The Universe is Not Isotropic

Glenn Starkman

Case Western Reserve University

Dark Side of the Universe

Sept 2024

Image: ESA/AOES Medialab

The Universe is Not Isotropic

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S. Aiola, M. O'Dwyer, O. Gungor, J. Gurian, J. Oskilt, P. Petersen, V. Vardanyan, P. Vaudrevange, A. Yoho,

Image: NASA/WMAP

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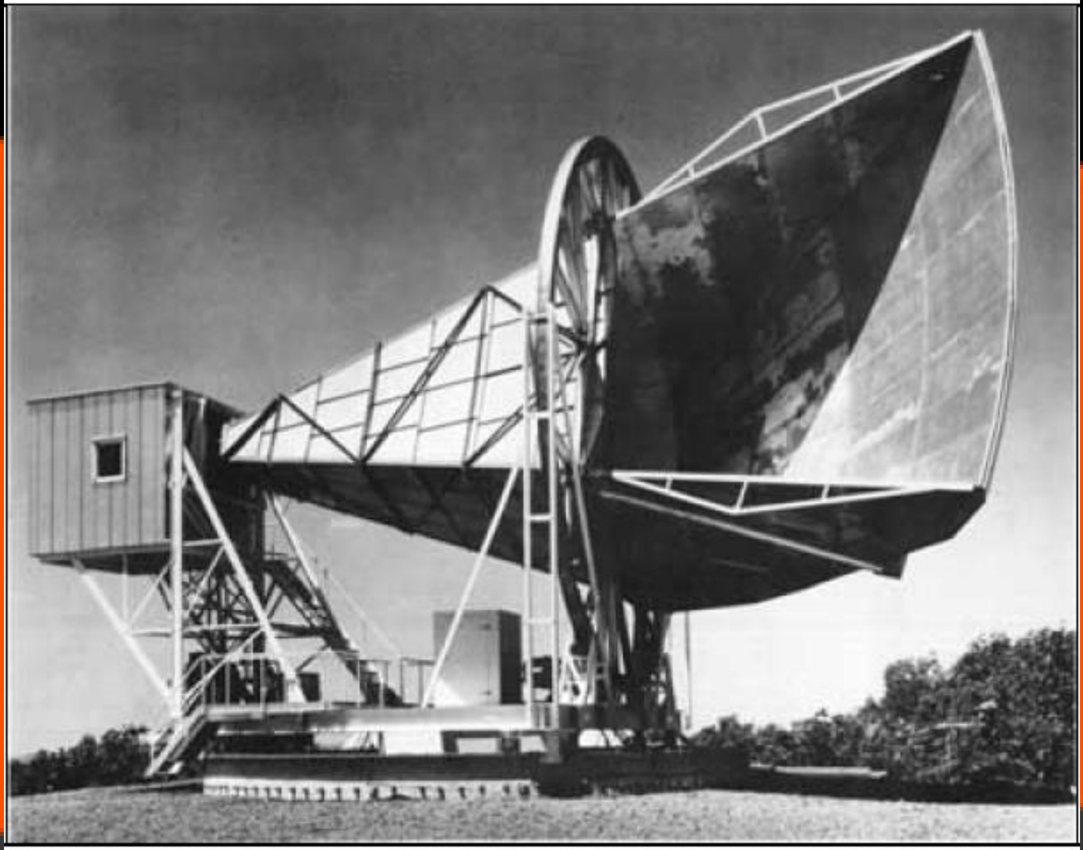
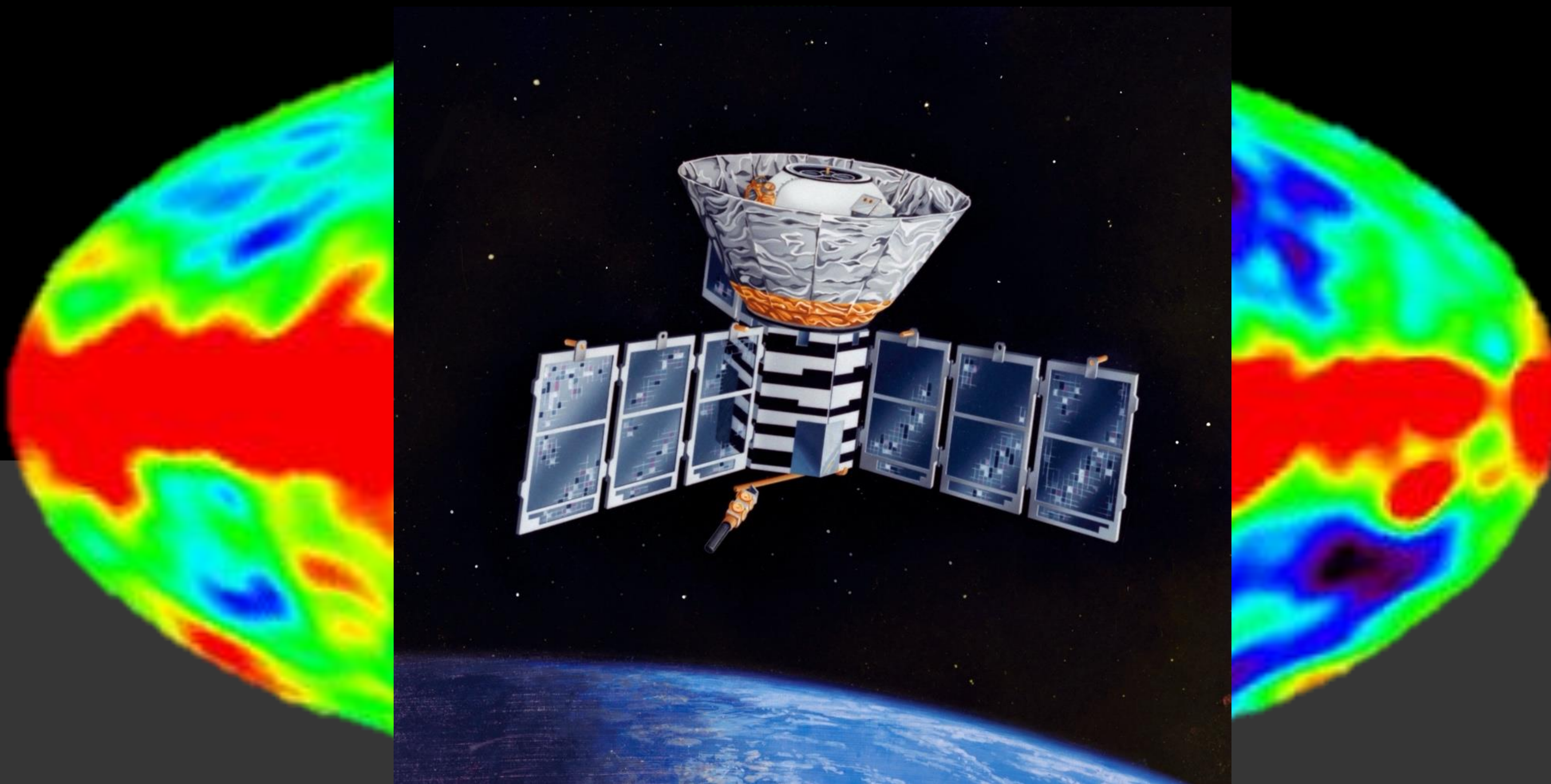
Penzias & Wilson (1965)



Horn Antenna — Holmdel, New Jersey.
Horn Antenna, circa 1960.
(Photo Credit: Bell Labs)

T=2.728K

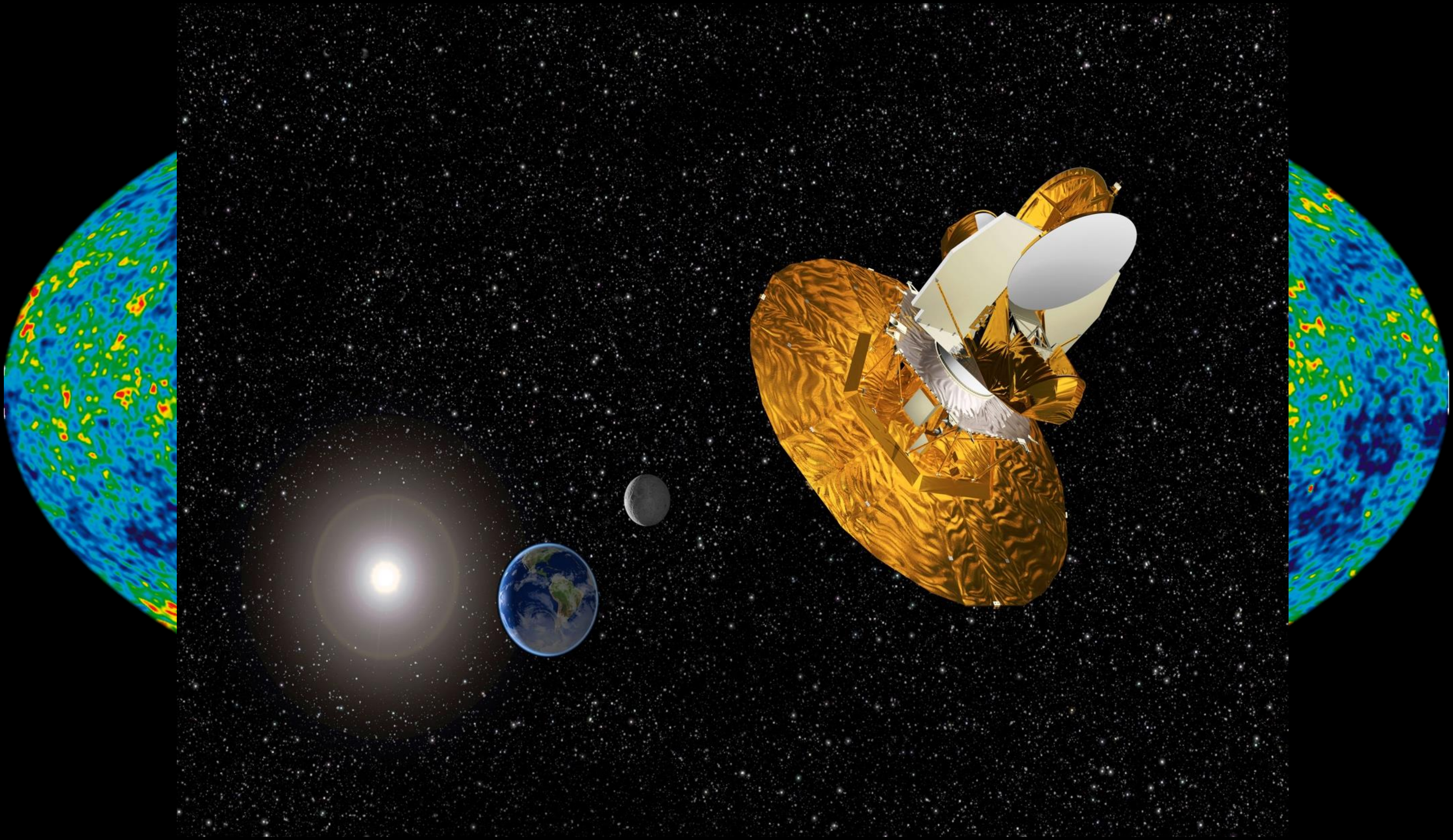
COBE - DMR



NASA/COBE-DMR science team

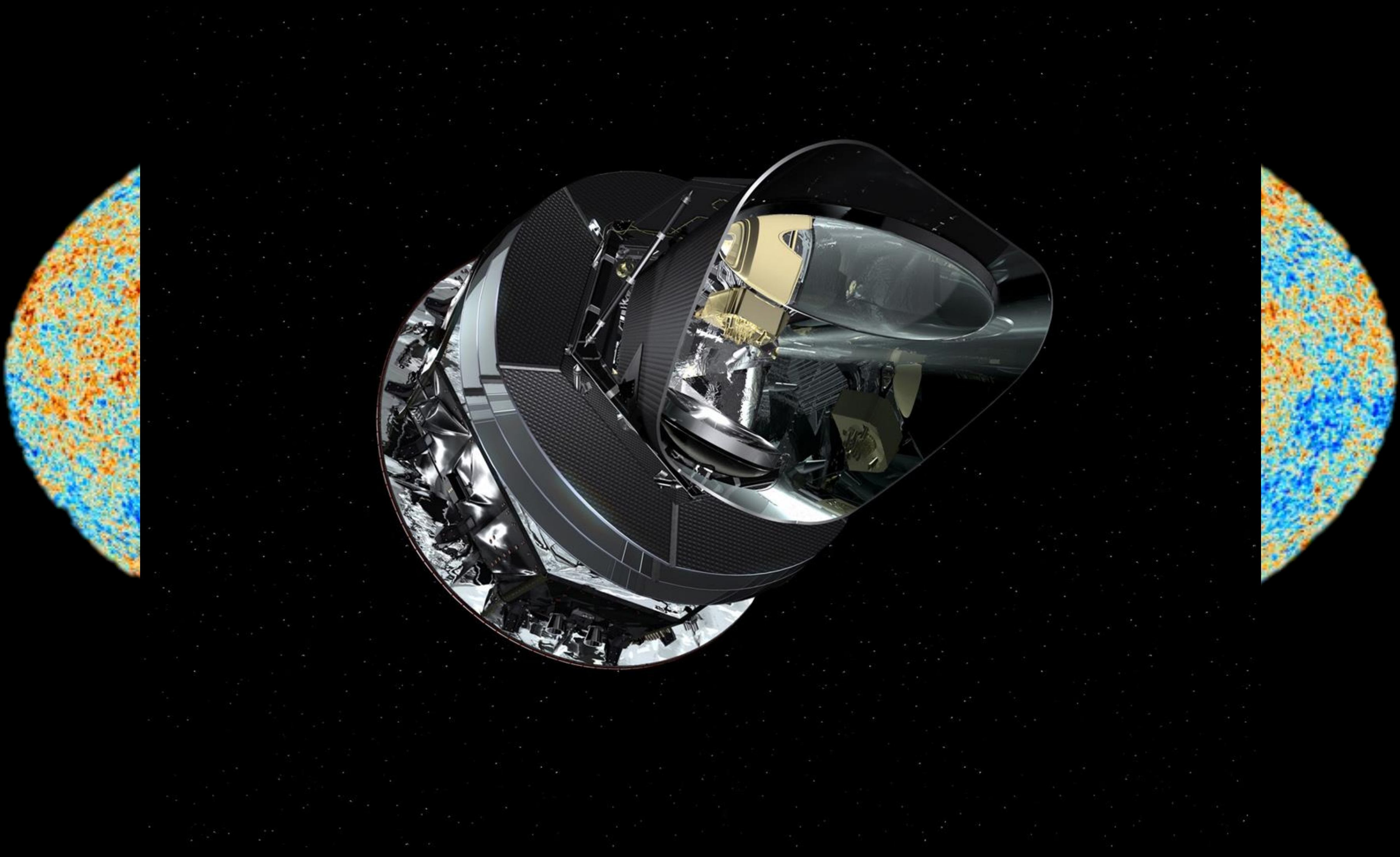
$T = 18 \mu K$

WMAP



NASA/WMAP Science team

Planck



ESA/Planck Science team

Angular Power Spectrum

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

Angular Power Spectrum

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

Standard model for the fluctuations (inflation):

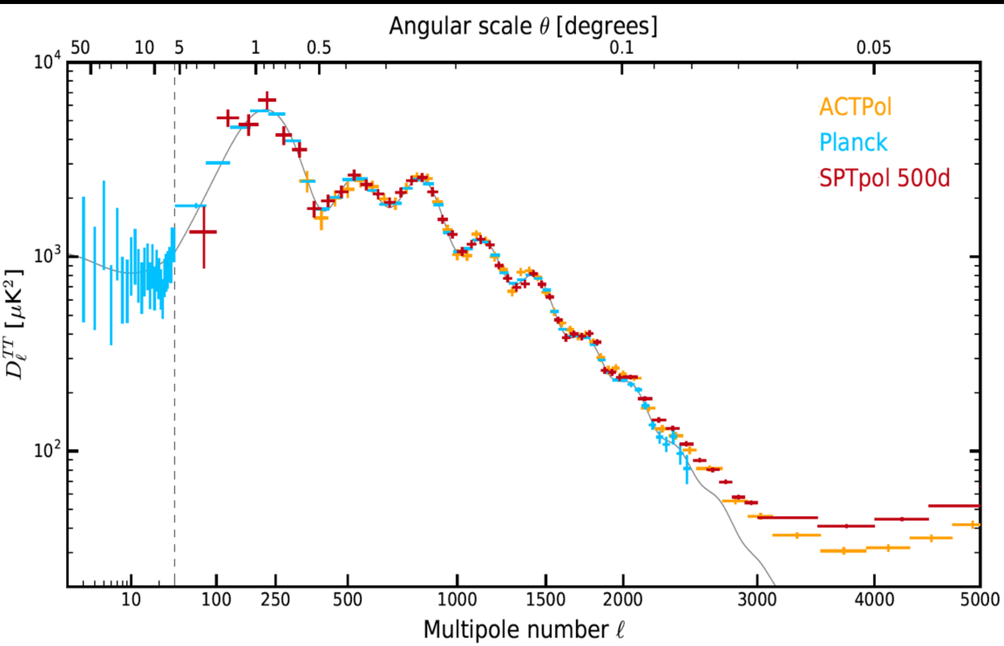
- Sky is statistically isotropic
- $a_{\ell m}$ are independent Gaussian random variables

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \, \delta_{\ell \ell'} \, \delta_{mm'}$$

ALL interesting information is contained in:

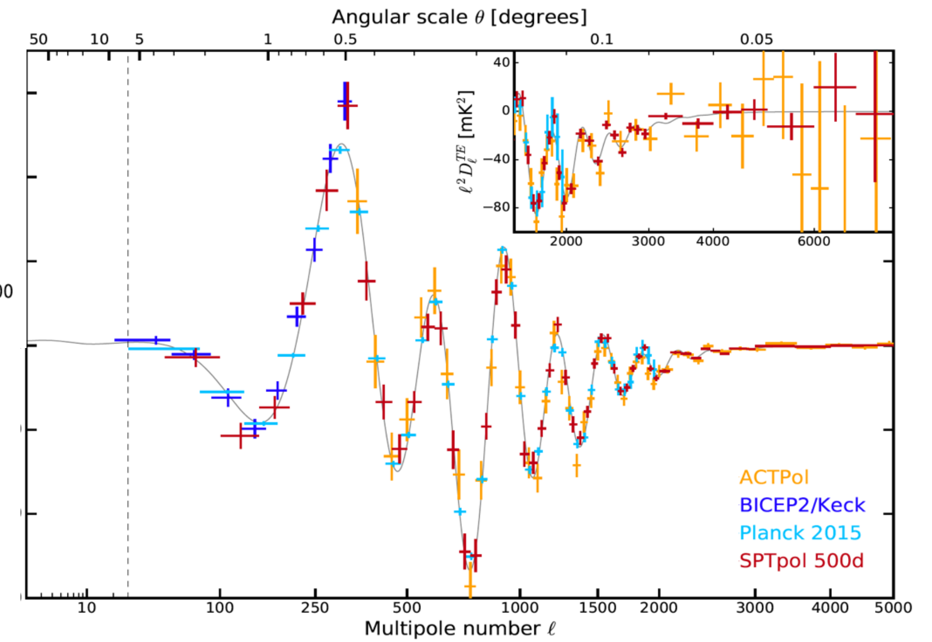
$$C_\ell = (2\ell + 1)^{-1} \sum_m |a_{\ell m}|^2$$

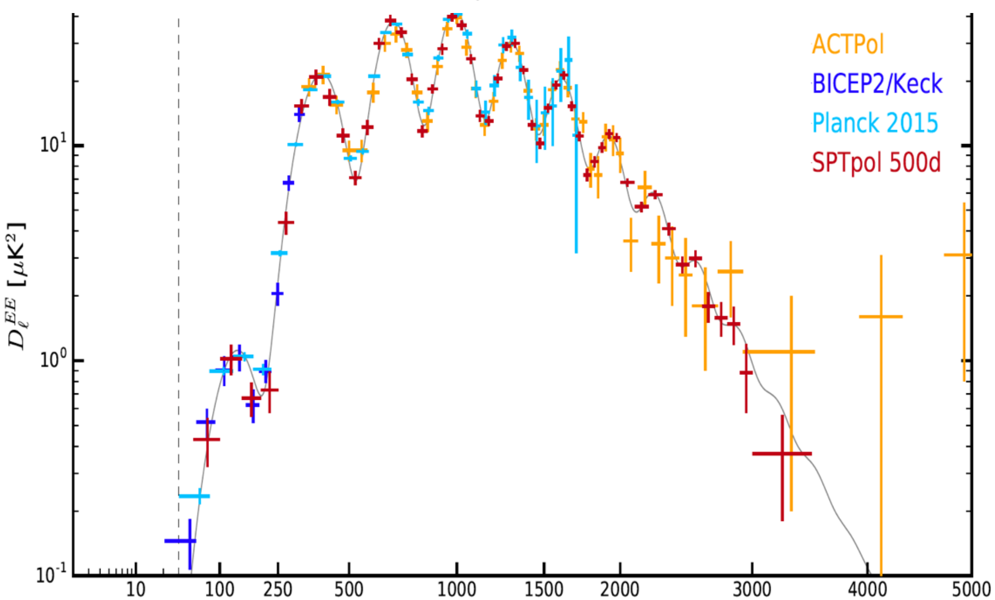
Angular Power Spectrum



6 or 7 parameter fit

to >>7 points





SPTPol arXiv:1707.09353

- **Astonishing**

  experimental accomplishment

- **Remarkable**

  agreement with theory

BUT !

Standard Model for fluctuations (inflation):

- Sky is statistically isotropic
- $a_{\ell m}$ are independent (very nearly) Gaussian random variables

$$< a_{\ell m} a^*_{\ell' m'} > = C_\ell \delta_{\ell \ell'} \delta_{mm'}$$

ALL interesting information is contained in: $\mathbf{C_\ell}$

Shouldn't we check?!

Outline

Troubles in (iso)tropical paradise:

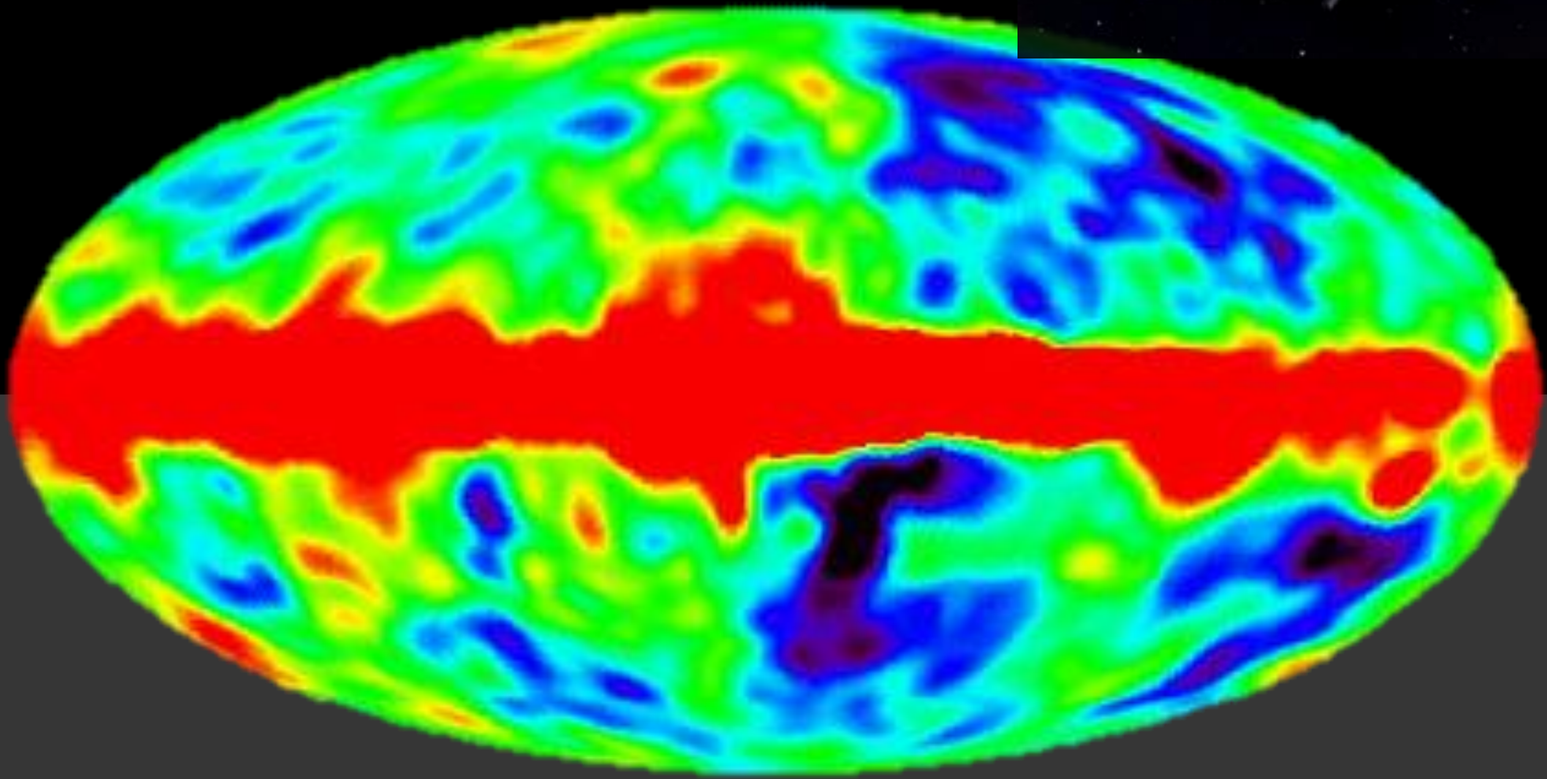
- (low-ℓ) large-angle problem: $C(\theta > 60^o) \simeq 0$
- low-ℓ alignments
- hemispheres
- parity
- *etcetera*

Bottom line:

The Universe is not statistically isotropic

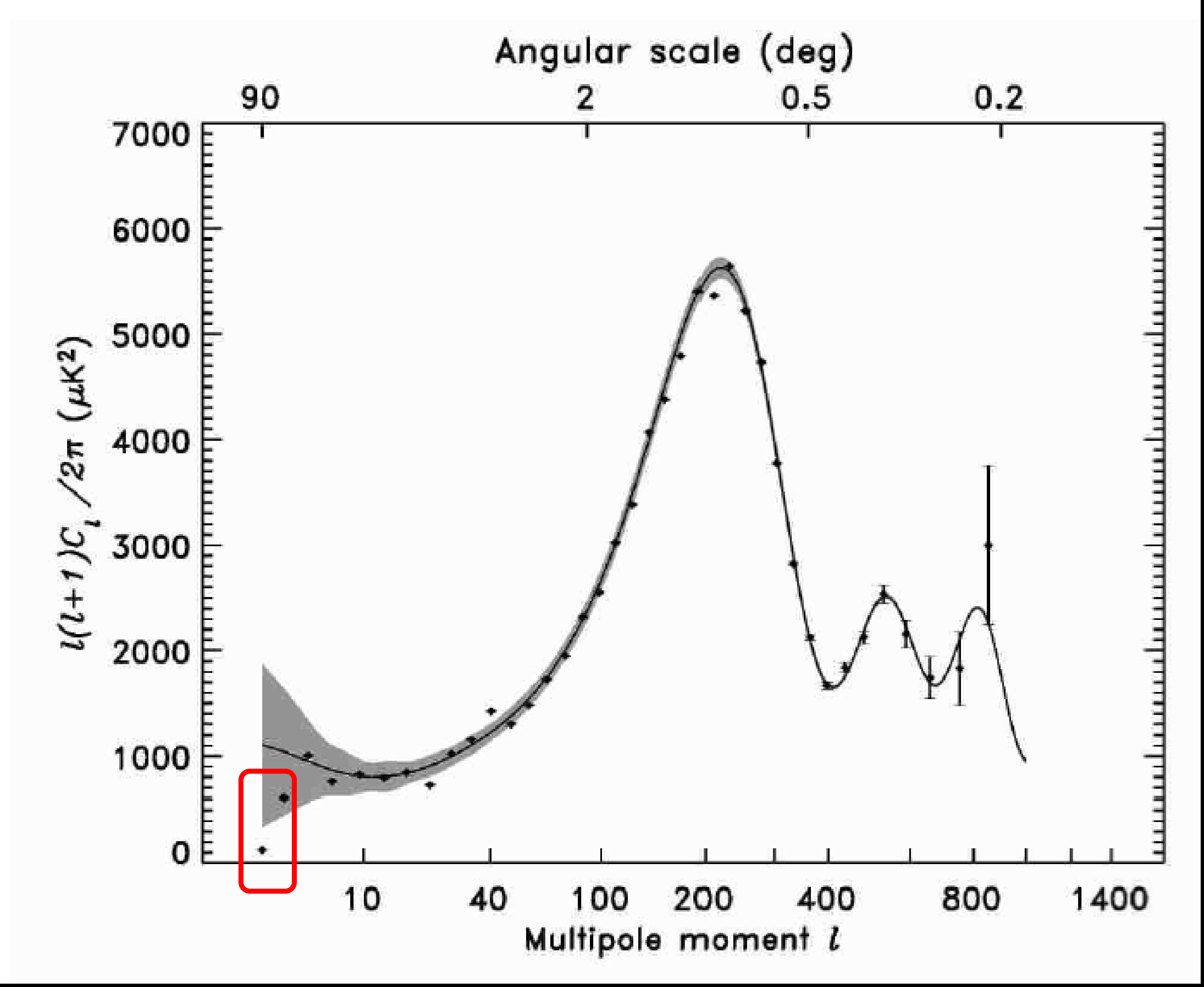
Promises of topological musings

COBE - DMR



NASA/COBE-DMR science team

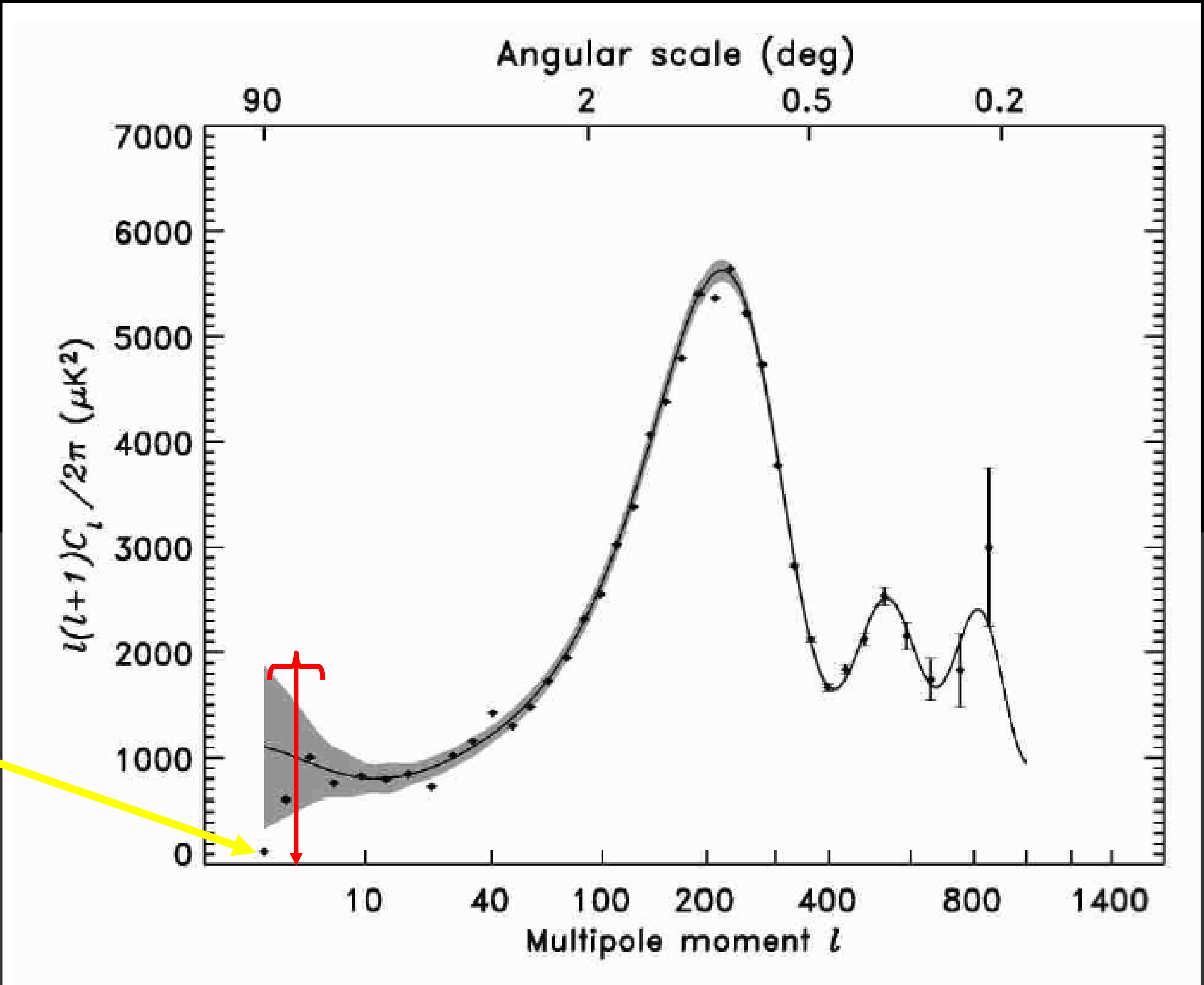
The first hint: "The low-ℓ Anomaly"



NASA WMAP
Science Team
WMAP 1

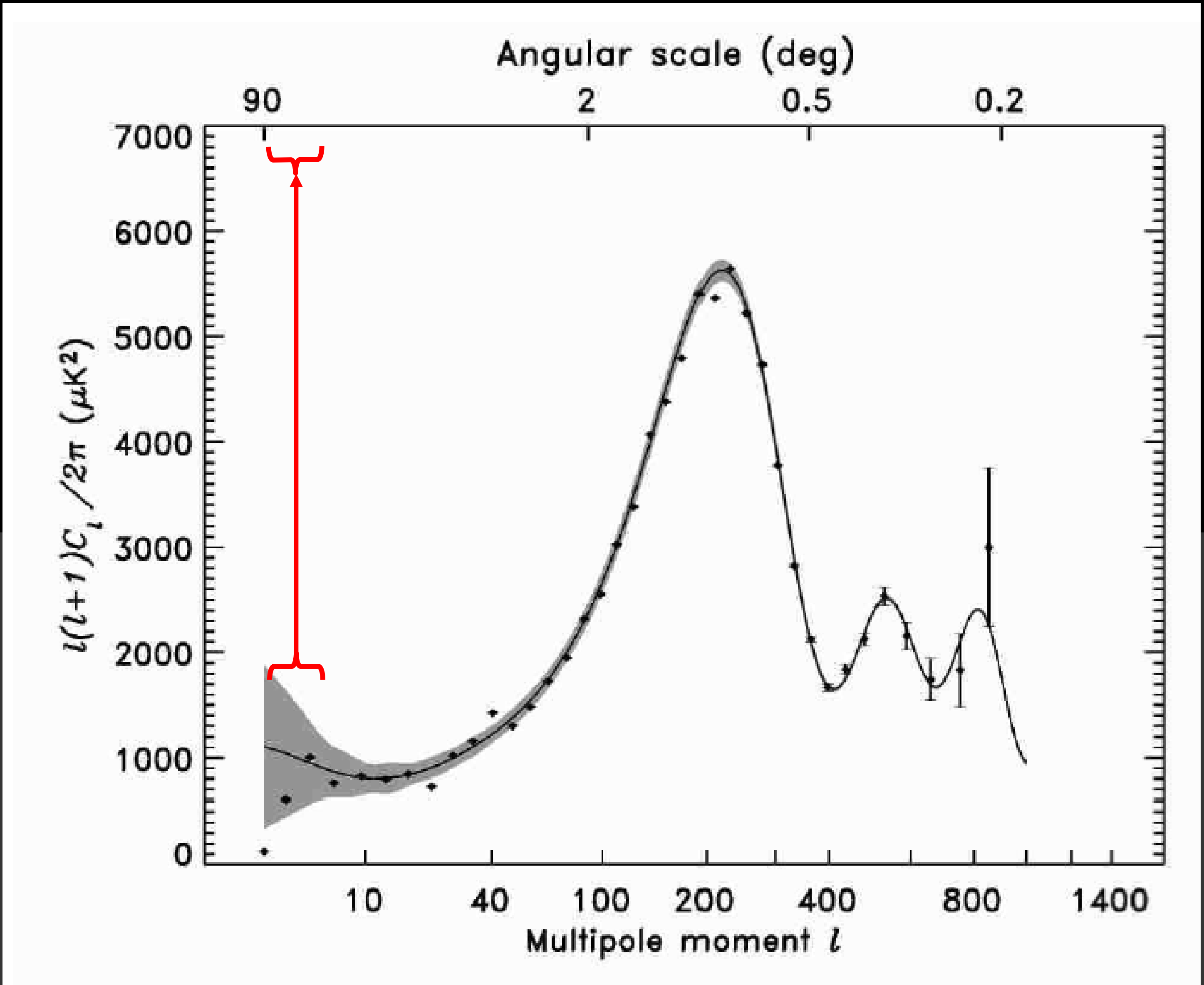
The uncorrelation …

“The Low-*l* Anomaly”



The low quadrupole

“The Large-Angle Anomaly”



Angular Correlation Function $C(\theta)$

$$C(\theta) = < T(\Omega_1)T(\Omega_2)>_{\Omega_1.\Omega_2=\cos\theta}$$

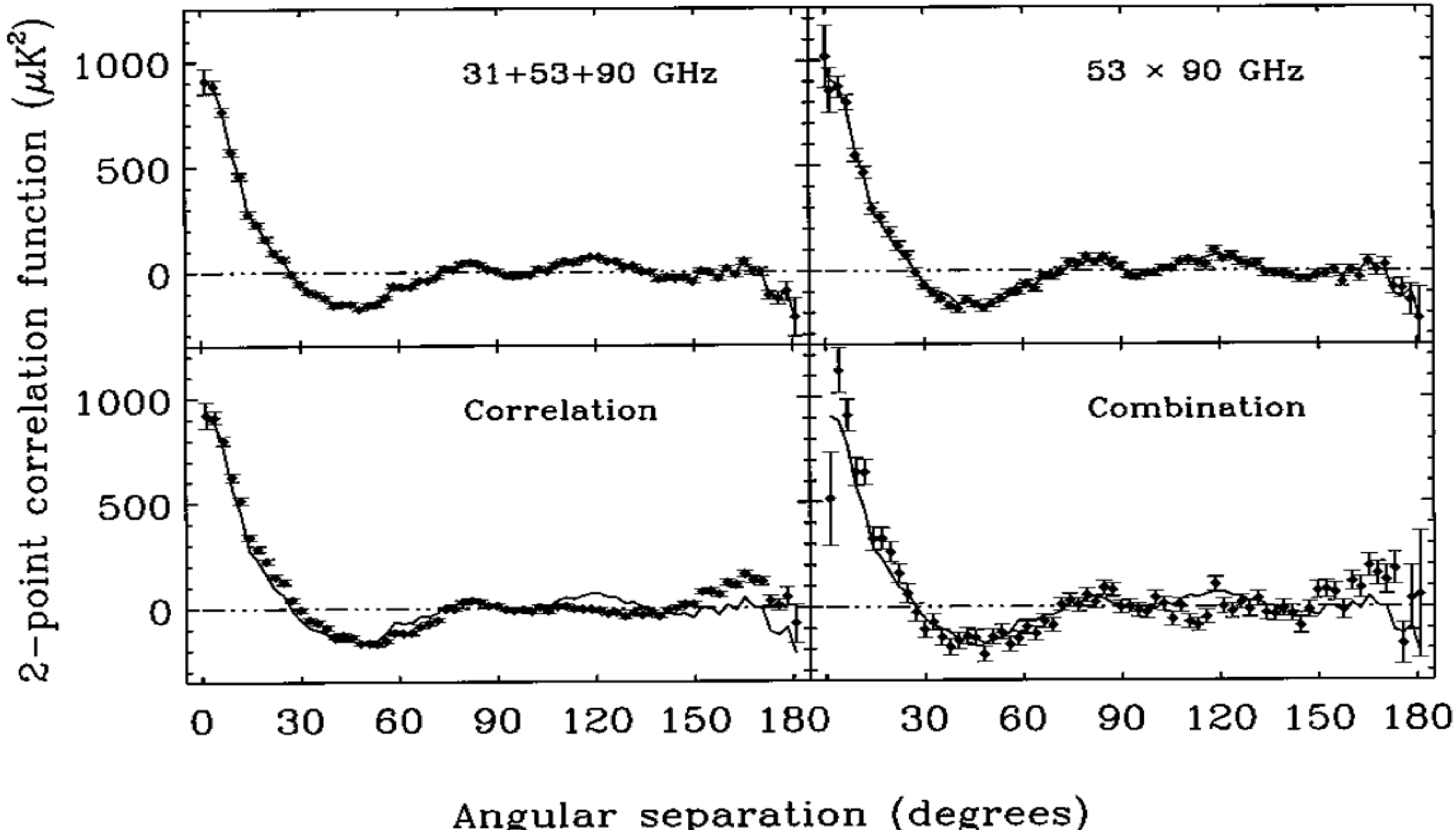
But $C(\theta) = \sum_l C_l P_l(\cos(\theta))$

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

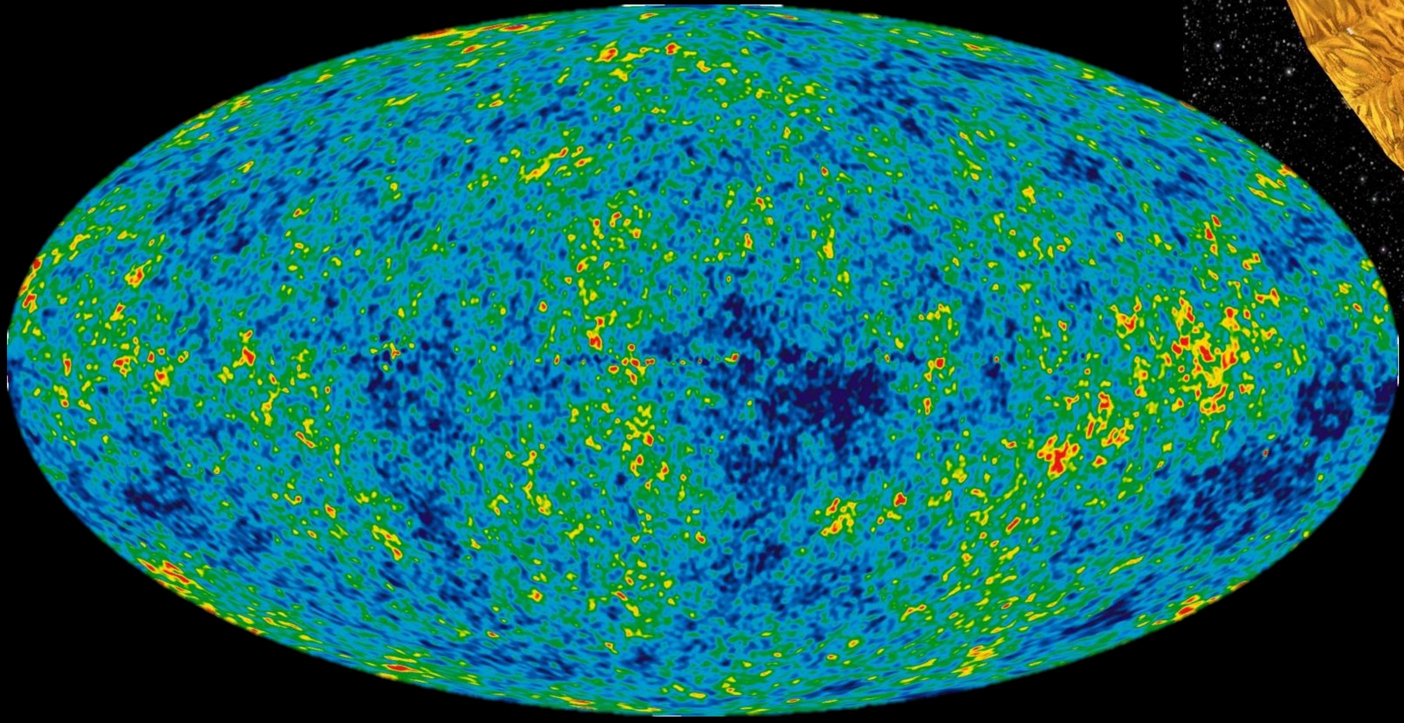
THE ASTROPHYSICAL JOURNAL, 464:L25–L28, 1996 June 10

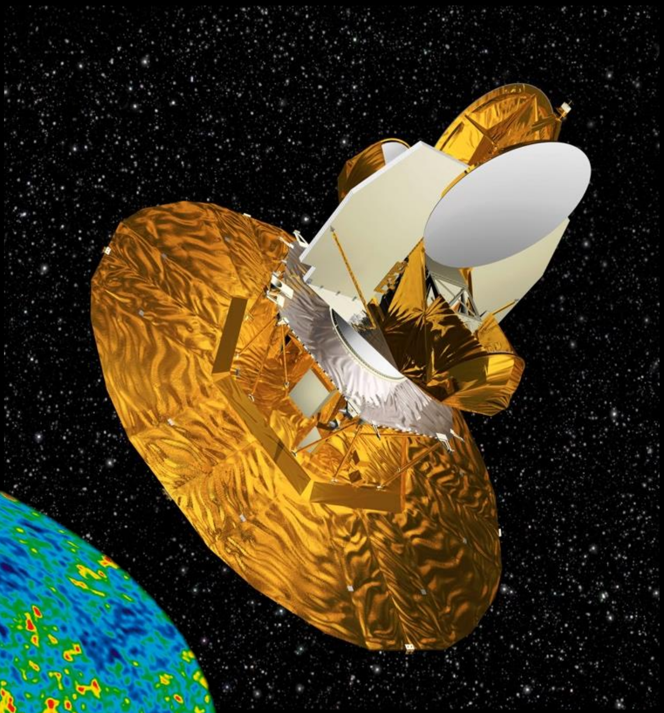
TWO-POINT CORRELATIONS IN THE *COBE*[1] DMR FOUR-YEAR ANISOTROPY MAPS

G. HINSHAW,[2,3] A. J. BANDAY,[2,4] C. L. BENNETT,[5] K. M. GÓRSKI,[2,6] A. KOGUT,[2] C. H. LINEWEAVER,[7] G. F. SMOOT,[8] AND E. L. WRIGHT[9]
Received 1996 January 9; accepted 1996 March 21



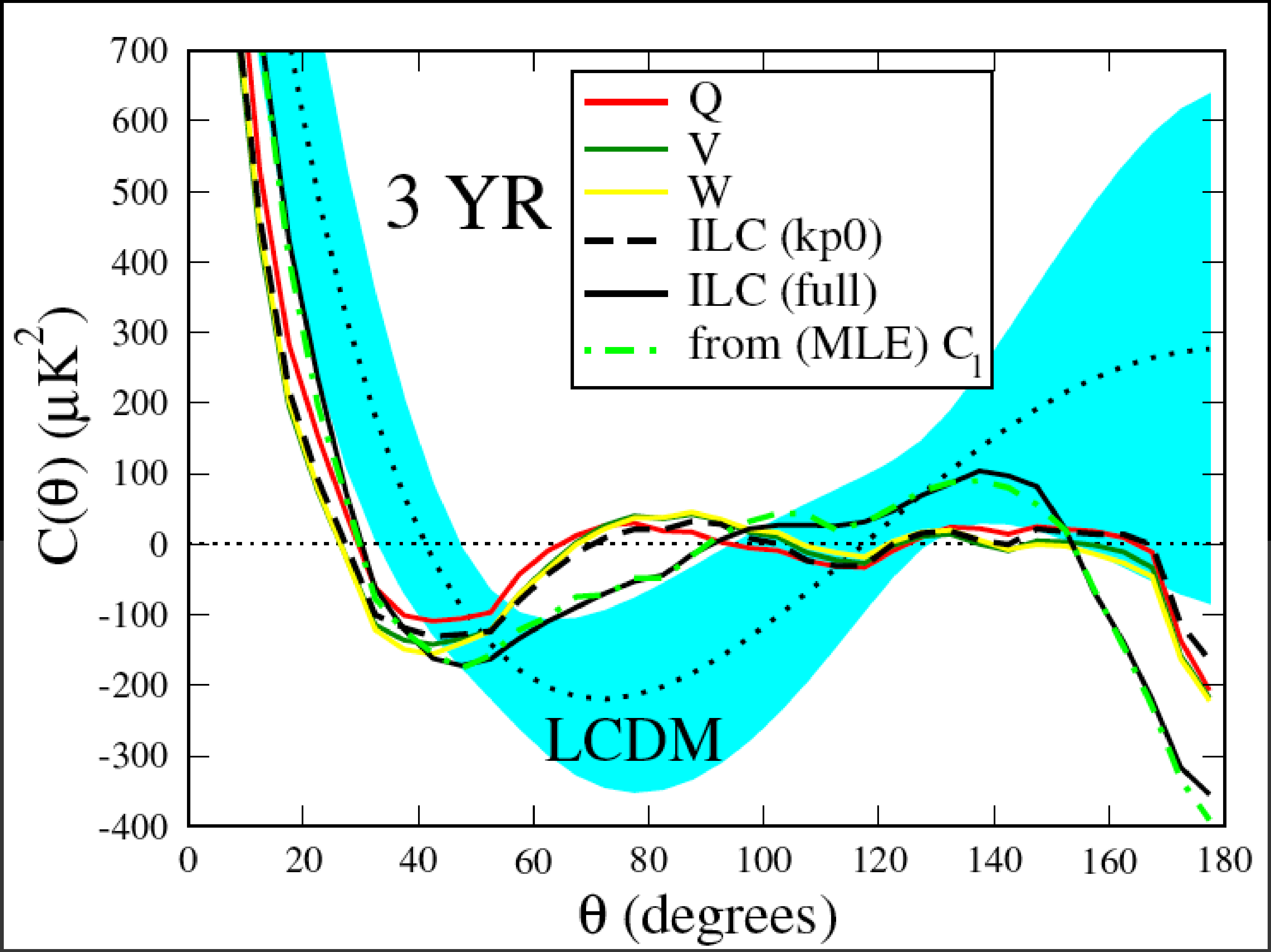
WMAP





NASA/WMAP Science team

Two-point angular correlation function



Is the Large-Angle Anomaly Significant?

One measure (WMAP1):

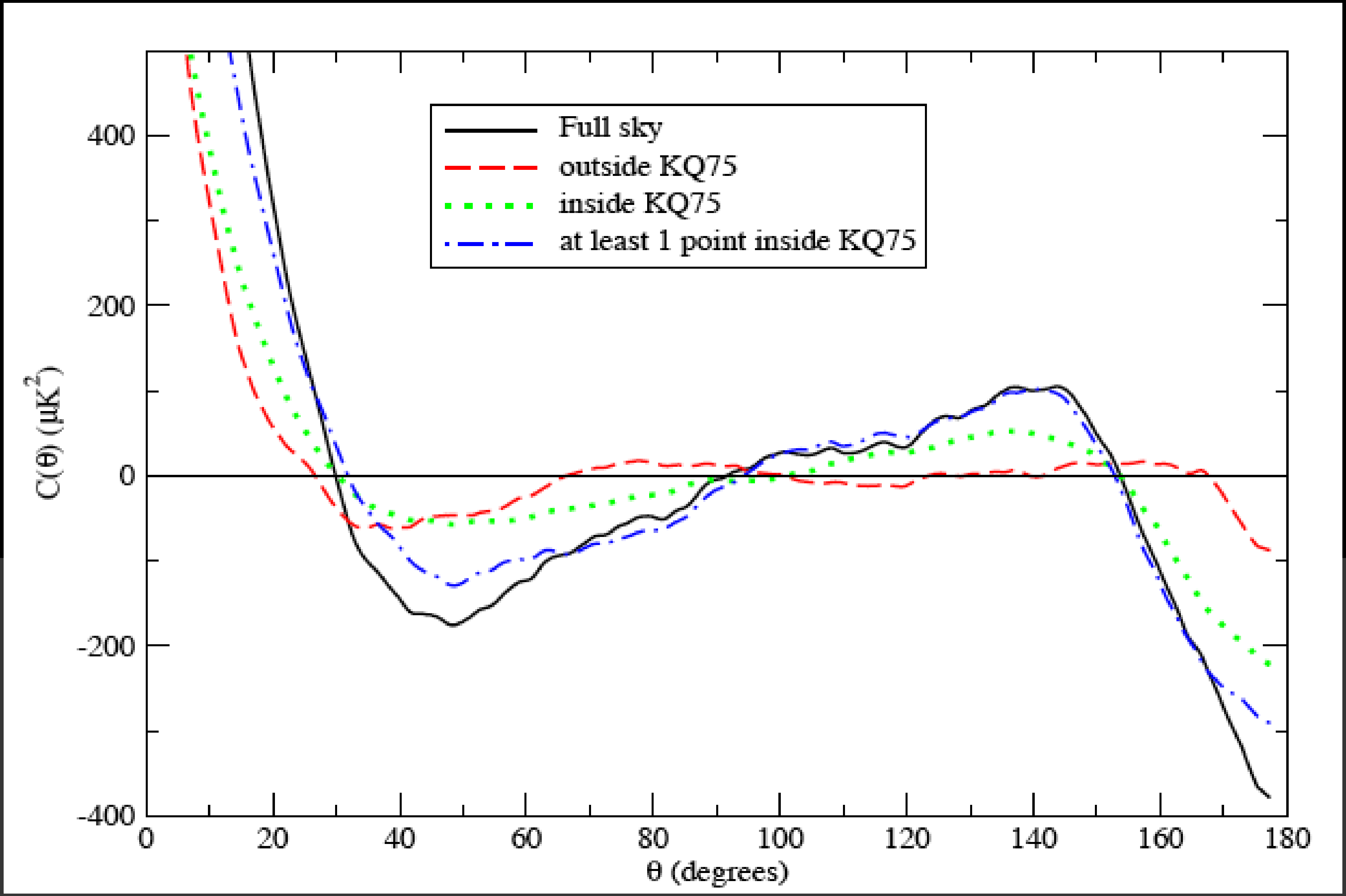
$$S_{1/2} = \int_{-1}^{1/2} [C(\theta)]^2 \, d \cos \theta$$

WMAP 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.

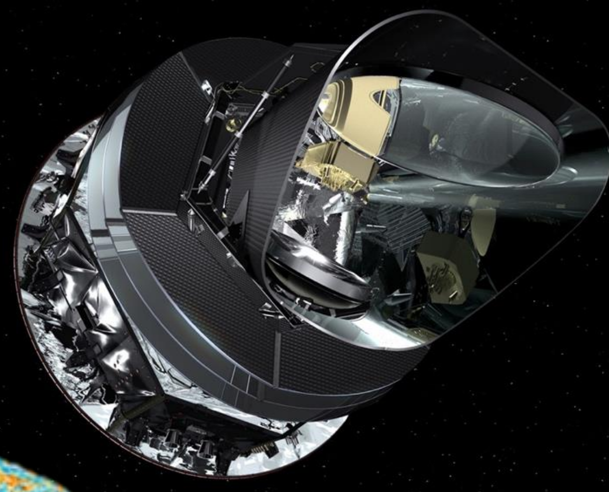
Data Source	$S_{1/2}$ $(\mu K)^4$	$P(S_{1/2})$ (per cent)	$6C_2/2\pi$ $(\mu K)^2$	$12C_3/2\pi$ $(\mu K)^2$	$20C_4/2\pi$ $(\mu K)^2$	$30C_5/2\pi$ $(\mu K)^2$
V3 (kp0, DQ)	1288	0.04	77	410	762	1254
W3 (kp0, DQ)	1322	0.04	68	450	771	1302
ILC3 (kp0, DQ)	1026	0.017	128	442	762	1180
ILC3 (kp0), $C(> 60°) = 0$	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

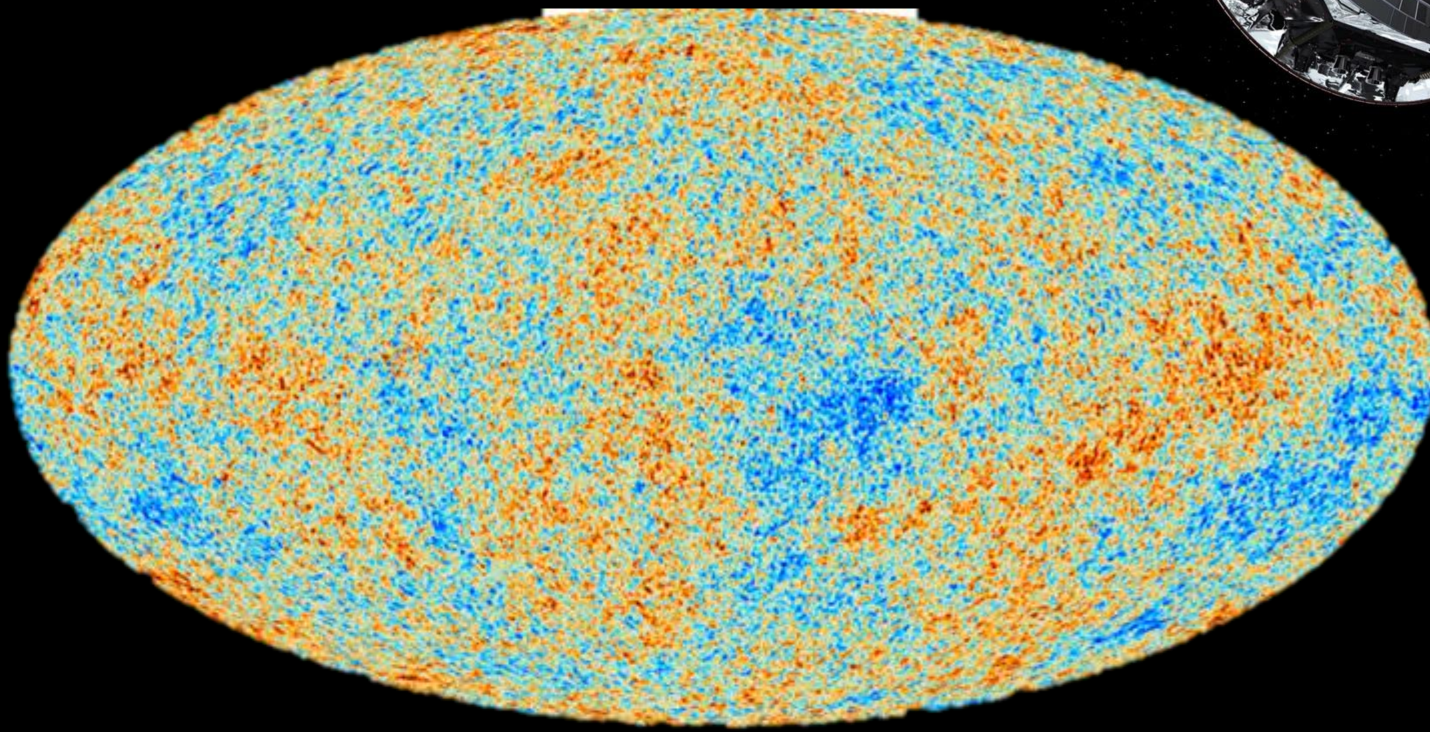
Origin of C(θ)



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

Planck

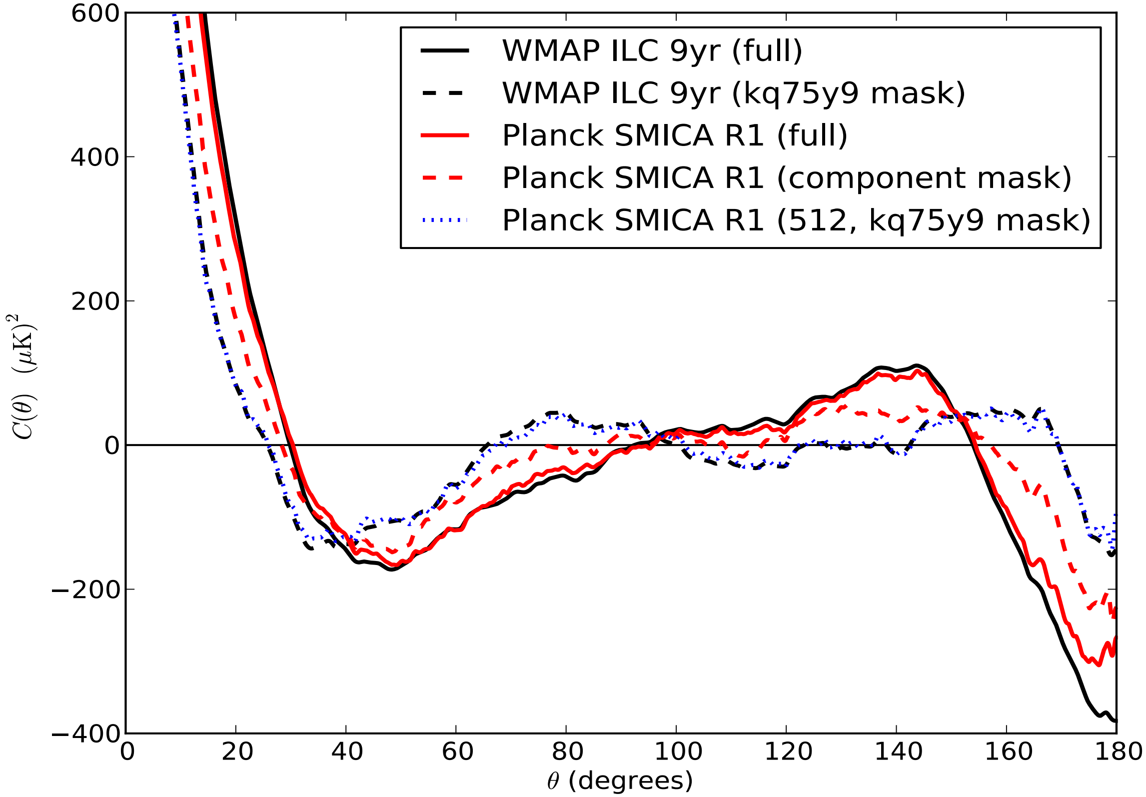




ESA/Planck Science team

Did this change in Planck?

Nope



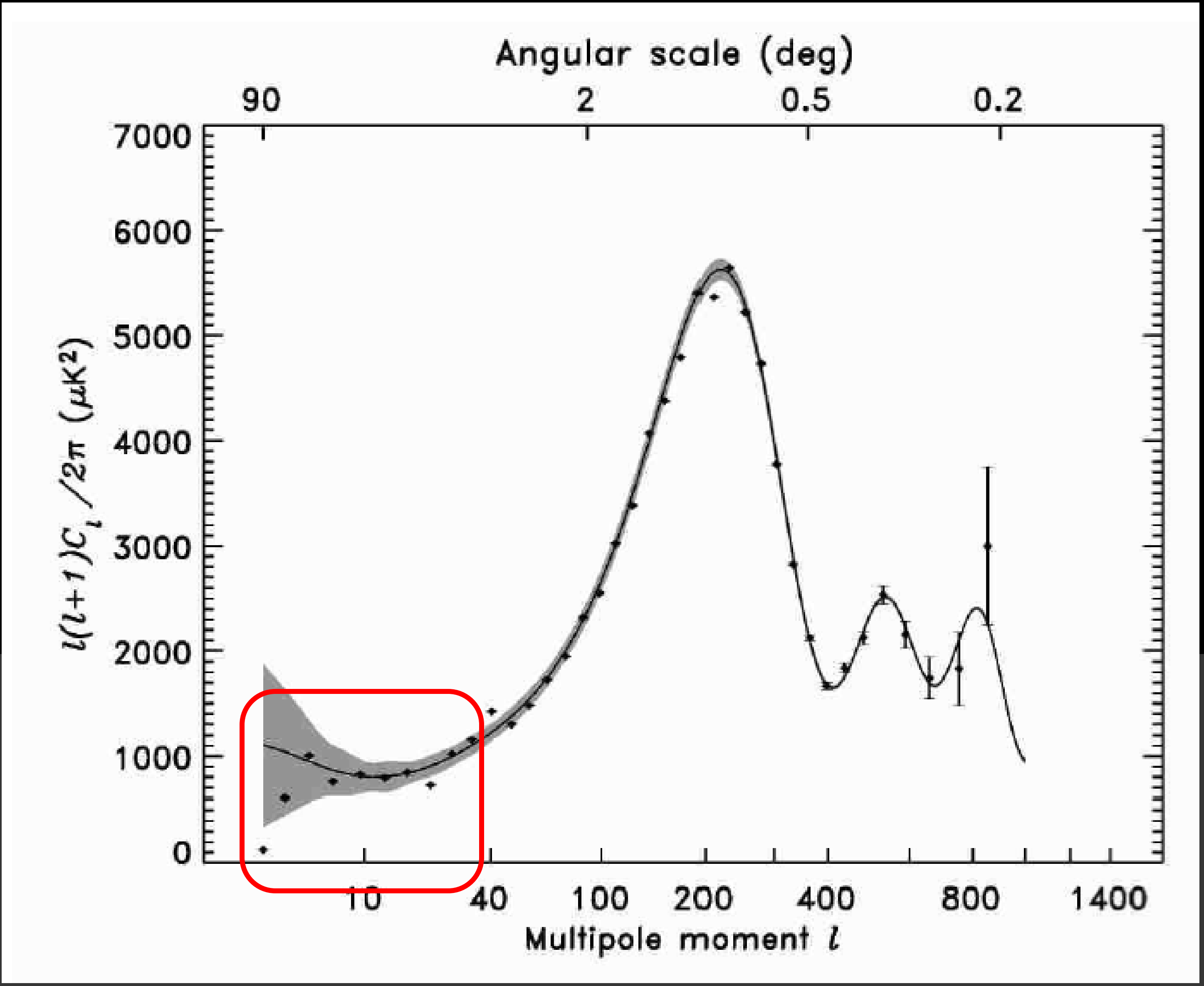
Planck 2018
A&A 641, A7
(2020)

	$S_{1/2}^{XY}$ [μK^4]			
Statistic	Comm.	NILC	SEVEM	SMICA
TT	1209.2	1156.6	1146.2	1142.4
	Probability [%]			
	Comm.	NILC	SEVEM	SMICA
	>99.9	>99.9	>99.9	>99.9

Statistics of C(θ)

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

and most of those have all low-ℓ C_ℓ small



Angular scale (deg)
90
2
0.5
0.2
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
10
40
100
200
400
800
1400
Multipole moment l

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

To obtain $S_{1/2} < 1000$ with the observed C_ℓ requires correlating 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 so little correlation in a particular realization…

and most of those would be much poorer fits to that theory than is the current data

Explaining small $S_{1/2}$

1. "Didn't that go away?"
2. "I never believe *a posteori* statistics."
3. Cosmic variance -- "I never believe anything less than a (choose one:) 5σ 10σ 20σ result."
4. "Inflation can do that"

5. New physics <u>that correlates C_l's</u>

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle \not\propto \delta_{\ell\ell'}$$

$$\Longrightarrow \langle a_{\ell m} a^*_{\ell' m'} \rangle \neq C_\ell \delta_{\ell\ell'} \delta_{mm'}$$

Beyond C_ℓ:

Searching 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.*)
- bipolar spherical harmonics (BiPoSH) (Souradeep *et al.*)
- north-south asymmetries (Eriksen *et al.*, Hansen *et al.*)
- dipolar modulations
- cold hot spots, hot cold spots (Larson and Wandelt)
- Land & Magueijo scalars/vectors
- even/odd C_ℓ anomaly
- your favourite technique/anomaly that I missed
- multipole vectors (Copi, Huterer, Schwarz, GDS; Weeks; Seljak and Slosar; Dennis)

Alignments …

Multipole Vectors

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

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

Dipole (ℓ =1) :

$$\sum_m \mathbf{a}_{1m} \mathbf{Y}_{1m} (\theta,\phi) = A^{(1)}\, \hat{\mathbf{u}}_x^{(1,1)} .(\sin\theta \cos\phi, \sin\theta \sin\phi, \cos\theta)$$

Advantages:

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

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

Multipole Vectors

General ℓ, write:

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

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

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

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

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

Maxwell Multipole Vectors

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

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,

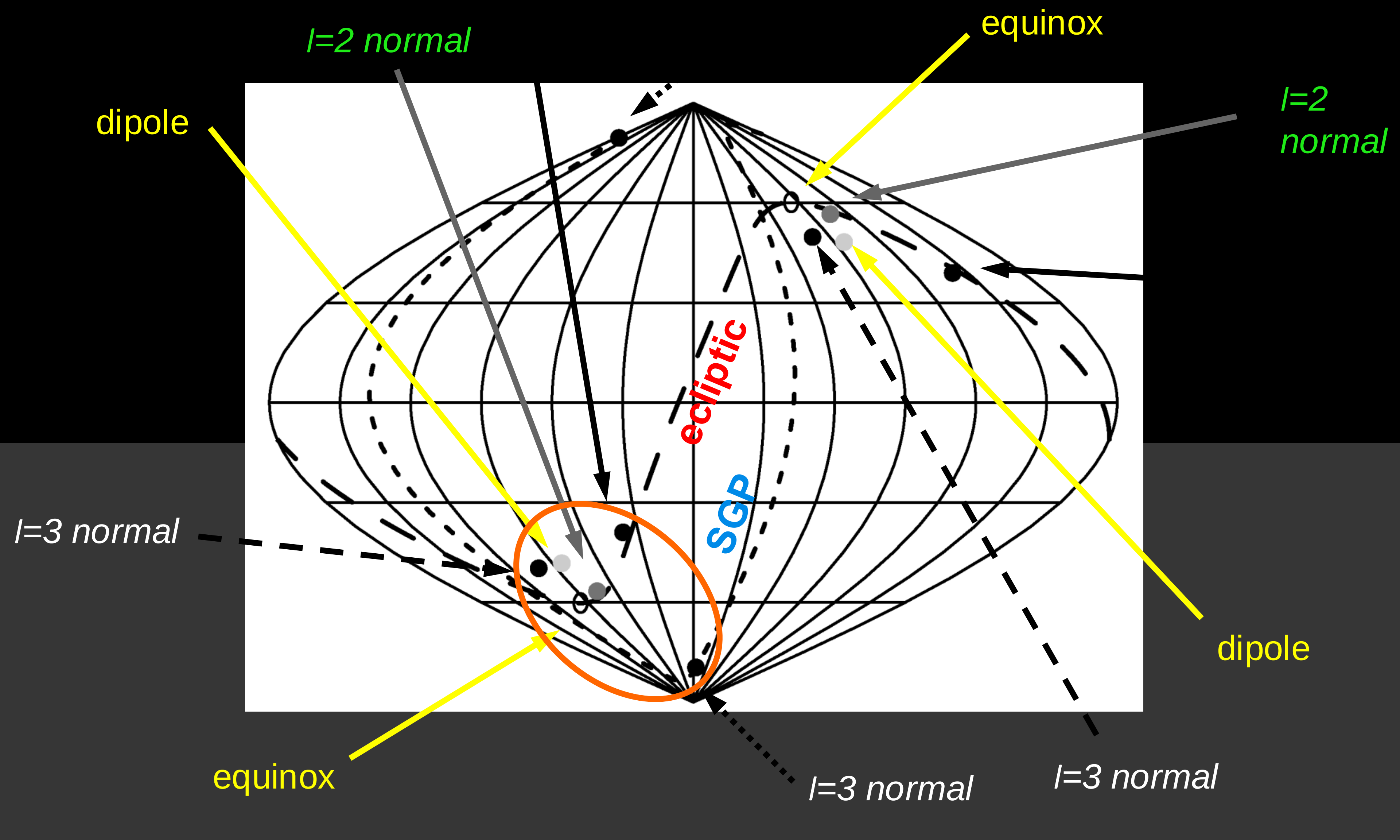
  i.e. octopole is 3 planes

Suggests defining:

$$\mathbf{w}^{(\ell,i,j)} \equiv (\hat{u}^{(\ell,i)} \times \hat{u}^{(\ell,j)}) \quad \text{“area vectors”}$$

Carry some, but not all, of the information

ℓ =2&3 Area Vectors



Quadrupole plane & 3 octopole planes are aligned with one another

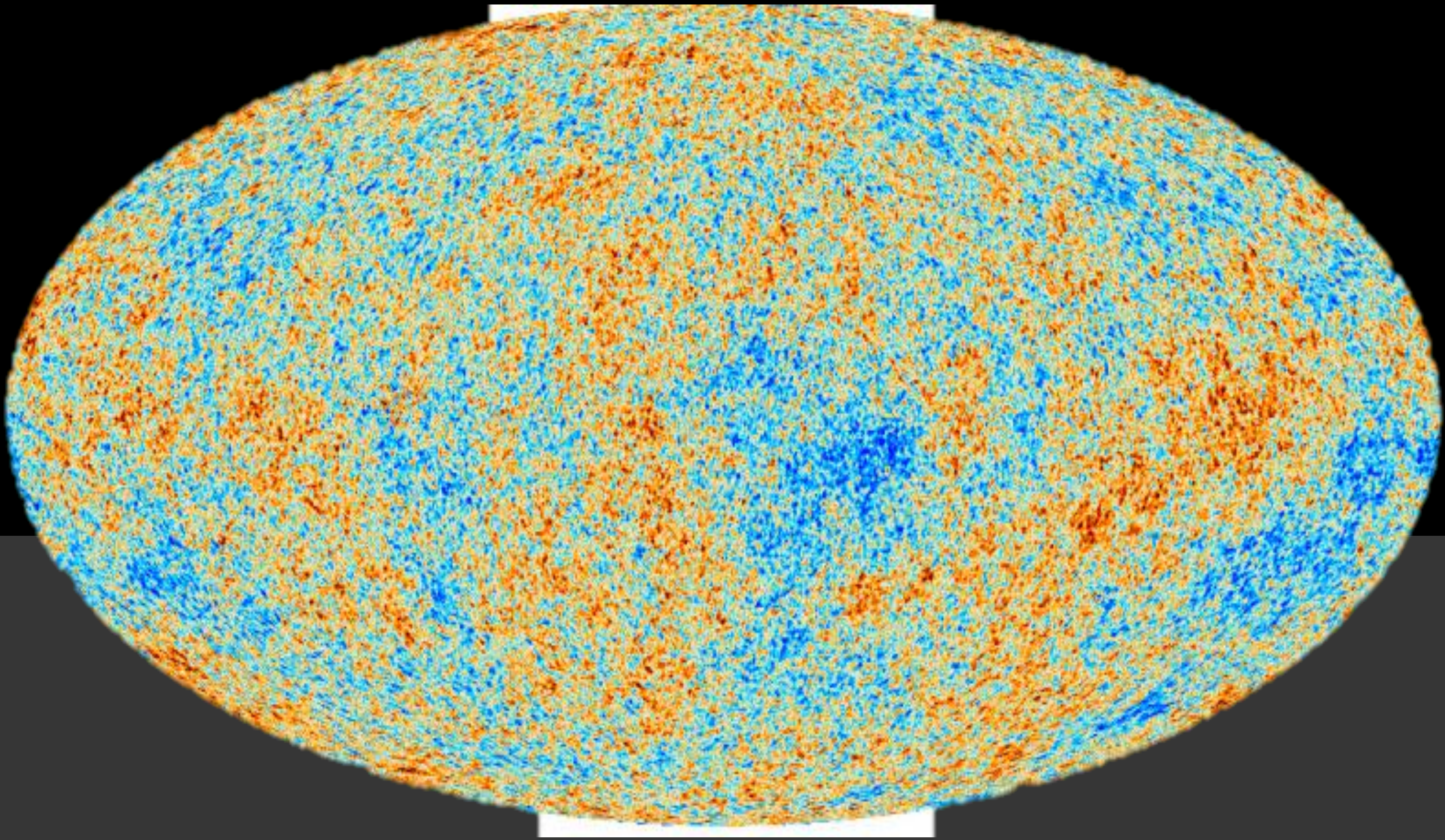
p-value of the quadrupole & octopole planes being so aligned: (0.1-0.6)%

Power asymmetry

Dipole modulation

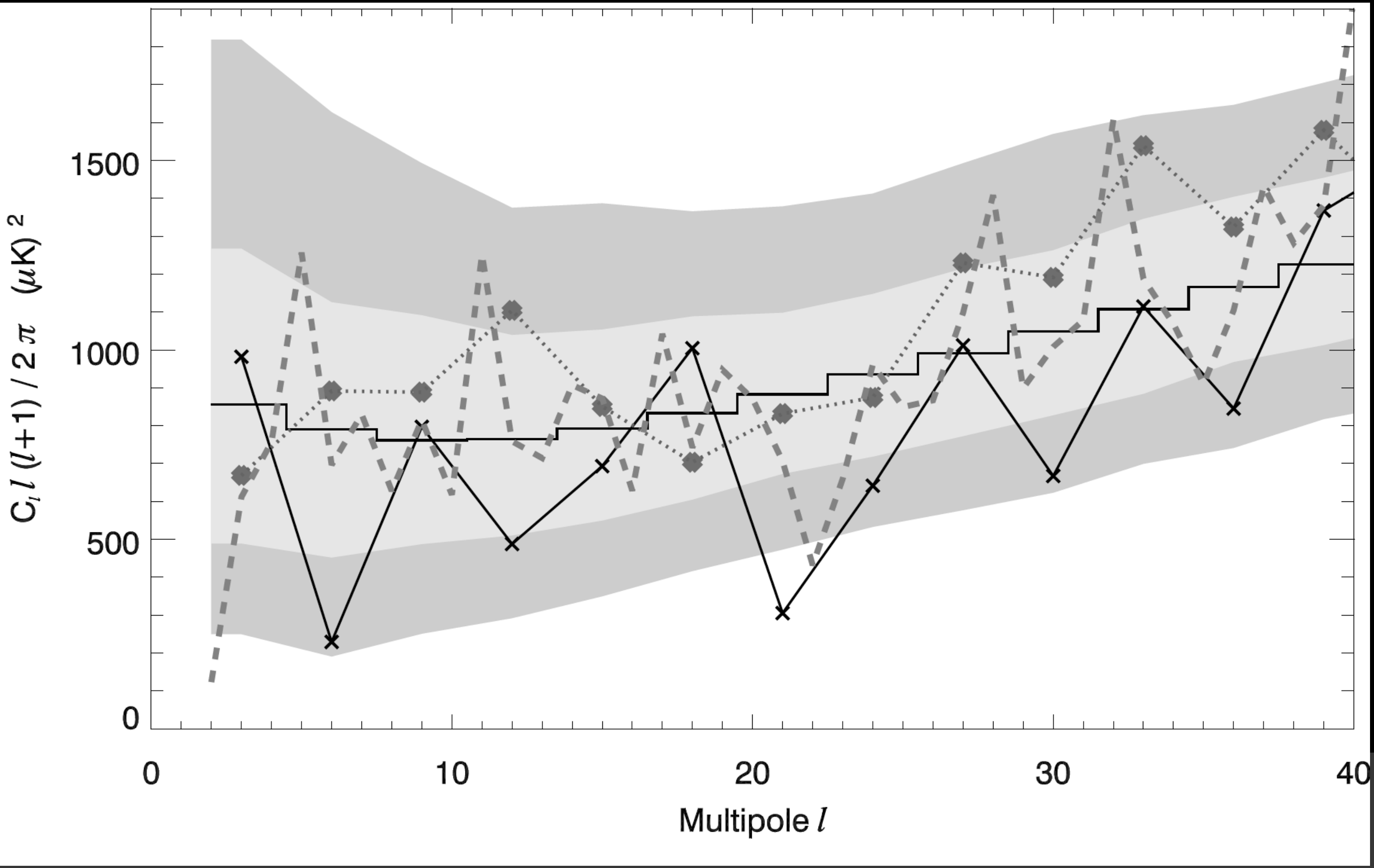
Low Northern Variance

O’Dwyer, Copi, Knox, GDS MNRAS 470 (2017), 372



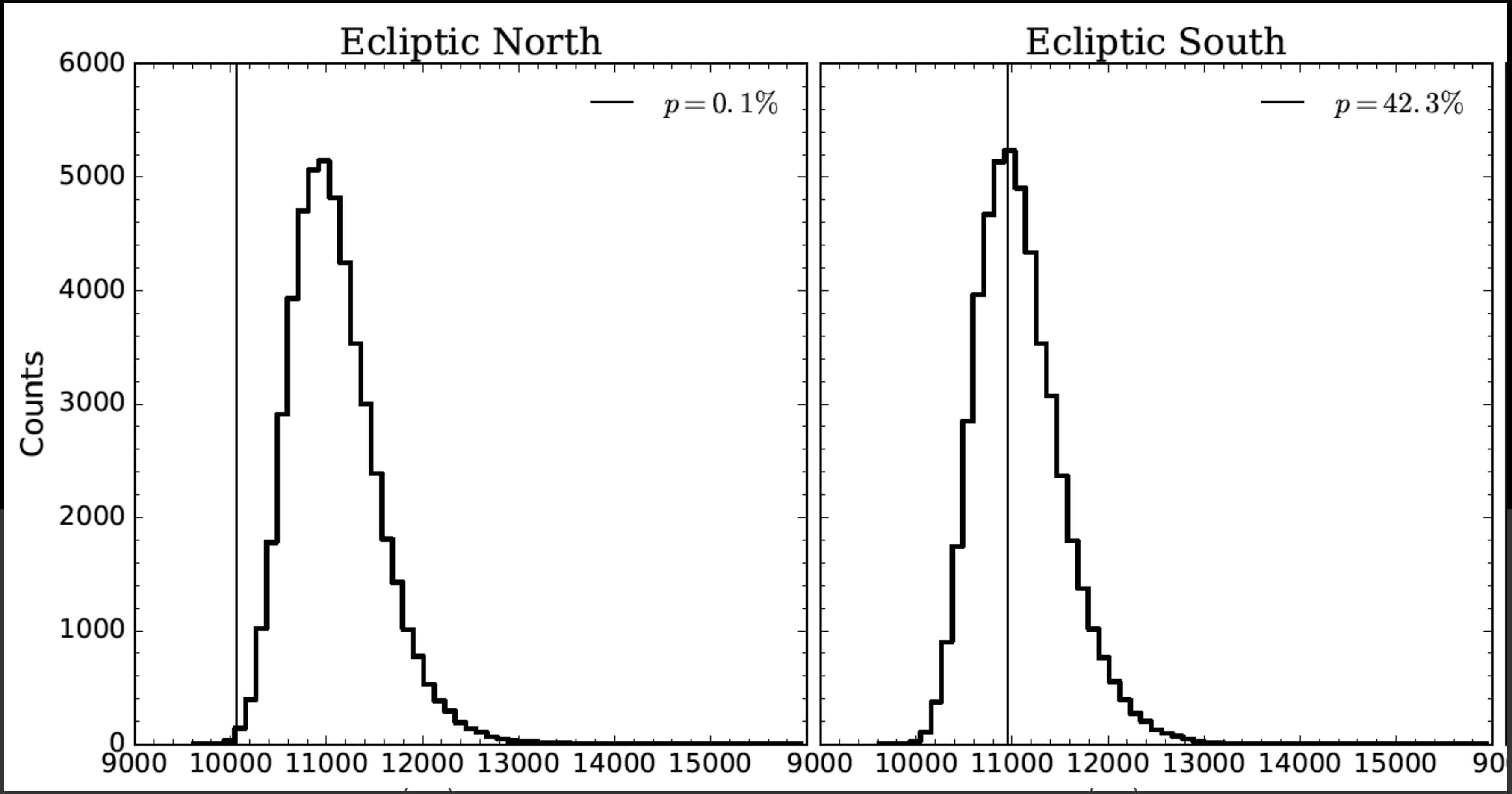
Bennett et al 2003

Eriksen et al 2004, and many others



Eriksen, Hansen, Banday, Gorski and Lilje 2004 Astrophys. J. 605 , 114 binned angular power spectrum over the whole unmasked sky (dashed), northern hemisphere (solid line), and southern hemisphere (dotted line). Optimized N vs. S is approximately ecliptic

SMICA N vs S variance

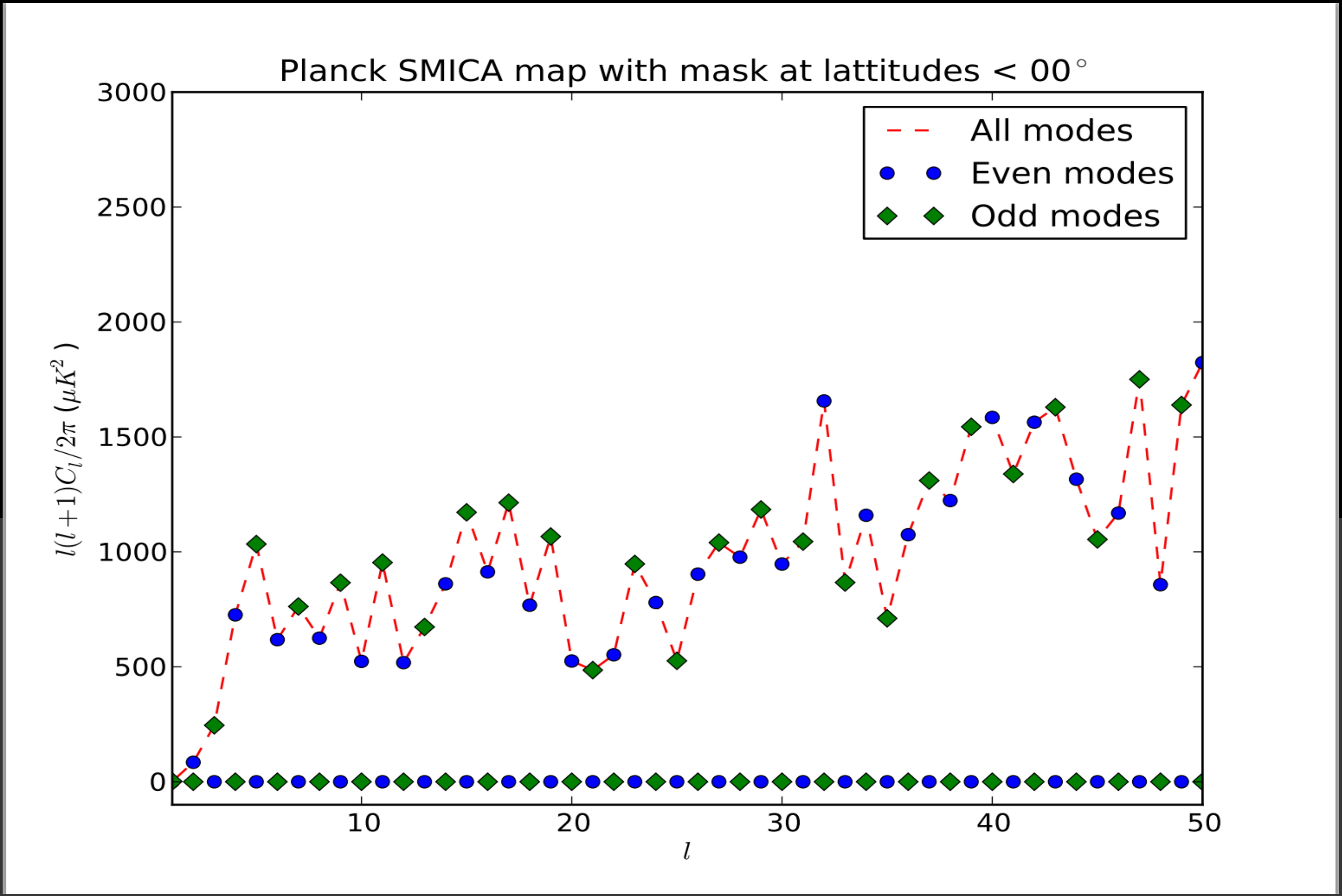


p ~ 0.001

Parity

Parity

Parity anomaly

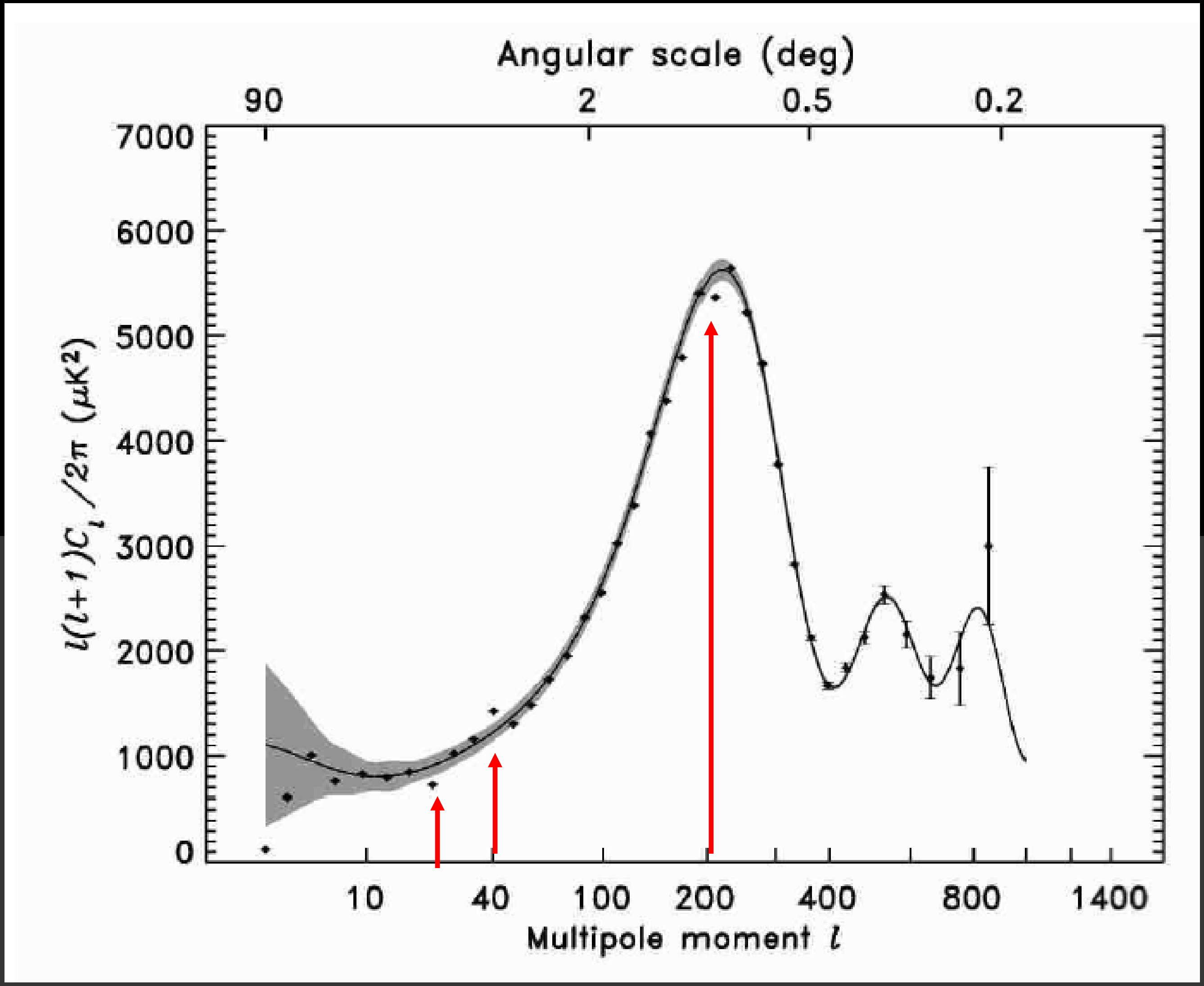


Plot by J. Muir (then U Michigan)

And …

(N) ecliptic polar excursions

Angular Power Spectrum



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

Power spectrum: ecliptic plane vs. poles

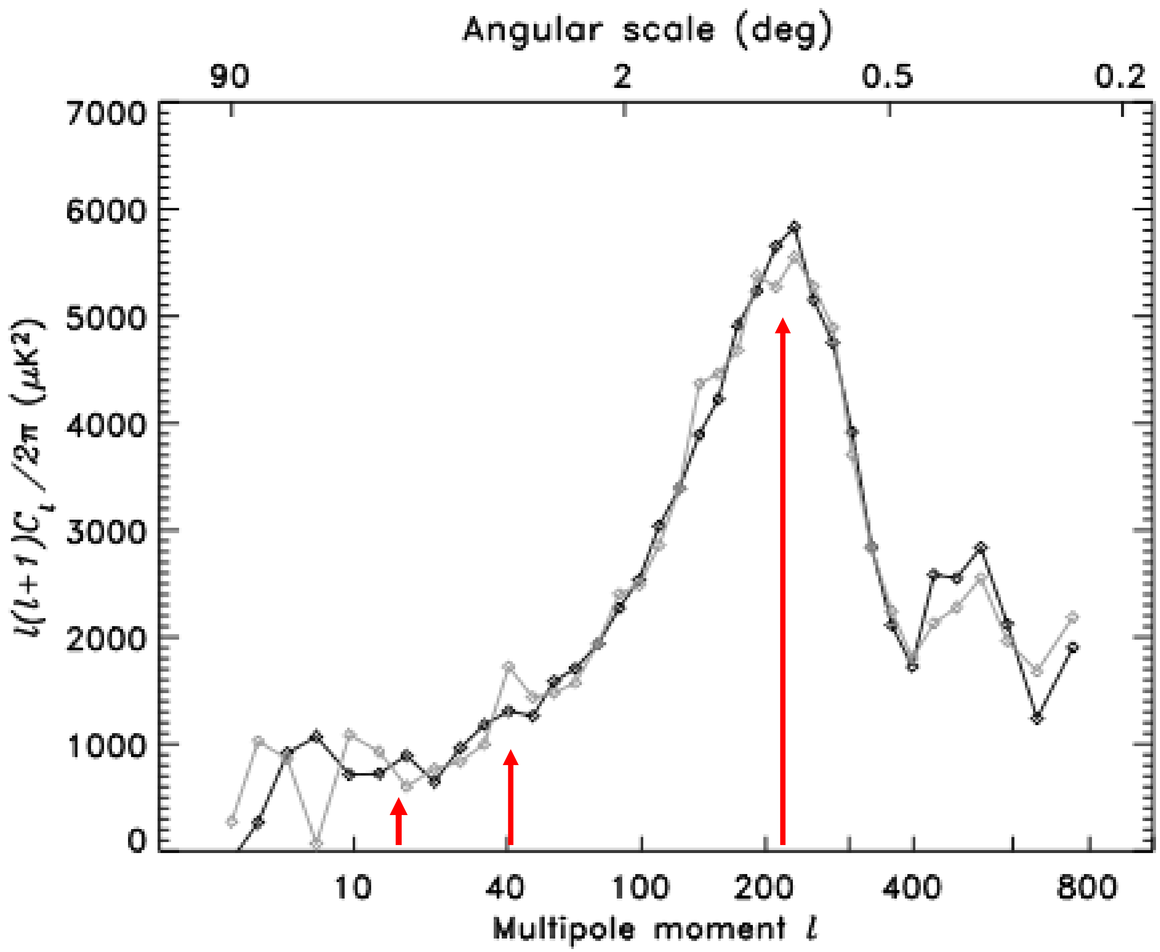


Fig. 7.— A comparison of the power spectrum computed with data from the ecliptic plane (black) vs. data from the ecliptic poles (grey). Note that some of the "bite" features that appear in the combined spectrum are not robust to data excision. There is also no evidence that beam ellipticity, which would 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).

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

With so many anomalies, what do we do?

In preparation: Large-angle anomalies of the CMB and the evidence against statistical isotropy, Physics Reports arXiv > astro-ph > arXiv:2310.12859

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 19 Oct 2023]

The Universe is not statistically isotropic

Joann Jones, Craig J. Copi, Glenn D. Starkman, Yashar Akrami

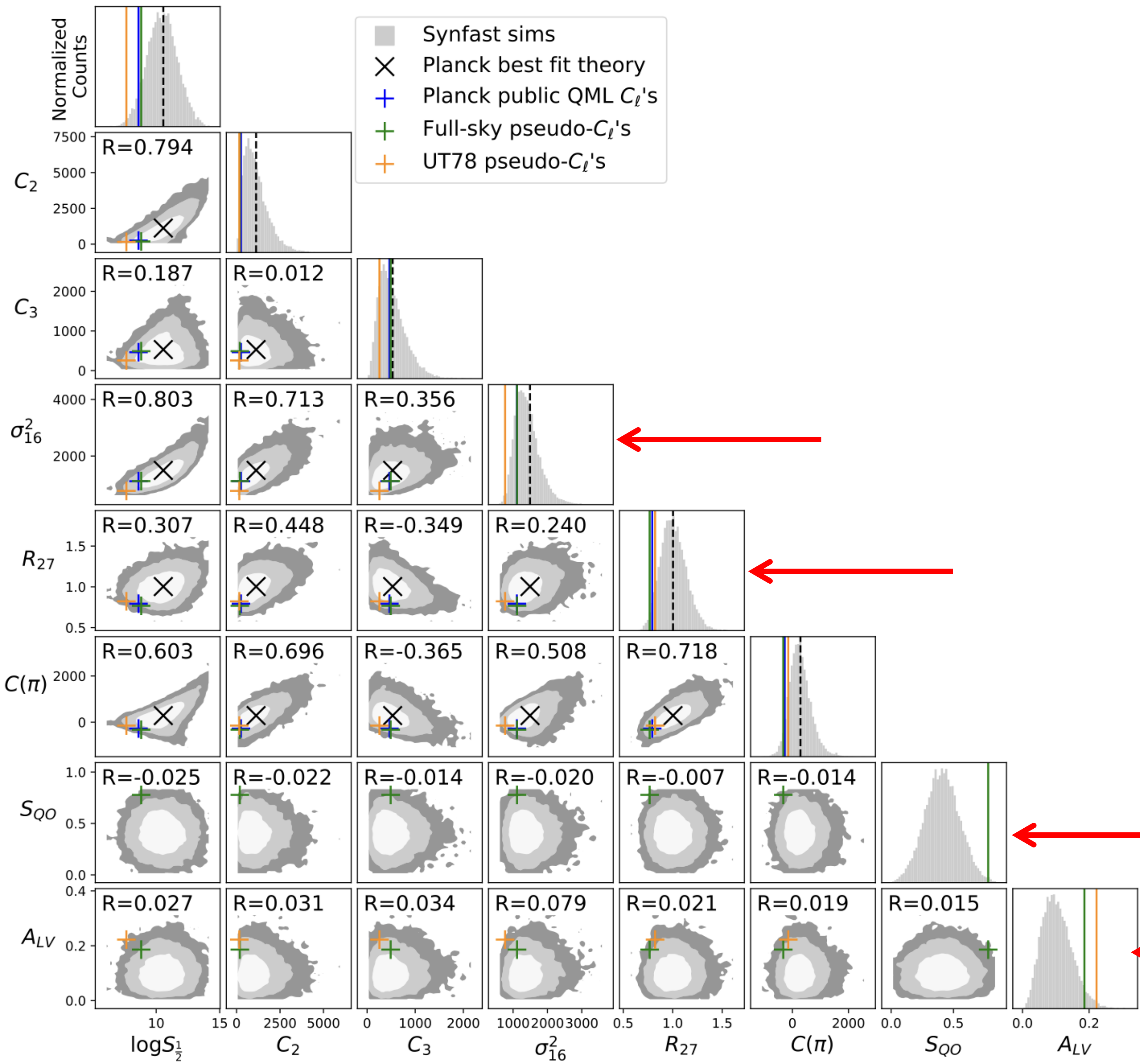
The standard cosmological model predicts statistically isotropic cosmic microwave background (CMB) fluctuations. However, several summary statistics of CMB isotropy have anomalous values, including: the low level of large-angle temperature correlations, $S_{1/2}$; the excess power in odd versus even low-ℓ multipoles, R^{TT}; the (low) variance of large-scale temperature anisotropies in the ecliptic north, but not the south, σ^2_{16}; and the alignment and planarity of the quadrupole and octopole of temperature, S_{QO}. Individually, their low p-values are weak evidence for violation of statistical isotropy. The correlations of the tail values of these statistics have not to this point been studied. We show that the joint probability of all four of these happening by chance in ΛCDM is likely $\leq 3 \times 10^{-8}$. This constitutes more than 5σ evidence for violation of statistical isotropy.

Four "representative" anomaly statistics:

- **$S_{1/2}$** – lack of large-angle correlations, $p \simeq 10^{-3}$
- **R_{TT}** – odd-parity preference, $p \simeq 0.01 - 0.05$
- $\boldsymbol{\sigma_{16}^2}$ – low northern variance, $p \simeq (2-4) \times 10^{-3}$
- **S_{QO}** – quadrupole-octupole alignment, $p \simeq 4 \times 10^{-(2-4)}$

in Planck 2018 Commander, NILC, SEVEM, SMICA

But are these statistics correlated in LCDM?



Muir, Adikhari, Huterer (PRD 98 (2018), 023521) :

$S_{1/2}$ & σ_{16}^2 are somewhat correlated

Others, not really

But are the anomalies (tails) correlated?

- 10^8 realizations of CMB in best fit LCDM

← pairwise correlations

Stat.	Value	$S_{1/2}$	R^{TT}	σ^2_{16}	S_{QO}
		Commander			
$S_{1/2}$	1272	1.5×10^{-3}	$\times 0.6$	$\times 27$	$\times 1.3$
R^{TT}	0.7896	2.8×10^{-5}	3.0×10^{-2}	$\times 1.1$	$\times 1.0$
σ^2_{16}	617.6	1.2×10^{-4}	1.0×10^{-4}	3.1×10^{-3}	$\times 1.7$
S_{QO}	0.7630	8.3×10^{-6}	1.3×10^{-4}	2.3×10^{-5}	4.4×10^{-3}
		NILC			
$S_{1/2}$	1218	1.3×10^{-3}	$\times 0.4$	$\times 29$	$\times 1.3$
R^{TT}	0.7448	4.8×10^{-6}	1.0×10^{-2}	$\times 1.0$	$\times 1.0$
σ^2_{16}	605.9	9.2×10^{-5}	2.4×10^{-5}	2.5×10^{-3}	$\times 1.9$
S_{QO}	0.8203	6.3×10^{-7}	3.8×10^{-6}	1.8×10^{-6}	3.9×10^{-4}
		SEVEM			
$S_{1/2}$	1215	1.3×10^{-3}	$\times 0.8$	$\times 33$	$\times 1.2$
R^{TT}	0.8194	5.6×10^{-5}	5.4×10^{-2}	$\times 1.2$	$\times 1.0$
σ^2_{16}	583.4	6.5×10^{-5}	1.0×10^{-4}	1.6×10^{-3}	$\times 1.5$
S_{QO}	0.6547	6.3×10^{-5}	2.2×10^{-3}	9.8×10^{-5}	4.1×10^{-2}
		SMICA			
$S_{1/2}$	1257	1.4×10^{-3}	$\times 0.6$	$\times 25$	$\times 1.3$
R^{TT}	0.7906	2.8×10^{-5}	3.0×10^{-2}	$\times 1.1$	$\times 1.0$
σ^2_{16}	631.0	1.4×10^{-4}	1.3×10^{-4}	3.9×10^{-3}	$\times 1.8$
S_{QO}	0.8048	1.7×10^{-6}	2.9×10^{-5}	6.6×10^{-6}	9.2×10^{-4}

triplet correlations ↓

	$S_{1/2}$ and σ^2_{16}	S_{QO}
	Commander	
$S_{1/2}$ and σ^2_{16}	1.2×10^{-4}	$\times 1.7$
S_{QO}	9.1×10^{-7}	4.4×10^{-3}
	NILC	
$S_{1/2}$ and σ^2_{16}	9.2×10^{-5}	$\times 0.6$
S_{QO}	2.0×10^{-8}	3.9×10^{-4}
	SEVEM	
$S_{1/2}$ and σ^2_{16}	6.5×10^{-5}	$\times 1.3$
S_{QO}	3.6×10^{-6}	4.1×10^{-2}
	SMICA	
$S_{1/2}$ and σ^2_{16}	1.4×10^{-4}	$\times 2.1$
S_{QO}	2.7×10^{-7}	9.2×10^{-4}

Are the anomalies correlated in LCDM?

Map	p_4	Correlation Factor
Commander	3×10^{-8}	51
NILC	$< 1 \times 10^{-8}$	N/A
SEVEM	18×10^{-8}	40
SMICA	1×10^{-8}	64

Answer: only weakly

Conclusion:

Statistical isotropy is falsified at $>5\sigma$ in CMB TT correlations!

The Universe is not Statistically Isotropic

Conversation points:

1. You can't believe data without a model;
i.e., you can't falsify a model without an alternative

2. Look elsewhere penalties
i.e., you can always find anomalous statistics

The Universe is NOT Statistically Isotropic

The End?

Making Progress

1. Find a fundamental physics model, make testable predictions.

2. Make reasonable phenomenological extrapolations and test them.

3. Continue to test the “fluke hypothesis.”

   i.e. test LCDM!

Testing the fluke hypothesis

Philosophy: assume LCDM is correct, predict how measured anomalies affect predictions for other observables, test them.

Note:
this is a fundamentally frequentist approach.

Phenomenological extrapolations

Philosophy:

1. Assume statistical isotropy is violated, identify generic predictions

2. Assume each anomaly is “physical” and guess what that implies for other observables

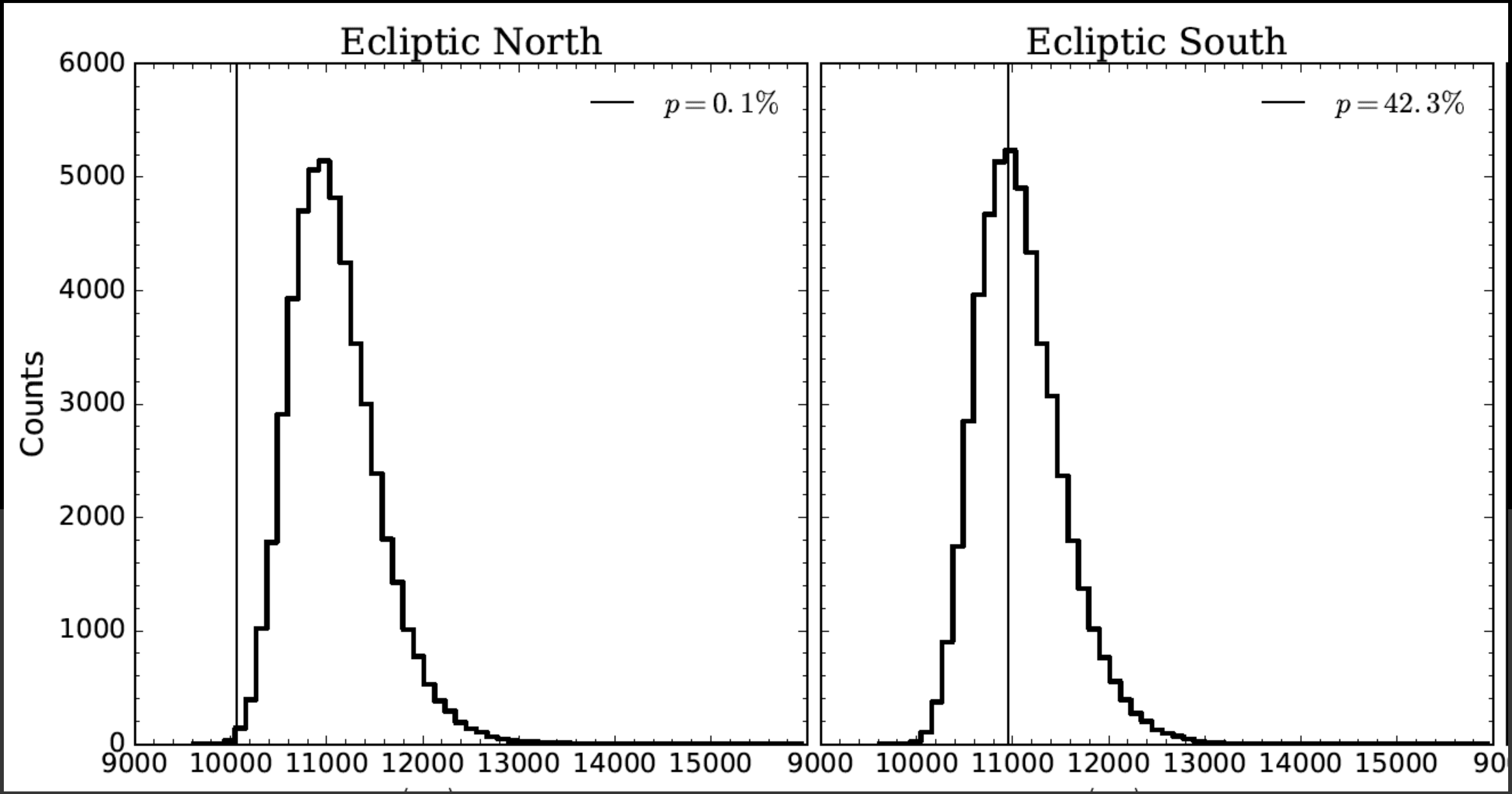
Testing the fluke hypothesis

Phenomenological extrapolations

go hand in hand

Example 1: Low N variance in E

Low N variance in T



Phenomenological guess

Low variance in T
over a large region of the sky

$$\Downarrow$$

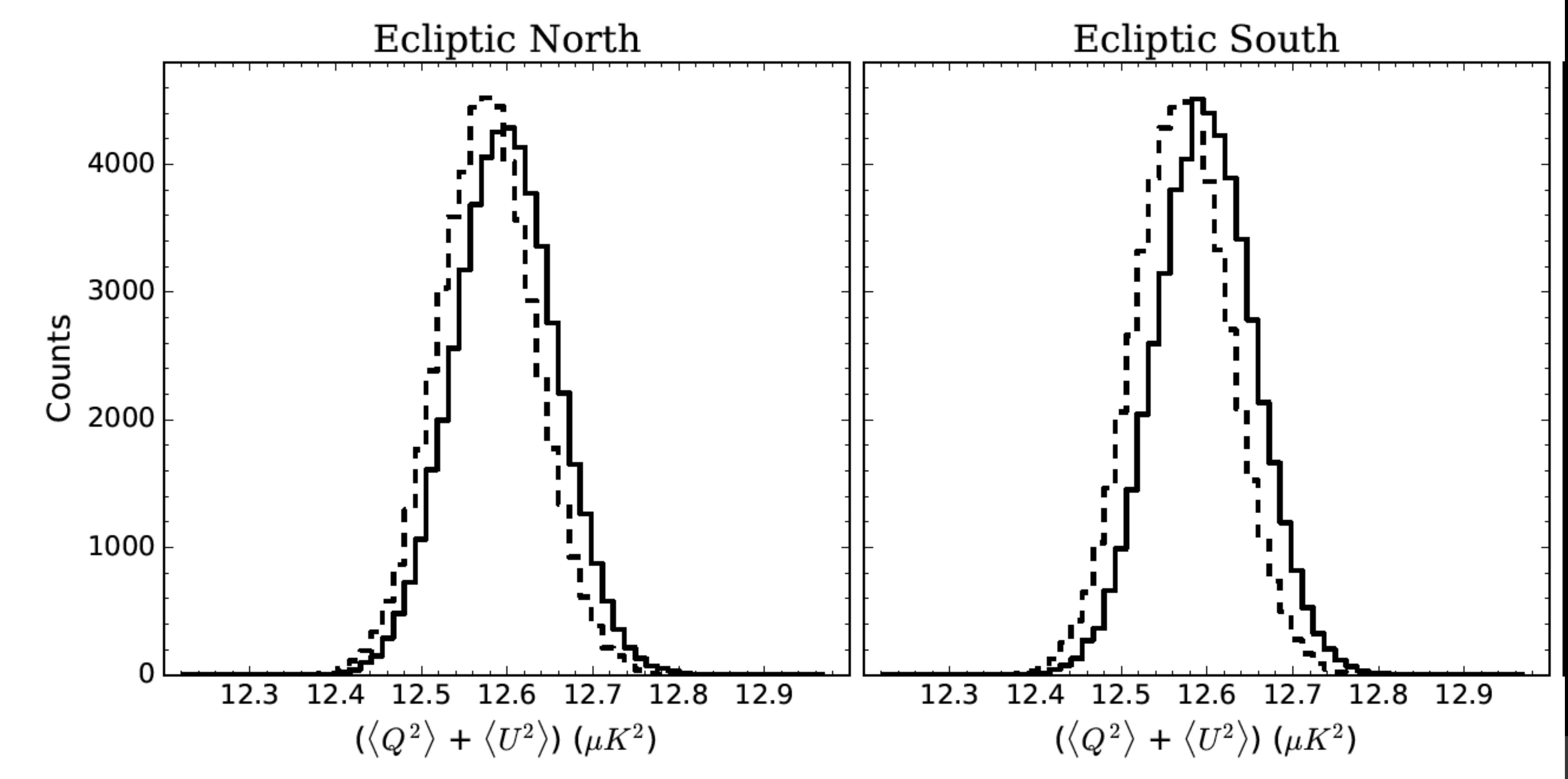
Low variance in underlying curvature fluctuations

$$\Downarrow$$

low variance in E-mode polarization
in that same region

What does LCDM say?

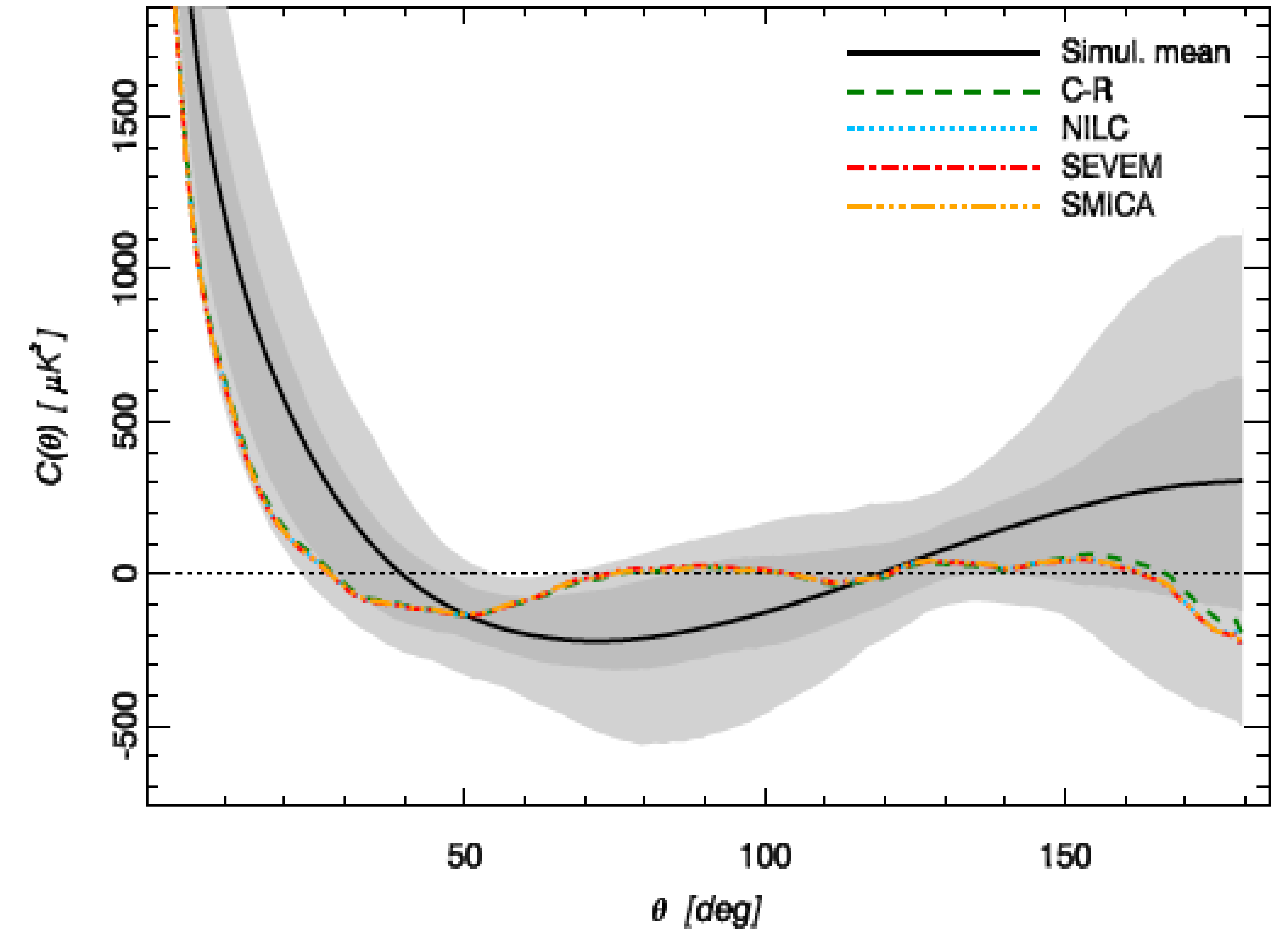
After all, T-E are correlated!



Observe:

- a small reduction in the polarization variance
- approximately equal in N and S

Example 2: Absence of angular correlation in Q,U,E


Simul. mean
C-R
NILC
SEVEM
SMICA
1500
1000
500
0
-500
$C(\theta)$ [μK^2]
50
100
150
θ [deg]

Phenomenological guess

Low correlation in T

$$\Downarrow$$

Low correlation in curvature fluctuations

$$\Downarrow$$

low correlation in Q,U,E polarization

Constrained-LCDM QQ and UU correlations

A. Yoho, A. Aiola, C. Copi, A. Kosowsky, GDS (PRD91 (2015) 12, 123504)

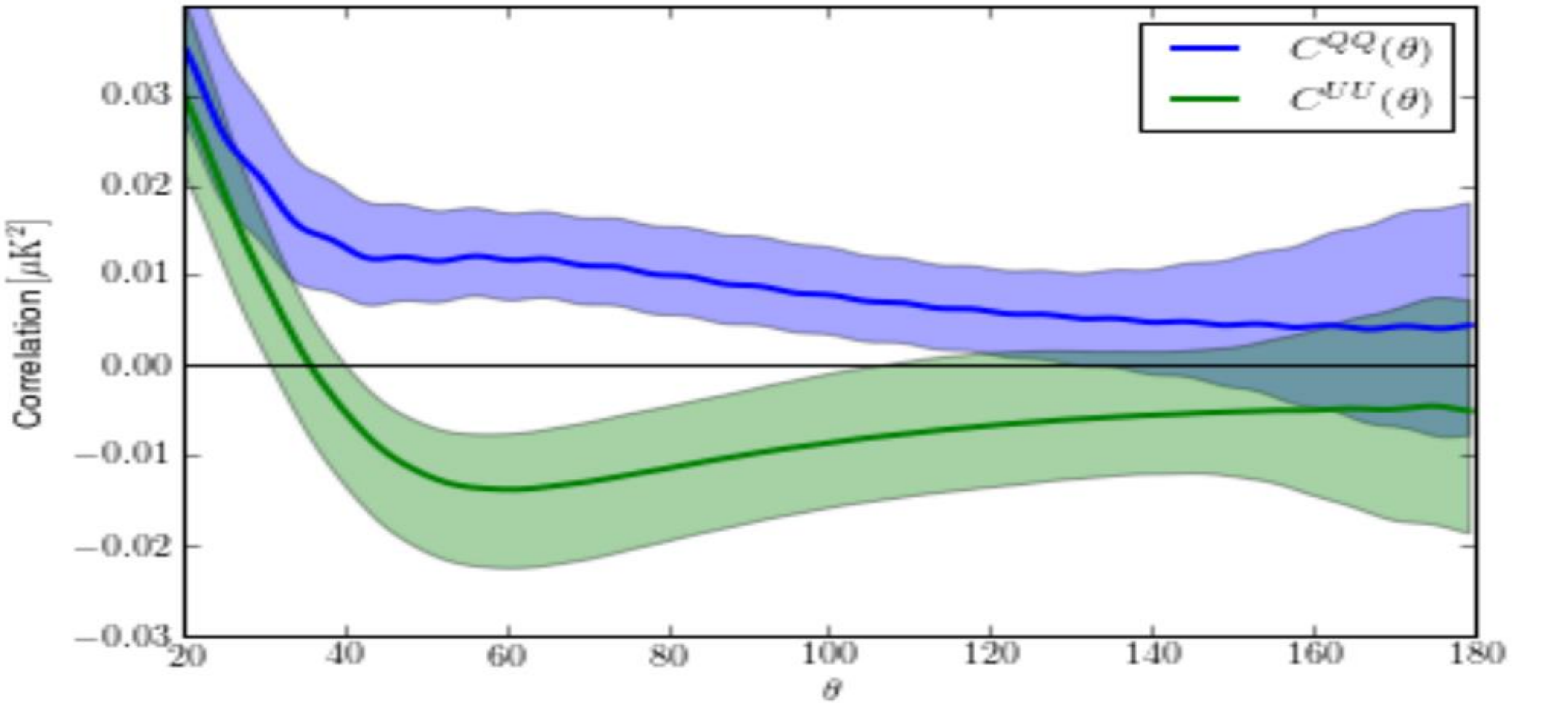


FIG. 5: Angular correlation function of Q and U polarizations with $r = 0.1$. The shaded regions correspond to the 68% C.L. errors. The ranges include instrumental noise for a future generation PIXIE-like experiment and cosmic variance.

Constrained-LCDM EE correlations

A. Yoho, A. Aiola, C. Copi, A. Kosowsky, GDS (PRD91 (2015) 12, 123504)

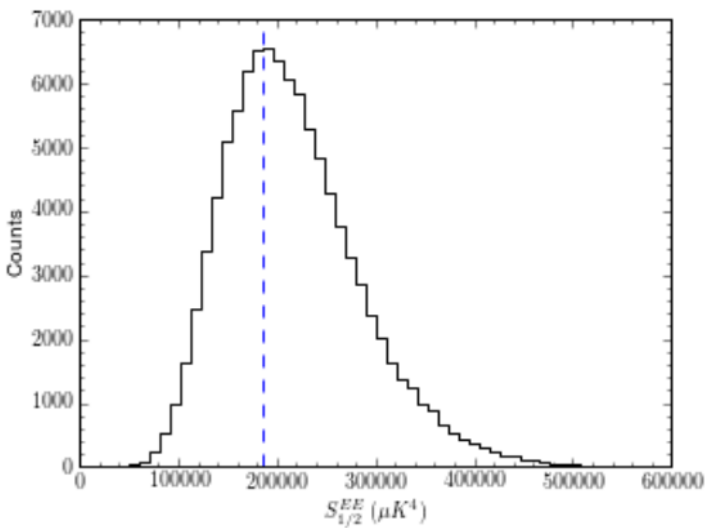
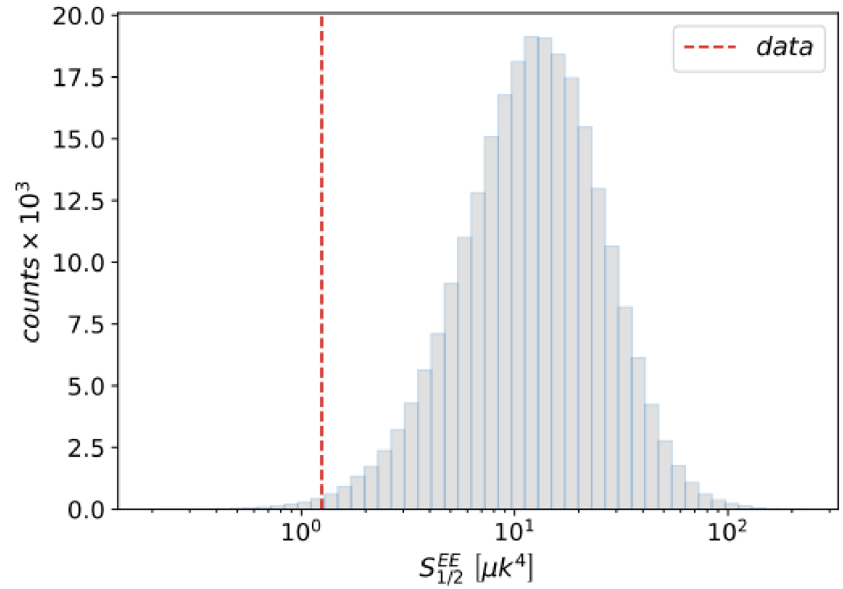


FIG. 3: $S_{1/2}$ statistic distribution for the angular correlation function of E-modes $r = 0.1$ with $\sigma_{\rm beam} = 2.7°$ radian smoothing. The blue dashed line marks the ΛCDM prediction for the ensemble average.



$S_{1/2}$ statistic for the angular correlation function of E-modes in Planck 2018 HFI 100

Lack-of-correlation anomaly in CMB large scale polarisation maps, C.Chiocchetta, A. Gruppuso, M.Lattanzi, P. Natoli, L. Pagano arXiv:2012.00024

Consequence 1

A broken symmetry offers no protection

Statistical isotropy

- Forbids off–diagonal TT, EE, BB correlations:

$$\langle a^{X}_{\ell m} a^{X*}_{\ell' m'} \rangle = C^{X}_{\ell} \delta_{\ell\ell'} \delta_{mm'}$$, X=T,E,B

- Forbids TB, EB correlations:

$$\langle a^{X}_{\ell m} a^{B*}_{\ell' m'} \rangle = 0$$, X=T,E

Common misconception:

this is due to parity invariance

Statistical anisotropy $\Longrightarrow$

General Correlation matrix

$$\langle a^{X}_{\ell m} a^{Y*}_{\ell' m'} \rangle = C^{XY}_{\ell m \ell' m'}$$

- Some terms require parity violation
- Statistical anisotropy tied to statistical inhomogeneity
- Statistical inhomogeneity $\Longrightarrow$ parity violation
- the anomalies are parity violating

COMPACT: A. Samandar *et al. (2407.09400)*

Consequence 2

Anisotropy is not non-Gaussianity

Violation of SI does not imply (or preclude) NG;

but it may make it much harder to measure

NG statistical tests (often?) assume SI

$$\hat{f}_{\rm NL} = \frac{1}{N}\sum_{X_i,X_i'}\sum_{\ell_i,m_i}\sum_{\ell_i',m_i'} \mathcal{G}^{\ell_1\,\ell_2\,\ell_3}_{m_1m_2m_3}\, b^{X_1X_2X_3,\,\rm th}_{\ell_1\ell_2\ell_3}\Big\{\Big[\big(\mathsf{C}^{-1}_{\ell_1m_1,\ell_1'm_1'}\big)^{X_1X_1'} a^{X_1'}_{\ell_1'm_1'} \times \big(\mathsf{C}^{-1}_{\ell_2m_2,\ell_2'm_2'}\big)^{X_2X_2'} a^{X_2'}_{\ell_2'm_2'}\big(\mathsf{C}^{-1}_{\ell_3m_3,\ell_3'm_3'}\big)^{X_3X_3'} a^{X_3'}_{\ell_3'm_3'}\Big] - \Big[\big(\mathsf{C}^{-1}_{\ell_1m_1,\ell_2m_2}\big)^{X_1X_2}\big(\mathsf{C}^{-1}_{\ell_3m_3,\ell_3'm_3'}\big)^{X_3X_3'} a^{X_3'}_{\ell_3'm_3'} + \text{cyclic}\Big]\Big\}, \quad (25)$$

Optimal estimator given SI

$$\hat{f}_{\rm NL} = \frac{1}{N}\sum_{X_i,X_i'}\sum_{\ell_i,m_i} \mathcal{G}^{\ell_1\,\ell_2\,\ell_3}_{m_1m_2m_3}(\mathsf{C}^{-1})^{X_1X_1'}_{\ell_1}(\mathsf{C}^{-1})^{X_2X_2'}_{\ell_2}(\mathsf{C}^{-1})^{X_3X_3'}_{\ell_3}\, b^{X_1X_2X_3,\,\rm th}_{\ell_1\ell_2\ell_3} \times \Big[a^{X_1'}_{\ell_1m_1} a^{X_2'}_{\ell_2m_2} a^{X_3'}_{\ell_3m_3} - \mathsf{C}^{X_1'X_2'}_{\ell_1m_1,\ell_2m_2} a^{X_3'}_{\ell_3m_3} - \mathsf{C}^{X_1'X_3'}_{\ell_1m_1,\ell_3m_3} a^{X_2'}_{\ell_2m_2} - \mathsf{C}^{X_2'X_3'}_{\ell_2m_2,\ell_3m_3} a^{X_1'}_{\ell_1m_1}\Big]. \quad (27)$$

diagonal covariance approximation, given SI

From Planck 2018 IX Constraints on PNG

Violation of SI affects the bispectrum/f_{NL}, and σ_{fNL}

$$< a^X_{\ell m} a^Y_{\ell' m'} a^Z_{\ell'' m''} > \neq \mathcal{G}^{\ell\ell'\ell''}_{mm'm''} b^{XYZ}_{\ell\ell'\ell''}$$

Q: how would we even estimate f_{NL}?!

$$< a_{\ell m} a_{\ell' m'} a_{\ell'' m''} > \neq 0$$

implies NG distribution for $a_{\ell m}$

but how do you construct a summary statistic

and an estimator if

$$< a_{\ell m} a^*_{\ell' m'} > \neq C_\ell \delta_{\ell\ell'} \delta_{mm'} ?$$

And if $< a\ a\ a\ a\ a\ a > \neq < a\ a\ a\ a\ a\ a >_{\mathrm{SI}}$?

Nearly all NG statistical results assume SI

NG is not just about the bispectrum —
e.g. features in the tail of the distribution of … $a_{\ell m}$?

But the tails of what distribution if not SI?

What if $a_{\ell m} = 0$ for certain m? and $a_{\ell m} = a_{\ell m'}$ for other m?

New Models

New Models

List of new fundamental physics models known to explain all/most/several anomalies:

Requirements:

- Break statistical isotropy
- Affect scales that were causally disconnected until recently

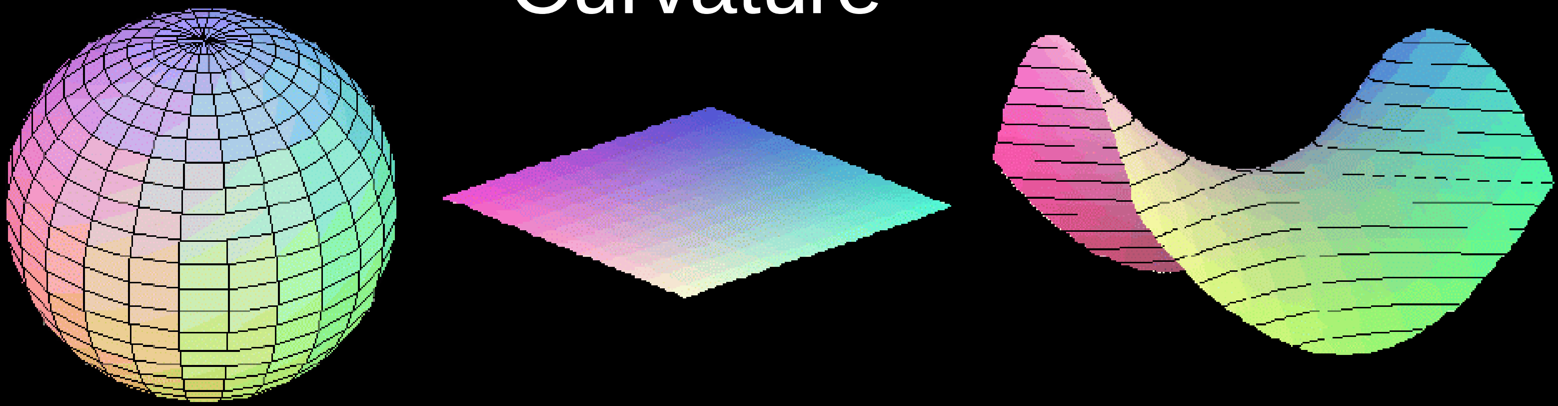
New Models

Fundamental physics phenomena that break isotropy and are already in our theory:

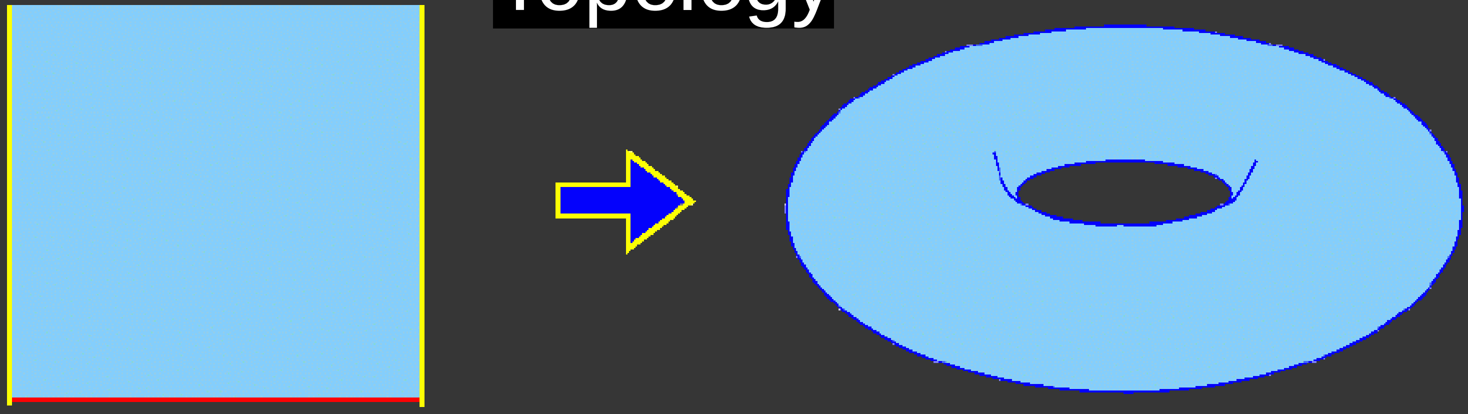
Non-trivial cosmic topology

Cosmic Geometry

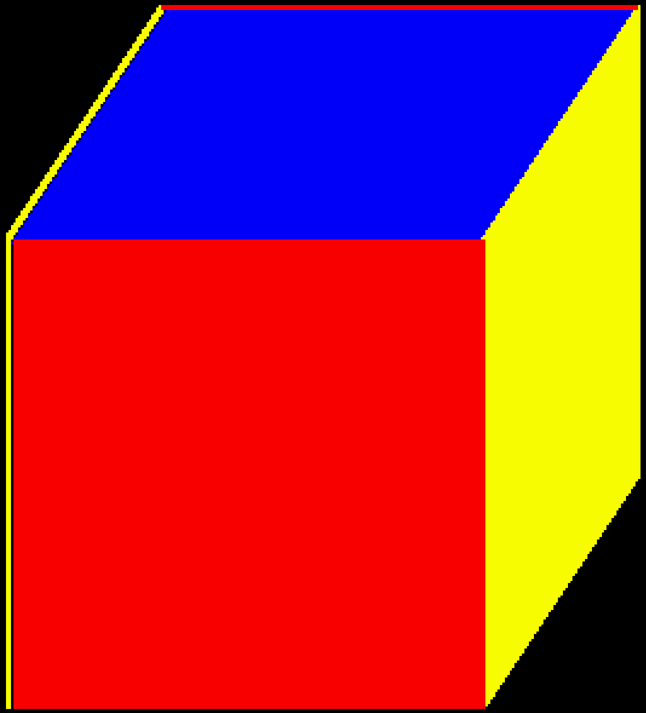
Curvature

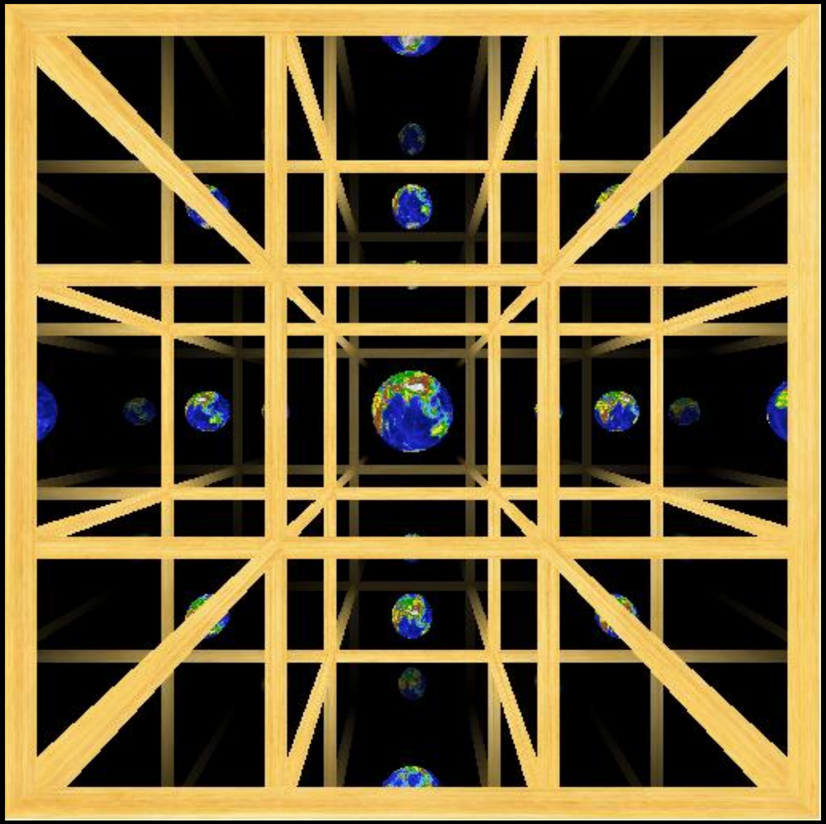


Topology



Three Torus

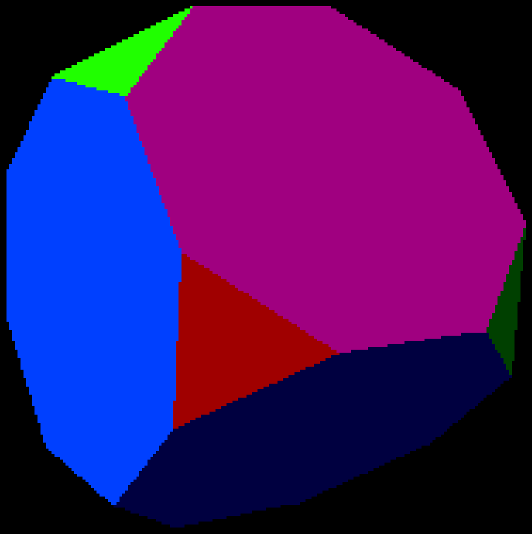


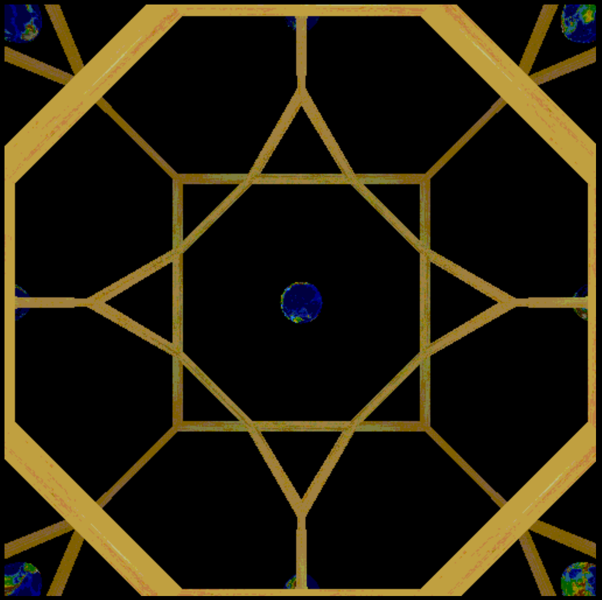


Same idea works in three space dimensions

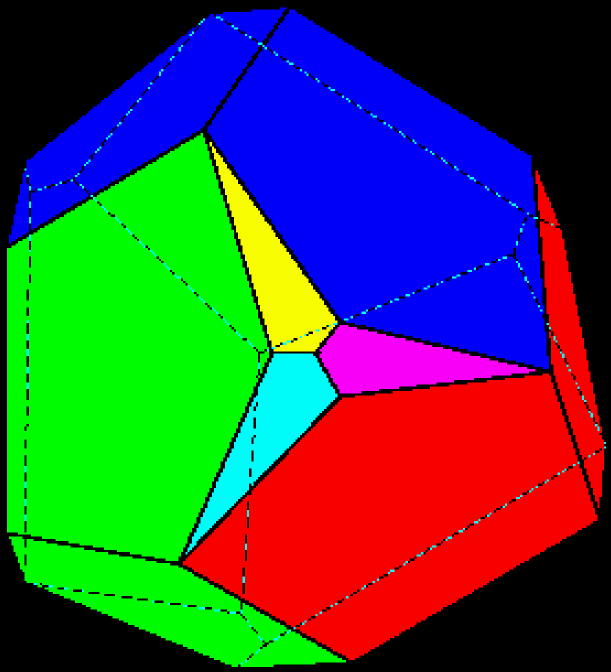
Spherical Topologies

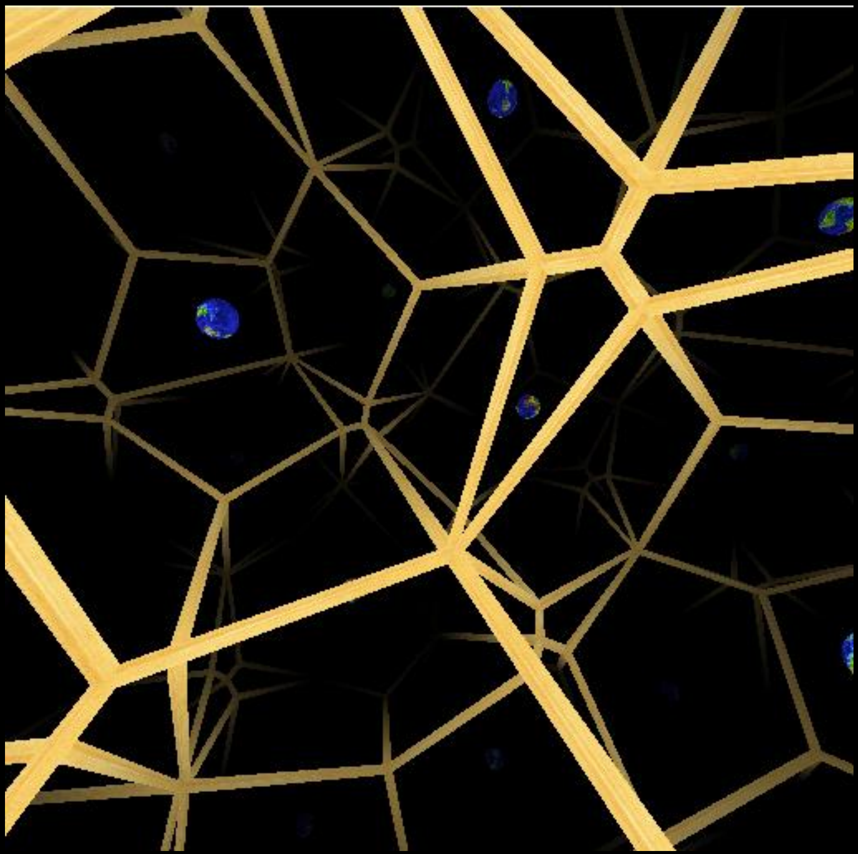
This example only works in spherical space





Infinite number of tiling patterns





This one only works in hyperbolic space

arXiv > astro-ph > arXiv:2210.11426

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 20 Oct 2022 (v1), last revised 5 Mar 2024 (this version, v3)]

The Promise of Future Searches for Cosmic Topology

Yashar Akrami, Stefano Anselmi, Craig J. Copi, Johannes R. Eskilt, Andrew H. Jaffe, Arthur Kosowsky, Pip Petersen, Glenn D. Starkman, Kevin González-Quesada, Özenç Güngör, Deyan P. Mihaylov, Samanta Saha, Andrius Tamosiunas, Quinn Taylor, Valeri Vardanyan (COMPACT Collaboration)

The shortest distance around the Universe through us is unlikely to be much larger than the horizon diameter if microwave background anomalies are due to cosmic topology. We show that observational constraints from the lack of matched temperature circles in the microwave background leave many possibilities for such topologies. We evaluate the detectability of microwave background multipole correlations for sample cases. Searches for topology signatures in observational data over the large space of possible topologies pose a formidable computational challenge.

PRL 132 (2024) 17

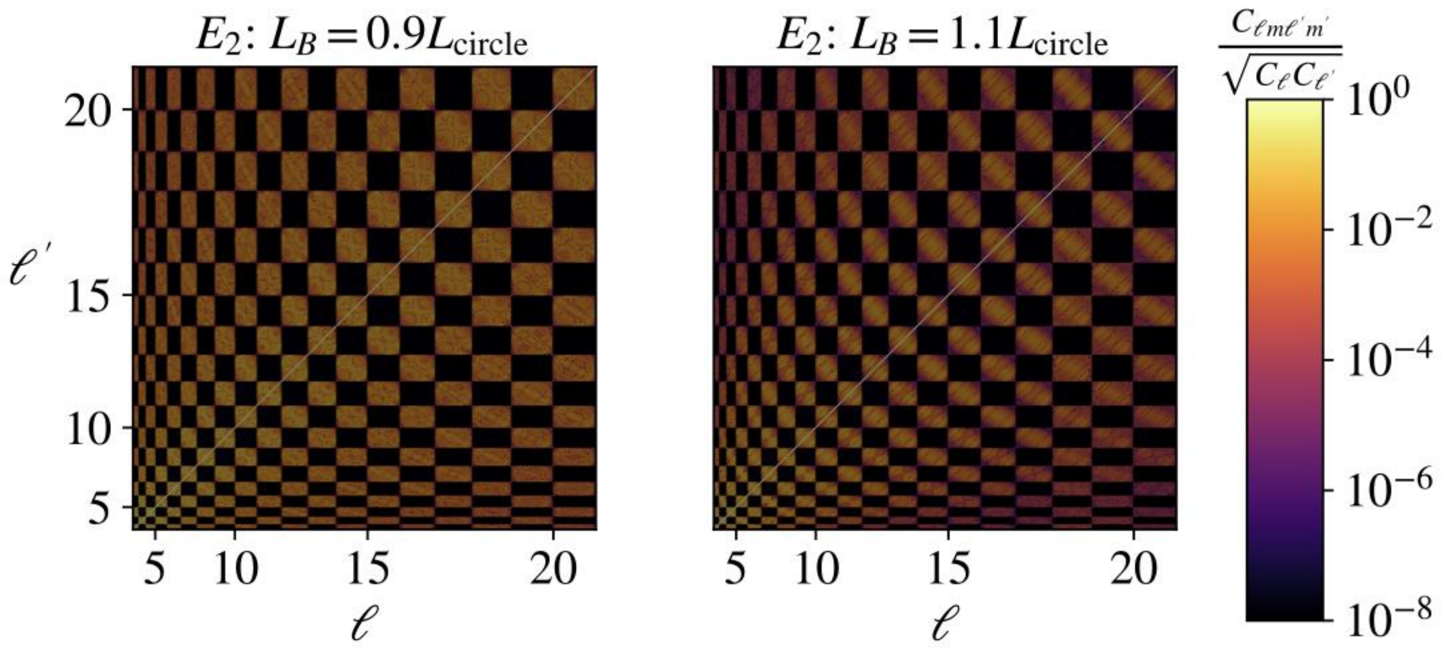


FIG. 1. Portions of rescaled CMB temperature correlation matrices for a half-turn space (E_2). L_{circle} is the length scale below which matched circles would be detected; $L_B = \{0.9, 1.1\}L_{\text{circle}}$ is the length along the corkscrew axis; $L_A = 1.4L_{\text{LSS}}$ is the other topological length scale. The observer is off-axis at $x_0 = (0.35, 0, 0)L_{\text{LSS}}$

SUMMARY

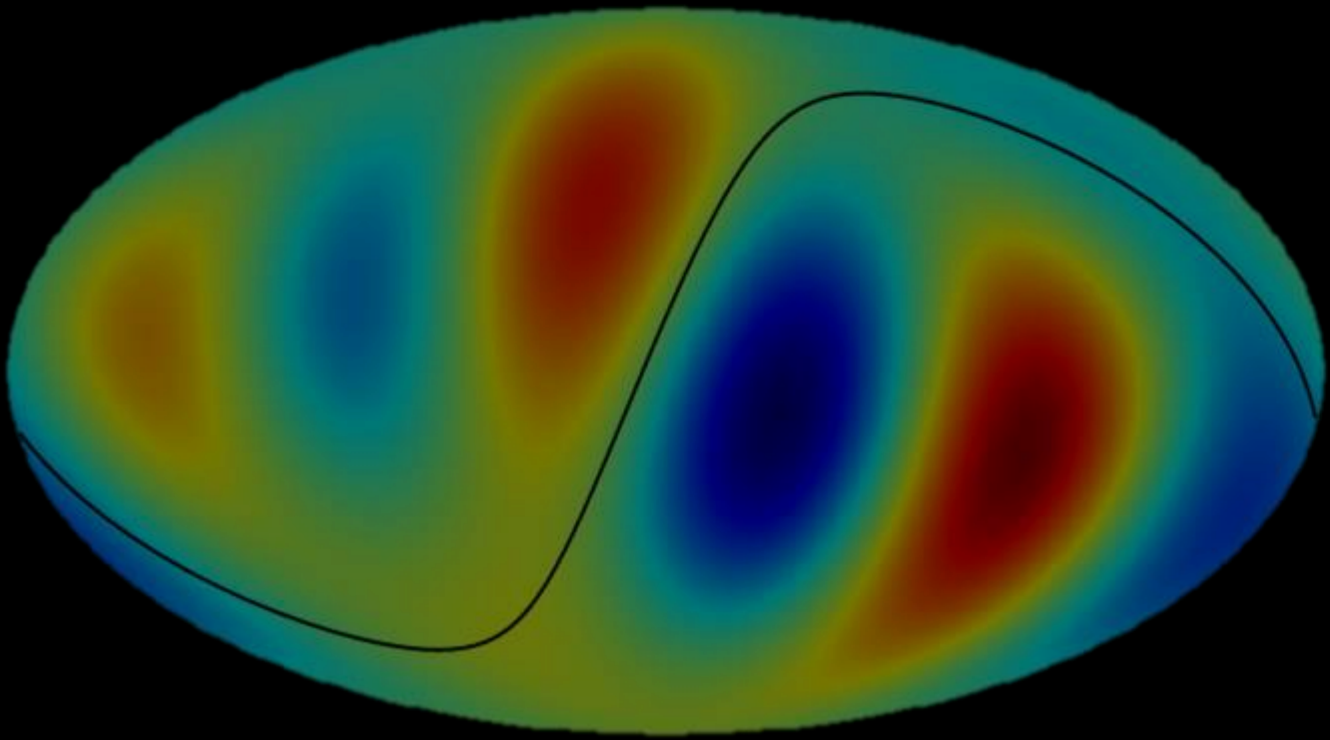
The CMB is NOT the realization of a Gaussian random statistically isotropic field.

The Universe is NOT Statistically Isotropic

No proven “model” so far:

- ~~Systematics~~
- ~~Foregrounds~~
- Cosmology – topology?

The cosmic orchestra may be playing a LCDM symphony,
But somebody gave the bass and tuba the wrong score.
They tried hard to keep it quiet. They failed.



We must find an explanation