Large-Scale Anomalies in the Cosmic Microwave Background

Current Status, Future Prospects, and Possible Explanations

Work in progress in collaboration with:

Glenn Starkman, Craig Copi, Andrew Jaffe, Arthur Kosowsky

Andrius Tamosiunas, Deyan Mihaylov, Valeri Vardanyan

Johannes Eskilt, Ozenc Gungor, Lucas Makinen, Pip Samuel Petersen, Samanta Saha, Quinn Taylor

Yashar Akrami

Instituto de Física Teórica (IFT) UAM-CSIC, Madrid, Spain
Case Western Reserve University, Cleveland, Ohio, USA
Imperial College London, UK

Tensions in Cosmology

Corfu, September 08, 2022

Instituto de Física Teórica UAM-CSIC

Excelencia Severo Ochoa

Gobierno de España

Ministerio de Ciencia, Innovación y Universidades

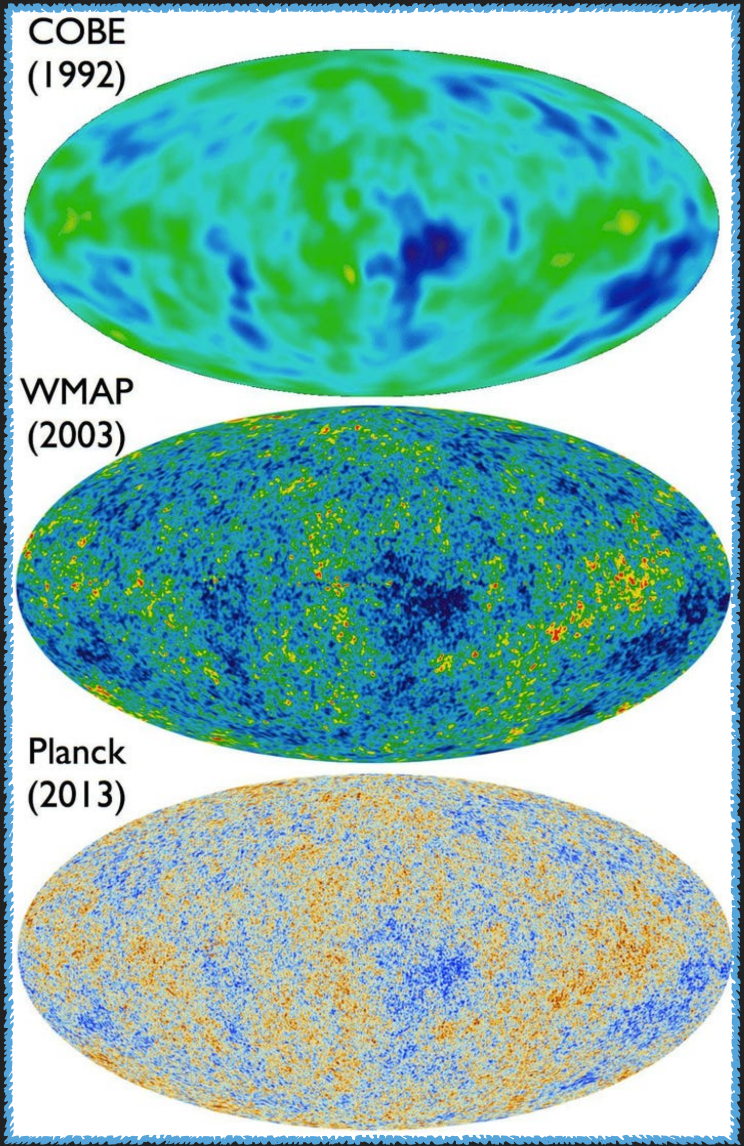
CSIC Consejo Superior de Investigaciones Científicas

UAM Universidad Autonoma de Madrid

Case Western Reserve University Est. 1826

Imperial College London

COSMIC MICROWAVE BACKGROUND (CMB)



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

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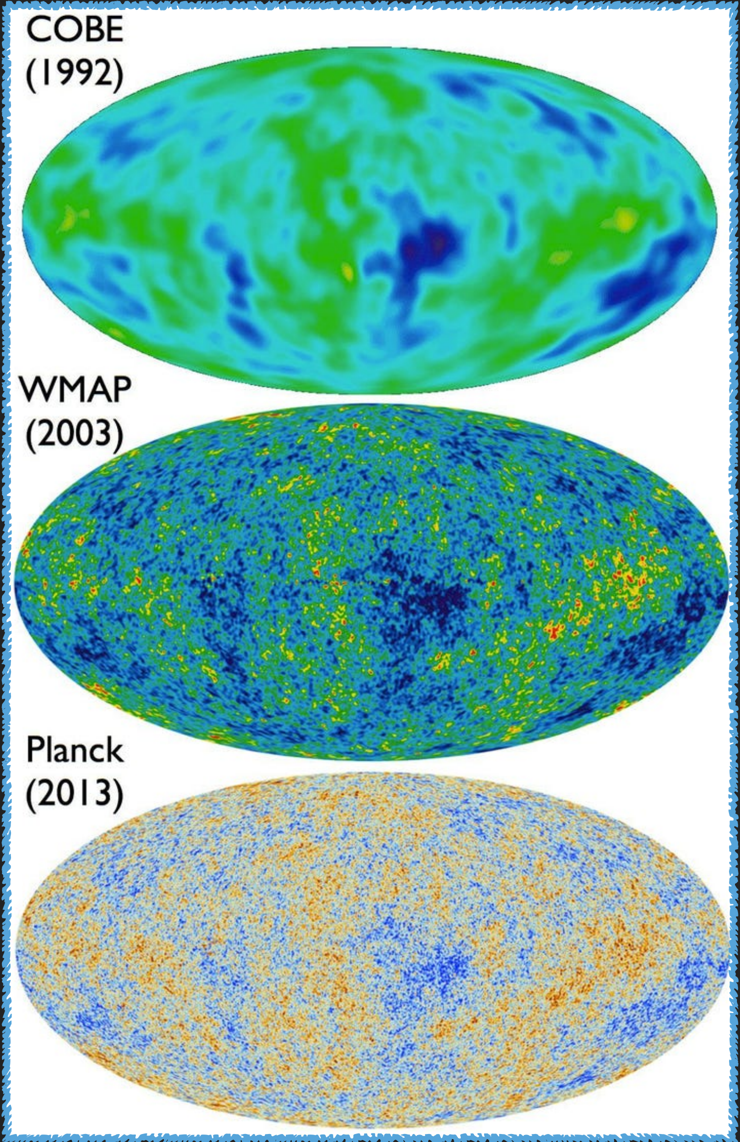

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Standard model for the fluctuations (inflation):

- Sky is statistically isotropic
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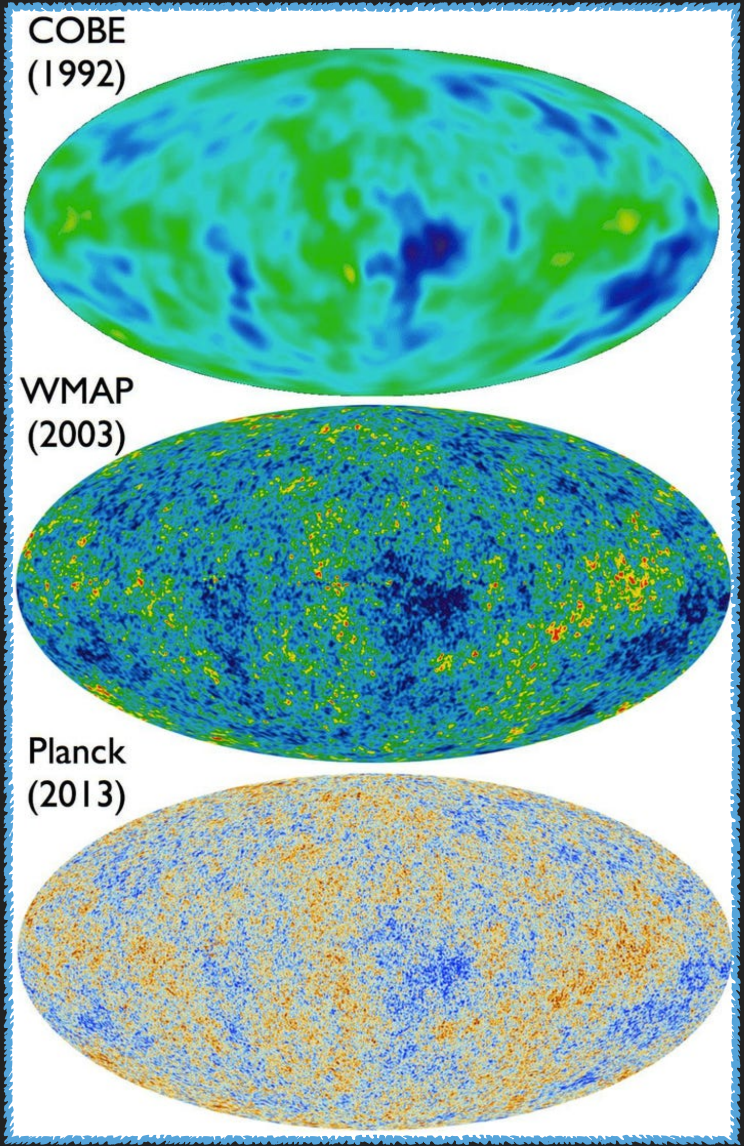

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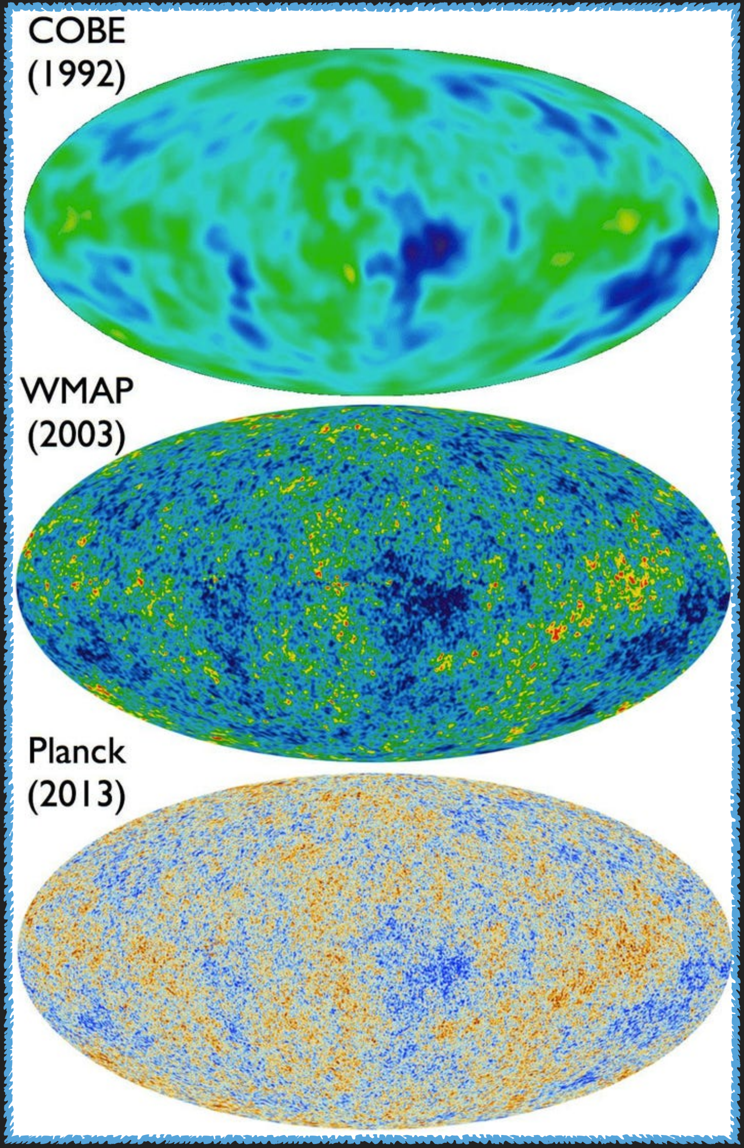

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Angular Power Spectrum

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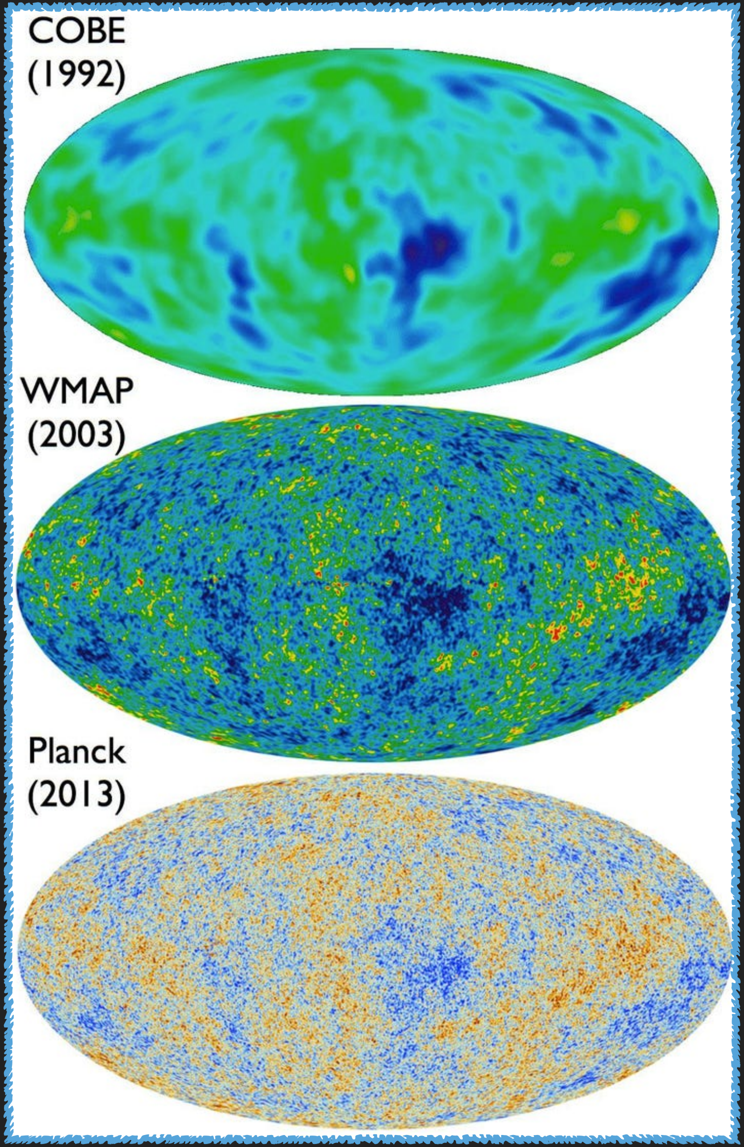

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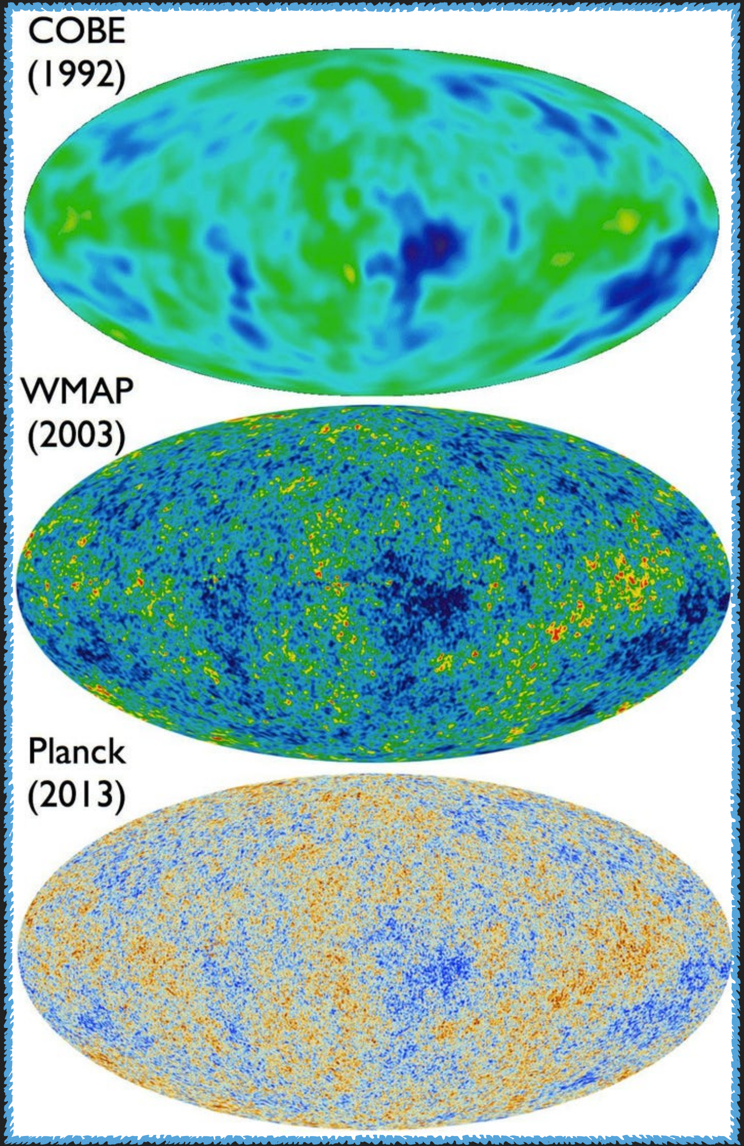

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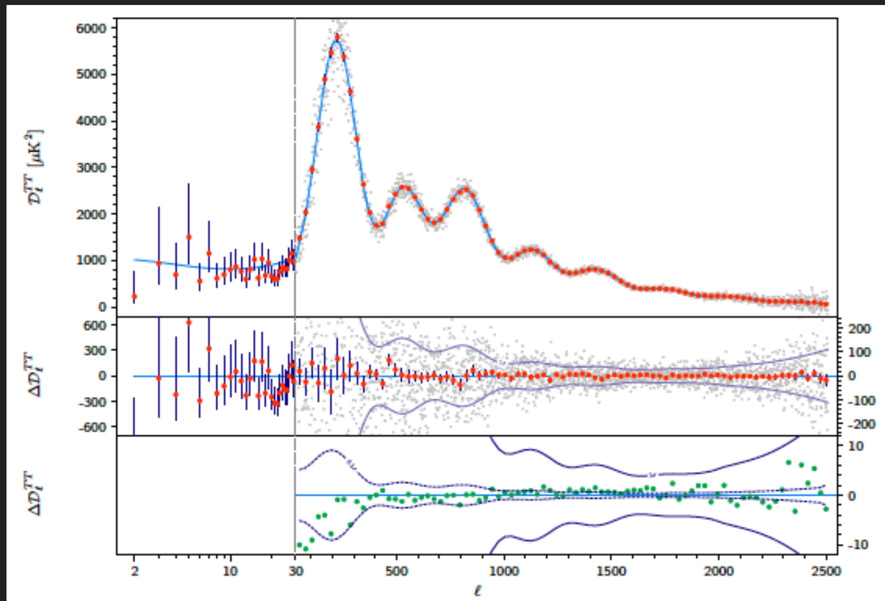
This estimator is unbiased and minimizes variance:

$$\langle \hat{C}_\ell \rangle = C_\ell \qquad \mathrm{Var}[\hat{C}_\ell] = \frac{2}{2\ell+1} C_\ell^2$$

MEASURED ANGULAR POWER SPECTRA

Planck Collaboration A&A 641 (2020) A5 [arXiv:1907.12875]

TT



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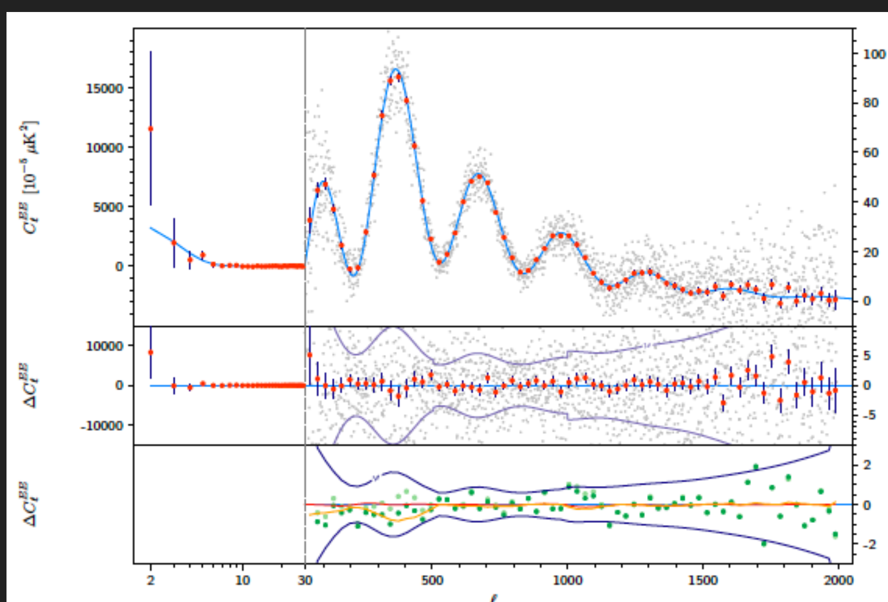

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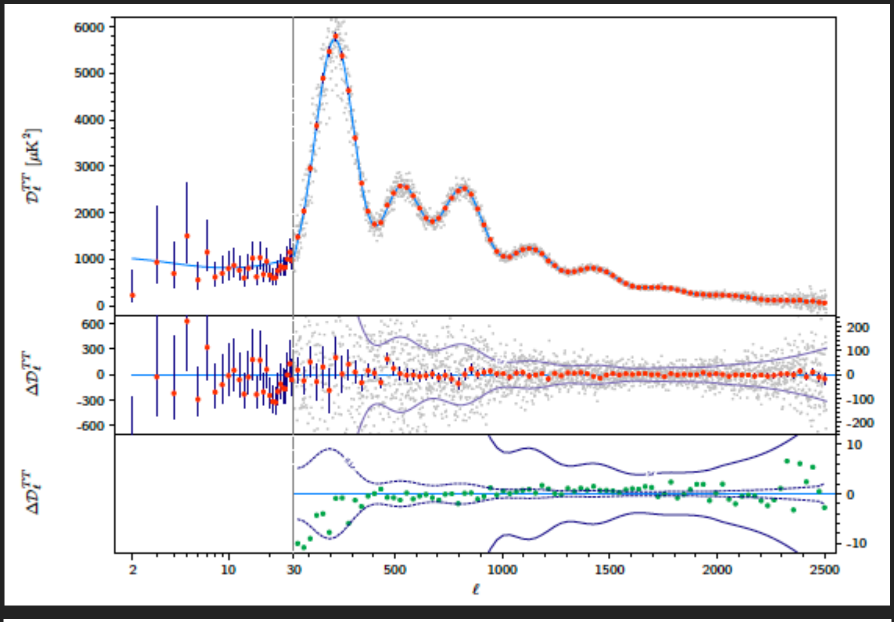

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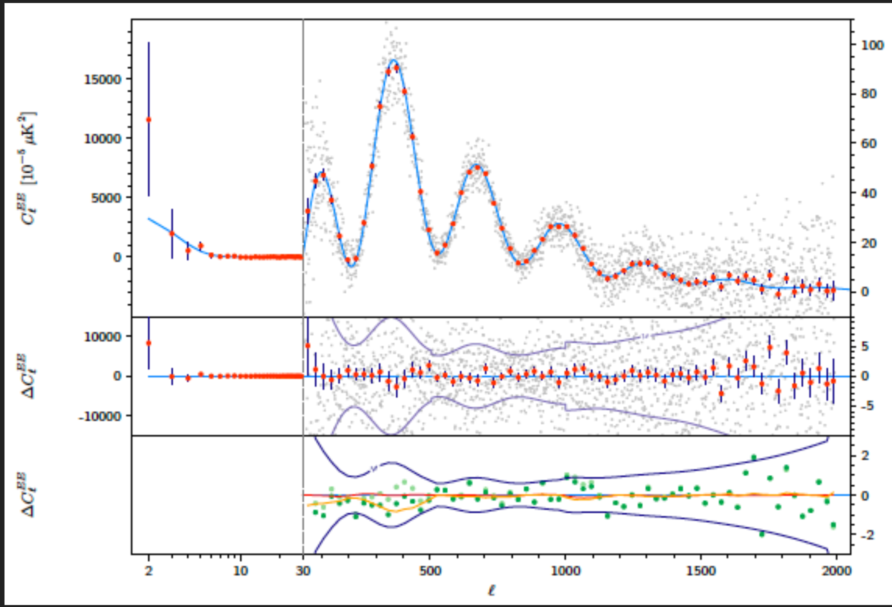

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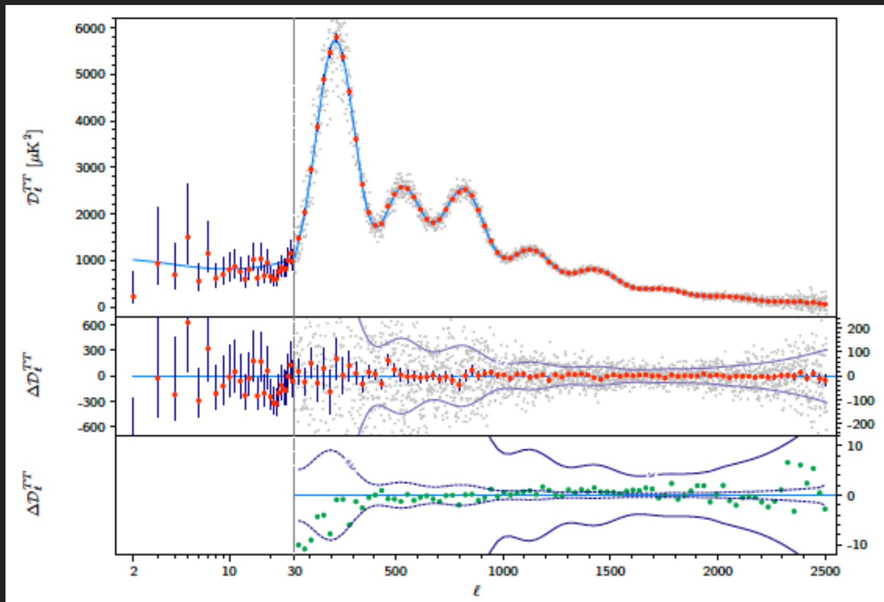

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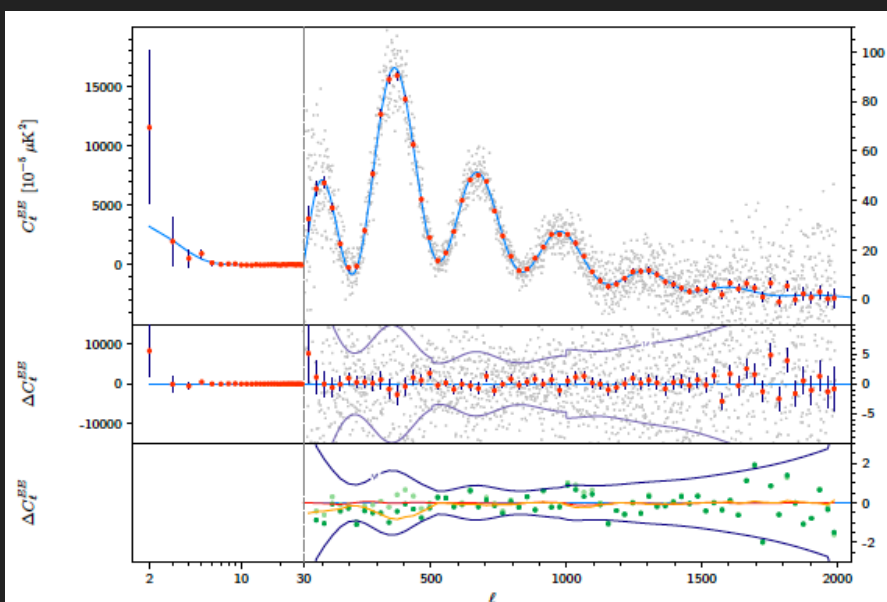

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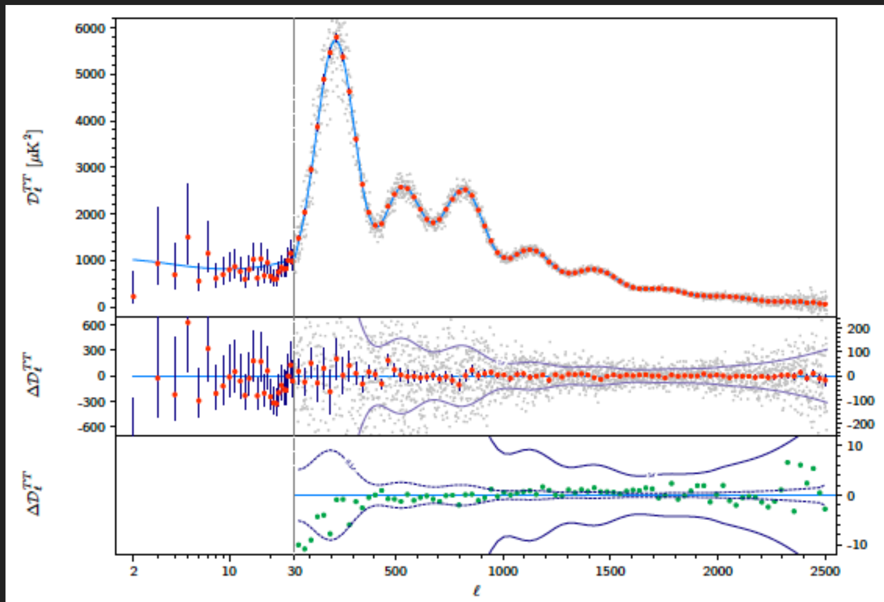

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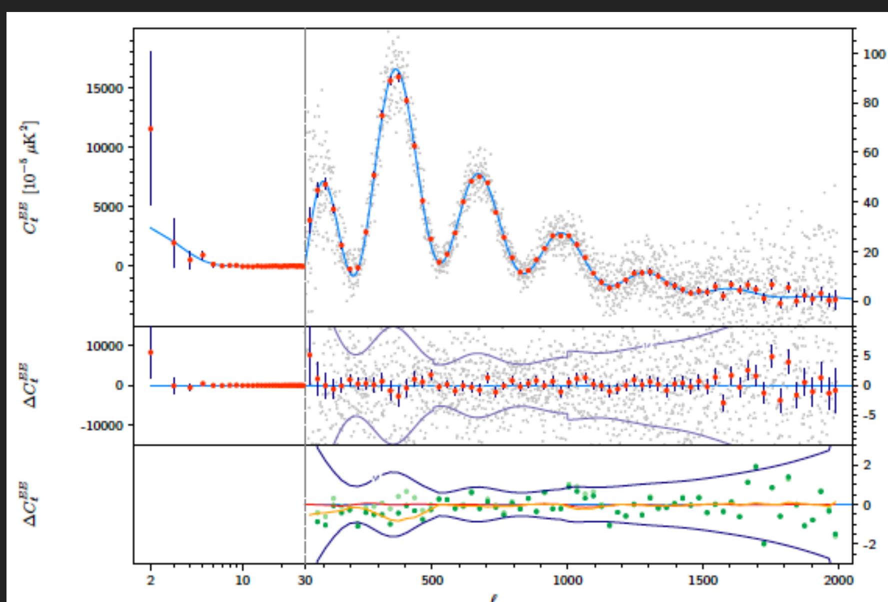

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VII. Isotropy and statistics of the CMB
(Affiliations can be found after the references)
Received 4 February 2019 / Accepted 3 May 2019

Finding:

There are (large-scale) anomalous features that are unexpected or extremely unlikely in ΛCDM

CMB anomalies:

1. The Lack of Large-Angle CMB Temperature Correlations
2. Hemispherical Power Asymmetry
3. Quadrupole and Octopole Alignments
4. Point-Parity Anomaly
5. The Cold Spot
6. …

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All imply violation of statistical isotropy

AN UNCOOPERATIVE UNIVERSE

This has been checked by different groups for both WMAP and Planck data


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In preparation:

Comprehensive and critical review for Physics Reports

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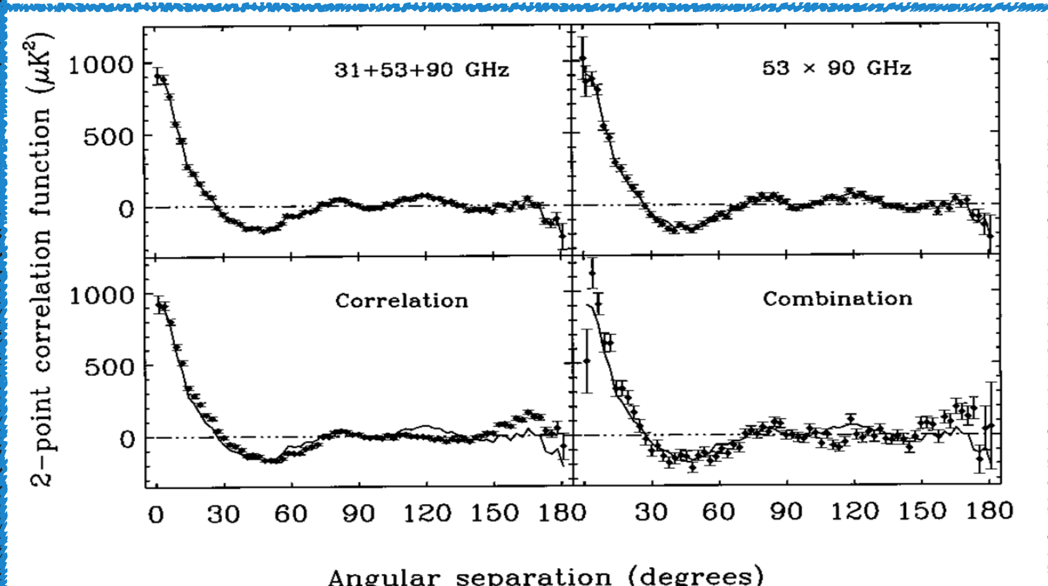
The Astrophysical Journal, 464:L25–L28, 1996 June 10

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



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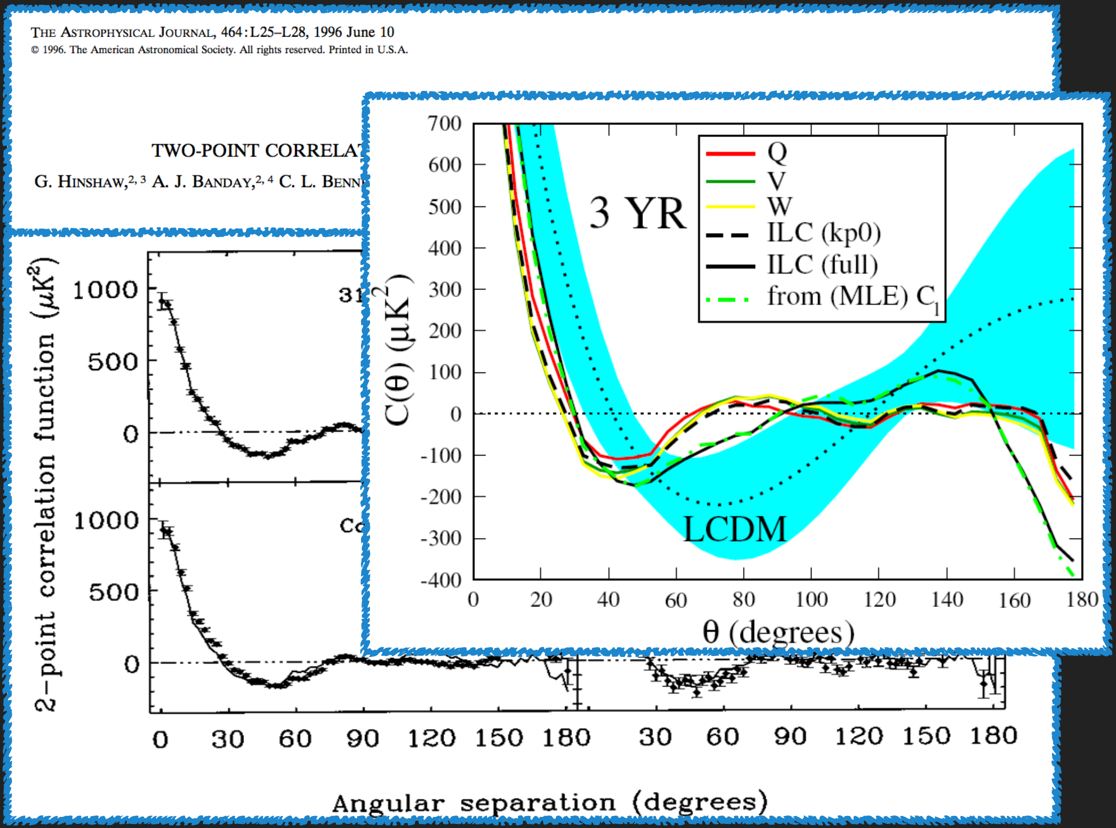

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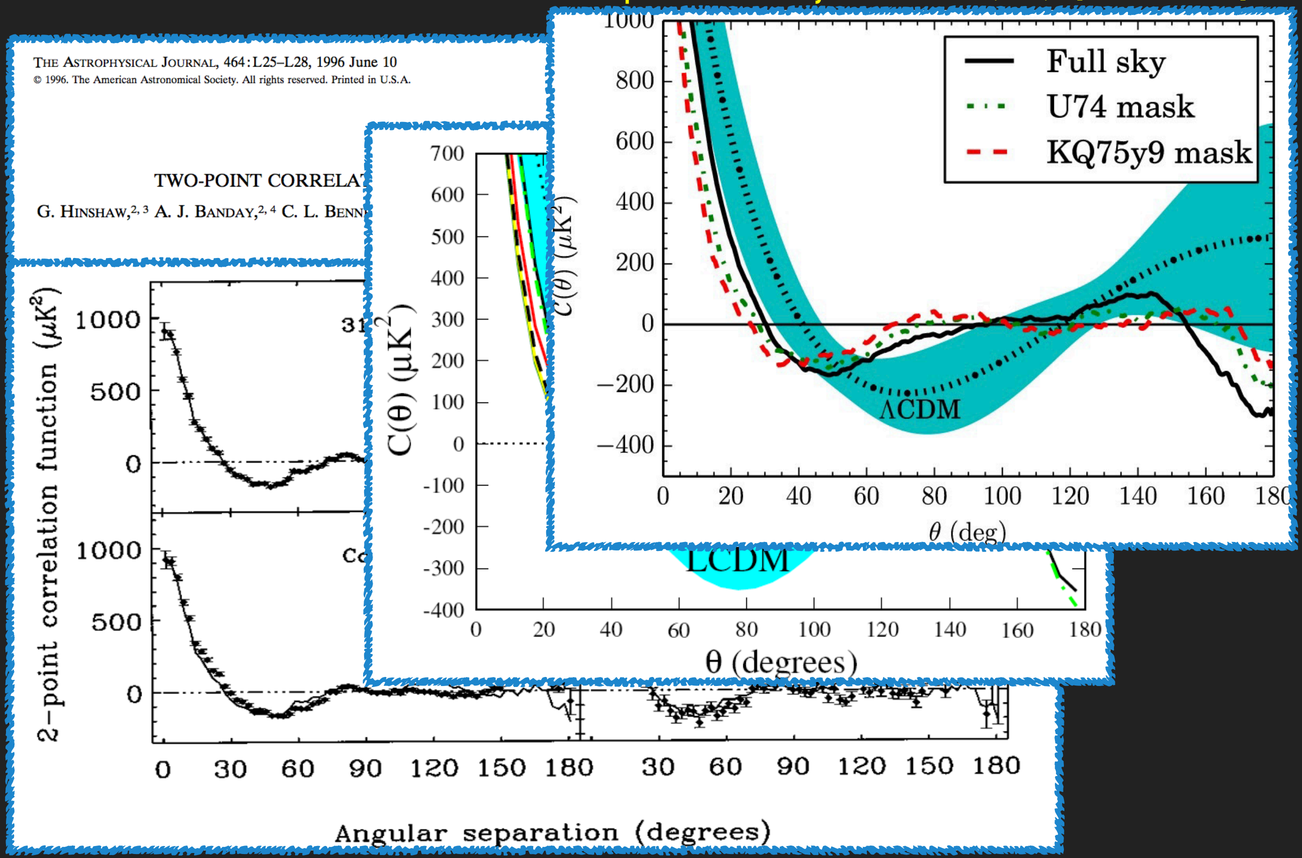

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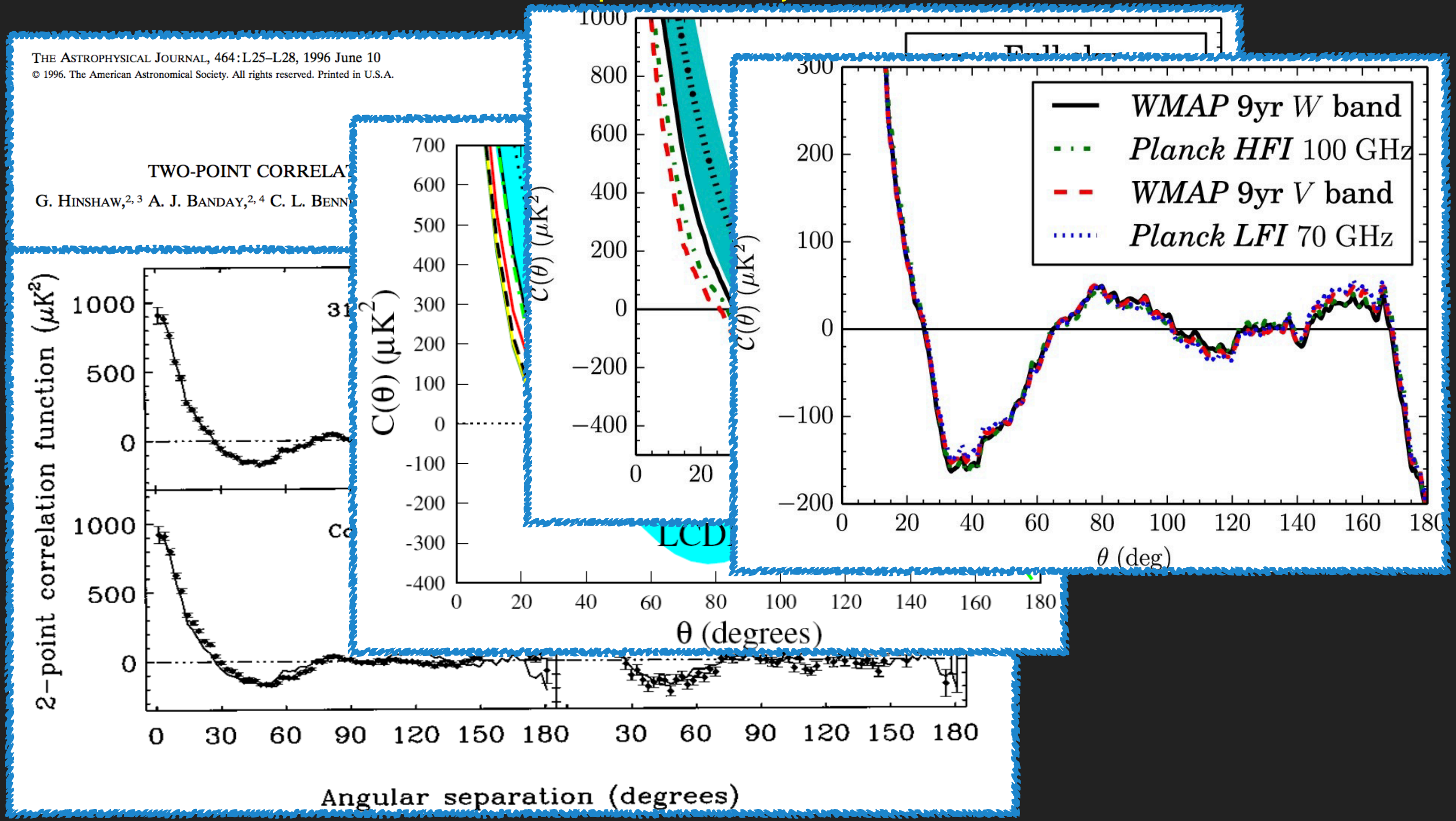

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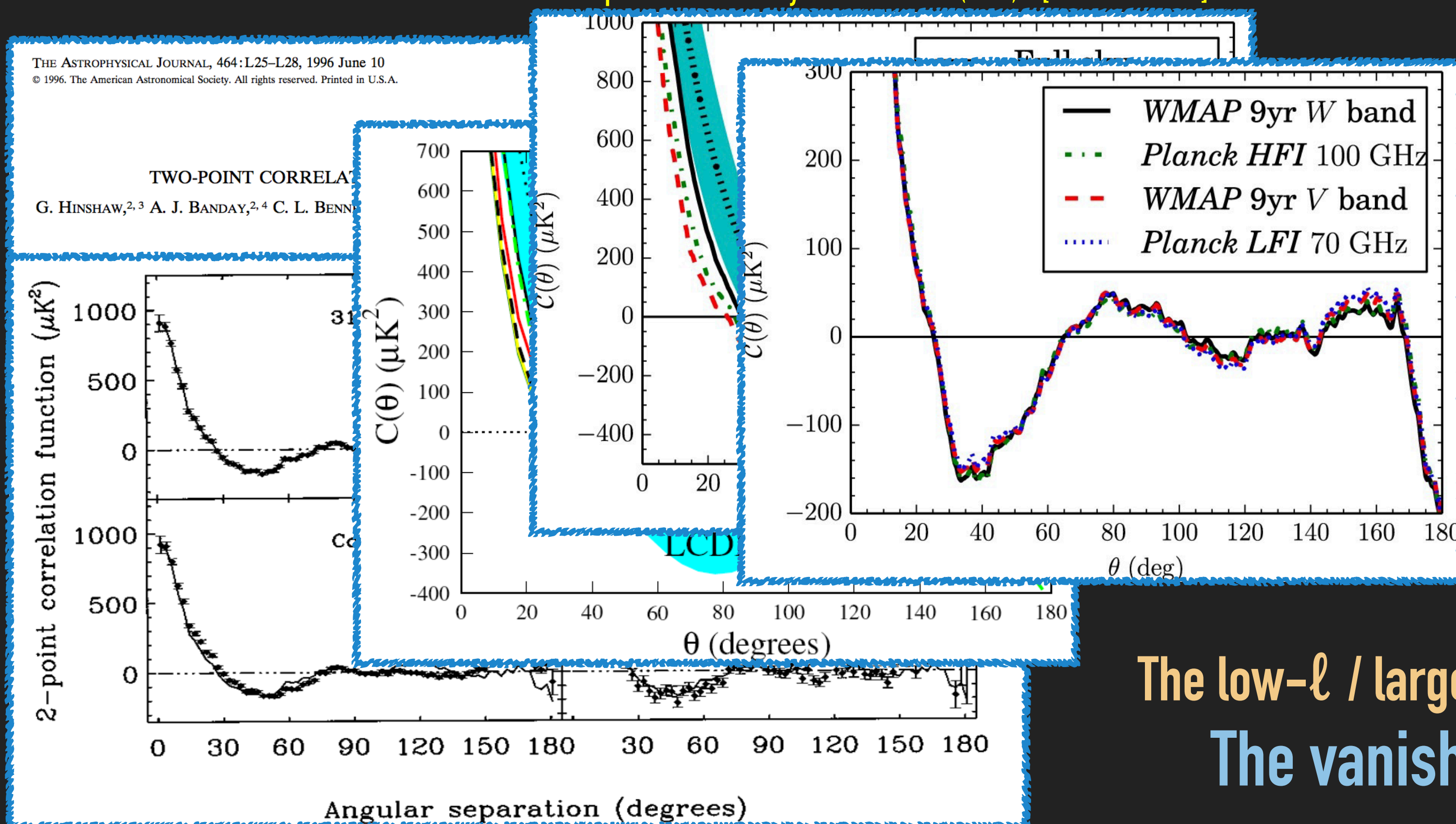

The low-ℓ / large-angle problem:

The vanishing of C(θ)

IS THE LARGE-ANGLE ANOMALY SIGNIFICANT?

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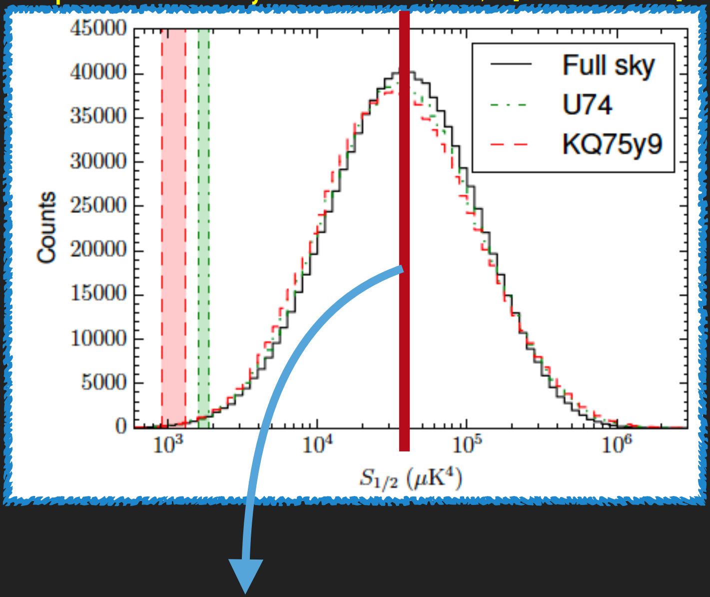

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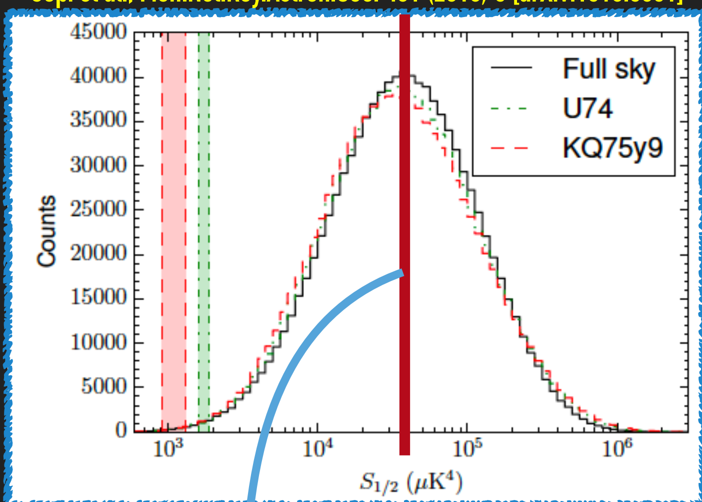

Planck Collaboration A&A 641 (2020) A7 [arXiv:1906.02552]

Table 11. Values for the $S^{XY}_{1/2} \equiv S^{XY}(60°, 180°)$ statistic (in units of μK^4) for the *Planck* 2018 data with resolution parameter $N_{\rm side} = 64$.

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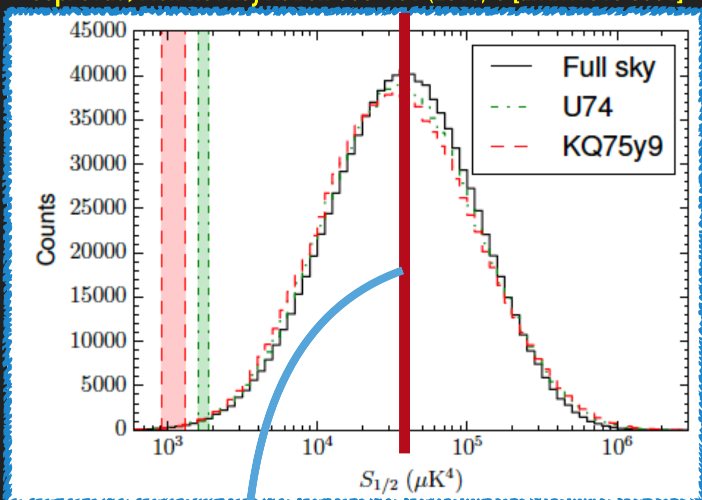

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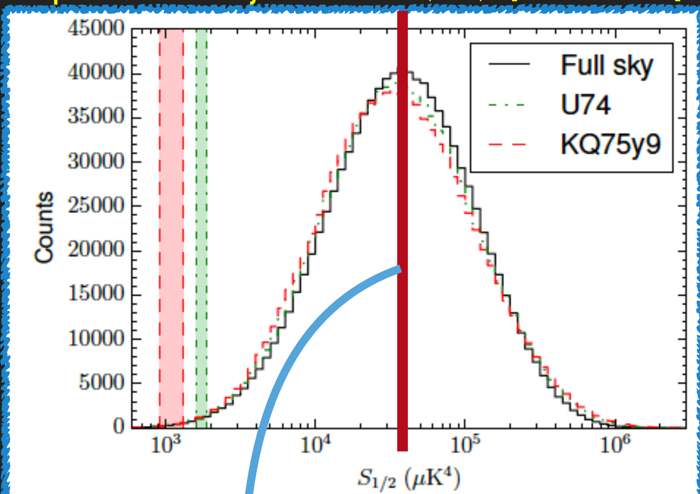

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- And all low-ℓ C_ℓ are small for most of those realizations! (which is not what the observed sky tells us!)

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C_ℓ Source	L = 2	3	4	5	6	7	8
Theory	7624	922	118	23	7	3	0.7
Theory 95 per cent	6100–12300	750–1500	100–200	20–40	7–14	3–6	1–3
WMAP	8290	2530	2280	800	350	150	130
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- The minimum $S_{1/2}$ falls off much more slowly in the WMAP C_ℓ than in the theory.
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What is strange about the low-ℓ C_ℓ is how the various C_ℓ are correlated with each other.

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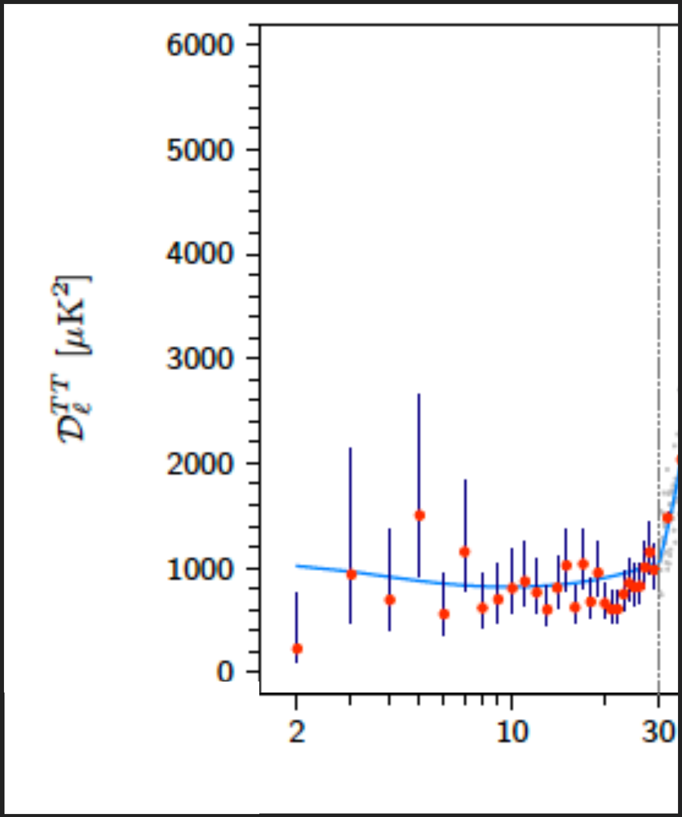

- Even if we replaced all the theoretical C_ℓ by their measured values up to ℓ=20, cosmic variance would give only a 3% chance of recovering so little correlation in a particular realization.
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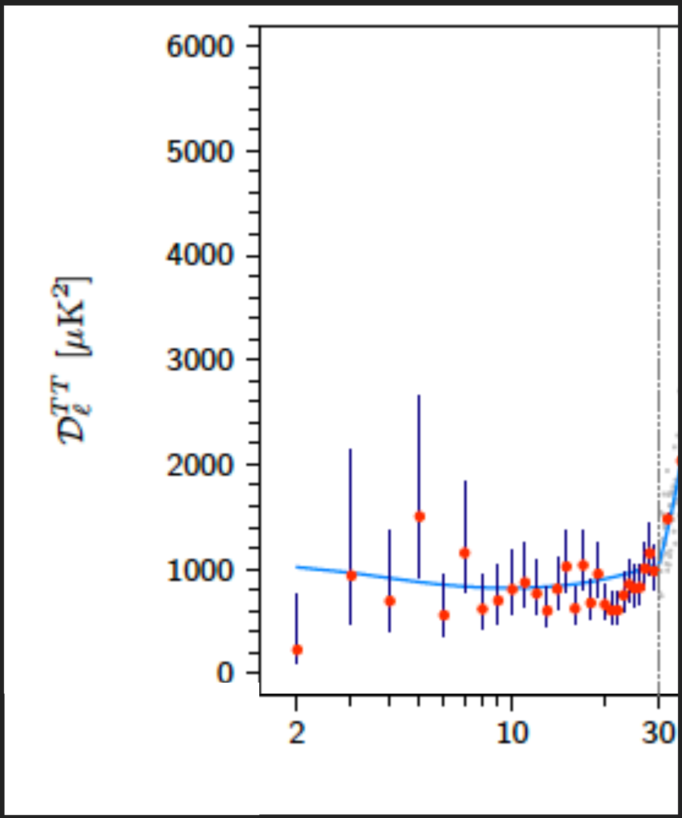

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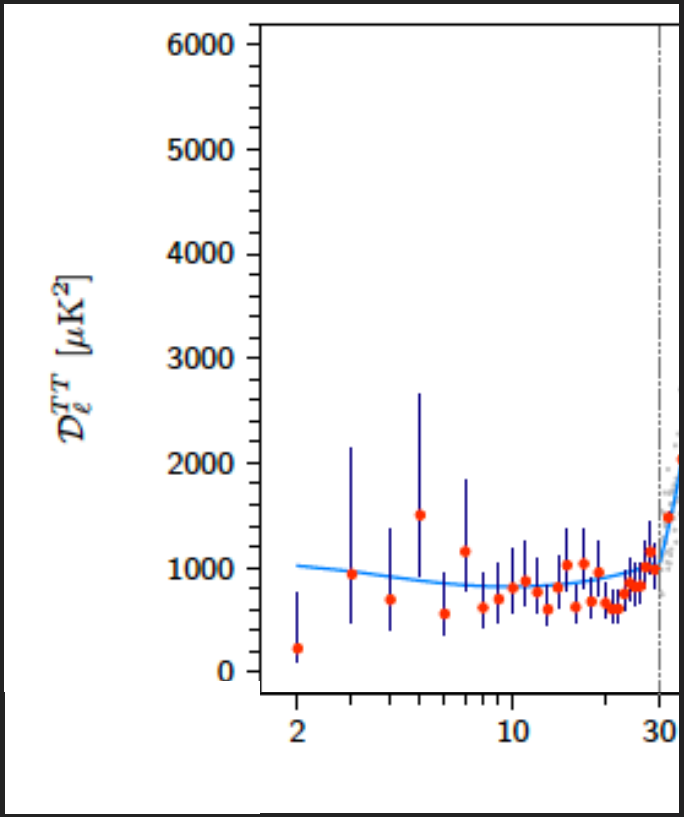

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2. "I never believe a posteriori statistics."
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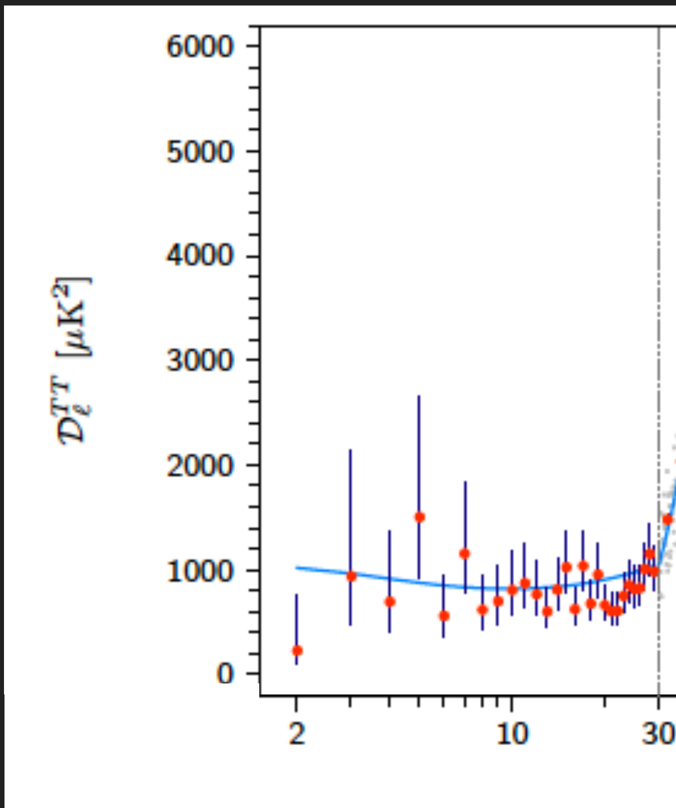

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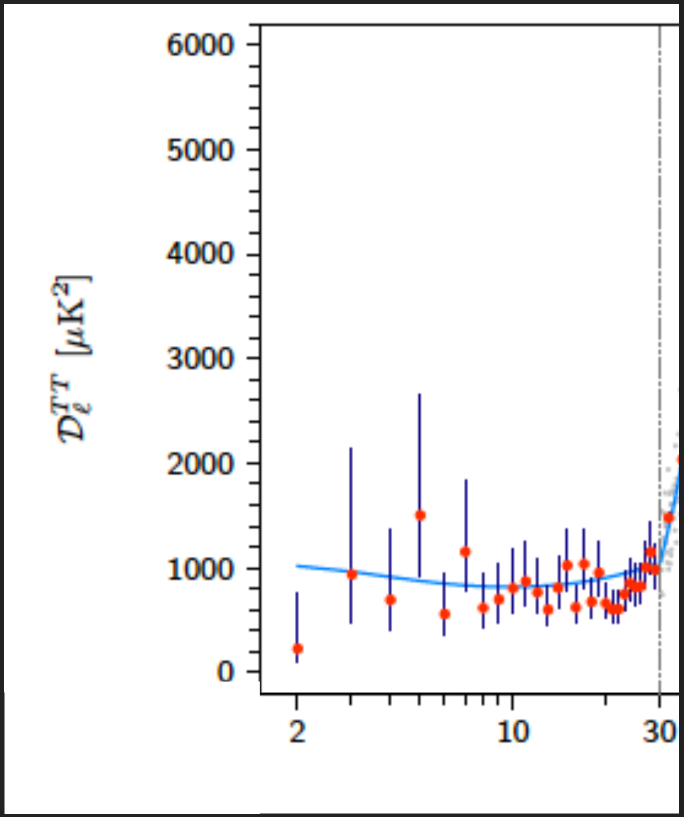

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Other CMB anomalies (many are beyond C_ℓ):

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p-values $\leq 0.1\% - 1\%$

(may become as low as 10^{-7})

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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.
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.

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Phenomenological guess:

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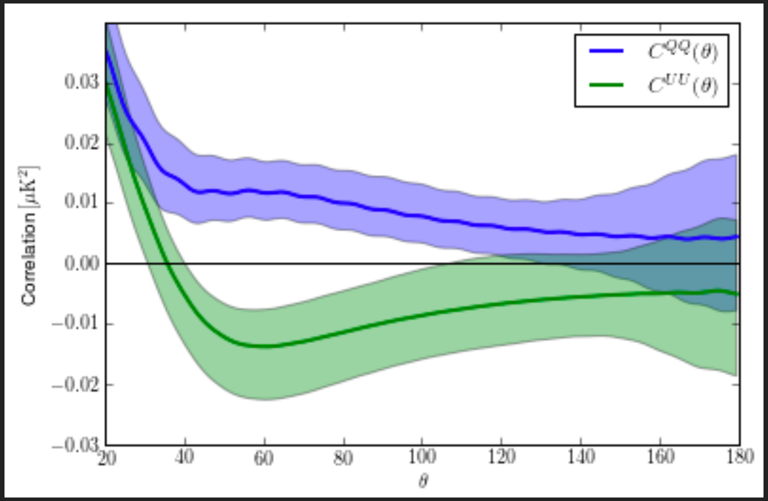

Yoho et al., Phys. Rev. D 91, 123504 (2015) [arXiv:1503.05928]

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.

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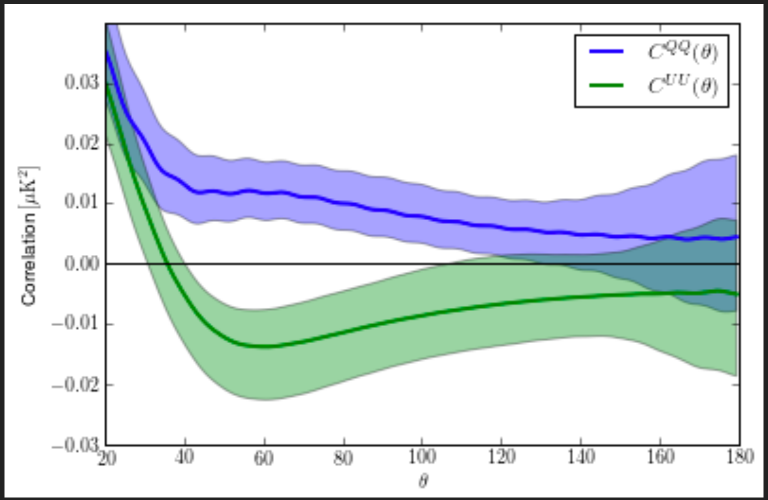
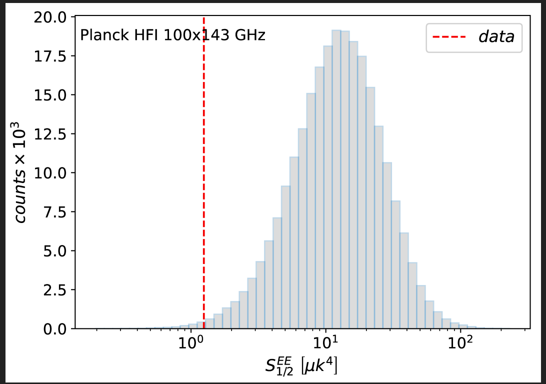


Yoho et al., Phys. Rev. D 91, 123504 (2015) [arXiv:1503.05928]

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.

Lack-of-correlation anomaly in CMB large scale polarization maps:



Chiocchetta et al., JCAP 08 (2021) 015 [arXiv:2012.00024]

Local E mode

$$C^{\hat{E}\hat{E}}(\theta) = \sum_\ell \frac{2\ell+1}{4\pi}\frac{(\ell+2)!}{(\ell-2)!}C_\ell^{EE}P_\ell(\cos\theta)$$

$$S^{EE}_{1/2} = \sum_{\ell=2}^{\ell_{\max}}\sum_{\ell'=2}^{\ell'_{\max}} \frac{2\ell+1}{4\pi}\frac{(\ell+2)!}{(\ell-2)!}\frac{2\ell'+1}{4\pi}\frac{(\ell'+2)!}{(\ell'-2)!}C_\ell^{EE}I_{\ell\ell'}C_{\ell'}^{EE}$$

EXAMPLE: ABSENCE OF TWO-POINT ANGULAR CORRELATION

More phenomenological guesses:

1. Absence of angular correlation is due to absence of spatial correlation in 3D
   Consequence: expect low or no correlation in:
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SUMMARY

1. The sky appears NOT to be a typical realization of a Gaussian random statistically isotropic field.
2. Temperature multipoles are aligned with one another and/or with the ecliptic/dipole
3. The temperature sky lacks large angle correlations
4. There are noticeable hemispherical asymmetries/differences
5. . . .

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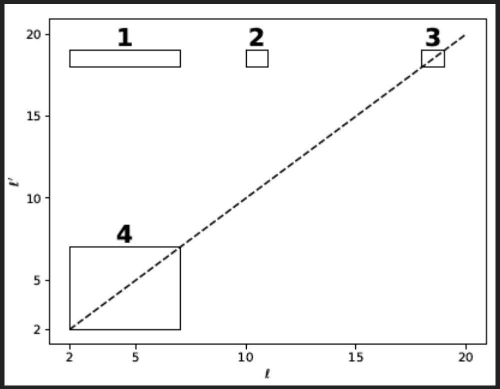

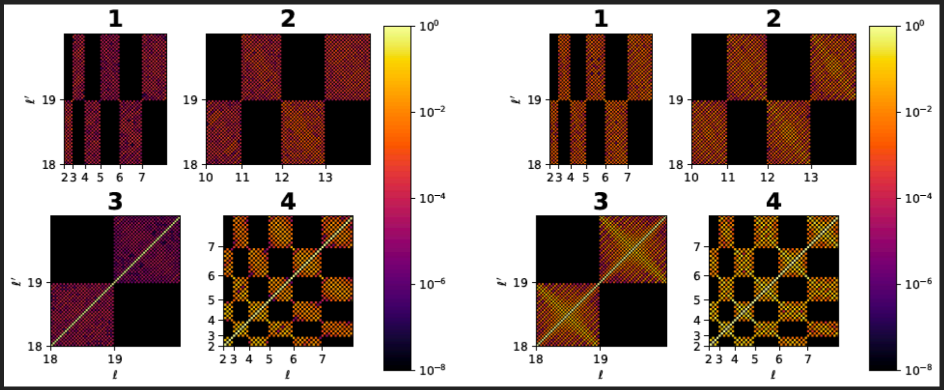

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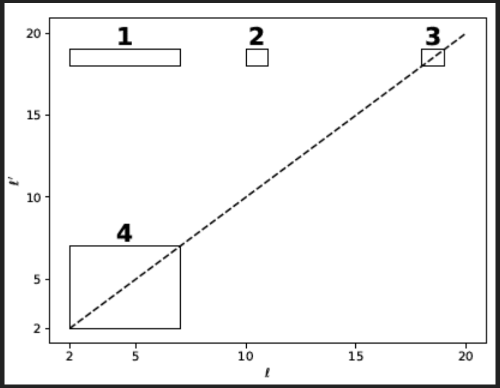

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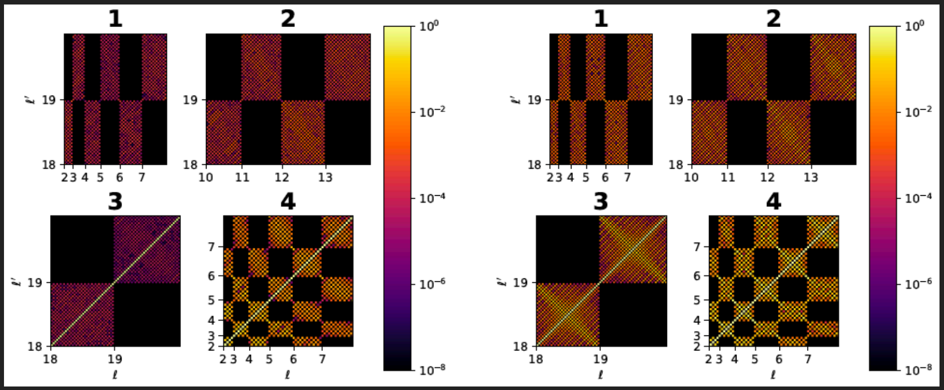
- What has been explored/constrained so far is a set of measure zero in the space of possible cases and parameter values.
- Most of interesting/relevant cases remain to be explored/tested/constrained.
- Discovering nontrivial topology would have enormous impact on fundamental physics.
- We'll be doing this in the next 5-10 years.



"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.

We must demand an explanation."

Glenn Starkman