The Universe is Not Statistically Isotropic

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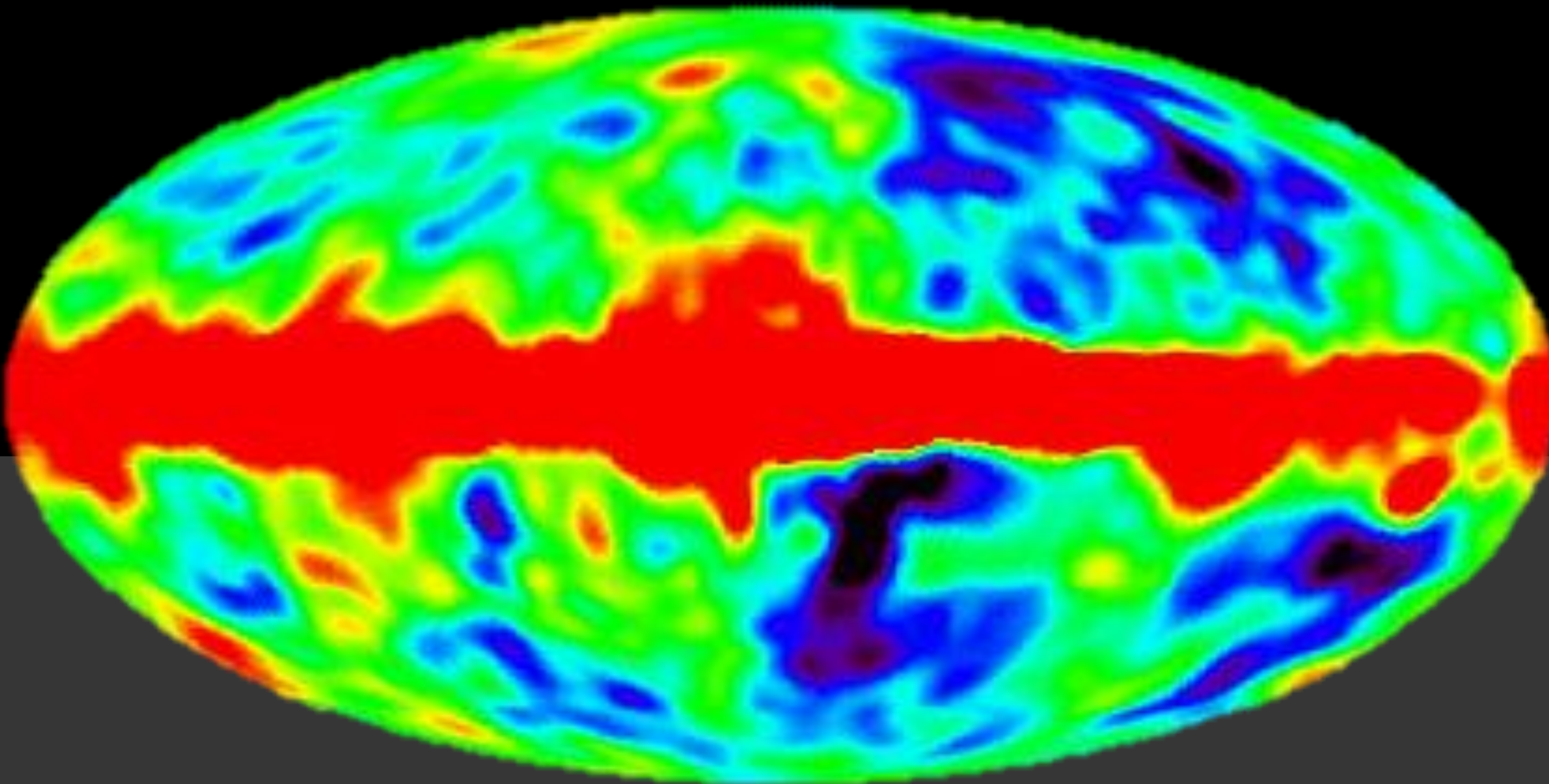
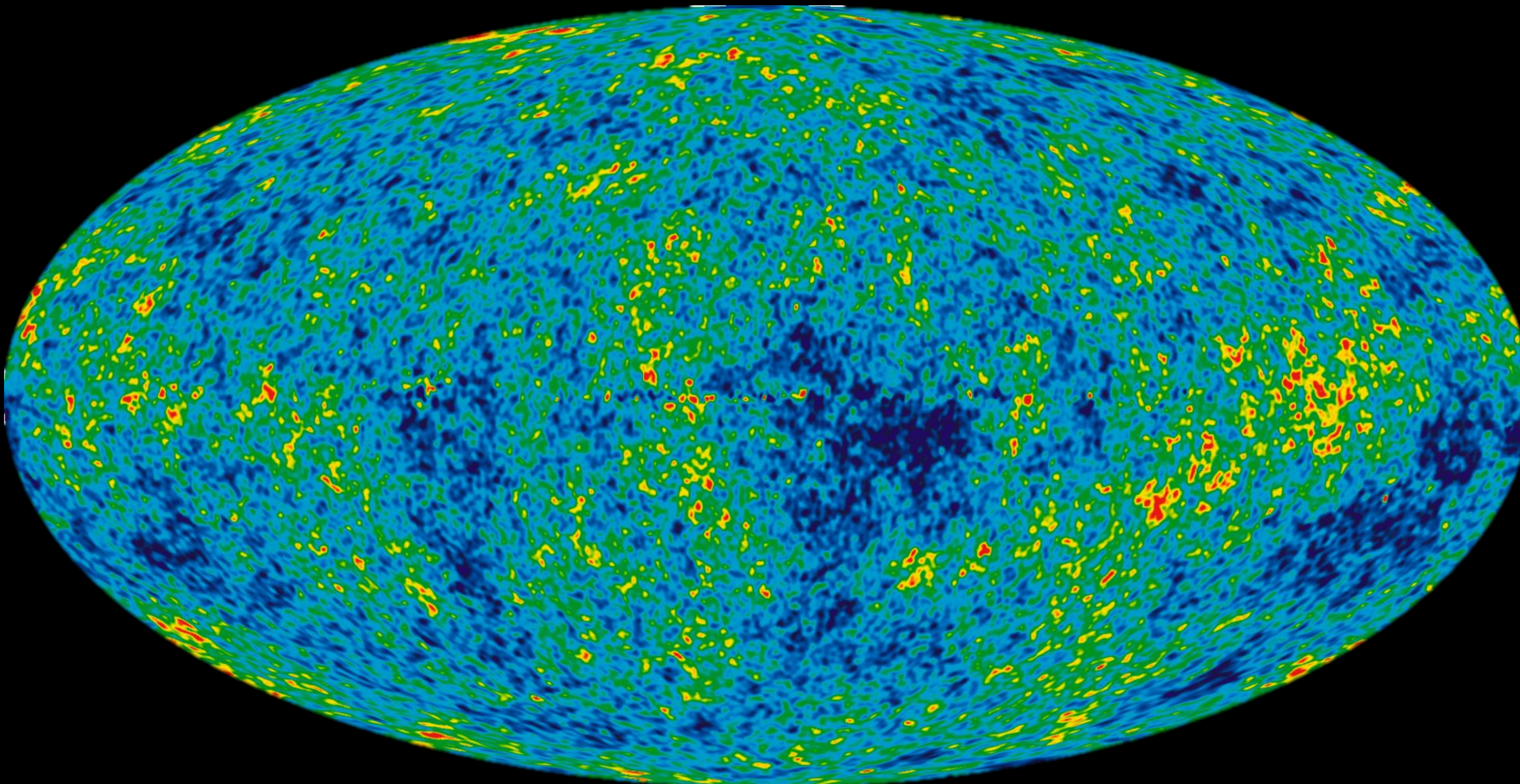
COBE - DMR



NASA/COBE-DMR science team

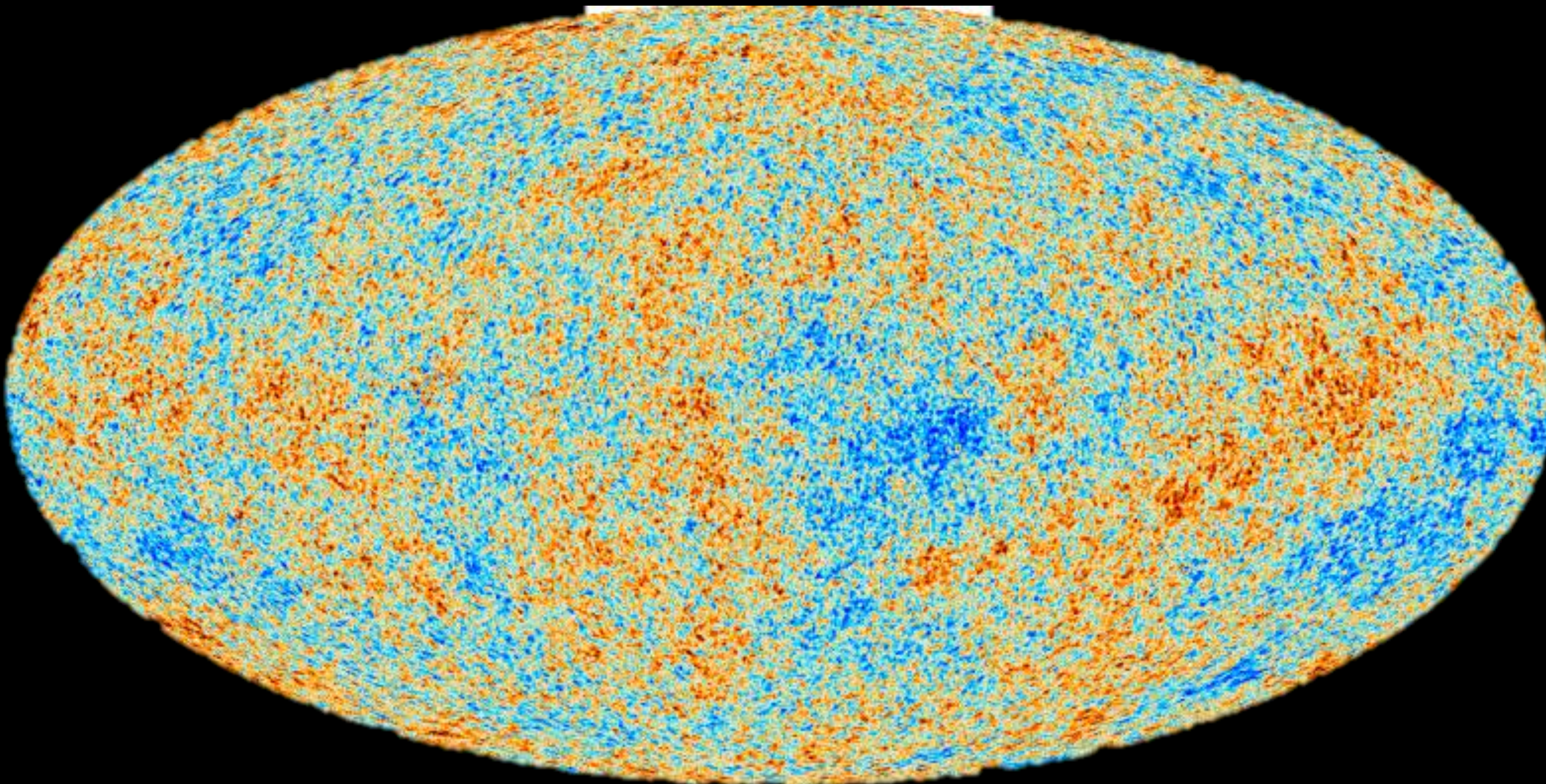
T=18μK

WMAP



NASA/WMAP Science team

Planck



ESA/Planck Science team

ACT

SPT

SO

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):

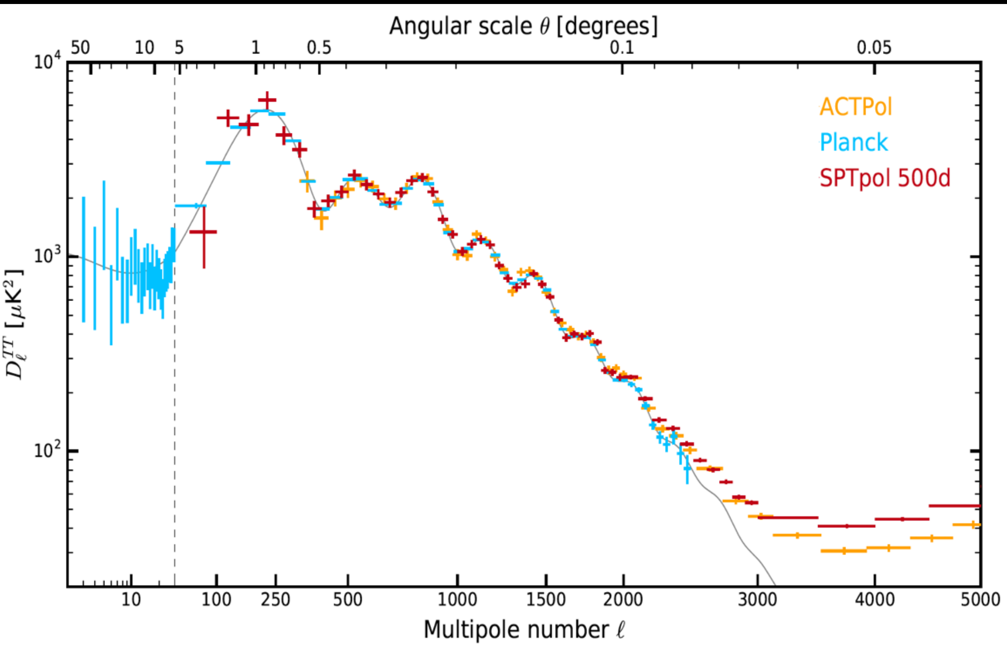
- Sky is statistically isotropic
- $a_{\ell m}$ are independent Gaussian random variables

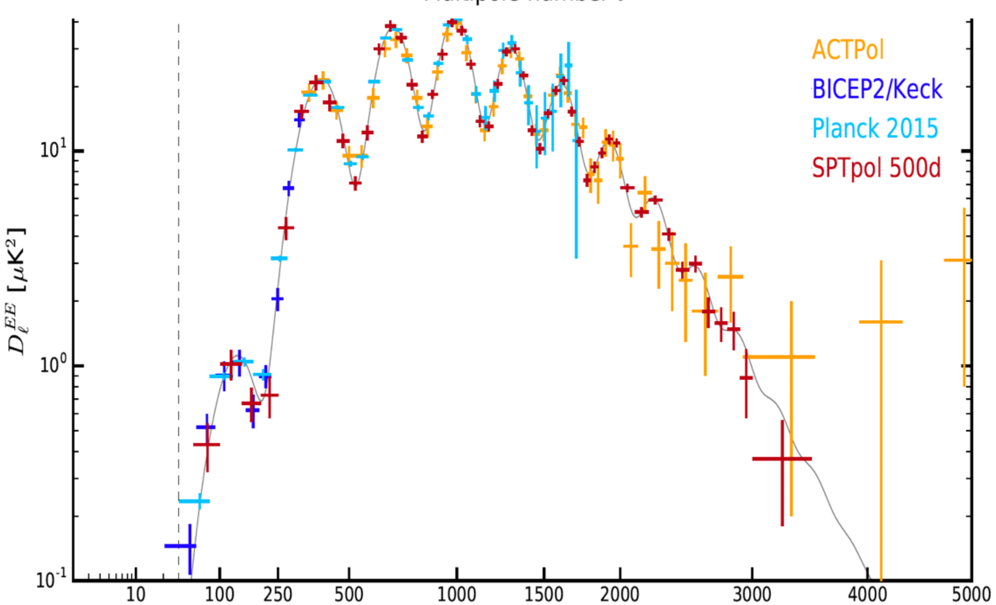
$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \, \delta_{\ell \ell'} \, \delta_{mm'}$$

ALL(~) interesting information is contained in:

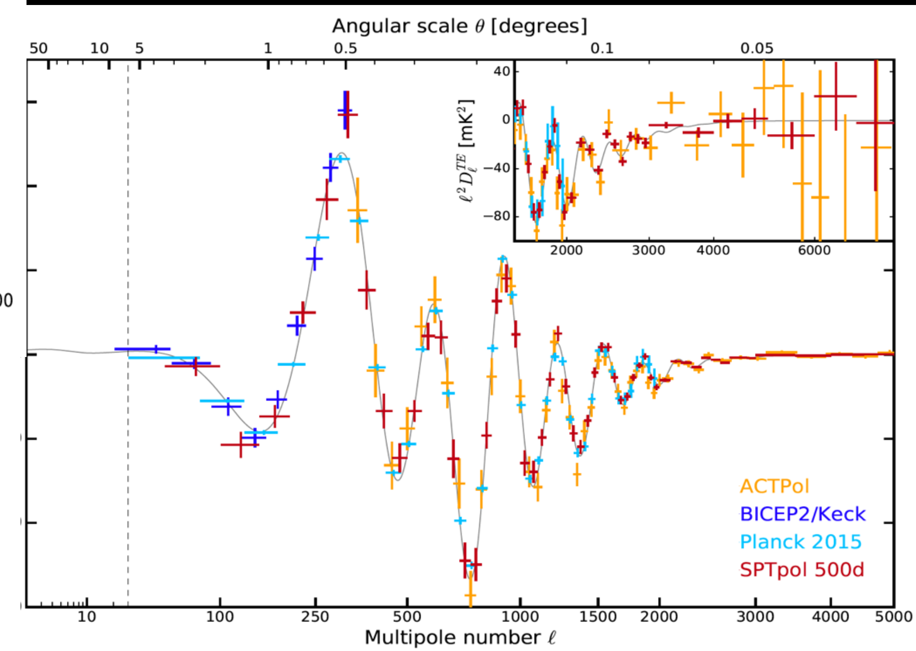
$$\hat{C}_\ell = (2\ell + 1)^{-1} \sum_m |a_{\ell m}|^2$$

Angular Power Spectrum





6 (really 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

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

ALL interesting information is contained in: C_ℓ

Shouldn't we check?!

Outline

Troubles in (iso)tropical paradise:

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

Bottom line:

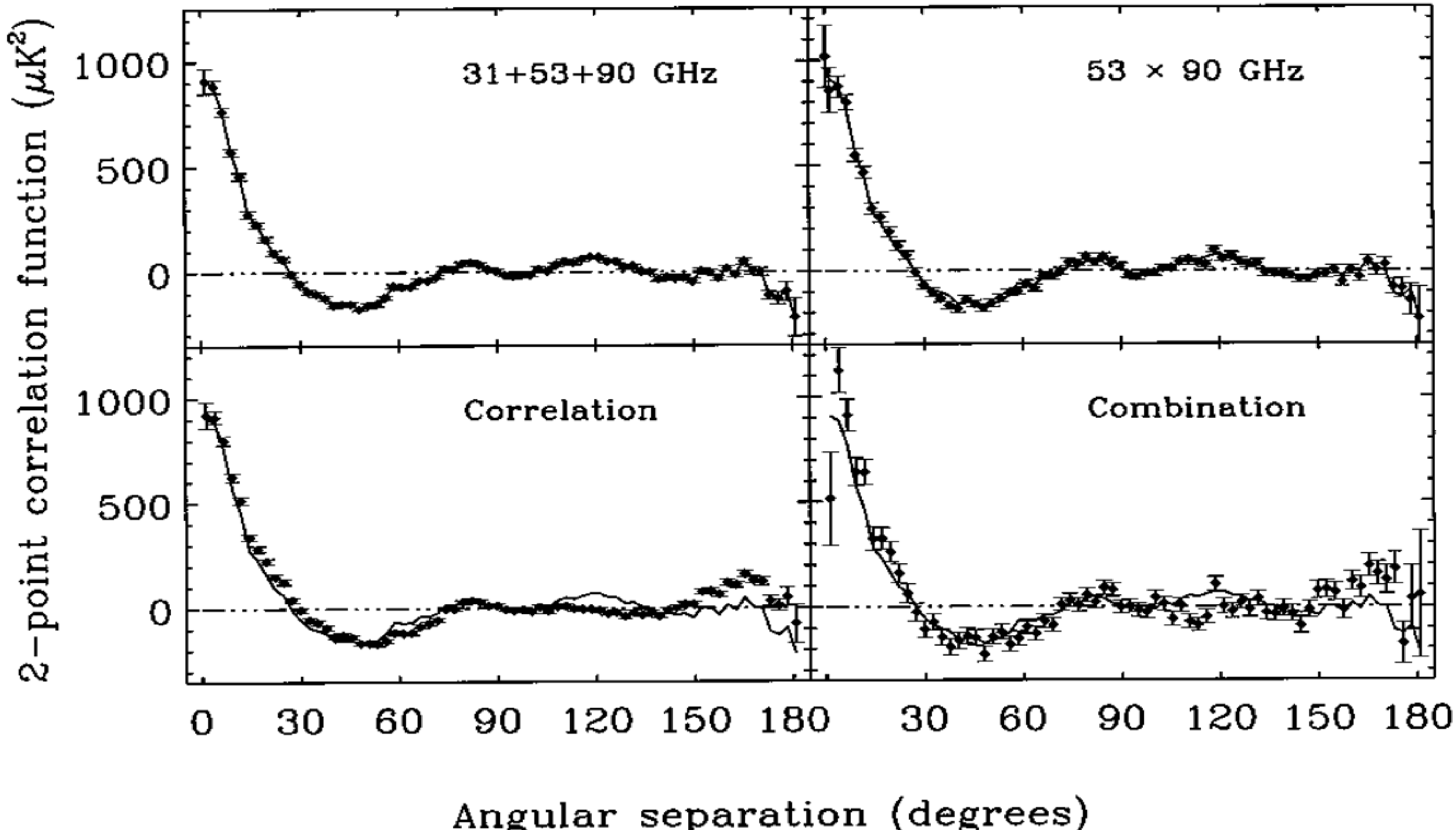
>5σ evidence against GRSI LCDM realization in ways that demand statistical anisotropy.

Promise-of-topology musings

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



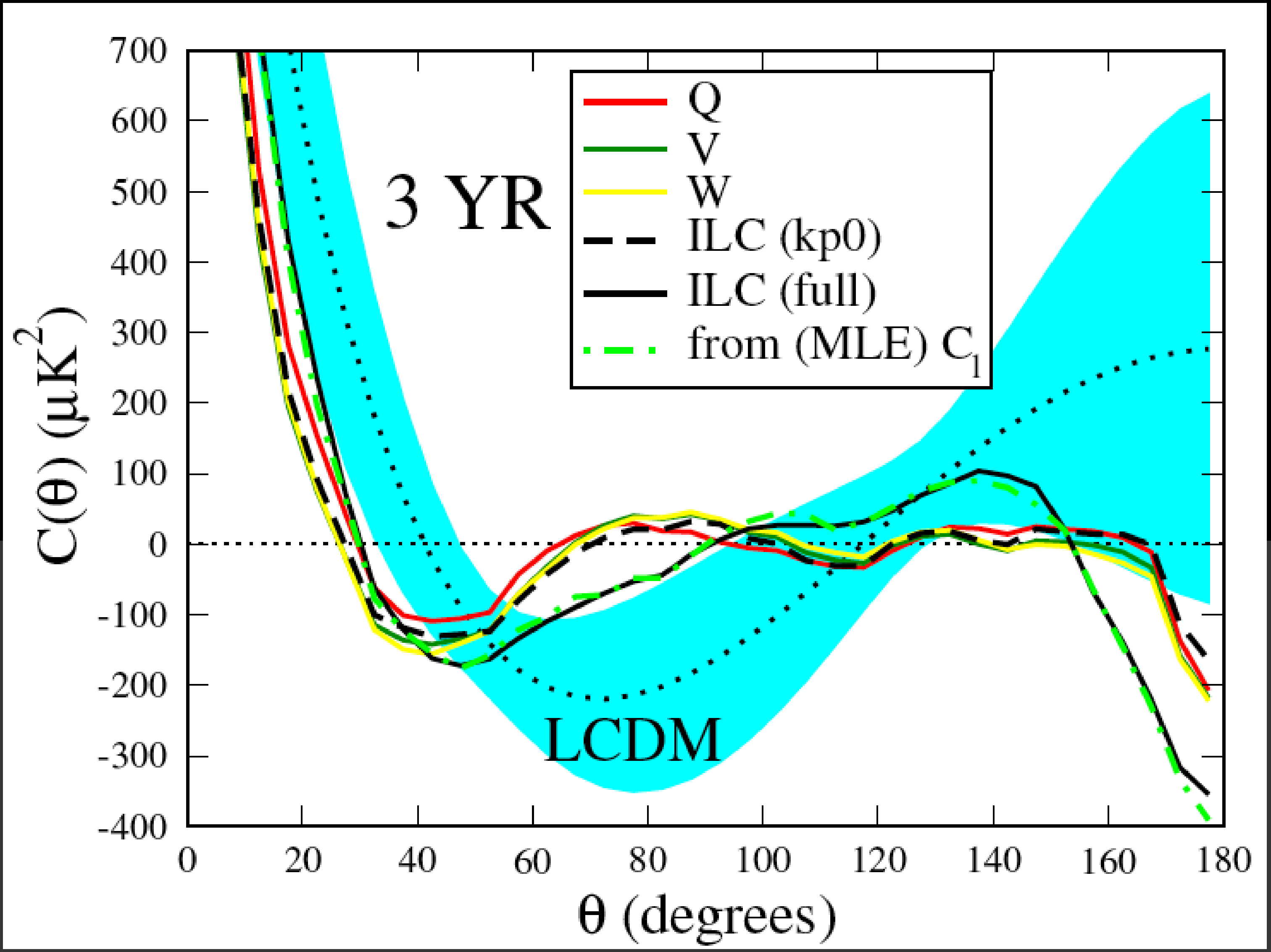
Angular Correlation Function $C(\theta)$

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

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

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

Two-point angular correlation function



Is the Large-Angle Anomaly Significant?

One measure (WMAP1):

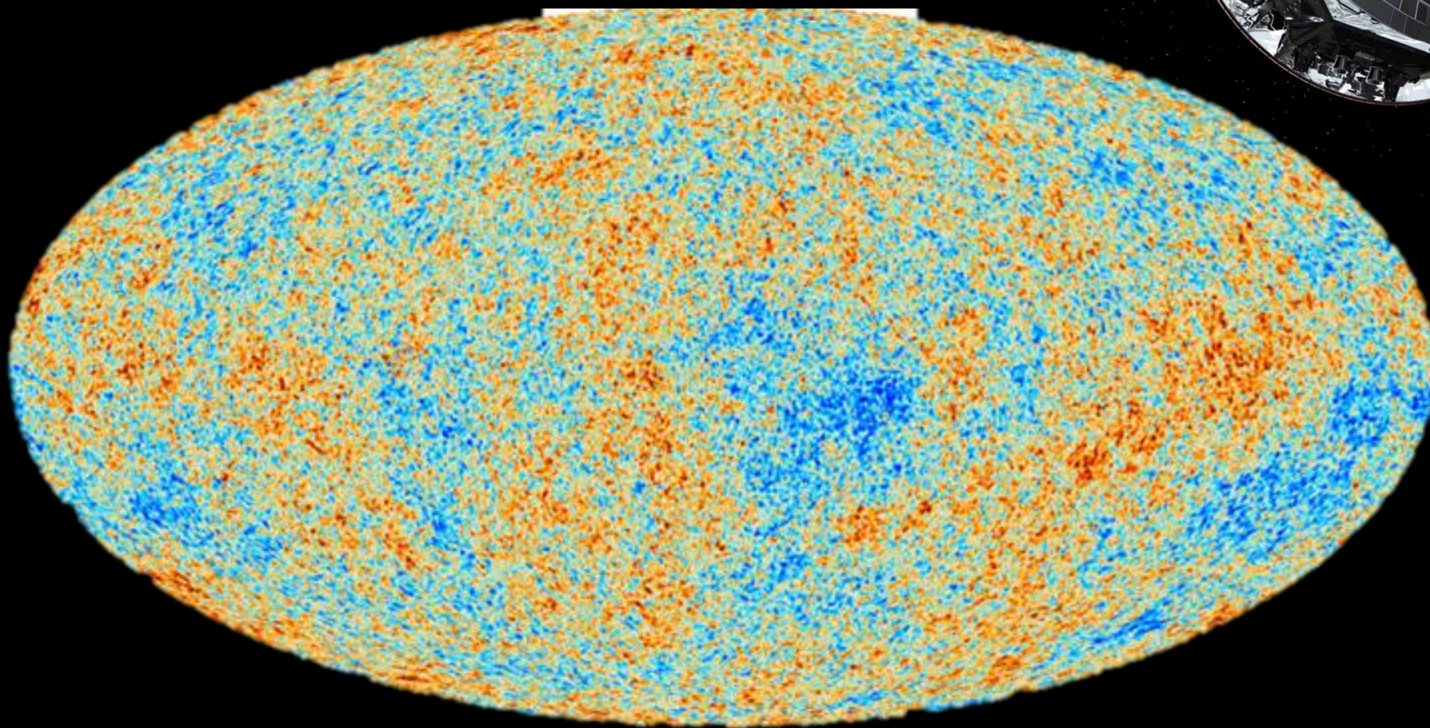
$$S_{1/2} = \int_{-1}^{1/2} [C(\theta)]^2 \, d \cos \theta$$

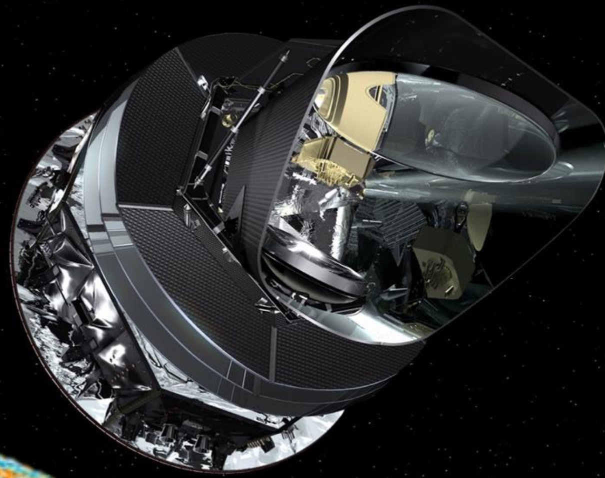
WMAP statistics of C(θ)

Table 1. The $\mathcal{C}_\ell$ 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.

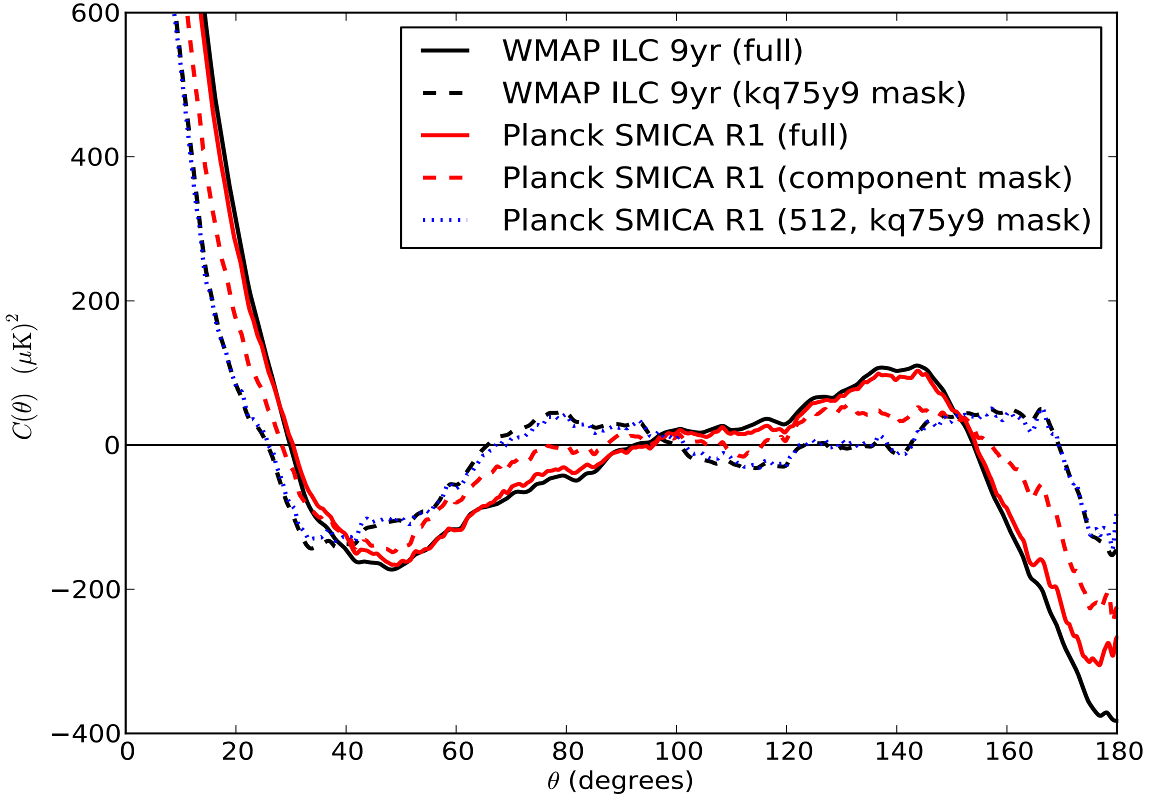
Data Source	$S_{1/2}$ $(\mu K)^4$	$P(S_{1/2})$ (per cent)	$6C_2/2\pi$ $(\mu K)^2$	$12C_3/2\pi$ $(\mu K)^2$	$20C_4/2\pi$ $(\mu K)^2$	$30C_5/2\pi$ $(\mu K)^2$
V3 (kp0, DQ)	1288	0.04	77	410	762	1254
W3 (kp0, DQ)	1322	0.04	68	450	771	1302
ILC3 (kp0, DQ)	1026	0.017	128	442	762	1180
ILC3 (kp0), $\mathcal{C}(>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

Planck





ESA/Planck Science team



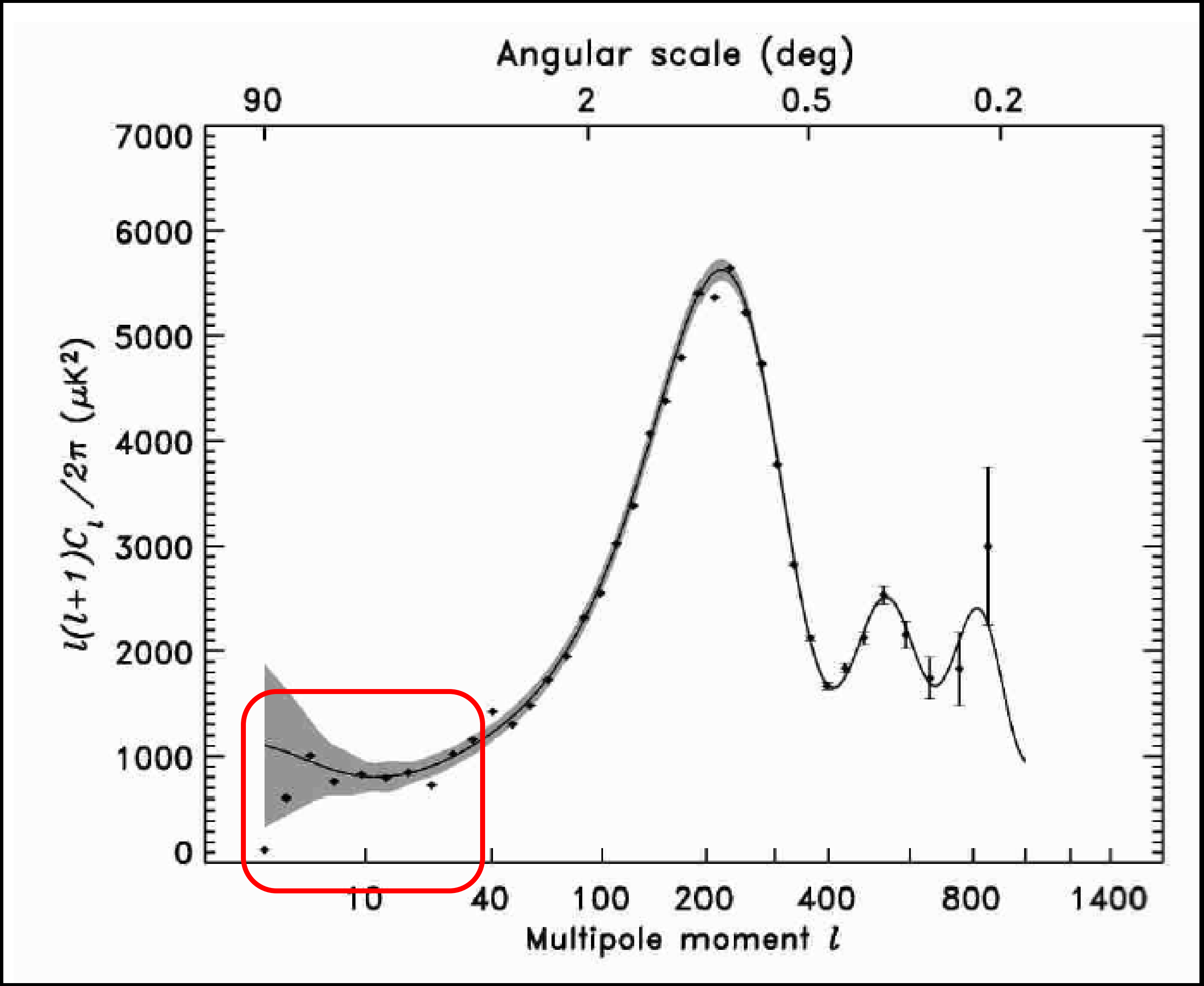
Planck 2018
A&A 641, A7
(2020)

Statistic	$S_{1/2}^{XY}$ $[\mu K^4]$			
	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

Conspiracy: how the sky minimizes $S_{1/2}$

To obtain $S_{1/2} < \sim 1000$ with the observed C_ℓ requires correlating C_2, C_3, C_4 & C_5!

It's not the inflaton potential: 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

Understanding 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 that correlates C_l's

$$\langle C_\ell C_{\ell'} \rangle \not\propto \delta_{\ell\ell'}$$

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

Beyond C_ℓ: Searching for Departures from Gaussianity/Statistical Isotropy

- angular momentum dispersion axes (da Oliveira-Costa, *et al.*)
- BiPoSH coefficients (Souradeep *et al.*)
- cold hot spots, hot cold spots (Larson and Wandelt)
- dipolar modulations
- genus curves (Park)
- hemispherical asymmetries (Eriksen *et al.*, Hansen *et al.*)
- Land & Magueijo scalars/vectors
- multipole vectors (Copi, Huterer, Schwarz, GDS; Weeks; Seljak and Slosar; Dennis)
- parity anomaly
- spherical Mexican-hat wavelets (Vielva *et al.*)
- your favourite technique/anomaly that I missed

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) :

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

Advantages:

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

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

Multipole Vectors

General ℓ, write:

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

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

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

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

2) Only $A^{(\ell)}$ 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

Area Vectors

Notice:

- Quadrupole has 2 vectors,

  i.e. quadrupole is a plane
- Octopole has 3 vectors,

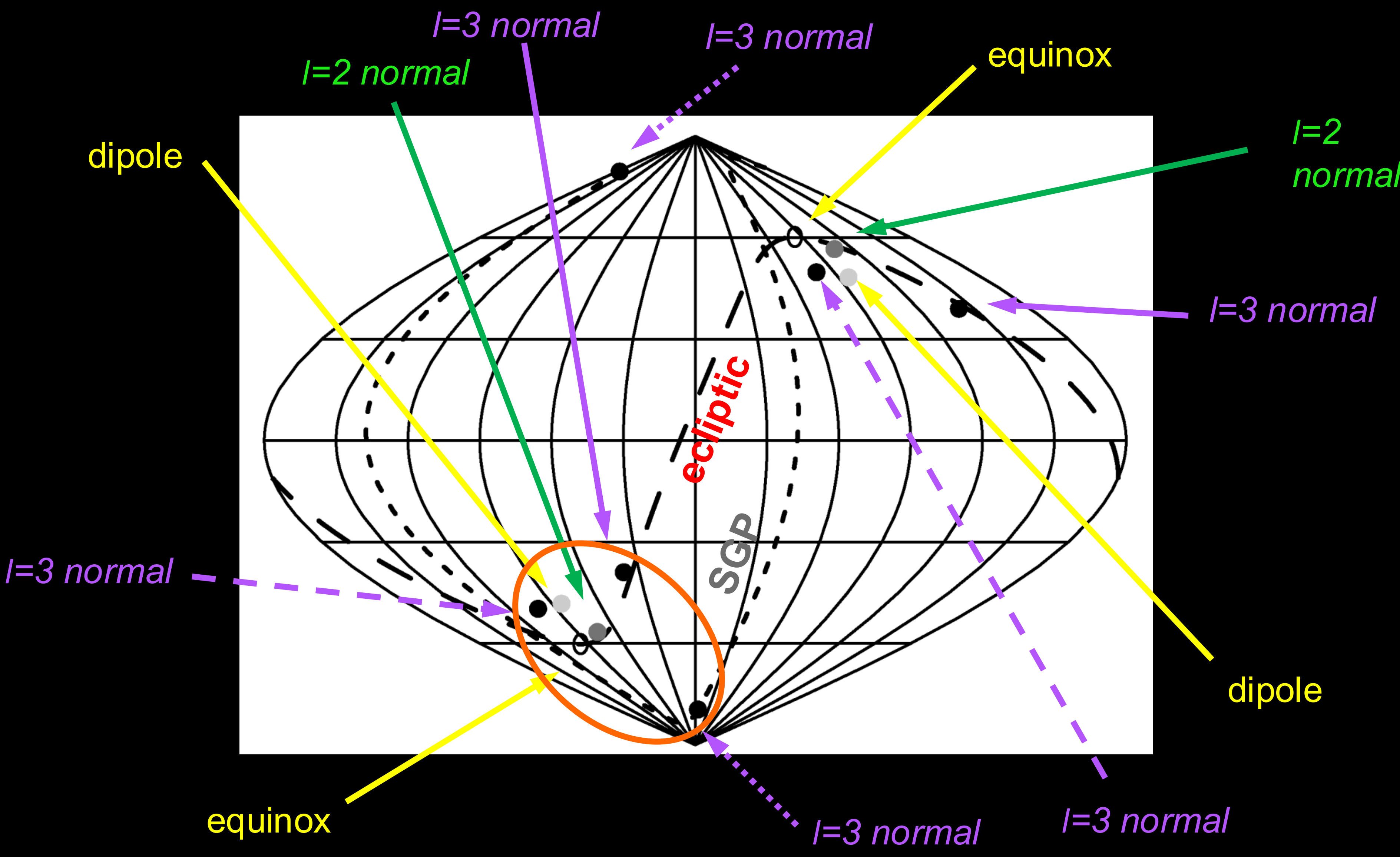
  i.e. octopole is 3 planes

Suggests defining:

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

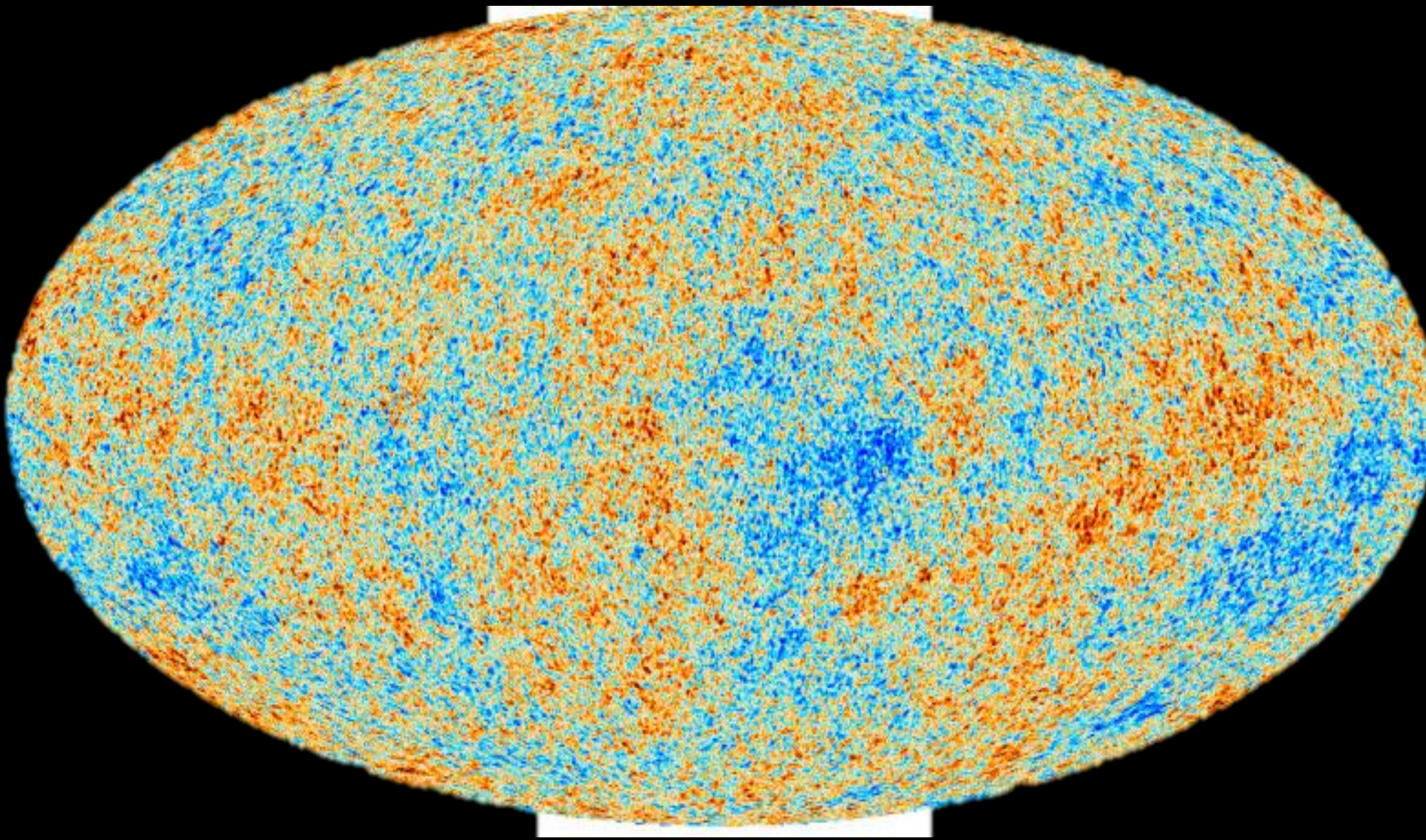
p-value of the quadrupole & octopole
planes being so aligned: (0.1-0.6)%

Power asymmetry

Dipole modulation

Low Northern Variance

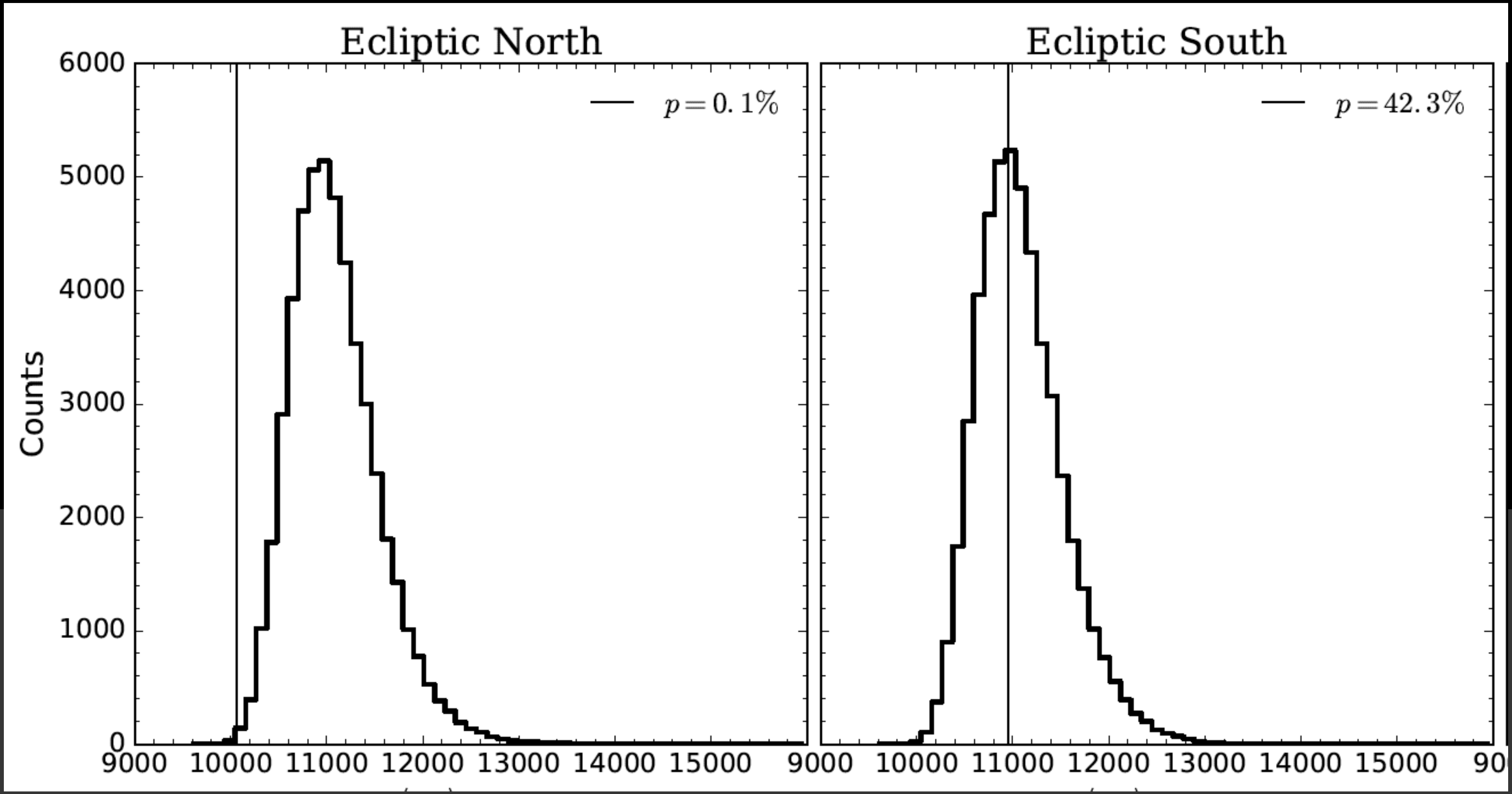
Marcio O'Dwyer (with GDS, Copi, Knox)



Bennett et al 2003

Eriksen et al 2004, and many others

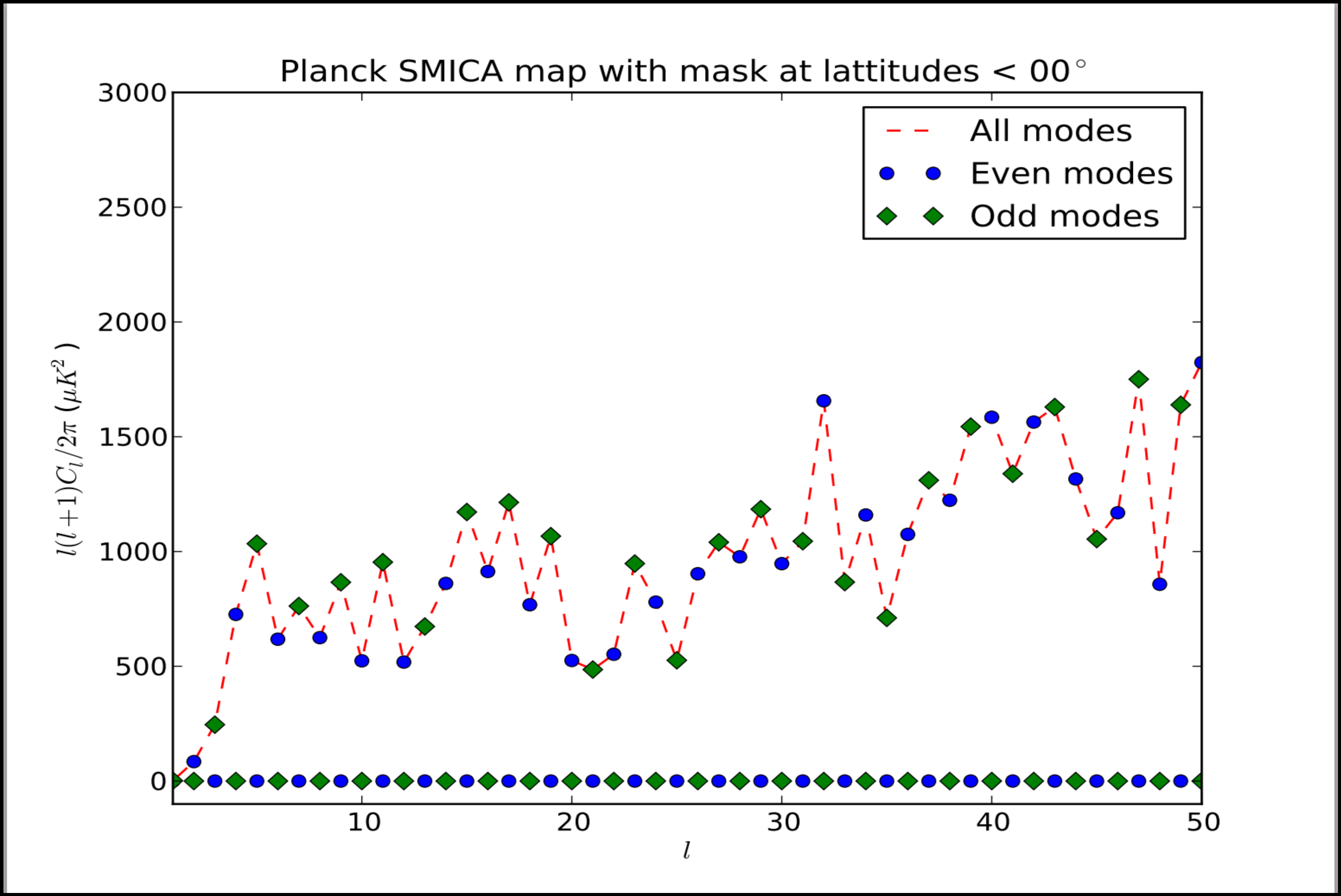
SMICA N vs S variance



p ~ 0.001

Parity anomaly

Parity anomaly



Plot by J. Muir, U. Pittsburgh

With so many anomalies, what do we do?

In preparation: Large-angle anomalies of the CMB and the evidence against statistical isotropy, Physics Reports

[Submitted on 19 Oct 2023]

The Universe is not statistically isotropic

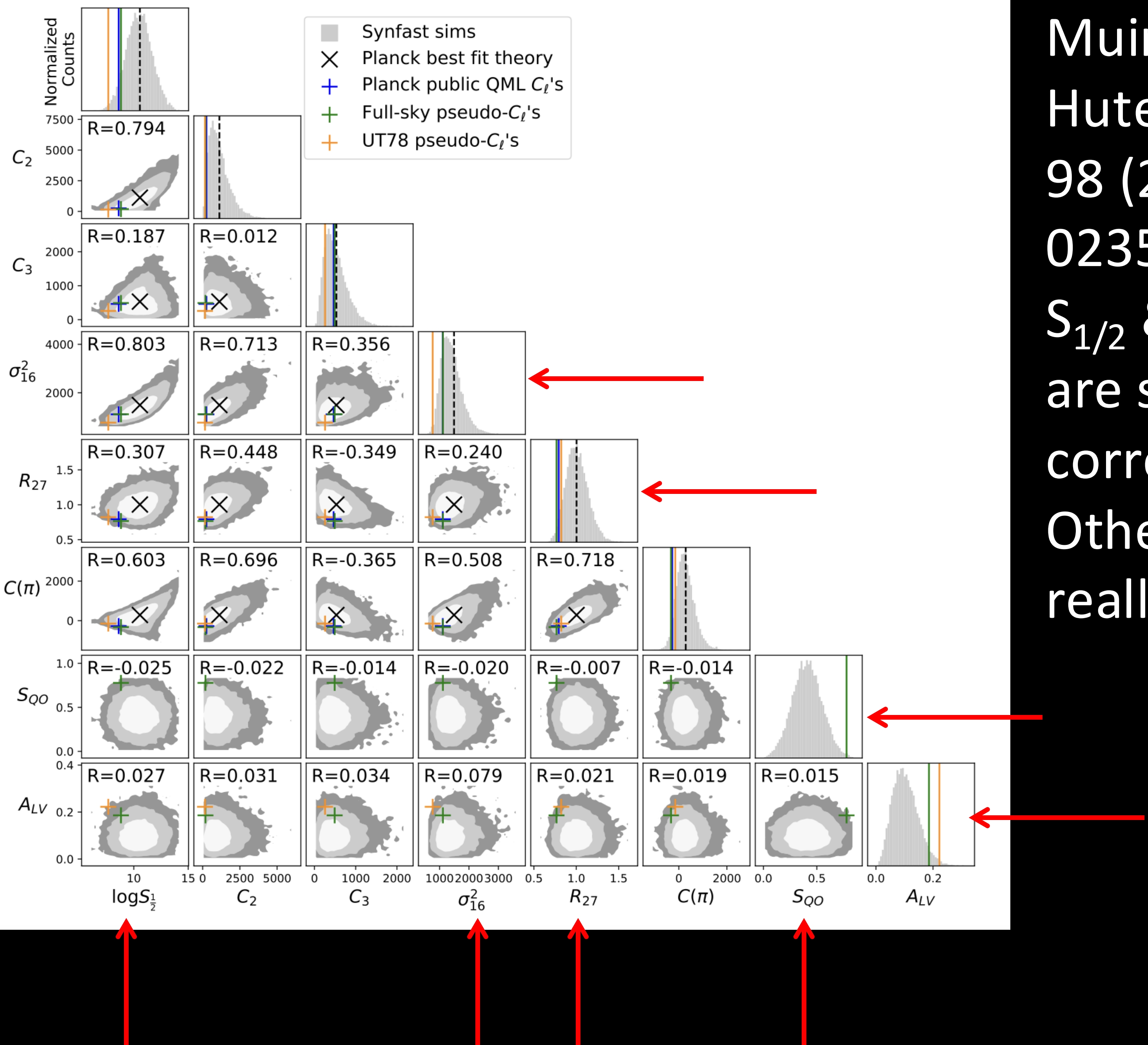
Joann Jones, Craig J. Copi, Glenn D. Starkman, Yashar Akrami

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



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

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

Others, not really

Four "representative" anomaly statistics:

- **$S_{1/2}$** – lack of large-angle correlations, $p \simeq 10^{-3}$
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in Planck 2018 Commander, NILC, SEVEM, SMICA

But are they correlated in the <u>tails</u> of their pdfs?

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 >5σ in CMB TT correlations!

Discuss:

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

Look elsewhere penalties vs. look more closely rewards

Look elsewhere penalties vs. look more closely rewards

$S_{1/2}$ – lack of large-angle correlations, $p \simeq 10^{-3}$

Look elsewhere:

- **why 60^0? why 180^0? why $C(\theta)^2$? why $d\ cos\theta$?**

Look more closely:

- $p(S^{EE}_{1/2}) \sim 10^{-3}$

Look elsewhere penalties vs. look more closely rewards

$\boldsymbol{\sigma_{16}^2}$ – low northern variance, $p \simeq 3 \times 10^{-3}$

Look elsewhere:

- **why N? why ecliptic? why N_{side}=16?**

Look more closely: (Planck 2013 Isotropy and Statistics)

- **ecliptic not optimum, galactic also ~0.003**
- **p(low (north) skewness, N_{side}=32) = 0.02-0.03**
- **p(high kurtosis, N_{side}=32) = 0.03**

Look elsewhere penalties vs. look more closely rewards

- **R_{TT}** – odd-parity preference, $p \simeq 0.01 - 0.05$

Look elsewhere:

- **why ℓ_{max}=27? why odd>even not even>odd**

Look more closely:

- **first 9 consecutive pairs $C_{2\ell+1} > C_{2\ell}, \ell = 1, \ldots, 9$; estimate $p \sim 2 \times 2^{-9} \approx 0.004$ (w. look-elsewhere)**

Look elsewhere penalties vs. look more closely rewards

- **S_{QO}** – quadrupole-octupole alignment, $p \simeq 4 \times 10^{-(2-4)}$

Look elsewhere:

- **??**

Look more closely:

- **"axis of evil" ℓ=2-5 (Land & Magueijo PRL95 (2005) 071301)**
- **"uncanny correlation of azimuthal phases between ℓ=3 & ℓ=5. (*ibid.*)**
- **oriented areas ℓ=2-8 inconsistent at 0.2% (Copi, Huterer, Starkman PRD 70 (2004) 043515)**

Look-elsewhere penalty estimate

- two ~3$\boldsymbol{\sigma}$ combinations: $S_{1/2}$ (0.0015), S_{QO}(0.004)
- two ~2$\boldsymbol{\sigma}$ combinations: $\boldsymbol{\sigma}_{16}{}^2$| $S_{1/2}$ (0.08), R_{TT} (0.03)
- Look elsewhere
- $\left[\frac{2\pi^{\frac{n}{2}} r^{n-1}}{\Gamma\left(\frac{n}{2}\right)}\right] \boldsymbol{\Delta} r,\, n = 4,\, r = \sqrt{3 * 2},\, \boldsymbol{\Delta} r \approx 1/r$: ~120

Stat.	Value	$S_{1/2}$	R^{TT}	σ^2_{16}	S_{QO}
			Commander		
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Look-more-closely reward estimate

- $p(S_{1/2}^{EE})$ ~ 10^{-3}
- p(low (north) skewness, N_{side}=32) ~ 0.03
- R_{TT} vs. $C_{2\ell+1} > C_{2\ell}$, $\ell = 1, \dots, 9$;p~ $\frac{2^{-8}}{0.03} \approx 0.13$
- Extra correlation w ℓ>3 – p~ 0.1

- **Collectively < 10^{-6}**

The CMB sky is NOT a realization of a Statistically Isotropic physical system

The End?

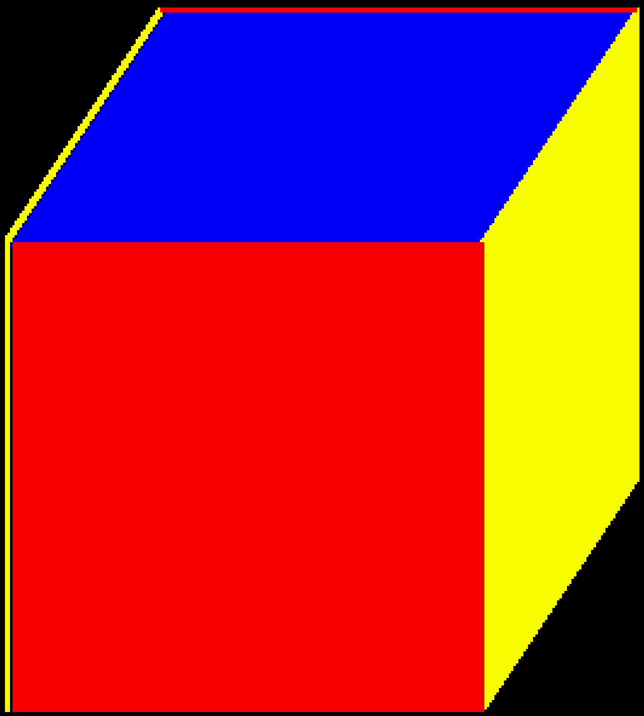
New Models

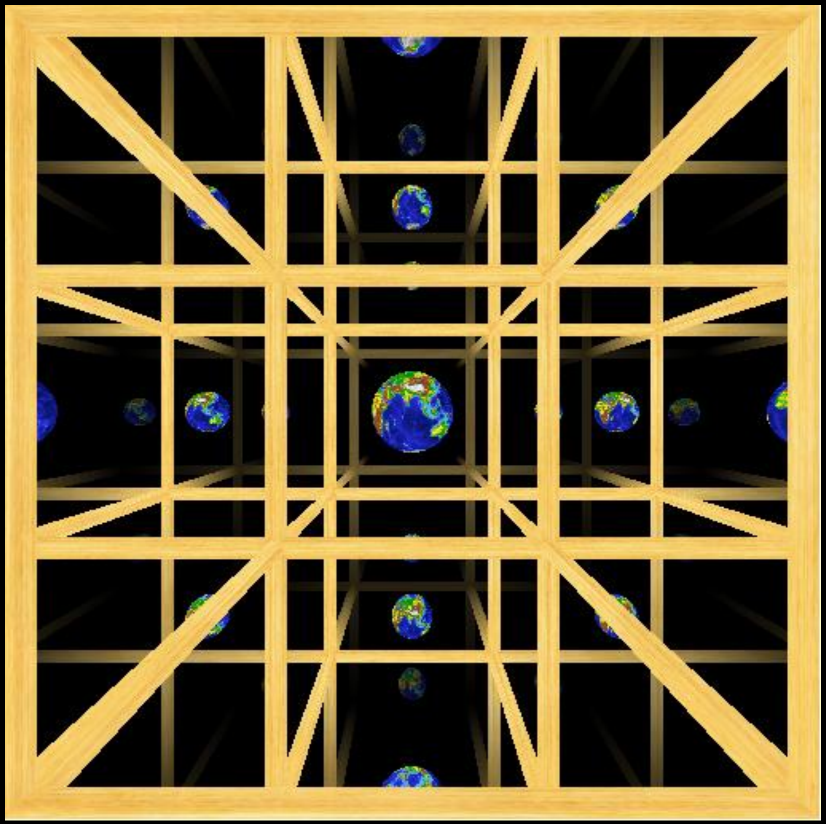
New Models

Physics phenomena that break isotropy and are <u>already in our theory</u>:

Non-trivial cosmic topology

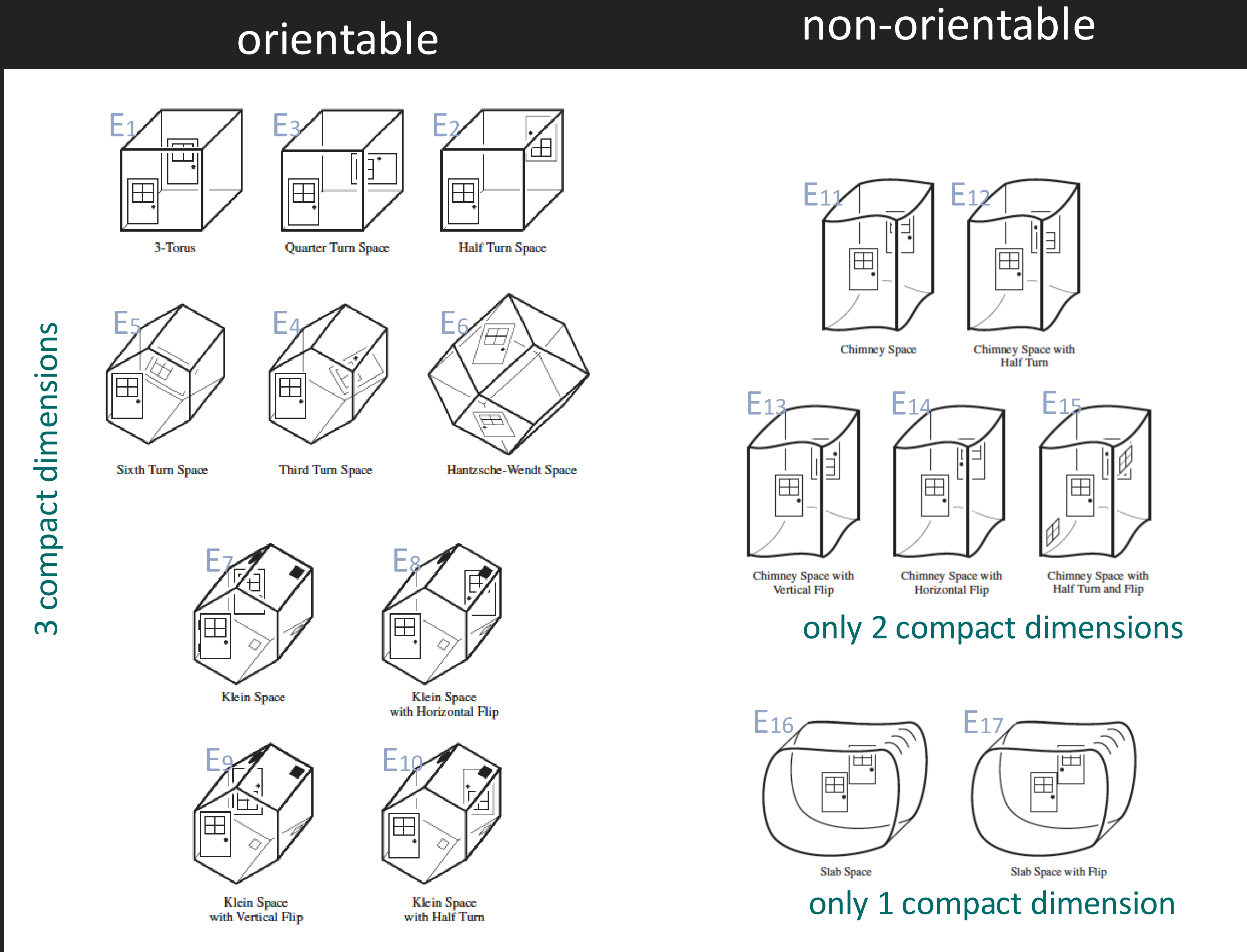
3-torus





Same idea works in three space dimensions

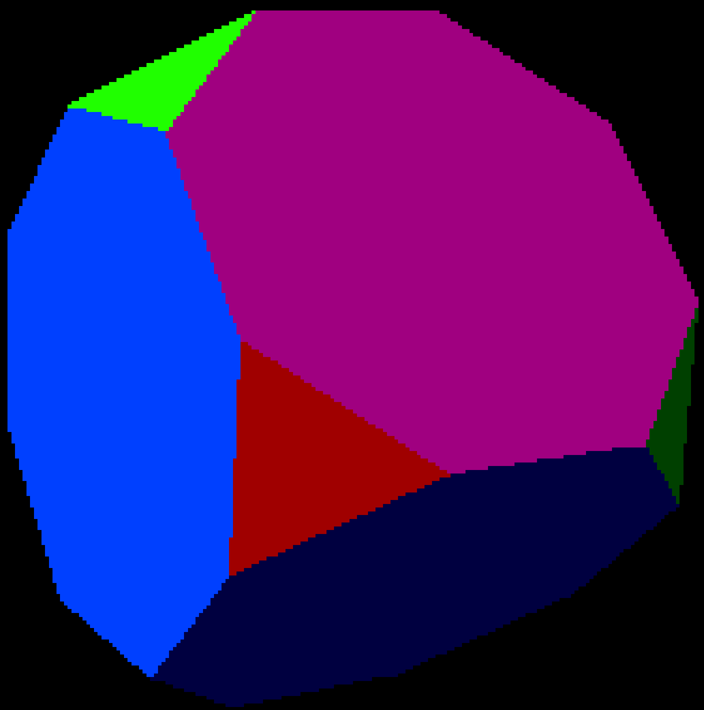
17 NON-TRIVIAL EUCLIDEAN TOPOLOGIES

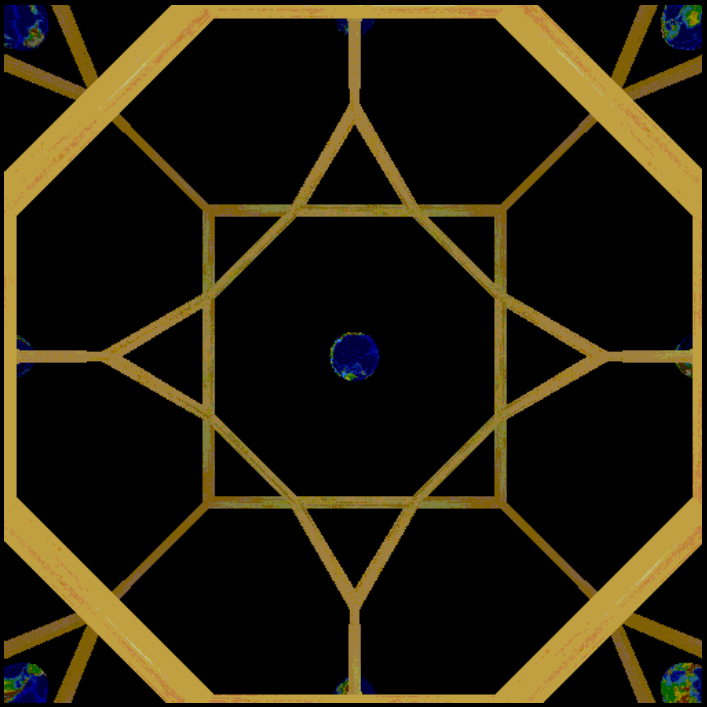


Riazuelo et al. Phys.Rev. D69 (2004) 103518 [arXiv:astro-ph/0311314]

spherical topologies

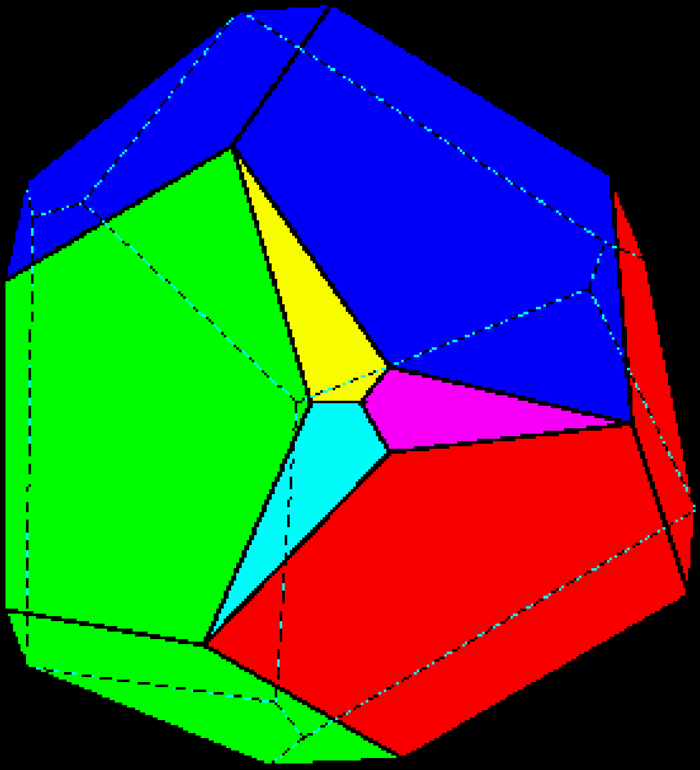
This example only works in spherical space

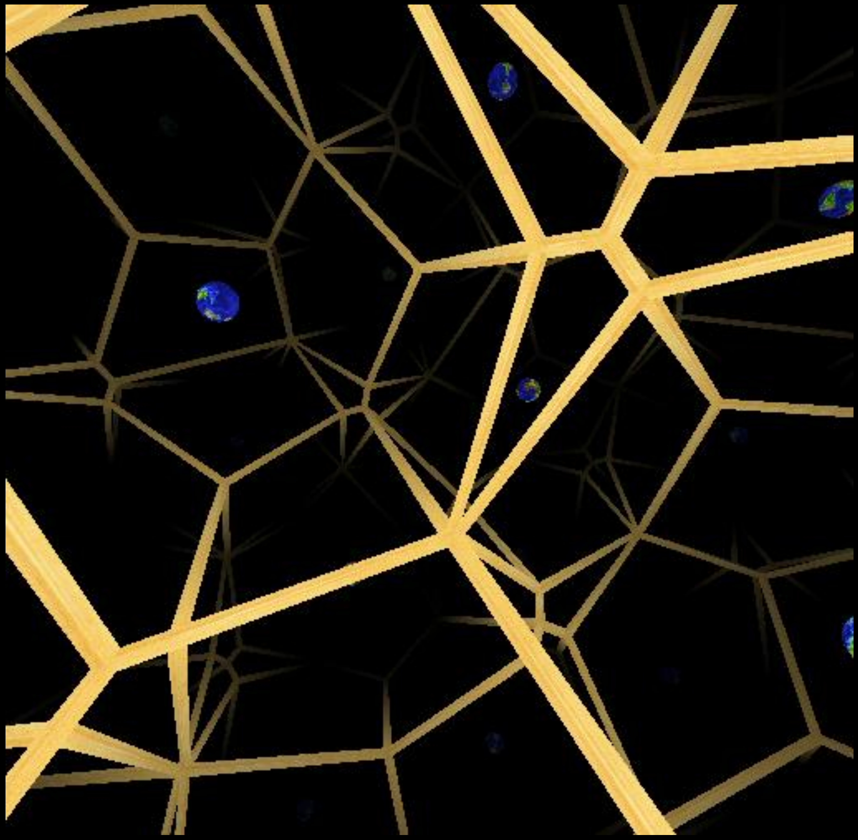




countable infinity of S^3 topologies

infinite number of tiling patterns





This one only works in hyperbolic space

countable infinity of H^3 topologies

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.

PRL132 (2024) 17, 17

Parallel session:

- Andrius Tomasiunas: ML searches for topology
- Deyan Mihaylov: circle searches for topology
- Benjamin Muntz: Is this the End of the World?
- Mikel Martin: topology and CMB polarization

A new and very odd foreground?

A&A, 696, A184 (2025)
https://doi.org/10.1051/0004-6361/202453117

Astronomy & Astrophysics

A $p < 0.0001$ detection of cosmic microwave background cooling in galactic halos and its possible relation to dark matter

Frode K. Hansen[1,★], Diego Garcia Lambas[2,3,4], Heliana E. Luparello[2], Facundo Toscano[2], and Luis A. Pereyra[2]

arXiv > astro-ph > arXiv:2506.08832

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 10 Jun 2025]

Evidence for a sign change of the ISW effect in the very recent universe: hot voids and cold overdensities at $z < 0.03$

Frode K. Hansen, Diego Garcia Lambas, Andrés N. Ruiz, Facundo Toscano, Luis A. Pereyra

No proven "model" so far:

- ~~Systematics~~
- Foreground? – weird & makes it worse
- Cosmology – topology?

Would this explain anomalies?

Quadrupole-octopole alignment:
  if the local LSS has that alignment
  and intrinsic C_2 & C_3 even lower!

Low N-variance
  more local LSS in S => low N+S variance!

Lack of large-angle correlations:
  makes worse?

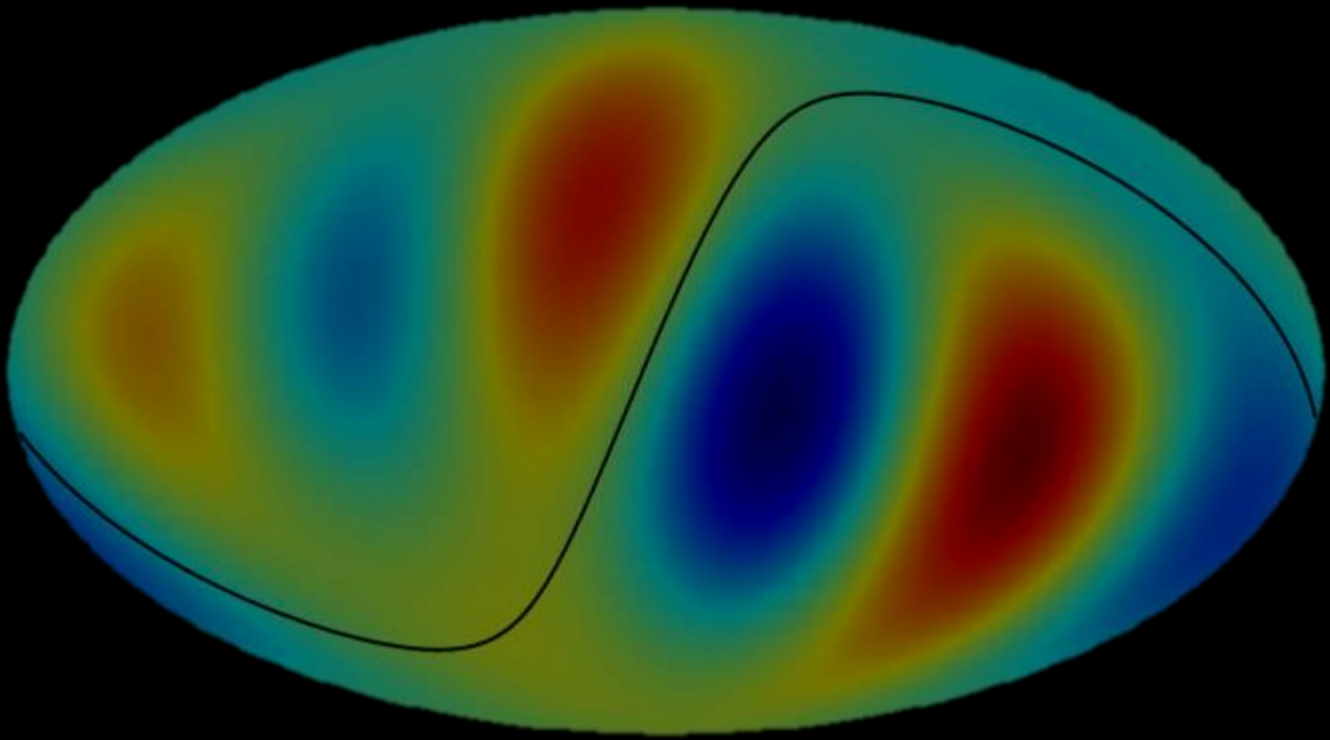
Parity: not clear

SUMMARY

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

The Universe is NOT Statistically Isotropic

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