Dobler & Finkbeiner 2008; Ghosh et al. 2012). In addition to these three, the existence of a fourth low-frequency foreground component, known as the “Galactic haze”, has been claimed, possibly due to a hard-spectrum synchrotron population near the Galactic centre (e.g., Finkbeiner 2004; Dobler & Finkbeiner 2008; Pietrobon et al. 2012; Planck Collaboration Int. IX 2013).

At frequencies higher than 100 GHz, thermal dust emission dominates over most of the sky and is commonly described by a modified blackbody spectrum with power-law emissivity, $\nu^\alpha$, and temperature, $T_d$. Both the temperature and spectral index, $\alpha$, vary spatially. Prior to Planck, the best-fitting single component dust model had a temperature $T_d \approx 18$ K and spectral index $\alpha \approx 1.7$ (Finkbeiner et al. 1999; Bennett et al. 2003; Gold et al. 2011), although there is evidence of flattening of the spectral index from around 1.8 in the far-infrared to 1.55 in the microwave region (Planck Collaboration 2012), the interpretation of which is still under study.

In addition to these Galactic components, extragalactic emission contributes at Planck frequencies. In particular, a large number of radio and far-infrared (FIR; Planck Collaboration XIII 2011) galaxies, clusters of galaxies and the Cosmic Infrared Background (CIB; Planck Collaboration XVIII 2011) produce a statistically isotropic foreground, with frequency spectra well approximated by models similar to those applicable to the Galactic foregrounds (modified blackbody spectra, power laws, etc.). Except for a frequency-dependent absolute set, which may be removed as part of the overall removal procedure, these extragalactic components are therefore typically absorbed by either the low-frequency or thermal dust components during component separation. No special treatment is given here to extragalactic foregrounds, beyond the masking of bright objects. Dedicated scientific analyses of these sources are described in detail in Planck Collaboration XVIII (2011), Planck Collaboration XXVIII (2013), and Planck Collaboration XXIX (2013). In the Planck likelihood, extragalactic sources are modelled in terms of power spectrum templates at high $\ell$ (Planck Collaboration XV 2013).

Other relevant sources include emission from molecular clouds, supernova remnants, and compact H$\text{ii}$ regions inside our own Galaxy, as well as the thermal and kinetic SZ effects, due to inverse Compton scattering of CMB photons off free electrons.
cosmic variance ("theory error")

measurement & its error

WMAP angular power spectrum
Philosophy:

Anomalies are almost always \textit{a posteriori} nature – they are not \textit{(a priori)} predicted

Not every ‘anomaly’ is equally compelling: in this talk, the \textbf{largest-scale} anomalies

Summary:

1. Angular 2-pt function $C(\theta)$ vanishes for $\theta \approx 60$ deg
2. Quadrupole and octopole are unusually planar, and the plane is nearly perpendicular to some special directions on the sky
Missing Large-Angle Power
NOT the “low quadrupole”...
Power at $\theta \approx 60$ deg vanishes in cut-sky maps

Copi et al, arXiv:1310.3831
Low power: COBE and WMAP

Spergel et al 2003: 0.2% of sims have less power at angles >60 deg
\( S_{1/2} \equiv \int_{-1}^{1/2} [C(\theta)]^2 d(\cos \theta) \)

<table>
<thead>
<tr>
<th>Map</th>
<th>U74</th>
<th>KQ75y9</th>
</tr>
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<tbody>
<tr>
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<td>( S_{1/2} ) (( \mu )K)(^4)</td>
<td>( S_{1/2} ) (( \mu )K)(^4)</td>
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<tr>
<td>WMAP ILC 7yr</td>
<td>1620.3</td>
<td>1247.0</td>
</tr>
<tr>
<td>WMAP ILC 9yr</td>
<td>1677.5</td>
<td>1311.8</td>
</tr>
<tr>
<td>Planck SMICA</td>
<td>1606.3</td>
<td>1075.5</td>
</tr>
<tr>
<td>Planck NILC</td>
<td>1618.6</td>
<td>1096.2</td>
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<td>Planck SEVEM</td>
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<tr>
<td>WMAP W 7yr</td>
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<td>1128.5</td>
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<td>WMAP W 9yr</td>
<td>1864.2</td>
<td>1138.3</td>
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<td>Planck HFI 100</td>
<td>1707.5</td>
<td>916.3</td>
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</tr>
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<td>WMAP V 9yr</td>
<td>1840.4</td>
<td>1268.8</td>
</tr>
<tr>
<td>Planck LFI 70</td>
<td>1801.7</td>
<td>1282.1</td>
</tr>
</tbody>
</table>

(frequentist) significance \( \geq 99.7\% \) in all cases
Remarkably consistent across experiments, frequencies, foreground cleanings:

$C(\theta) \; (\mu K^2)$

$\theta \; (\text{deg})$

$\Rightarrow$ primordial? or a statistical fluke?

Copi et al, arXiv:1310.3831
## Summary of missing-power statistics

\[ S_{1/2} \equiv \int_{-1}^{1/2} [C(\theta)]^2 d(\cos \theta) \]

<table>
<thead>
<tr>
<th>Theory</th>
<th>Probability</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCDM</td>
<td>50%</td>
<td>50,000 (\mu K^4)</td>
</tr>
<tr>
<td>best-fit theory (e.g. WMAP (C_1))</td>
<td>5%</td>
<td>8,000 (\mu K^4)</td>
</tr>
<tr>
<td>WMAP cut-sky (&lt;T_i T_j&gt;)</td>
<td>0.03%</td>
<td>1,000 (\mu K^4)</td>
</tr>
</tbody>
</table>
Large-scale alignments
$\ell = 2, 3$ are aligned and planar

$\ell = 2$

$\ell = 3$

$\ell = 4$

$\ell = 3$ is planar: $P \sim 1/20$

$\ell = 2, 3$ is are aligned: $P \sim 1/60$

\[ \hat{L}_\ell^2 \equiv \sum_{m=-\ell}^{\ell} m^2 |a_{\ell m}|^2 \]
\[ \ell^2 \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2 \]
... and still are

<table>
<thead>
<tr>
<th>Map</th>
<th>Uncorrected</th>
<th></th>
<th>DQ corrected</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$</td>
<td>\hat{n}_2 \cdot \hat{n}_3</td>
<td>$</td>
<td>$p$-value (%)</td>
</tr>
<tr>
<td>WMAP ILC 7yr</td>
<td>0.9999</td>
<td>0.006</td>
<td>0.9966</td>
<td>0.327</td>
</tr>
<tr>
<td>WMAP ILC 9yr</td>
<td>0.9985</td>
<td>0.150</td>
<td>0.9948</td>
<td>0.511</td>
</tr>
<tr>
<td>Planck NILC</td>
<td>0.9902</td>
<td>0.955</td>
<td>0.9988</td>
<td>0.118</td>
</tr>
<tr>
<td>Planck SEVEM</td>
<td>0.9915</td>
<td>0.825</td>
<td>0.9995</td>
<td>0.055</td>
</tr>
<tr>
<td>Planck SMICA</td>
<td>0.9809</td>
<td>1.883</td>
<td>0.9965</td>
<td>0.338</td>
</tr>
</tbody>
</table>

- Based on $10^6$ simulated maps
- We inpaint Planck maps with Galactic cuts - numerically heavy part of calculation
- Correcting for the kinematic quadrupole (DQ) is important
Multipole vectors!

Spherical Harmonics:

\[
\frac{\delta T}{T}(\theta, \phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi), \quad C_\ell \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2
\]

Multipole Vectors:

\[
\sum_{m=-\ell}^{\ell} a_{lm} Y_{lm}(\theta, \phi) = A^{(\ell)} \left( v_1^{(\ell)} \cdot e \right) \cdots \left( v_{\ell}^{(\ell)} \cdot e \right)
\]

"\(a^{(\ell)}_{i_1 \ldots i_{\ell}} \leftrightarrow A^{(\ell)} \left[ v_1^{(\ell)} \otimes v_2^{(\ell)} \otimes \ldots \otimes v_{\ell}^{(\ell)} \right]""

L\(\ell\)th multipole \(\leftrightarrow\) \(L\) (headless) vectors, plus a constant

Multipole vectors of our sky

L=2

L=3

L=4

L=5

L=6

L=7

L=8

http://www.phys.cwru.edu/projects/mpvectors/
Multipole vectors, intuitively

Potential of:

Dipole: $\nabla_{v_1} \frac{1}{r} \left[ = -\frac{v_1 \cdot r}{r^3} \right]$

Quadrupole: $\nabla_{v_2} \nabla_{v_1} \frac{1}{r} \left[ = \frac{3(v_1 \cdot r)(v_2 \cdot r) - r^2(v_1 \cdot v_2)}{r^5} \right]$

..........

l’th multipole: $\nabla v_\ell \ldots \nabla_{v_2} \nabla_{v_1} \frac{1}{r}$

$v_1 \ldots v_\ell$ are the multipole vectors
Why multipole vectors?

- A different representation of the CMB sky than the spherical harmonics, related highly non-linearly
- Ideally suited for looking for planarity/directionality
- Many interesting properties, theorems (Katz & Weeks 2004, Weeks 2005, Lachieze-Rey 2004, Dennis 2005...)
- (Reviewed in Copi, Huterer, Schwarz & Starkman MNRAS 2006)

Also:

discussed by J.C. Maxwell in his “Treatise on Electricity and Magnetism” in 1892!
Normals to multipole vectors

\[ w^{(\ell)}_{ij} \equiv \pm \left( v^{(\ell)}_i \times v^{(\ell)}_j \right) \]  

“oriented areas”
Ecliptic Plane

L=2+3 map

Ecliptic plane

Normals to quad, octopole

Copi et al, arXiv:1311.4562
Probability for alignment of Q+O structure with Ecliptic: 2%-4%

Probability for alignment of Q+O structure with Dipole: 0.1%-0.4%

which are independent of the previously quoted

Probability for Q and O to be mutually aligned and planar 0.05%-0.3%

Copi et al, arXiv:1311.4562
Other notable claimed anomalies

- North/South power asymmetry
- CMB Cold Spot
The “cold spot”

Radius about 5 degrees, detected with wavelets; significant at >99.5% C.L.
Vielva et al. 2004

BUT: evidence disappears once you try “finding” it with something other than a mexican hat wavelet (e.g. a top hat)
Zhang & Huterer, 2010
Cold spot in the galaxy distribution??
In same direction as the CMB cold spot

- Detected in Pan-STARRS1 in same angular direction as CMB cold spot!
- However, ISW effect from this Pan-STARRS “hole” only explains 10% of the CMB cold spot (Zibin 2014, Nadathur et al 2014)
N/S power asymmetry

South (ecliptic) has more power than north

Eriksen et al 2004;
Hansen, Banday and Gorski 2004
shown below:  

$$2 \frac{C_{\ell}^{\text{south}} - C_{\ell}^{\text{north}}}{C_{\ell}^{\text{south}} + C_{\ell}^{\text{north}}}$$
Attempts at a theoretical explanation: missing large-angle power and alignments
4 classes of explanations:

- **Astrophysical** (e.g. an object or other source of radiation in the Solar System)
  - BUT: we think we know the Solar System. It would need to be a large source and undetected in data cross-checks.

- **Instrumental** (e.g. there is something wrong with WMAP instrument measuring CMB at large scales)
  - BUT: the instruments have been extremely well calibrated and checked. Plus, why would they pick out the Ecliptic plane?

- **Cosmological** (e.g. some property of the universe – inflation or dark energy for example – that we do not understand)
  - This is the most exciting possibility. BUT: why would the new/unknown physics pick out the Ecliptic plane?
  - These alignments are a pure fluke!
  - BUT: they are <0.1% likely!
Suppose that the WMAP detectors are slightly (1%) nonlinear

\[ T_{\text{obs}}(\hat{n}) = T(\hat{n}) + \alpha_2 T(\hat{n})^2 + \alpha_3 T(\hat{n})^3 + \ldots \]

The biggest signal on the sky is the dipole

\[ T(\hat{n}) = 3.3 mK \cos(\theta) \]

So with \( \alpha_2 \sim \alpha_3 \sim 10^{-2} \), dipole anisotropy is modulated into a \( 10^{-5} \) quadrupole and octopole with \( m = 0 \) in the dipole frame.

Sadly: doesn’t work since would have been seen when observing \( \sim 1K \) sources (in lab, Jupiter, etc).

Gordon, Hu, Huterer & Crawford 2005
Example: Spontaneous Isotropy Breaking

- To explain/model the apparent lack of isotropy on largest scales seen by WMAP

\[ V(\phi) = V_0[1 + f \cos(\phi/M_0)] \]

\[ \phi(z) = A + Bz \]

Modulates the CMB anisotropy through the ISW effect
Nonlinear modulation \( \Rightarrow \) a range of multipoles affected

Gordon, Hu, Huterer & Crawford 2005
Additive schemes “don’t work”

\[ \hat{T}(\hat{n}) = T_{\text{intr}}(\hat{n}) + T_{\text{extra}}(\hat{n}) \]

Double (likelihood) penalty:

- Intrinsic sky is **less likely** than observed
- Requires a **chance cancellation**

True for all additive schemes:
- Solar System contamination,
- Bianchi models,
- etc

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Gordon, Hu, Huterer & Crawford 2005
Multiplicative modulation can work

\[ \hat{T}(\hat{n}) = T(\hat{n}) [1 + w(\hat{n})] \]

\[ w(\hat{n}) \propto Y_{20}(\hat{n}) \] example

Gordon, Hu, Huterer & Crawford 2005
More recently, Bennett et al. (2011) also comment (within low resolution) that the simple modulation model in Eq. 35 is inadequate and within 3σ, the amplitude of the dipole is consistent with zero. However, the amplitude of the dipole is consistent with zero within 3σ at the low-resolution map.

Since this approach enables the reconstruction of the CMB sky, we then extend the analysis to higher resolution using maps at the resolution of the CMB maps.

We establish that significant power in the dipolar modulation is limited to \( L = 1 \) and \( L = 2 \), and \( L = 3 \). The modulation spectra obtained from the Doppler boost induced BipoSH coherency, we first implement an equivalent description in terms of the Doppler boost induced anisotropy, and note that these results are consistent with those derived from the Commander, NILC, SEVEM, SMICA, and WMAP data (Eriksen et al. 2007a; Hoftuft et al. 2009). Note that the consistency between component separation algorithms (Commander, NILC, SEVEM, SMICA) is reached using the low-resolution map.

In Fig. 32, we compare the results from all four CMB solutions for all smoothing scales. At least two significant peaks are observed for the 3-year and 5-year Planck data (Eriksen et al. 2007a; Hoftuft et al. 2009). The modulation at the Doppler boost induced anisotropy is not detected by the modulation estimator, but a null result, as seen in the derived maximum-likelihood point and the isotropic model, is reached using the low-resolution map by Eriksen et al. (2007a), demonstrating consistency only for the lowest bin (Planck Collaboration XV (2014)).

In Fig. 33, we show the log-likelihood distribution for the dipolar modulation and the CMB multipoles, as a function of smoothing scale. The power spectrum parameters are kept fixed at the best-fit values for both points, leading to a slight trend toward a steeper possible value of \( \bar{v} = 1.0 \). Taken at face value, the results presented here are suggestive but clearly not decisive, resulting in an unchanged situation with respect to the Planck Collaboration XXVII (2014). To understand why a Doppler boost-induced anisotropy is not detected by the modulation estimator, we first implement an equivalent description in terms of coherency, with the help of the Doppler boost induced anisotropy. The derived maximum-likelihood point and the isotropic model, as measured by the dipole modulation likelihood, are consistent with each other. Dipole, \( L = 1 \), is only significant at \( \ell = 64 \), \( \ell = 128 \), \( \ell = 192 \), \( \ell = 256 \), \( \ell = 320 \), \( \ell = 384 \). Consistency between component separation algorithms is seen here. First, while there is clearly interesting points can be seen here. First, while there is clearly an instrument, it is expected that the observed CMB map is statistically consistent with the local maximum. In particular, there appears to be a slight trend toward a steeper possible value of \( \bar{v} = 1.0 \).
No compelling theoretical (or systematic) explanations for large-angle anomalies as yet
Can other observations confirm or refute the anomalies?

CMB polarization?
Large-scale structure?
If this is a statistical fluke, CMB polarization may successfully confirm that

Copi et al, *MNRAS* 434, 3590 (2013),
Can one see effect of such large-angle power suppression in future LSS surveys?

Answer: yes, though it will be challenging; below, hypothesis that $P(k)$ is suppressed, using LSST

Consistent with suppressed large-angle CMB power
Dangers of working on anomalies: geocentrists are very interested!

Entertaining story by Adam Becker on Story Collider: “How to save your PhD supervisor”
https://soundcloud.com/the-story-collider/adam-becker-how-to-save-your-phd-supervisor
Conclusions

• Angular power is nearly zero at $\theta \gtrapprox 60$ deg

• Quadrupole and octopole planar, nearly perpendicular to ecliptic plane

• Several separate $\gtrapprox 3$-sigma anomalies, they are $\alpha$ posteriori...

• ... but all have to do with largest observed scales!

• Suppression of $C(\theta)$ seems very robust to map/experiment choice, frequency, etc

• No compelling explanations to date, cosmological or systematic
EXTRA SLIDES
Distance from center of spot (degrees)

Profile (arbitrary units)

Disk

Wavelet

Averaged CMB temperature

Zhang & Huterer, arXiv:0908.3988
**Theorem:** Every homogeneous polynomial $P$ of degree $\ell$ in $x$, $y$ and $z$ may be written as

$$P(x, y, z) = \lambda \cdot (a_1 x + b_1 y + c_1 z) \cdot (a_2 x + b_2 y + c_2 z) \ldots (a_\ell x + b_\ell y + c_\ell z) + (x^2 + y^2 + z^2) \cdot R$$

where $R$ is a homogeneous polynomial of degree $\ell - 2$. The decomposition is unique up to reordering and rescaling the linear factors.

**Example ($Y_{20}$):**

$$P(x, y) = x^2 + y^2 - 2z^2 = -3(z)(z) + (x^2 + y^2 + z^2)(1)$$

Katz & Weeks, astro-ph/0405631
Harmonic inpainting: produces mutually consistent reconstructions of maps

![Graphs showing harmonic inpainting results for different maps and methods.](image)
MLE reconstruction is ‘optimal’, but
− need to smooth map => mix up with Gal cut region
− if not smoothing, returns a biased result:

![Graph showing MLE reconstruction with Pseudo-CL and MLE comparisons]

- Pixel based
- Reconstructed
Published values of the power spectrum coefficients differ by many times the error

\[ D_\ell \equiv \frac{\ell(\ell + 1)C_\ell}{2\pi} \]

<table>
<thead>
<tr>
<th>Data Release</th>
<th>( D_2 )</th>
<th>( D_3 )</th>
<th>( D_4 )</th>
<th>( D_5 )</th>
<th>( S_{1/2} ) (( \mu K^4 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMAP 3yr</td>
<td>211</td>
<td>1041</td>
<td>731</td>
<td>1521</td>
<td>8330</td>
</tr>
<tr>
<td>WMAP 5yr</td>
<td>213</td>
<td>1039</td>
<td>674</td>
<td>1527</td>
<td>8915</td>
</tr>
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<td>WMAP 7yr</td>
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<td>1051</td>
<td>694</td>
<td>1517</td>
<td>8938</td>
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<td>WMAP 9yr</td>
<td>151</td>
<td>902</td>
<td>730</td>
<td>1468</td>
<td>5797</td>
</tr>
<tr>
<td>Planck R1</td>
<td>299</td>
<td>1007</td>
<td>646</td>
<td>1284</td>
<td>8035(^a)</td>
</tr>
</tbody>
</table>

\(^a\)The Gaussian error was used for planck data release 1.
Alignments from WMAP and Planck

Figure 5. Quadrupole and octopole multipole vectors for the DQ corrected SMICA map in Galactic coordinates. The background shows the quadrupole+octopole pattern from the DQ corrected SMICA map. The multipole vectors are shown as circles, in red and labelled 'Qv' for the quadrupole and in black and labelled 'Ov' for the octopole. The direction of the area vectors defined in Eq. (23), \( \hat{w}(\`;i,j) \), are shown as squares. Again the quadrupole area vector is in red and labelled 'Qa' and the octopole area vectors are in black and labelled 'Oa'. Since the multipole vectors are only determined up to a sign each vector appears twice in the figure. The area vectors have only been plotted in the southern hemisphere to avoid cluttering the plot. The maximum angular momentum dispersion direction for the octopole, \( \hat{n}_3 \), is shown as the black star. Since \( \hat{n}_2 = \hat{w}(2;1,2) \) it is also represented by the red square. The direction of \( \hat{n}_2 \) without the DQ correction is shown as the red diamond. For reference also shown in the figure is the Ecliptic plane (black line), the locations of the north (NEP) and south (SEP) Ecliptic poles, and the direction of our motion with respect to the CMB (dipole). The coordinates of the vectors are listed in Table 6.

Table 7. The \( S \) and \( T \) alignment statistics from Eq. (25) for various directions. Listed are the \( p \)-values in per cent of \( \nu_{CDM} \) producing a value larger than that found in the given map based on \( 10^6 \) realizations of \( \nu_{CDM} \). The directions tested are the quadrupole+octopole alignment (Q+O), the Ecliptic plane, the north Galactic pole (NGP), and the direction of our motion with respect to the CMB (dipole). The results for the SMICA and NILC maps are based on the average of the \( S \) statistic from 5 \( \times \) 10^5 harmonic inpaintings of these maps.

<table>
<thead>
<tr>
<th>Map</th>
<th>Q+O</th>
<th>Ecliptic Plane</th>
<th>NGP</th>
<th>dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( S )</td>
<td>( T )</td>
<td>( S )</td>
<td>( T )</td>
</tr>
<tr>
<td>WMAP ILC 7yr</td>
<td>0.22</td>
<td>0.10</td>
<td>2.66</td>
<td>2.70</td>
</tr>
<tr>
<td>WMAP ILC 9yr</td>
<td>0.18</td>
<td>0.08</td>
<td>1.96</td>
<td>1.82</td>
</tr>
<tr>
<td>Planck NILC</td>
<td>1.85</td>
<td>1.05</td>
<td>2.80</td>
<td>3.04</td>
</tr>
<tr>
<td>Planck SEVEM</td>
<td>0.41</td>
<td>0.22</td>
<td>2.52</td>
<td>2.94</td>
</tr>
<tr>
<td>Planck SMICA</td>
<td>1.62</td>
<td>0.93</td>
<td>3.74</td>
<td>4.16</td>
</tr>
</tbody>
</table>
Systematic checks: foreground missubtraction

Adding (known) foregrounds leads to galactic, and not ecliptic, alignments
