Is the large-angle CMB anomalous?

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,

The large-angle CMB is still anomalous

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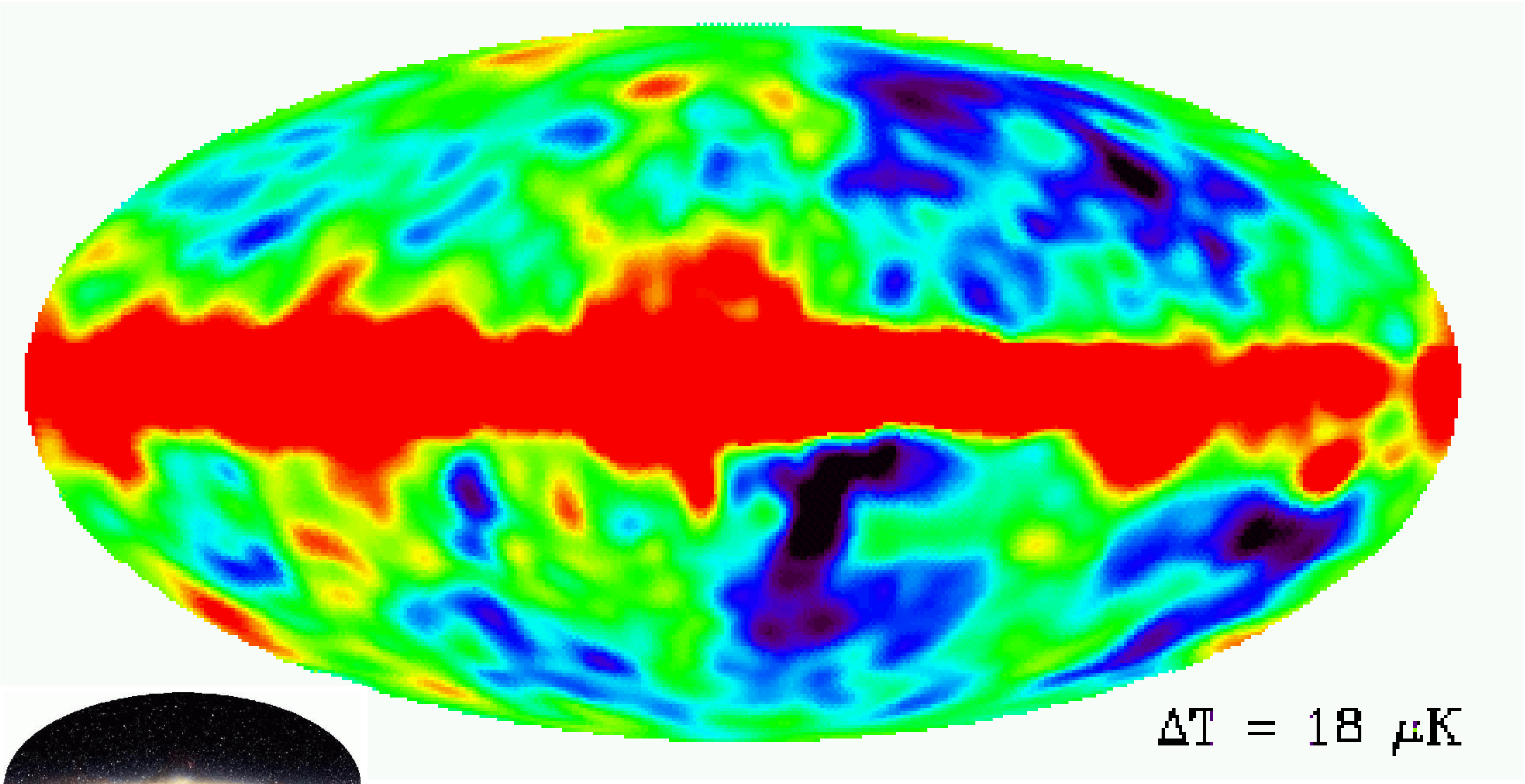
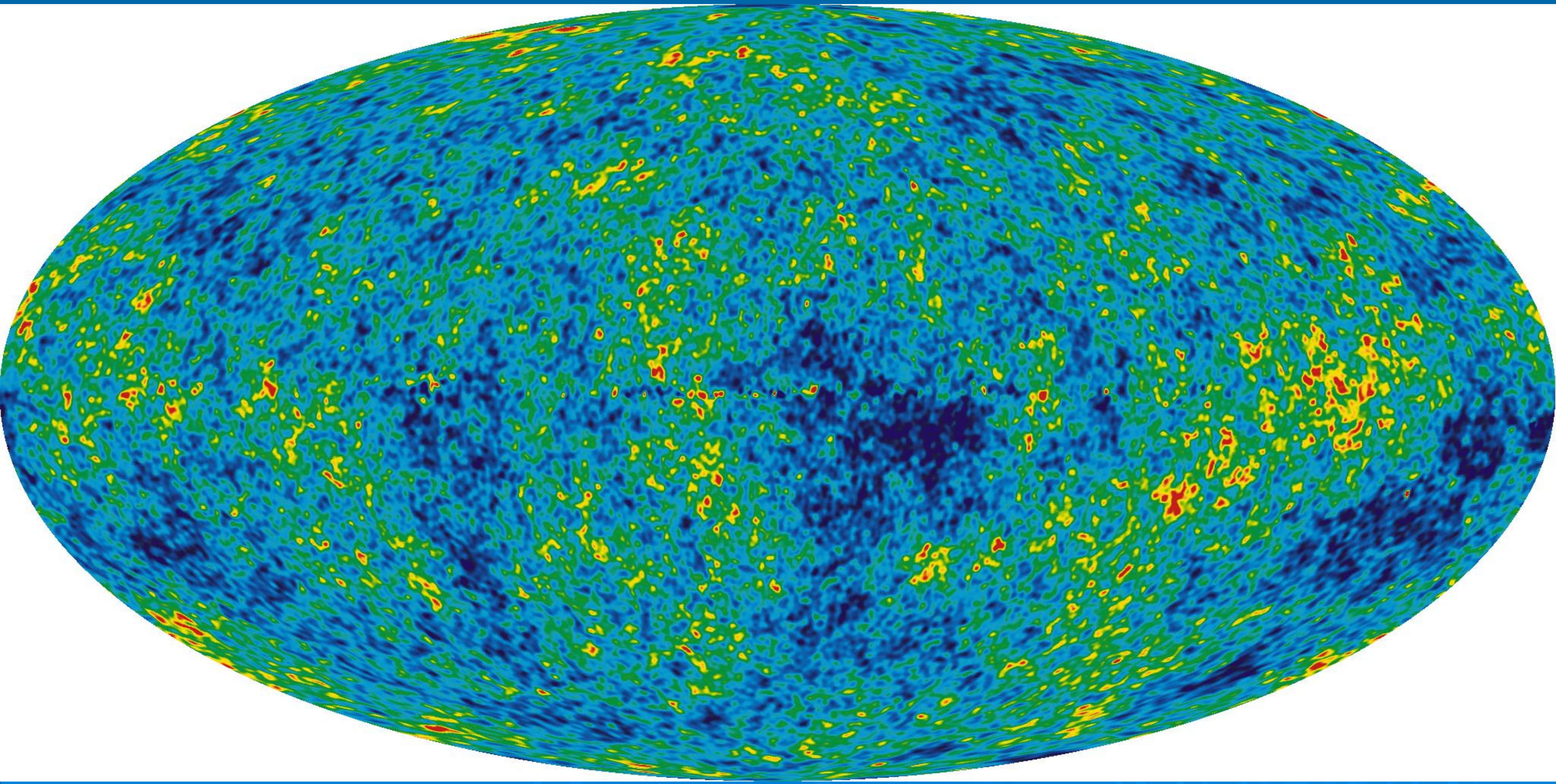
COBE - DMR

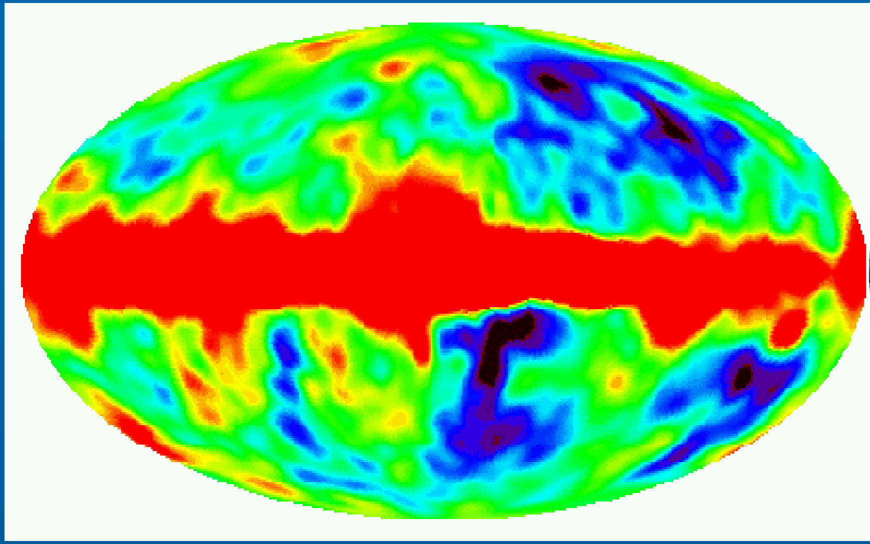


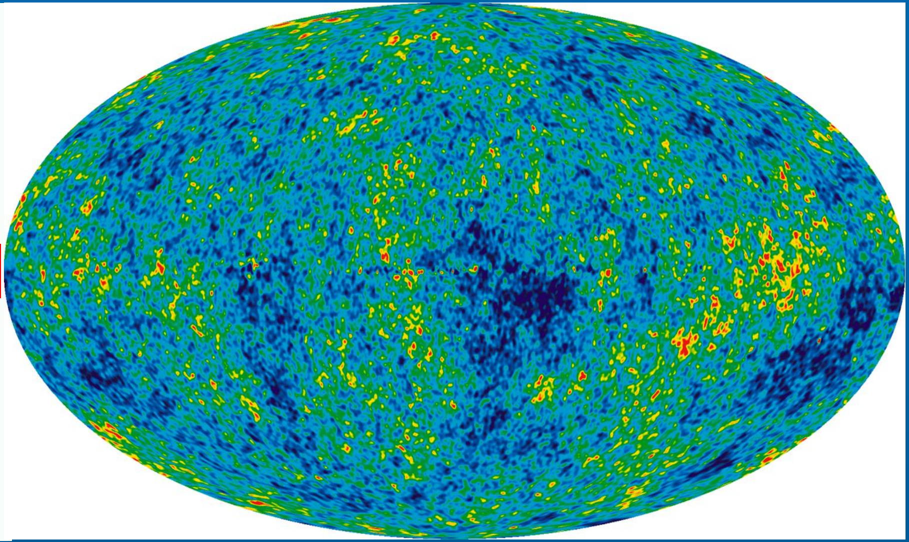
The WMAP Sky



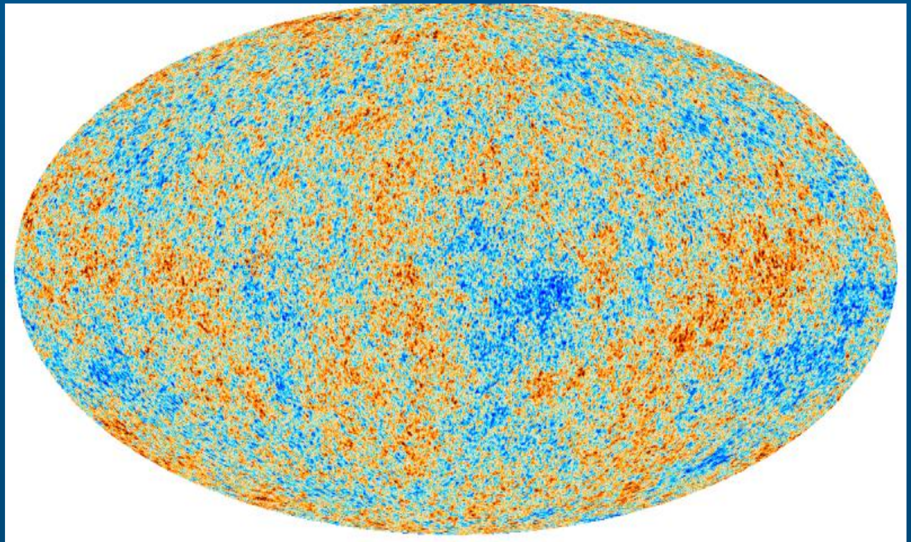
NASA/WMAP Science team

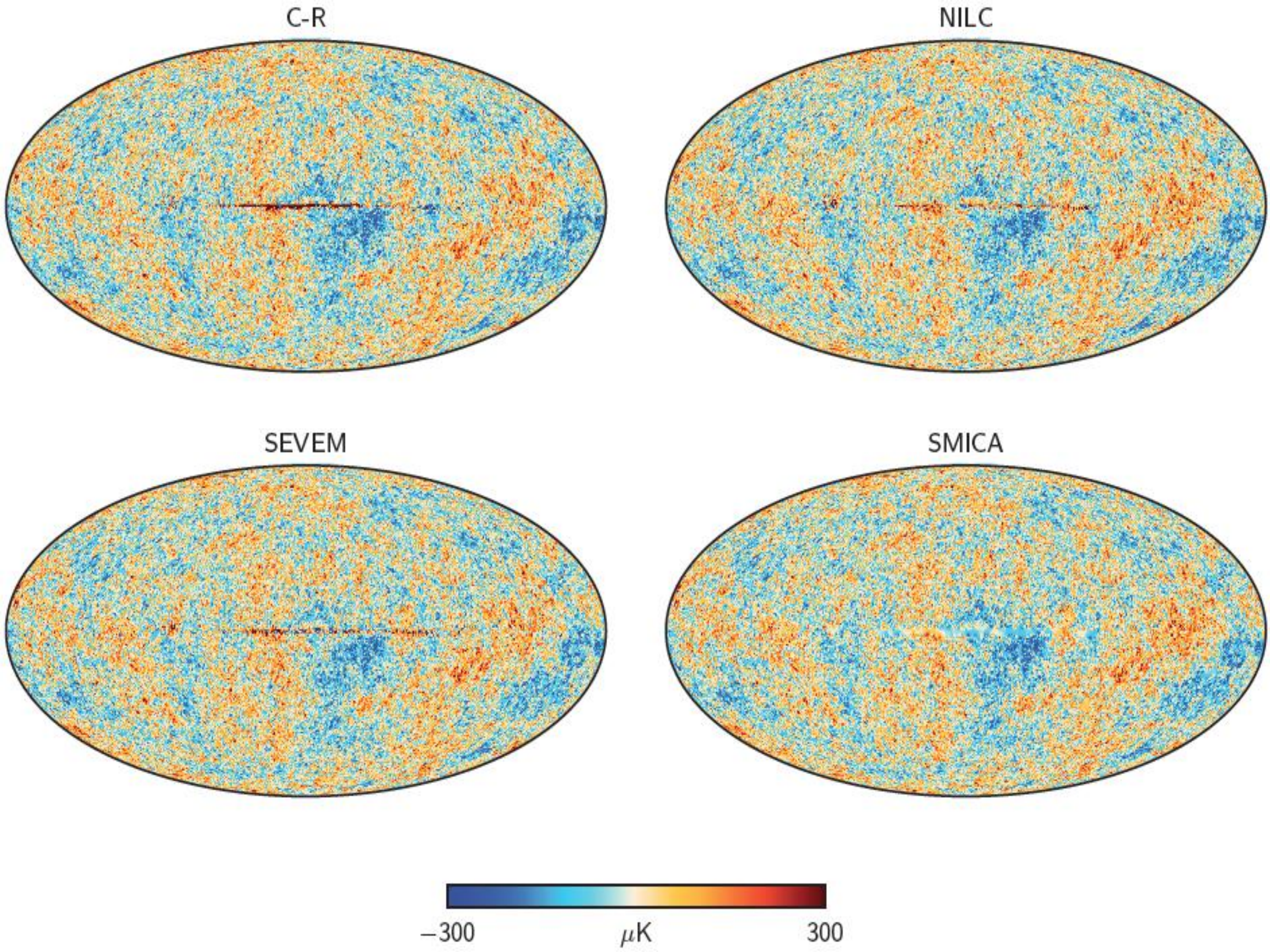
COBE vs. WMAP





vs. Planck





C-R
NILC
SEVEM
SMICA
−300
μK
300

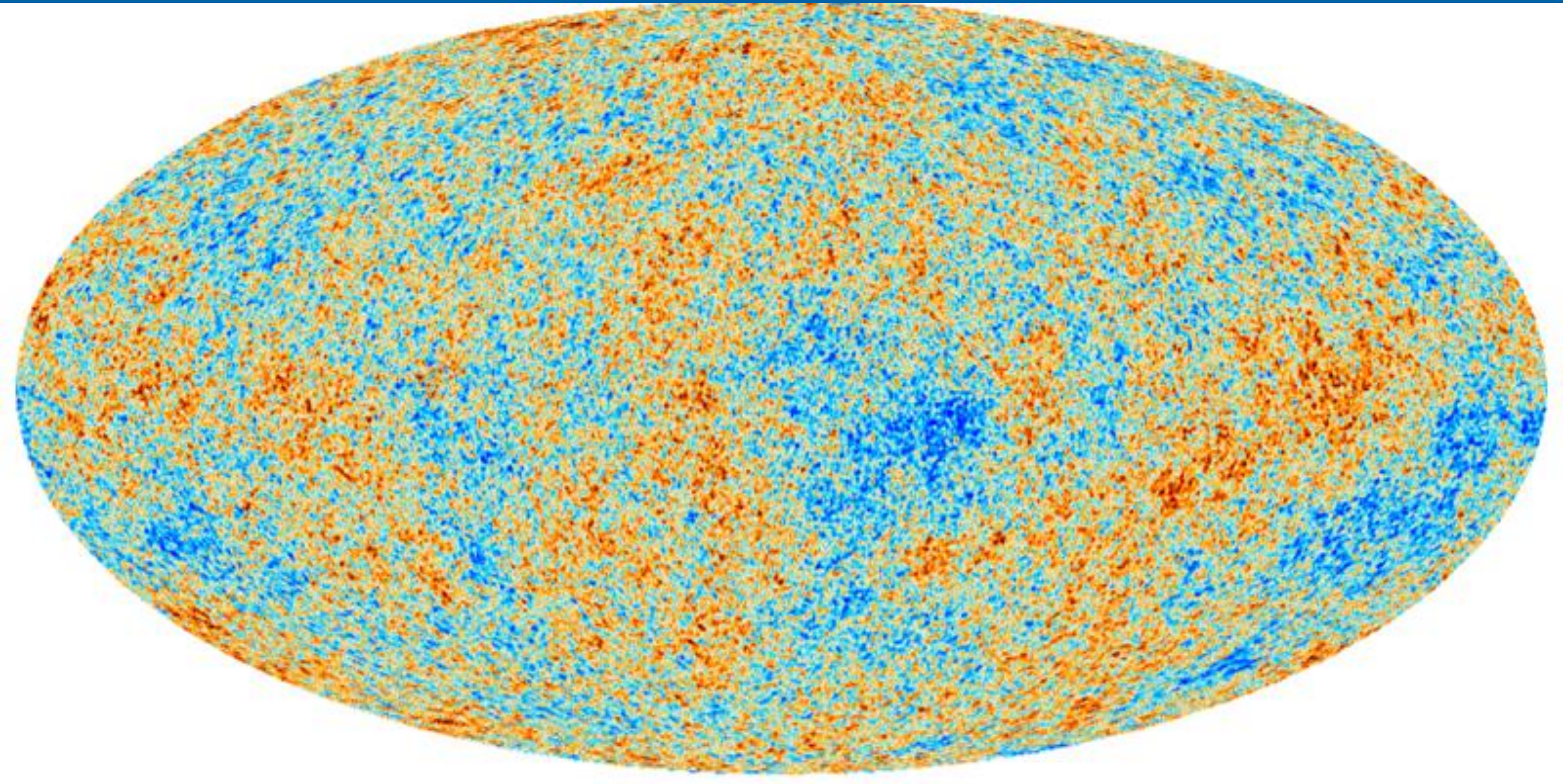
Outline

The largest scale properties of the universe:

- Alignments at low-ℓ :
  - Multipole vectors and the full sky failure of statistical isotropy.
  - seeing the solar system in the microwave background
- The low-ℓ / large-angle problem
  - from C_ℓ to $C(\theta)$

Troubles in cosmological paradise

The CMB Sky



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Angular Power Spectrum

$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$

$$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

$C_\ell = (2\ell + 1)^{-1} \sum_m |a_{\ell m}|^2$

Standard model for the origin of fluctuations (inflation):

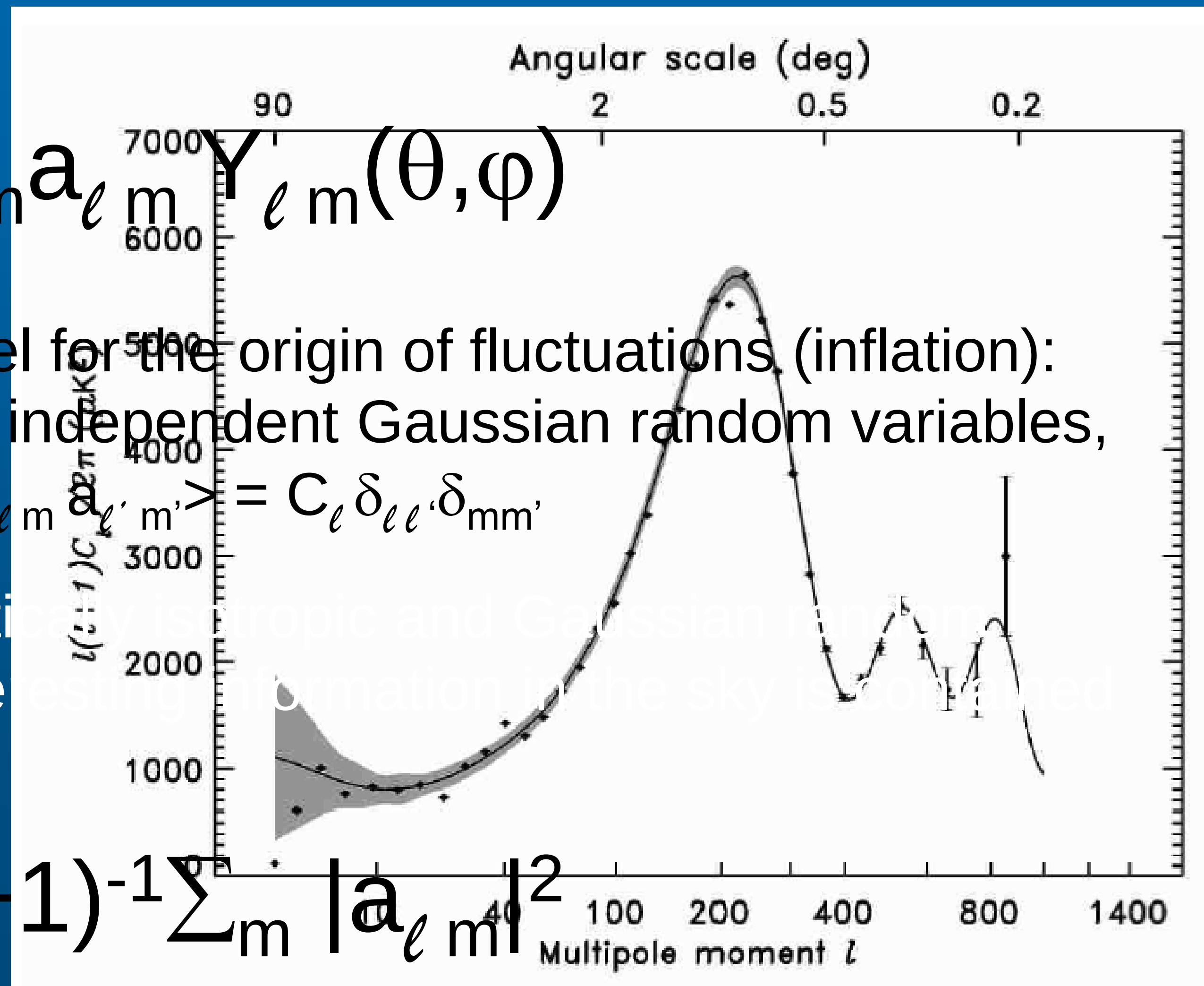
$a_{\ell m}$ are independent Gaussian random variables, with $\langle a_{\ell m}\, a_{\ell' m'} \rangle = C_\ell\, \delta_{\ell \ell'} \delta_{mm'}$

6 parameter fit to >>6 points

$\Rightarrow$ Sky is statistically isotropic and Gaussian random:

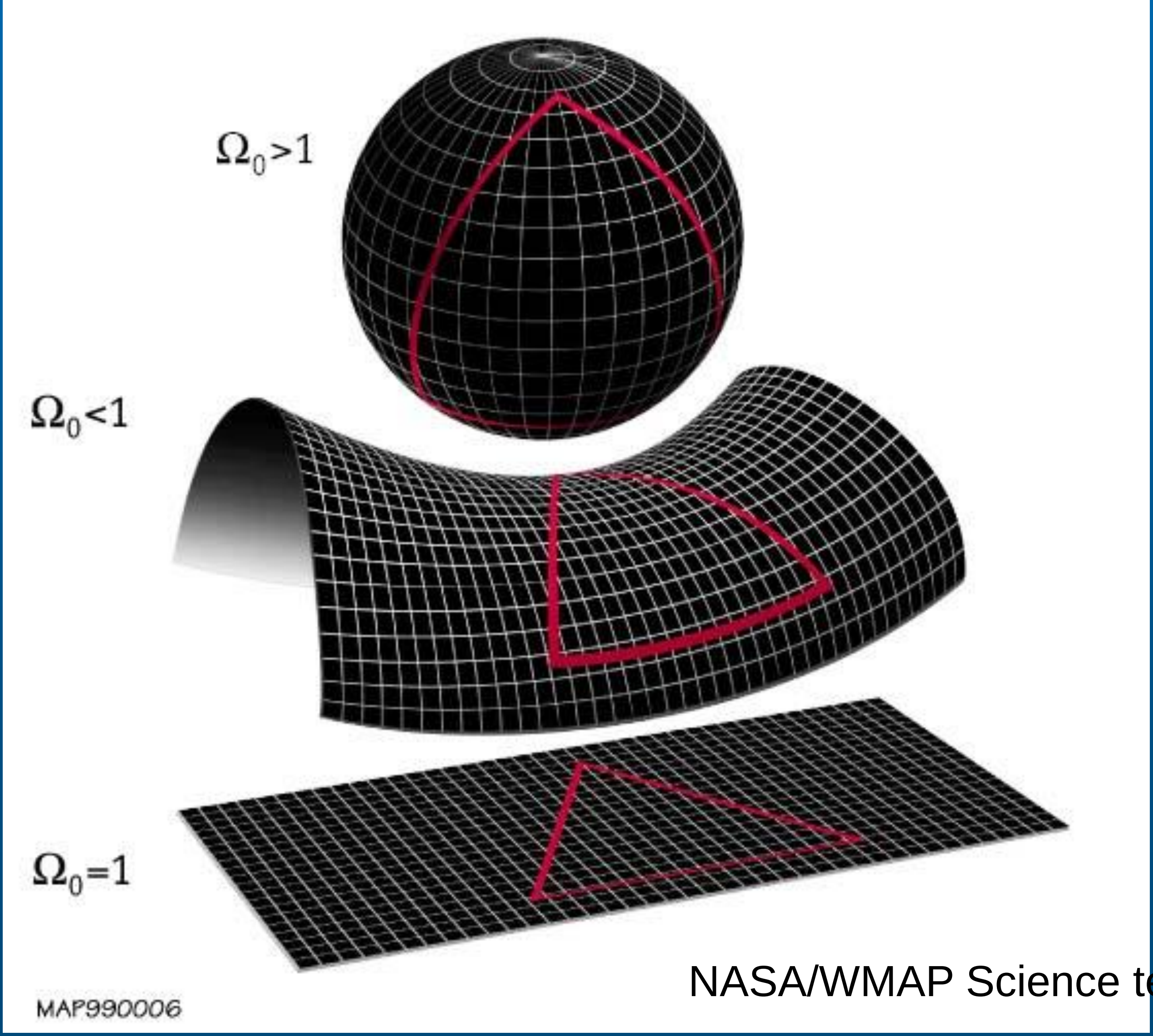
ALL interesting information in the sky is contained in C_ℓ

$$C_\ell = (2\ell + 1)^{-1} \sum_m |a_{\ell m}|^2$$



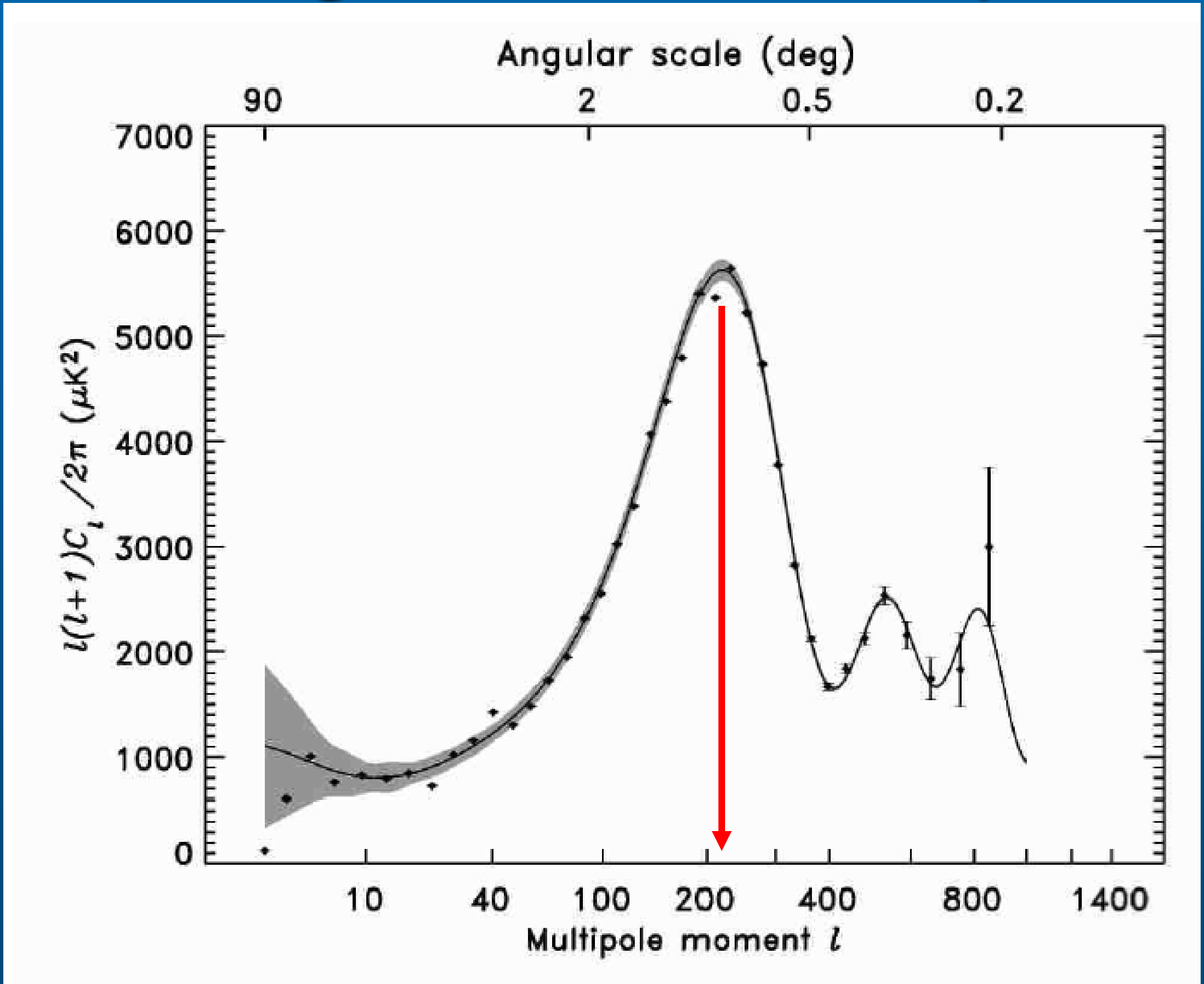
NASA/WMAP Science team

Measuring the shape of space



NASA/WMAP Science team

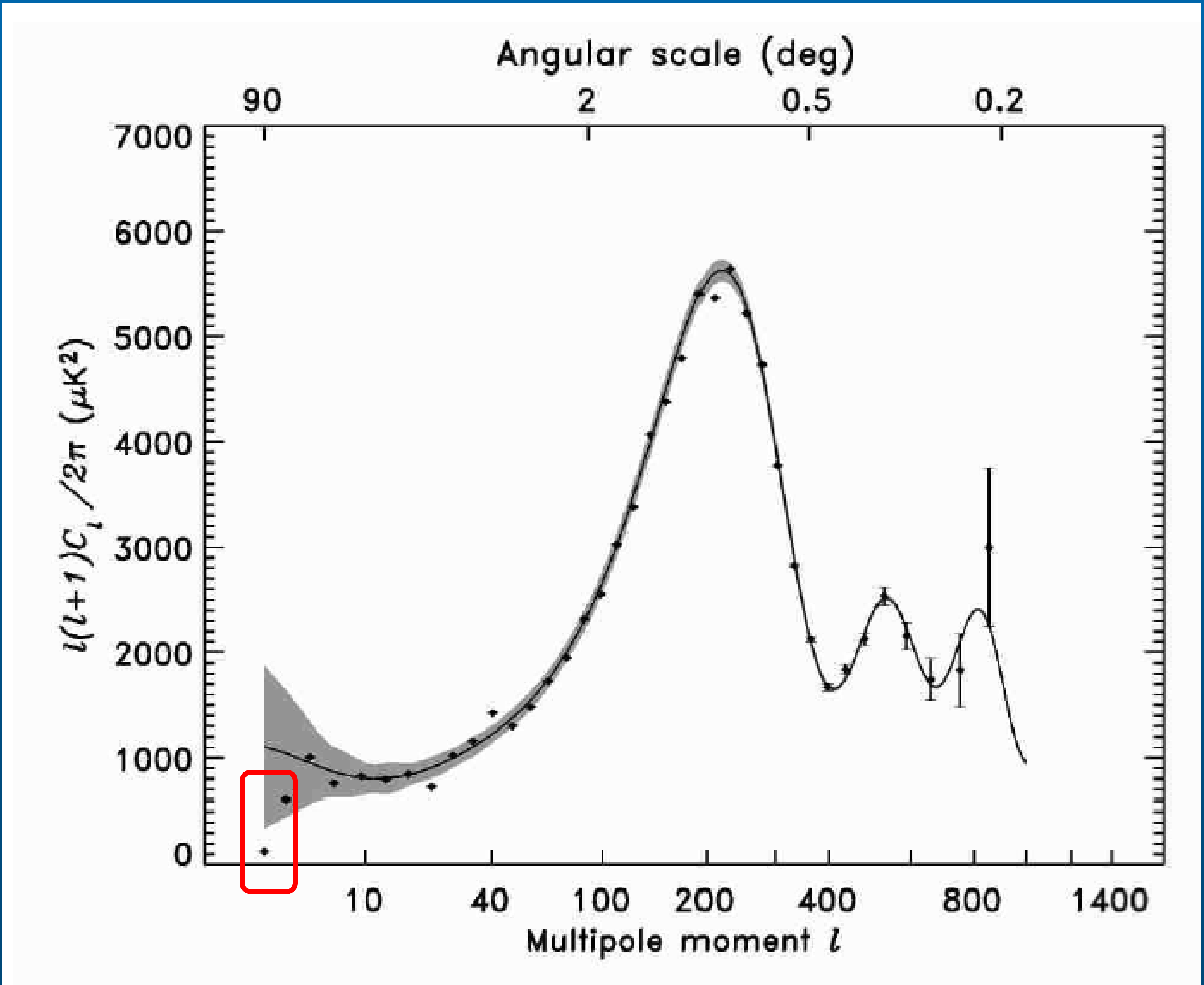
Angular Power Spectrum



Ω= 1 ± .0x

Is there anything interesting left to learn about the Universe on large scales?

Motivation: “The Low-*l* Anomaly”



Beyond C_ℓ: Searches for Departures from Gaussianity/Statistical Isotropy

- angular momentum dispersion axes (da Oliveira-Costa, *et al.*)
- Genus curves (Park)
- Spherical Mexican-hat wavelets (Vielva *et al.*)
- Bispectrum (Souradeep *et al.*)
- North-South asymmetries in multipoint functions
  (Eriksen *et al.*, Hansen *et al.*)
- Cold hot spots, hot cold spots (Larson and Wandelt)
- Land & Magueijo scalars/vectors
- even/odd C_ℓ anomaly
- **multipole vectors**
  (Copi, Huterer & GDS; Schwarz, SCH; CHSS;
  also Weeks; Seljak and Slosar; Dennis)

Multipole Vectors

Q: What are the directions associated with the ℓ th multipole:

$$\Delta T_\ell(\theta,\phi) \equiv \sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) \;\; ?$$

Dipole (ℓ =1) :

$$\sum_m a_{1m} Y_{1m}(\theta,\phi) = A^{(1)} (\hat{u}_x^{(1,1)}, \hat{u}_y^{(1,1)}, \hat{u}_z^{(1,1)}) .(\sin\theta \cos\phi, \sin\theta \sin\phi, \cos\theta)$$

Advantages: 1) $\hat{u}^{(1,1)}$ is a vector, $A^{(1)}$ is a scalar

2) Only $A^{(1)}$ depends on C_1

Shape and Alignment of the Quadrupole and Octopole

A. de Oliveira-Costa, M. Tegmark, M. Zaldarriaga, A. Hamilton. **Phys.Rev.D69:063516,2004**
astro-ph/0307282

For each ℓ, find the axis $\mathbf{n}_\ell$ around which the angular momentum dispersion :

$$(\Delta L)^2 \equiv \sum_m m^2 \, |a^{\ell m}(\mathbf{n}_\ell)|^2$$

is maximized

Results (WMAP1):

	Probability
• octopole is unusually "planar" (dominated by $\|m\| = 3$ if $z \equiv \mathbf{n}_3$).	1/20??
• $\mathbf{n}_2 \cdot \mathbf{n}_3 = 0.9838$	1/60

Multipole Vectors

General ℓ, write:

$$\sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) \approx$$
$$A^{(\ell)} \, [(\hat{u}^{(\ell,1)} \cdot \hat{e}) \ldots (\hat{u}^{(\ell,\ell)} \cdot \hat{e}) \text{ - all traces}]$$

$$\{\{a_{\ell m,}\ m=-\ell,\ldots,\ell\},\ \ell=(0,1,)2,\ldots\} \Rightarrow$$

$$\{A^{(\ell)}, \{\hat{u}^{(\ell,i)}, \ell=1,\ldots \ell\}, \ell=(0,1,)2,\ldots\}$$

Advantages: 1) $\mathbf{\hat{u}}^{(\ell,i)}$ are vectors, $\mathbf{A}^{(\ell)}$ is a scalar

2) Only $\mathbf{A}^{(\ell)}$ depends on C_ℓ

Maxwell Multipole Vectors

$$\sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) = \left[(\mathbf{u}^{(\ell,1)} \cdot \nabla) \ldots (\mathbf{u}^{(\ell,\ell)} \cdot \nabla) r^{-1} \right]_{r=1}$$

manifestly symmetric AND trace free:

$$\nabla^2 (1/r) \propto \delta(r)$$

J.C. Maxwell, *A Treatise on Electricity and Magnetism*, v.1, 1873 (1st ed.)

Area Vectors

Notice:

- Quadrupole has 2 vectors, *i.e.* quadrupole is a plane
- Octopole has 3 vectors, *i.e.* octopole is 3 planes

Suggests defining:

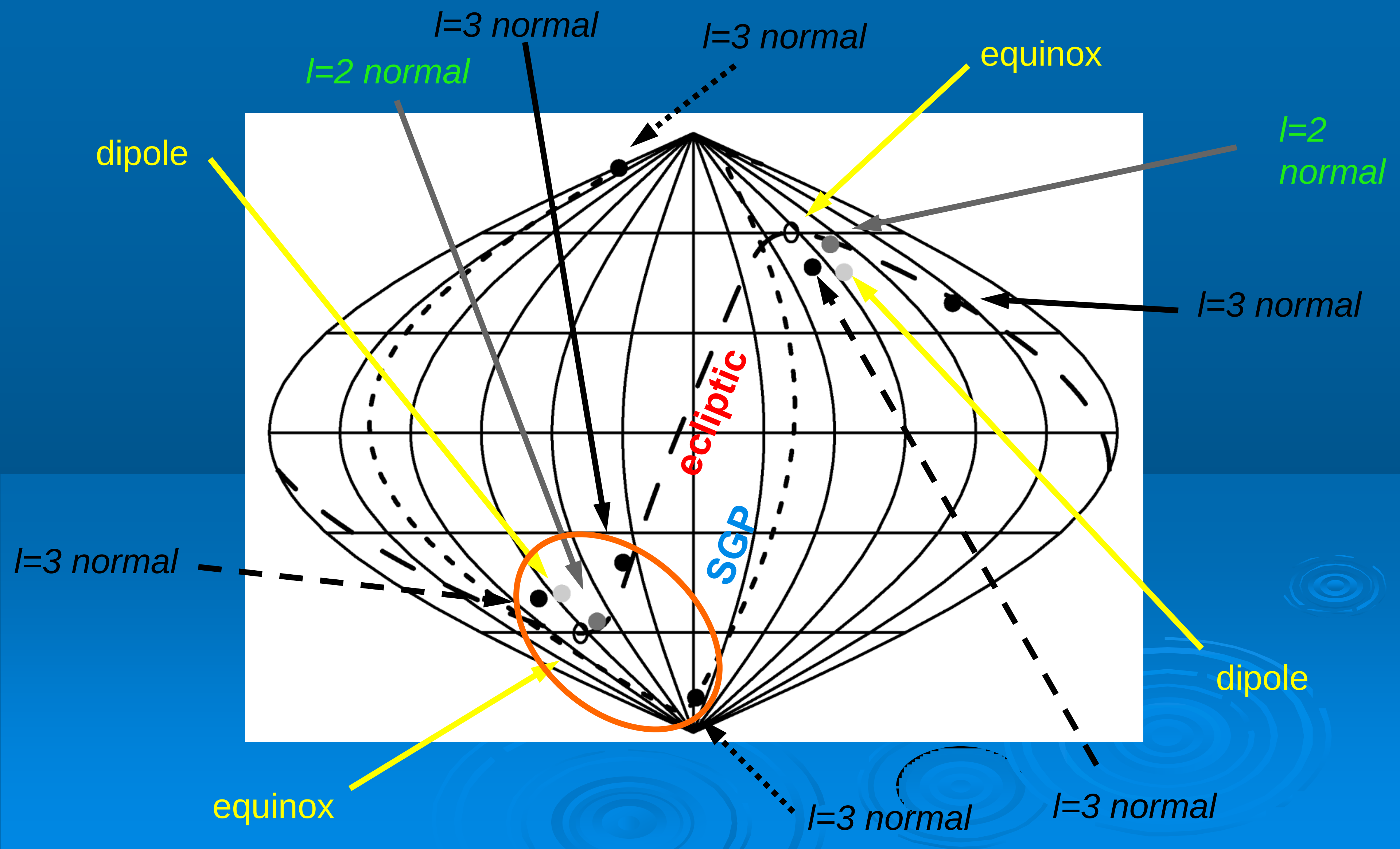
$\mathbf{w}^{(\ell,i,j)} \equiv (\hat{u}^{(\ell,i)} \times \hat{u}^{(\ell,j)})$ "area vectors"

Carry some, but not all, of the information

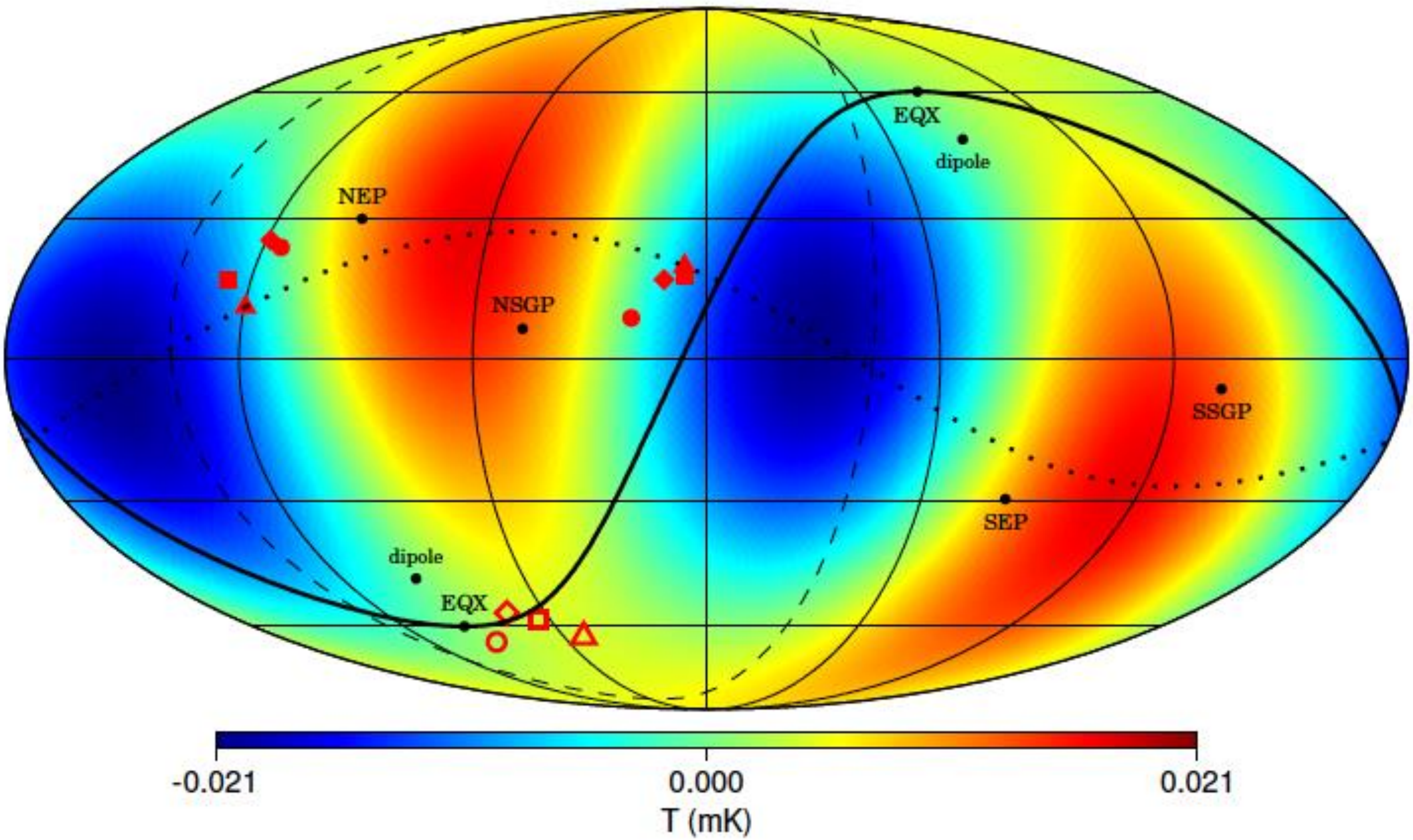
Relation to n_i:

- $\mathbf{w}^{(2,2,2)} \parallel n_2$
- octopole is perfectly planar if $\mathbf{w}^{(3,1,2)} \parallel \mathbf{w}^{(3,2,3)} \parallel \mathbf{w}^{(3,3,1)}$ and then: $n_3 \parallel \mathbf{w}^{(3,i,j)}$

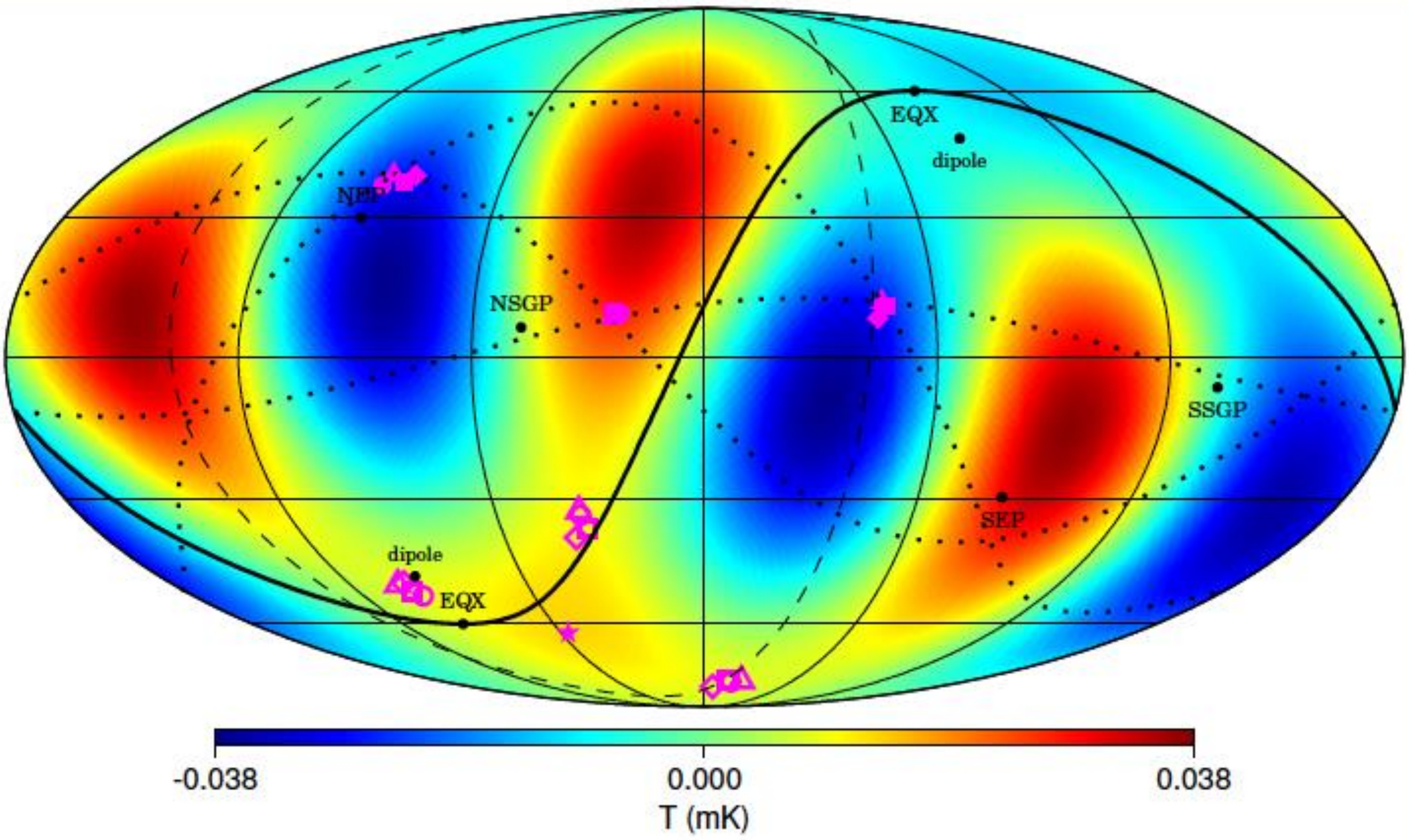
l=2&3 Area Vectors



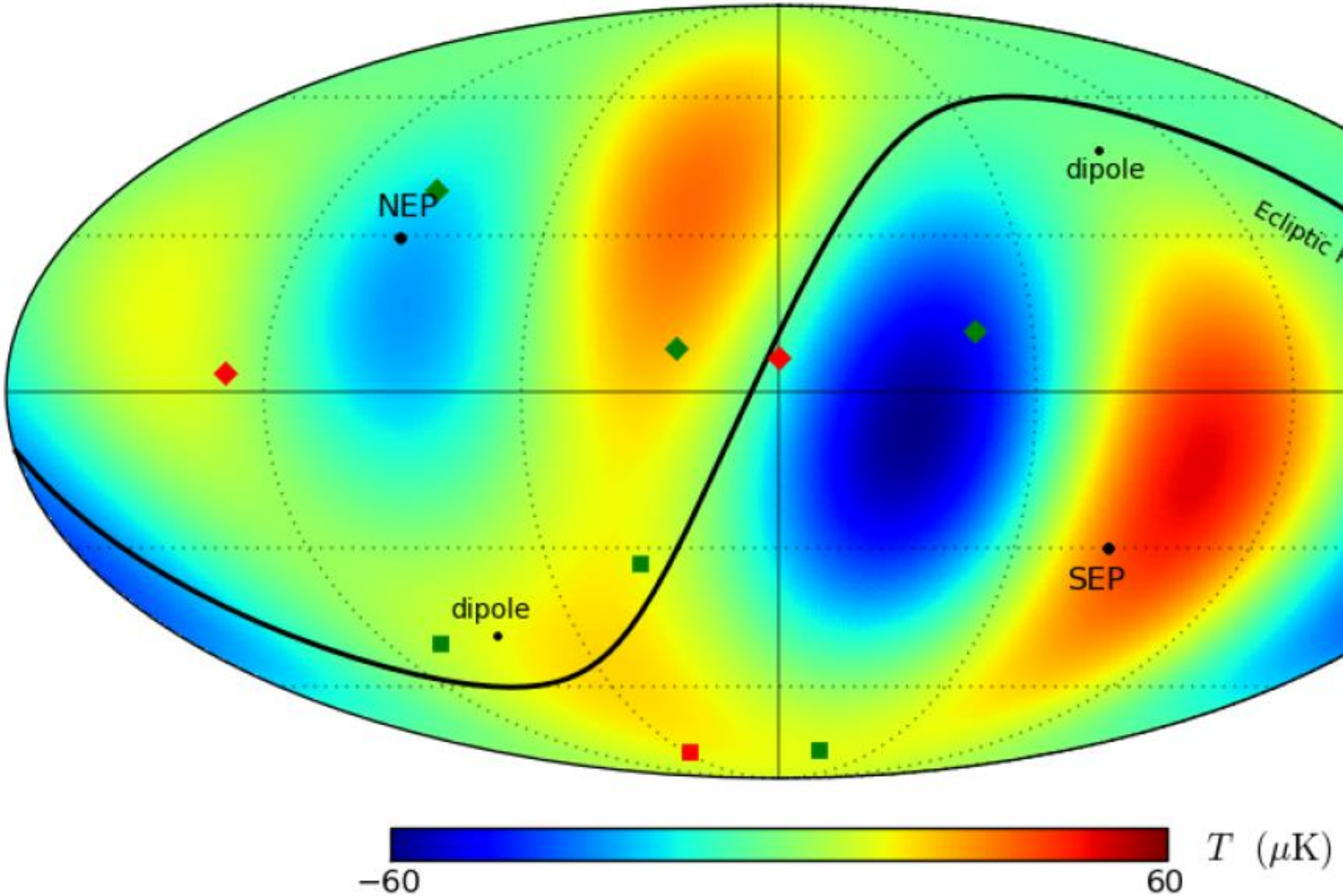
Quadrupole



Octopole



Quadrupole + Octopole



Alignment probabilities

Probability of the quadrupole and octopole planes being so aligned:

(0.1-0.6)%

Conditional probability of the aligned planes being so perpendicular to the the solar system plane (eclpitic):

(0.2-1.7)%

Conditional probability of aligned planes perpendicular to the ecliptic pointing at the dipole/equinox:

few%

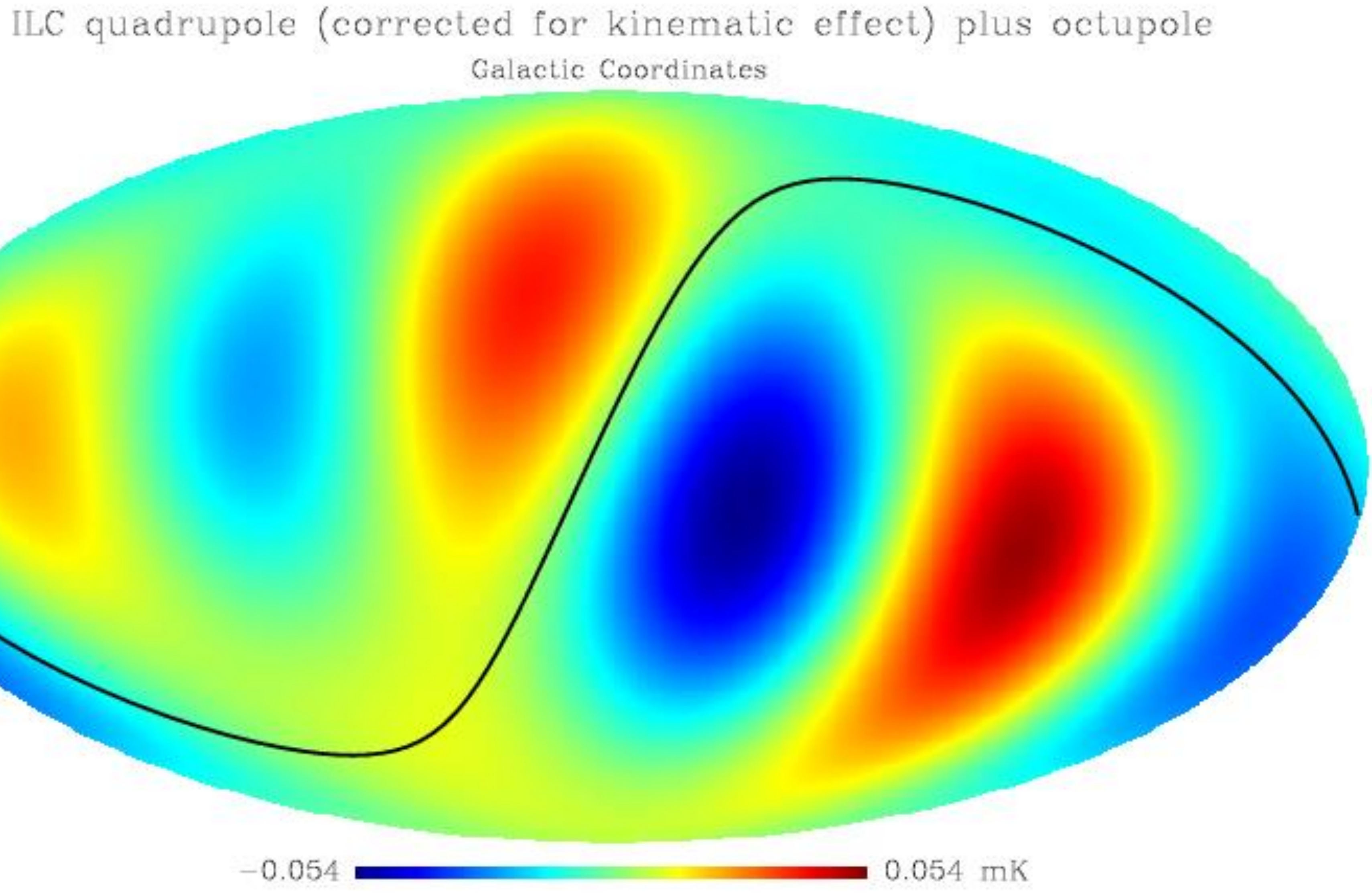
Net : $< 10^{-5}$

Area vectors tell about the orientations of the multipole planes.

DON’T include all the information (multipole vectors do).

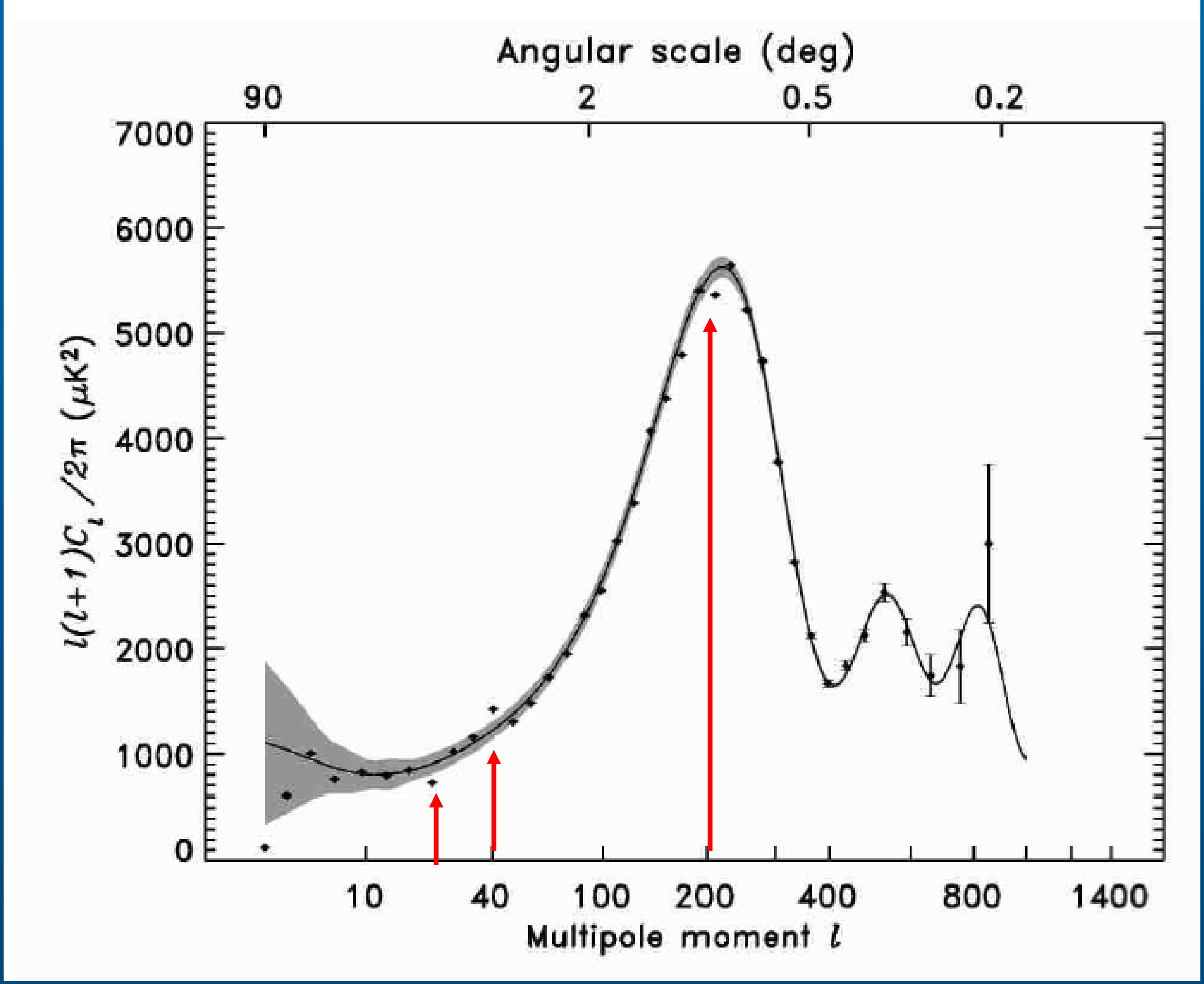
Can rotate the aligned planes about their “common axis.”

l=2&3 : The Map



ILC quadrupole (corrected for kinematic effect) plus octupole
Galactic Coordinates
−0.054
0.054 mK

Angular Power Spectrum



At least 3 other major deviations in the C_l in 1st year data

Power spectrum: ecliptic plane vs. poles

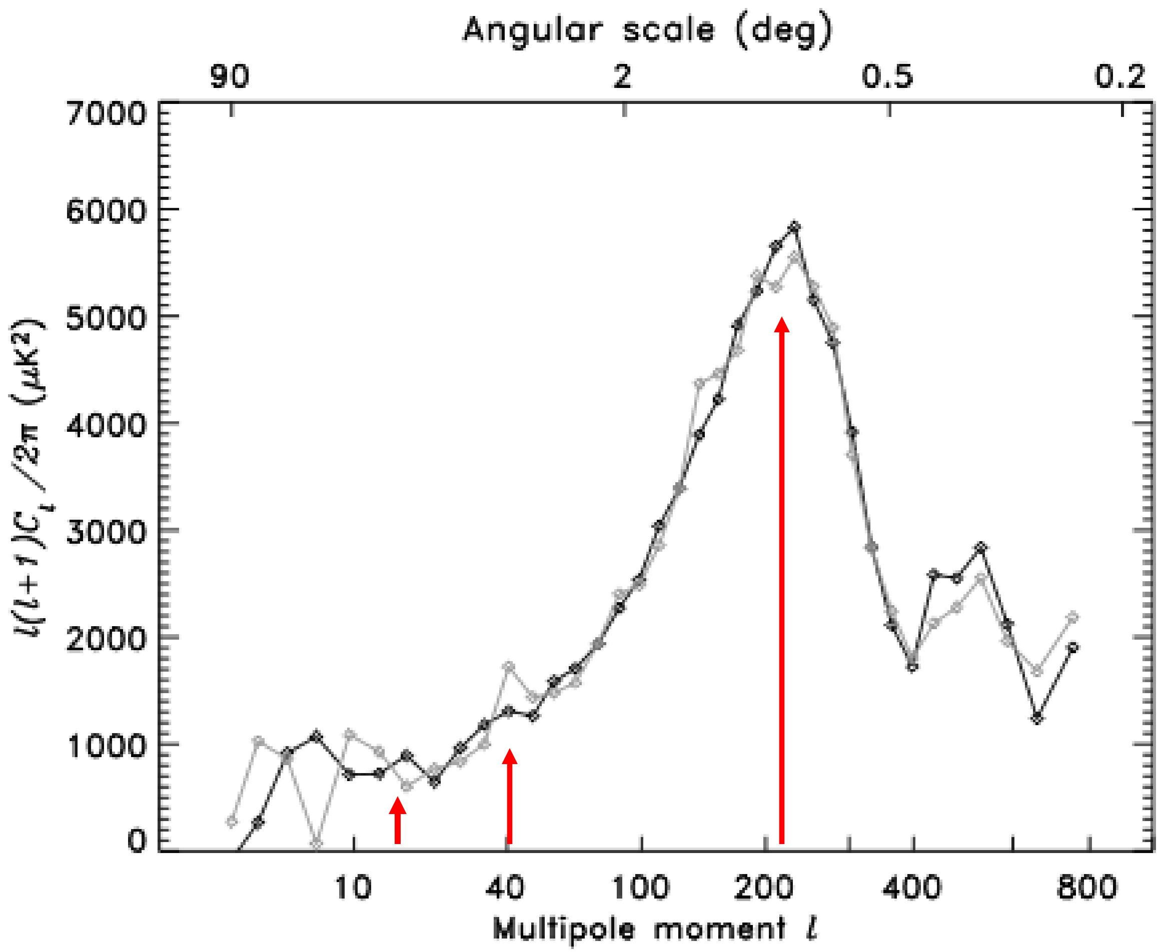
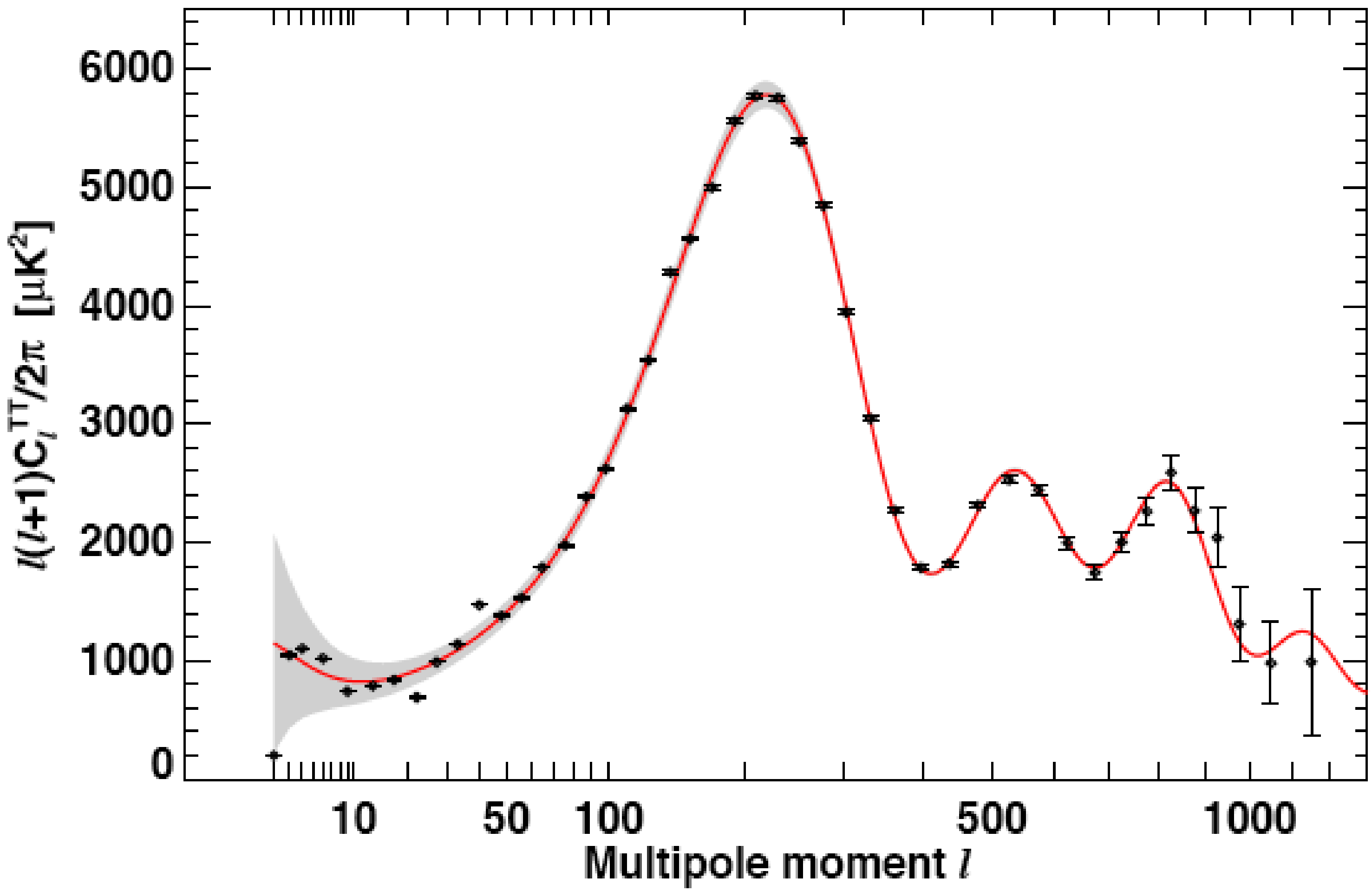


Fig. 7.— A comparison of the power spectrum computed with data from the ecliptic plane (black) vs. data from the ecliptic poles (grey). Note that some of the "bite" features that appear in the combined spectrum are not robust to data excision. There is also no evidence that beam ellipticity, which would be more manifest in the plane than in the poles, systematically biases the spectrum. This is consistent with estimates of the effect given by Page et al. (2003a).

"First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: The Angular Power Spectrum"
G. Hinshaw, et.al., 2003, ApJS, **148**, 135 --
only v.1 on archive

All 3 other major deviations are in the ecliptic polar C_l only!!

Dip? What dip?



WMAP 3

Caution!

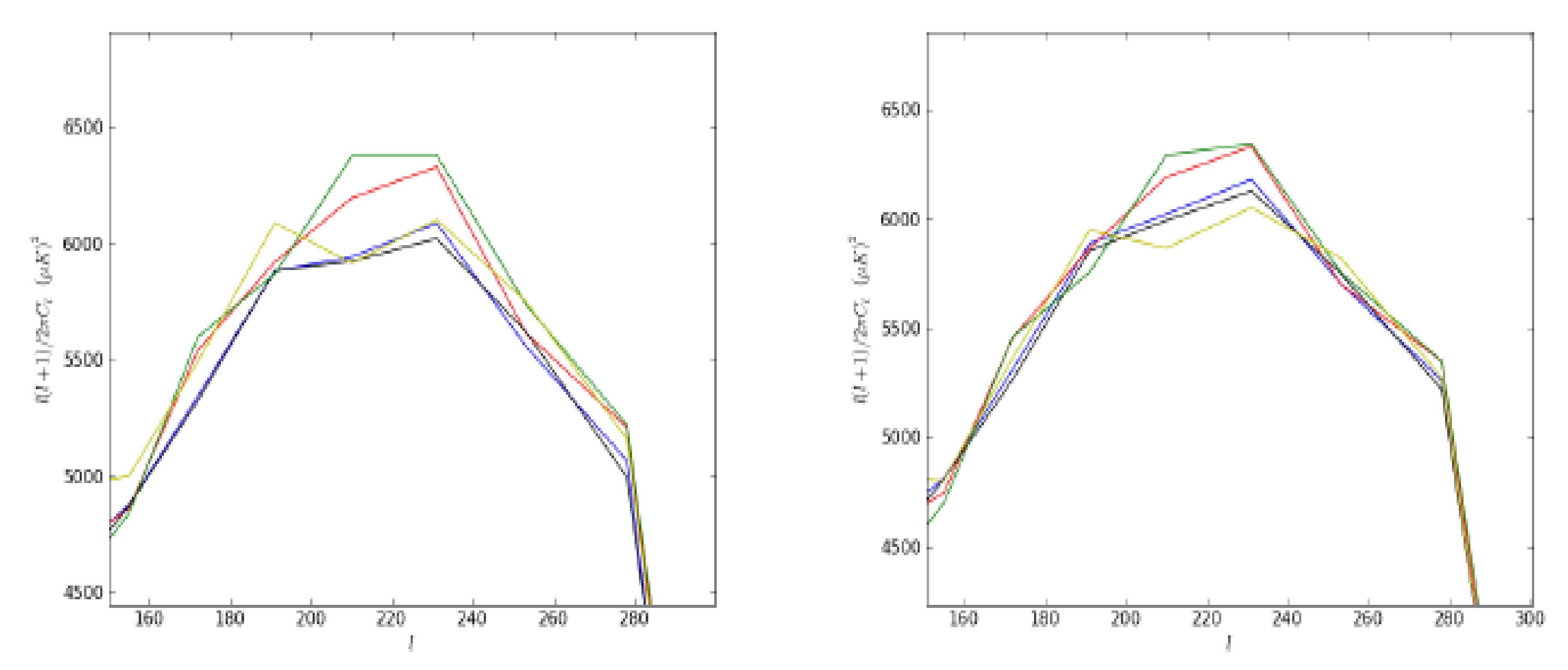
Anomalies in our data should disappear because:

- More data => better statistics
- Better theory

BEWARE:

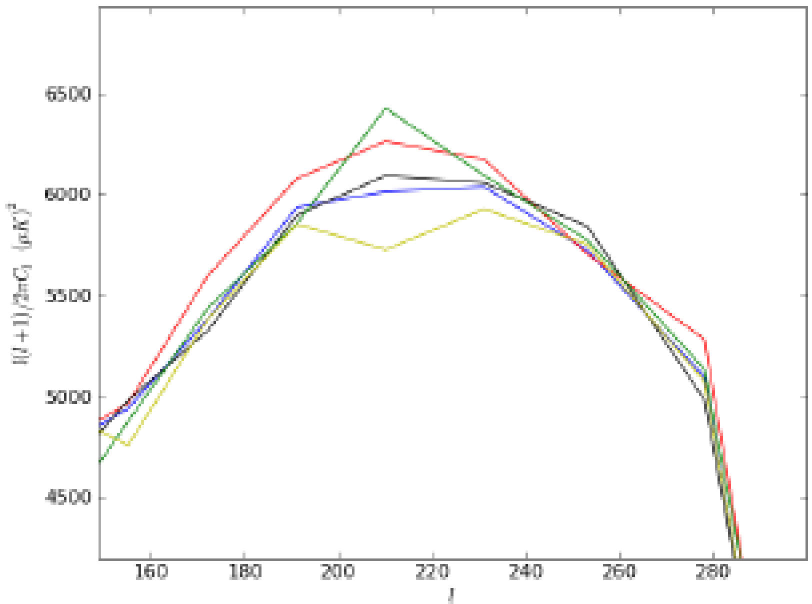
- New and improved systematics
- New and improved analysis

Different weighting schemes:



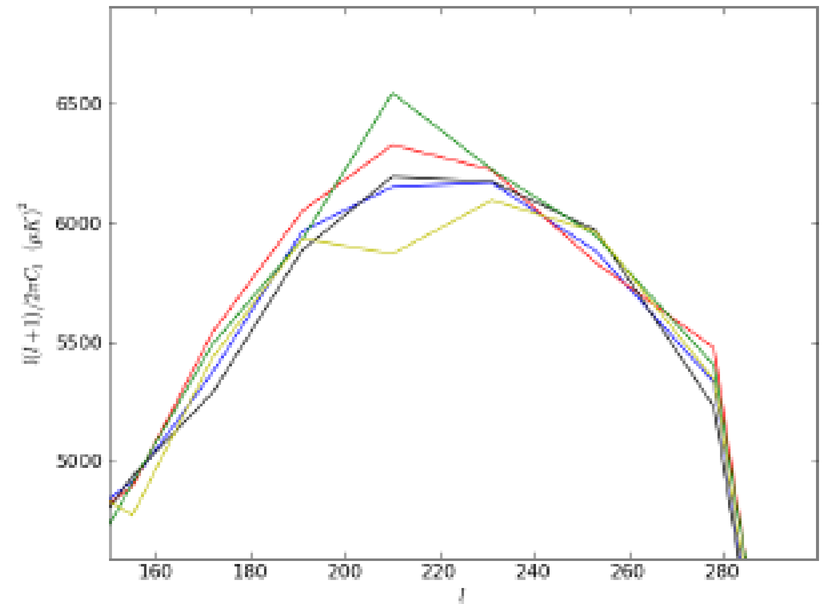
Degree-scale anomalies in the CMB:
localizing the first peak dip to a small patch of the north ecliptic sky. **Amanda Yoho, Francesc Ferrer, Glenn D. Starkman, Phys.Rev. D83 (2011) 083525**
http://arXiv.org/pdf/1005.5389

No first peak at the N pole?



(c)Fifth year data.

FIG. 1: Power spectra for each data release year using the first year weighting schemes. We show the power spectra extracted from the full sky (blue), full sky without the north (red) and south (black) ecliptic caps, the ecliptic plane only (green), and the ecliptic poles only (yellow). The galaxy is always masked out.



(c)Fifth year data.

FIG. 2: Power spectra for each data release year using the third year weighting schemes. We show the power spectra extracted from the full sky (blue), full sky without the north (red) and south (black) ecliptic caps, the ecliptic plane only (green), and the ecliptic poles only (yellow). The galaxy is always masked out.

No first peak at the N pole?

$$S_{\text{peak}} \equiv 2 \frac{\sum_{\ell=\ell_{min}}^{\ell_{max}} \left(C_\ell^{KQ85+add'l\ mask} - C_\ell^{KQ85} \right)}{\sum_{\ell=\ell_{min}}^{\ell_{max}} \left(C_\ell^{KQ85+add'l\ mask} + C_\ell^{KQ85} \right)}$$

TABLE I: The first columns under the weight scheme headings list the peak statistic calculated for each data release. The second columns list the corresponding significance.

	1st year weighting		3rd year weighting	
1-year	.0347	99.52%	.0206	99.35%
3-year	.0274	95.78%	.0166	97.47%
5-year	.0278	96.23%	.0154	96.24%

Did Planck change the alignment significance?

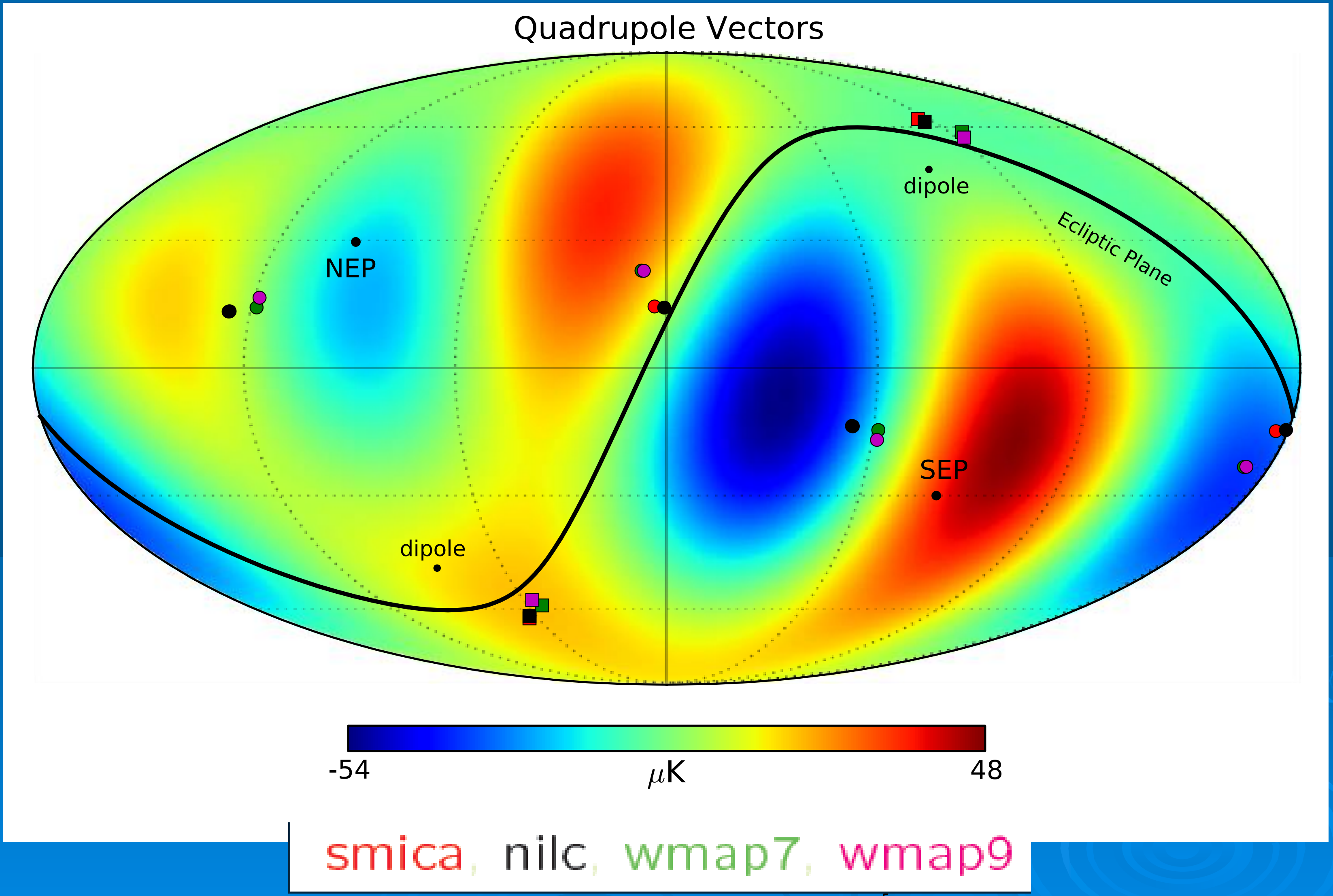
	$\underline{n}_2 \bullet \underline{n}_3$	$\underline{P(n}_2 \bullet \underline{n}_3)$
WMAP 9	0.998	0.2%
Planck XXIII	0.977	3.2%
Inpainted SMICA	0.981	1.9%
DQ-corrected Inpainted SMICA	0.9965	0.338%

Note: important to remove the Doppler quadrupole!

An alternative method, based on the multipole vector decomposition (Copi et al. 2004; Schwarz et al. 2004; Bielewicz et al. 2005; Bielewicz & Riazuelo 2009) of the data has also been used to verify the robustness of the results presented here, and excellent consistency is found.

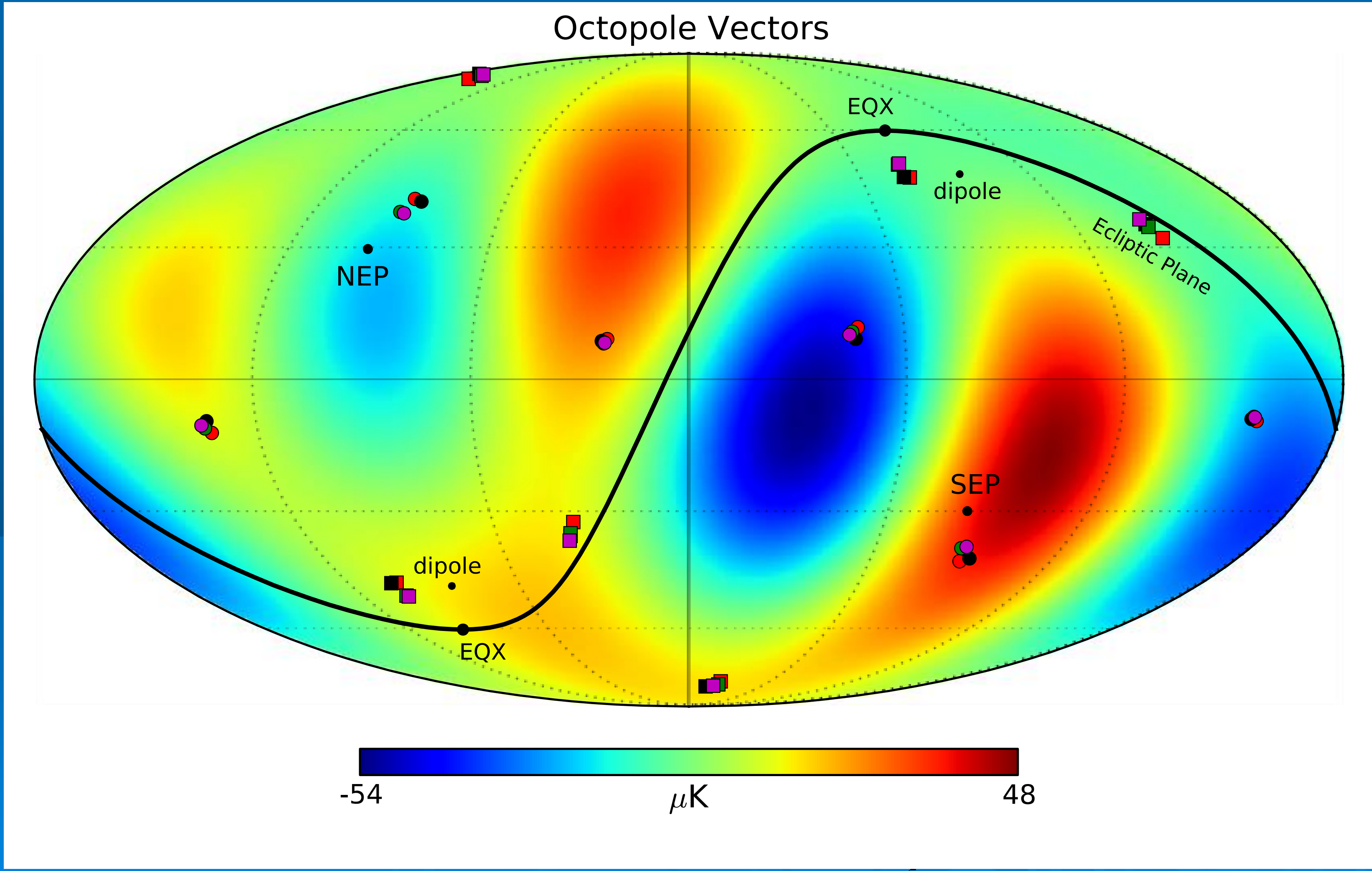
Planck XXIII: arXiv 1303.5083

Planck vs. WMAP MPV

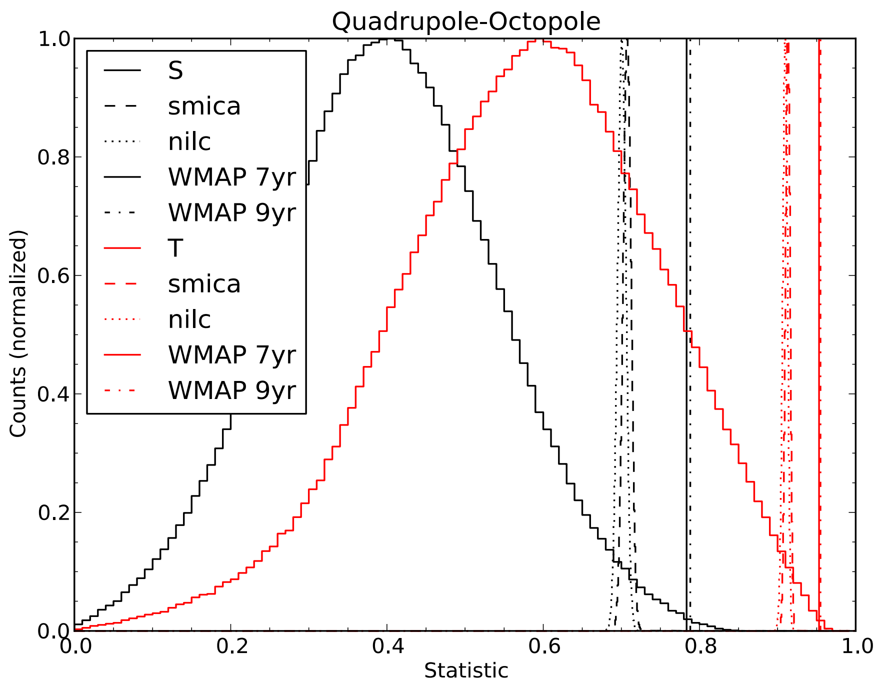


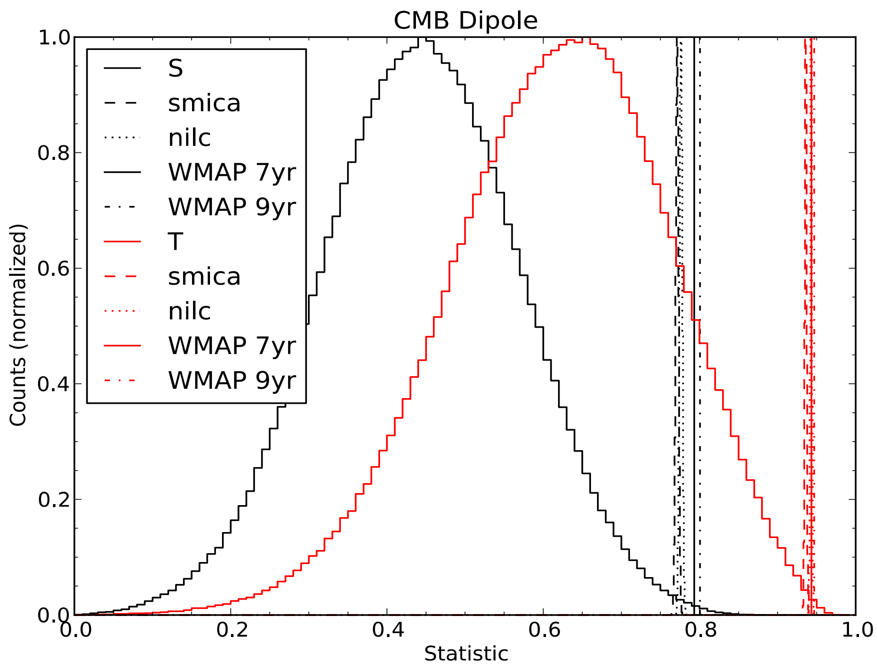
Important to remove Doppler quadrupole

Planck vs. WMAP MPV



smica, nilc, wmap7, wmap9





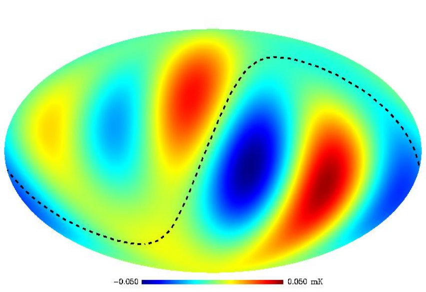
Quadrupole-Octopole

# Stat map	%
S : smica	98.3743
S : nilc	98.1518
S : WMAP 7yr	99.7838
S : WMAP 9yr	99.8223
T : smica	99.07
T : nilc	98.951
T : WMAP 7yr	99.8988
T : WMAP 9yr	99.9147

CMB Dipole

# Stat map	%
S : smica	99.6266
S : nilc	99.6822
S : WMAP 7yr	99.8195
S : WMAP 9yr	99.864
T : smica	99.7035
T : nilc	99.813
T : WMAP 7yr	99.8045
T : WMAP 9yr	99.8456

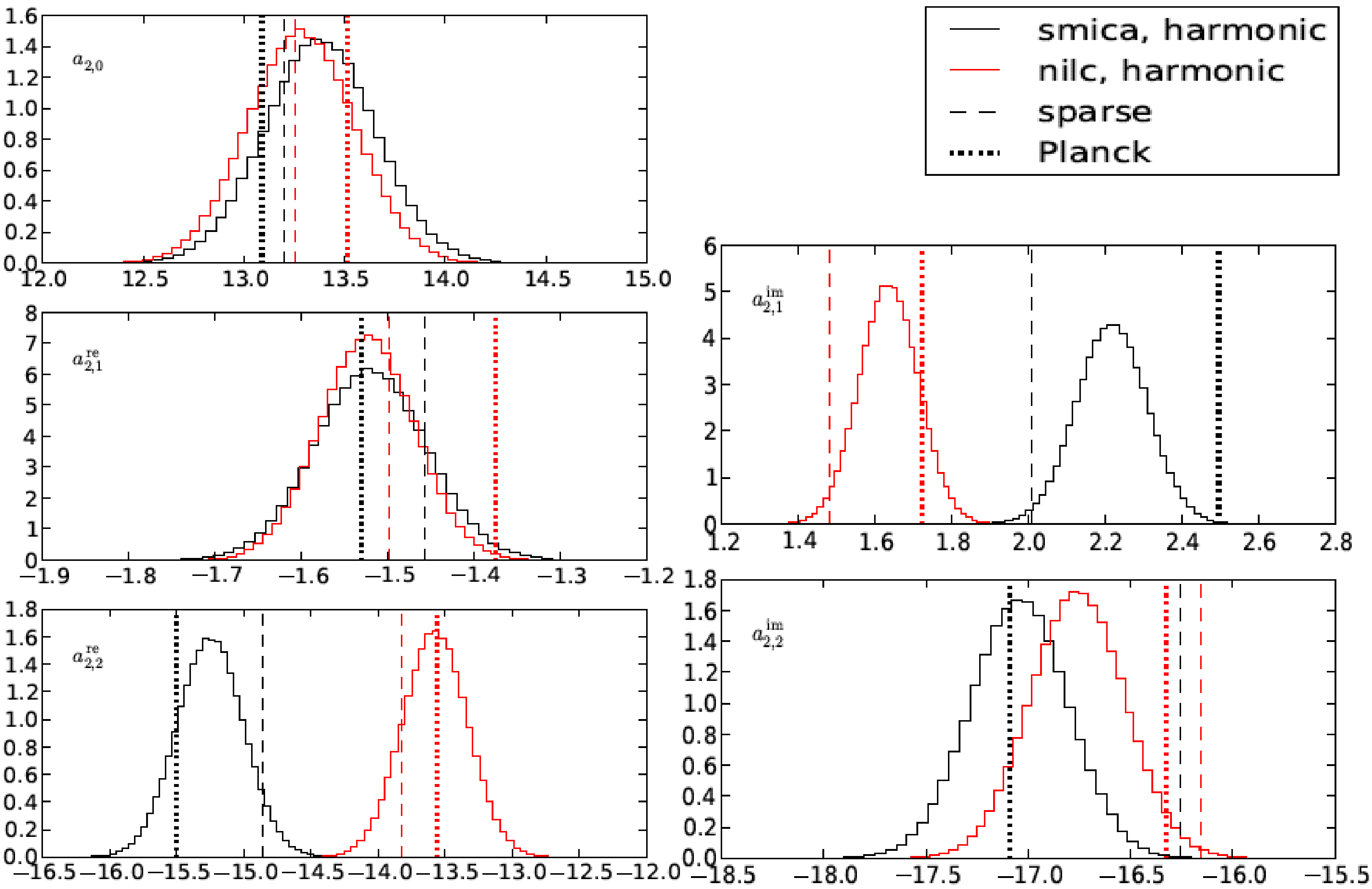
Quadrupole+Octopole Correlations -- Explanations: more galaxy?



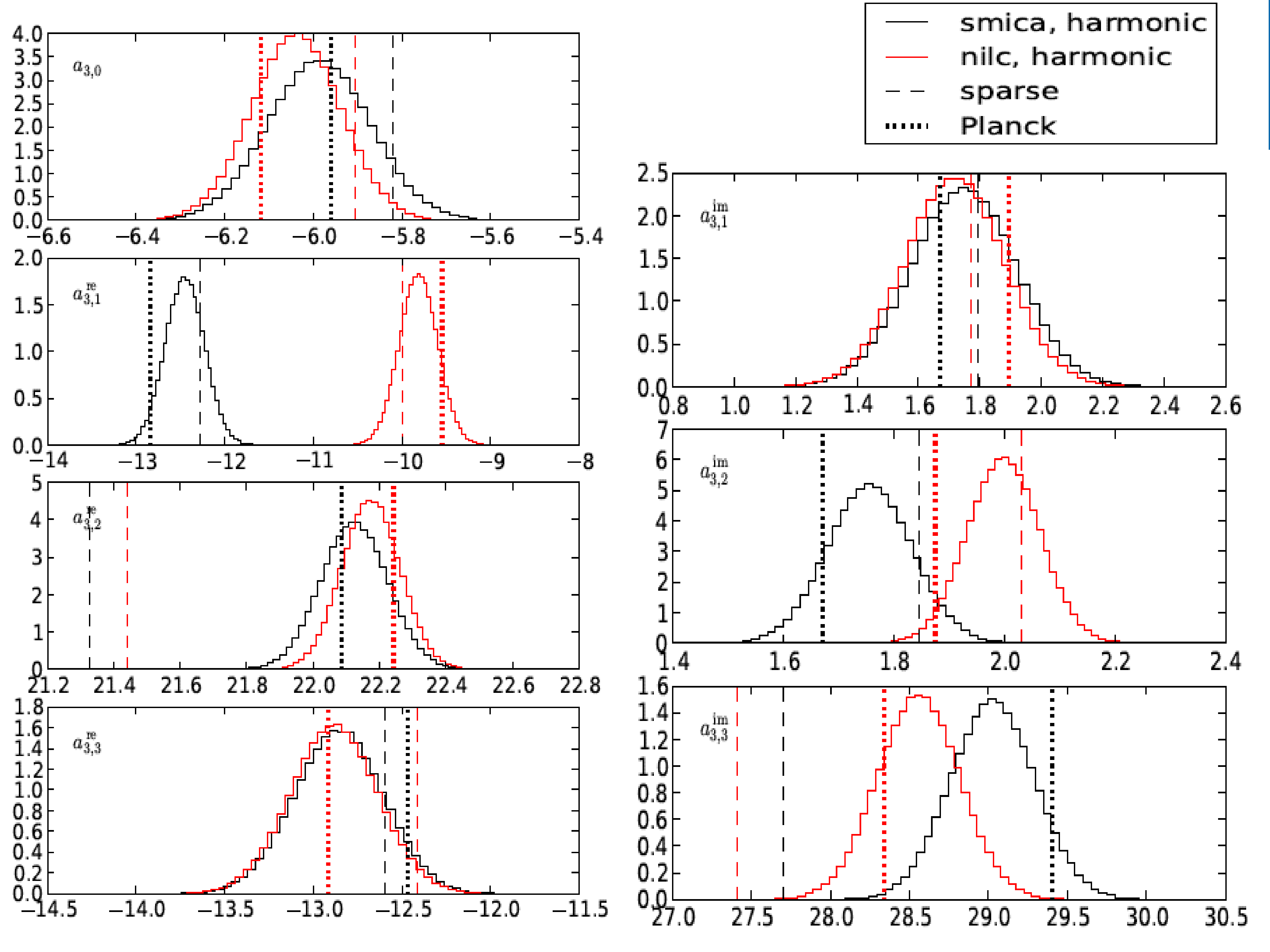
- Cosmology
  - but how to get dipole correlation?
  - how to get $C_2 < C_3$?
- Systematics
  - how do you get such an effect?
  - esp., how do you get a N-S ecliptic asymmetry? (dipole mis-subtraction?)
  - how do you avoid oscillations in the time-ordered data?
- The Galaxy:
  - has the wrong multipole structure (shape)
  - is likely to lead to GALACTIC not ECLIPTIC/DIPOLE/EQUINOX correlations
- Foregrounds -- difficult:
  - Changing a patch of the sky typically gives you: Y_{l0}
  - Sky has 5x more octopole than quadrupole
  - How do you get a physical ring <u>perpendicular</u> to the ecliptic
  - Caution: can add essentially arbitrary dipole, which can entirely distort the ring! (Silk & Inoue)
  - How do you hide the foreground from detection? $T \approx T_{CMB}$

If Planck changes a low-l (full or cut) sky result, is it better?

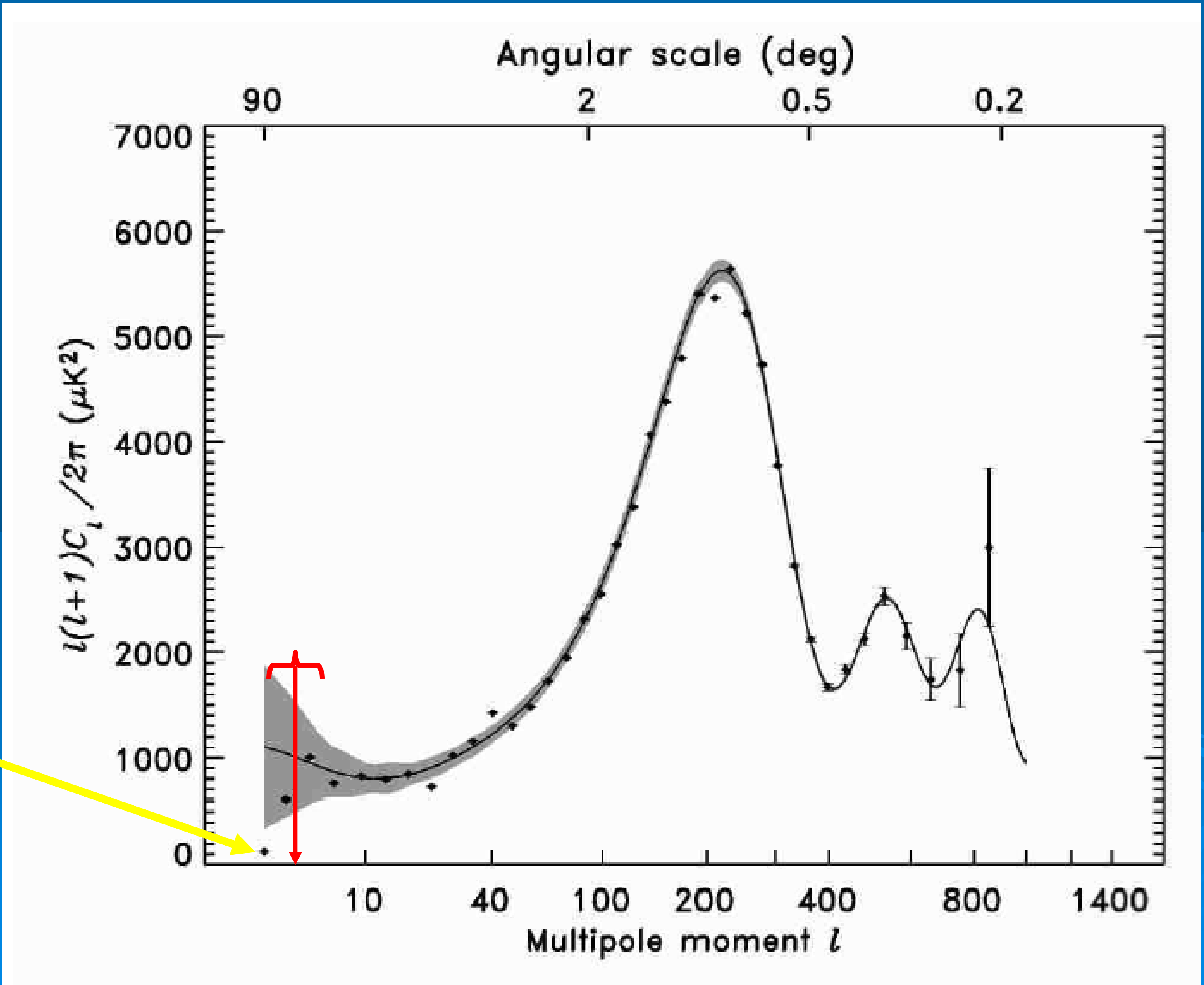
Inpainting



smica, harmonic
nilc, harmonic
sparse
Planck
$a_{2,0}$
$a_{2,1}^{re}$
$a_{2,2}^{re}$
$a_{2,1}^{im}$
$a_{2,2}^{im}$

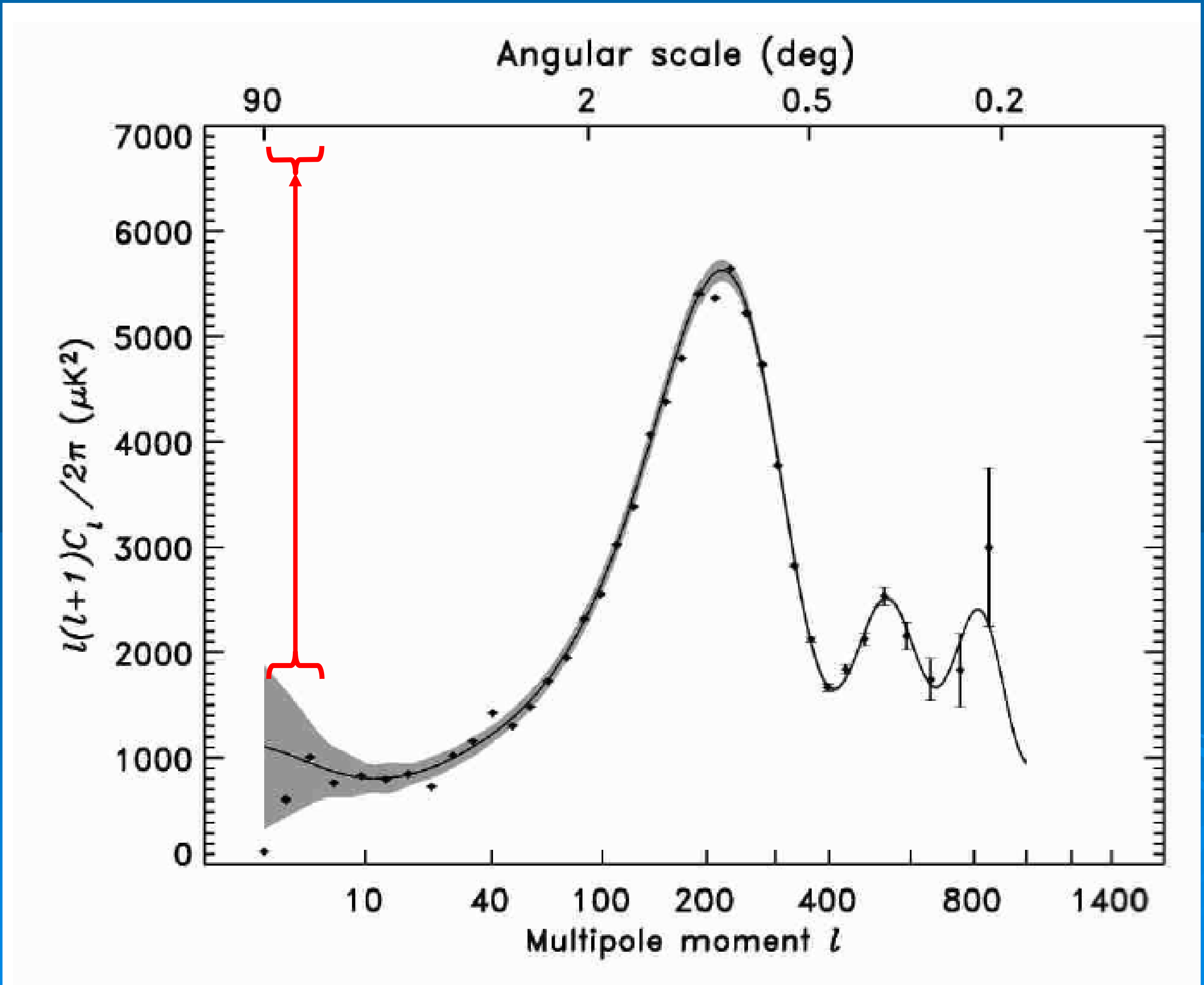

smica, harmonic
nilc, harmonic
sparse
Planck
$a_{3,0}$
$a^{re}_{3,1}$
$a^{re}_{3,2}$
$a^{re}_{3,3}$
$a^{im}_{3,1}$
$a^{im}_{3,2}$
$a^{im}_{3,3}$

“The Low-*l* Anomaly”

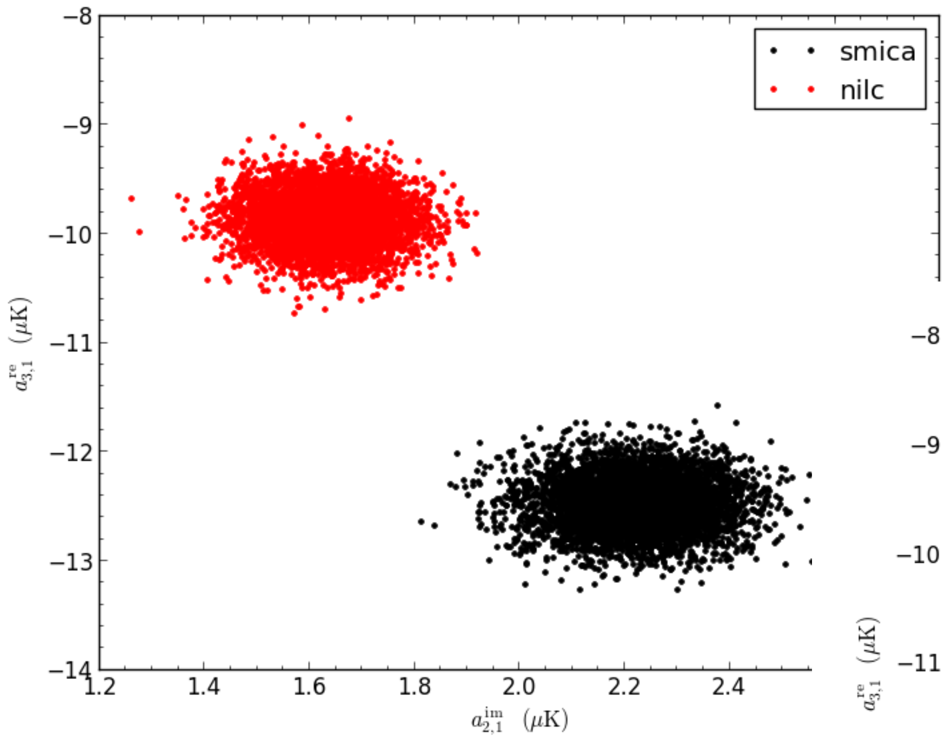


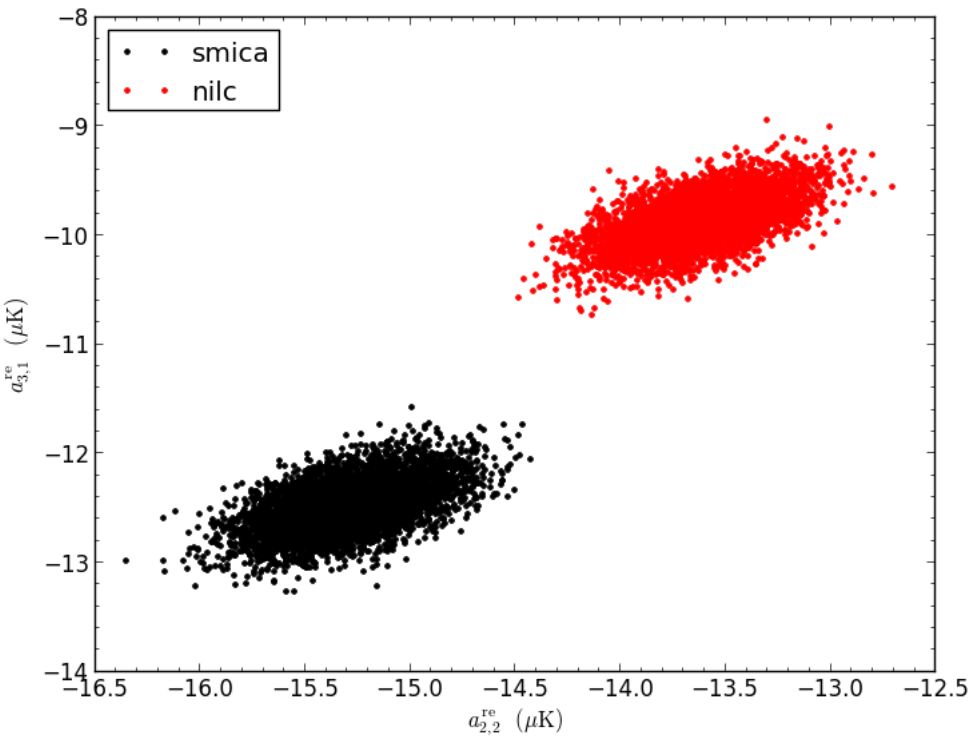
The low quadrupole

"The Large-Angle Anomaly"



Systematic uncertainties about full-skies





Hidden correlations

The Angular Correlation Function, $C(\theta)$

$C(\theta) = \langle T(\Omega_1)T(\Omega_2)\rangle_{\Omega_1.\Omega_2=\cos\theta}$

But (established lore):
$C(\theta) = \sum_l C_l P_l(\cos(\theta))$

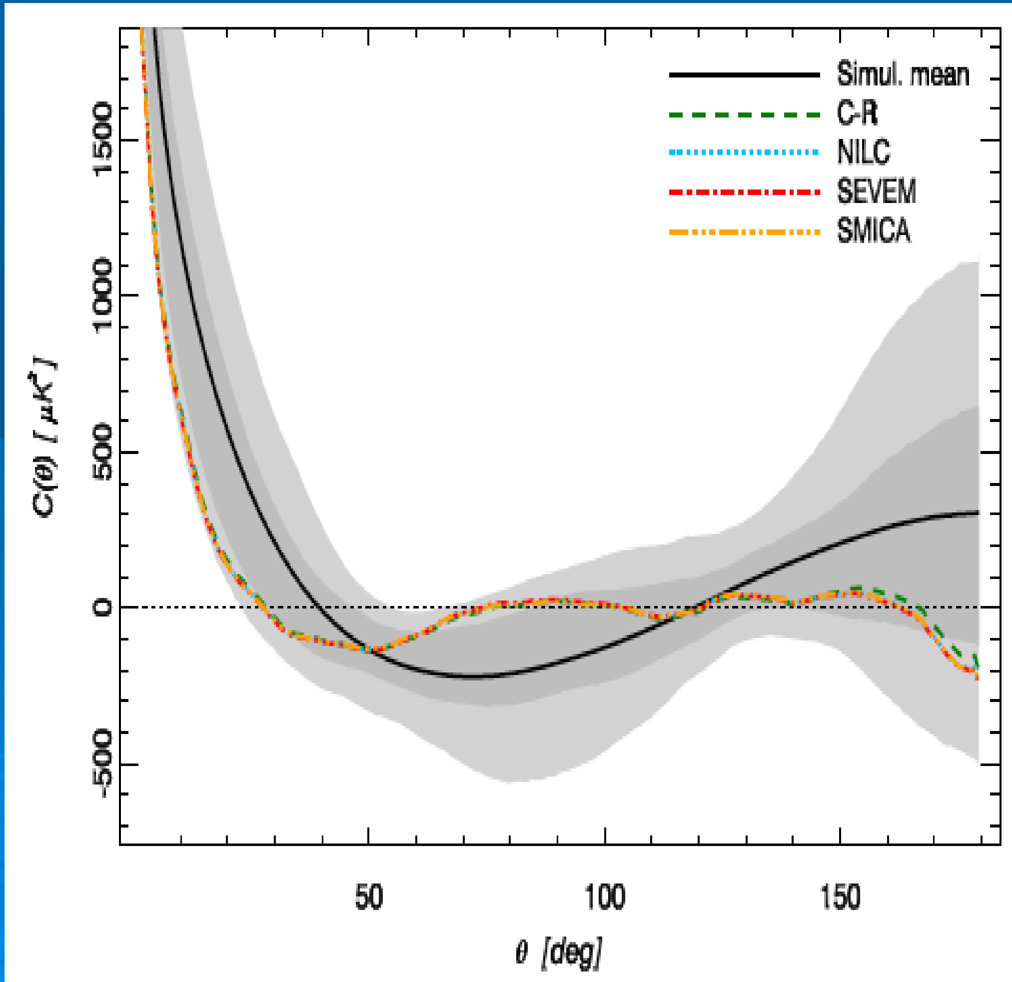
$\Rightarrow$ Same information as C_l, just differently organized

IF

- $C(\theta)$ is obtained by a full sky average

or

- the sky is statistically isotropic, i.e. if $\langle a_{lm}\, a^*_{l'm'}\rangle=\delta_{ll'}\,\delta_{mm'}C_l$



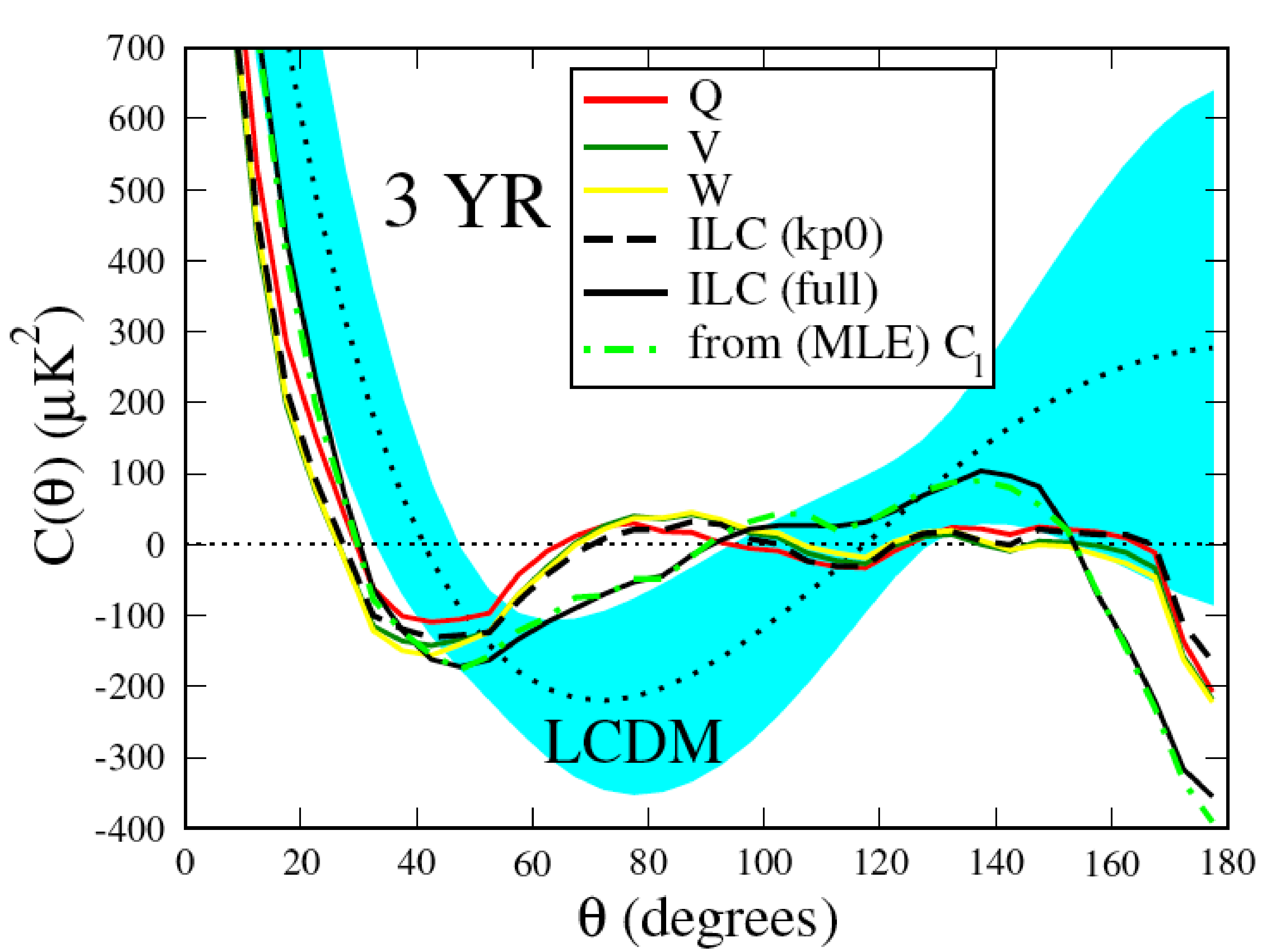
Is the Large-Angle Anomaly Significant?

One measure (WMAP1):

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

Only 0.15% of realizations of **inflationary** ΛCDM universe with the best-fit parameters have lower S!

Two point angular correlation function -- WMAP3

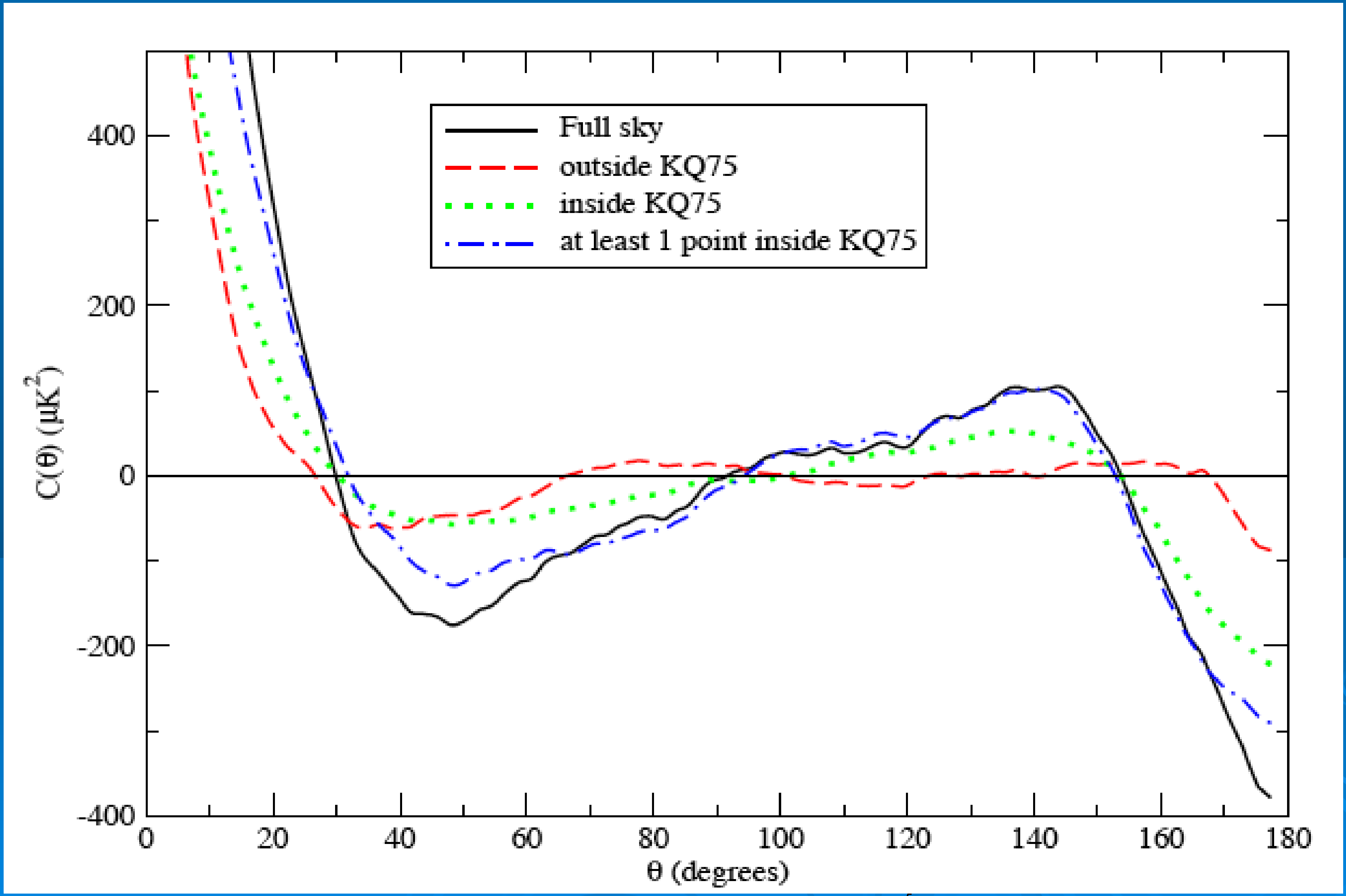


Statistics of C(θ)

Table 1. The C_ℓ calculated from $C(\theta)$ for the various data maps. The WMAP (pseudo and reported MLE) and best-fit theory C_ℓ are included for reference in the bottom five rows.

Data Source	$S_{1/2}$ $(\mu K)^4$	$P(S_{1/2})$ (per cent)	$6C_2/2\pi$ $(\mu K)^2$	$12C_3/2\pi$ $(\mu K)^2$	$20C_4/2\pi$ $(\mu K)^2$	$30C_5/2\pi$ $(\mu K)^2$
V3 (kp0, DQ)	1288	0.04	77	410	762	1254
W3 (kp0, DQ)	1322	0.04	68	450	771	1302
ILC3 (kp0, DQ)	1026	0.017	128	442	762	1180
ILC3 (kp0), $C(> 60°) = 0$	0	—	84	394	875	1135
ILC3 (full, DQ)	8413	4.9	239	1051	756	1588
V5 (KQ75)	1346	0.042	60	339	745	1248
W5 (KQ75)	1330	0.038	47	379	752	1287
V5 (KQ75, DQ)	1304	0.037	77	340	746	1249
W5 (KQ75, DQ)	1284	0.034	59	379	753	1289
ILC5 (KQ75)	1146	0.025	81	320	769	1156
ILC5 (KQ75, DQ)	1152	0.025	95	320	768	1158
ILC5 (full, DQ)	8583	5.1	253	1052	730	1590
WMAP3 pseudo-C_ℓ	2093	0.18	120	602	701	1346
WMAP3 MLE C_ℓ	8334	4.2	211	1041	731	1521
Theory3 C_ℓ	52857	43	1250	1143	1051	981
WMAP5 C_ℓ	8833	4.6	213	1039	674	1527
Theory5 C_ℓ	49096	41	1207	1114	1031	968

Origin of C(θ)



Full sky
outside KQ75
inside KQ75
at least 1 point inside KQ75
400
200
0
-200
-400
C(θ) (μK²)
0
20
40
60
80
100
120
140
160
180
θ (degrees)

Is it an accident?

Only 2% of rotated and cut full skies have this low a cut-sky $S_{1/2}$

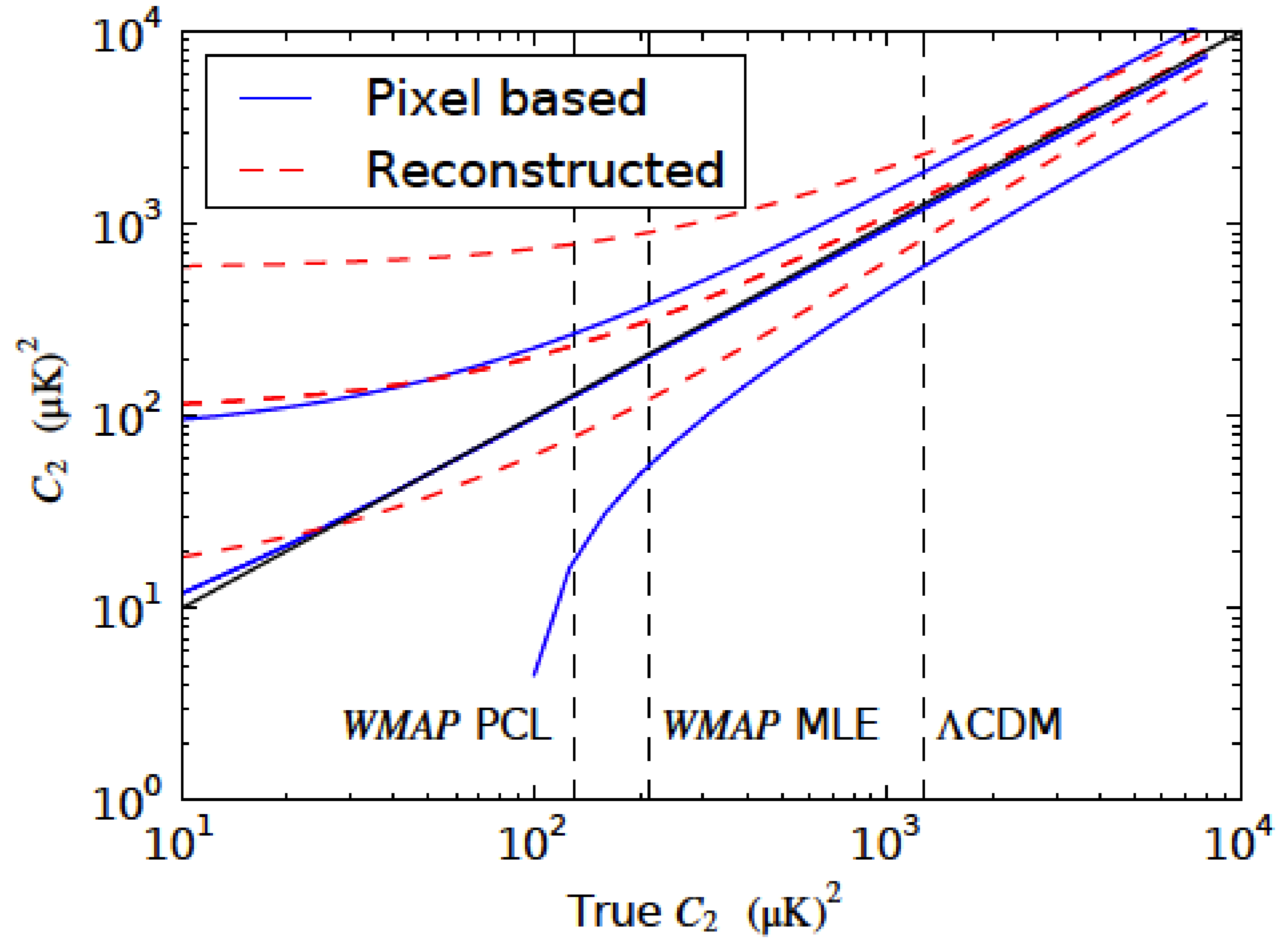
Statistics of $C(\theta)$

- 0.03-0.1% of realizations of the concordance model of inflationary ΛCDM have so little **cut sky** large-angle correlation !

- Either: this reflects a <0.1% probable full sky $C(\theta)$, or a 5% probable $C(\theta)$ and a 2% probably alignment with the galaxy

Statistics of C(θ)

Efstathiou, Ma and Hanson:
Direct calculation of C(θ) on the cut sky is a suboptimal estimator of C(θ) on the full sky.
The estimator which is optimal if the sky is GRSI (C(θ) calculated from reconstructed full sky C_l) yields a larger $S_{1/2}$, which is less significant in its smallness.



Pixel based
Reconstructed
WMAP PCL
WMAP MLE
ΛCDM
C_2 (μK)^2
True C_2 (μK)^2
10^0
10^1
10^2
10^3
10^4

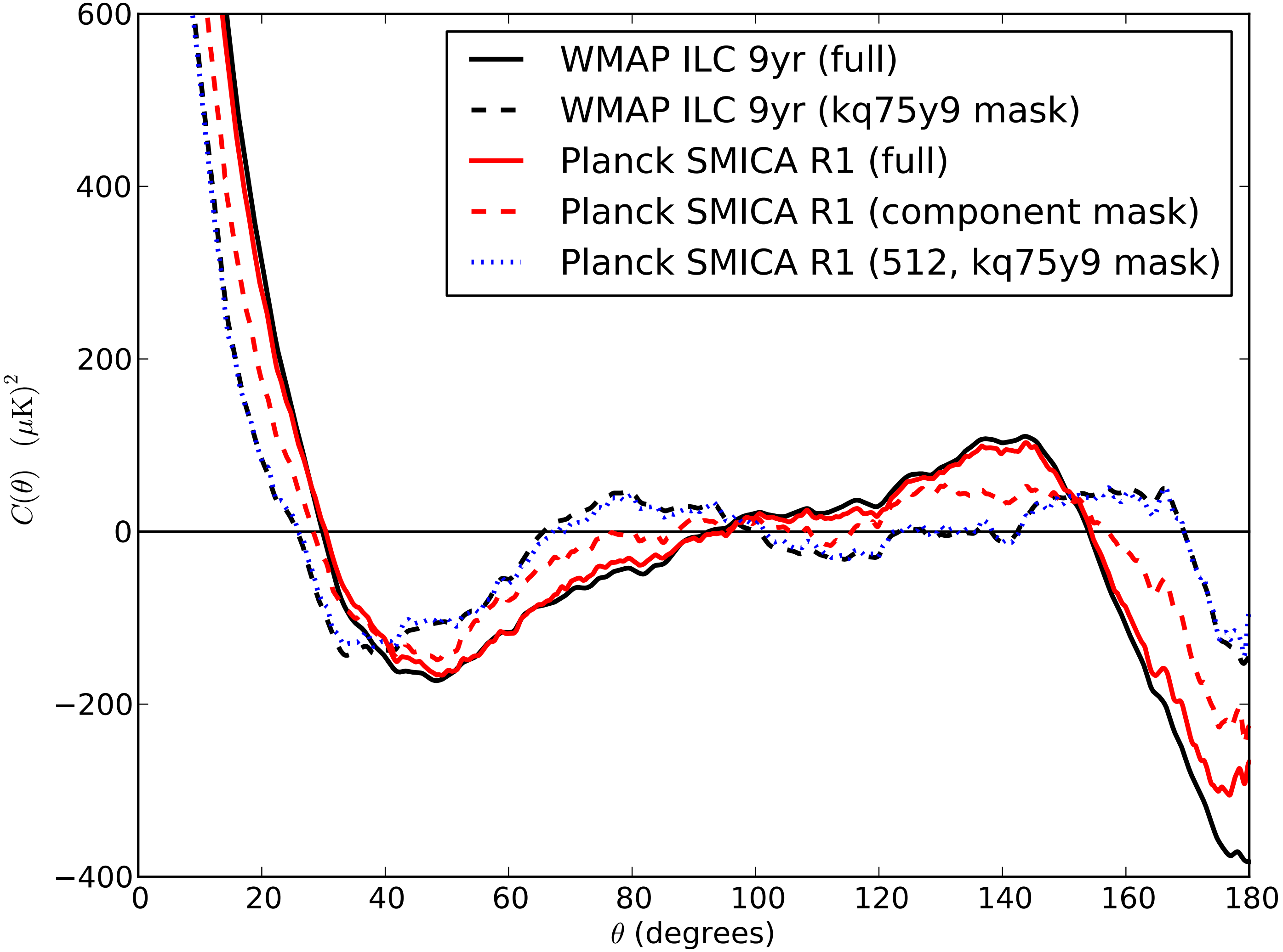
Statistics of C(θ)

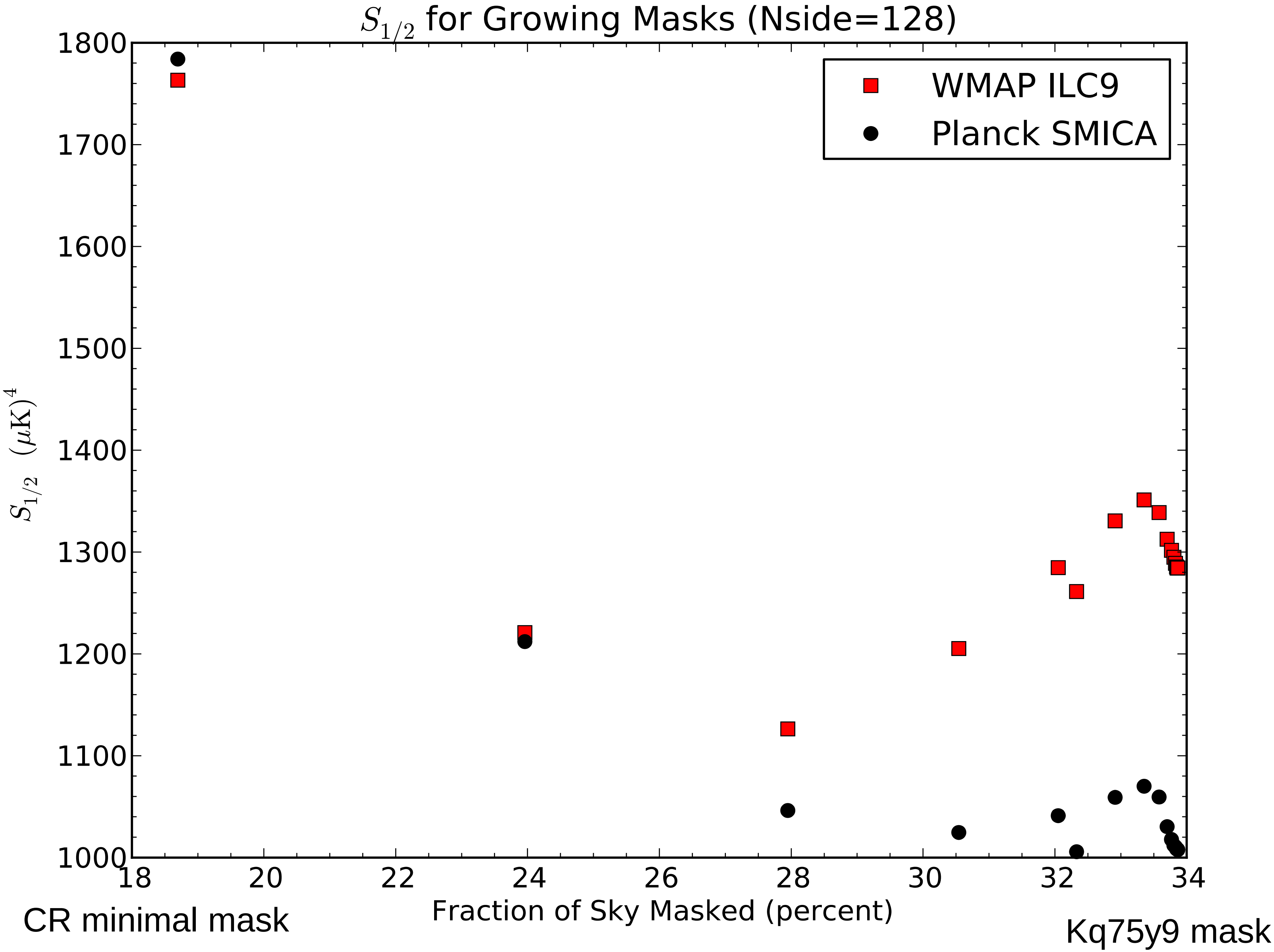
Response:

- So what ? This is completely consistent with what we said. What is odd is the CUT-SKY C(θ) !

- Not true anyway (CHSS MNRAS. 418, 505–515 (2011)):
    - Reconstructed C_l are biased upward
    - "Weighted" reconstructed C_l are not biased, but require smoothing when calculated at low Nside – smoothing causes contamination
    - When reconstructing full sky C_l from smoothed cut skies – everything depends on how you fill the cut

Did this change in Planck?




$S_{1/2}$ for Growing Masks (Nside=128)
WMAP ILC9
Planck SMICA
$S_{1/2}$ $(\mu\mathrm{K})^4$
1800
1700
1600
1500
1400
1300
1200
1100
1000
18
20
22
24
26
28
30
32
34
Fraction of Sky Masked (percent)
CR minimal mask
Kq75y9 mask

# Stat map	fraction (percentage)
Quadrupole-Octopole	
S : smica	98.3743
S : nilc	98.1518
S : WMAP 7yr	99.7838
S : WMAP 9yr	99.8223
T : smica	99.07
T : nilc	98.951
T : WMAP 7yr	99.8988
T : WMAP 9yr	99.9147

The Conspiracy theory: minimizing $S_{1/2}$

Table 3. Minimum $S_{1/2}$ in $(\mu\mathrm{K})^4$ for the best fit theory and WMAP C_ℓ as a function of the cutoff multipole, L. Also shown is the 95% confidence region of the minimum $S_{1/2}$ derived from chain 1 of the WMAP MCMC parameter fit.

C_ℓ	L						
Source	2	3	4	5	6	7	8
Theory	7624	922	118	23	7	3	0.7
Theory 95%	6300–1400	770–1600	100–200	20–40	7–14	3–6	1–2
WMAP	8290	2530	2280	800	350	150	130

To obtain $S_{1/2}$ < 1000 with the WMAP C_l requires varying C_2, C_3, C_4 & C_5!

Violation of GRSI

Even if we replaced all the theoretical C_l by their measured values up to l=20, cosmic variance would give only a 3% chance of recovering this low a $S_{1/2}$ in a particular realization and most of thost of those are much poorer fits with the theory than is the current data

(Copi, GDS in preparation)

Translation: The observed absence of large-angle correlation is inconsistent (>>97%) with the most fundamental prediction of inflationary cosmology!

SUMMARY

If you believe the observed full-sky CMB:

There are signs that the sky is NOT statistically isotropic

- These are VERY statistically significant (>>99.9%)

- The observed low-l fluctuations appear correlated to the solar system (but not to other directions)

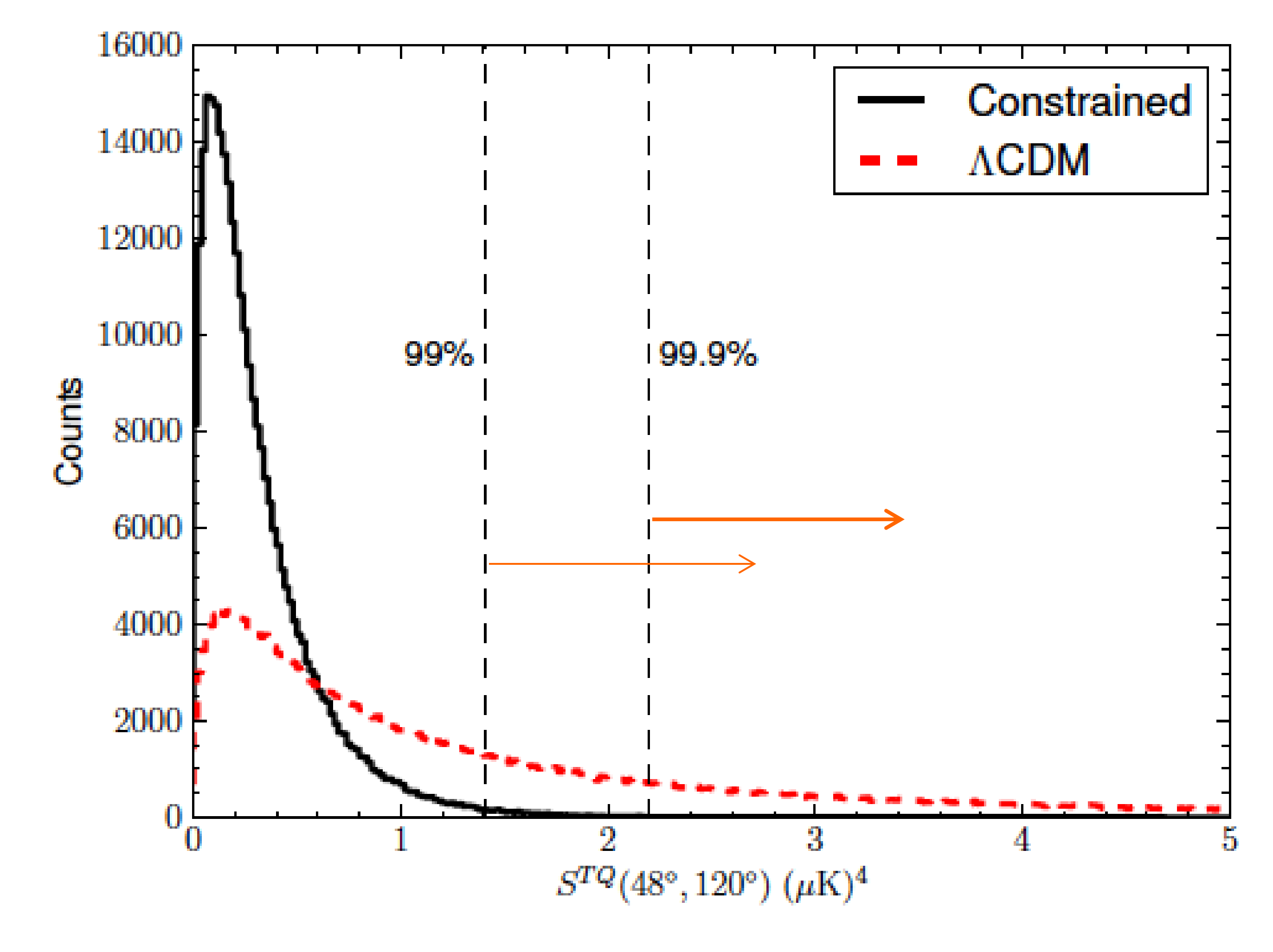
This lack of correlations/power could be due to:

- Statistical fluctuation -- incredibly unlikely

- features in the inflaton potential -- contrived, and << 3% chance of such low $S_{1/2}$

- Topology

Ruling out the fluke hypothesis (if we're lucky)



CHSS 2012 arXiv:1303.4786

Can do the same with $T\varphi$, $T\kappa$,…

Copi, Kosowsky, Starkman and Yoho, in preparation

SUMMARY

If you don’t believe the CMB inside the Galaxy **is reliable** then**:**

CMB lacks large angle correlations

- first seen by COBE (~5% probable),
- now statistically much less likely (<0.1% probable)

This lack of correlations/power could be due to:

- Statistical fluctuation -- incredibly unlikely

- features in the inflaton potential -- contrived, and << 3% chance of such low $S_{1/2}$

- Topology -- not (yet?) seen

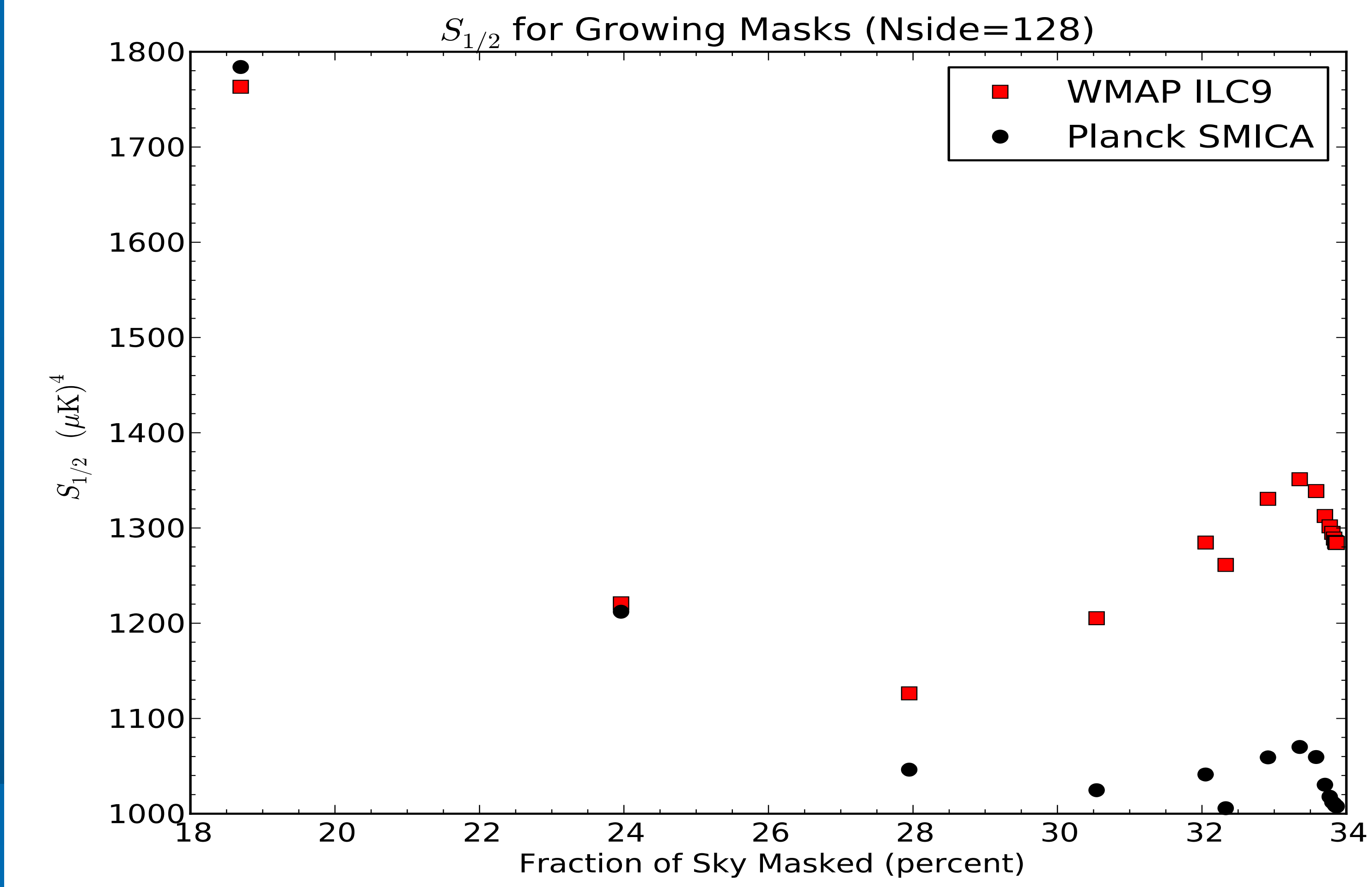
While the cosmic orchestra may be playing the inflation symphony, somebody gave the bass and the tuba the wrong score. They're trying very hard to hush it up.

There is no good explanation for any of this.

Yet.

Planck may teach us that this has all been a wild goose chase,

or show us that the Universe still has some important mysteries for us to decipher



WMAP ILC9

Minimal CR: p=0.3%

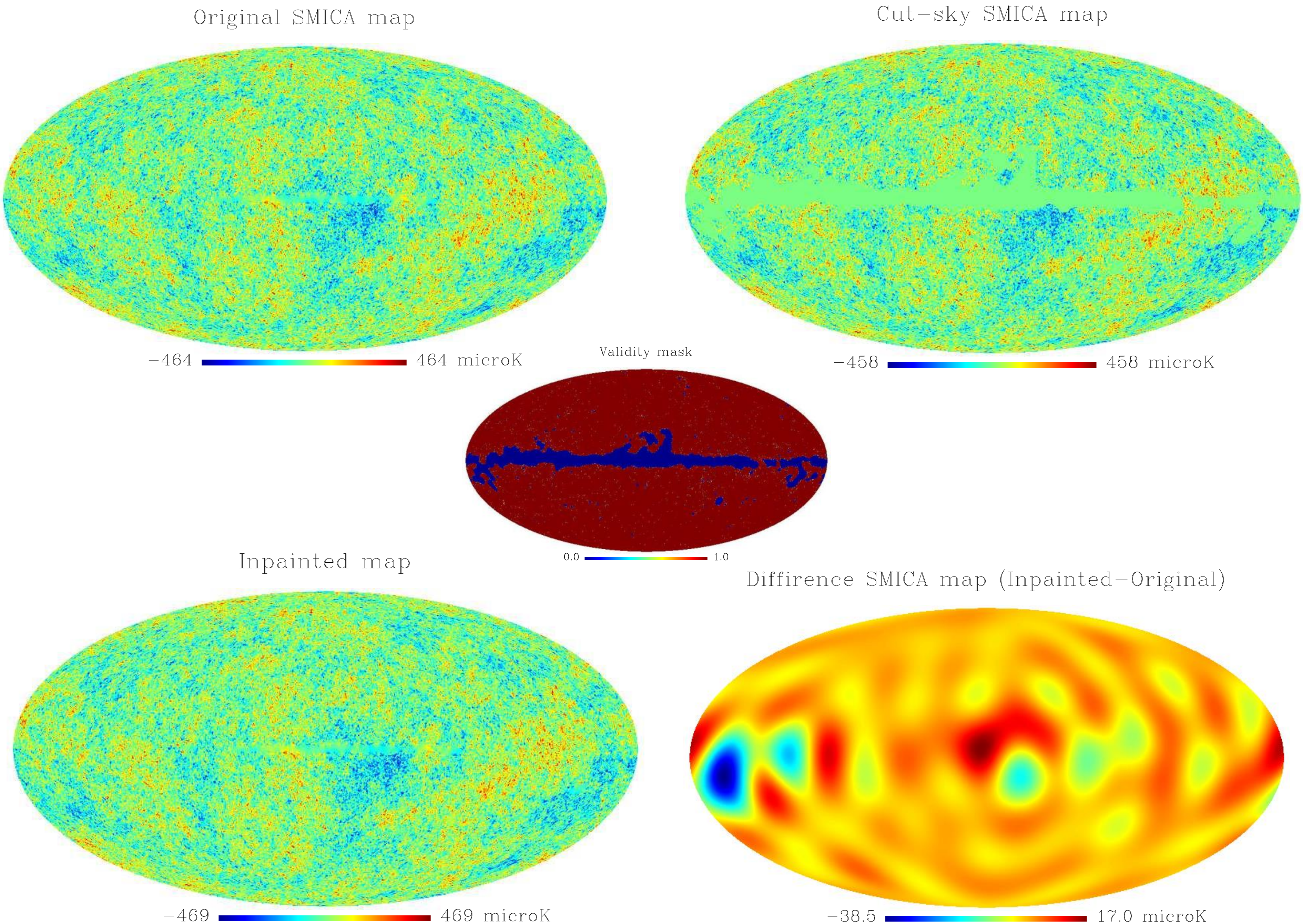
Kp75y9: p=0.1%

SMICA

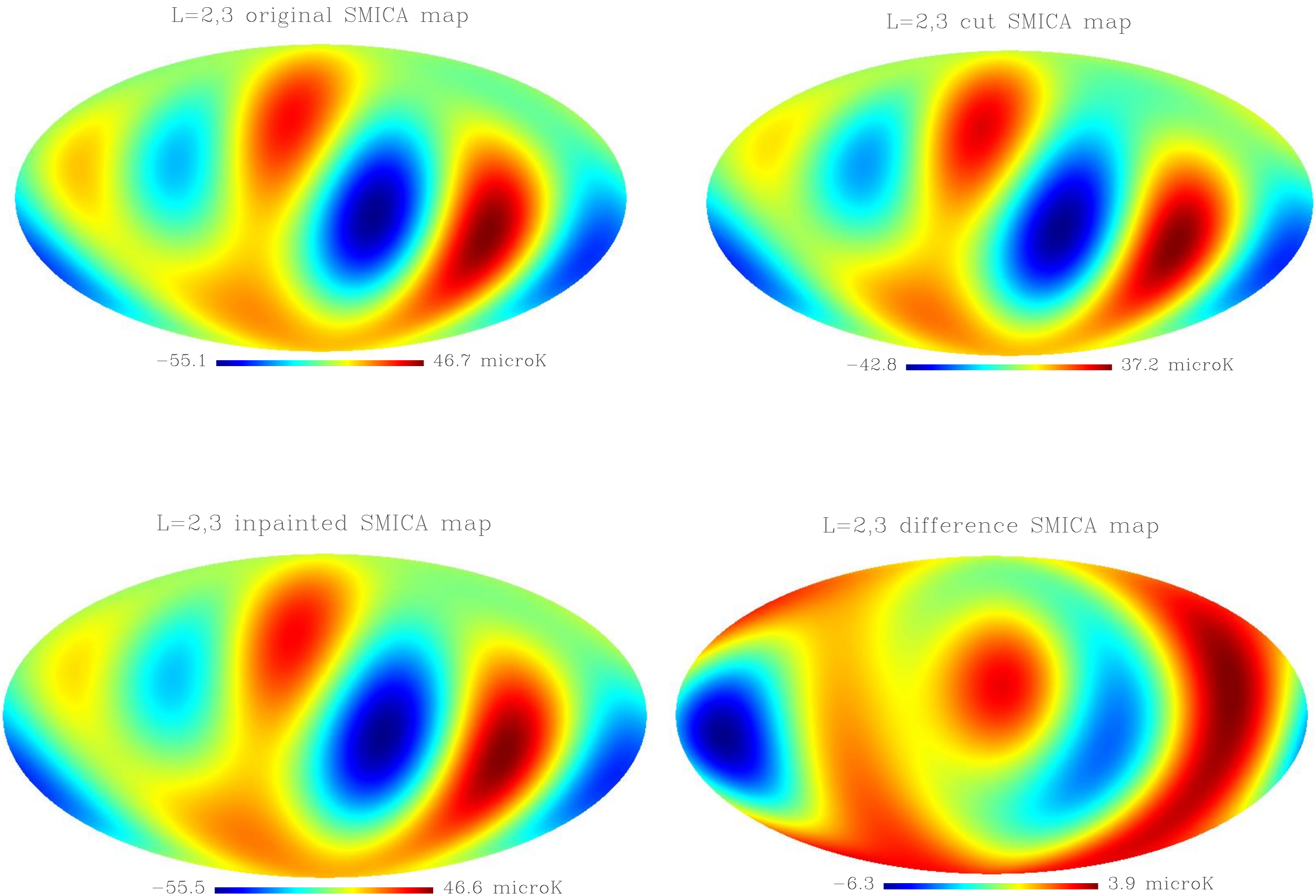
Minimal CR: p=0.3%

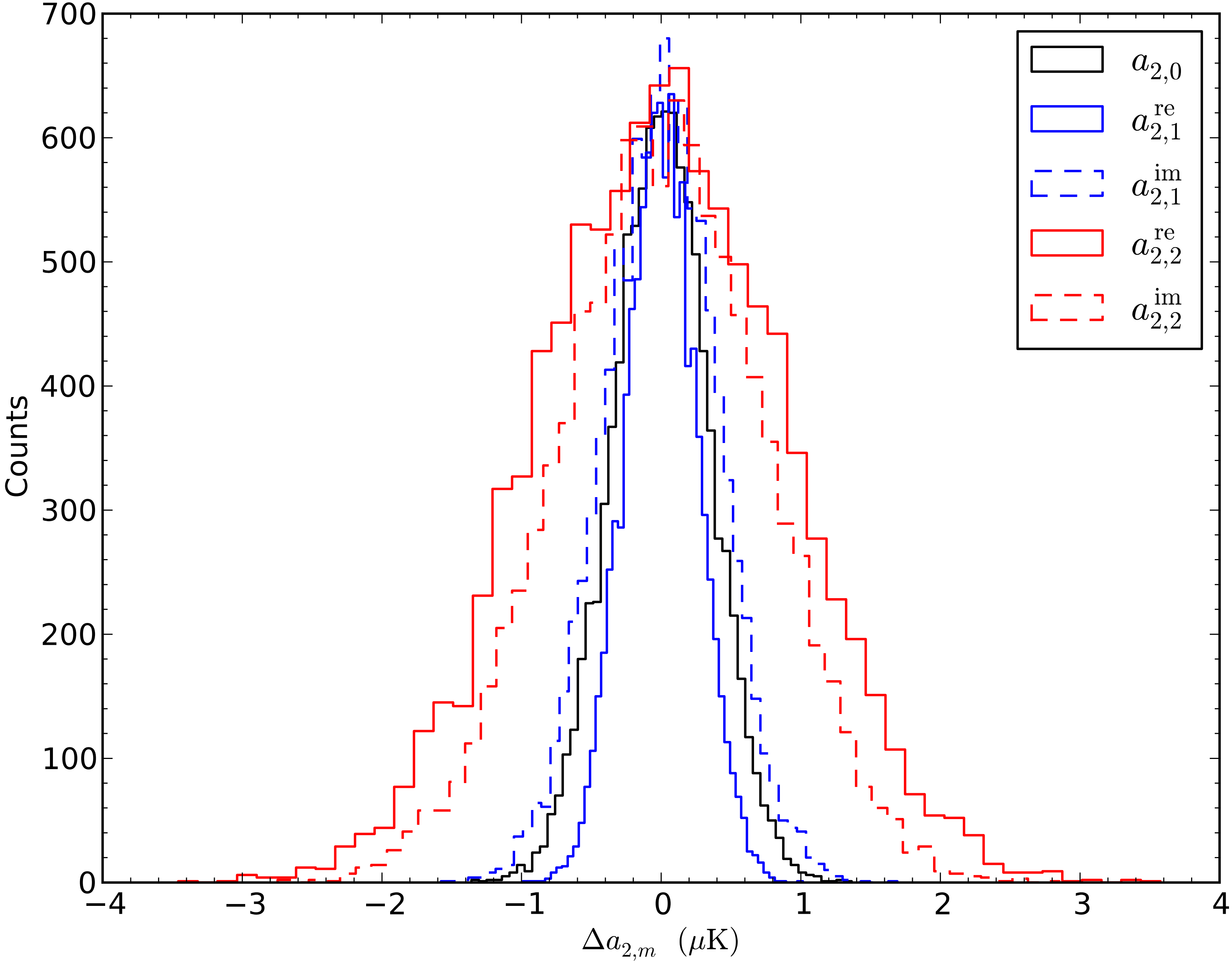
Kp75y9:

p=0.05

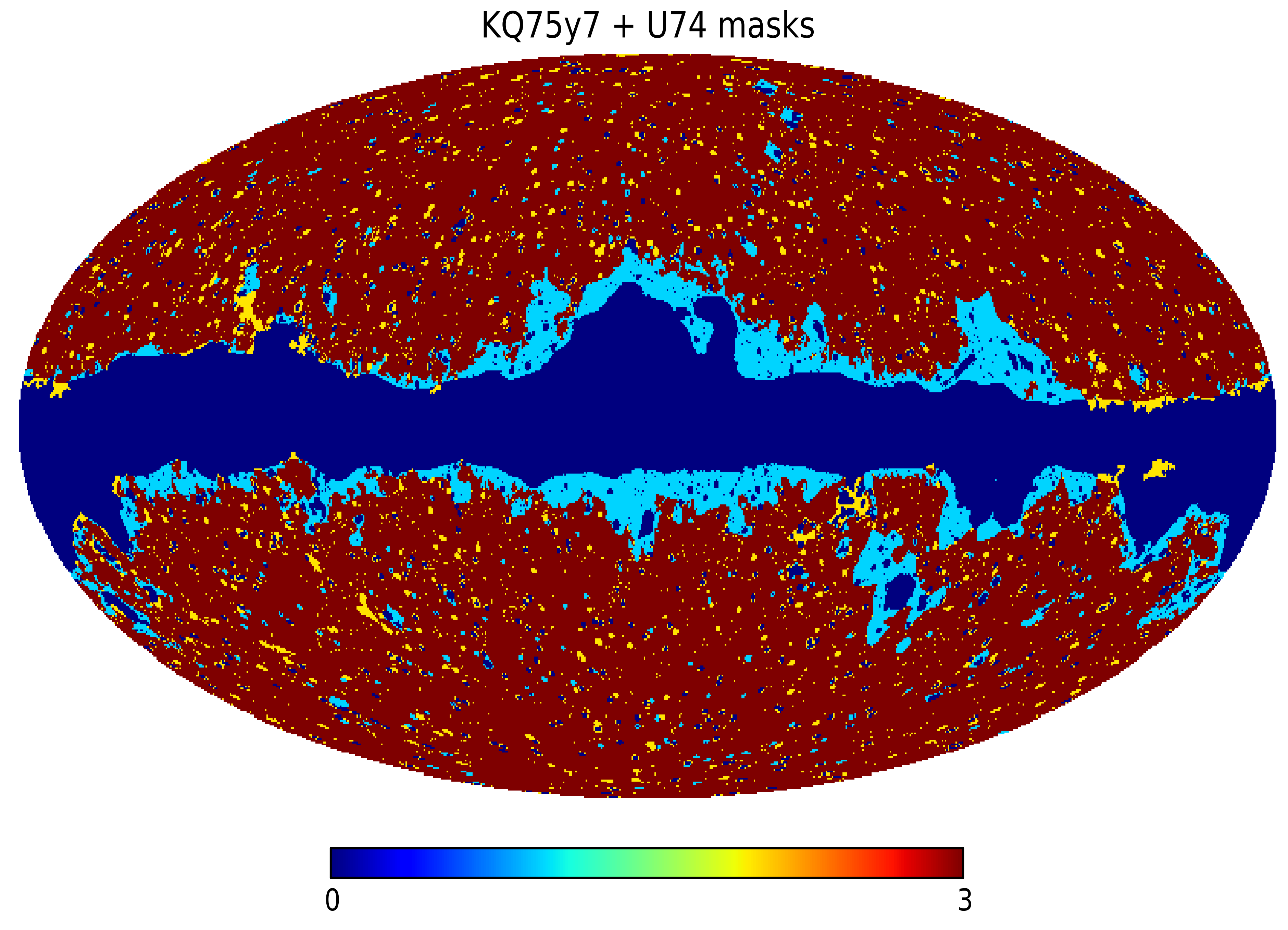


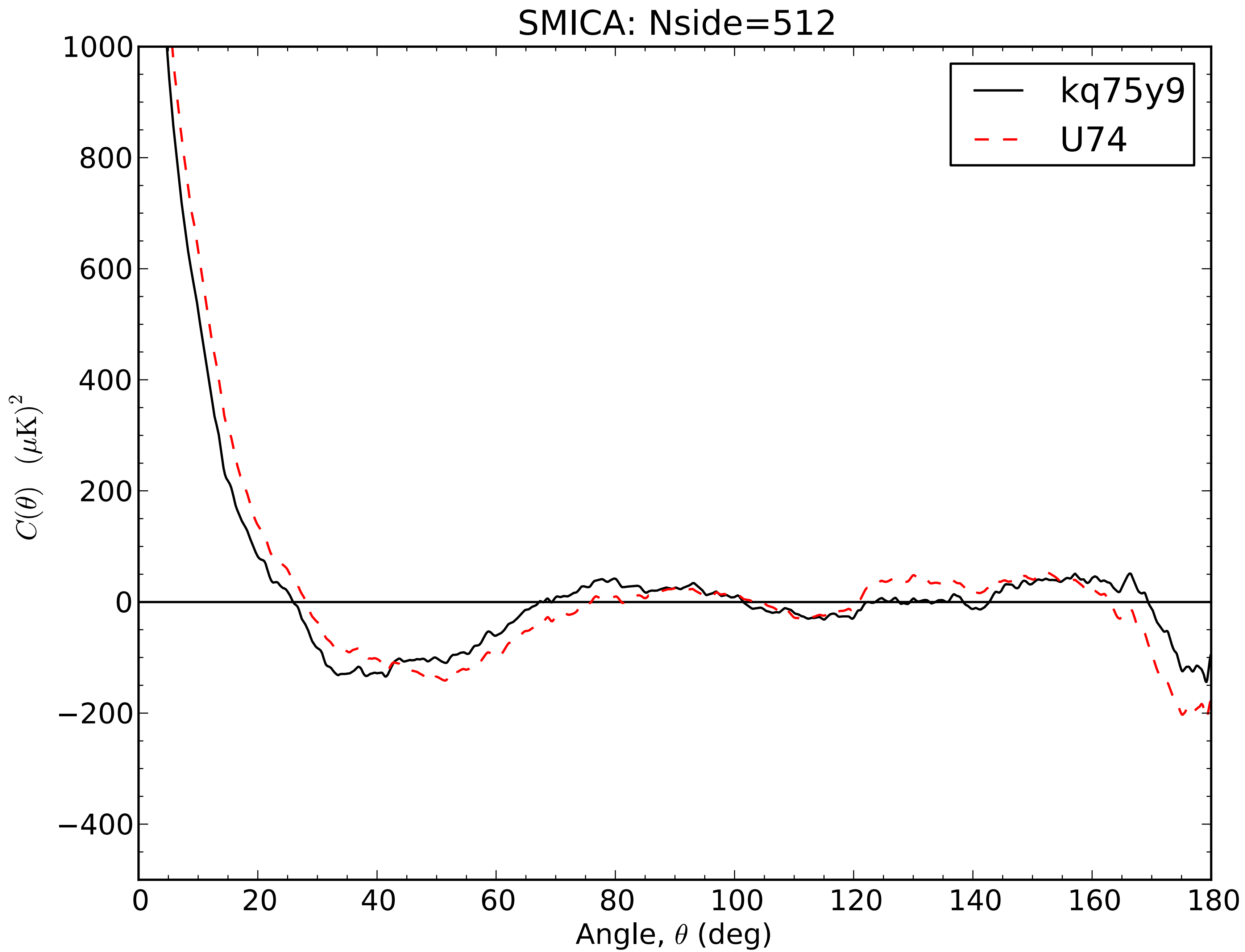
Original SMICA map
−464
464 microK
Cut−sky SMICA map
−458
458 microK
Validity mask
0.0
1.0
Inpainted map
−469
469 microK
Diffirence SMICA map (Inpainted−Original)
−38.5
17.0 microK


L=2,3 original SMICA map
−55.1
46.7 microK
L=2,3 cut SMICA map
−42.8
37.2 microK
L=2,3 inpainted SMICA map
−55.5
46.6 microK
L=2,3 difference SMICA map
−6.3
3.9 microK



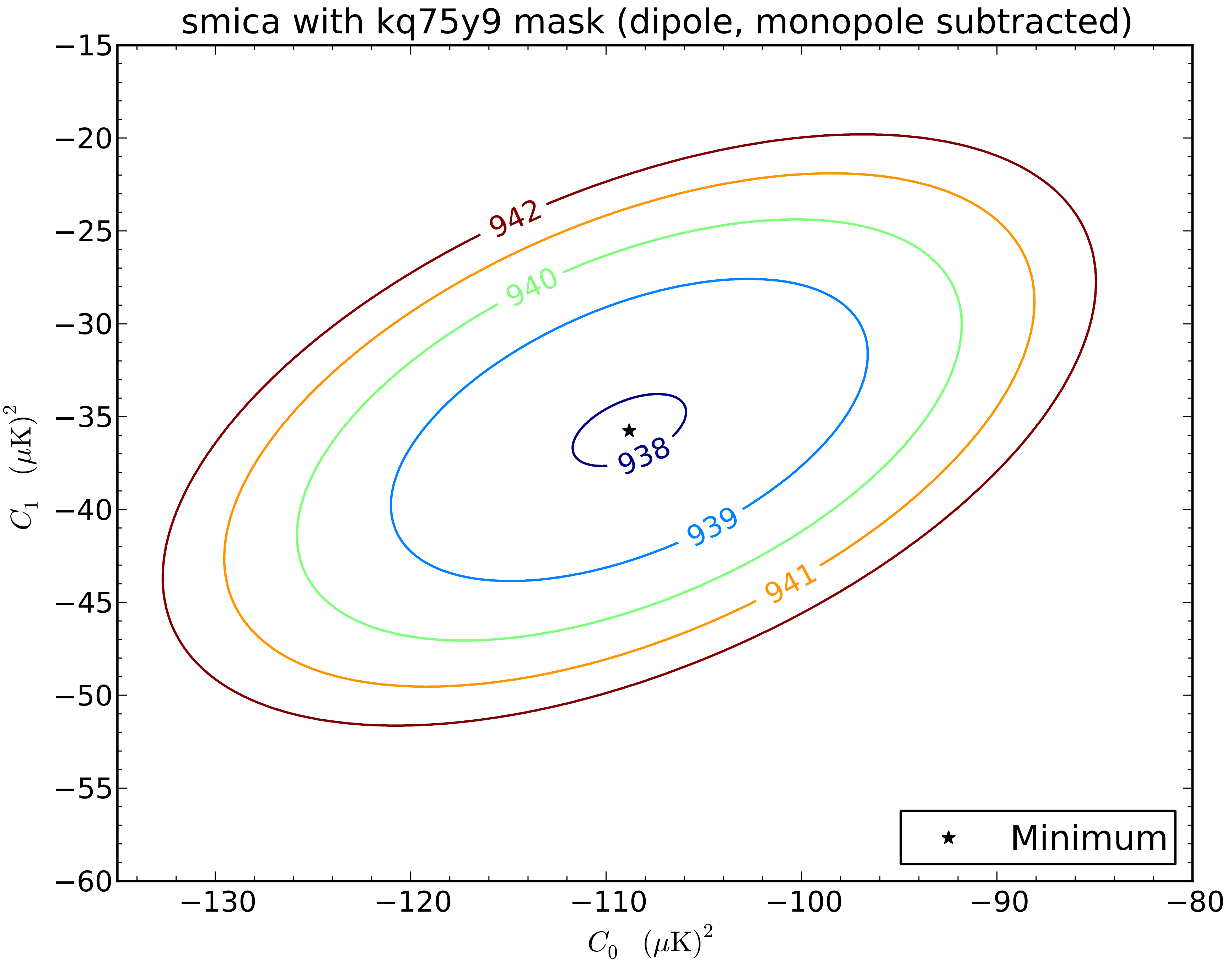
700
600
500
400
300
200
100
0
Counts
−4
−3
−2
−1
0
1
2
3
4
$\Delta a_{2,m}$ (μK)
$a_{2,0}$
$a_{2,1}^{\rm re}$
$a_{2,1}^{\rm im}$
$a_{2,2}^{\rm re}$
$a_{2,2}^{\rm im}$


KQ75y7 + U74 masks
0
3

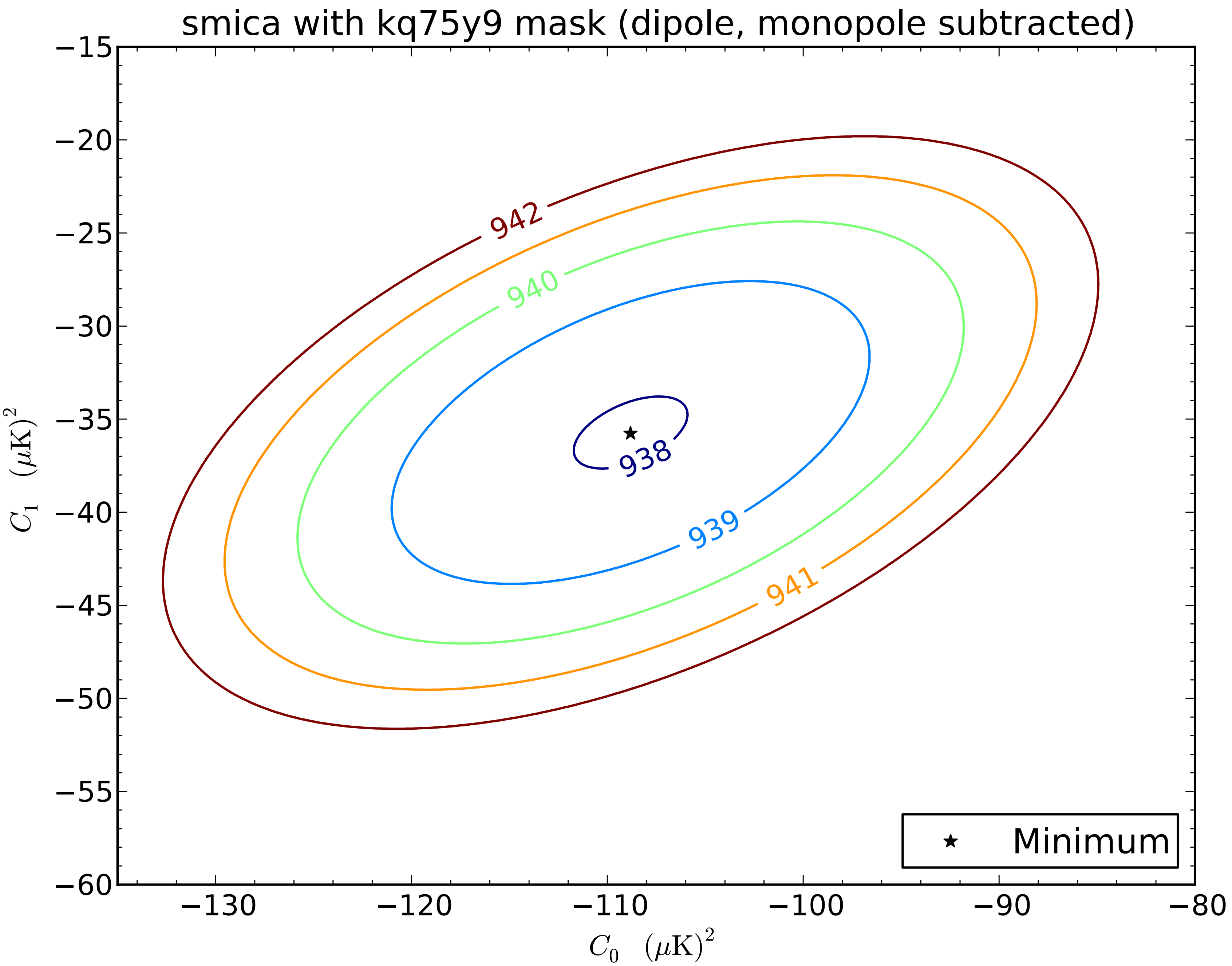

SMICA: Nside=512
kq75y9
U74
$C(\theta)\ \ (\mu K)^2$
Angle, θ (deg)
1000
800
600
400
200
0
−200
−400
0
20
40
60
80
100
120
140
160
180

S12 for different maps/masks

MAP \ MASK	U74	KQ75y9	UW
WMAP ILC9	1626	1278	1436
SMICA	1578	1022	1174
NILC	1589	1038	1187
SEVEM	1658	1153	1315



smica with kq75y9 mask (dipole, monopole subtracted)
942
941
940
939
938
Minimum
−15
−20
−25
−30
−35
−40
−45
−50
−55
−60
−130
−120
−110
−100
−90
−80
$C_0 \quad (\mu\mathrm{K})^2$
$C_1 \quad (\mu\mathrm{K})^2$



smica with kq75y9 mask (dipole, monopole subtracted)
−15
−20
−25
−30
−35
−40
−45
−50
−55
−60
$C_1 \quad (\mu\mathrm{K})^2$
−130
−120
−110
−100
−90
−80
$C_0 \quad (\mu\mathrm{K})^2$
942
941
940
939
938
Minimum