Cosmological anomalies: a holistic view

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based mostly on work with
Copi, Schwarz & Starkman (2004-2016)
and Jessica Muir (2016-2018)

review (of CMB anomalies after Planck) in
Schwarz, Copi, Huterer & Starkman (2016), arXiv:1510.07929

Cosmic anomalies: pros and cons

Cosmological principle is well worth investigating:

- May bring fascinating new insights into early-universe physics
- May bring insights into dark energy
- Should be (imo) near forefront of efforts with future surveys

BUT:

Extraordinary claims require extraordinary evidence:

- To account for the look-elsewhere effect
- To have respect for the effect of systematic errors
- Not every anomaly is equally “special” - beware of random things being off

Anomaly Philosophy

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

Not every ‘anomaly’ is equally compelling.
The pecking order goes as follows:

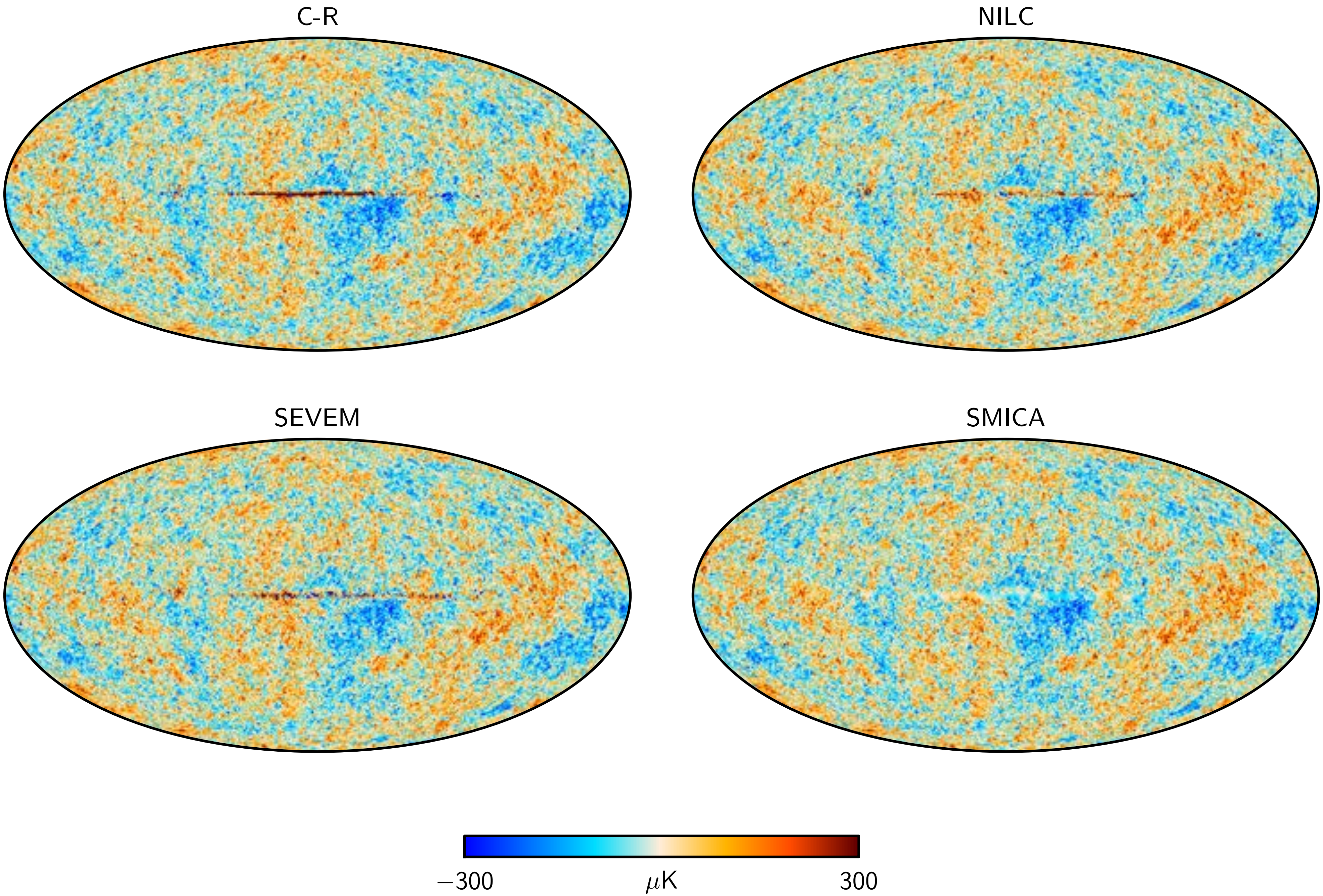
1. Large-scale anomalies (CMB mostly…)
2. Medium-scale anomalies (LSS, clustering)
3. Small-scales anomalies (galaxy morphology, satellites, etc)

This talk: only 1.
For 2. and 3., the bar should be VERY high to claim cosmological anomalies.

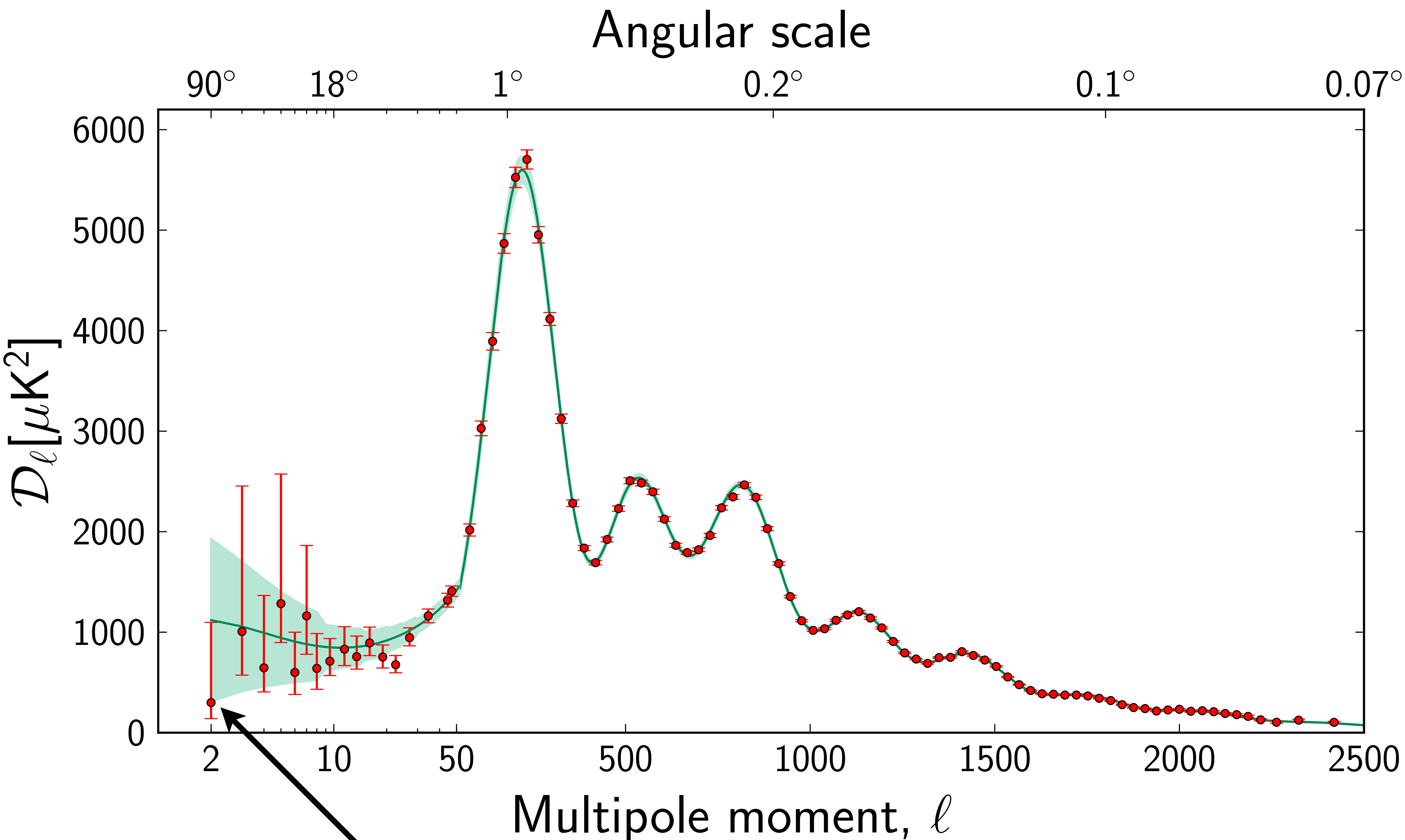
CMB anomaly Summary

(maybe incomplete list - but don't double-count!):

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
3. There is a N/S power asymmetry
4. There is an unusually cold spot
5. There is an "ISW anomaly" - too much ISW in CMBxLSS

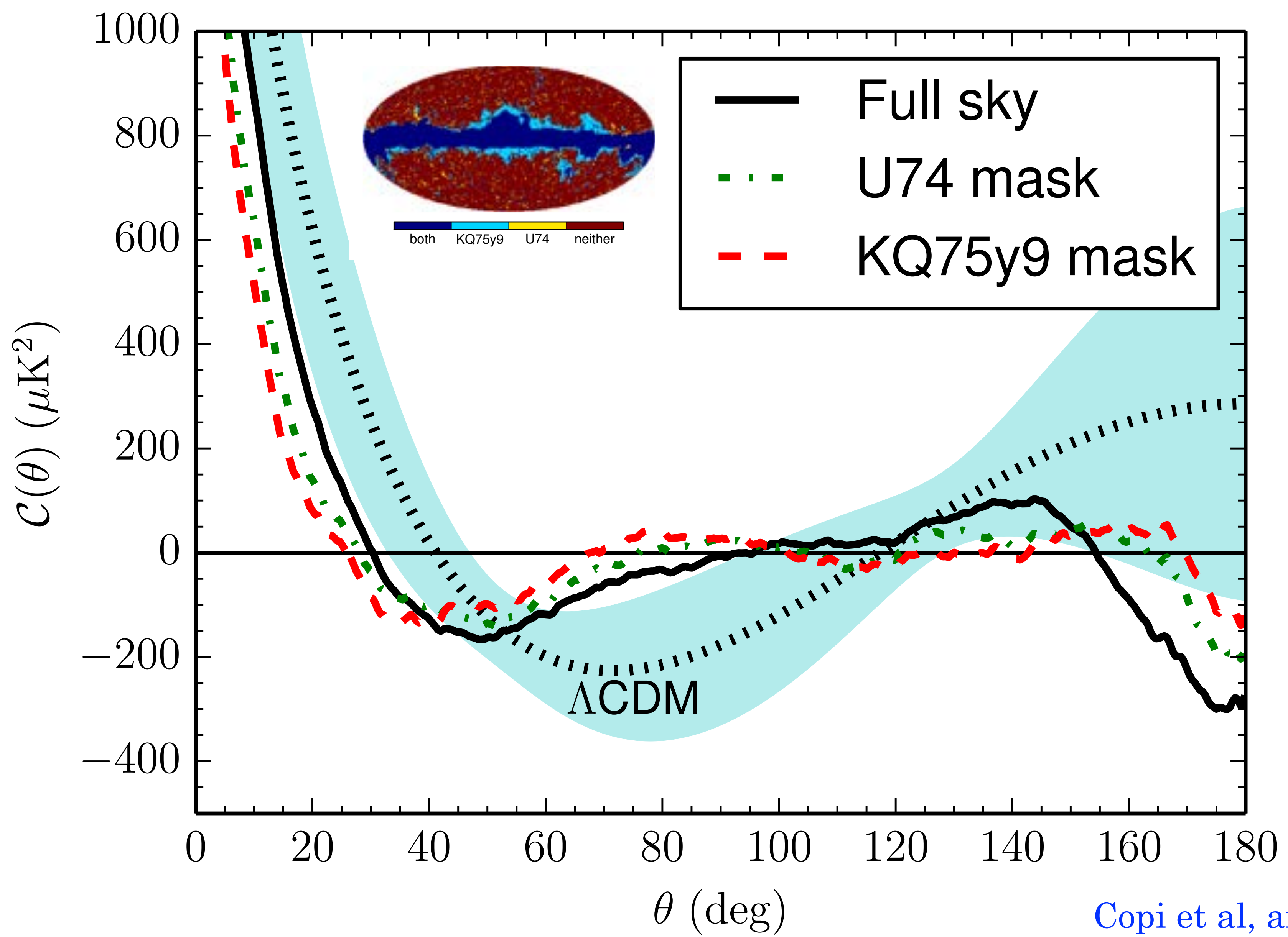

C-R
NILC
SEVEM
SMICA
−300
μK
300

Missing Large-Angle Power



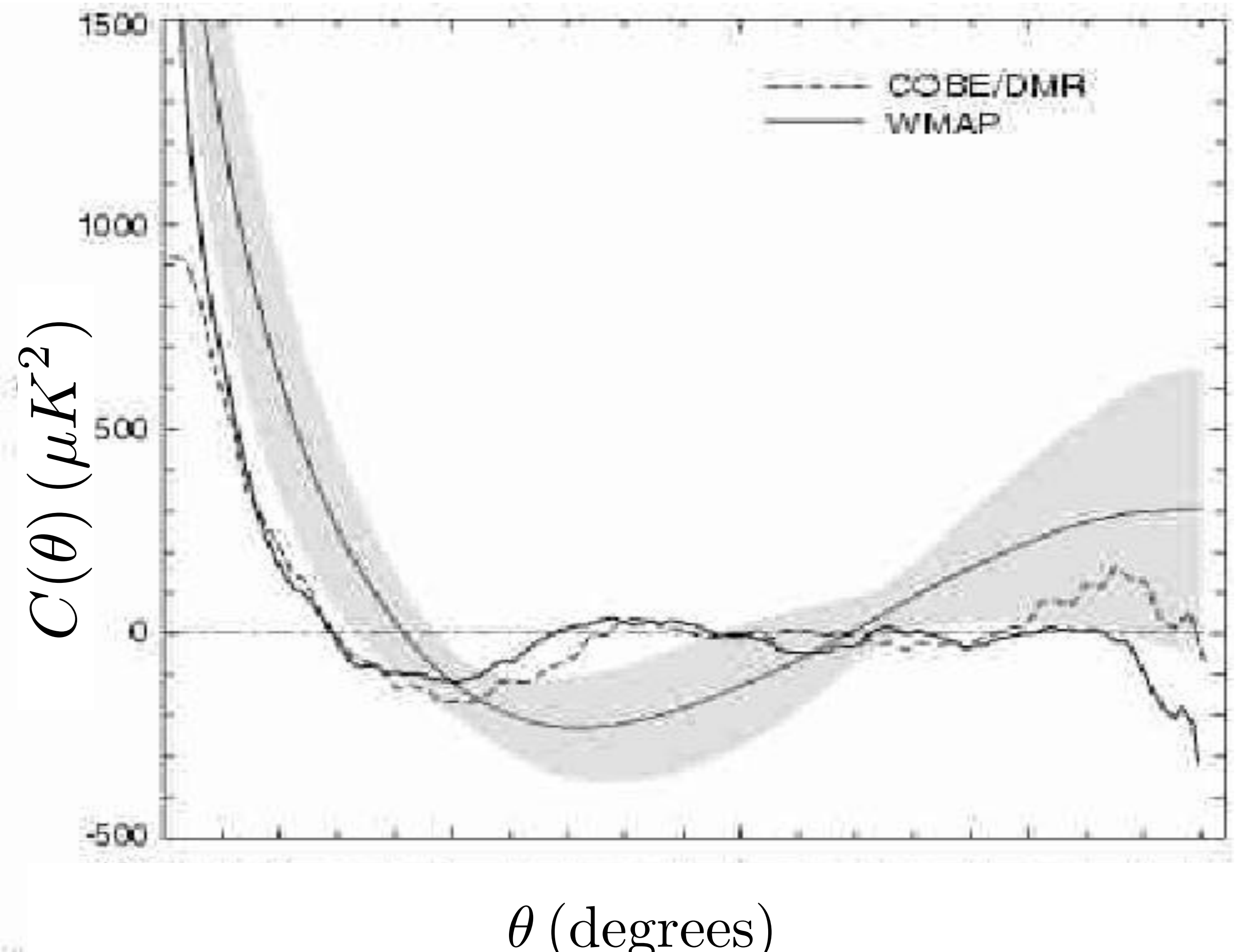
NOT the “low quadrupole”...

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

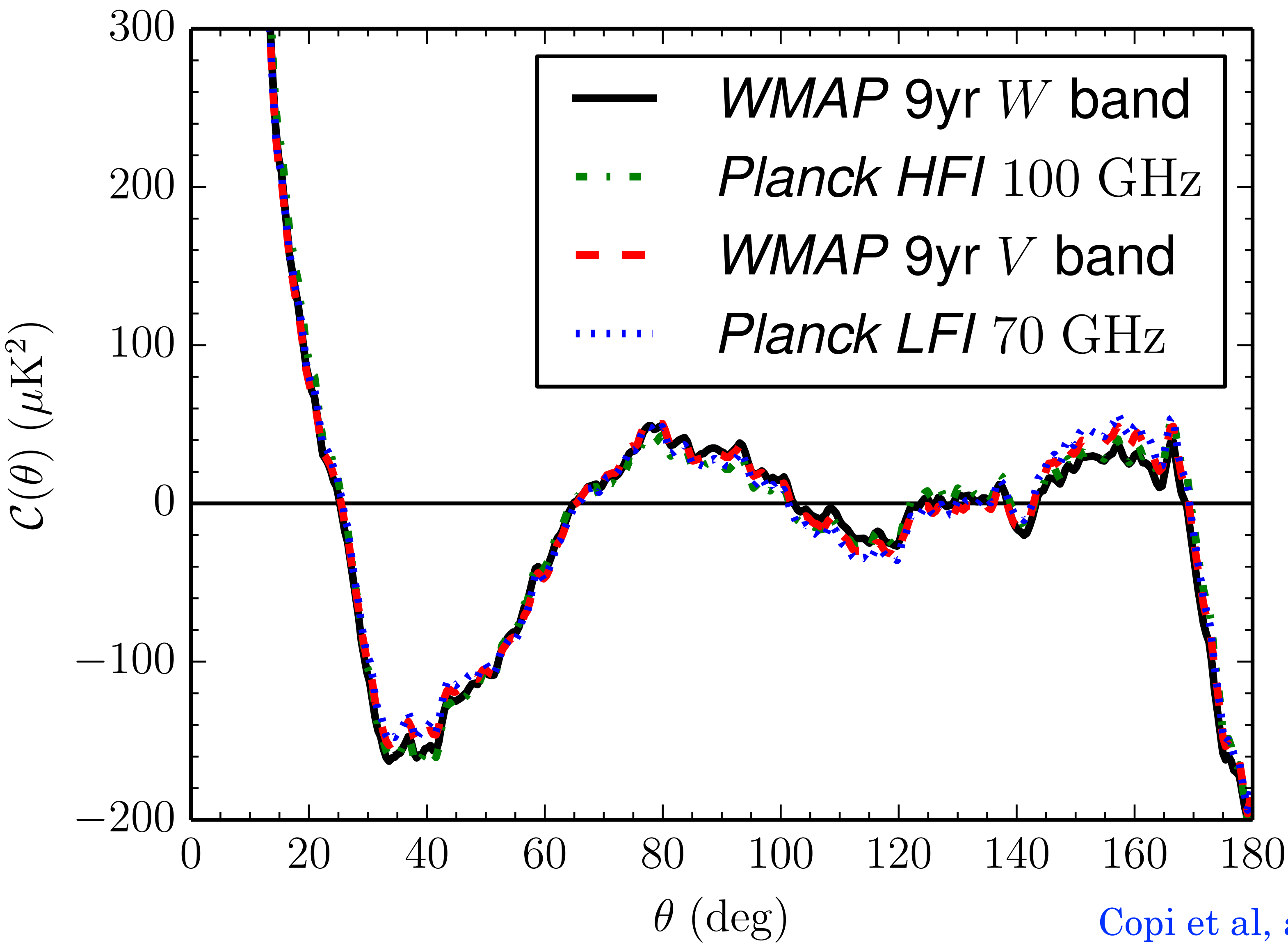
$S_{1/2}$ statistic:
(Spergel et al 2003)

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

	U74		KQ75y9	
Map	$S_{1/2}$ $(\mu K)^4$	p (%)	$S_{1/2}$ $(\mu K)^4$	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%

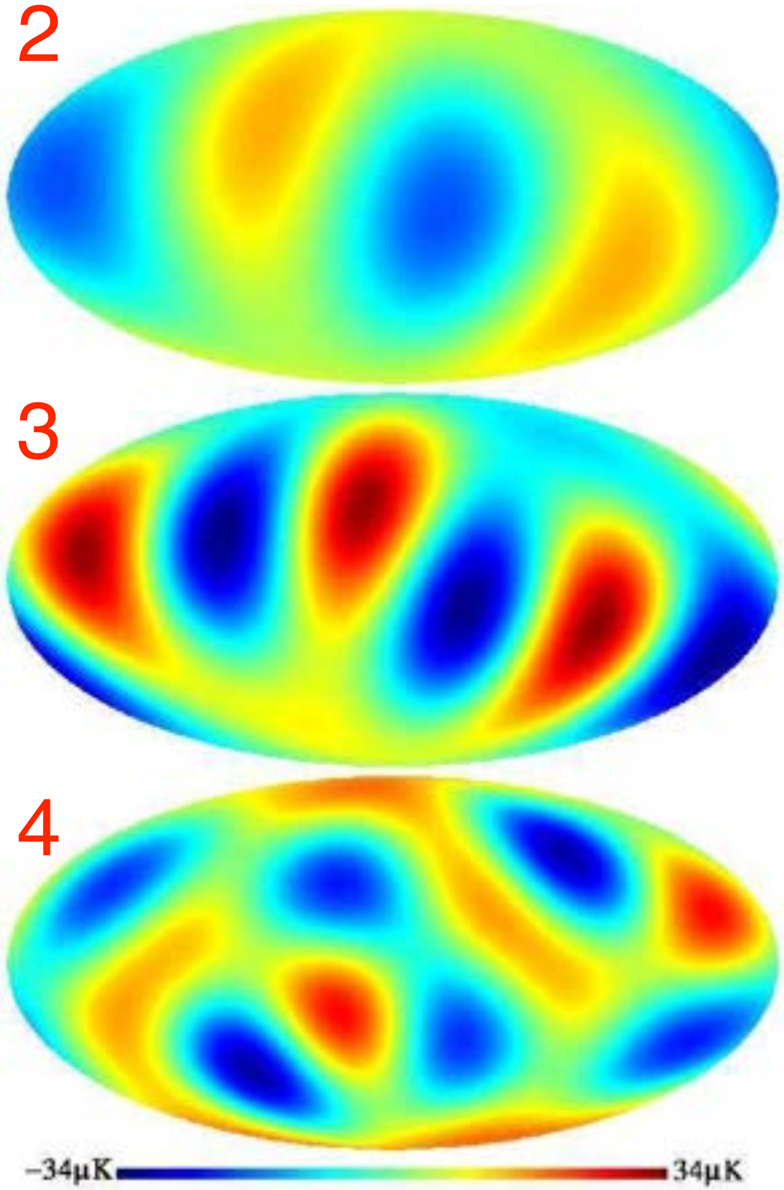
Large-scale alignments in the CMB

ℓ = 2, 3 are aligned and planar

ℓ= 2

ℓ= 3

ℓ= 4



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

ℓ=3 is planar: P~1/20

ℓ=2,3 is are aligned: P~1/60

de Oliveira-Costa, Tegmark, Zaldarriaga & Hamilton 2004

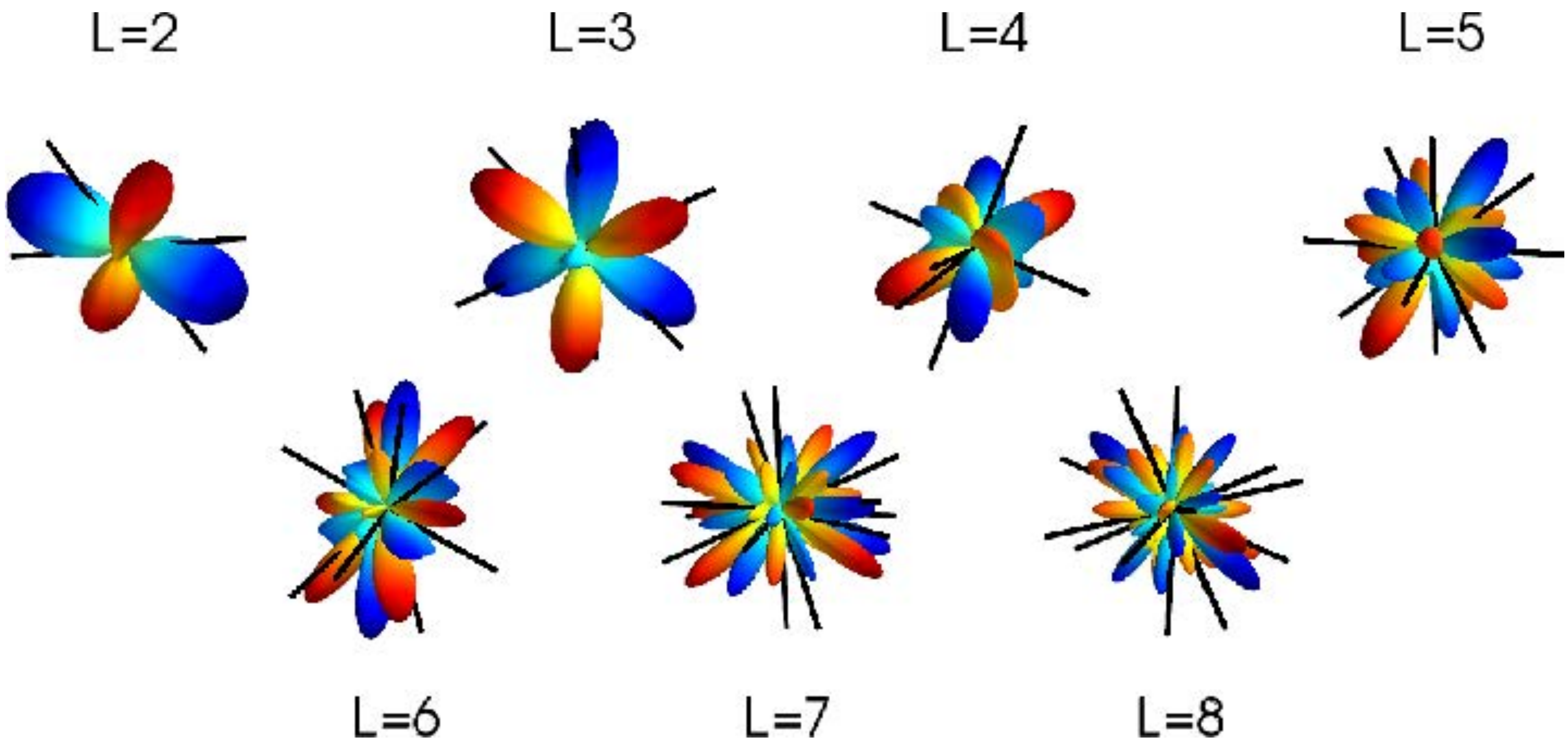
... and still are

	Uncorrected		DQ corrected	
Map	$\lvert\hat{\boldsymbol{n}}_2 \cdot \hat{\boldsymbol{n}}_3\rvert$	p-value (%)	$\lvert\hat{\boldsymbol{n}}_2 \cdot \hat{\boldsymbol{n}}_3\rvert$	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

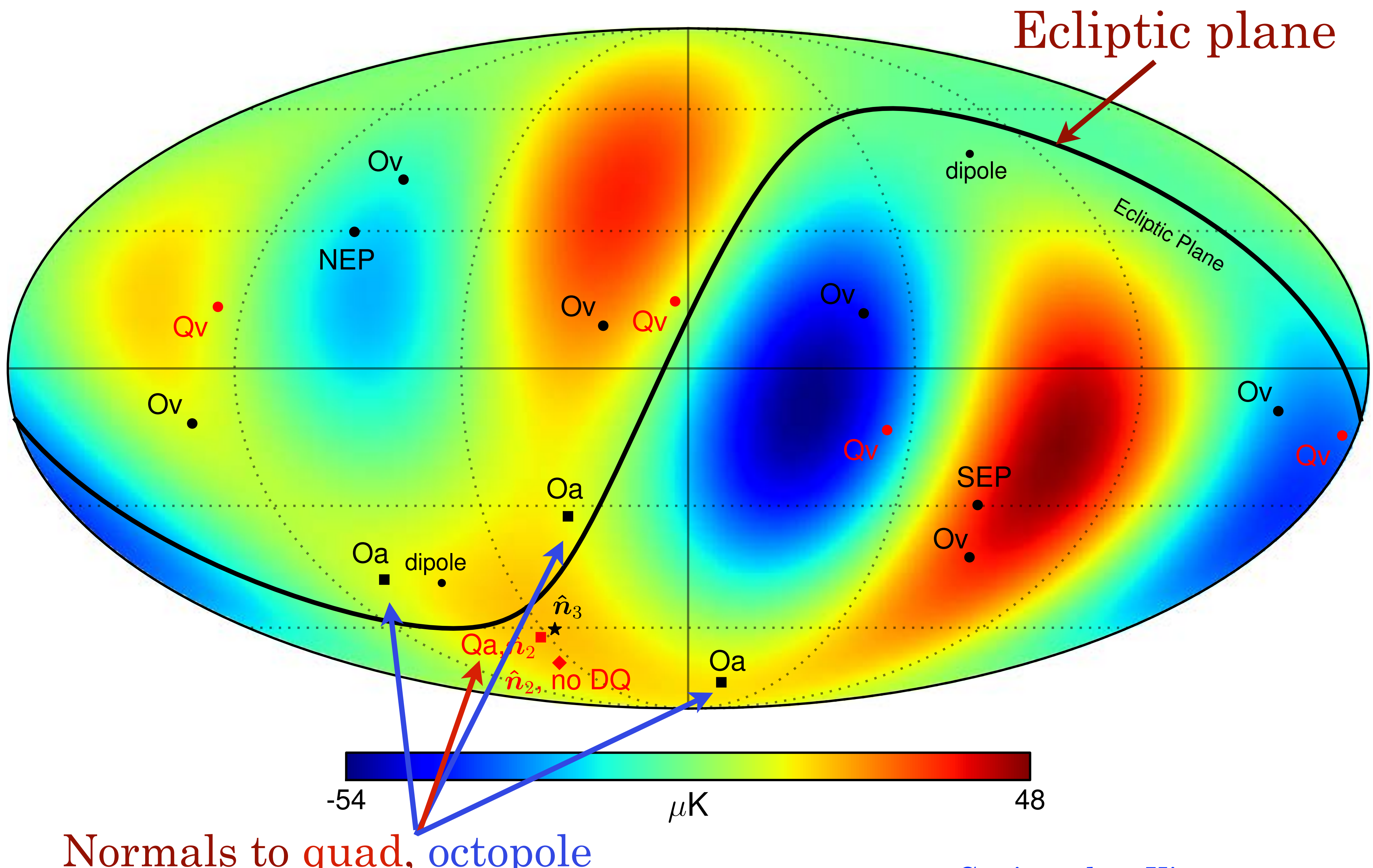
Copi et al, arXiv:1311.4562

Multipole vectors of our sky

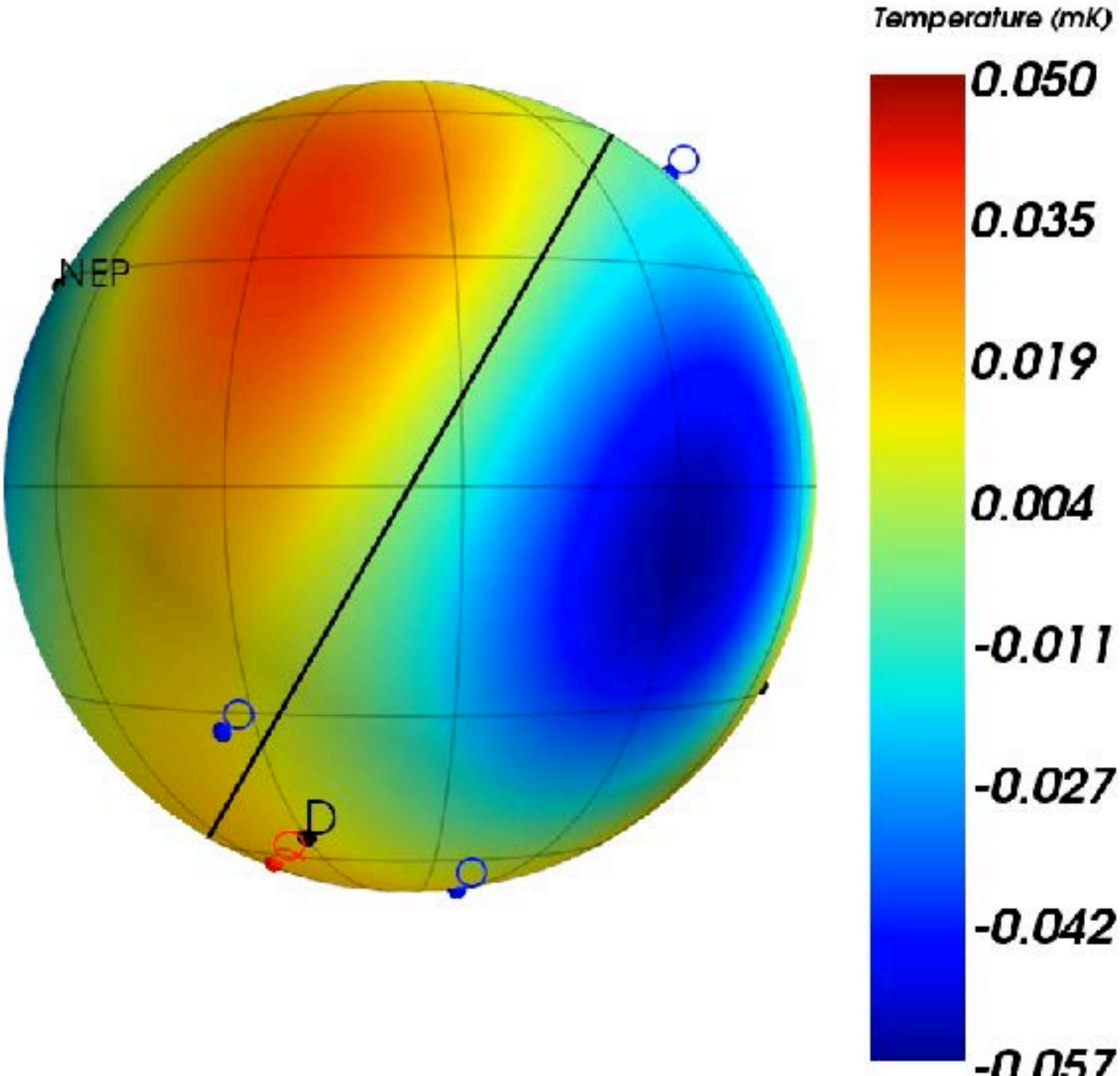


Cop, Huterer & Starkman, 2004

L=2+3 map



Copi et al, arXiv:1311.4562

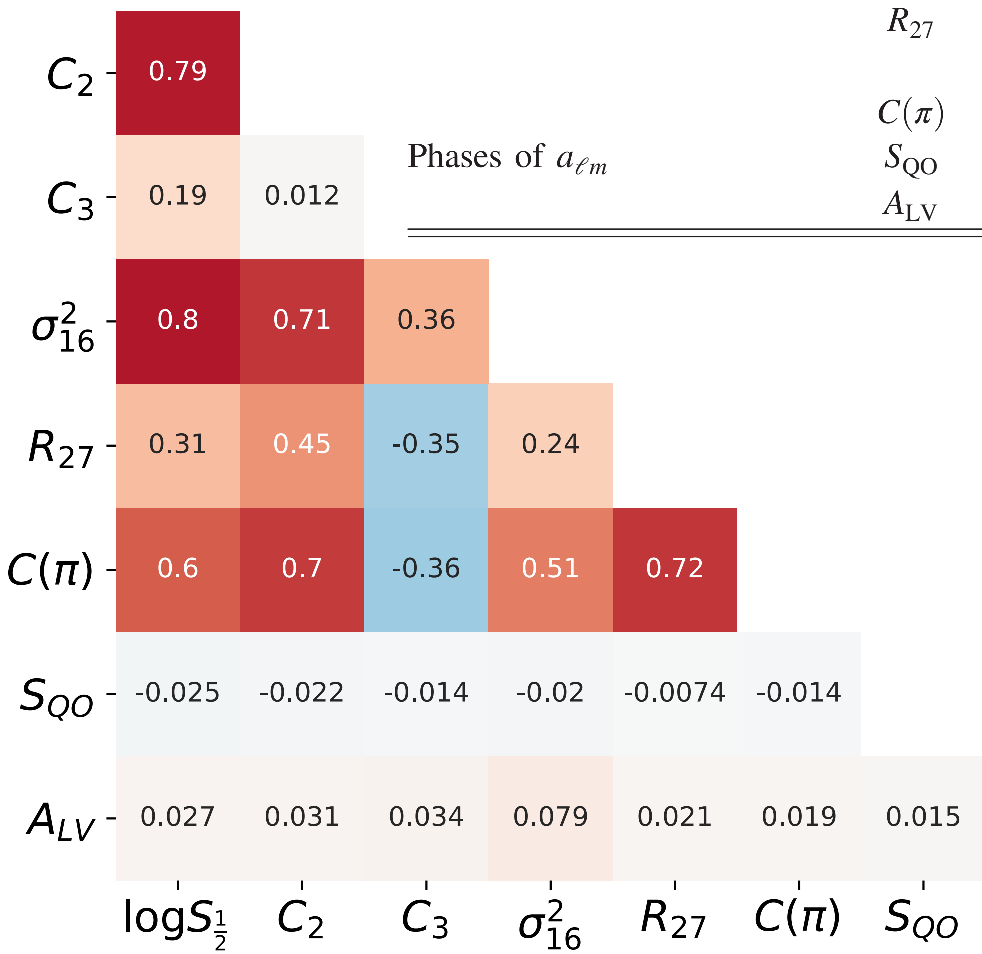


Movie by Craig Copi

Are the CMB large-scale anomalies correlated?

Not correlated, except for the "obvious" ones

Depends on	Quantity	Description	Multipoles	Section
Two-point functions only	$S_{1/2}$	Amount of angular power at $\theta > 60°$	2–100	III A 1
	C_2	Quadrupole amplitude	2	III A 2
	C_3	Octopole amplitude	3	III A 3
	σ^2_{16}	Variance of temperature fluctuations at $N_{\text{side}} = 16$	2–47	III A 4
	R_{27}	Ratio of power between even and odd multipoles	2–27	III A 5
	$C(\pi)$	Angular correlation at $\theta = 180°$	2–191	III A 6
Phases of $a_{\ell m}$	S_{QO}	Quadrupole-octopole alignment	2,3	III B 1
	A_{LV}	Hemispherical power asymmetry	2–191	III B 2



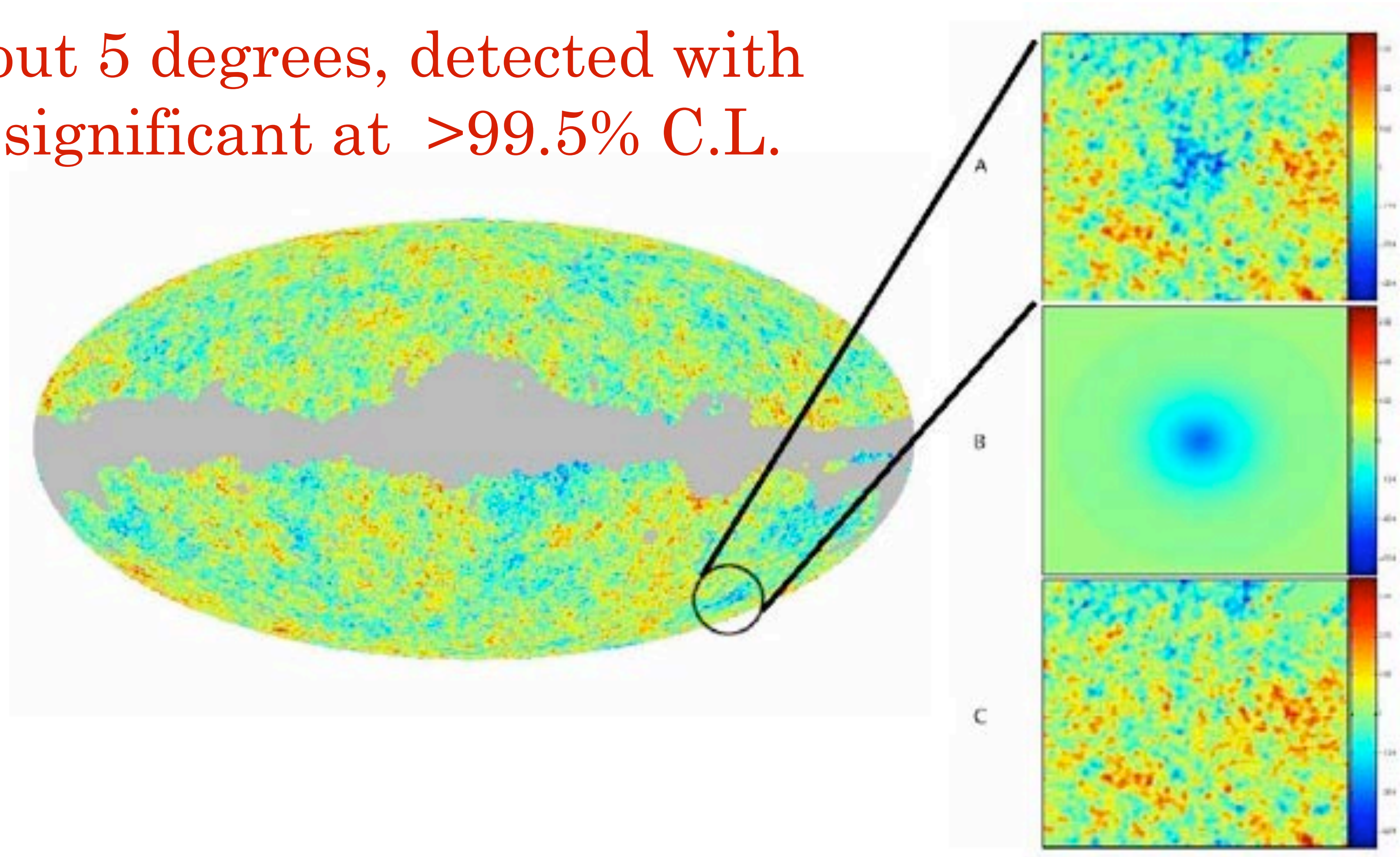
Jessie Muir
(Perimeter)

Muir, Adhikari & Huterer, arXiv:1806.02354

CMB cold spot

The “cold spot”

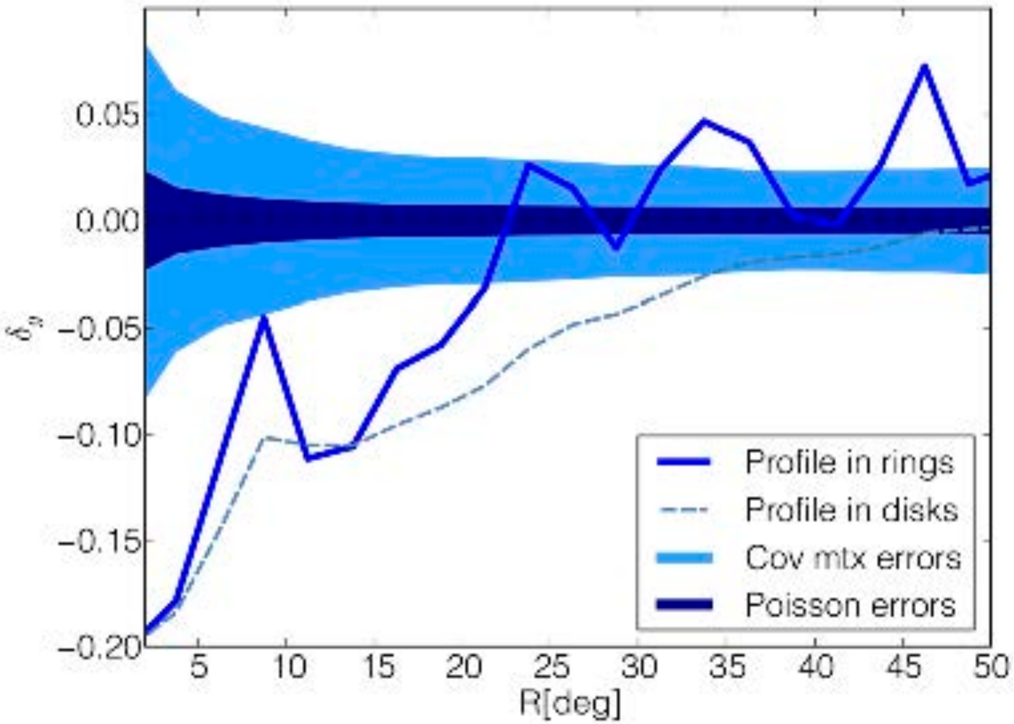
Radius about 5 degrees, detected with wavelets; significant at >99.5% C.L.

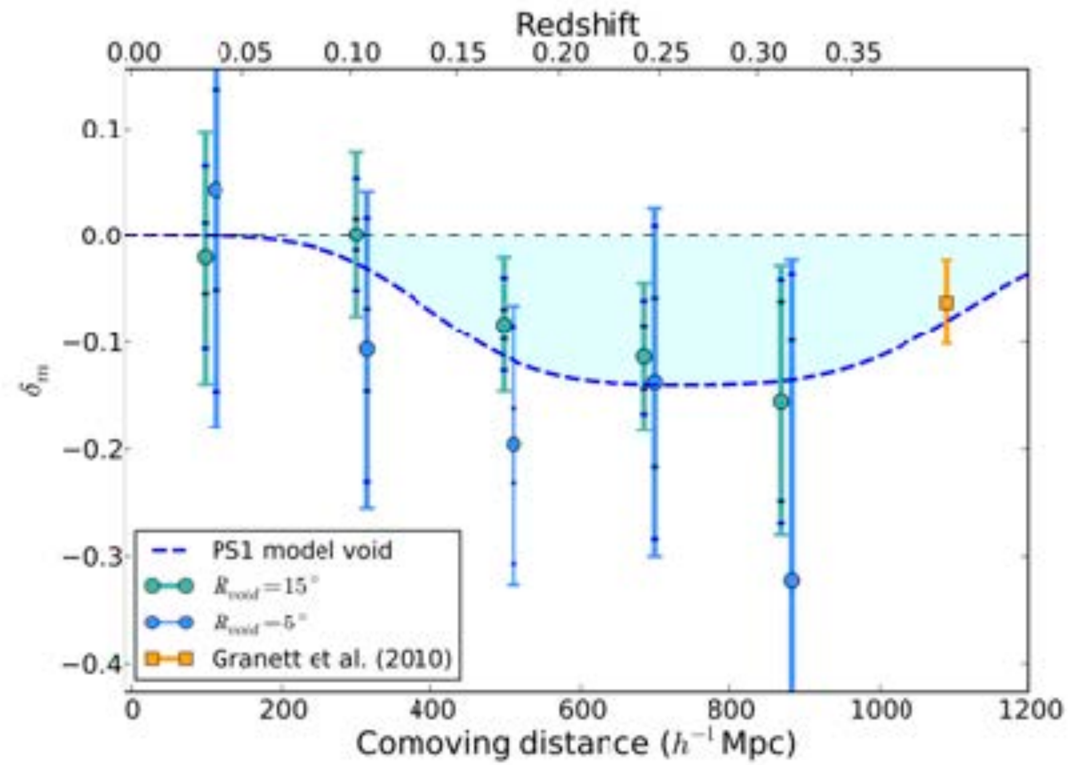


Reviewed in: Vielva 2004

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)

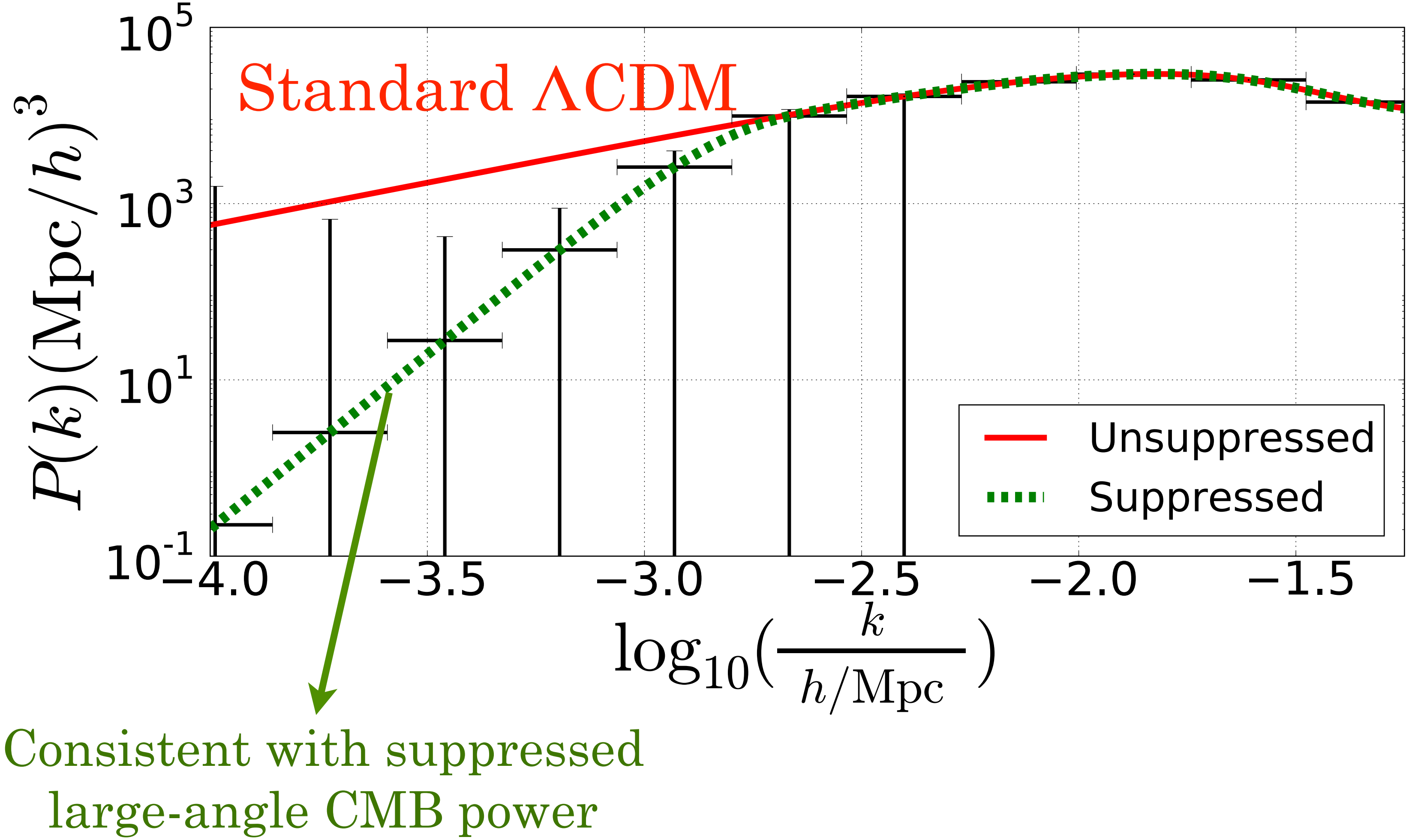
No compelling theoretical (or systematic) explanations for large-angle anomalies as yet

Can other observations confirm or refute the anomalies?

Large-scale structure?
CMB polarization?

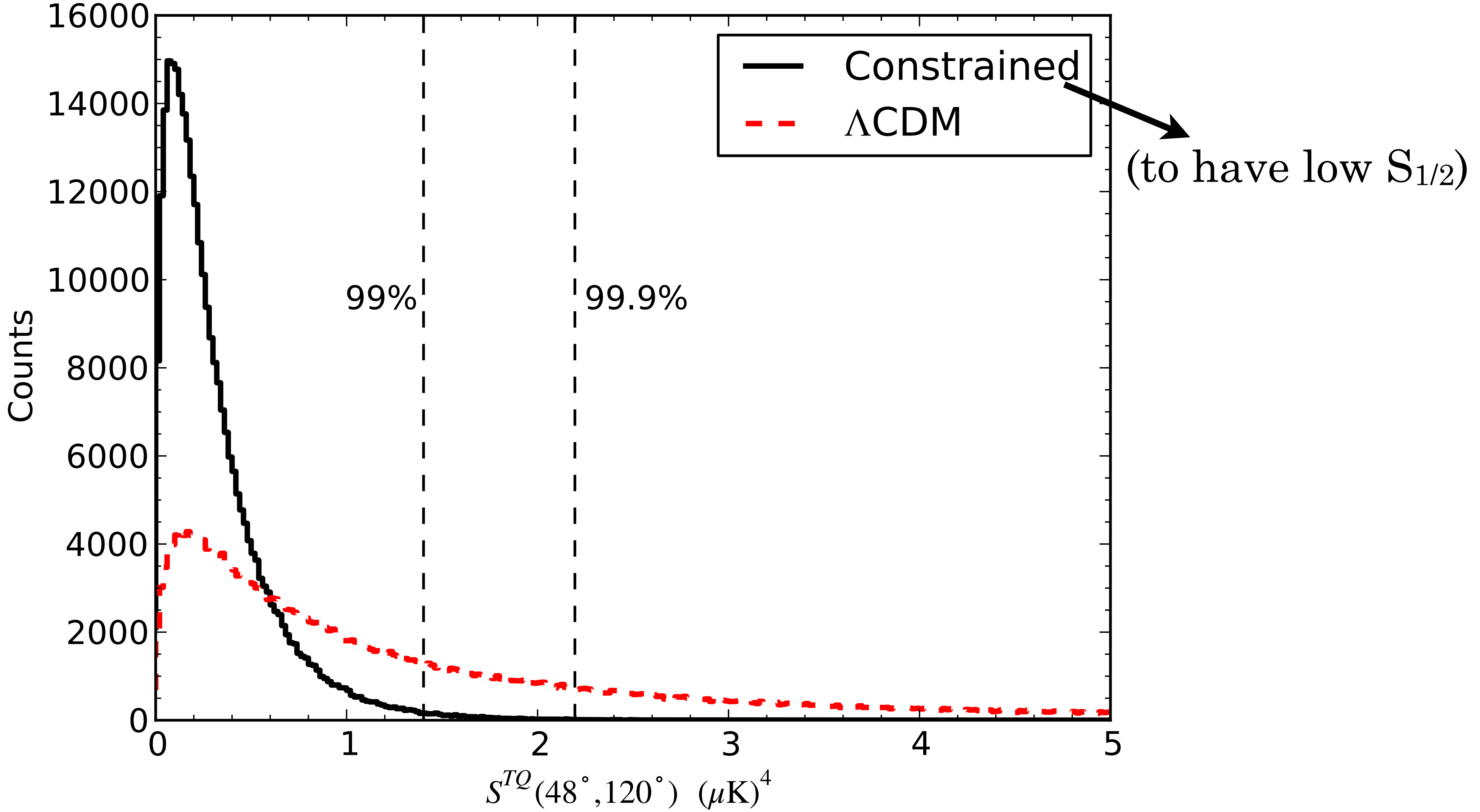
Can one see effect of such large-angle power suppression in future LSS surveys?

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



Gibelyou, Huterer & Fang 2010

If this is a statistical fluke,
CMB polarization may successfully confirm that



Polarization statistic

Copi et al, *MNRAS* **434,** 3590 (2013),

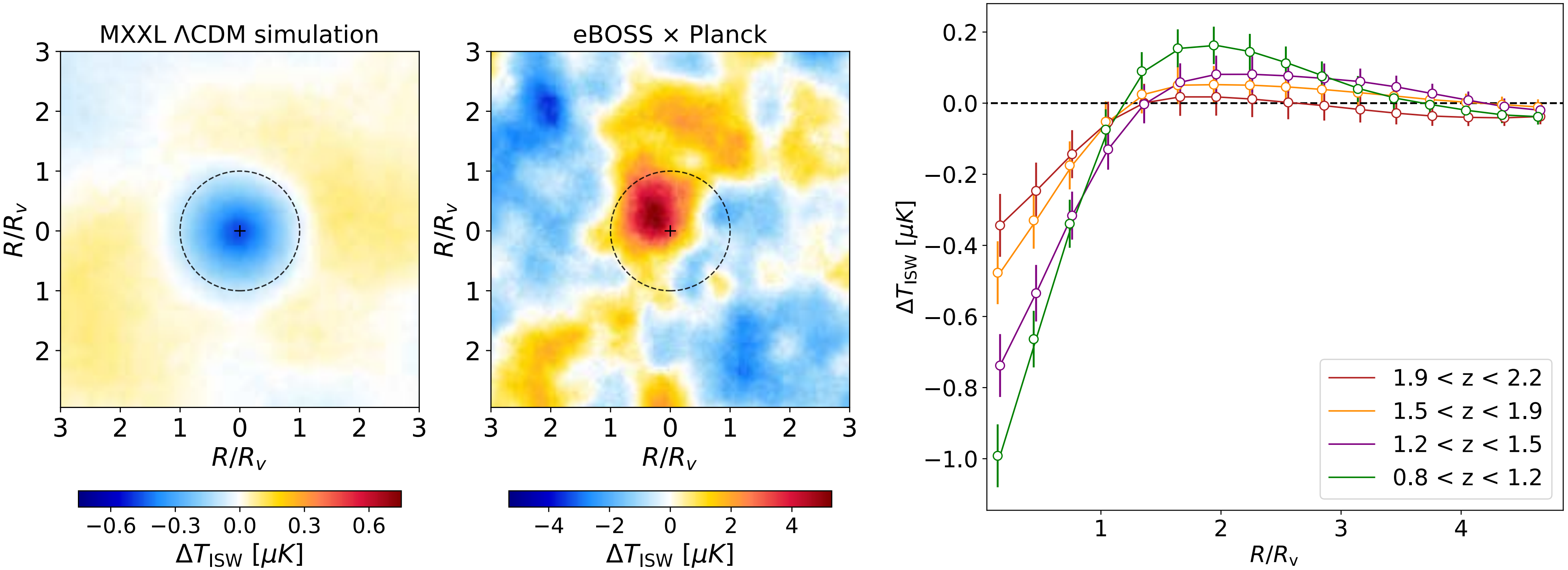
and,
as of recently,
presenting...

ISW anomaly
(CMB + DES or BOSS)

ISW anomaly

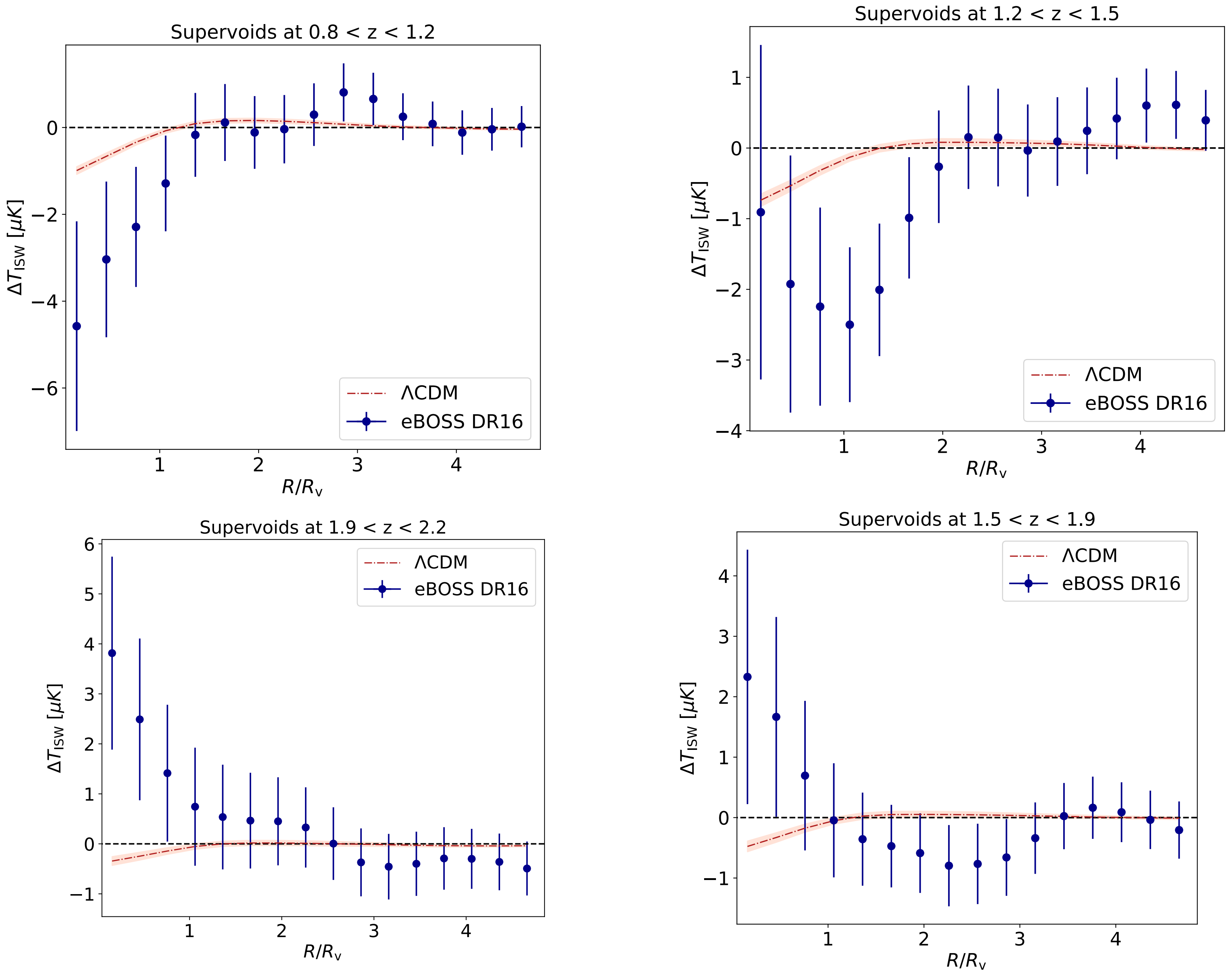
1. Detect superclusters and voids in BOSS/DES
2. Look at CMB temperature in those directions

The temperature averages out to zero, except for the ISW part.



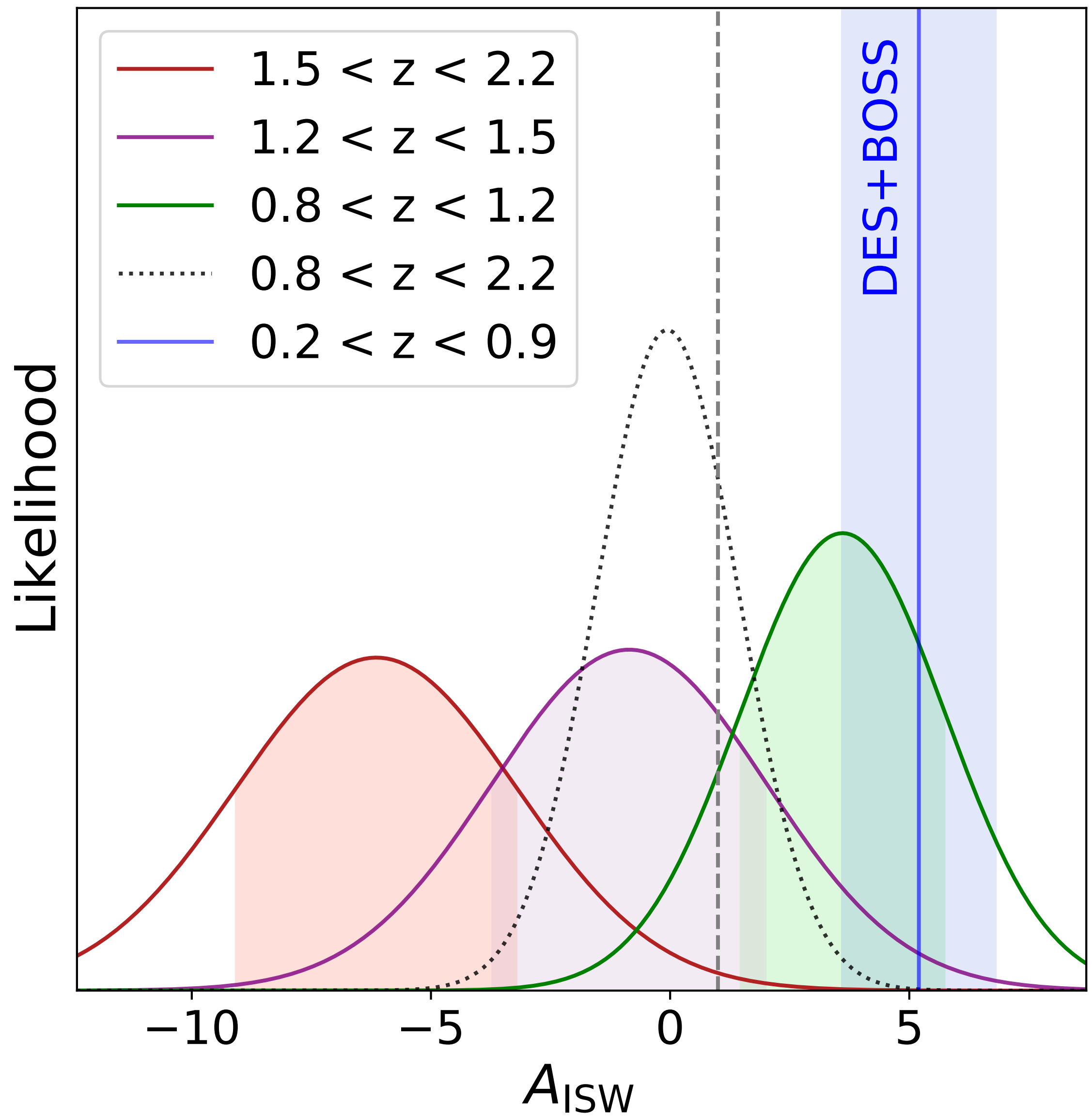
Kovacs et al, arXiv:2107.013038

ISW anomaly: Planck + BOSS QSO



Kovacs et al, arXiv:2107.013038

Planck + [DES Y1, BOSS QSO] summary



[$A_{ISW} = 1$
is the standard
LCDM value]

Kovacs et al, arXiv:1811.07812 (DES Y1); arXiv:2107.013038 (BOSS QSO)

Conclusions

- Anomalies are interesting and investigating them is important...

- ... but one has to be both careful and reasonable in interpreting their significance

- For non-CMB anomalies, the bar for claiming something is wrong with basic physics or LCDM should be very high

- For CMB anomalies, the most compelling ("special"?) still seems to be large-angle missing power, alignments

- Future surveys (LSS optical and radio in particular) should be able to significantly test the existing anomalies $\Rightarrow$ we should make predictions on what they will find!

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