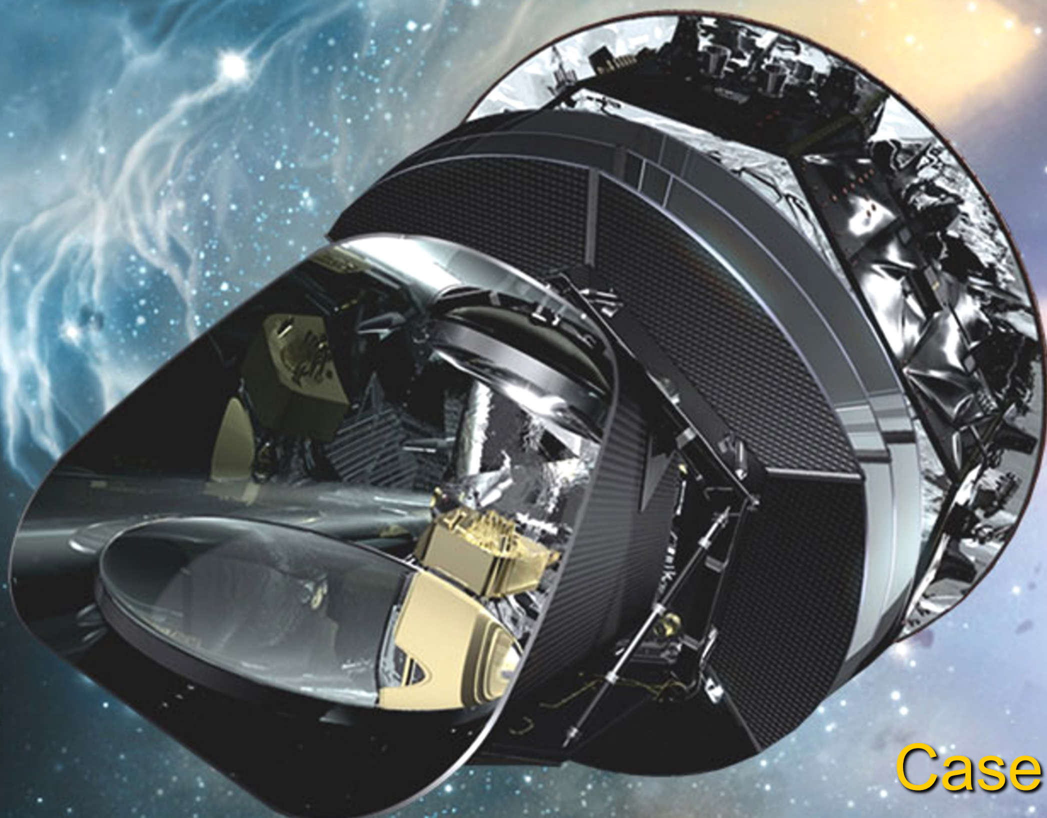
Our Anisotropic Universe



Glenn Starkman
Case Western Reserve University
IFT Madrid Sept 2022

Image: ESA/AOES Medialab

Our Anisotropic Universe

Yashar Akrami, Craig Copi,

Ozenc Gungor, Andrew Jaffe, Arthur Kosowsky, **Johannes Oskilt, Lucas Makinen, Pip Petersen, Samanta Saha, Quinn Taylor, Valeri Vardanyan**

Dragan Huterer & Dominik Schwarz

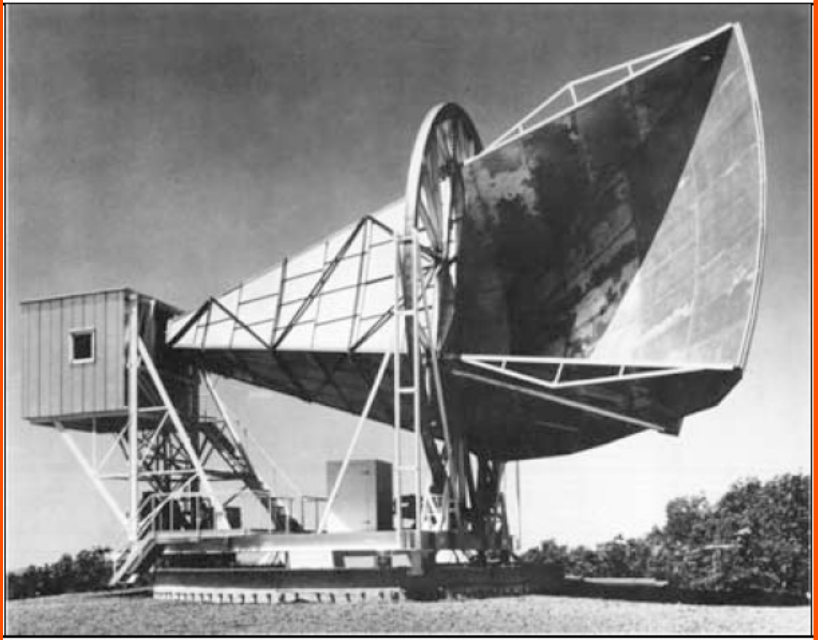
Francesc Ferrer, Amanda Yoho, Simone Aiola, Lloyd Knox, Marcio O’Dwyer

Image: NASA/WMAP

This is not the universe you think it is

This is not the universe you were told it should be

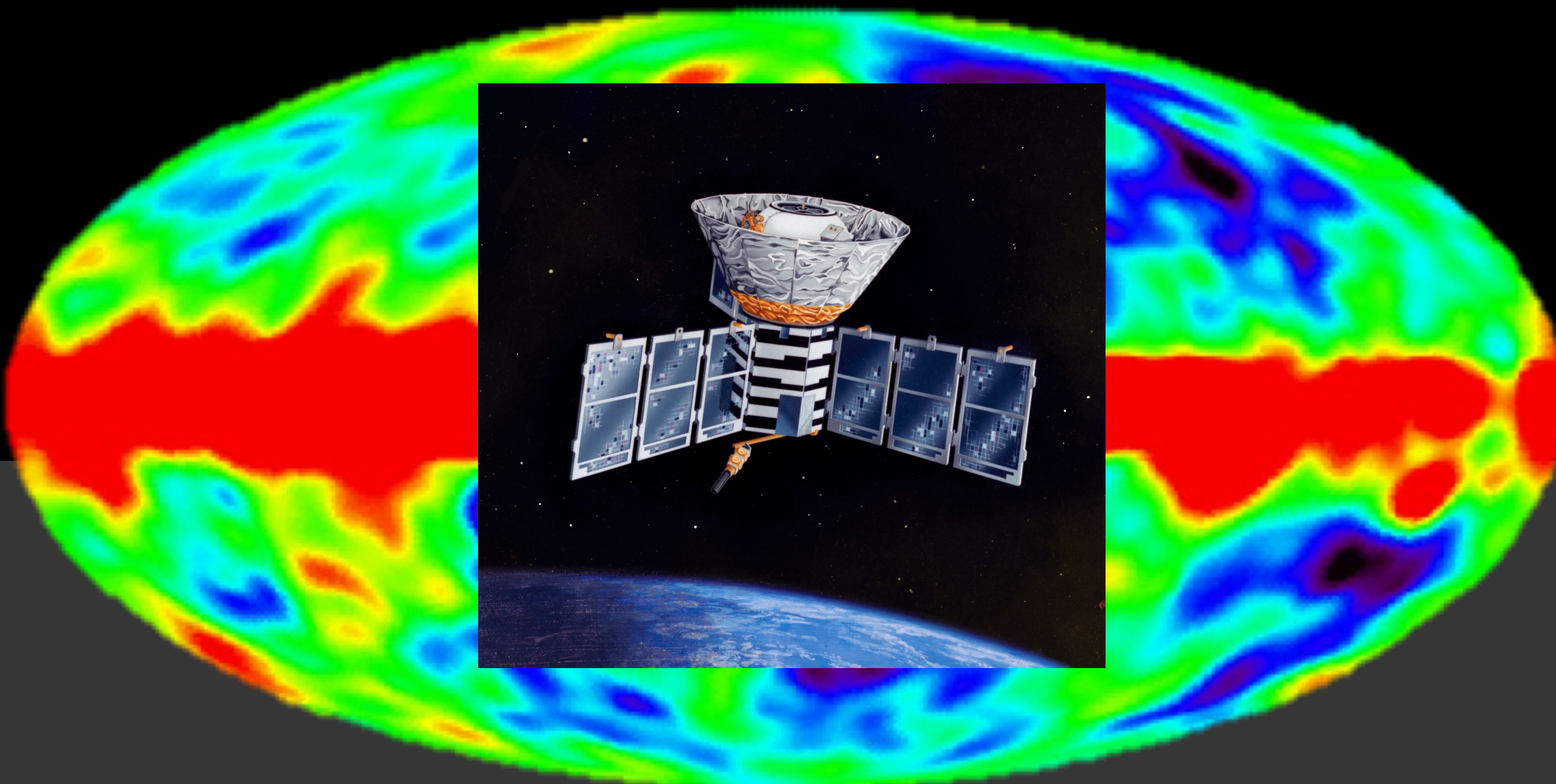
Penzias & Wilson (1965)



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

T=2.728K

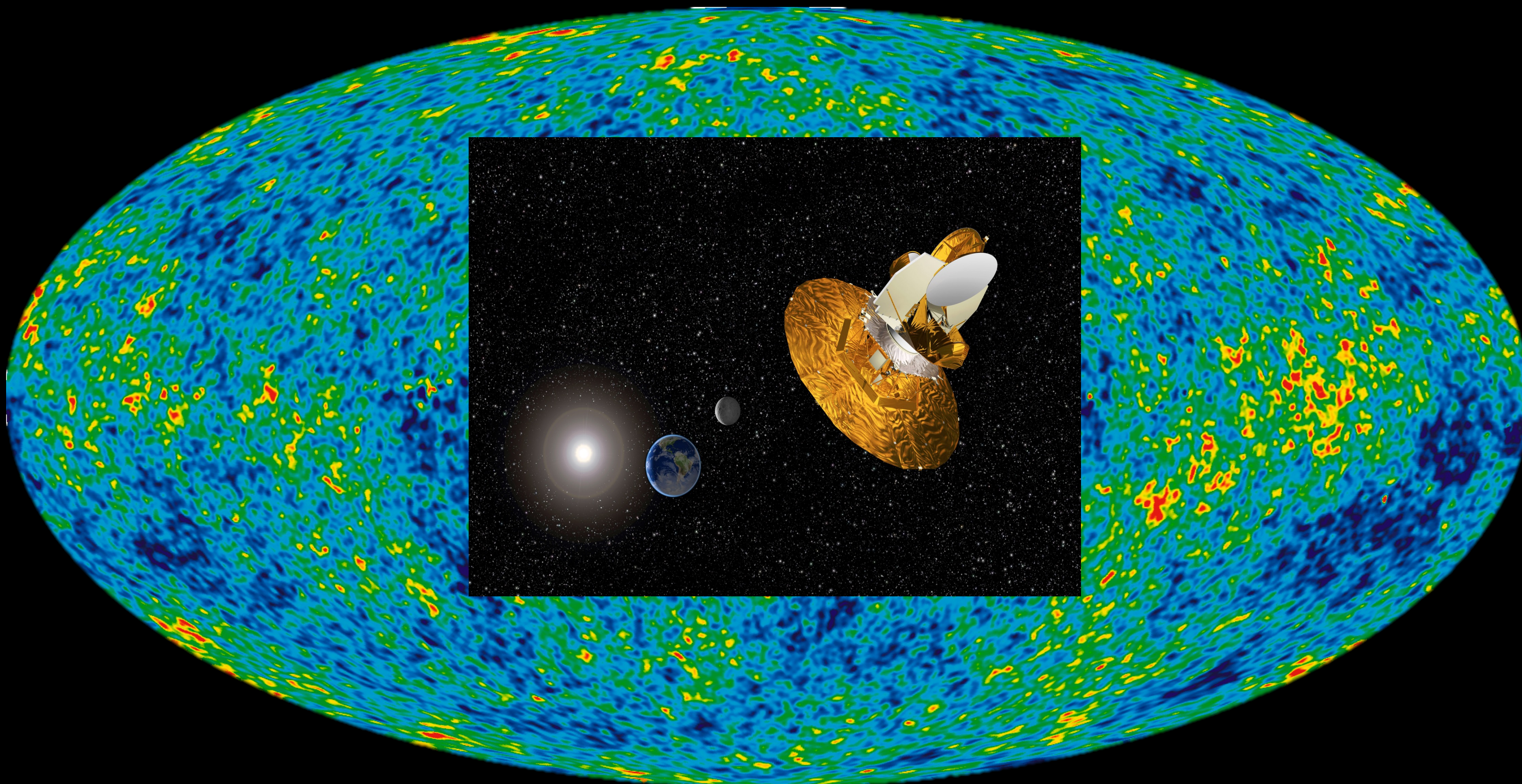
COBE - DMR



NASA/COBE-DMR science team

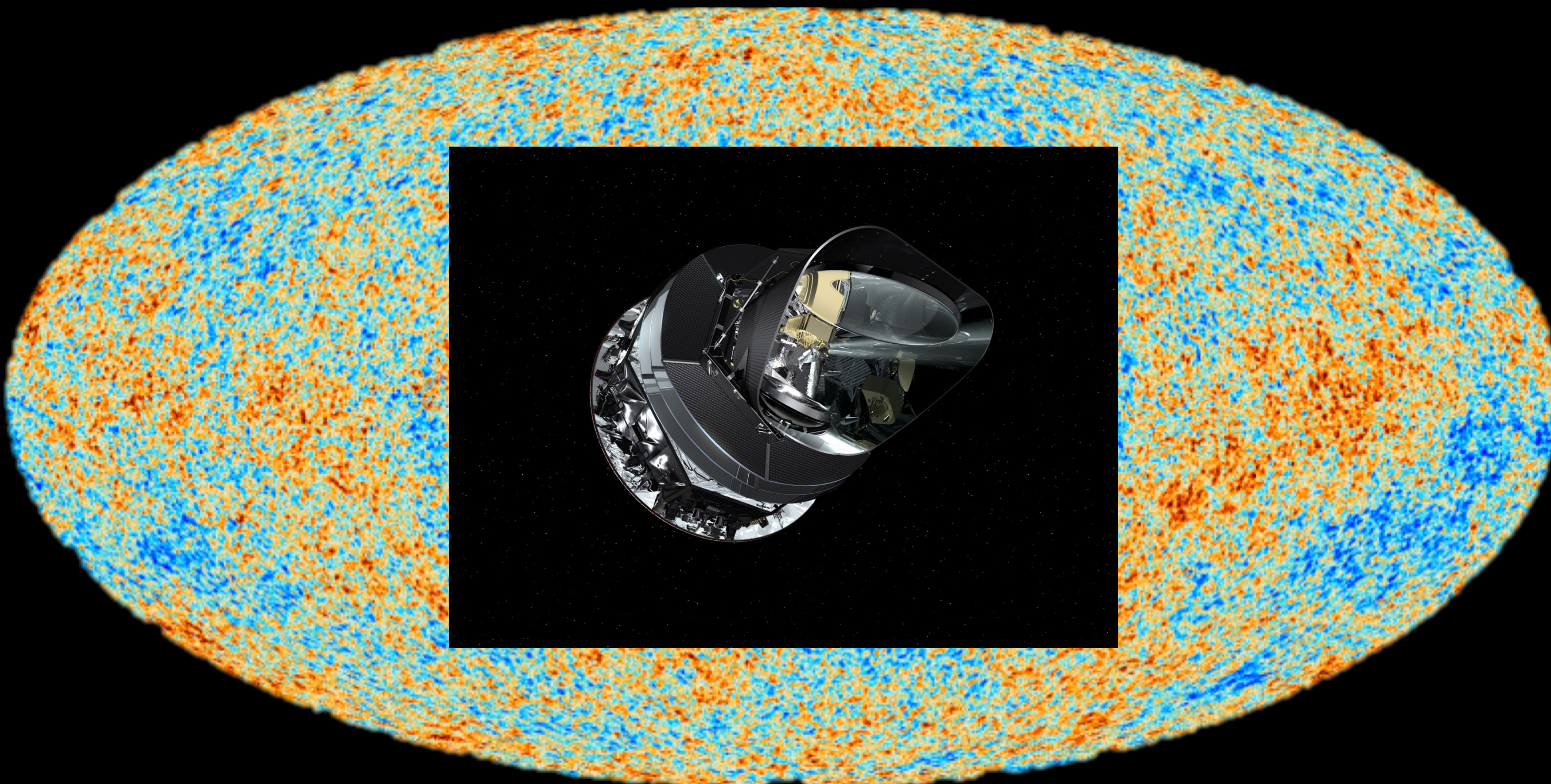
$T=18\mu K$

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):

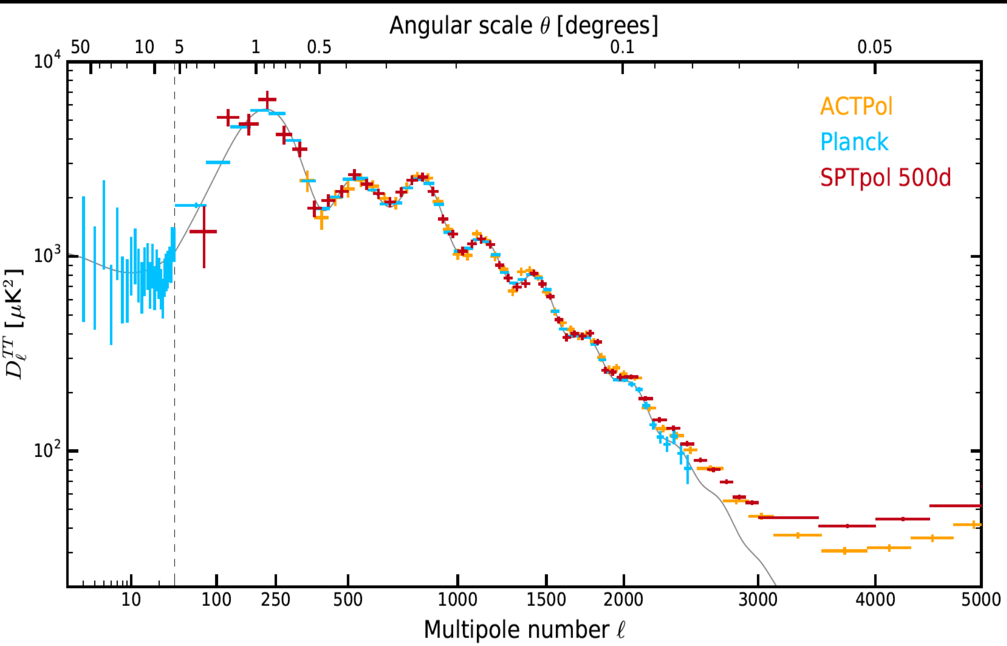
- Sky is statistically isotropic
- $a_{\ell m}$ -- independent (nearly) Gaussian random

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

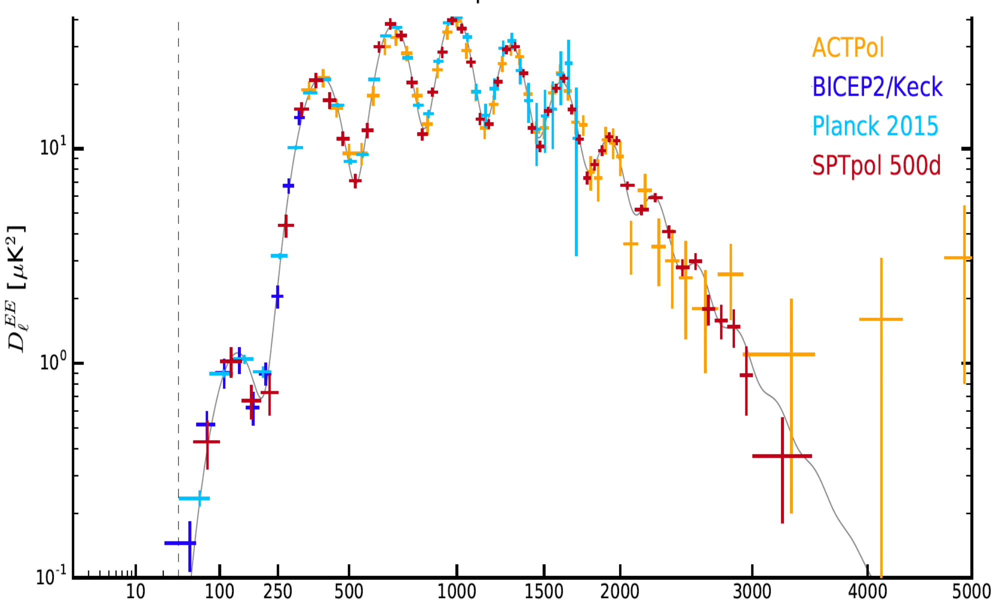
(Almost) ALL interesting information is in:

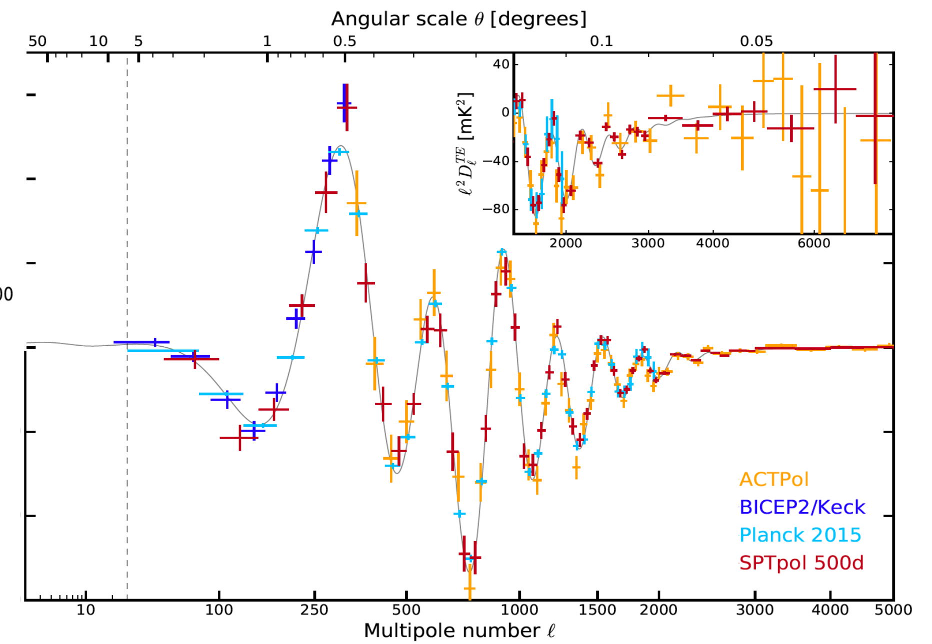
$$C_\ell = (2\ell + 1)^{-1} \sum_m |a_{\ell m}|^2$$

Angular Power Spectrum



7 parameter fit to >>7 points





SPTPol arXiv:1707.09353

- **Astonishing** experimental accomplishment
- **Remarkable** agreement with theory

especially for statistics the theory prefers

BUT !

is

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

Standard model for the fluctuations (inflation):

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

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

Shouldn't we check?

If not…

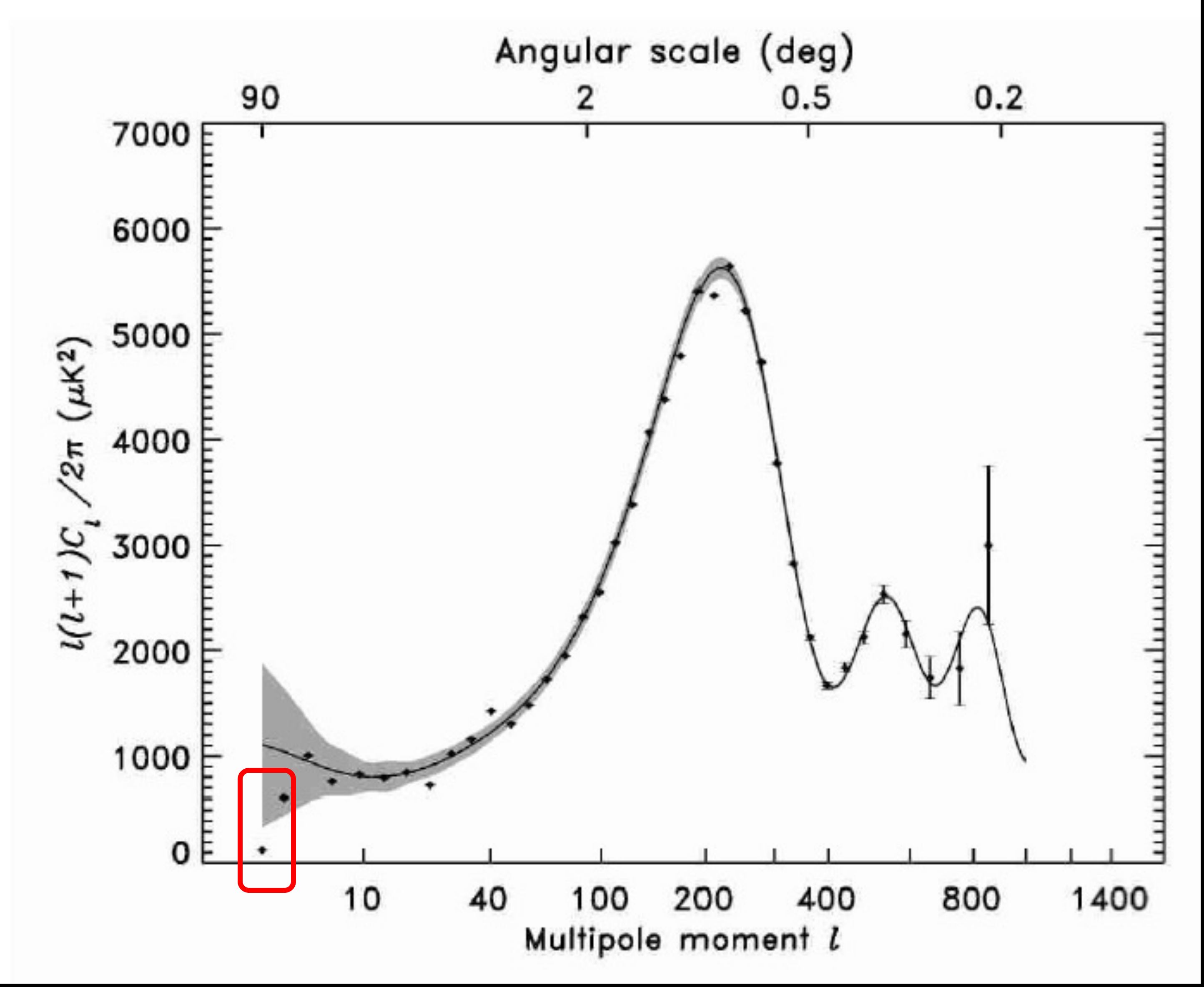
then how is the information on PNG to be extracted ?

$$< a_{\ell m} a^*_{\ell' m'} > = ?$$

$$< a_{\ell m} a_{\ell' m'} a_{\ell'' m''} > = ?$$

$$< a_{\ell m} a_{\ell' m'} a_{\ell'' m''} a_{\ell''' m'''} > = ?$$

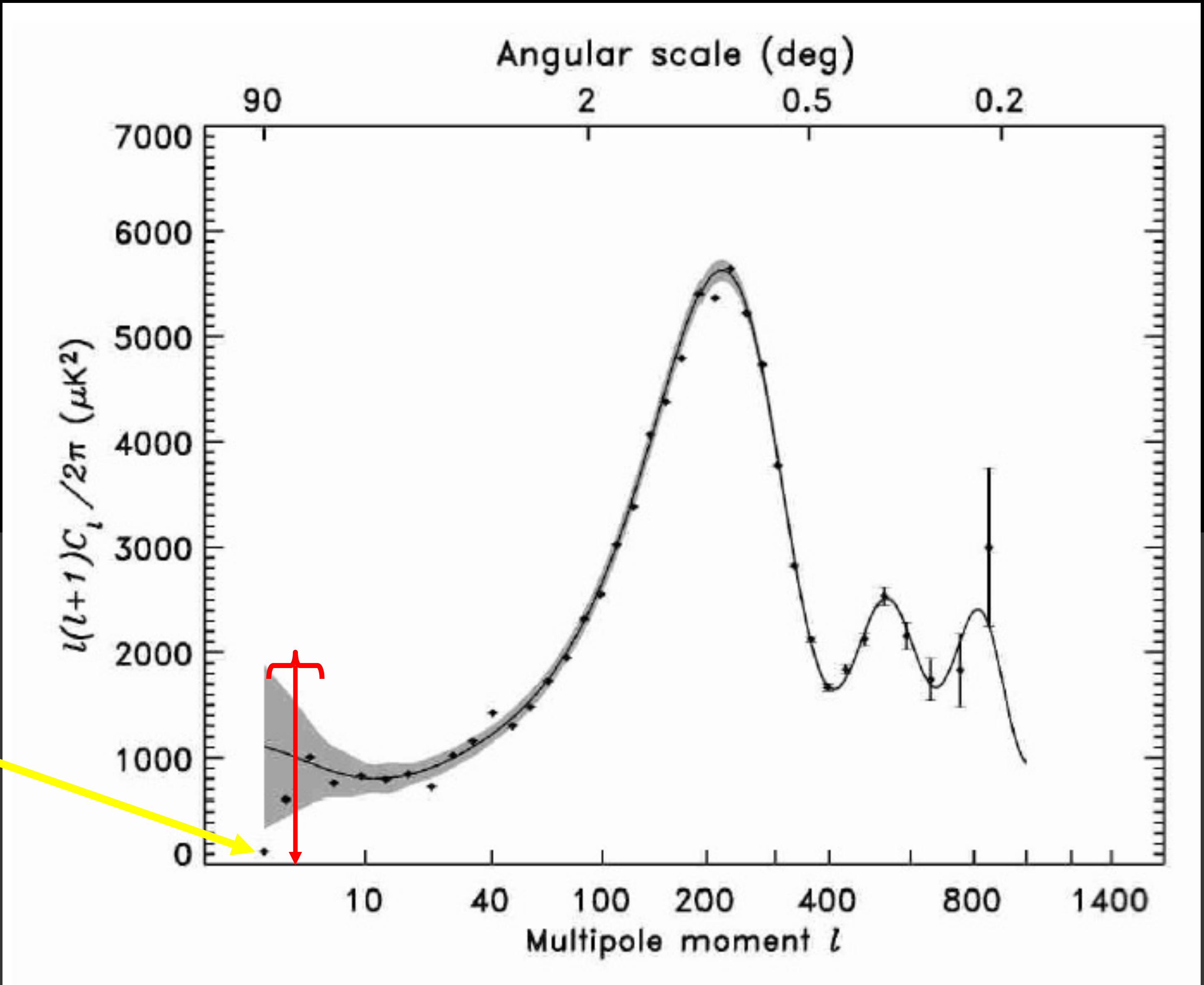
The first hint: “The Low-*l* Anomaly”



NASA WMAP Science Team
WMAP 1

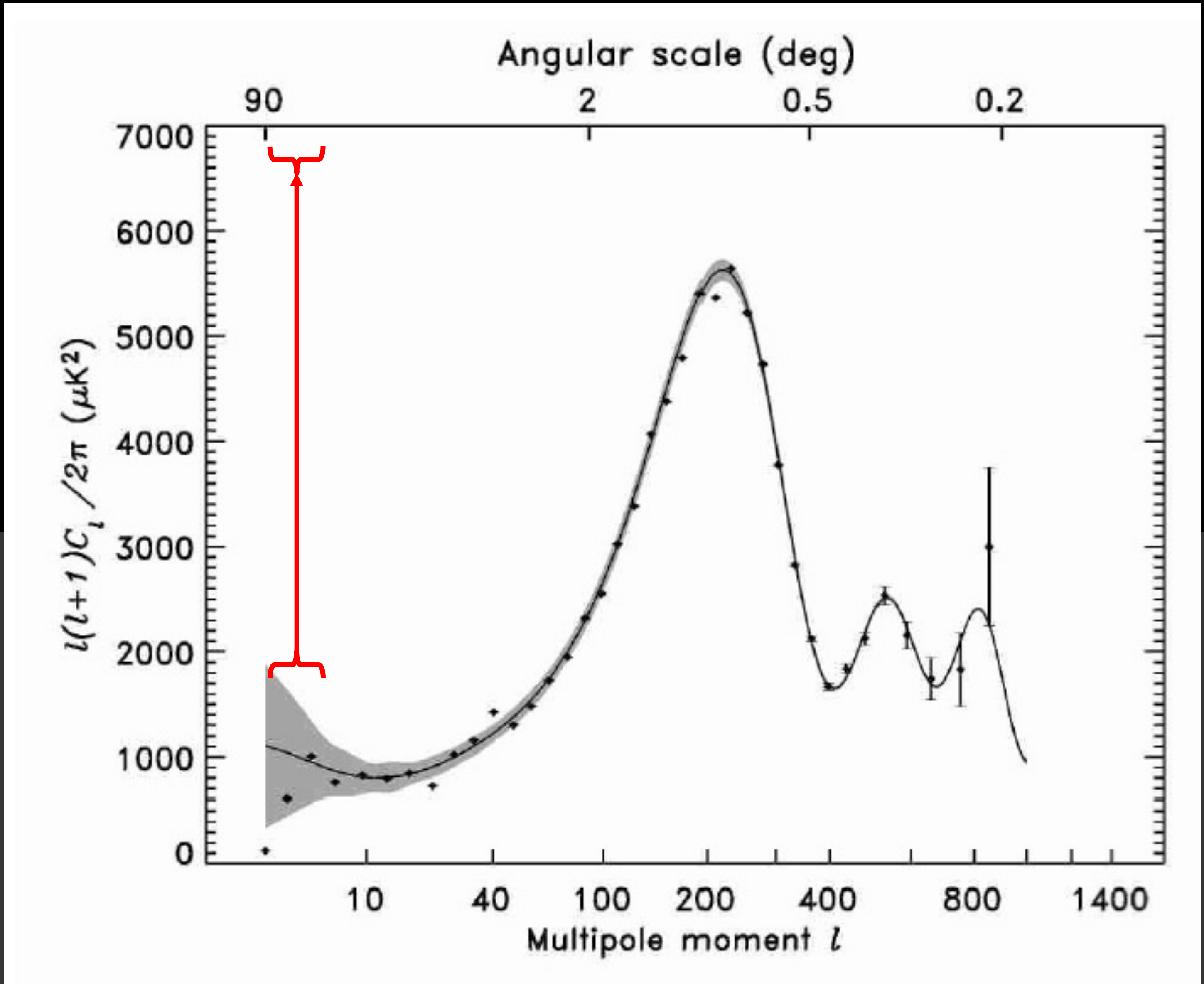
The uncorrelation …

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

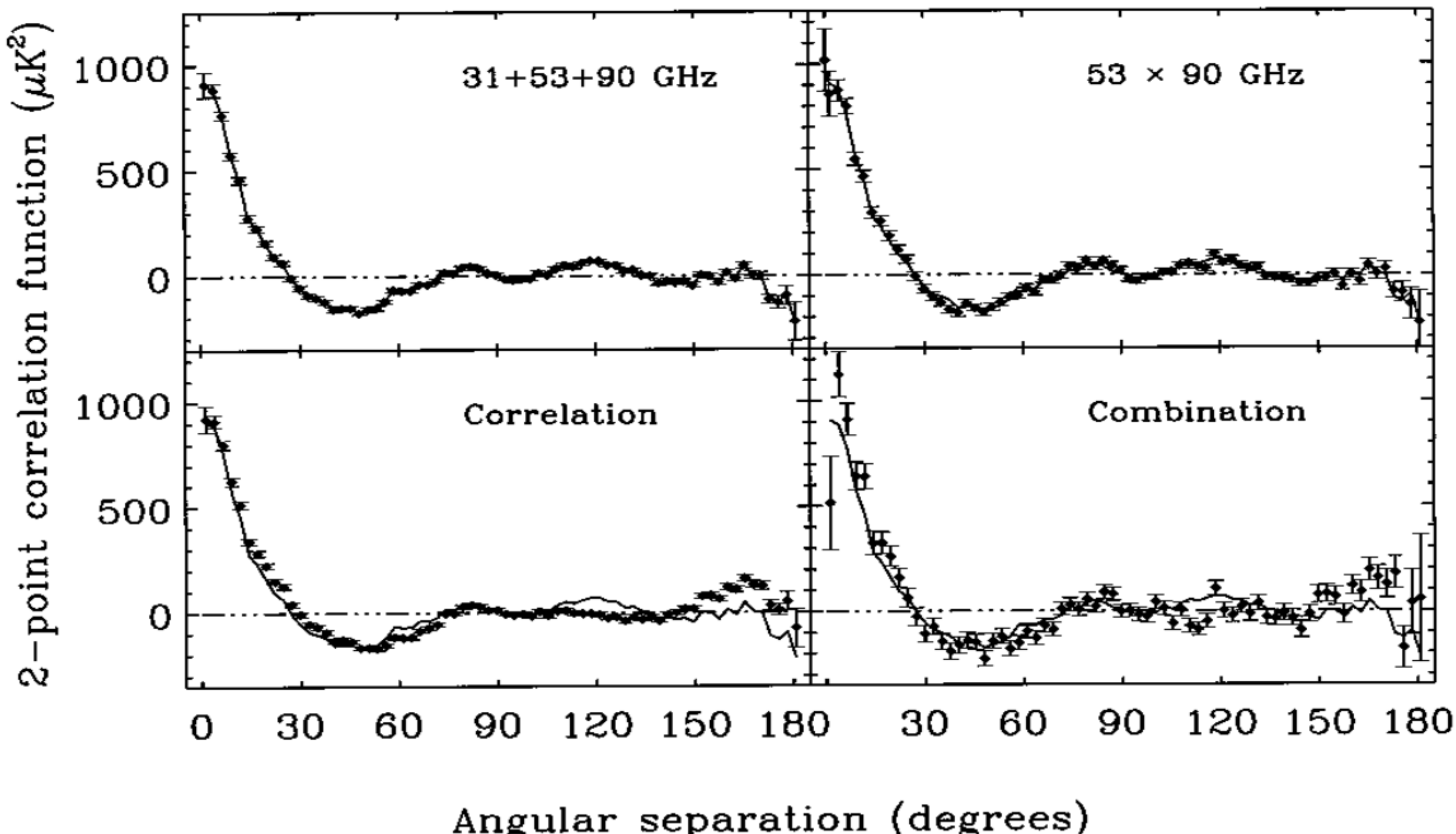
$\Rightarrow$ Same information as C_l, just differently organized

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



An Infrared Cutoff Revealed by the Two Years of COBE Observations of Cosmic Temperature Fluctuations

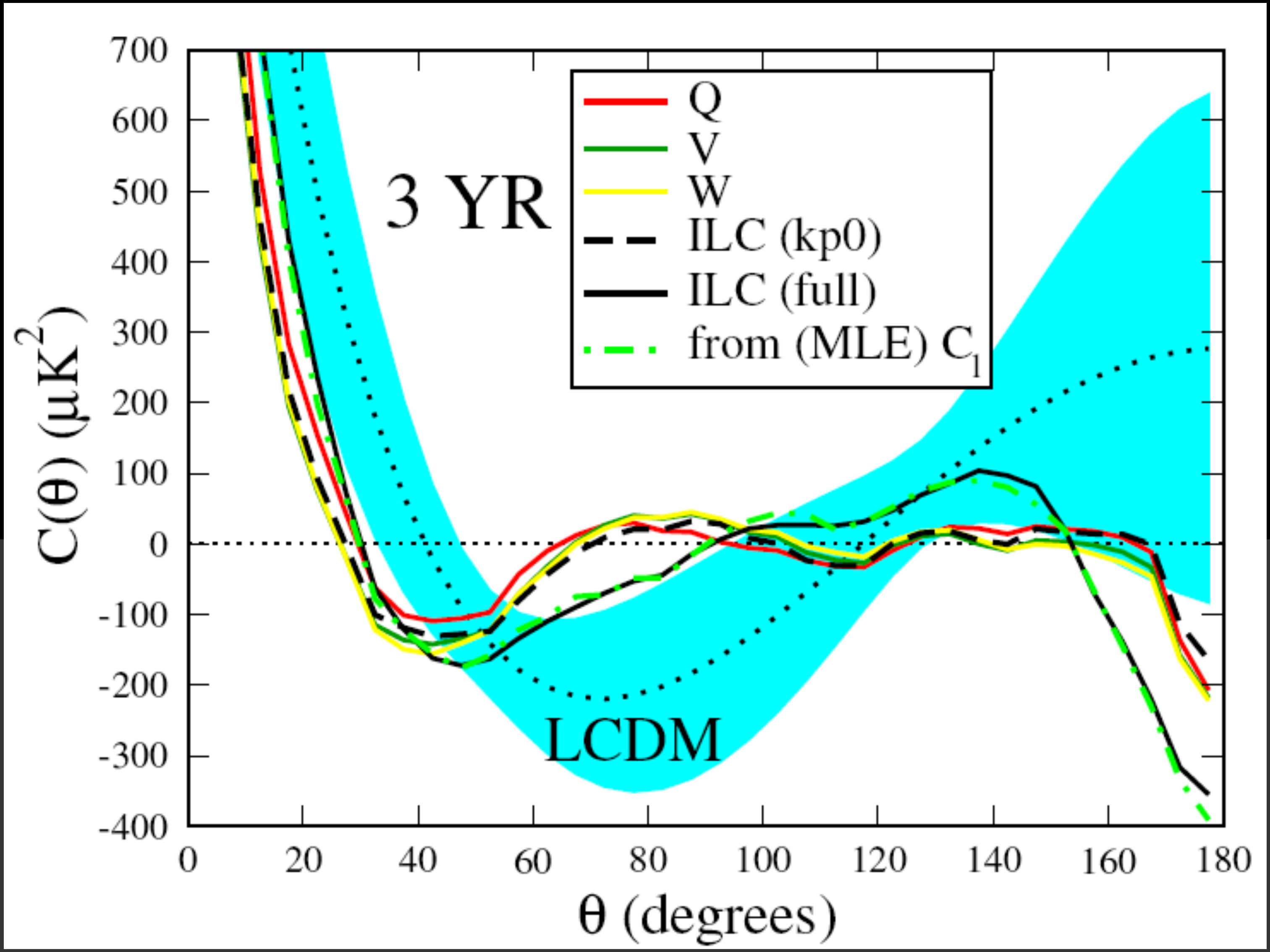
Yi-Peng Jing and Li-Zhi Fang
Phys. Rev. Lett. **73**, 1882 – Published 3 October 1994

ABSTRACT

We show that a good fitting to the first two years of observations by the Cosmic Background Explorer Differential Microwave Radiometers of the two-point angular correlation function of cosmic background radiation (CBR) temperature is given by models with a nonzero infrared cutoff $k_{\min}$ in the spectrum of the primordial density perturbations. If this cutoff comes from the finiteness of the universe, say, a topological T3 model, we find $k_{\min} \sim \left(0.3 - 1.1\right)\pi \frac{H_0}{c}$ with confidence level 95%. Such a nonzero $k_{\min}$ universe would also give a better match to the observations both of the rms quadrupole anisotropy of CBR and of galaxy clustering.

Received 25 March 1994

Two-point angular correlation function



Is the Large-Angle Anomaly Significant?

One measure (WMAP1):

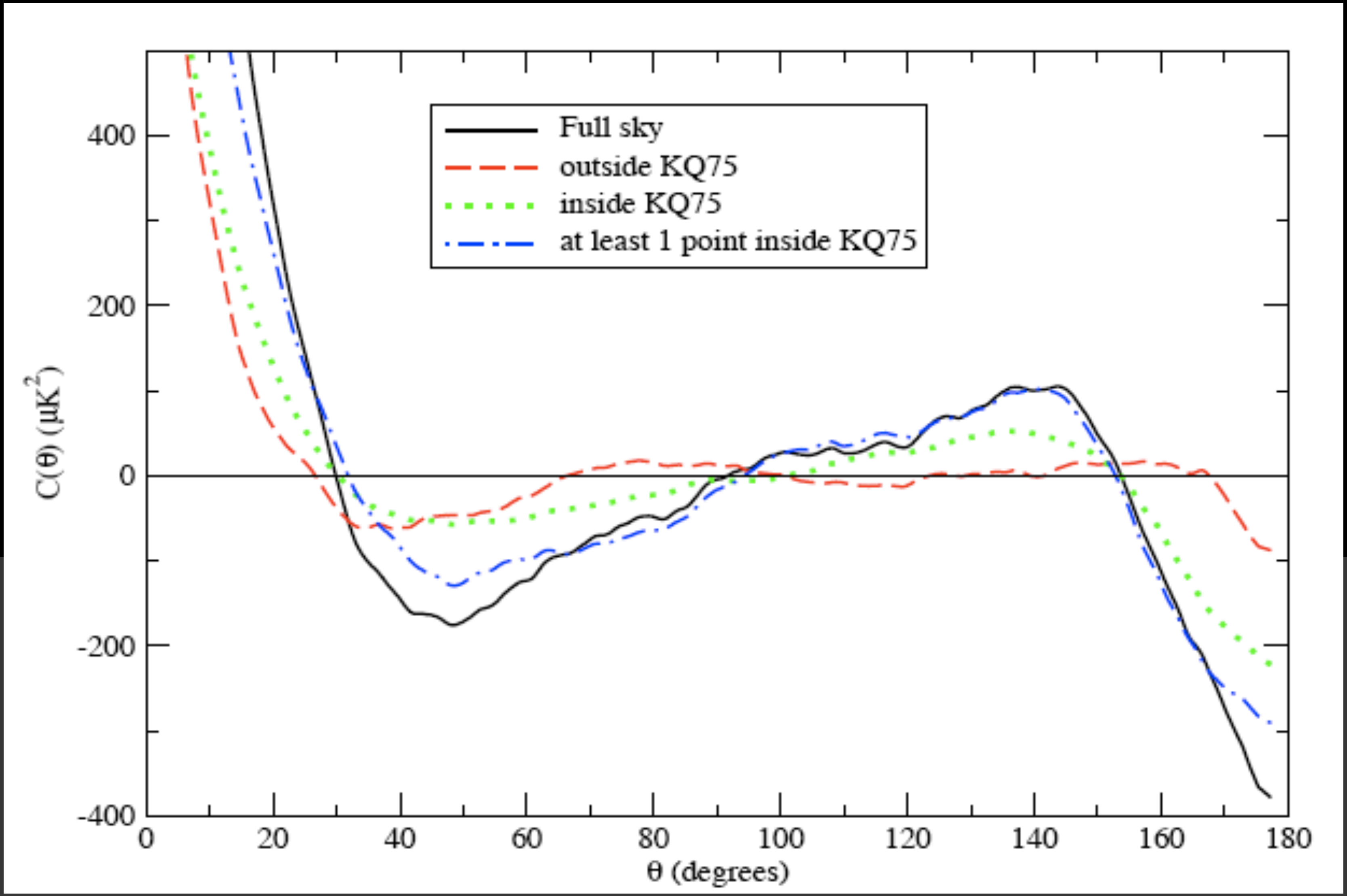
$$S_{1/2} = \int_{-1}^{1/2} [C(\theta)]^2 \, d \cos \theta$$

Statistics of $C(\theta)$

Table 1. The C_ℓ calculated from $\mathcal{C}(\theta)$ 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), $\mathcal{C}(> 60°) = 0$	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

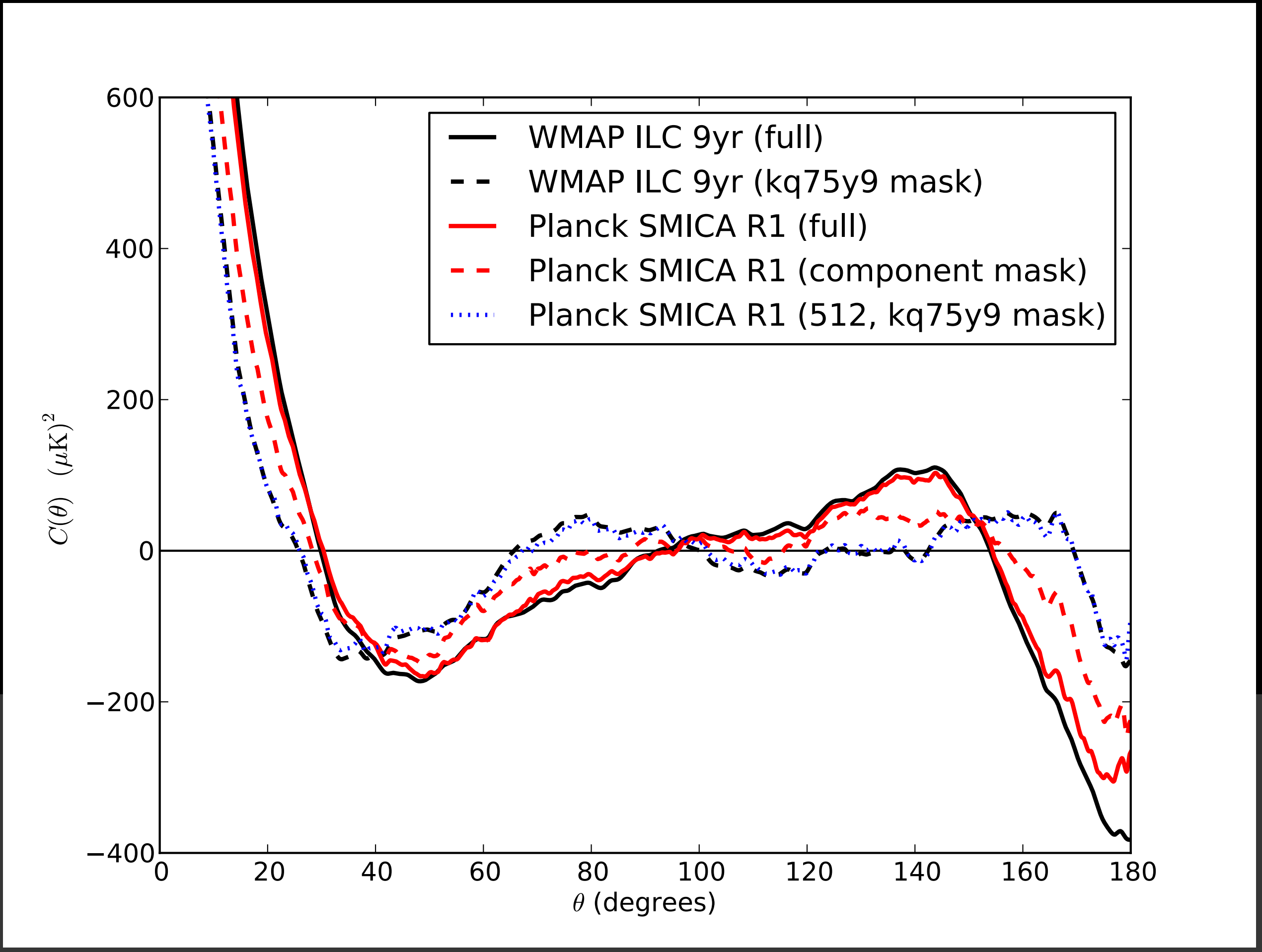
Origin of C(θ)



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)

Did this change in Planck?

No!



Planck 2018 (A&A 641, A7 (2020))

	Comm.	NILC	SEVEM	SMICA
$S_{1/2}(\mu K^4)$	1209.2	1156.6	1146.2	1142.4

Statistics of $C(\theta)$

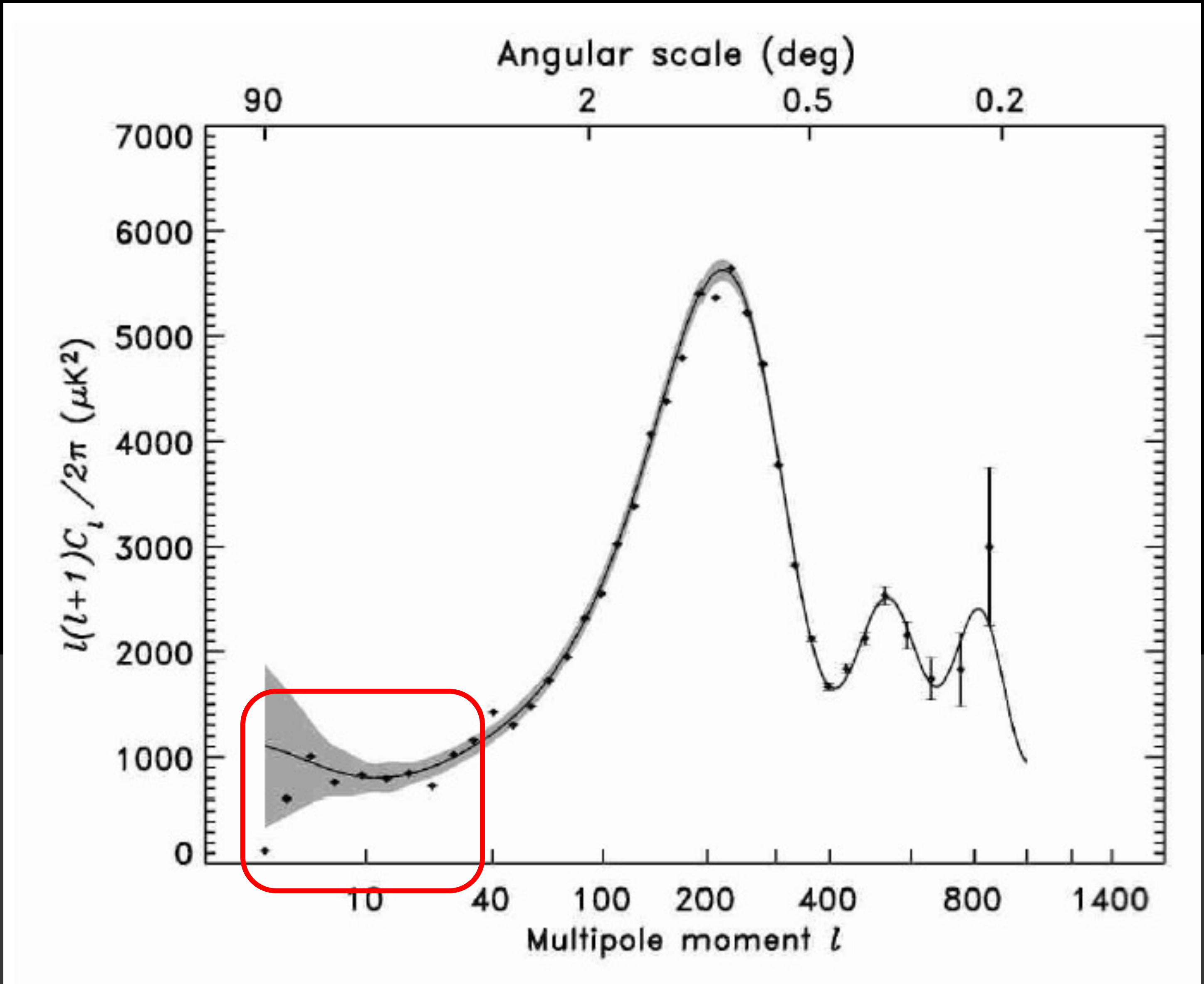
- 0.03-0.1% of realizations of the concordance model of inflationary ΛCDM have so little **cut sky** large-angle correlation !

and most of those have all low-l C_l small

Violation of (GR)SI

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 are much poorer fits to that theory than is the current data


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

Explaining $S_{1/2}$

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>**

Explanations

- This is a statistical fluke in standard LCDM
- Not a fluke:

Probable Implication:

$R(r)Y_{lm}(\Omega)$ are wrong basis to preserve Gaussianity

Example:

cosmic topology (=> scalar eigenmode basis)

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.*)
- bispectrum (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:

$$\Sigma_m a_{l\,m} Y_{l\,m}(\theta,\phi) \approx$$

$$A^{(\ell)} \, [(\hat{u}^{(l,1)} \cdot \hat{e}) \ldots (\hat{u}^{(l,\,l)} . \hat{e}) \text{ - all traces}]$$

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

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

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

2) Only $A^{(l)}$ depends on C_l

Maxwell Multipole Vectors

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

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

Area Vectors

Notice:

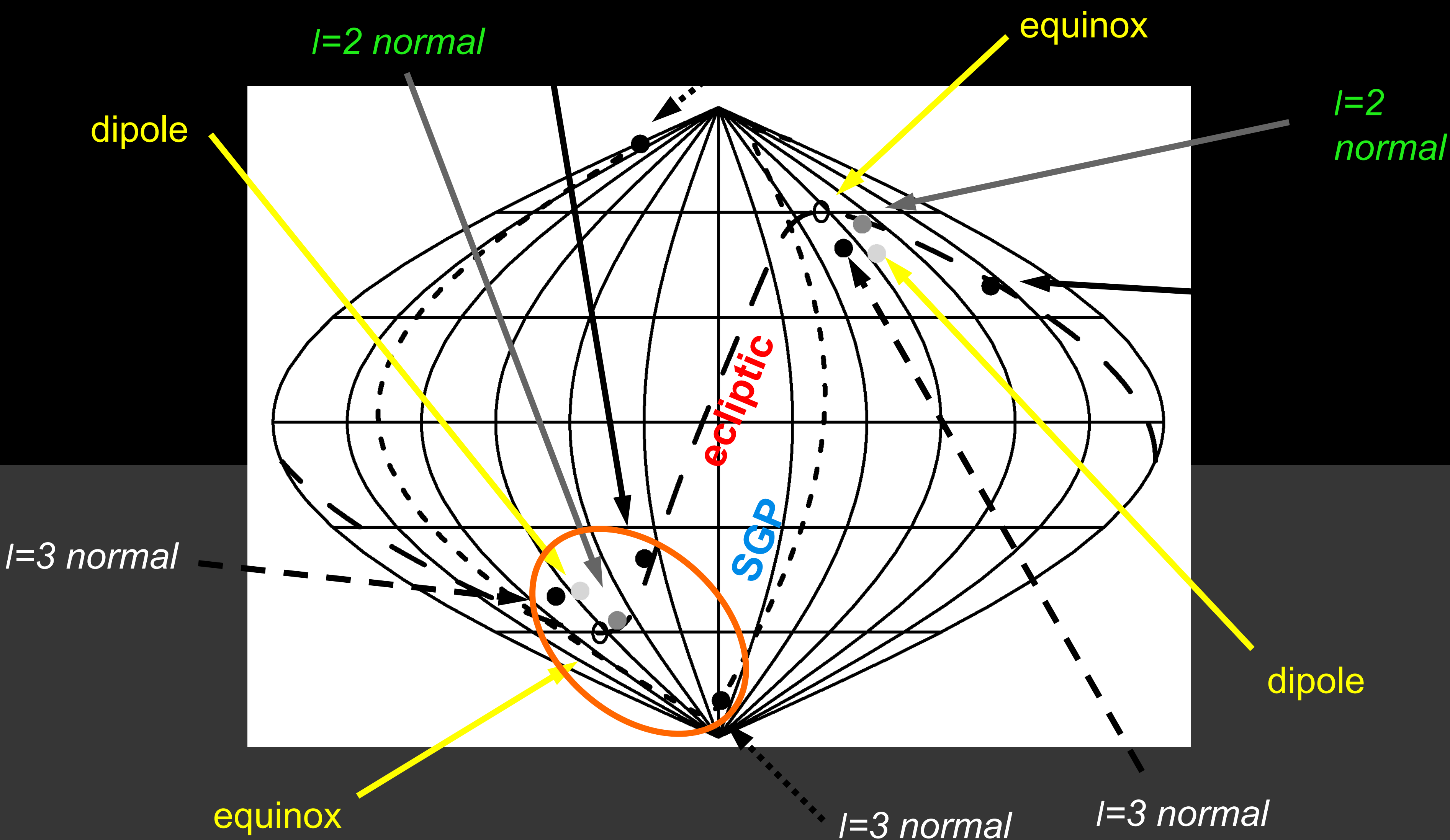
- Quadrupole has 2 vectors,
  i.e. quadrupole is a plane
- Octopole has 3 vectors,
  i.e. octopole is 3 planes

Suggests defining:

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

Carry some, but not all, of the information

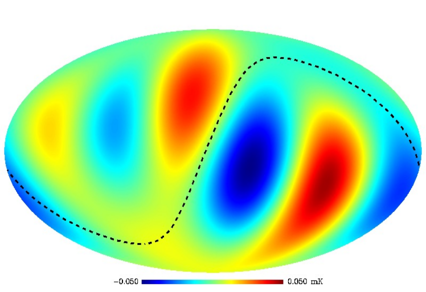
l=2&3 Area Vectors



Quadrupole-octupole alignment:

p-value: (0.1-0.6)%

Quadrupole+Octopole Correlations



- Cosmology ("Physical Model")
  - but how to get dipole correlation?
  - how to get $C_2 < C_3$?
- Systematics
  - how do you get the systematics in both WMAP and Planck?
- The Galaxy: (Systematics/Physical Model)
  - has the wrong multipole structure (shape)
  - is likely to lead to GALACTIC not ECLIPTIC/DIPOLE/EQUINOX correlations

- Other Foregrounds -- difficult:
  - Changing a patch of the sky typically gives you: Y_{l0}
  - Sky has 5x more octopole than quadrupole
  - How to get a physical ring (perpendicular to the ecliptic!)?
  - How to hide the foreground from detection? $T \approx T_{CMB}$

Conclusions?

Alignments are:

- Persistent
- Individually interesting, collectively significant
- but hard to explain, or establish “priority”

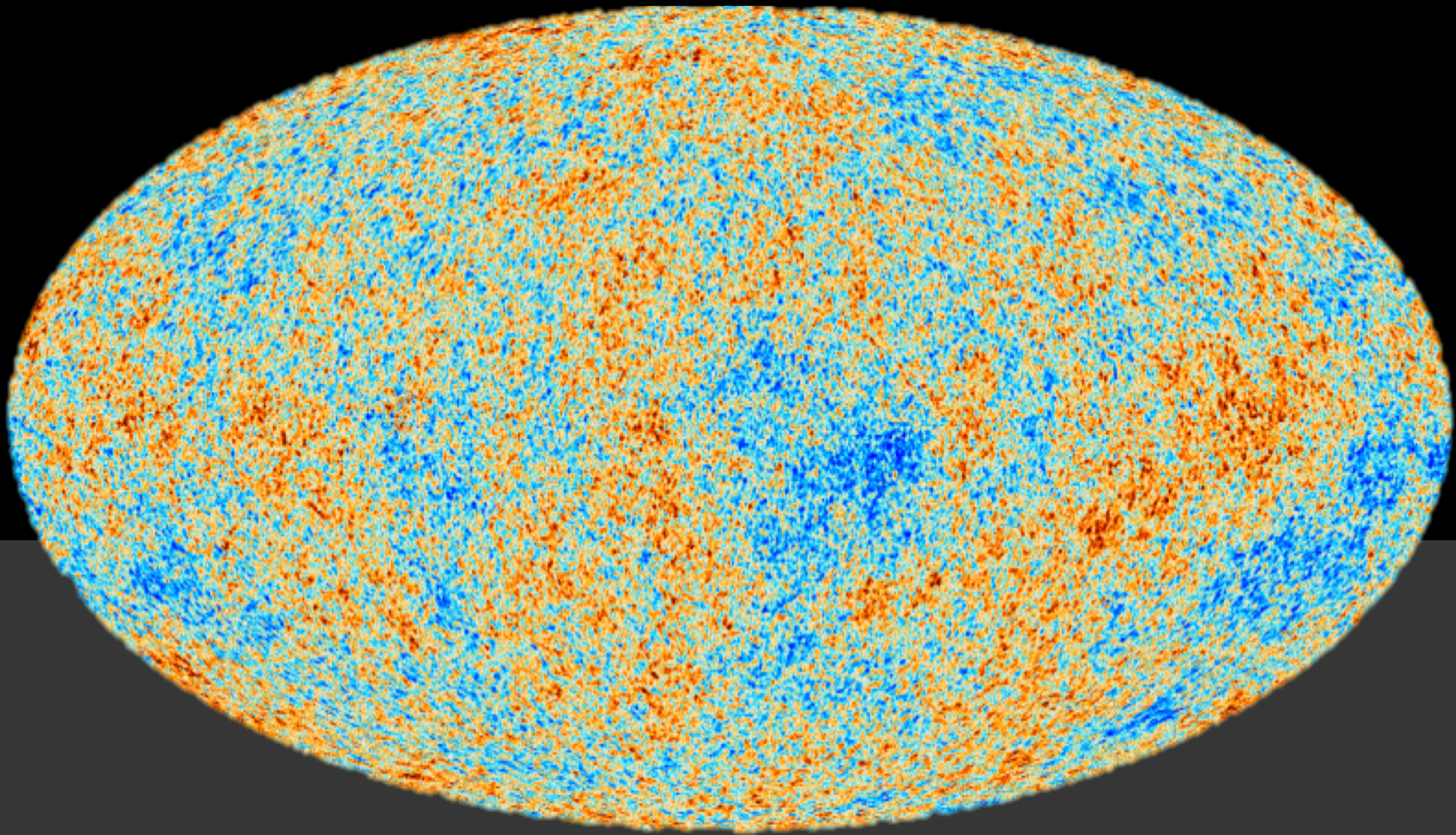
How to make progress?

Power asymmetry

Dipole modulation

Low Northern Variance

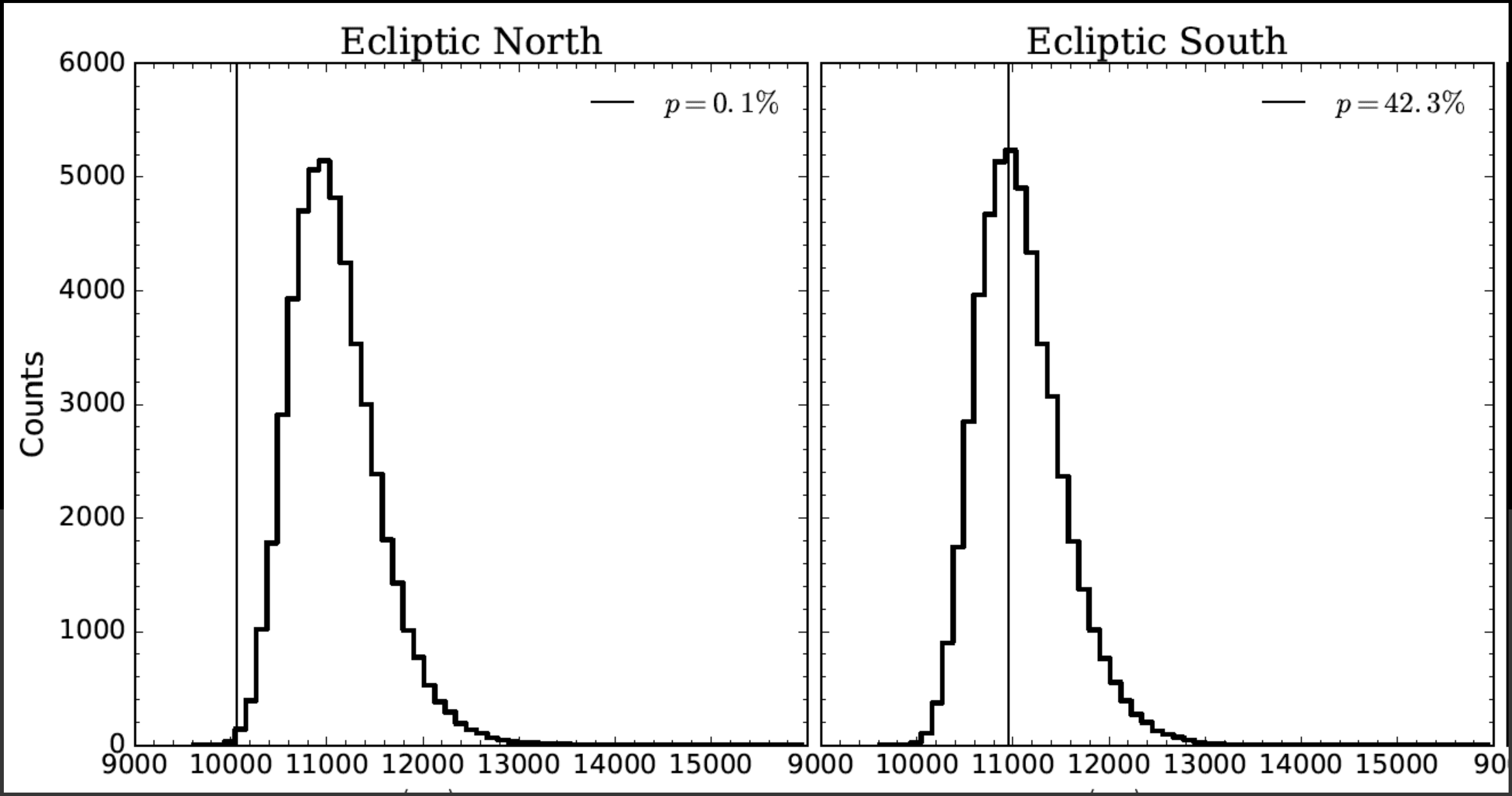
Marcio O’Dwyer (with GDS, Copi, Knox)



Bennett et al 2003

Eriksen et al 2004, and many others

SMICA N vs S variance



p ~ 0.001

SI violation ("dipole modulation") extends to high ℓ

A&A 594, A16 (2016)

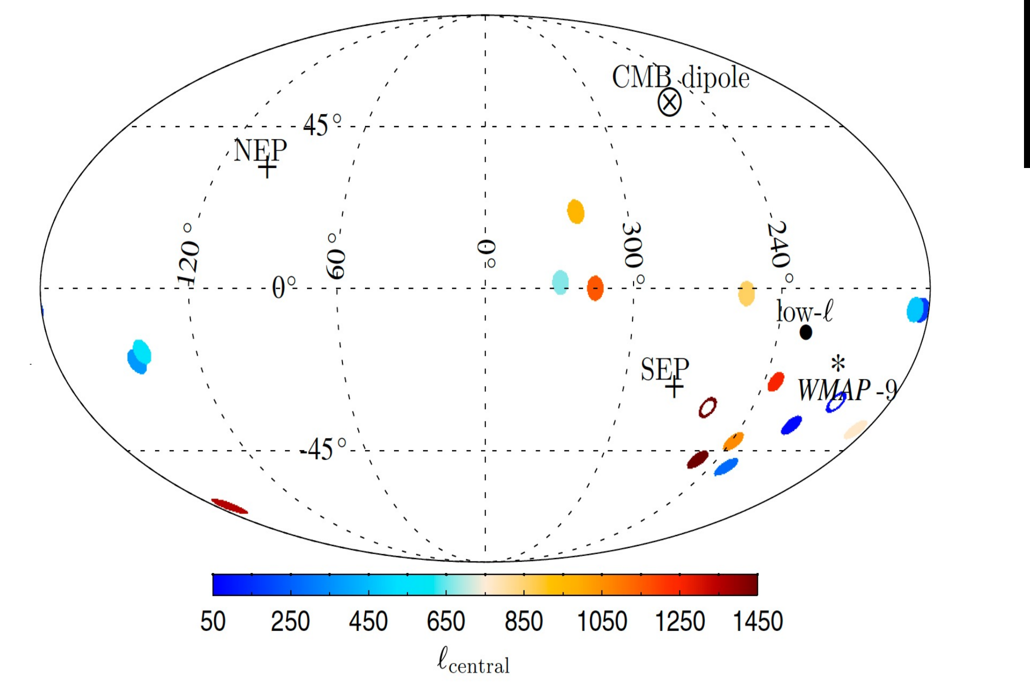


Fig. 35. Dipole directions for independent 100-multipole bins of the local power spectrum distribution from ℓ = 2 to 1500 in the SMICA map

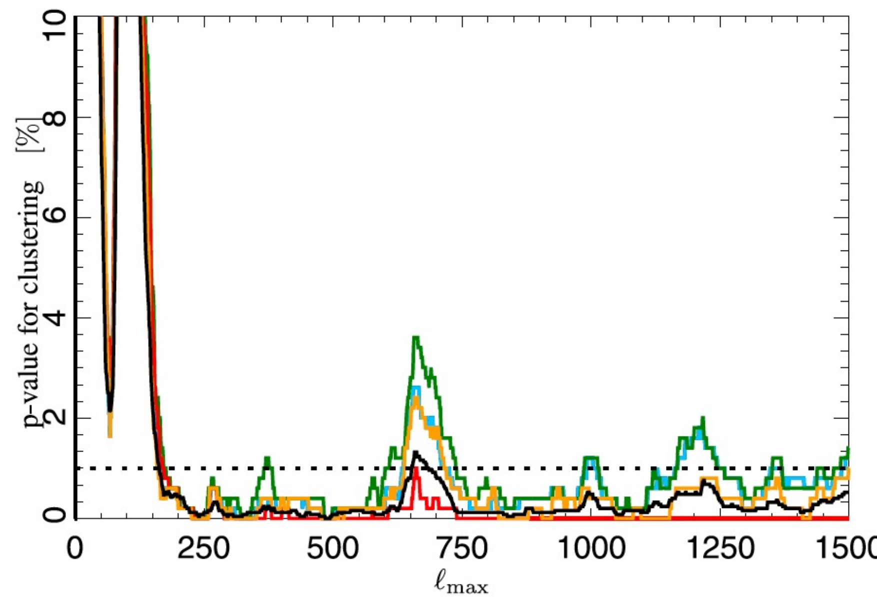


Fig. 36. Derived p-values for the angular clustering of the power distribution as a function of $\ell_{\max}$, determined for Commander (red), NILC (orange), SEVEM (green), and SMICA (blue), based on 500 simulations. For SMICA, the p-values based on 2500 simulations are also shown

p < 1%

Planck 2015

And …

A couple of more
that I find intriguing:
Mirror parity,
(N) ecliptic polar excursions

The Universe is either:

a) a likely realization of a statistically anisotropic cosmological model

b) a very unlikely realization of a SI cosmological model

With so many anomalies,
what do we do?

Making Progress

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

2. Make reasonable phenomenological extrapolations and test them.

3. Test the “fluke hypothesis.”   i.e. test LCDM!

Another talk …

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

but it may make it much harder to measure

All (?) NG statistical results assume SI

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

$$< a^{X}_{\ell m} a^{Y}_{\ell' m'} a^{Z}_{\ell'' m''} > \neq \mathcal{G}^{\ell \ell' \ell''}_{m m' m''} b^{XYZ}_{\ell \ell' \ell''}$$

$$\hat{f}_{\rm NL} = \frac{1}{N} \sum_{X_i, X_i'} \sum_{\ell_i, m_i} \sum_{\ell_i', m_i'} \mathcal{G}^{\ell_1\,\ell_2\,\ell_3}_{m_1 m_2 m_3} b^{X_1 X_2 X_3,\,\rm th}_{\ell_1 \ell_2 \ell_3} \left\{ \left[\left(\mathsf{C}^{-1}_{\ell_1 m_1, \ell_1' m_1'} \right)^{X_1 X_1'} a^{X_1'}_{\ell_1' m_1'} \times \left(\mathsf{C}^{-1}_{\ell_2 m_2, \ell_2' m_2'} \right)^{X_2 X_2'} a^{X_2'}_{\ell_2' m_2'} \left(\mathsf{C}^{-1}_{\ell_3 m_3, \ell_3' m_3'} \right)^{X_3 X_3'} a^{X_3'}_{\ell_3' m_3'} \right] - \left[\left(\mathsf{C}^{-1}_{\ell_1 m_1, \ell_2 m_2} \right)^{X_1 X_2} \left(\mathsf{C}^{-1}_{\ell_3 m_3, \ell_3' m_3'} \right)^{X_3 X_3'} a^{X_3'}_{\ell_3' m_3'} + \text{cyclic} \right] \right\}, \quad (25)$$

$$\hat{f}_{\rm NL} = \frac{1}{N} \sum_{X_i, X_i'} \sum_{\ell_i, m_i} \mathcal{G}^{\ell_1\,\ell_2\,\ell_3}_{m_1 m_2 m_3} (\mathsf{C}^{-1})^{X_1 X_1'}_{\ell_1} (\mathsf{C}^{-1})^{X_2 X_2'}_{\ell_2} (\mathsf{C}^{-1})^{X_3 X_3'}_{\ell_3} b^{X_1 X_2 X_3,\,\rm th}_{\ell_1 \ell_2 \ell_3} \times \left[a^{X_1'}_{\ell_1 m_1} a^{X_2'}_{\ell_2 m_2} a^{X_3'}_{\ell_3 m_3} - \mathsf{C}^{X_1' X_2'}_{\ell_1 m_1, \ell_2 m_2} a^{X_3'}_{\ell_3 m_3} - \mathsf{C}^{X_1' X_3'}_{\ell_1 m_1, \ell_3 m_3} a^{X_2'}_{\ell_2 m_2} - \mathsf{C}^{X_2' X_3'}_{\ell_2 m_2, \ell_3 m_3} a^{X_1'}_{\ell_1 m_1} \right]. \quad (27)$$

Optimal estimator given SI

diagonal covariance approximation, given SI

From Planck 2018 IX Constraints on PNG

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

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

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

What if

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

but summary statistics for

$\ell \neq \ell'$ or $\mathrm{m} \neq m'$

are inconsistent with 0?

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?

Making Progress

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

2. Make reasonable phenomenological extrapolations and test them.

3. Test the “fluke hypothesis.” i.e. test LCDM!

Another talk …

New Models

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

1.

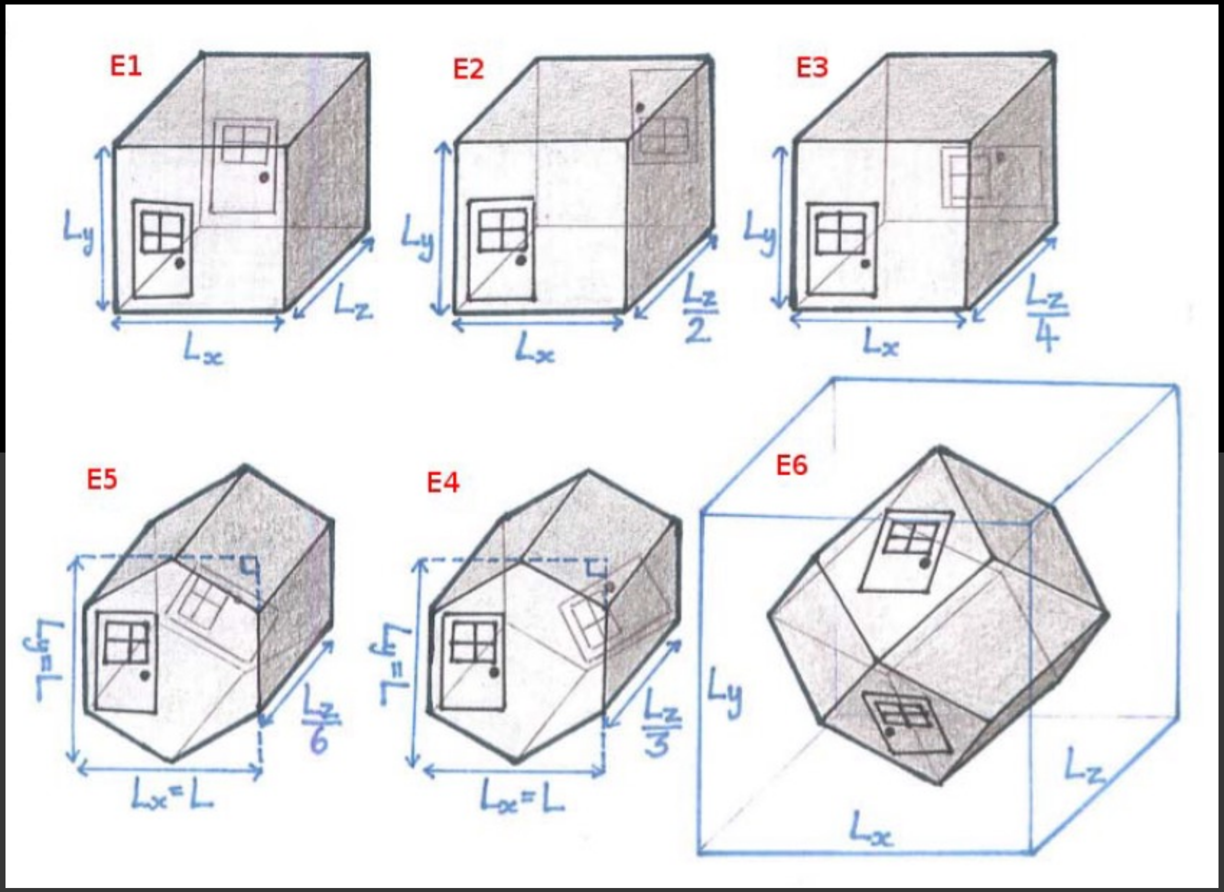
Requirements:

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

Topology — a (only??) stage for explaining multiple anomalies

Breaks SI – $R_{n\ell}(r)Y_{\ell m}(\theta,\phi)$
no longer the scalar eigenmodes

The 6 compact orientable E^3 manifolds



Topology — a (only??) stage for explaining anomalies

- Breaks SI – $R_{nl}(r)\ Y_{lm}$ no $R_{nl}(r)Y_{lm}$ longer scalar eigenmodes
- At all *l* – effects of topology extends to high *l*

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

$$| < \delta_{\vec{k'}} \delta_{\vec{k}} >| = | < \delta^*_{\vec{k}} \delta_{\vec{k}} >| \text{ for certain } \overrightarrow{k'} = R\ \vec{k}$$

Topology — a (only??) stage for explaining anomalies

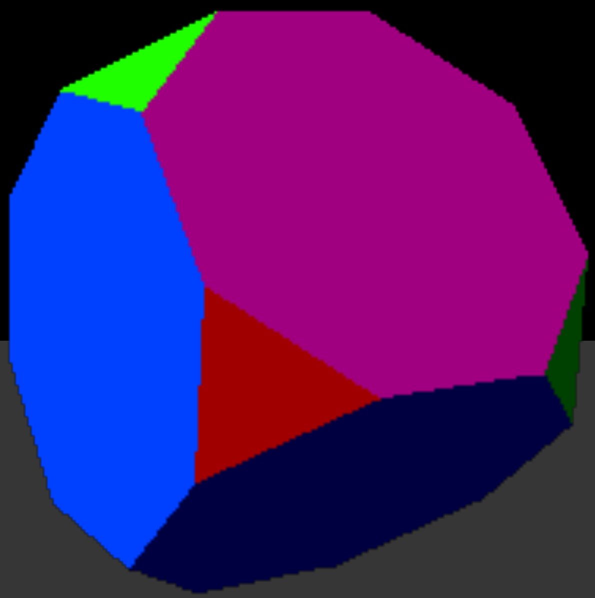
- Breaks SI – $R_{nl}(r)\ Y_{lm}$ no $R_{nl}(r) Y_{lm}$ longer scalar eigenmodes
- At all l – effects of topology extends to high l

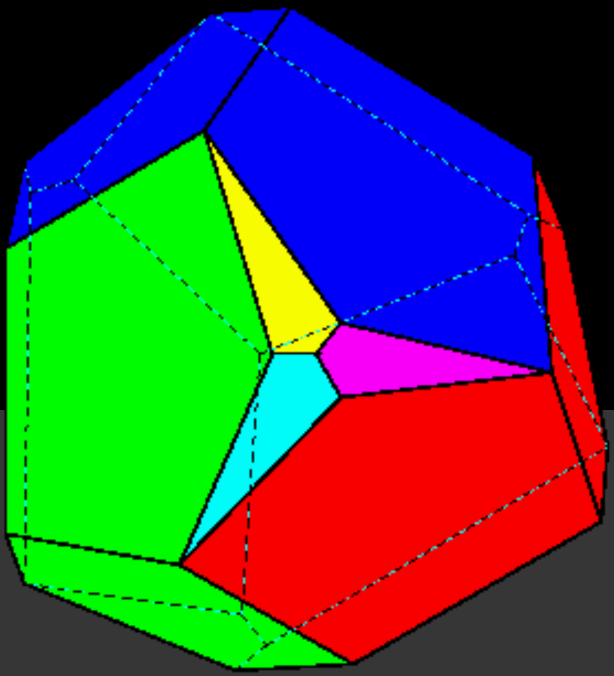
- In E^3 eigenmodes are (finite lc of) Fourier modes
  but discrete and w correlated amplitudes
- But **must** allow for $\Omega_K \neq 0$! (2207.06547)

There is no such thing as "flat ΛCDM". (Except topologically!)

- Eigenmodes are generically (in)finite lc of covering space eigenmodes

S^3 Manifold H^3 Manifold





Topology breaks statistical homogeneity

All (?) of the NG statistical results assume statistical homogeneity

How does that affect calculation/estimation of (P)NG?

Our universe makes
a very poor case
for statistical isotropy

Assume it at your peril