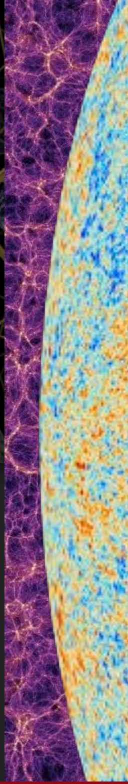
Large-Scale Cosmic anomalies



Current Status, Future Prospects, and Possible Explanations

Yashar Akrami

Instituto de Física Teórica (IFT) UAM-CSIC, Madrid, Spain
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CMB@60
Accademia delle Scienze di Torino
May 30, 2025

Instituto de Física Teórica UAM-CSIC

EXCELENCIA SEVERO OCHOA

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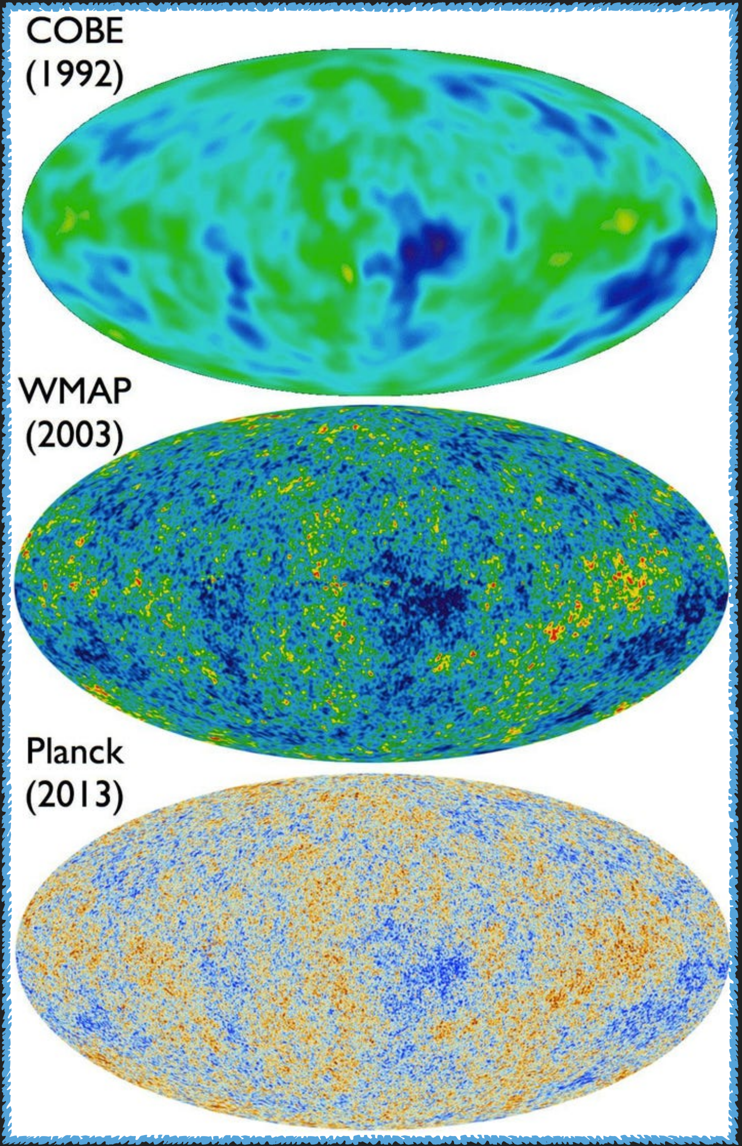
COSMIC MICROWAVE BACKGROUND (CMB)



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

Our standard model for the fluctuations (inflation):

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

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

Angular Power Spectrum

For full sky observations, **all** interesting information is contained in the estimator:

$$\hat{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

MEASURED ANGULAR POWER SPECTRA

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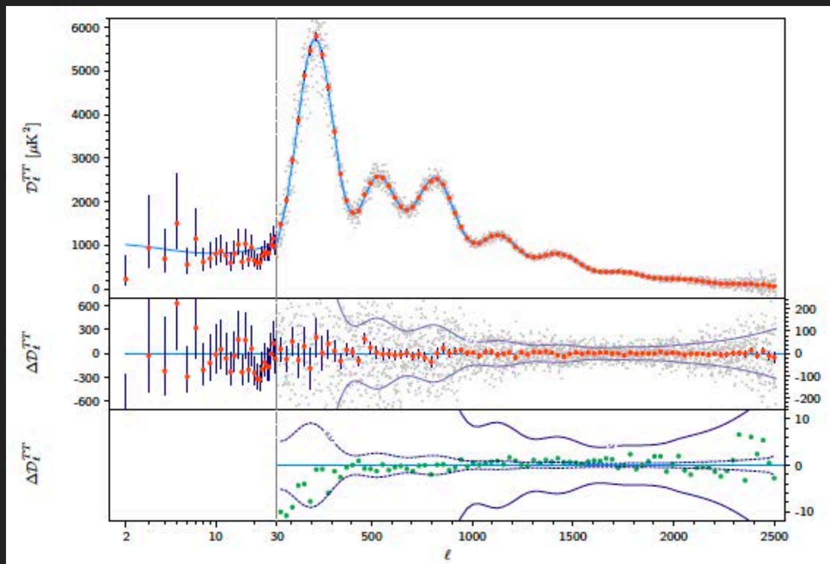
T T



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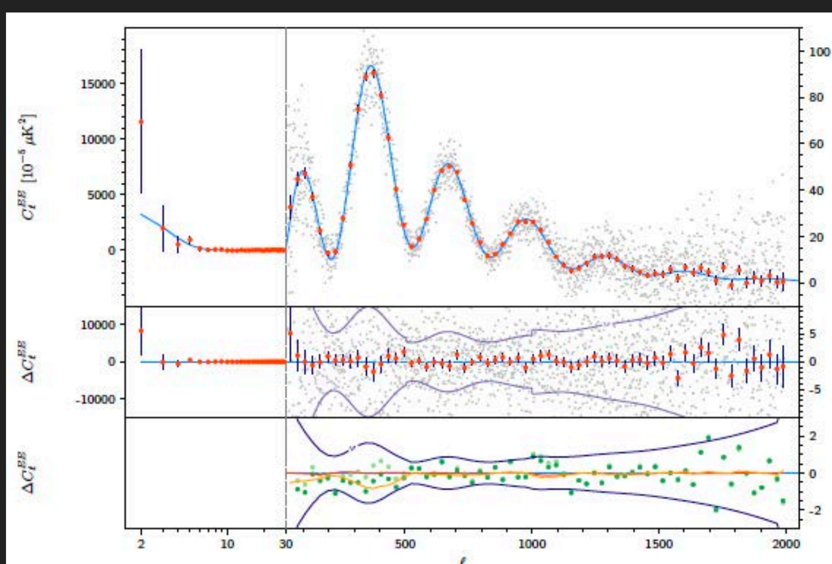

6-parameter fit to ≫6 points

- This is ASTONISHING experimental accomplishment.
- It shows REMARKABLE agreement with theory.

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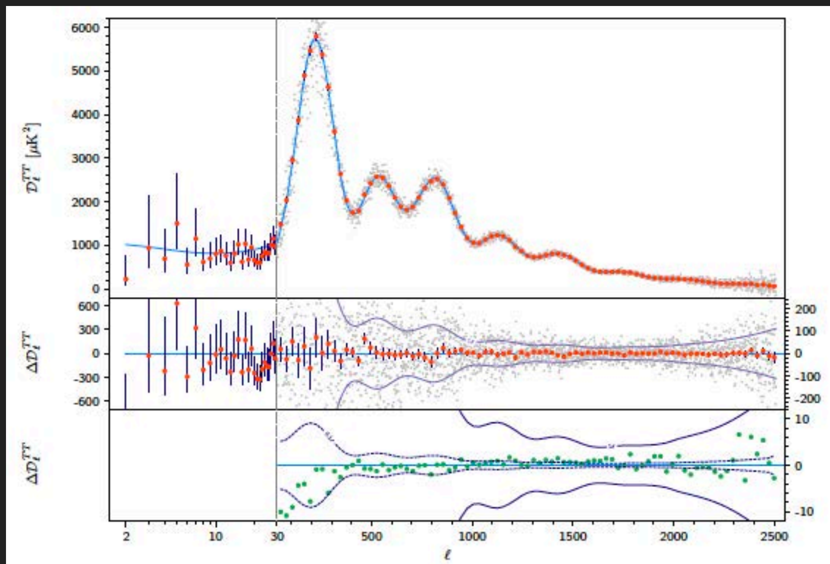

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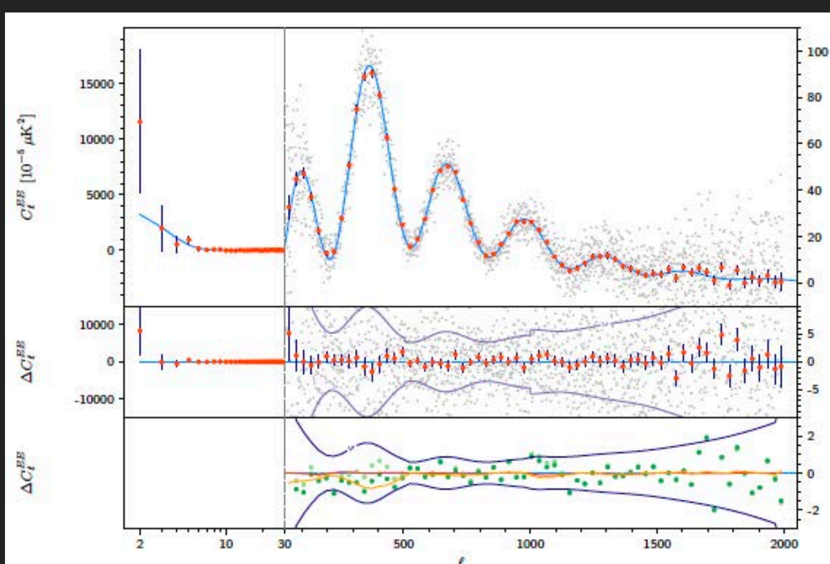

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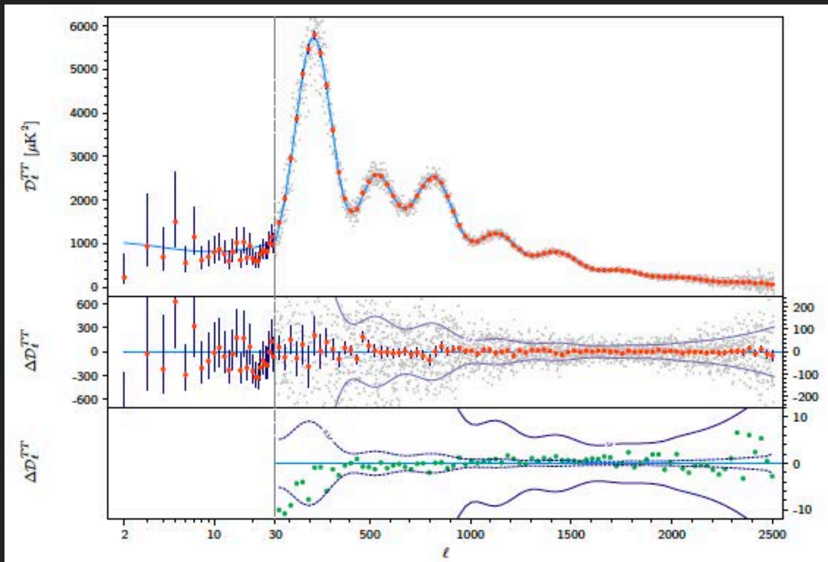

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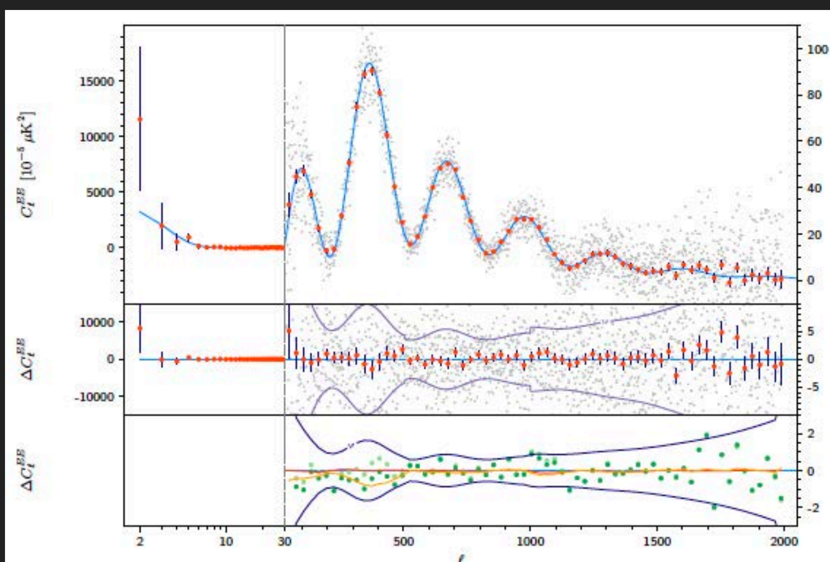

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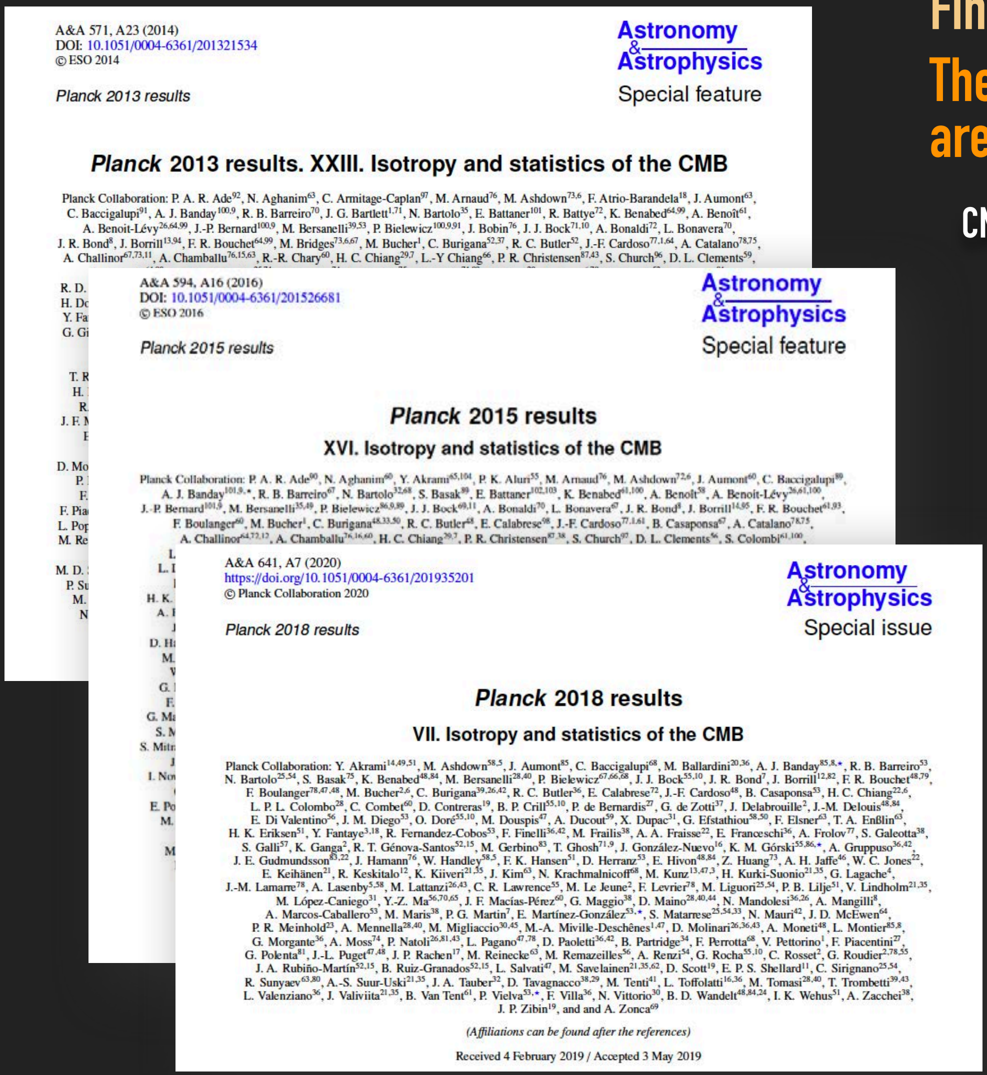
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See:

E. Abdalla et al., JHEAp 34 (2022) 49-211
Schwarz, Copi, Huterer, Starkman, Class.Quant.Grav. 33 (2016) 18

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Comprehensive and critical invited review for Physics Reports

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Almost everyone agrees now that these are real features on our CMB temperature sky and are not instrumental noise (as both WMAP and Planck found them) or foreground effects (as all component-separated maps found them).

Question:

Should we care? Are they hints of new physics?

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In preparation:

Comprehensive and critical invited review for Physics Reports

FOUR “REPRESENTATIVE” ANOMALY STATISTICS:

J. Jones, C. J. Copi, G. D. Starkman, Y. A. [arXiv:2310.12859]

$S_{1/2}$ — lack of large-angle correlations: $p \simeq 10^{-3}$
R_{TT} — odd-parity preference: $p \simeq 0.01 - 0.05$
σ^2_{16} — 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

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in Planck 2018 Commander, NILC, SEVEM, SMICA

1. Are they correlated in the tails of their pdfs?
2. What is their joint p-value?

- No cherry-picking or fine-tuning
- We took the statistics exactly as they were being used before

5σ Evidence Against a Gaussian Random Statistically Isotropic Universe

Joann Jones,[1,2,*] Craig J. Copi,[1,†] Glenn D. Starkman,[1,‡] and Yashar Akrami[3,1,§]

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(Dated: May 29, 2025)

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. We study the tail values of these statistics and find very little correlation among them. We show that the joint probability of all four anomalies occurring by chance in ΛCDM is likely $\leq 3\times10^{-8}$. We balance the impact of look-elsewhere effects and the existence of other anomalies on the significance of this result. We conclude that the anomalies should not be dismissed as flukes within ΛCDM.

jointly > 5σ significant!

The sky appears NOT to be a typical realization of a Gaussian random statistically isotropic field.

J. Jones, C. J. Copi, G. D. Starkman, Y. A. [arXiv:2310.12859]

10^8 realizations of CMB in best-fit ΛCDM

pairwise correlations

Stat.	Value	$S_{1/2}$	R^{TT}	σ^2_{16}	S_{QO}
			Commander		
$S_{1/2}$	1272	1.5×10^{-3}	×0.6	×27	×1.3
R^{TT}	0.7896	2.8×10^{-5}	3.0×10^{-2}	×1.1	×1.0
σ^2_{16}	617.6	1.2×10^{-4}	1.0×10^{-4}	3.1×10^{-3}	×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}	×0.4	×29	×1.3
R^{TT}	0.7448	4.8×10^{-6}	1.0×10^{-2}	×1.0	×1.0
σ^2_{16}	605.9	9.2×10^{-5}	2.4×10^{-5}	2.5×10^{-3}	×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}	×0.8	×33	×1.2
R^{TT}	0.8194	5.6×10^{-5}	5.4×10^{-2}	×1.2	×1.0
σ^2_{16}	583.4	6.5×10^{-5}	1.0×10^{-4}	1.6×10^{-3}	×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}	×0.6	×25	×1.3
R^{TT}	0.7906	2.8×10^{-5}	3.0×10^{-2}	×1.1	×1.0
σ^2_{16}	631.0	1.4×10^{-4}	1.3×10^{-4}	3.9×10^{-3}	×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}	×1.7
S_{QO}	9.1×10^{-7}	4.4×10^{-3}
	NILC	
$S_{1/2}$ and σ^2_{16}	9.2×10^{-5}	×0.6
S_{QO}	2.0×10^{-8}	3.9×10^{-4}
	SEVEM	
$S_{1/2}$ and σ^2_{16}	6.5×10^{-5}	×1.3
S_{QO}	3.6×10^{-6}	4.1×10^{-2}
	SMICA	
$S_{1/2}$ and σ^2_{16}	1.4×10^{-4}	×2.1
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Are the anomalies correlated in ΛCDM?

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

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Answer: only weakly

Our conclusion:

A Gaussian random statistically isotropic universe 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

The typical justification of a 5σ threshold for discovery is that it overwhelms even strong look-elsewhere concerns.

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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:

- $p(S_{1/2}^{EE}) \sim 10^{-3}$ [Chiocchetta et al., JCAP 08 (2021) 015]

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

Look elsewhere:

- why $\ell_{max}=27$? 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 $p \sim 2\times2^{-9} \approx 0.004$ (w. look-elsewhere)

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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

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Look elsewhere:

- ??

Look more closely:

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

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rns.

Loo

$S_{1/2}$

Loo

•

Loo

•

R_{TT}

Loo

•

Loo

•

While the cosmic orchestra may be playing the ΛCDM symphony, somebody gave the bass and tuba the wrong score.

They're trying very hard to keep quiet about it.

But we must demand an explanation.

Starkman PRD 70 (2004) 043515]

WITH SO MANY ANOMALIES, WHAT DO WE DO?

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Physics explanations:

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Making progress:

1. Test the "fluke hypothesis" (i.e. test ΛCDM!)
   - Philosophy: assume ΛCDM is correct and see how the measured anomalies affect predictions for other observables (like CMB polarization, large-scale structure, etc).
2. Make reasonable phenomenological extrapolations and test them.
   - Philosophy: assume each anomaly is "physical" and guess what that implies for other observables
3. Find a fundamental physics model, make testable predictions.

FUNDAMENTAL PHYSICS MODELS TO EXPLAIN CMB ANOMALIES

Requirements:

1. Break statistical isotropy
   $\Longrightarrow$ Generate nonzero off-diagonal elements in harmonic-space 2-point correlations

$$C_{\ell m \ell' m'} \equiv \langle a_{\ell m} a^*_{\ell' m'} \rangle$$

2. Affect scales that were causally disconnected until recently

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Our best bet: change of boundary conditions

$\Longrightarrow$ cosmic topology

FUNDAMENTAL PHYSICS MODELS TO EXPLAIN CMB ANOMALIES

Requirements:

COMPACT Collaboration, JCAP 03 (2024) 036

Symbol	Name	Compact Dimensions	Orientable	Homogeneous	Isotropic
E_1	3-torus	3	Yes	Yes	No
E_2	Half-turn	3	Yes	No	No
E_3	Quarter-turn	3	Yes	No	No
E_4	Third-turn	3	Yes	No	No
E_5	Sixth-turn	3	Yes	No	No
E_6	Hantzsche-Wendt	3	Yes	No	No
E_7	Klein space	3	No	No	No
E_8	— (horizontal flip)	3	No	No	No
E_9	— (vertical flip)	3	No	No	No
E_{10}	— (half-turn)	3	No	No	No
E_{11}	Chimney space	2	Yes	Yes	No
E_{12}	— (half-turn)	2	Yes	No	No
E_{13}	— (vertical flip)	2	No	No	No
E_{14}	— (horizontal flip)	2	No	No	No
E_{15}	— (half-turn + flip)	2	No	No	No
$E_{16}^{(h)}$	Slab (unrotated)	1	Yes	Yes	No
$E_{16}^{(i)}$	Slab (rotated)	1	Yes	No	No
E_{17}	Slab (flip)	1	No	No	No
E_{18}	Covering space	0	Yes	Yes	Yes

$'m'\rangle$

It is

Our

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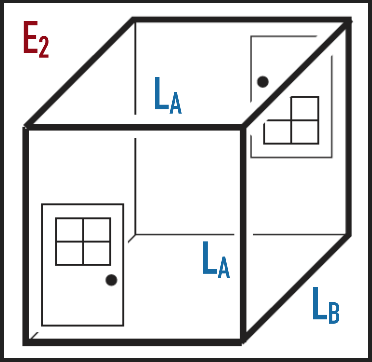
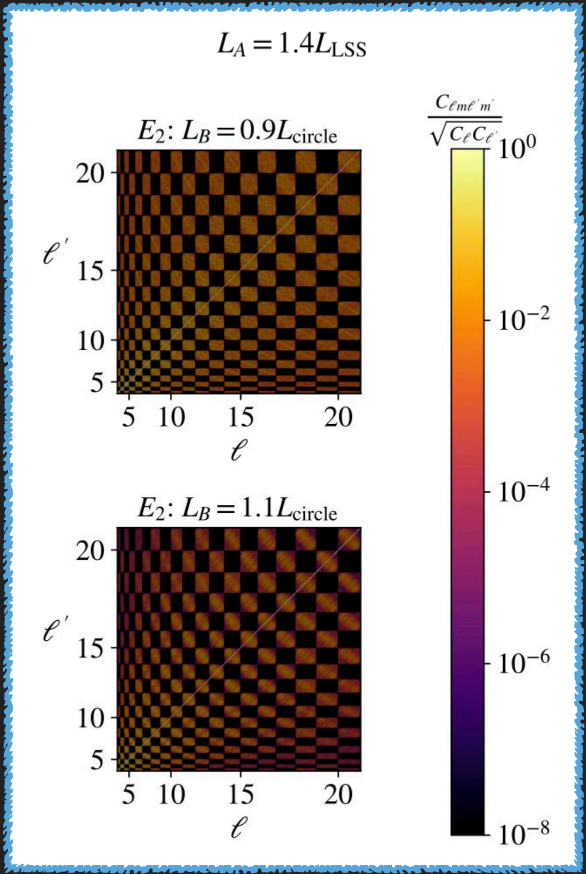
AN EXAMPLE:





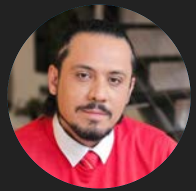
COMPACT Collaboration, arXiv:2210.11426, arXiv:2306.17112

COMPACT

[international theoretical collaboration founded by me and Glenn Starkman in 2022]

Collaboration for Observations, Models and Predictions of Anomalies and Cosmic Topology

A 10-year program to use all cosmological data (CMB, LSS, 21cm) to understand cosmic anomalies, and to discover the topology of the Universe.
(Or demonstrate conclusively that discovering it is beyond our reach for the foreseeable future.)


Yashar AKRAMI


Craig COPI


Andrew JAFFE


Arthur KOSOWSKY


Thiago PEREIRA


Glenn STARKMAN


Stefano ANSELMI


Fernando CORNET-GOMEZ


Javier DUQUE


Devan MIHAYLOV


Anna NEGRO


Andrius TAMOSIUNAS


Joline NOLTMANN


Mikel MARTIN


Pilar RENEDO


Amirhossein SAMANDAR


Ananda SMITH


Johannes ESKILT


Valeri VARDANYAN


Pip PETERSEN


Samanta SAHA


Quinn TAYLOR

A highly ambitious plan (currently funded by NASA)

Goals
Motivations
Search strategies

PHYSICAL REVIEW LETTERS 132, 171501 (2024)

Featured in Physics

Promise of Future Searches for Cosmic Topology

Yashar Akrami[1,2,3,*] Stefano Anselmi[4,5,6,†] Craig J. Copi[1,‡] Johannes R. Eskilt[7,3,§] Andrew H. Jaffe[3,‖] Arthur Kosowsky[8,¶] Pip Petersen[1,**] Glenn D. Starkman[1,3,††] Kevin González-Quesada,[1] Özenç Güngör,[1] Deyan P. Mihaylov[1] Samanta Saha,[1] Andrius Tamosiunas[1] Quinn Taylor,[1] and Valeri Vardanyan[9]

(COMPACT Collaboration)

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[3]Astrophysics Group and Imperial Centre for Inference and Cosmology, Department of Physics, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, United Kingdom
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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.

DOI: 10.1103/PhysRevLett.132.171501

COMPACT Collaboration (Y. A. et al.), Phys. Rev. Lett. 132 (2024) 17

(currently funded by NASA)

Johannes ESKILT Valeri VARDANYAN Pip PETERSEN Samanta SAHA Quinn TAYLOR

CONCLUSIONS

There are (large-scale) anomalous features in the CMB temperature sky that are unexpected or extremely unlikely in ΛCDM.

These cosmic anomalies are real and are not instrumental noise or foreground effects.

Their significance is 2.5σ - 4σ individually, but their joint significance in the tails of their distributions is $> 5\sigma$.

The typical justification of a 5σ threshold for discovery is that it overwhelms even strong look-elsewhere concerns.

Almost all of them imply violation of statistical isotropy.

One can/should study them further by testing the standard ΛCDM model, making phenomenological extrapolations, and finding fundamental physics models.

We need to study CMB polarization data, as well as other cosmological observables (LSS, 21cm, etc), to shed light on the nature of anomalies.

We should continue studying the anomalies and try to find more.