Is the large-angle CMB anomalous?

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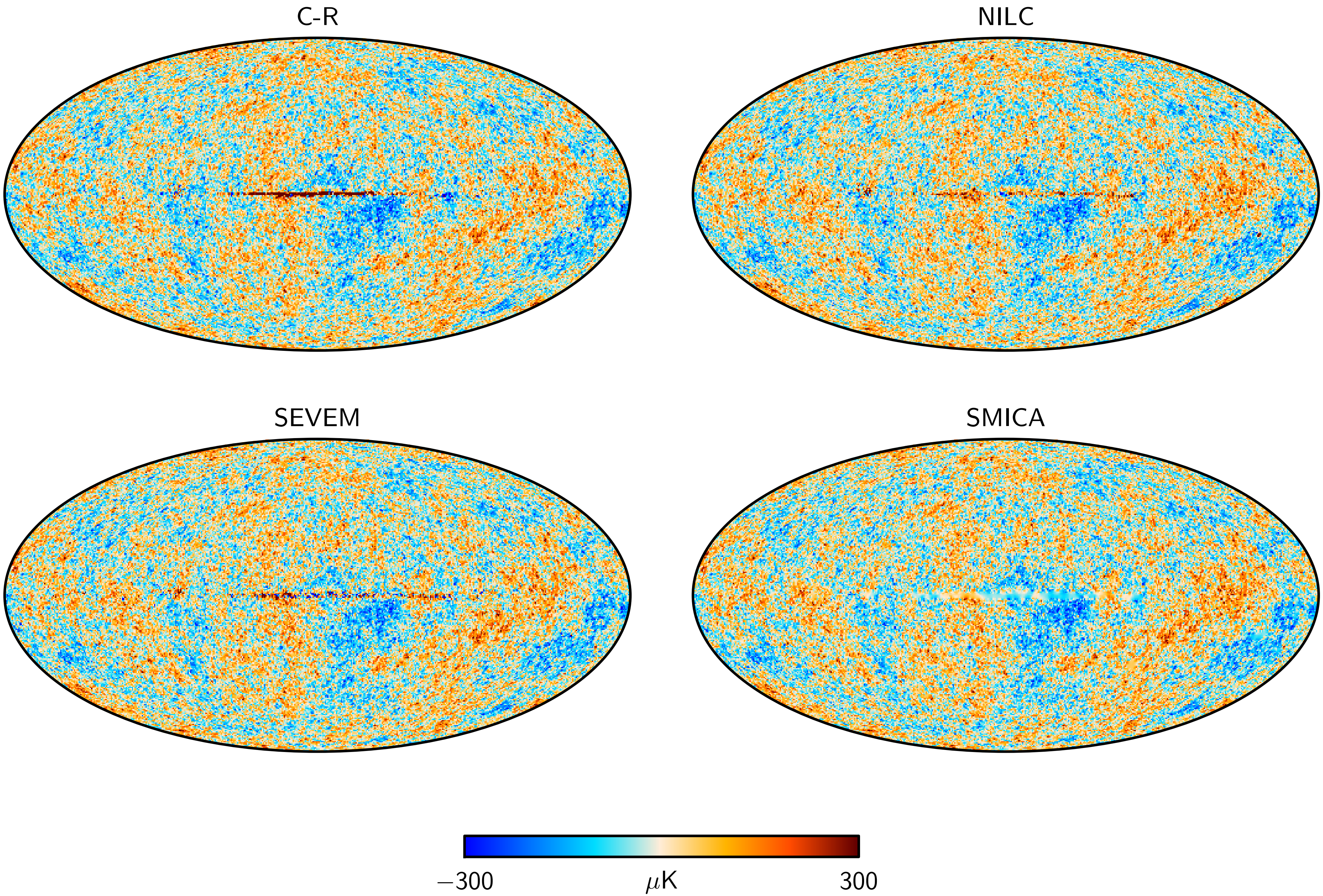
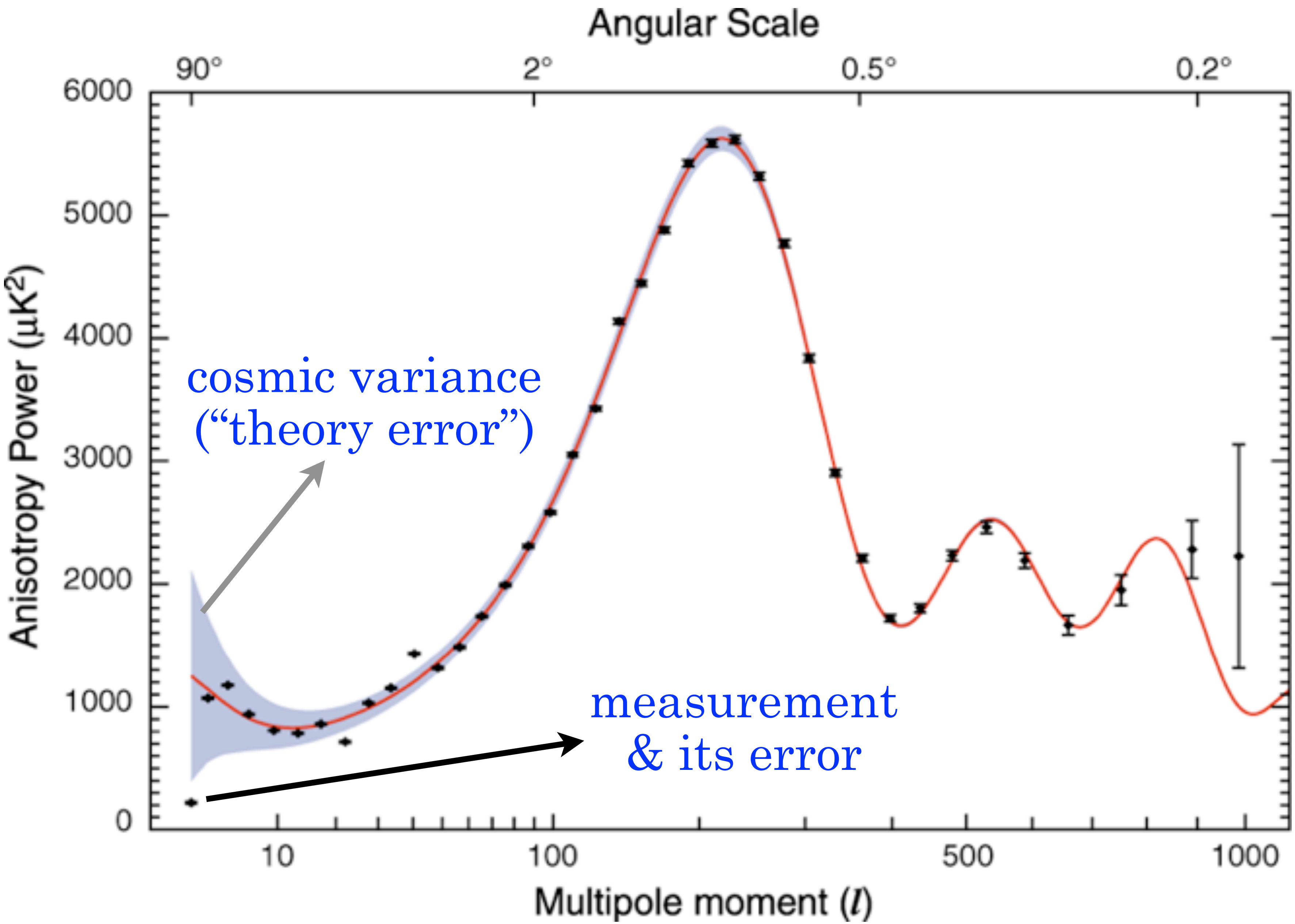
based mostly on work with
Copi, Schwarz & Starkman (2004-2014)
review in
Copi et al, Adv. Astro., 847531 (2010), arXiv:1004.5602


C-R
NILC
SEVEM
SMICA
−300
μK
300



WMAP angular power spectrum

Philosophy:

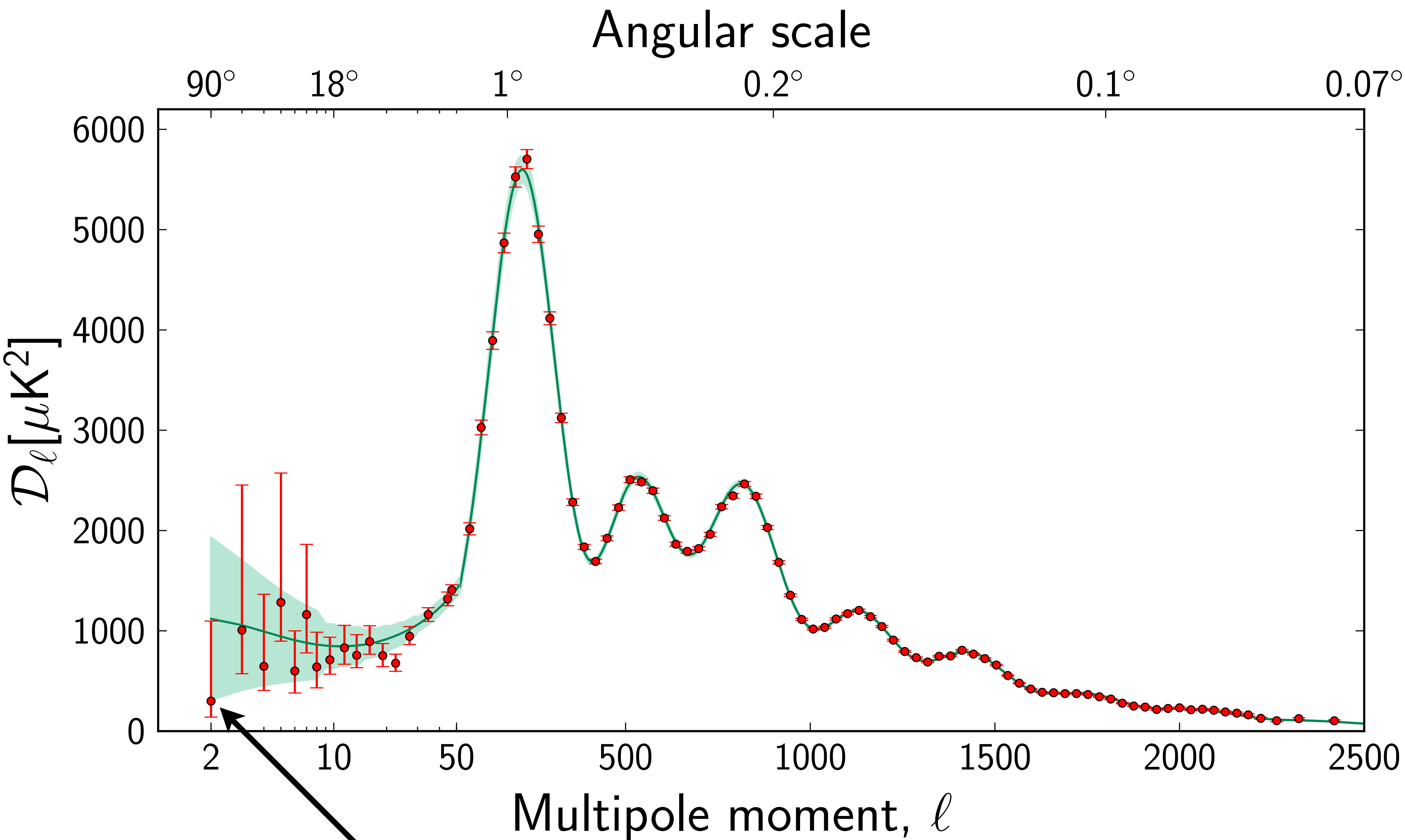
Anomalies are almost always *a posteriori* nature
– they are not (*a priori*) predicted

Not every 'anomaly' is equally compelling:
in this talk, the **largest-scale** anomalies

Summary:

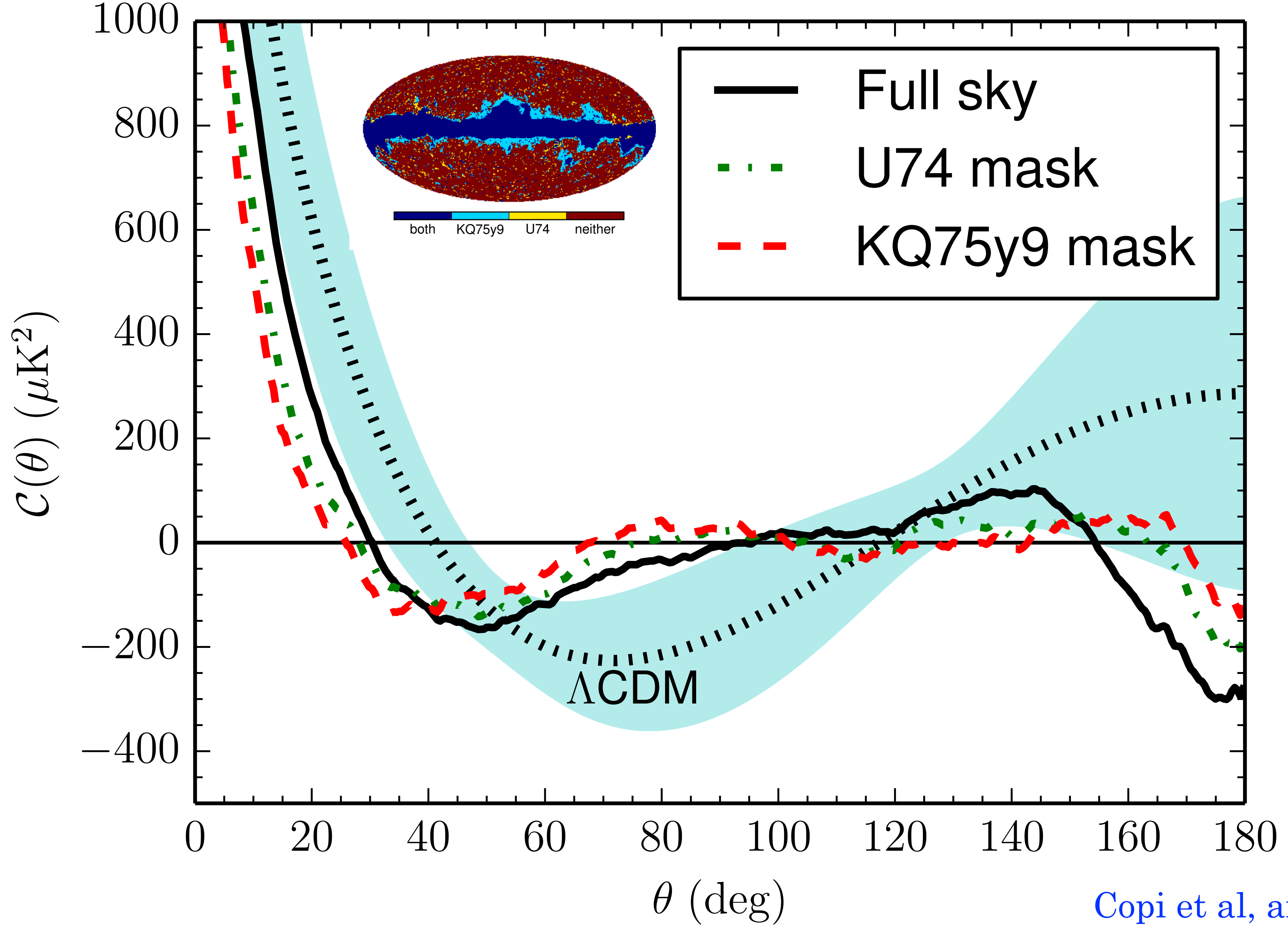
1. Angular 2-pt function $C(\theta)$ vanishes for $\theta \gtrsim 60$ deg
2. Quadrupole and octopole are unusually planar, and the plane is nearly perpendicular to some special directions on the sky

Missing Large-Angle Power



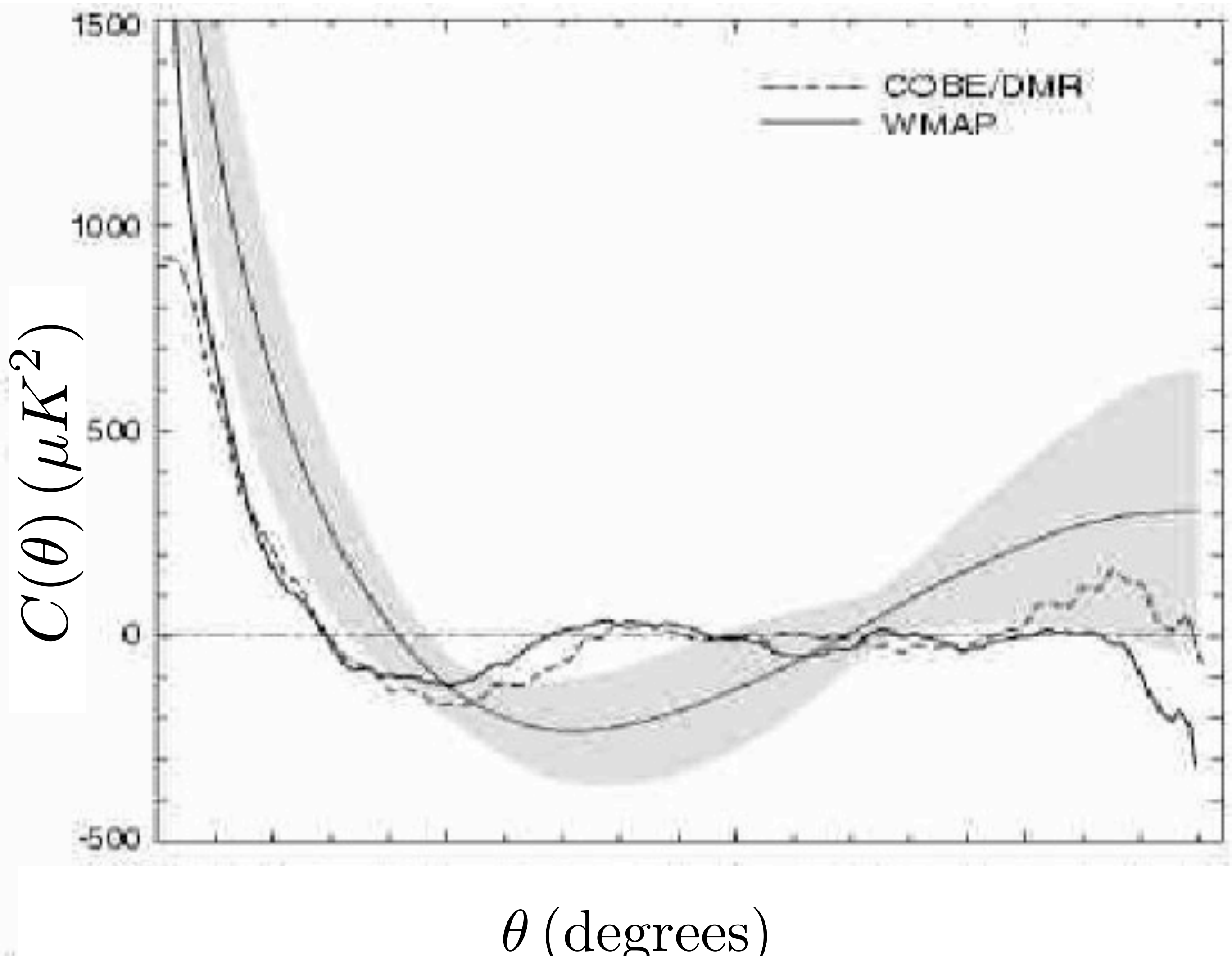
NOT the “low quadrupole”...

Power at θ≳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

$S_{1/2}$ statistic:

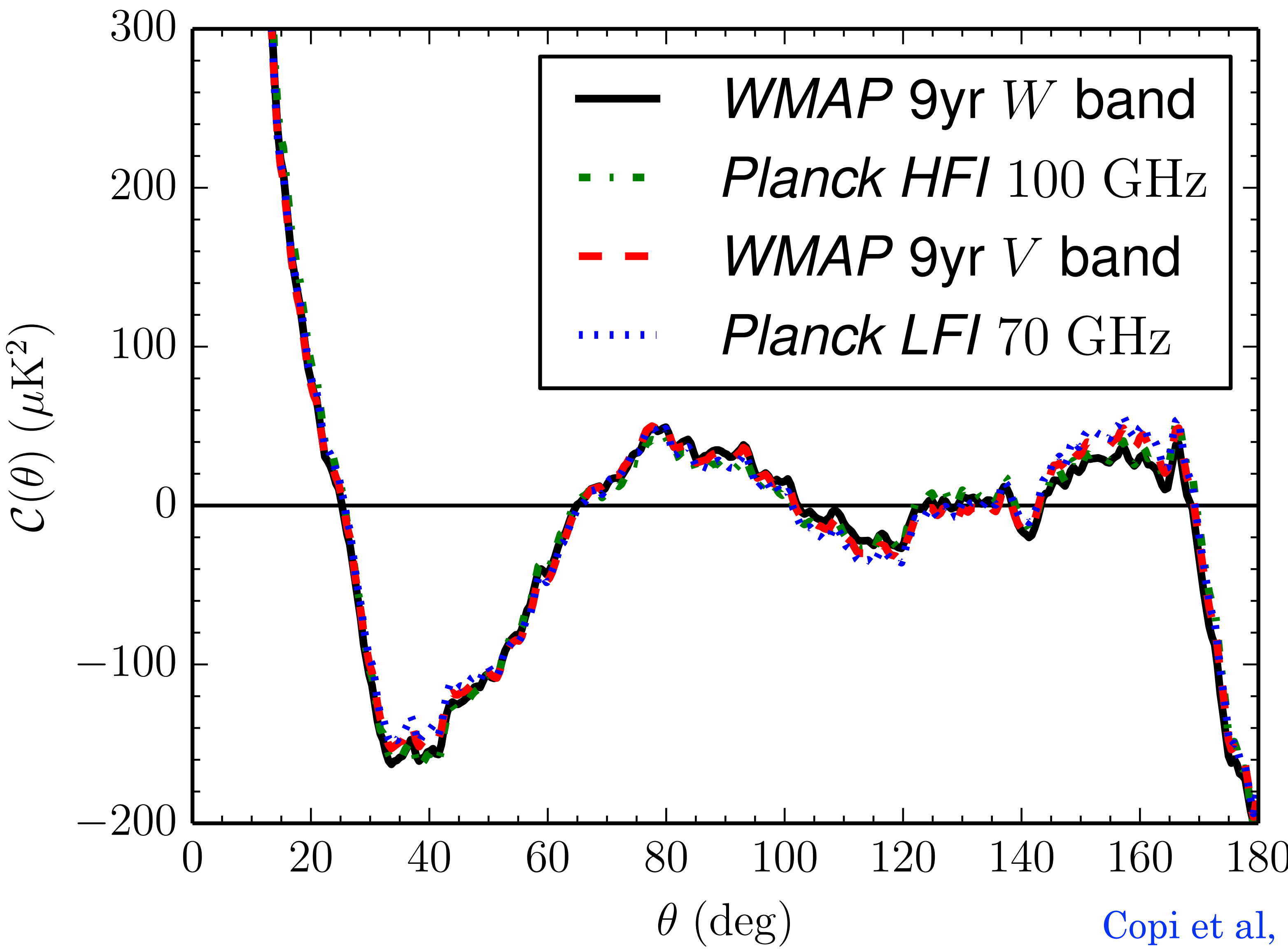
(Spergel et al 2003)

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

Map	U74 $S_{1/2}$ $(\mu K)^4$	U74 p (%)	KQ75y9 $S_{1/2}$ $(\mu K)^4$	KQ75y9 p (%)
WMAP ILC 7yr	1620.3	0.208	1247.0	0.090
WMAP ILC 9yr	1677.5	0.232	1311.8	0.109
Planck SMICA	1606.3	0.202	1075.5	0.053
Planck NILC	1618.6	0.208	1096.2	0.058
Planck SEVEM	1692.4	0.239	1210.5	0.082
WMAP W 7yr	1839.0	0.304	1128.5	0.064
WMAP W 9yr	1864.2	0.317	1138.3	0.066
Planck HFI 100	1707.5	0.245	916.3	0.028
WMAP V 7yr	1829.2	0.300	1276.2	0.099
WMAP V 9yr	1840.4	0.304	1268.8	0.097
Planck LFI 70	1801.7	0.287	1282.1	0.101

(frequentist) significance $\geq$ 99.7% in all cases

Remarkably consistent across experiments, frequencies, foreground cleanings:



Copi et al, arXiv:1310.3831

$\Rightarrow$ primordial? or a statistical fluke?

Summary of missing-power statistics

	$S_{1/2} \equiv \int_{-1}^{1/2} [\mathcal{C}(\theta)]^2 \, \mathrm{d}(\cos\theta)$	Probability
LCDM	50,000 μK^4	50%
best-fit theory (e.g. WMAP C_l)	8,000 μK^4	5%
WMAP cut-sky $\langle T_i \, T_j \rangle$	1,000 μK^4	0.03%

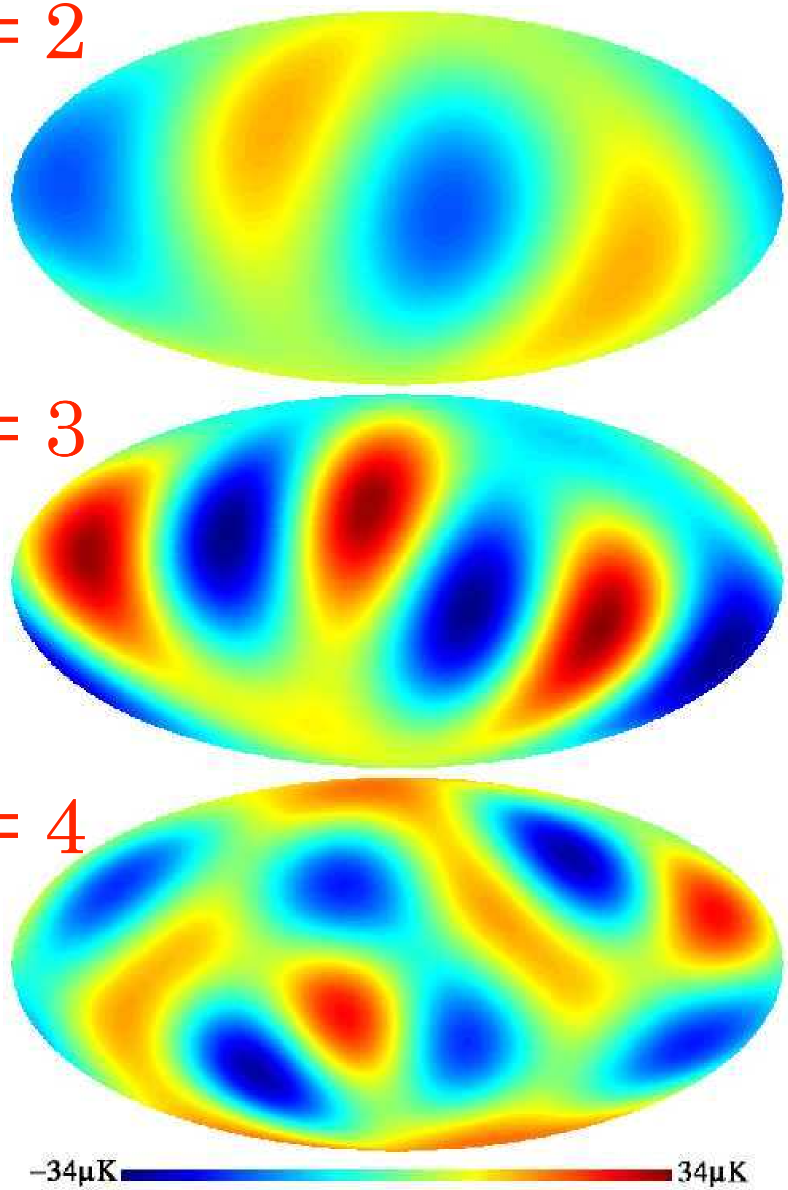
Large-scale alignments

$\ell = 2, 3$ are aligned and planar

$\ell = 2$

$\ell = 3$

$\ell = 4$



$$\hat{L}_\ell^2 \equiv \frac{\sum_{m=-\ell}^{\ell} m^2 |a_{\ell m}|^2}{\ell^2 \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}$$

ℓ=3 is planar: P~1/20

ℓ=2,3 is are aligned: P~1/60

de Oliveira-Costa, Tegmark, Zaldarriaga & Hamilton 2004

... and still are

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

- 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

Copi et al, arXiv:1311.4562

Multipole vectors!

Spherical Harmonics:

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

Multipole Vectors:

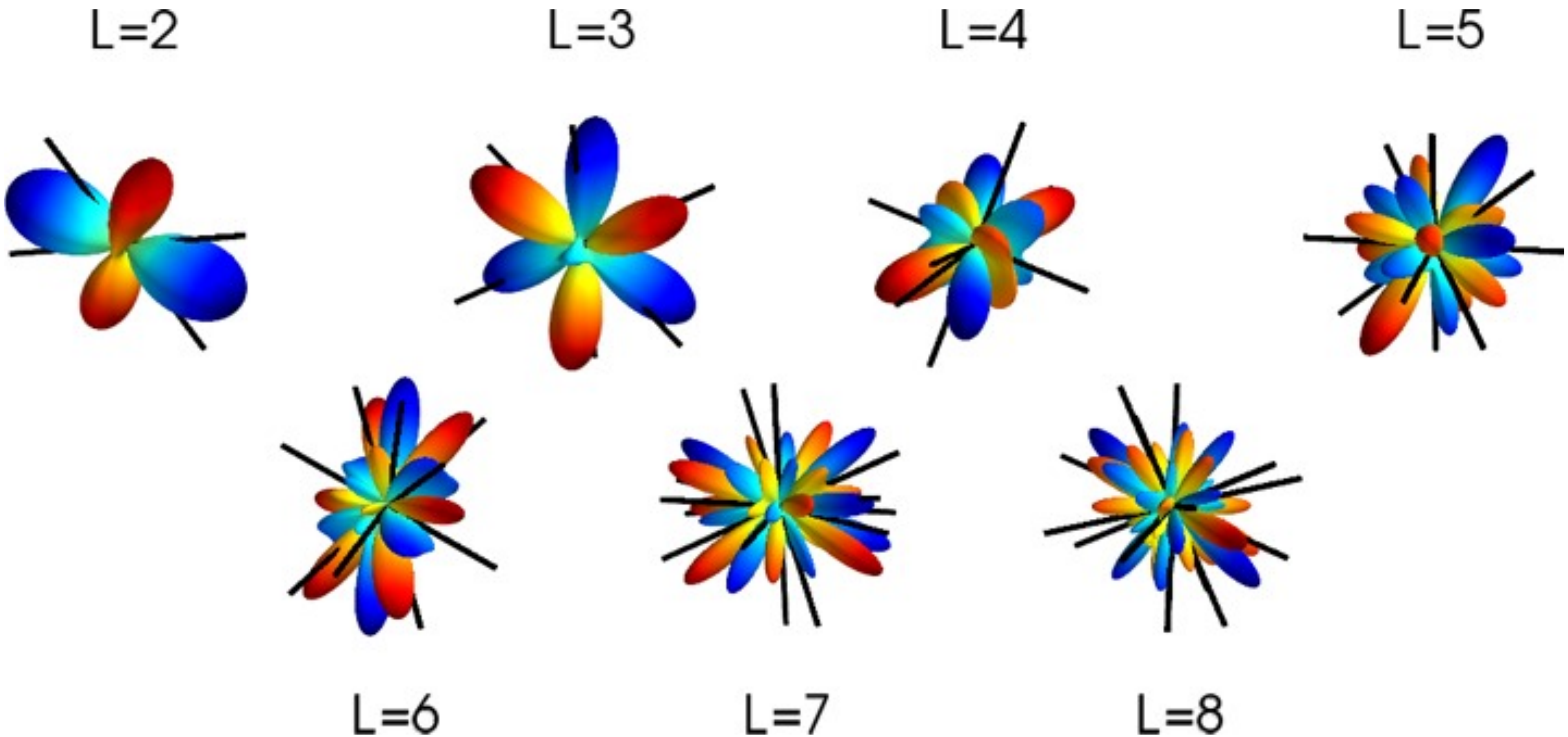
$$\sum_{m=-\ell}^{\ell} a_{lm} Y_{lm}(\theta,\phi) = A^{(\ell)}\left(\mathbf{v}_1^{(\ell)}\cdot\mathbf{e}\right)\cdots\left(\mathbf{v}_\ell^{(\ell)}\cdot\mathbf{e}\right)$$

$$\text{“}a^{(\ell)}_{i_1\ldots i_l} \leftrightarrow A^{(l)}\left[\mathbf{v}_1^{(\ell)}\otimes\mathbf{v}_2^{(\ell)}\otimes\ldots\mathbf{v}_\ell^{(\ell)}\right]\text{''}$$

Lth multipole <=> L (headless) vectors, plus a constant

Copi, Huterer & Starkman 2004; http://www.phys.cwru.edu/projects/mpvectors/

Multipole vectors of our sky



http://www.phys.cwru.edu/projects/mpvectors/

Multipole vectors, intuitively

Potential of:

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

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

....

l'th multipole: $$\nabla \mathbf{v}_\ell \ldots \nabla_{\mathbf{v_2}} \nabla_{\mathbf{v_1}} \frac{1}{r}$$

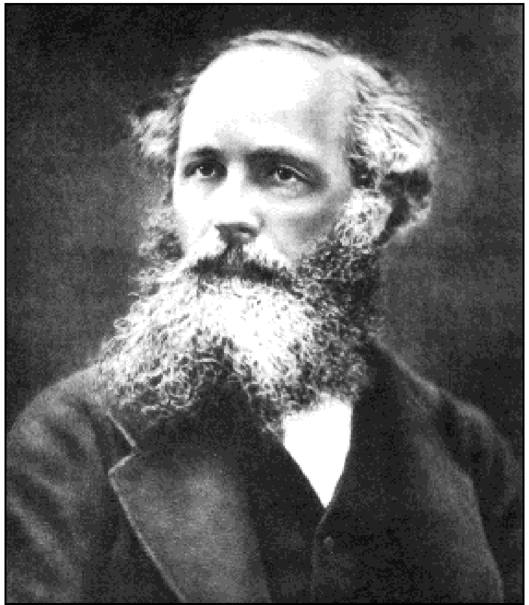
$\mathbf{v_1} \ldots \mathbf{v}_\ell$ are the multipole vectors

Weeks 2004

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)

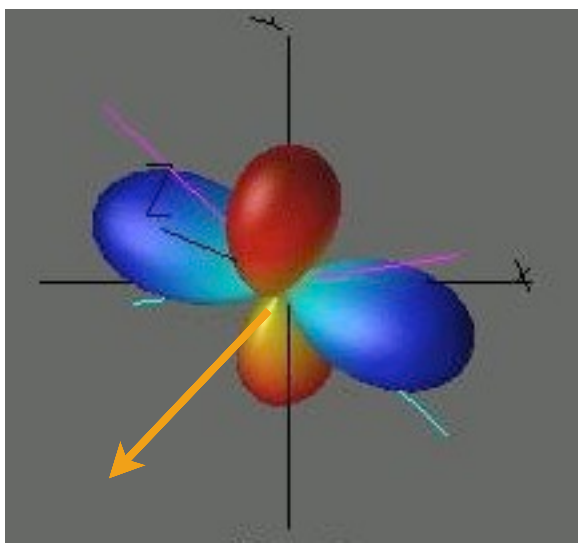
Also:
discussed by J.C. Maxwell in his "Treatise on Electricity and Magnetism" in 1892!



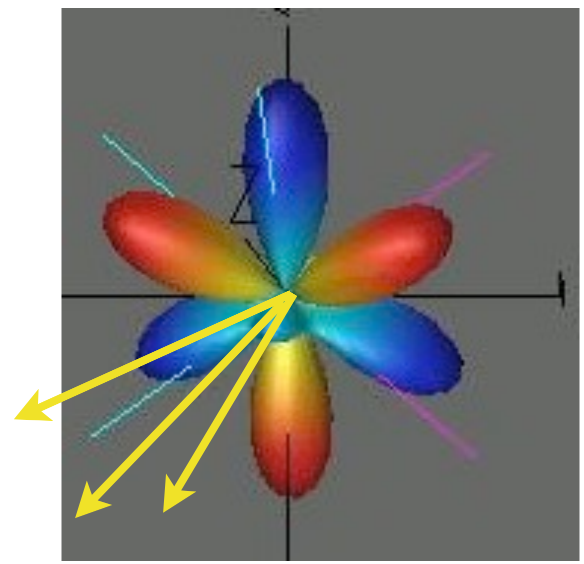
Normals to multipole vectors

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

"oriented areas"

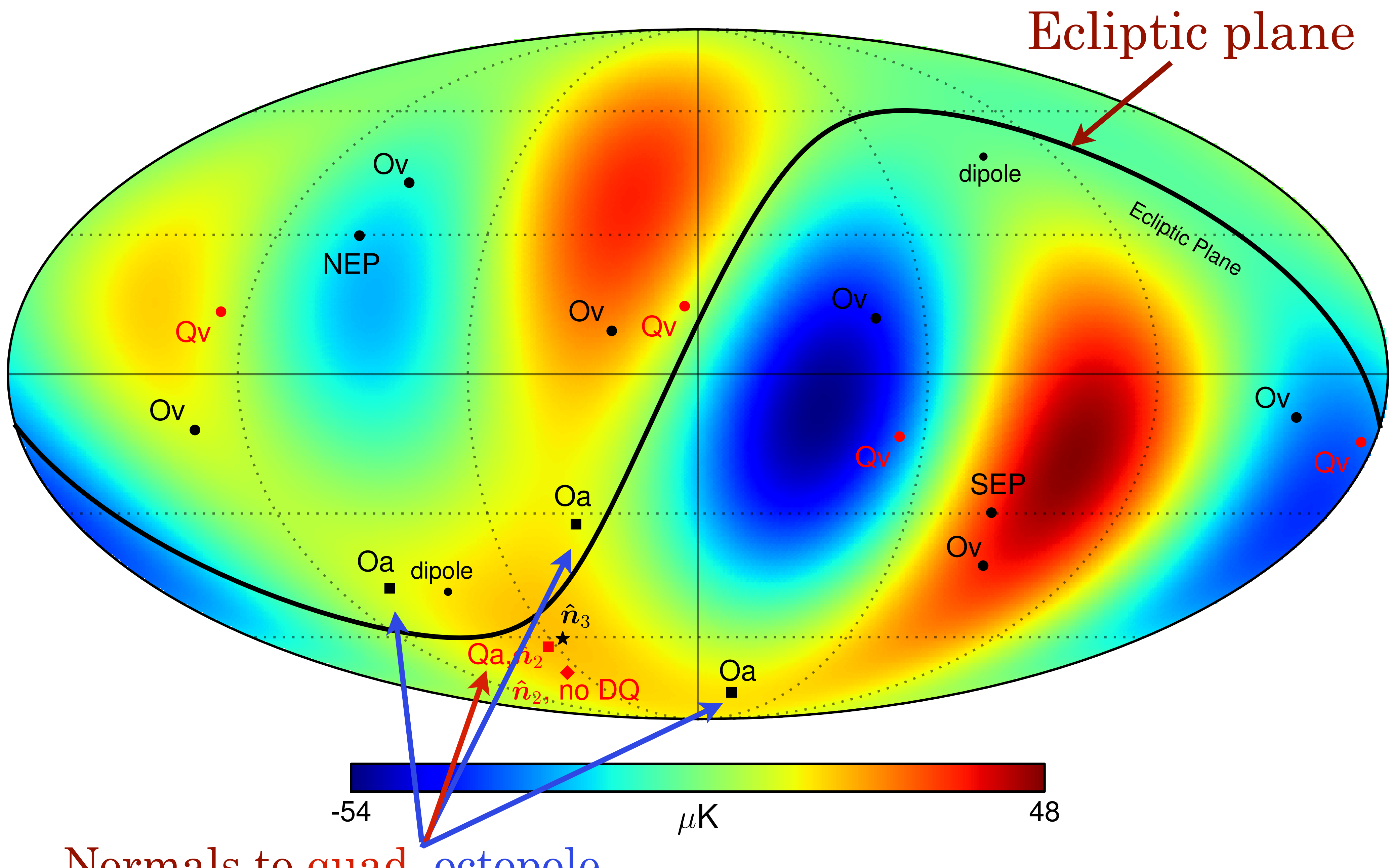


L=2



L=3

L=2+3 map



Copi et al, arXiv:1311.4562

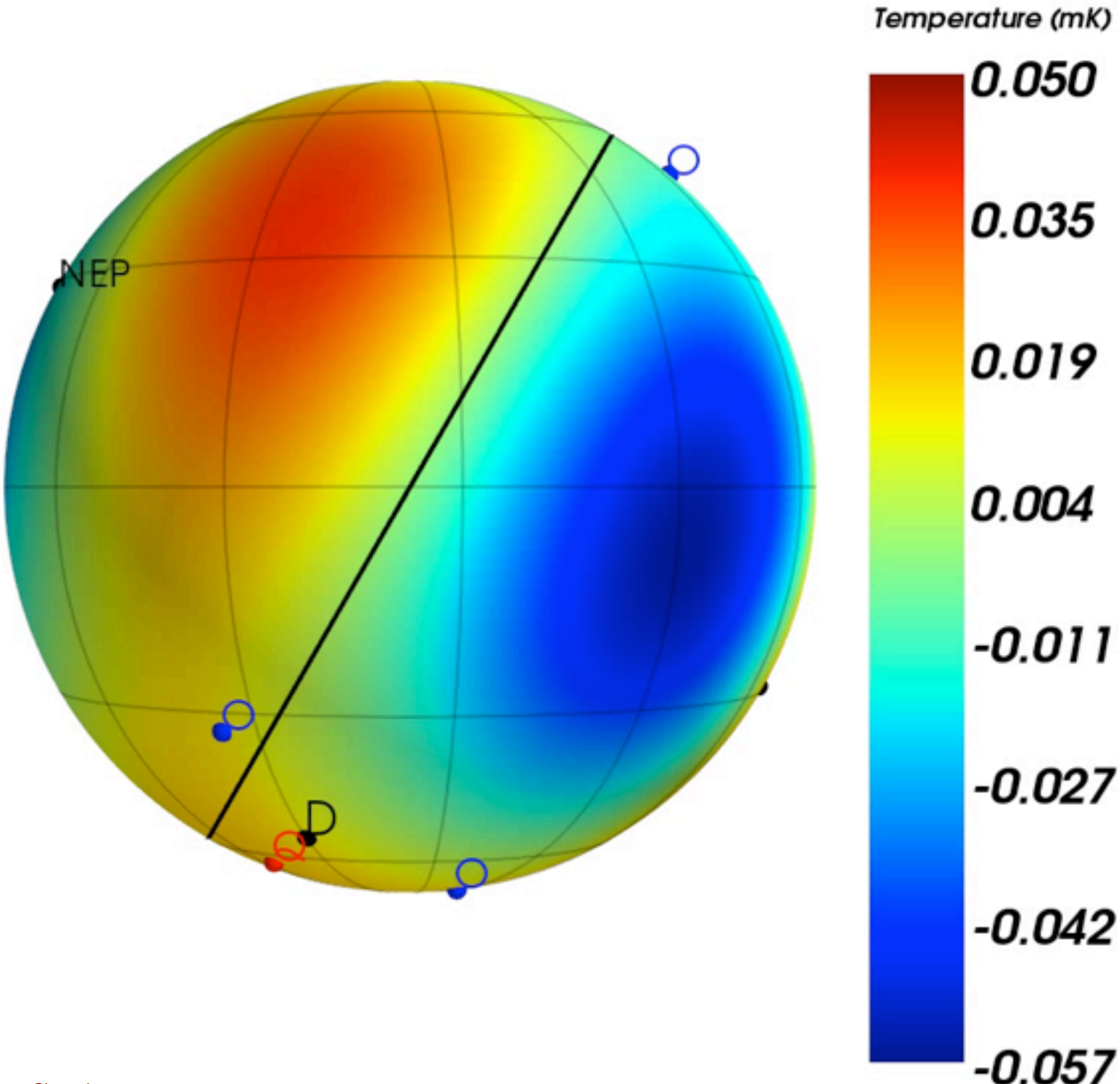
Probability for alignment of Q+O structure with Ecliptic:
2%-4%

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



Movie by Craig Copi

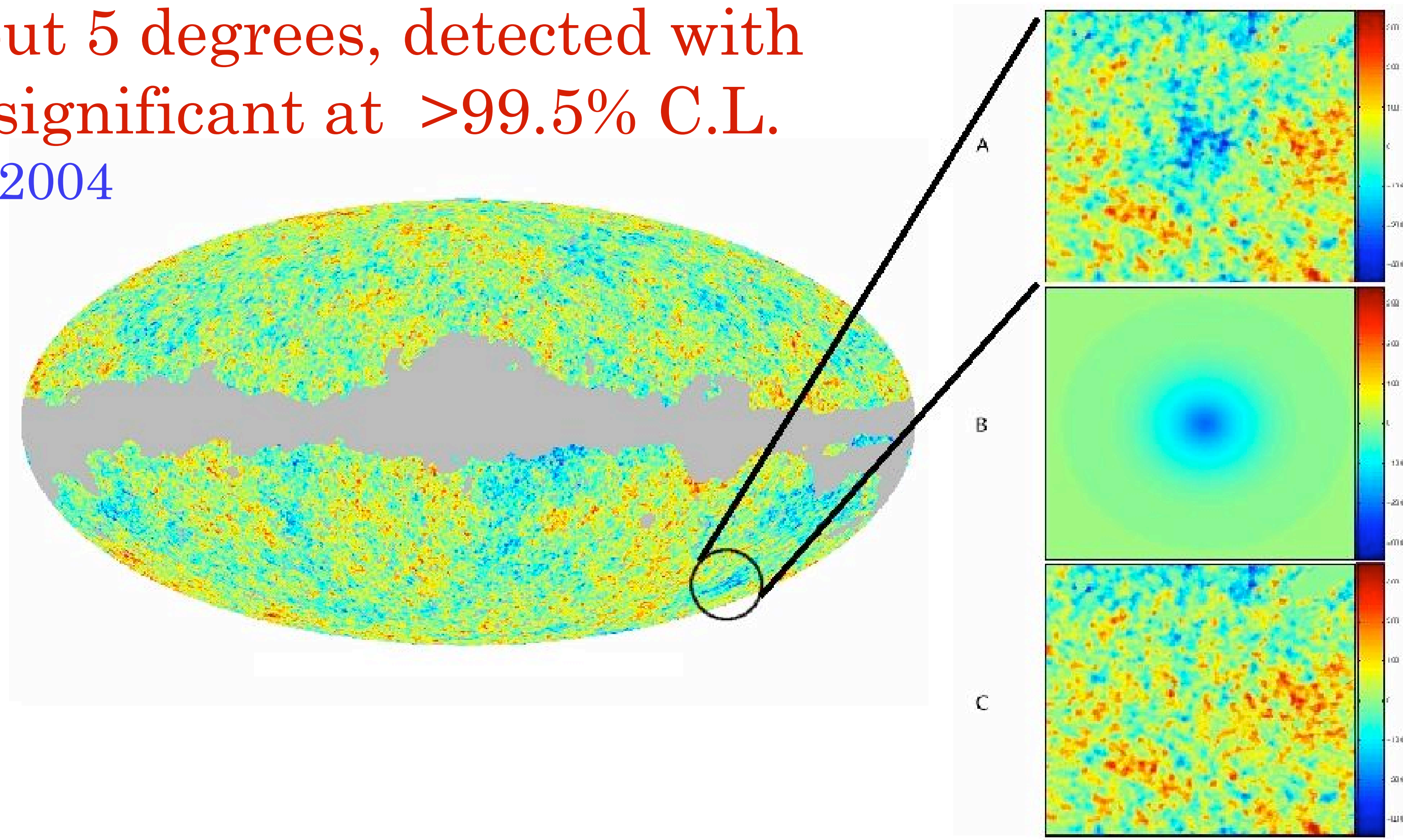
Other notable claimed anomalies

- 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

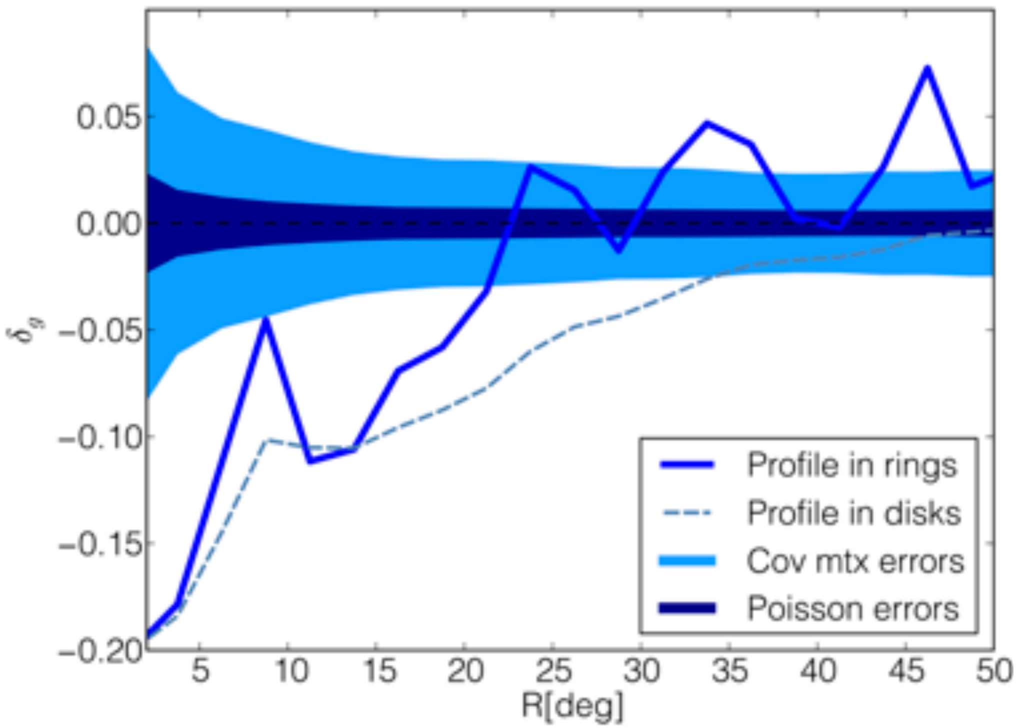


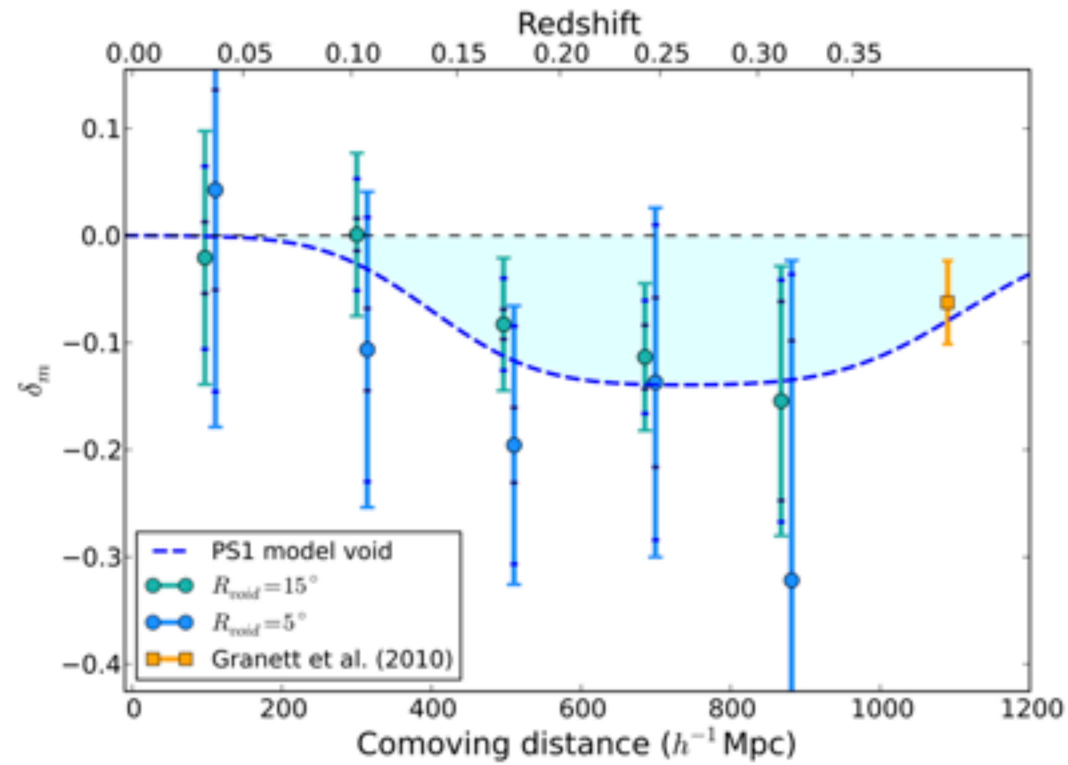
BUT: evidence disappears once you try “finding” it with something other than a mexican hat wavelet (e.g. a top hat)

Zhang & Huterer, 2010

Cold spot in the galaxy distribution??

In same direction as the CMB cold spot

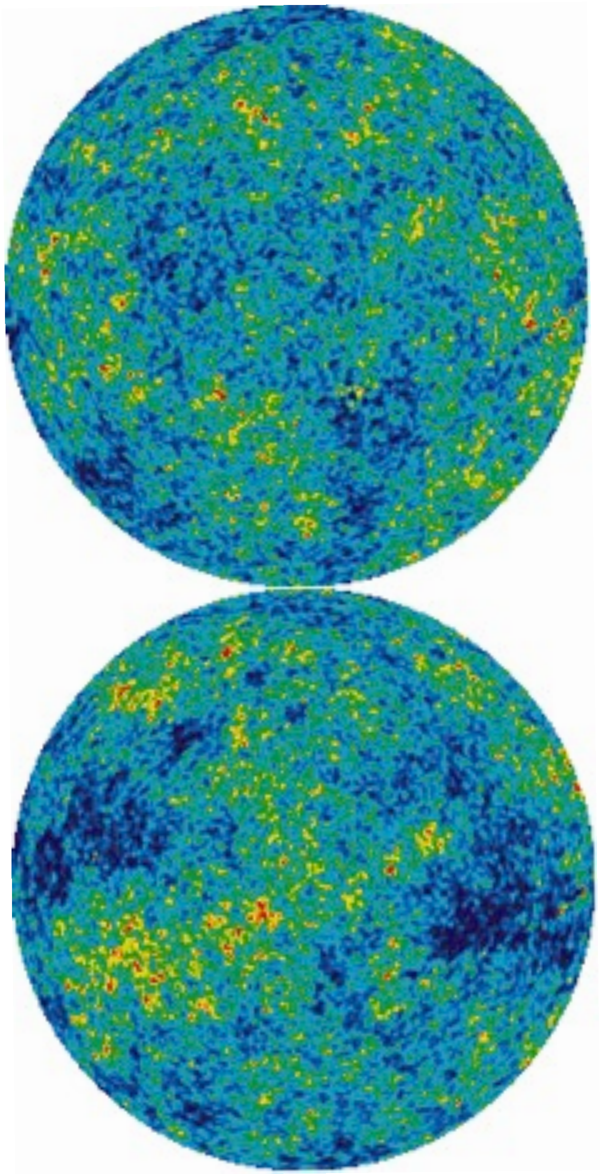




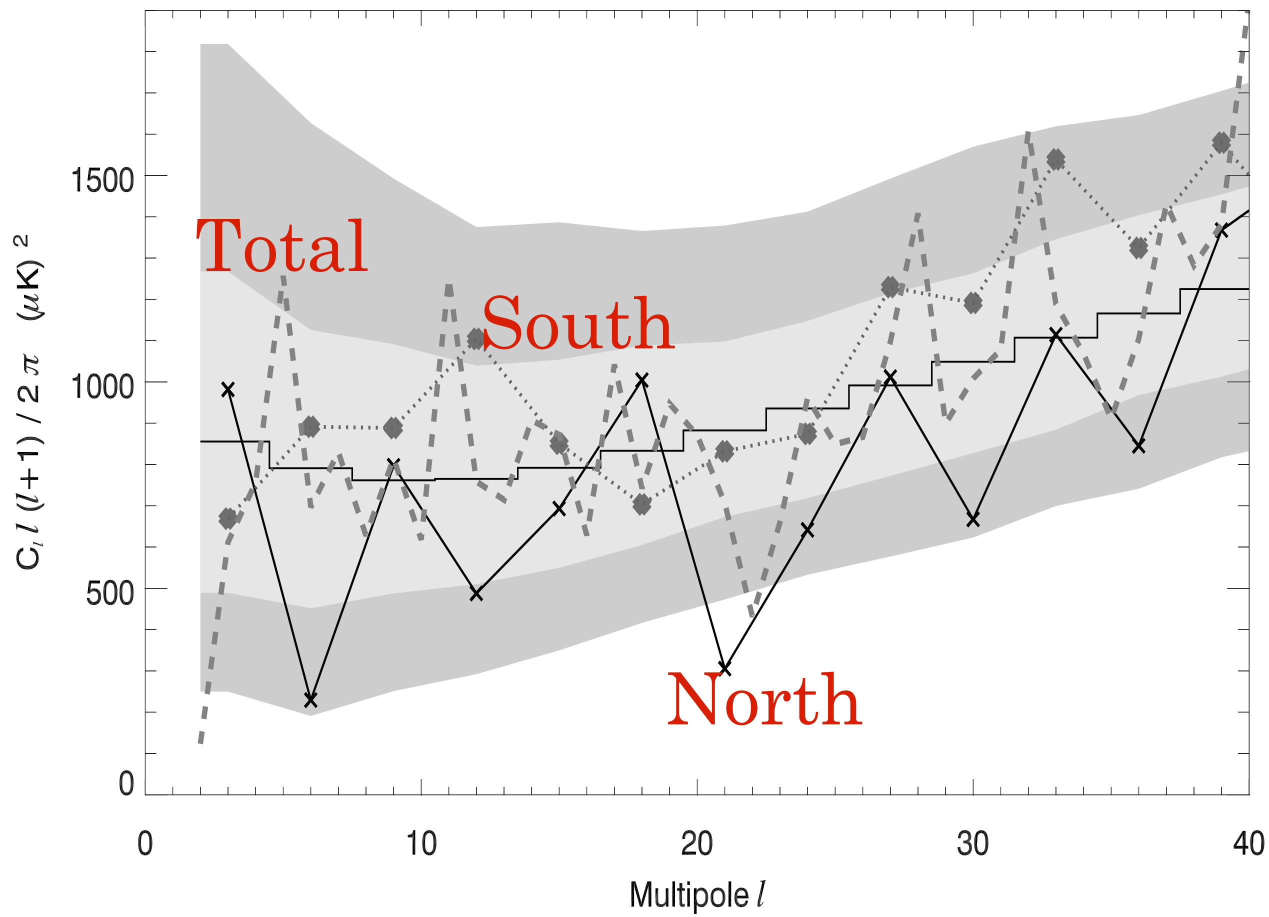
Szapudi et al, 1405.1566

- 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

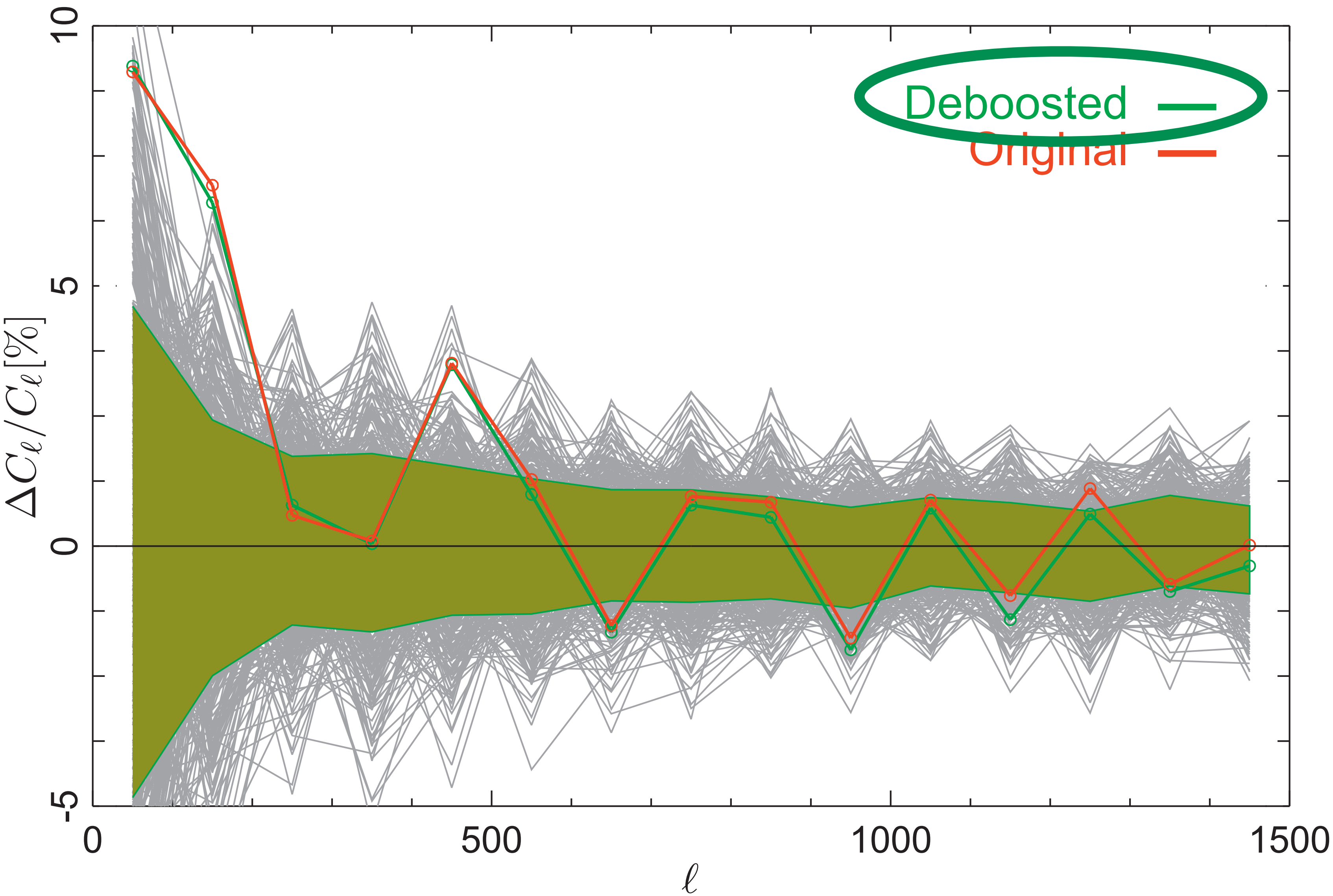


South (ecliptic) has more power than north



Eriksen et al 2004;
Hansen, Banday and Gorski 2004

shown below: $2\,\frac{C_\ell^{\rm south} - C_\ell^{\rm north}}{C_\ell^{\rm south} + C_\ell^{\rm north}}$



Planck XXIII, 2013

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!

Example: non-linear detector

Suppose that the WMAP detectors are slightly (1%) nonlinear

$$T_{\rm obs}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}) + \alpha_2 T(\hat{\mathbf{n}})^2 + \alpha_3 T(\hat{\mathbf{n}})^3 + \ldots$$

The biggest signal on the sky is the dipole

$$T(\hat{\mathbf{n}}) = 3.3mK\cos(\theta)$$

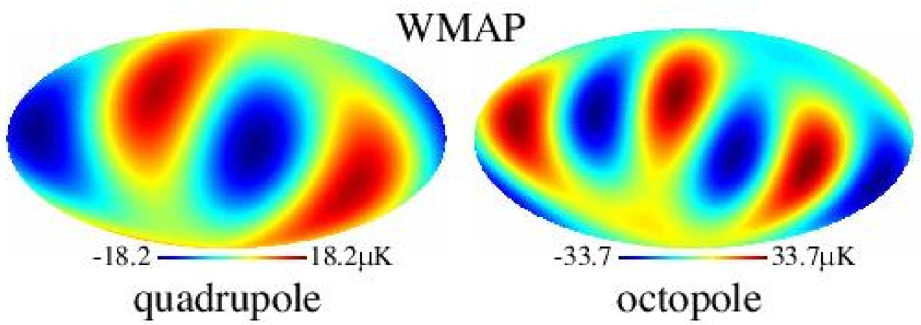
So with $\alpha_2 \sim \alpha_3 \sim 10^{-2}$, dipole anisotropy is modulated into a 10^{-5} quadrupole and octopole with $m=0$ in the dipole frame.

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 ⇨ a range of multipoles affected

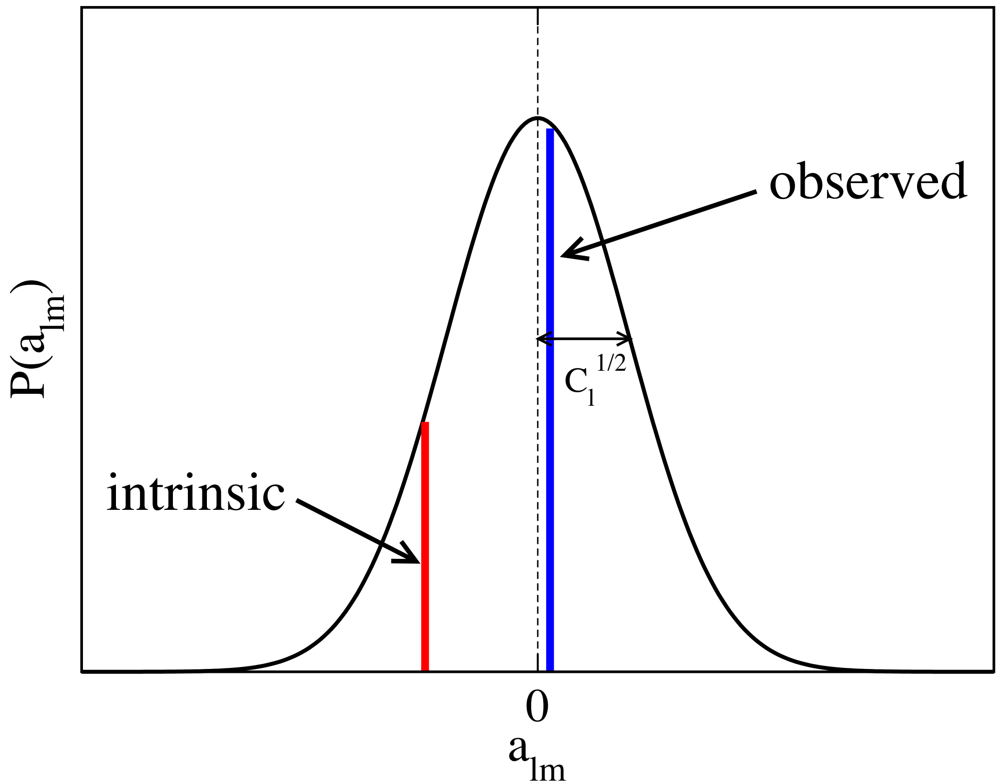
Gordon, Hu, Huterer & Crawford 2005

Additive schemes "don't work"

$$\hat{T}(\hat{\mathbf{n}}) = T_{\rm intr}(\hat{\mathbf{n}}) + T_{\rm extra}(\hat{\mathbf{n}})$$

Double (likelihood) penalty:

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



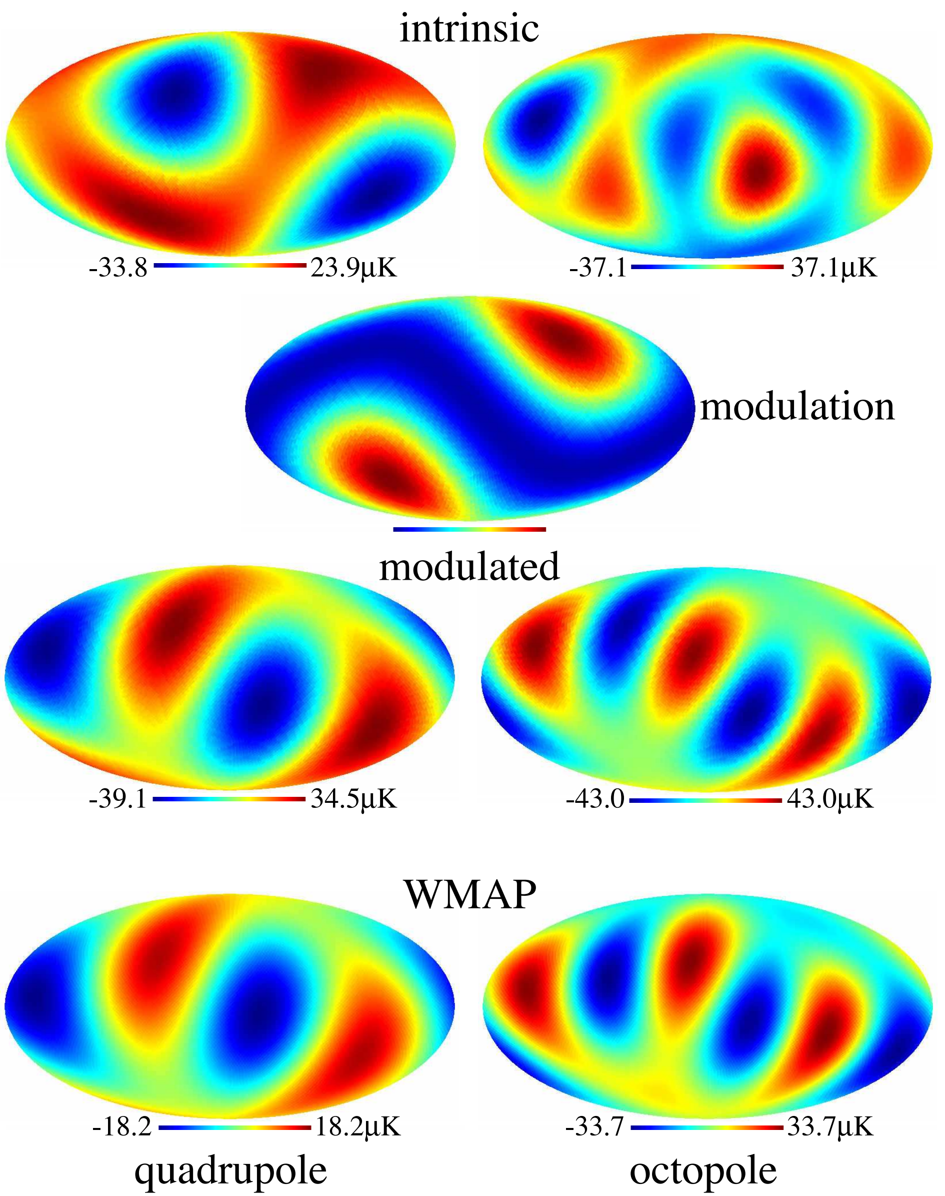
True for all additive schemes:
Solar System contamination,
Bianchi models,
etc

Gordon, Hu, Huterer & Crawford 2005

Multiplicative modulation can work

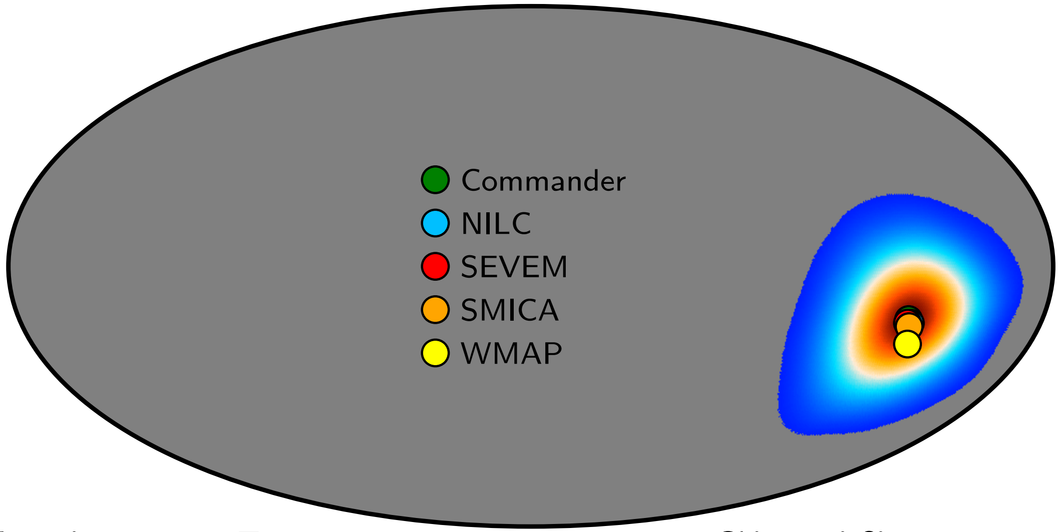
$$\hat{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}})\,[1 + w(\hat{\mathbf{n}})]$$

$w(\hat{\mathbf{n}}) \propto Y_{20}(\hat{\mathbf{n}})$ example

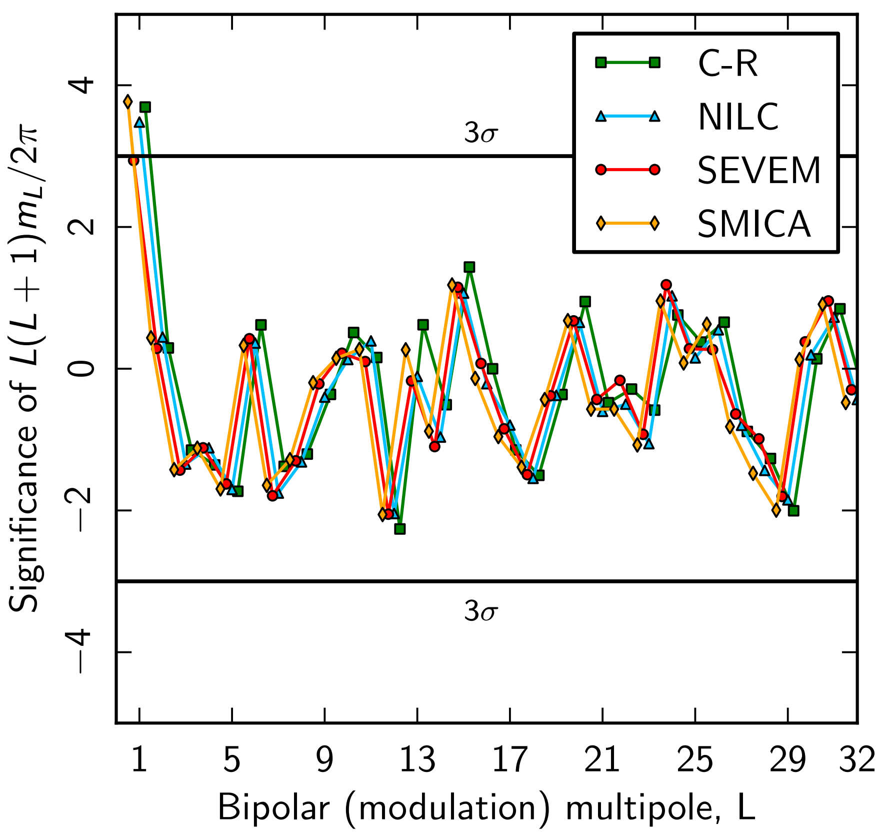


Gordon, Hu, Huterer & Crawford 2005

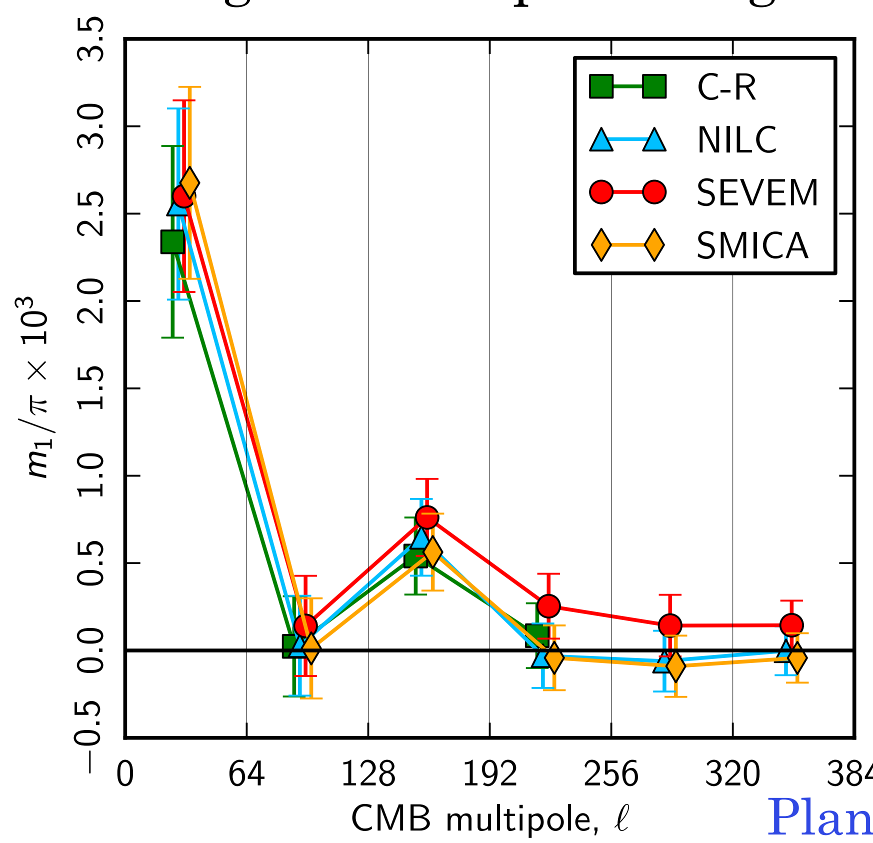
Dipolar modulation in Planck



Modulation at L



Significance per l range



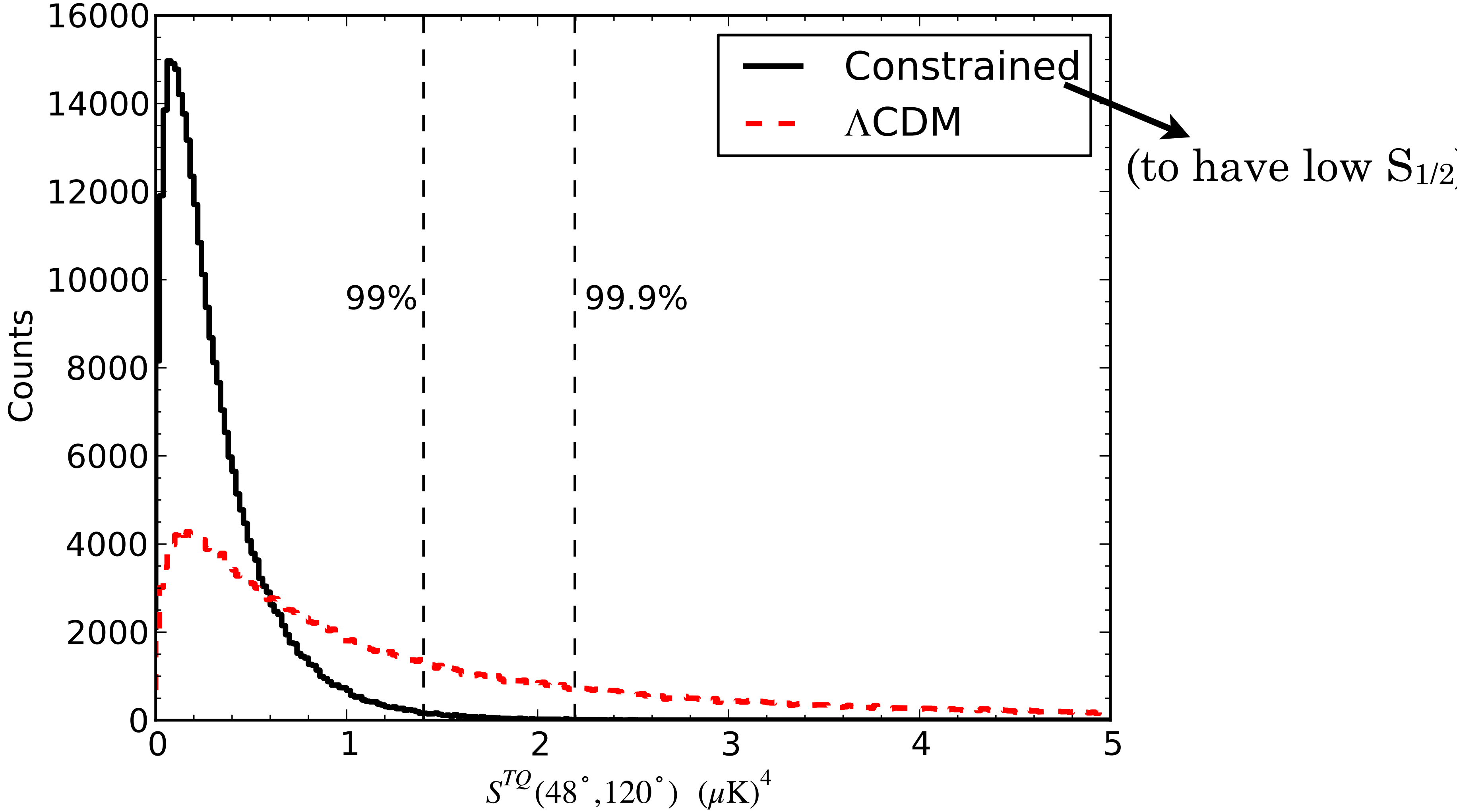
Planck XXIII

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 <u>may</u> successfully confirm that

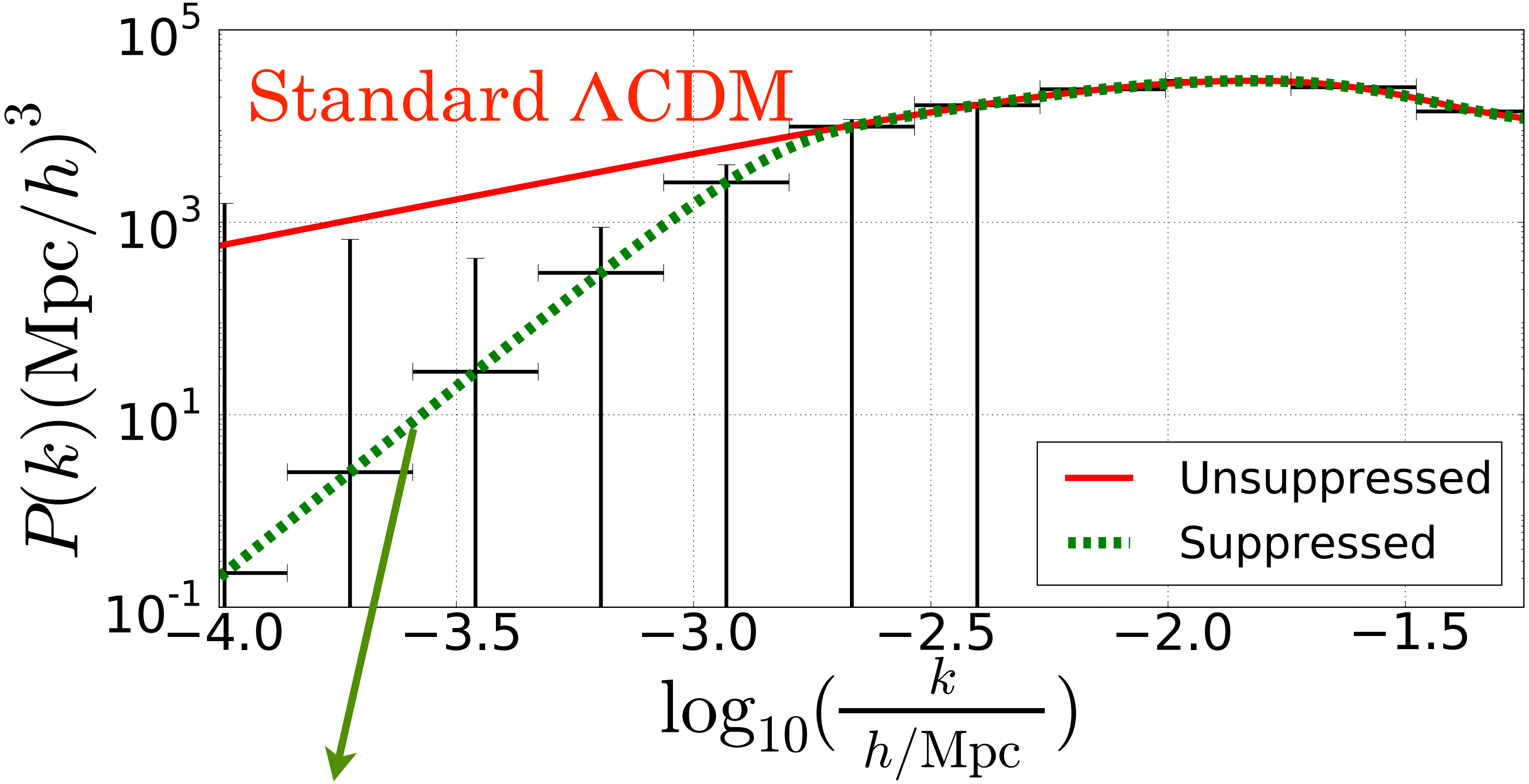


Polarization statistic

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

Gibelyou, Huterer & Fang 2010

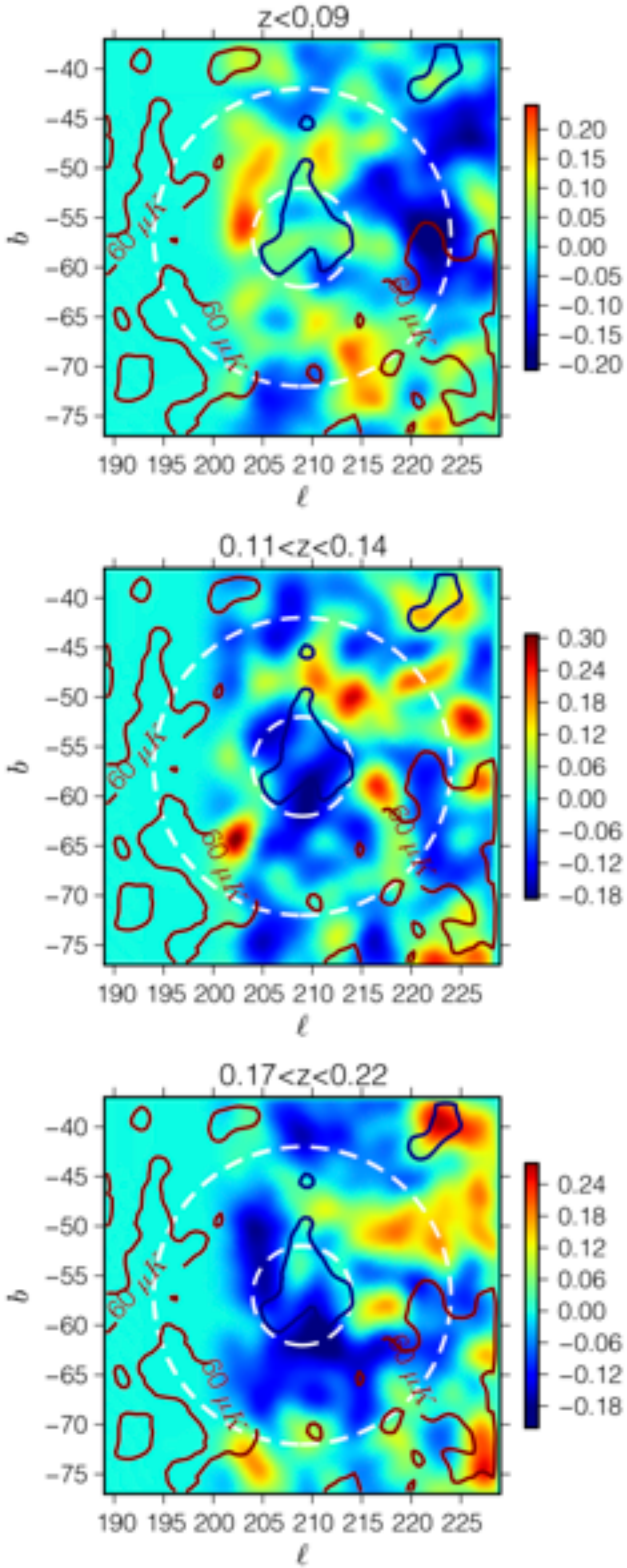
Dangers of working on anomalies: geocentrists are very interested!

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

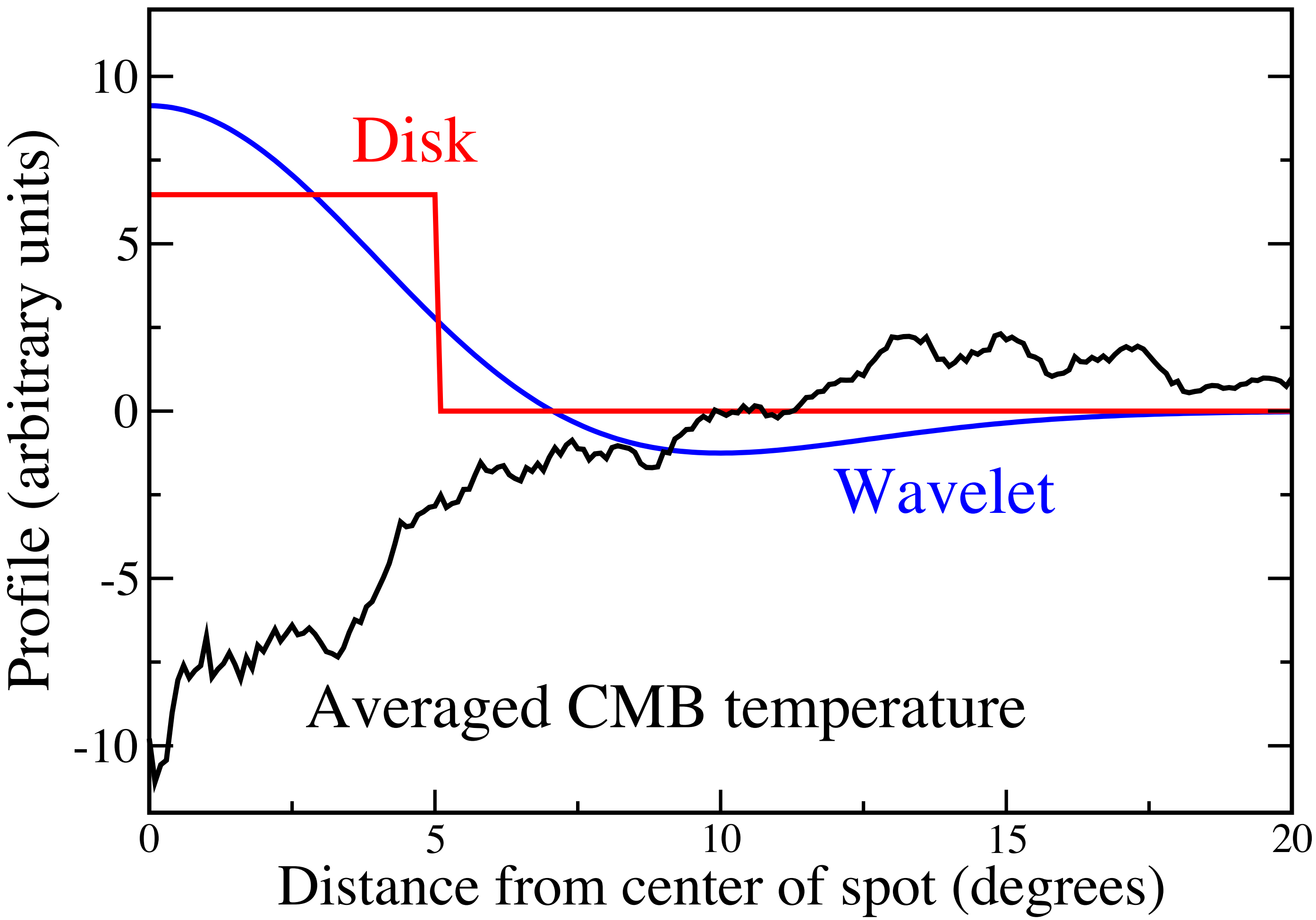
Conclusions

- Angular power is nearly zero at $\theta \gtrsim 60$ deg
- Quadrupole and octopole planar, nearly perpendicular to ecliptic plane
- Several separate $\gtrsim$3-sigma anomalies, they are *a posteriori*...
- ... but all have to do with <u>largest</u> 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



Szapudi et al, 1405.1566



Zhang & Huterer, arXiv:0908.3988

Another view

Theorem: Every homogeneous polynomial P of degree ℓ in x, y and z may be written as

$$\begin{aligned} P(x,y,z) &= \lambda\cdot(a_1x+b_1y+c_1z)\cdot(a_2x+b_2y+c_2z)\ldots\cdot(a_\ell x+b_\ell y+c_\ell z) \\ &+ (x^2+y^2+z^2)\cdot R \end{aligned}$$

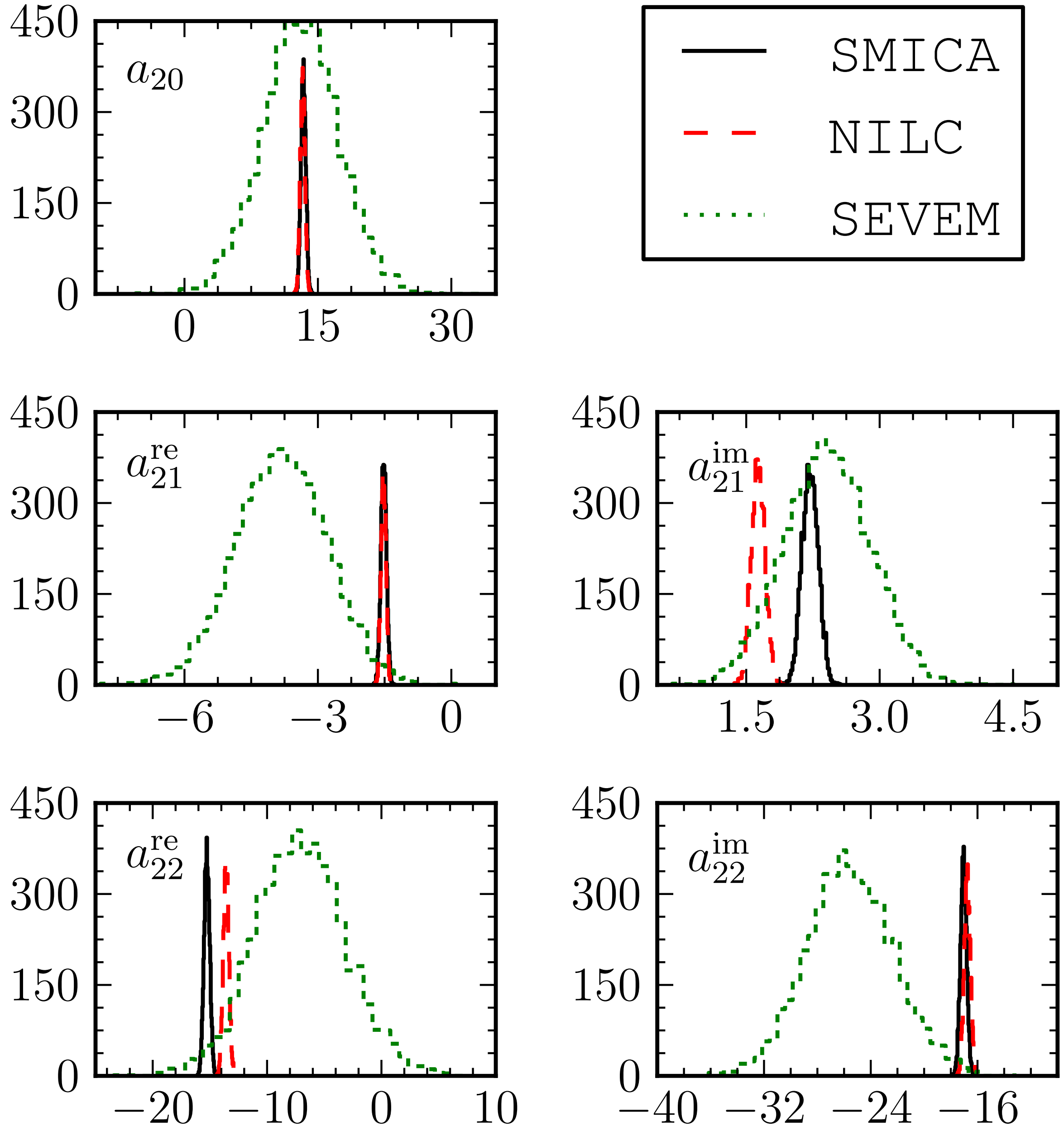
where R is a homogeneous polynomial of degree $\ell-2$. The decomposition is unique up to reordering and rescaling the linear factors.

Example (Y_{20}):

$$\begin{aligned} P(x,y) &= x^2+y^2-2z^2 \\ &= -3(z)(z)+(x^2+y^2+z^2)(1) \end{aligned}$$

Katz & Weeks, astro-ph/0405631

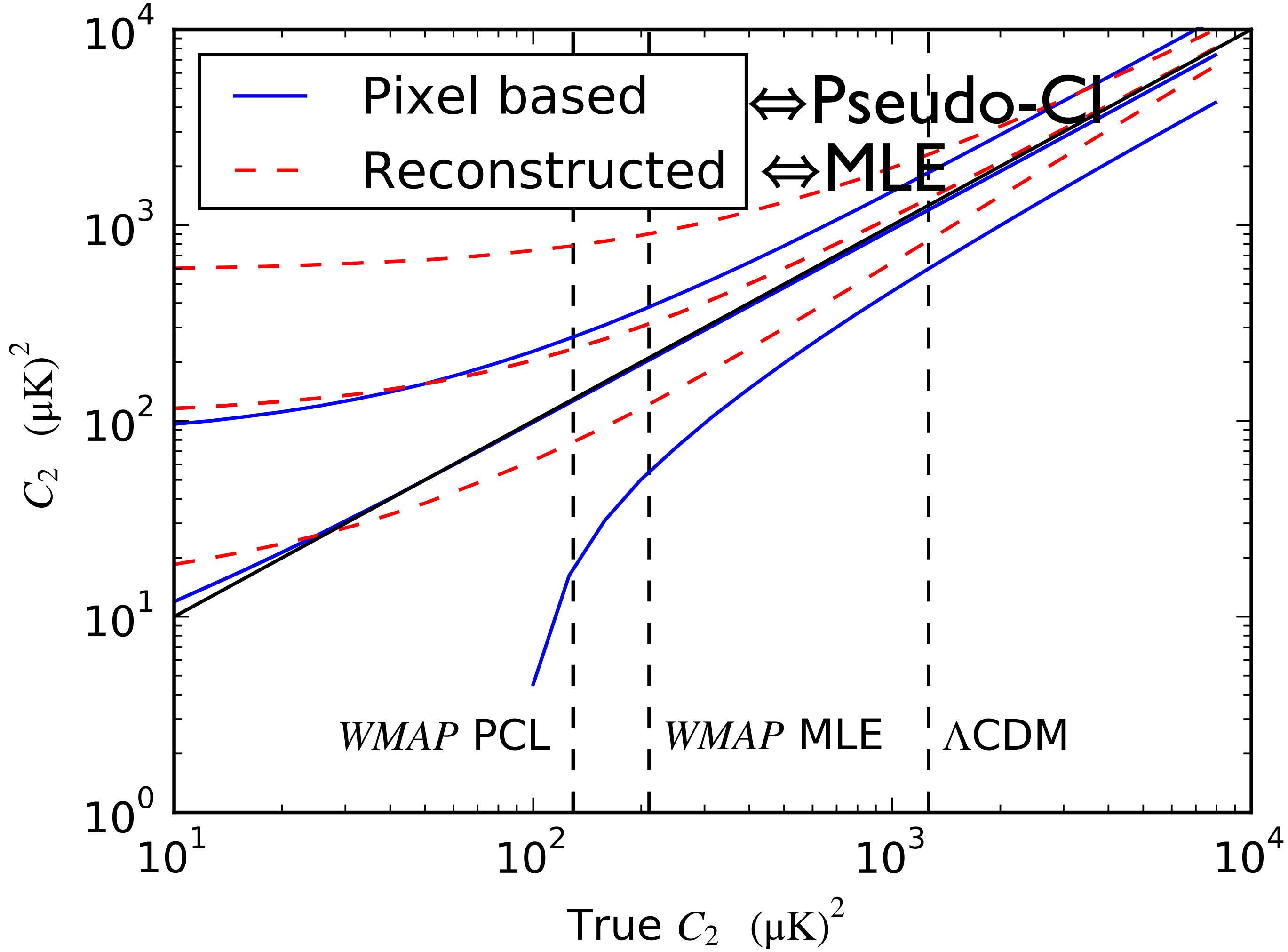
Harmonic inpainting: produces mutually consistent reconstructions of maps

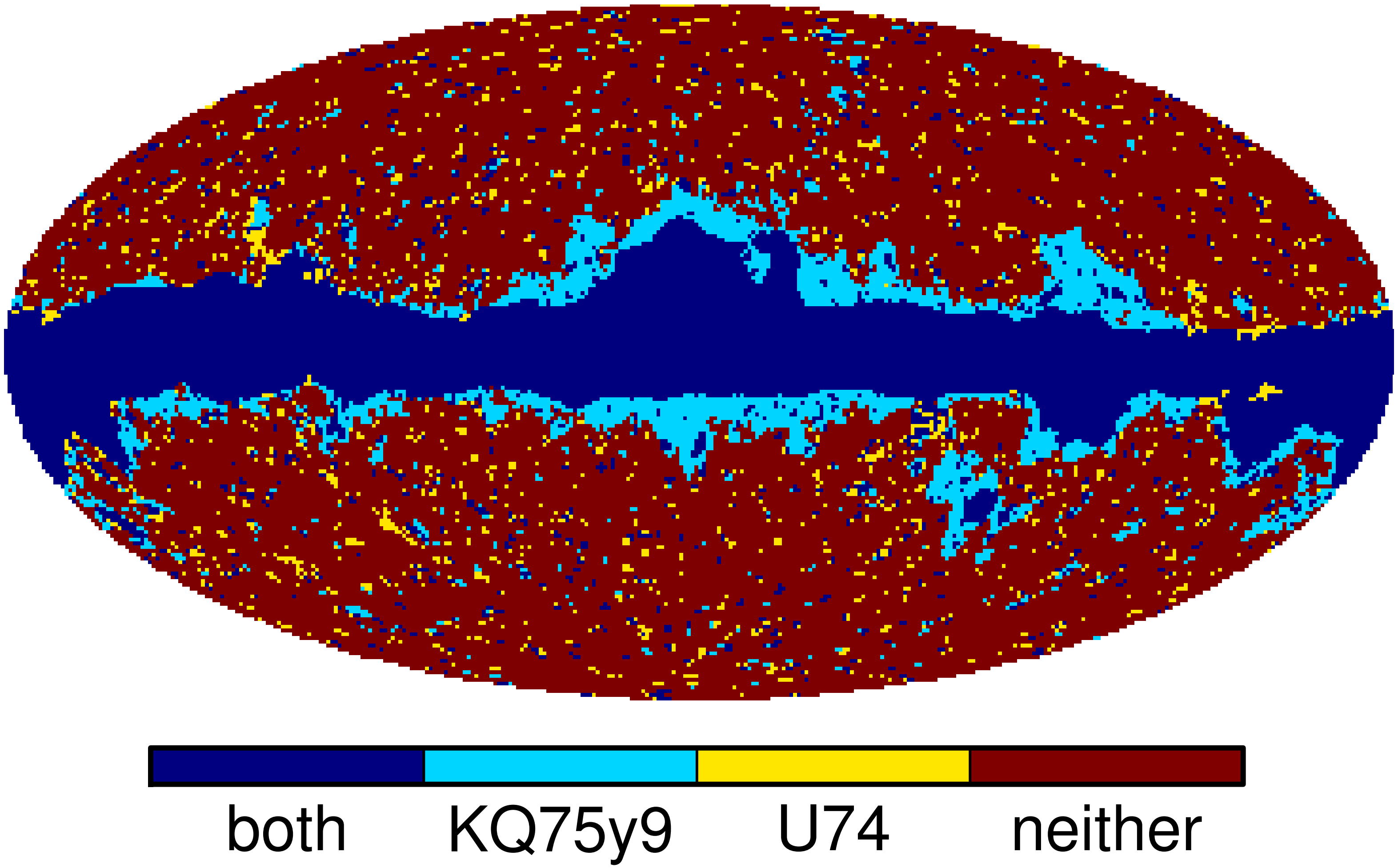


MLE reconstruction is ‘optimal’, but

− need to smooth map => mix up with Gal cut region

− if not smoothing, returns a biased result:




both
KQ75y9
U74
neither

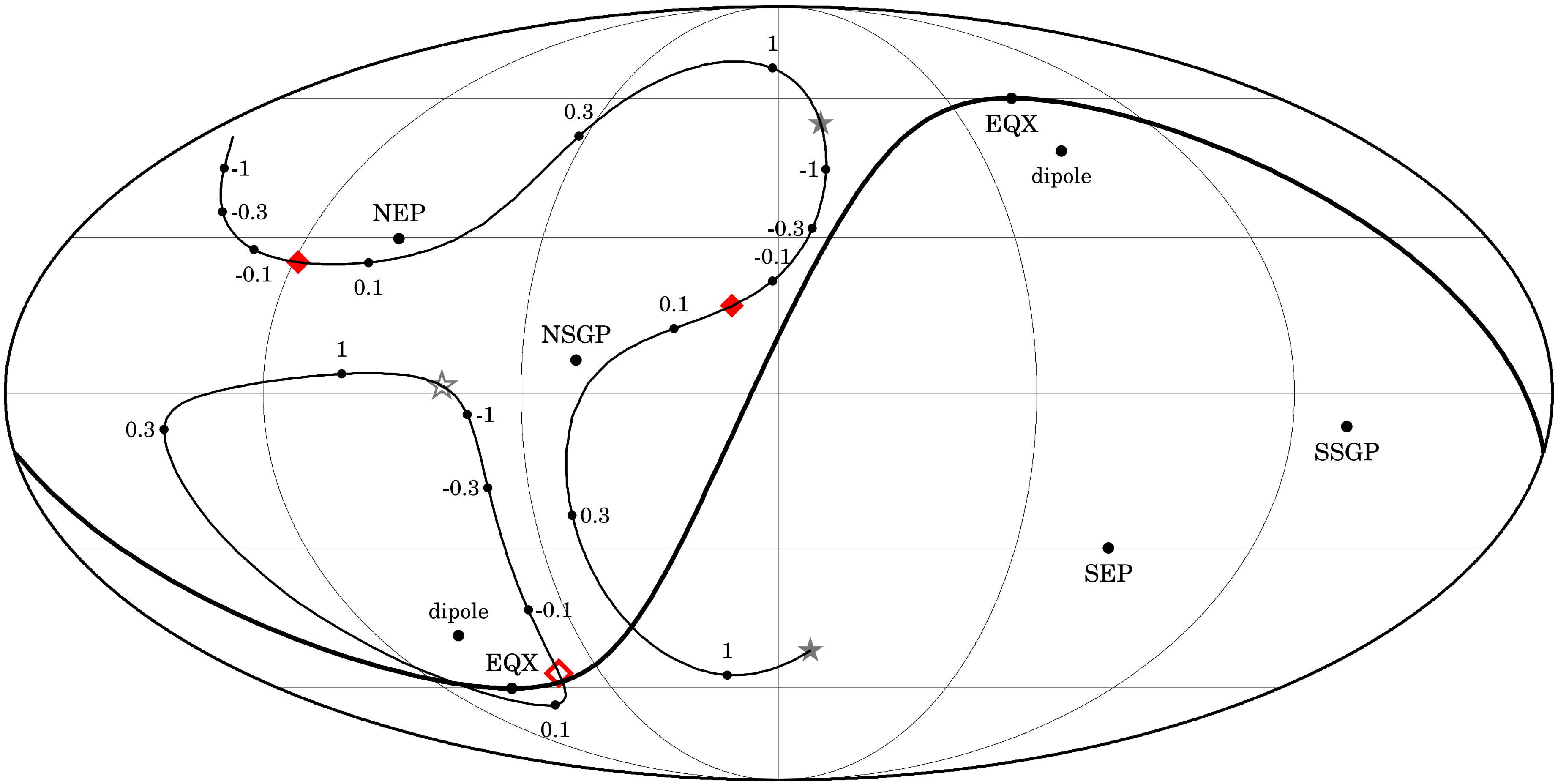
Published values of the power spectrum coefficients differ by many times the error

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

Data Release	D_2	D_3	D_4	D_5	$S_{1/2}$ (μK^4)
WMAP 3yr	211	1041	731	1521	8330
WMAP 5yr	213	1039	674	1527	8915
WMAP 7yr	201	1051	694	1517	8938
WMAP 9yr	151	902	730	1468	5797
Planck R1	299	1007	646	1284	8035[a]

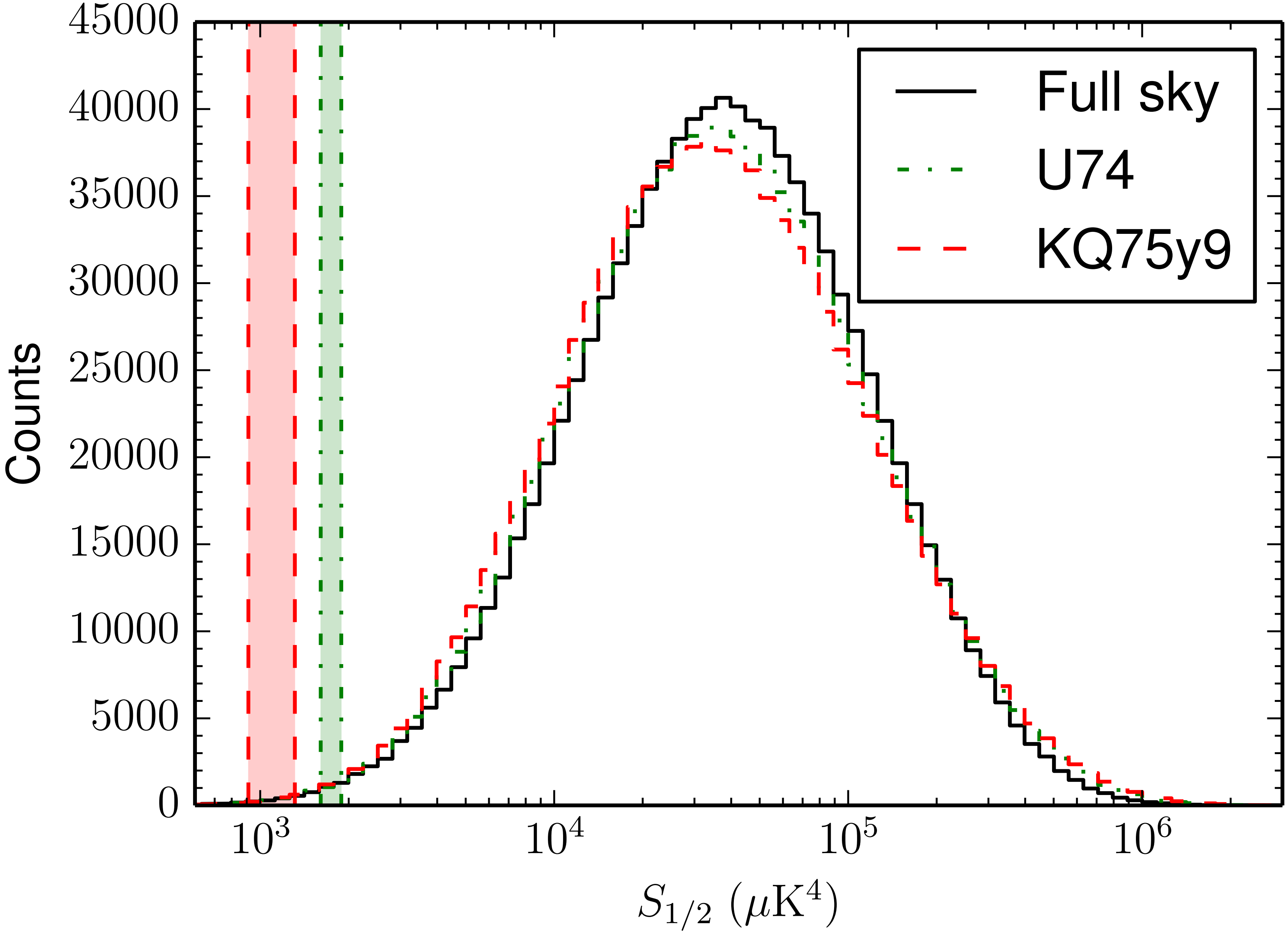
	Q+O		Ecliptic Plane		NGP		dipole	
Map	S	T	S	T	S	T	S	T
WMAP ILC 7yr	0.22	0.10	2.66	2.70	0.82	0.90	0.18	0.20
WMAP ILC 9yr	0.18	0.08	1.96	1.82	0.79	0.76	0.14	0.15
Planck `NILC`	1.85	1.05	2.80	3.04	1.41	1.26	0.32	0.19
Planck `SEVEM`	0.41	0.22	2.52	2.94	0.79	0.92	0.09	0.05
Planck `SMICA`	1.62	0.93	3.74	4.16	1.56	1.52	0.37	0.30

Systematic checks: foreground missubtraction



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

Copi, Huterer, Schwarz & Starkman, MNRAS, 2006



Full sky
U74
KQ75y9
Counts
$S_{1/2}$ (μK^4)