

LARGE-SCALE ANOMALIES IN THE COSMIC MICROWAVE BACKGROUND

Current Status, Future Prospects, and Possible Explanations

Work in progress in collaboration with:

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Tensions in Cosmology

Corfu, September 08, 2022



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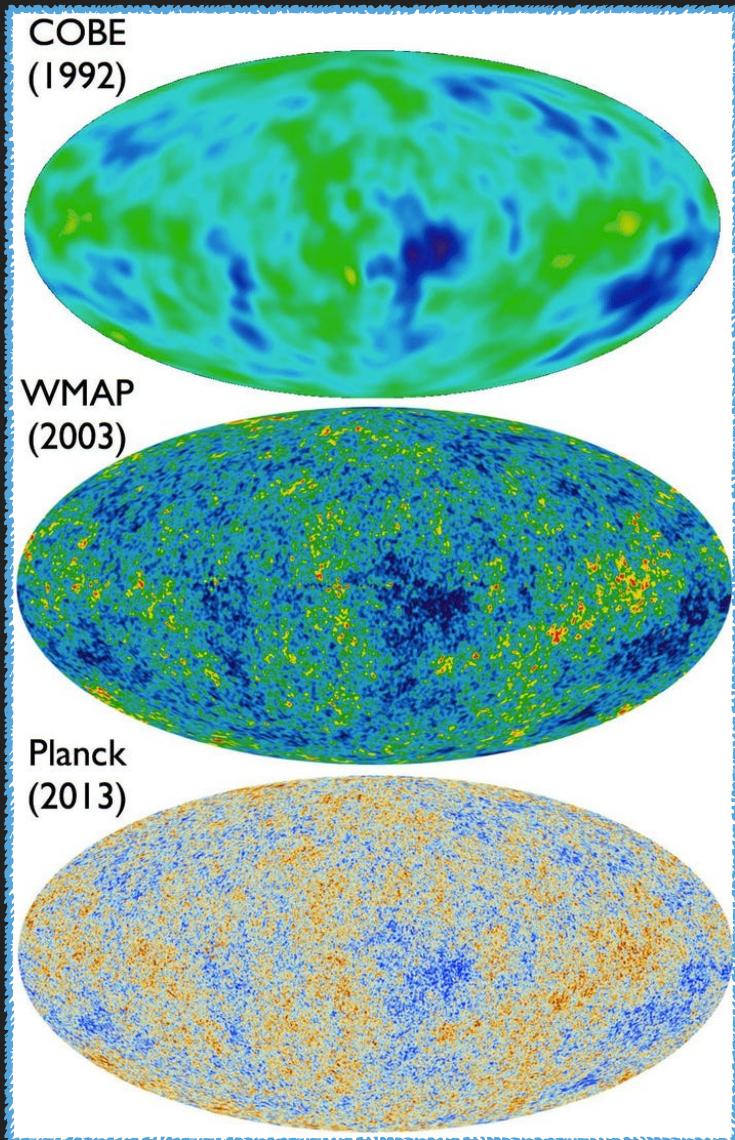
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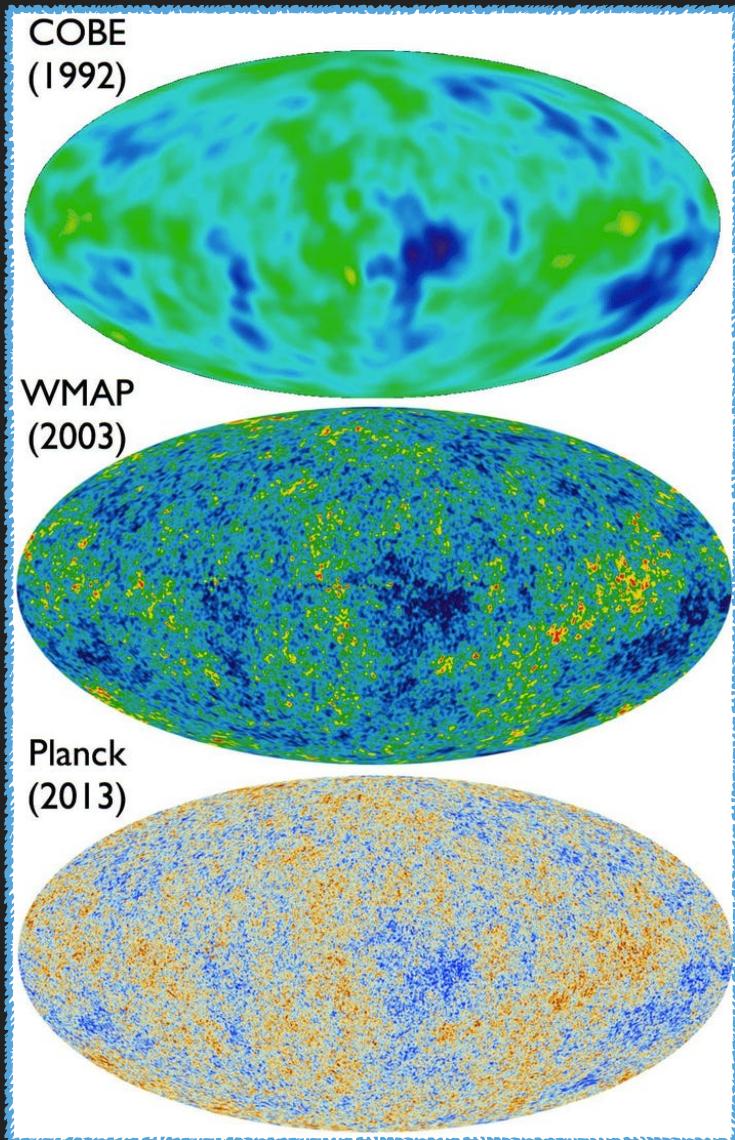
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London

COSMIC MICROWAVE BACKGROUND (CMB)



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

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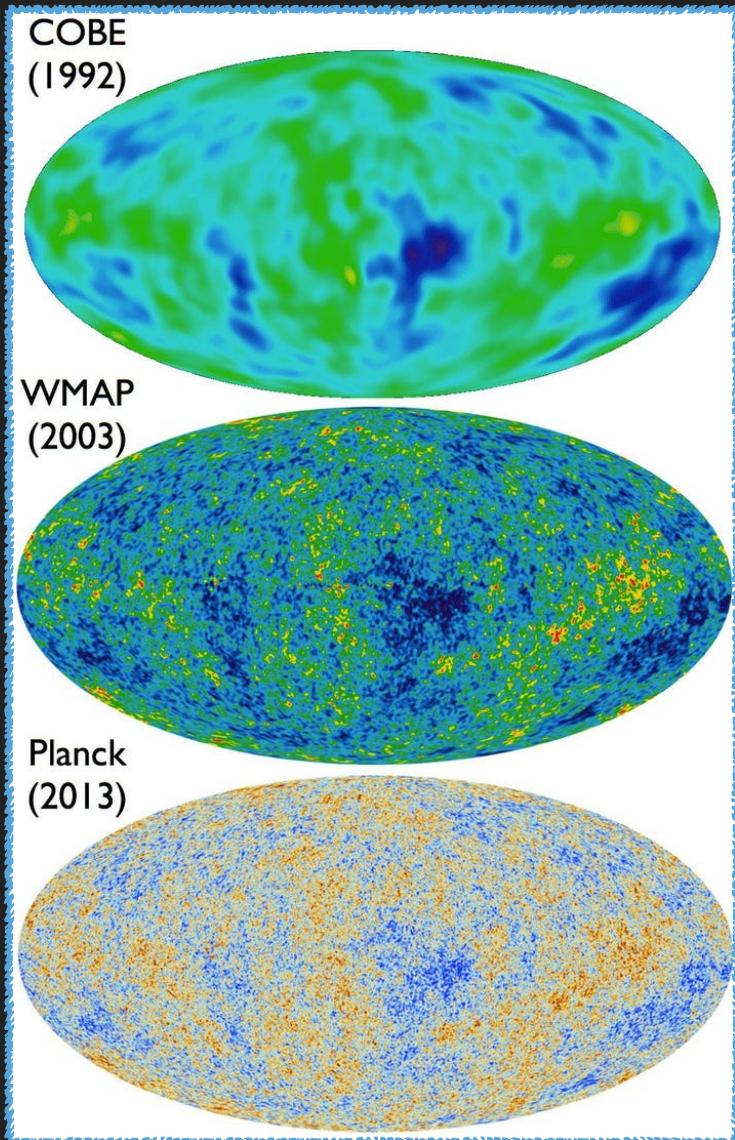


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Standard model for the fluctuations (inflation):

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

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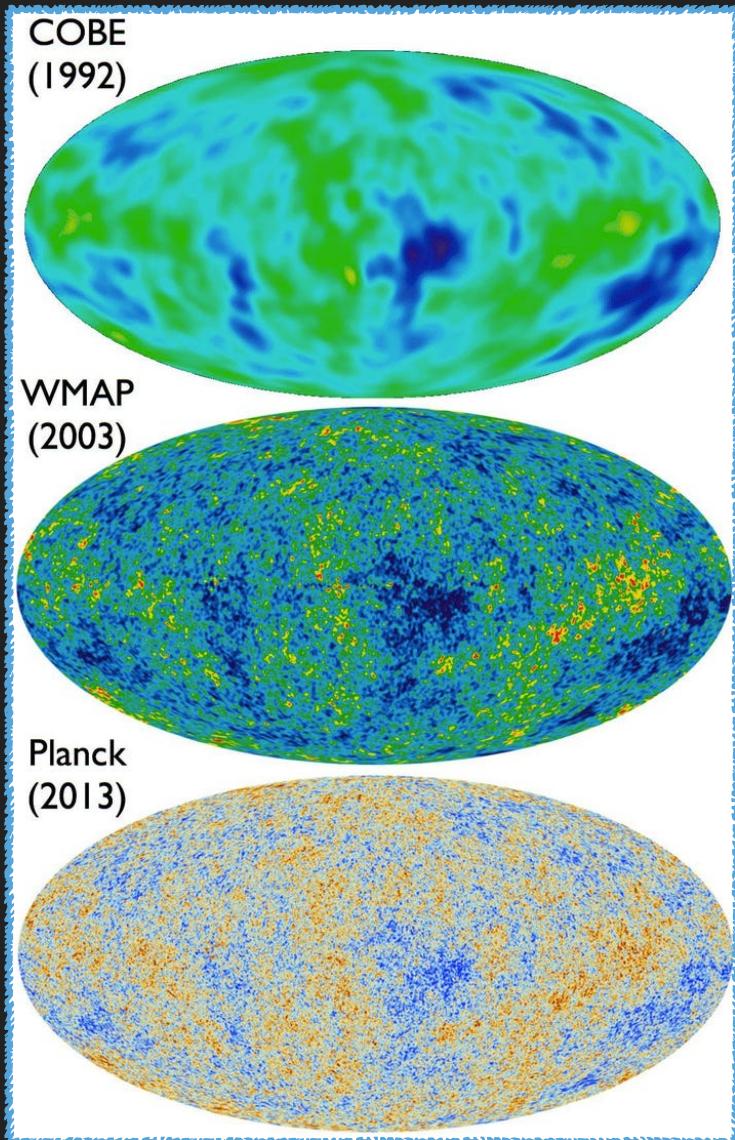
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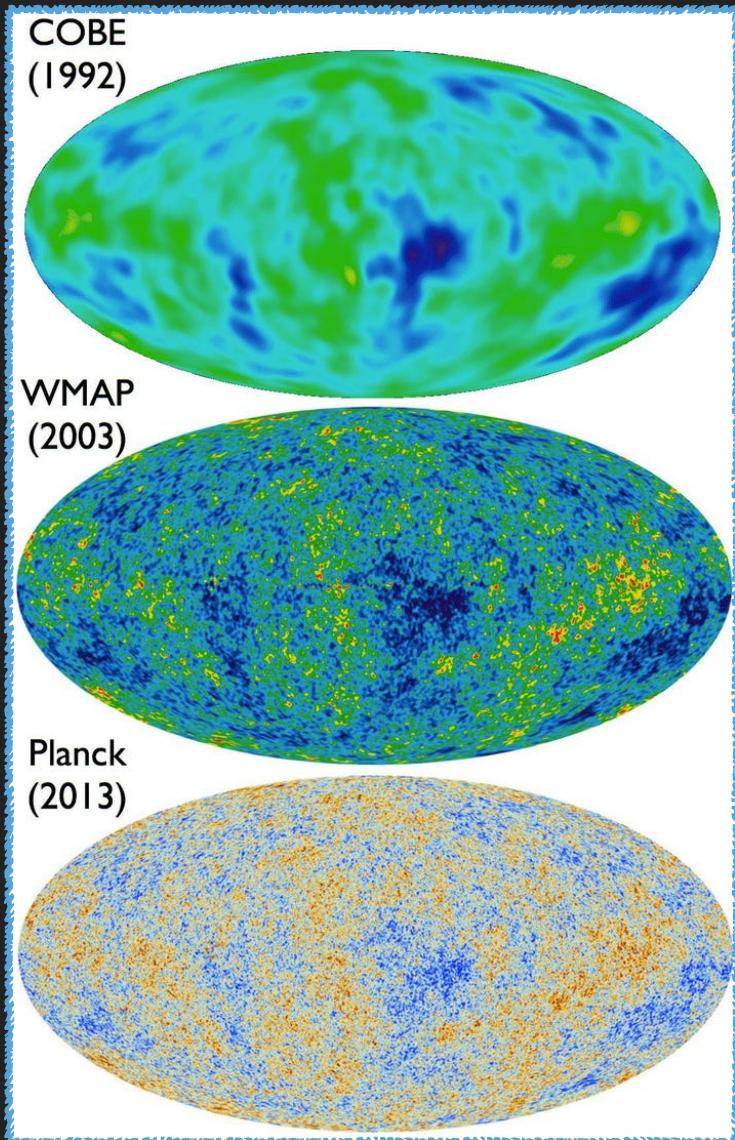
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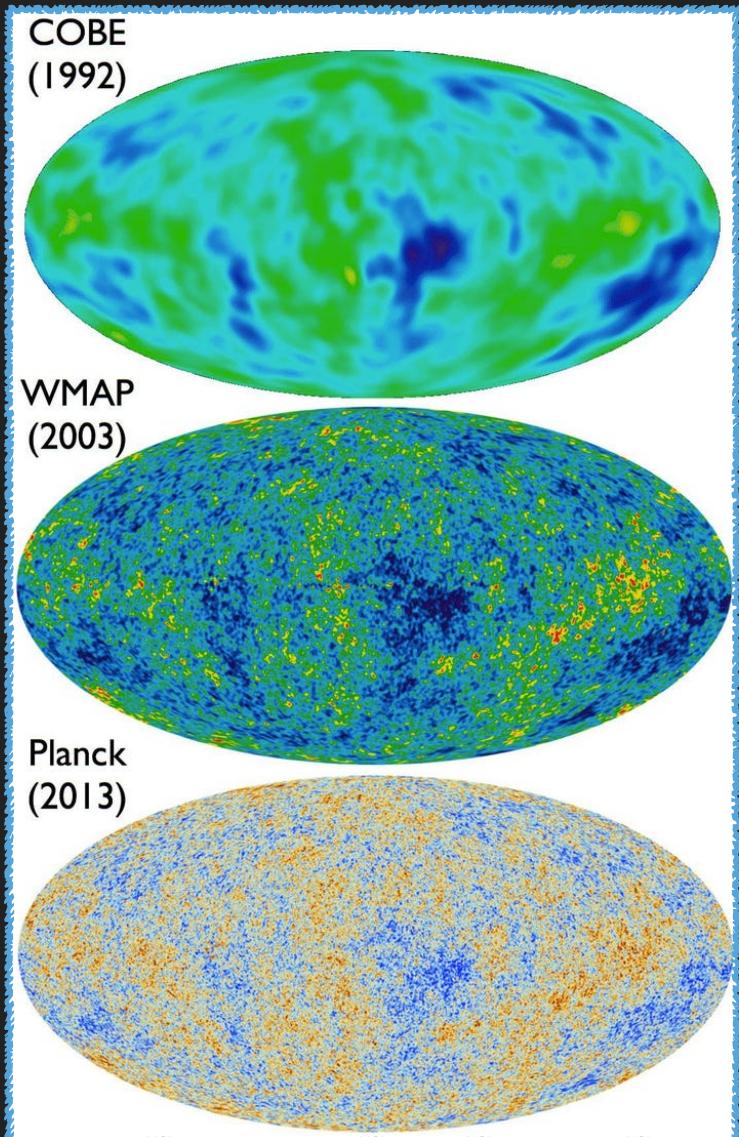
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$$\hat{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

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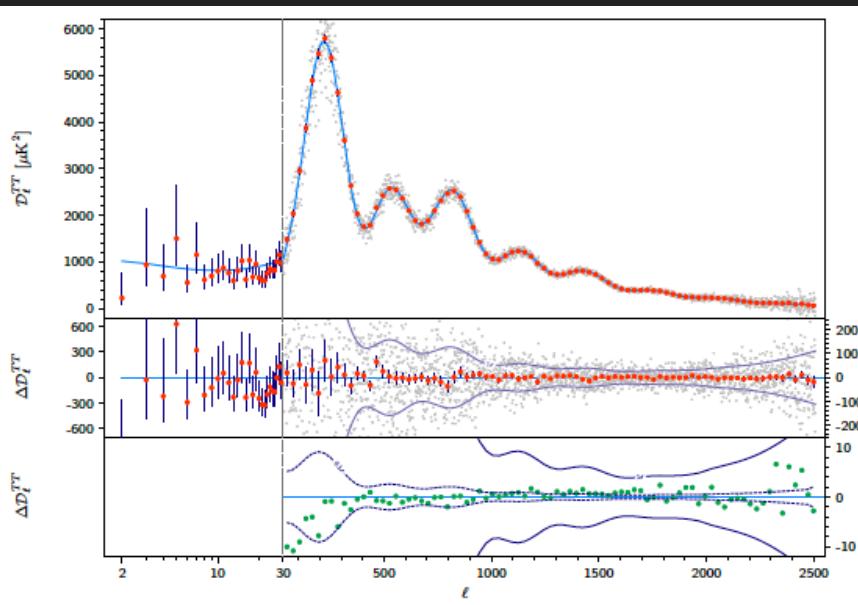
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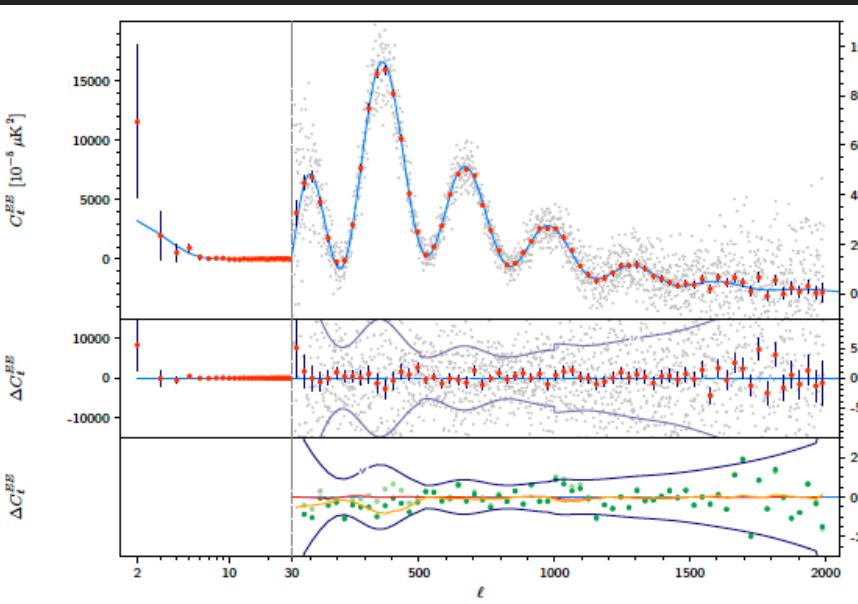
This estimator is unbiased and minimizes variance:

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

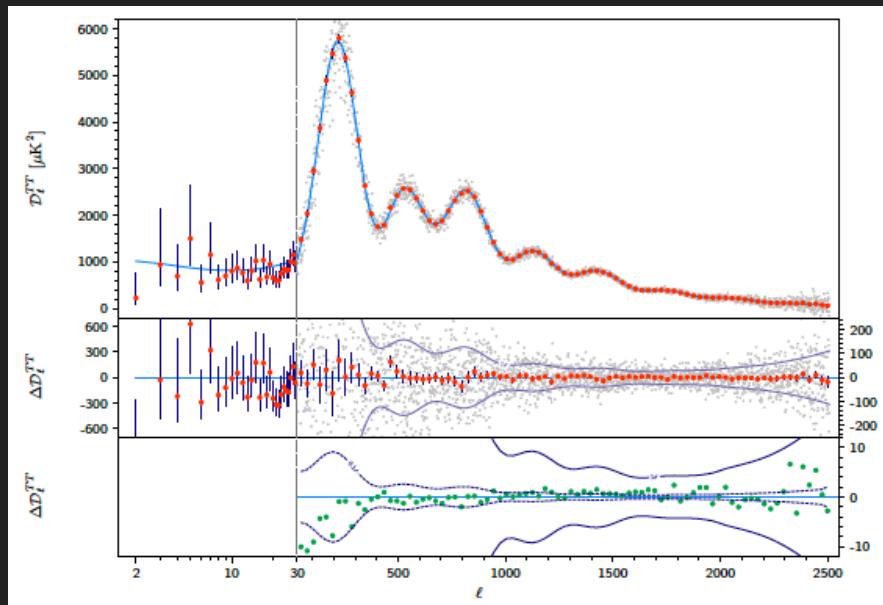
MEASURED ANGULAR POWER SPECTRA



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



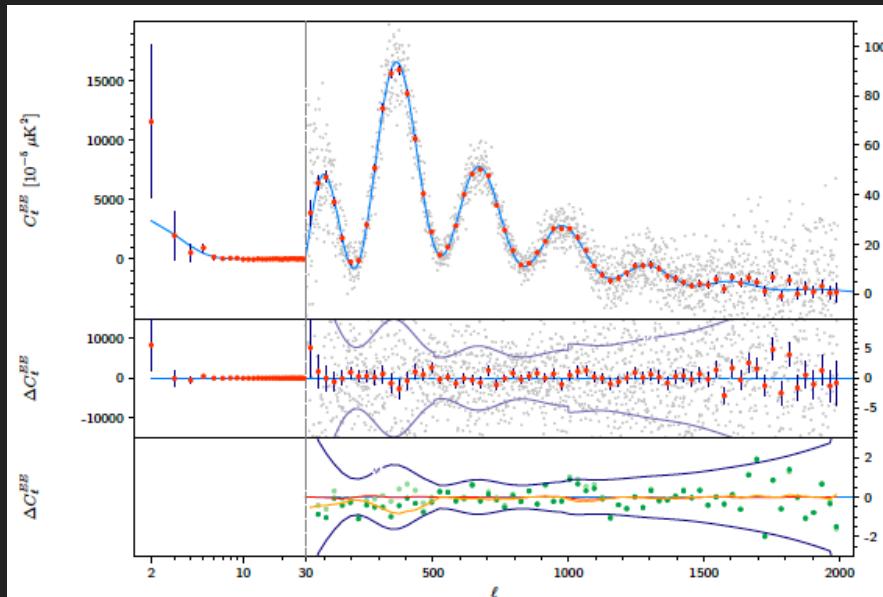
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6-parameter fit to >>6 points

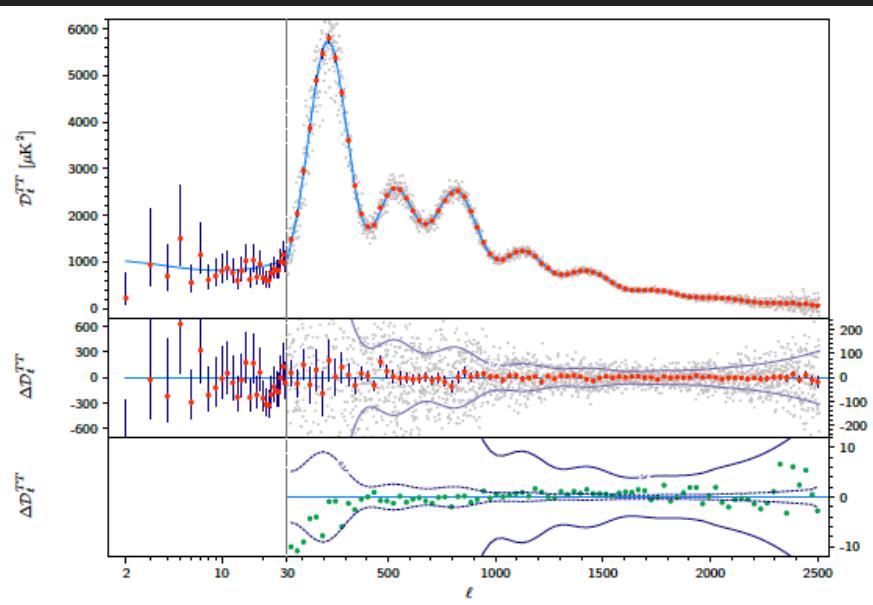
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- REMARKABLE agreement with theory
(especially for statistics the theory prefers)



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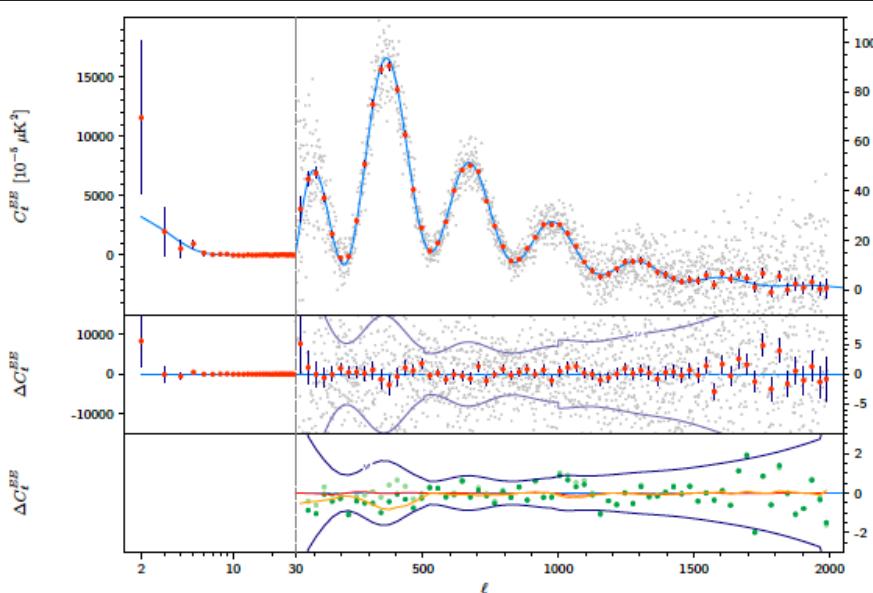


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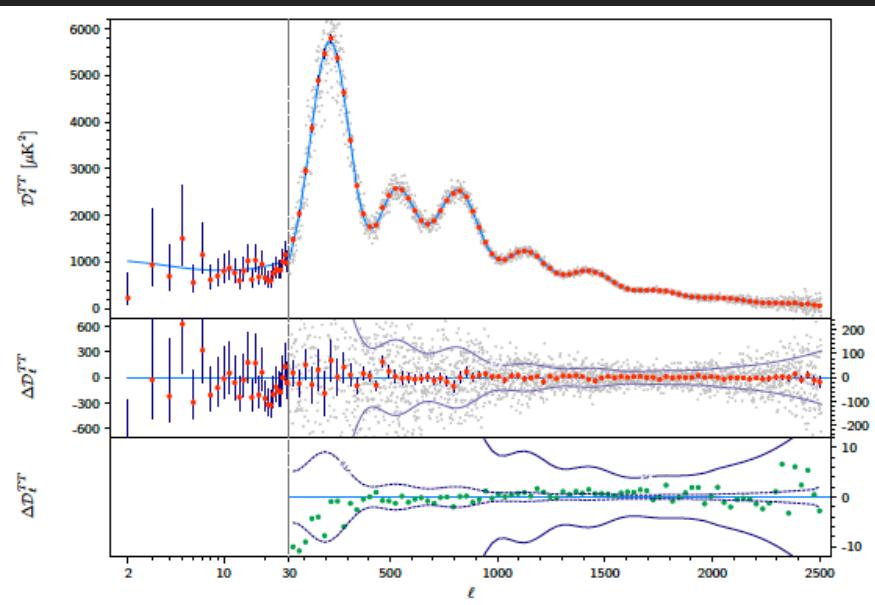
BUT!



We assumed:

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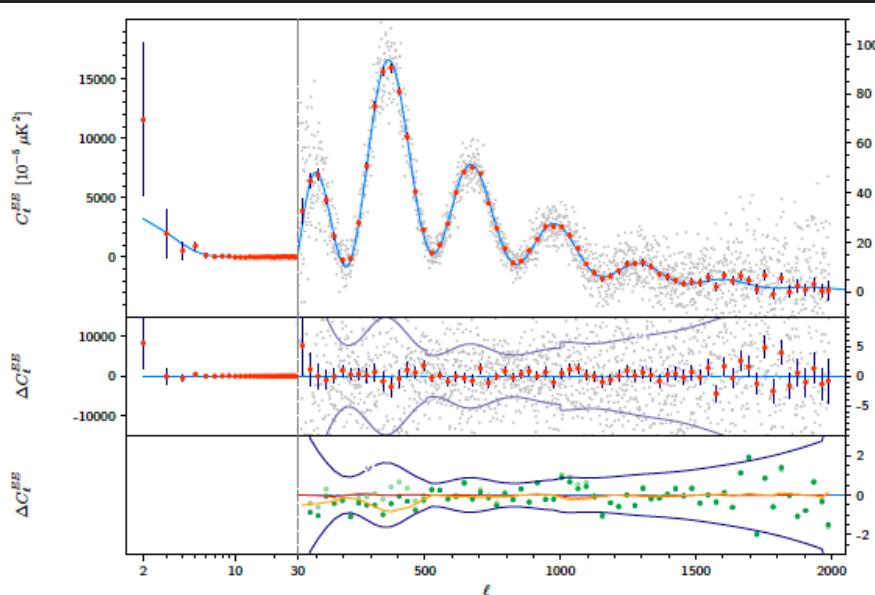


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We assumed:

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Shouldn't we check these?

AN UNCOOPERATIVE UNIVERSE

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

IS THE CMB SKY ISOTROPIC?

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A&A 571, A23 (2014)
 DOI: 10.1051/0004-6361/201321534
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Planck 2013 results

Astronomy & Astrophysics

Special feature

Planck 2013 results. XXIII. Isotropy and statistics of the CMB

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Finding:

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

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Planck Collaboration; P. A. R. Ade⁹², N. Aghanim⁹³, C. Armitage-Caplan⁹⁷, M. Arnaud⁹⁴, M. Ashdown⁹⁴, F. Atrio-Barandela¹⁸, J. Aumont⁶³, C. Baccigalupi⁹¹, A. J. Banday¹⁰², R. B. Barreiro⁷⁰, J. G. Bartlett¹⁰¹, N. Bartolo¹⁰, E. Battaner¹⁰¹, R. Battye⁷², K. Benabed⁴⁹, A. Benoit⁴⁹, A. Benoît-Lévy⁴⁹, J. P. Bernard¹⁰³, M. Bersanelli^{59,93}, P. Bliever^{103,94}, J. Bobin⁷¹, J. J. Bock^{71,16}, A. Bonaldi¹², L. Bonavera⁹⁹, J. R. Bond⁷, J. Borrill¹³, R. E. Boughn^{49,99}, M. Bridge^{73,86,77}, M. Bucher¹, C. Burigana^{52,77}, R. C. Butler^{2,9}, J. C. Cardoso^{77,64}, A. Catalano^{87,75}, A. Challinor^{67,71,11}, R. E. Combet^{16,63}, R. R. Chary⁷⁰, H. C. Chang^{62,77}, L.-Y. Chiang⁶⁶, P. Christensen^{87,43}, S. Church⁶³, D. L. Clements⁹⁹,

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D. H. J. *Planck 2018 results*

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VII. Isotropy and statistics of the CMB

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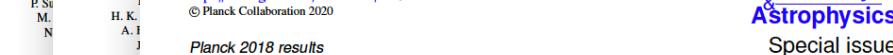
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$$C(\theta) = \langle \Delta T(\Omega_1) \Delta T(\Omega_2) \rangle$$

$$\Omega_1 \cdot \Omega_2 = \cos \theta$$

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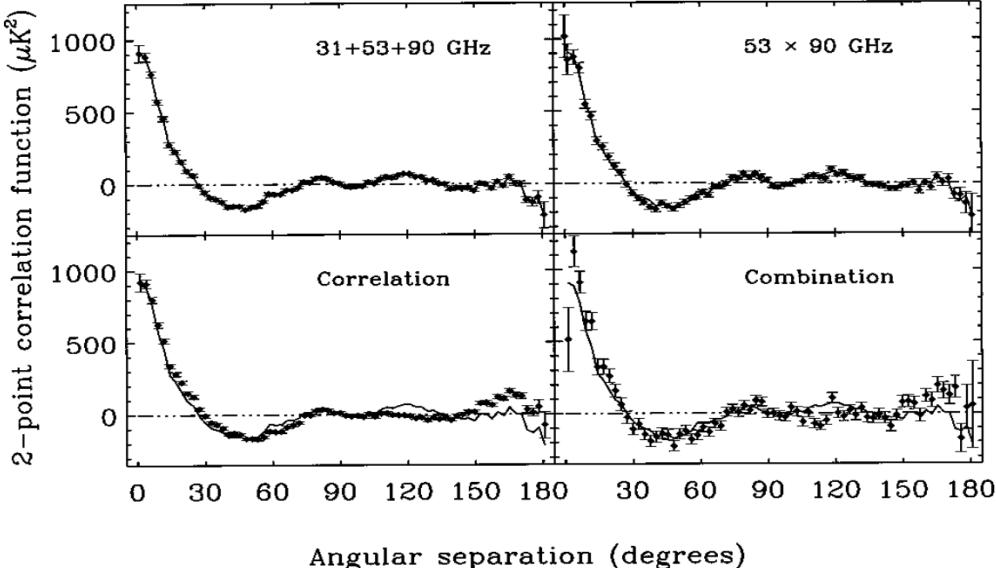
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THE ASTROPHYSICAL JOURNAL, 464:L25-L28, 1996 June 10
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TWO-POINT CORRELATIONS IN THE COBE¹ DMR FOUR-YEAR ANISOTROPY MAPS

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. WRIGHT⁹

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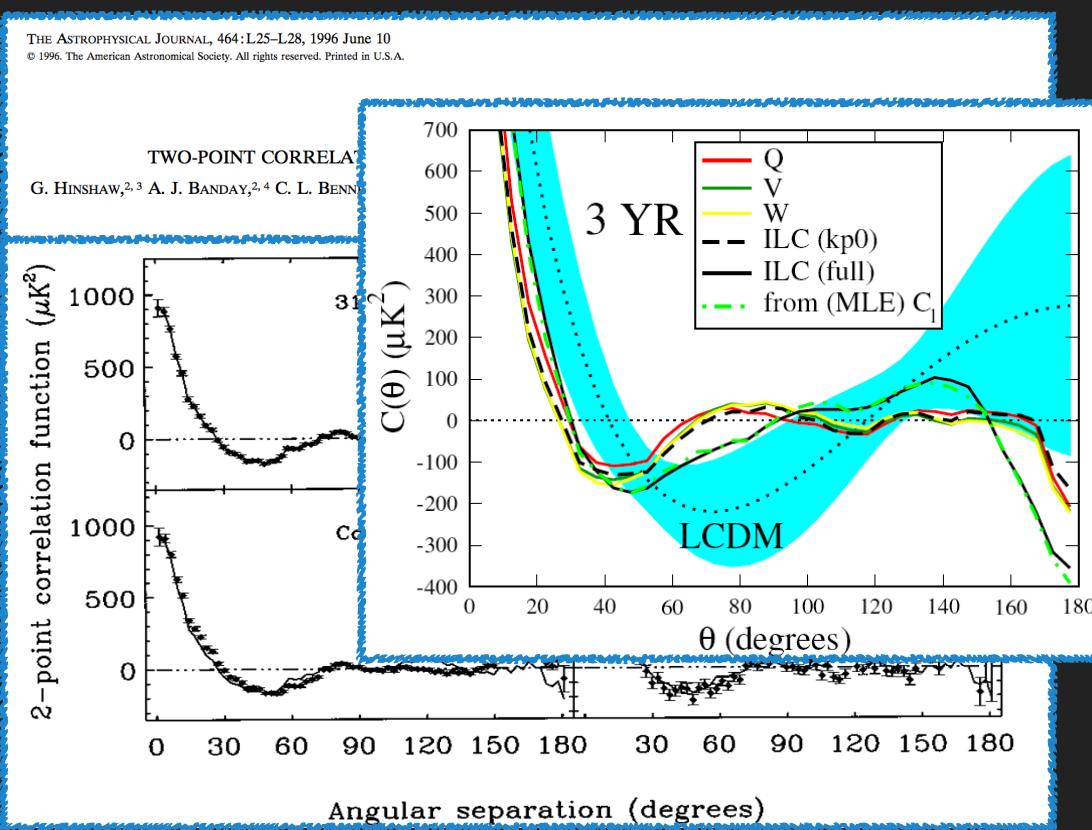
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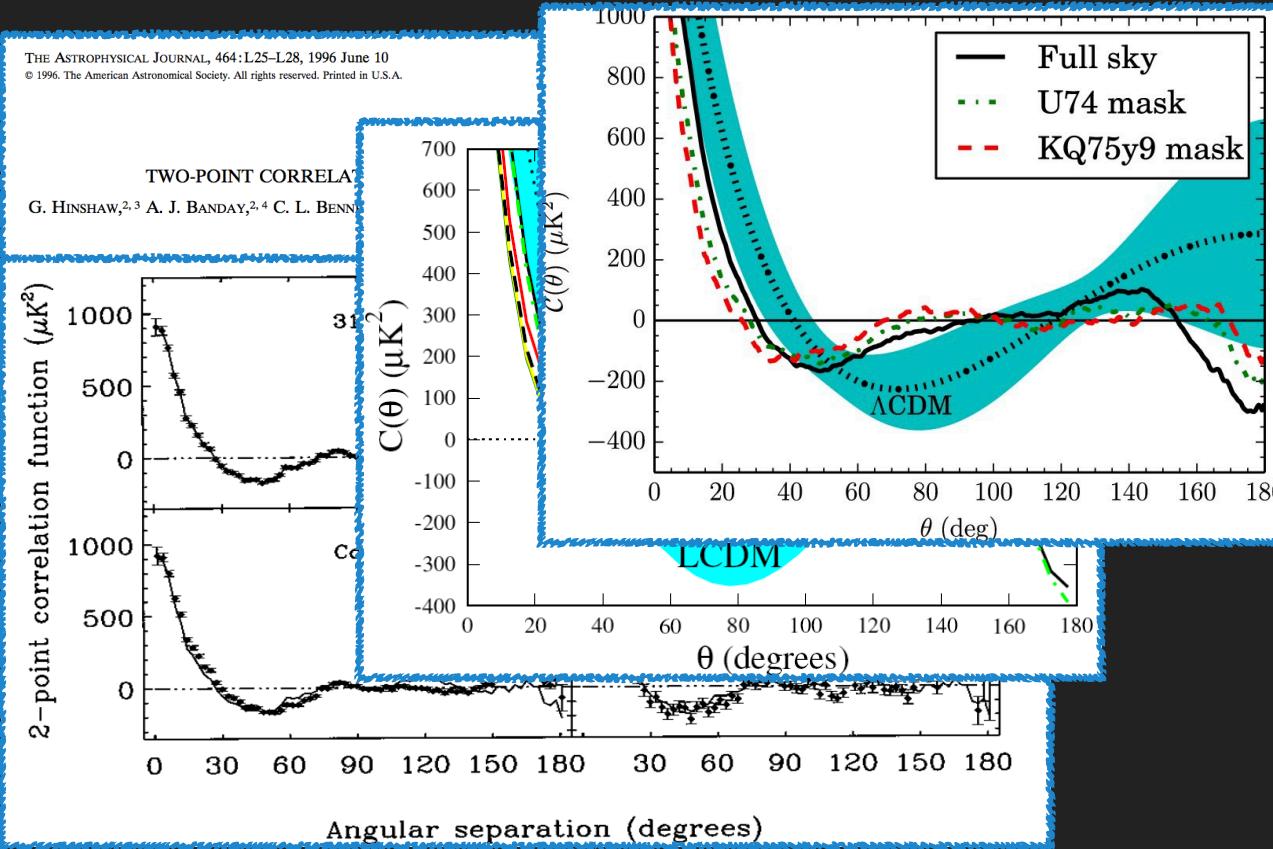
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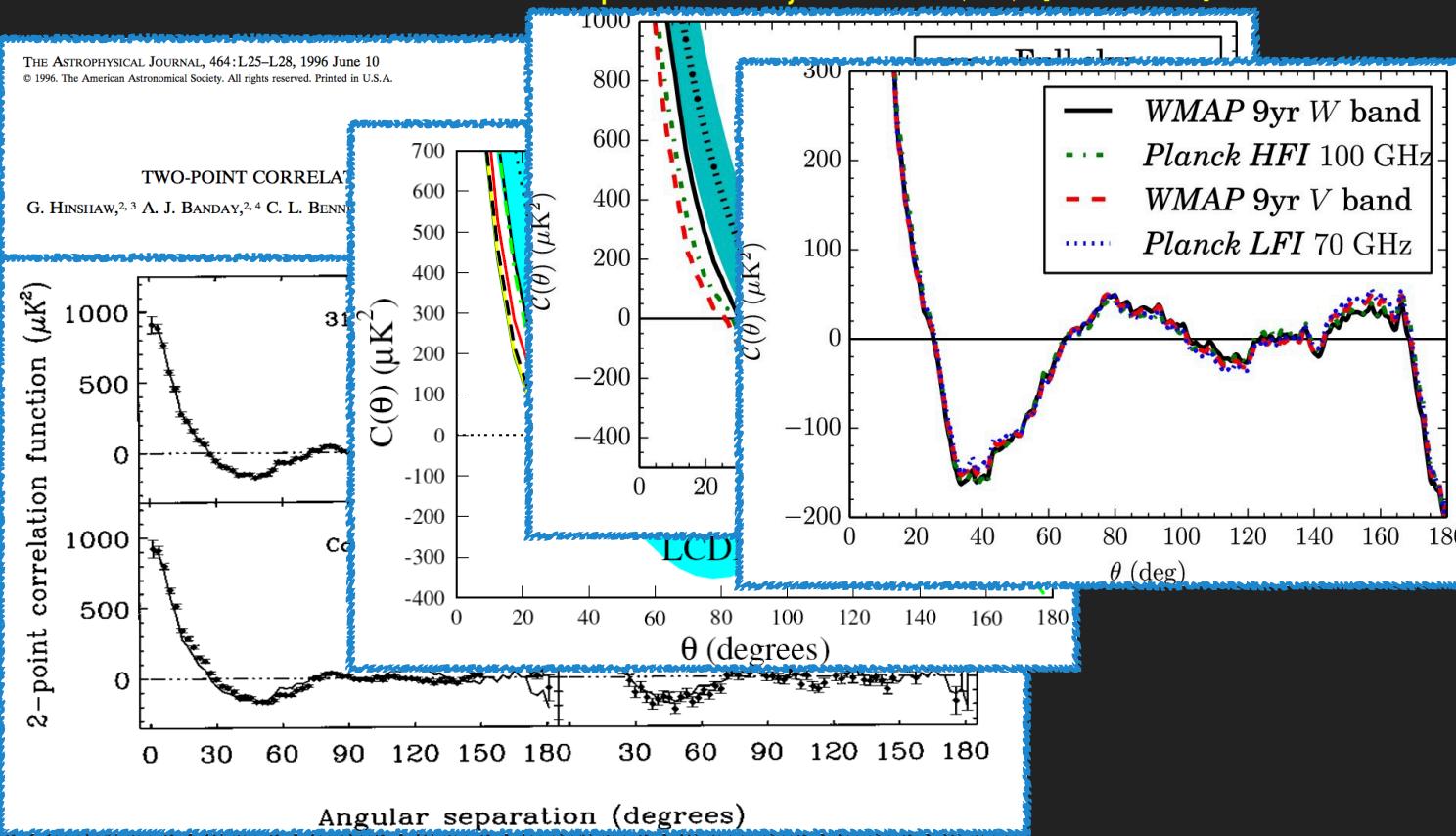
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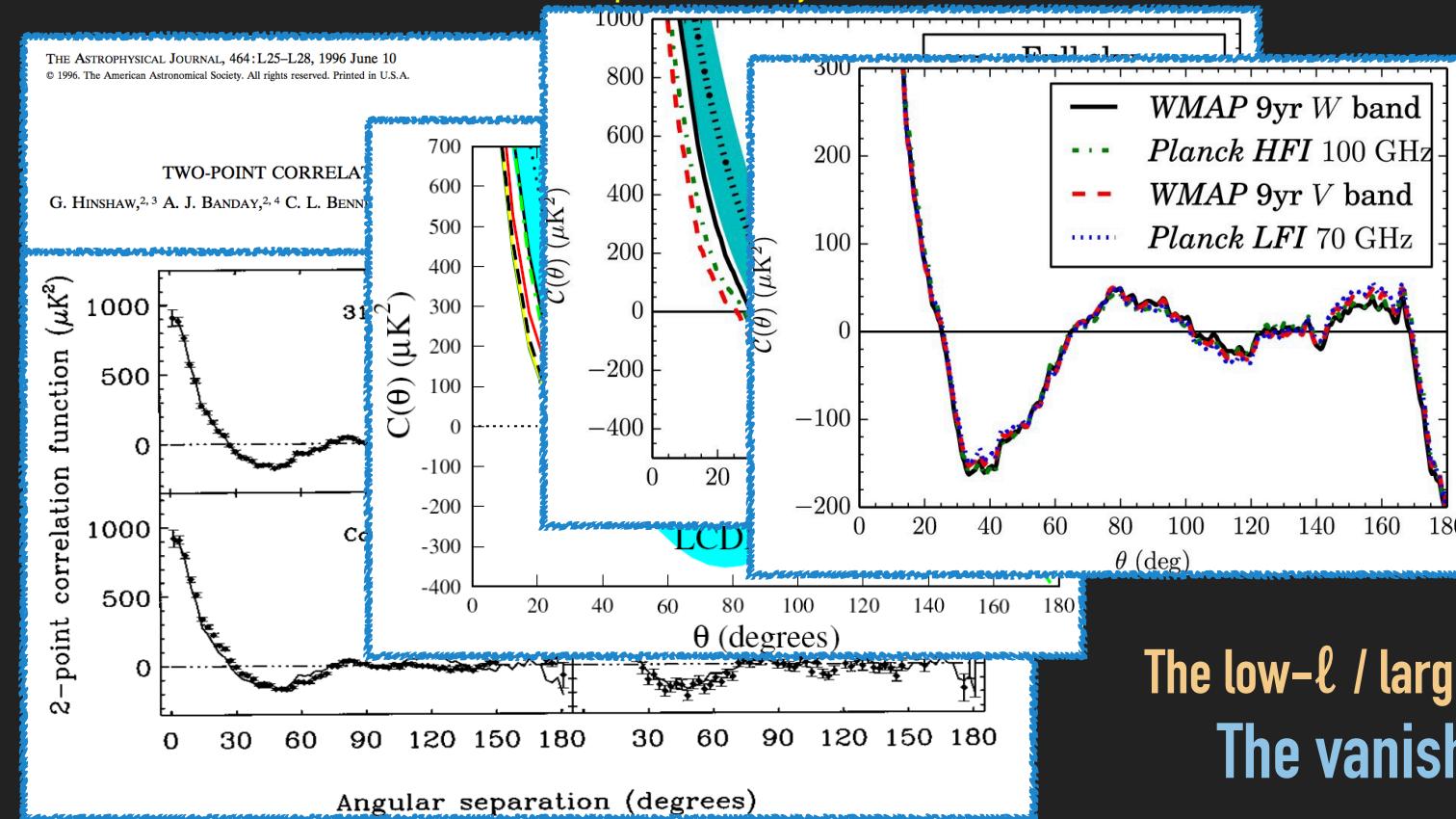
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The low- ℓ / large-angle problem: The vanishing of $C(\theta)$

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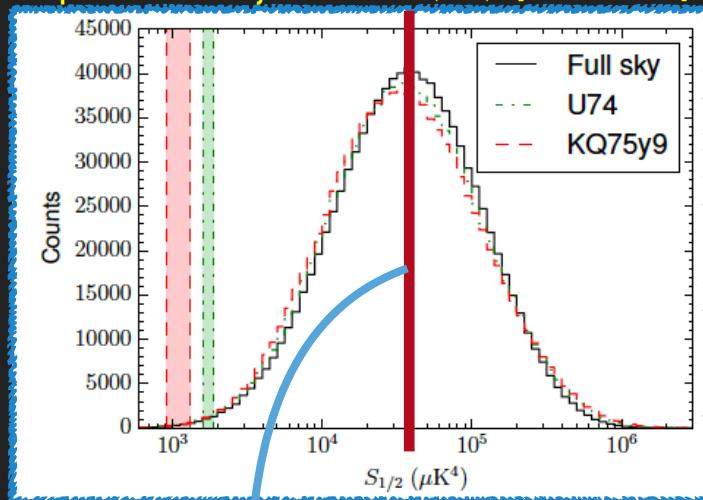
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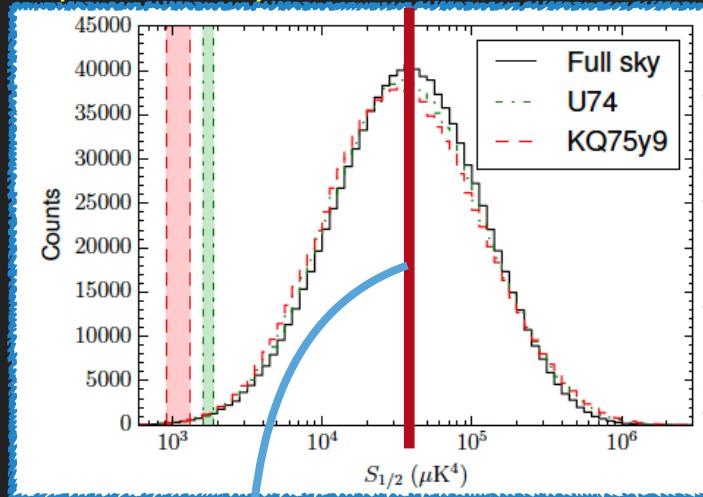
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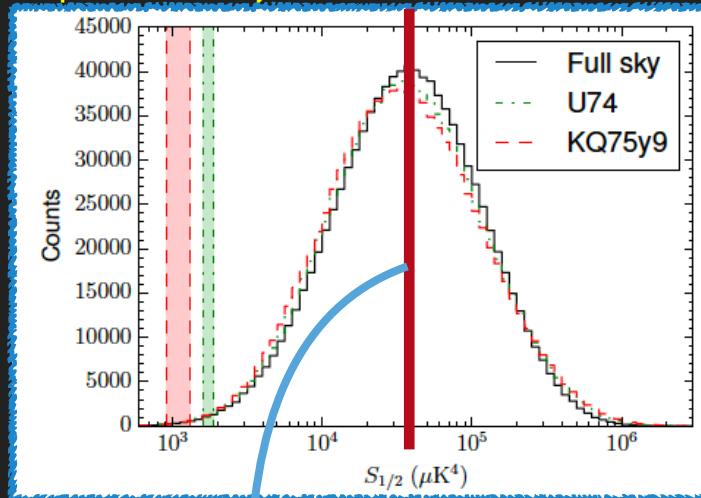
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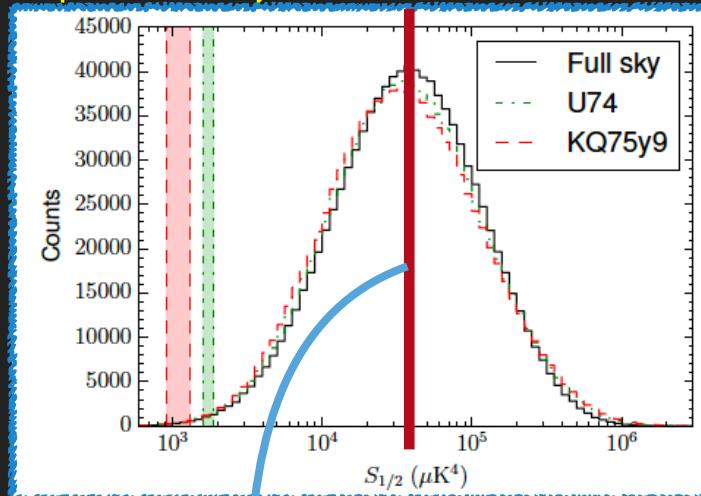
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- 0.03%-0.1% of realizations of the concordance model of inflationary Λ CDM have so little cut sky large-angle correlation!
- And all low- ℓ C_ℓ are small for most of those realizations! (which is not what the observed sky tells us!)

THE CONSPIRACY THEORY: MINIMIZING $S_{1/2}$

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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
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- This strongly suggests that important correlations exist in the data for $\ell > 8$ that do not exist in the theory.

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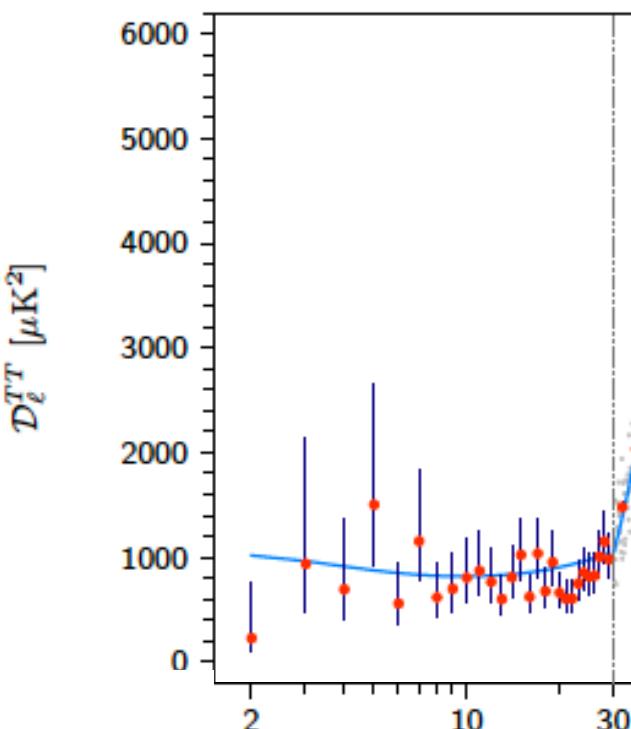
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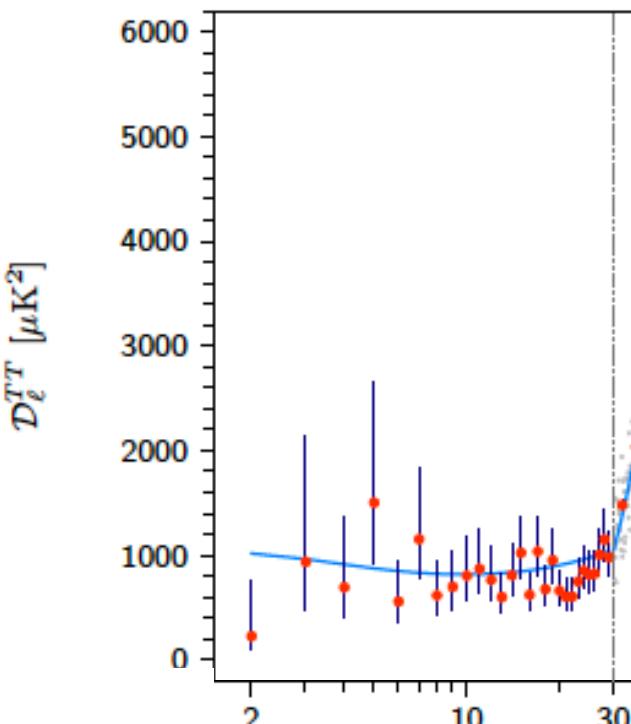
What is strange about the low- ℓ C_{ℓ} is how the various C_{ℓ} are correlated with each other.

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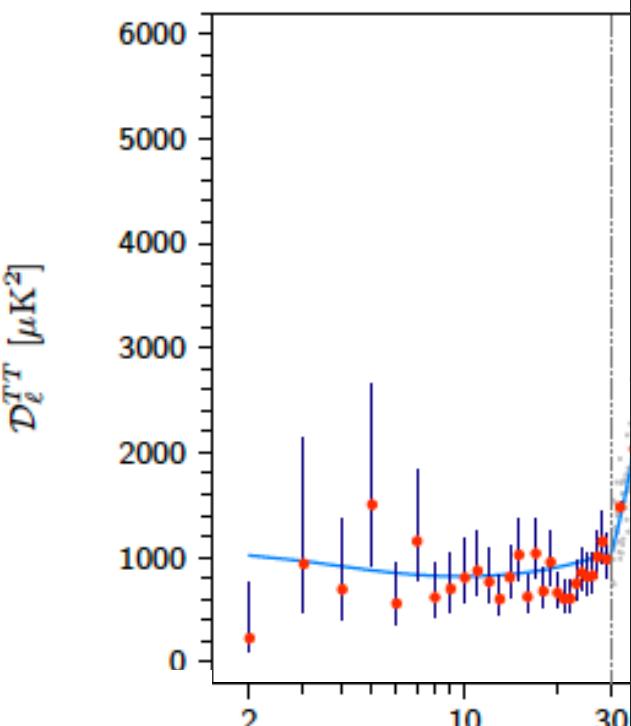
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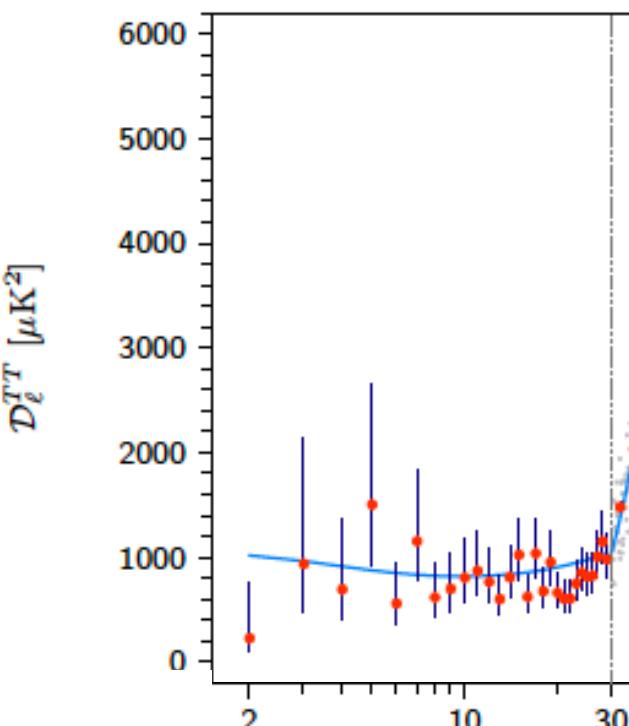


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1. "Didn't that go away?"
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4. "Inflation can do that"

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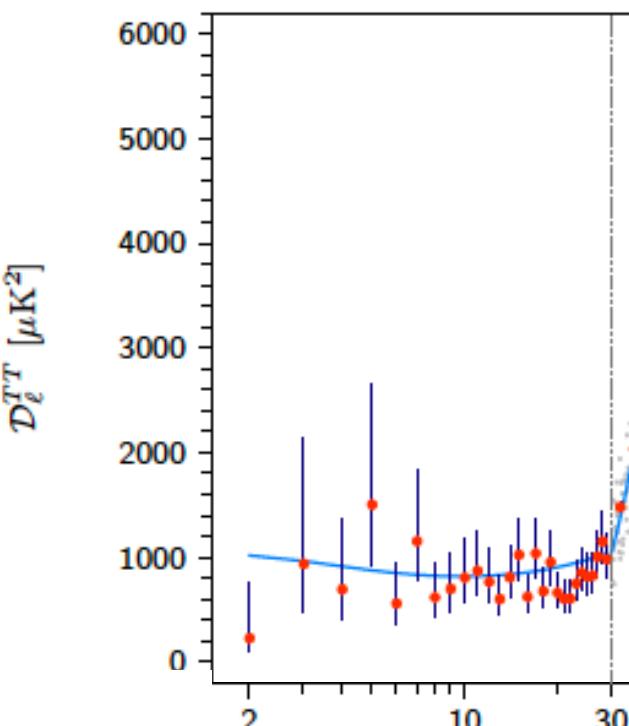


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Other CMB anomalies (many are beyond C_ℓ):

1. Hemispherical Power Asymmetry
2. Quadrupole and Octopole Alignments
3. Point-Parity Anomaly
4. The Cold Spot
5. ...

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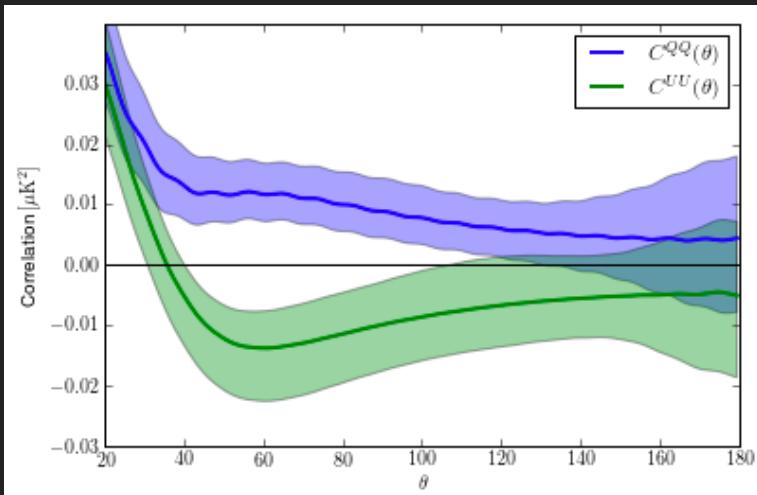
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Angular correlation function of Q and U polarizations with $r = 0.1$. The shaded regions correspond to the 68% C.L. errors. The ranges include instrumental noise for a future generation PIXIE-like experiment and cosmic variance.

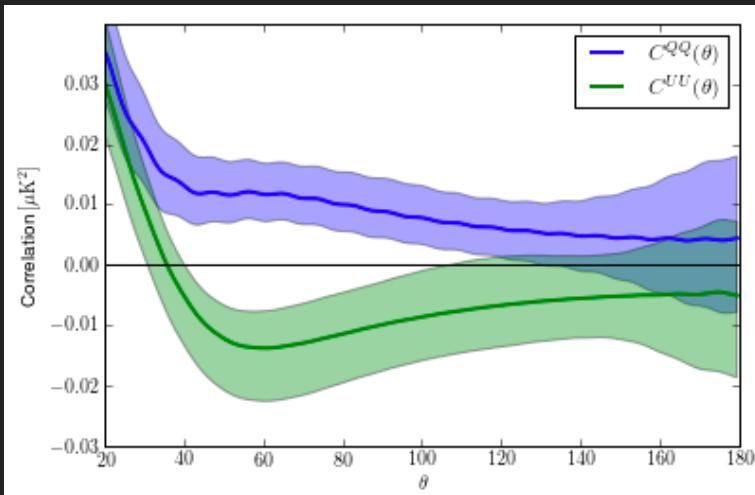
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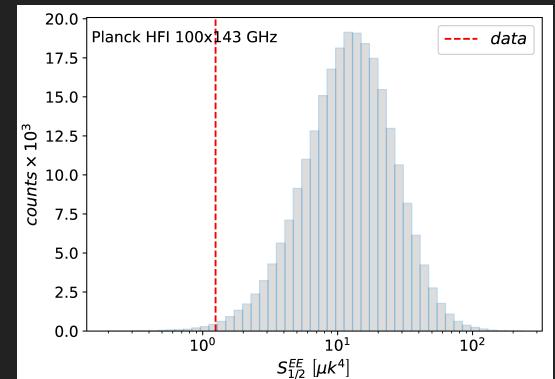
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Lack-of-correlation anomaly in CMB large scale polarization maps:



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

Local E mode

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

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

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More phenomenological guesses:

1. Absence of angular correlation is due to absence of spatial correlation in 3D

Consequence: expect low or no correlation in:

$$(\bar{T}, \bar{E}, \bar{B}?, \varphi, \delta(z), \dots) \times (\bar{T}, \bar{E}, \bar{B}?, \varphi, \delta(z'), \dots)$$

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- $C(\theta)$ has had the monopole and dipole subtracted
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- $C_1 < \sim 200 \text{ } (\mu\text{K})^2$ ($C_1^{\text{th}} \sim 3300 \text{ } (\mu\text{K})^2$)

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Q: Can you detect this dipole?

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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⇒ Generate nonzero off-diagonal elements in harmonic-space 2-point correlations

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Simplest topologies:

1. E^3 (flat): 18 topologies with ~ 10 free parameters each
2. S^3 (positively curved): (countably) infinite topologies
3. H^3 (negatively curved): (uncountably) infinite topologies

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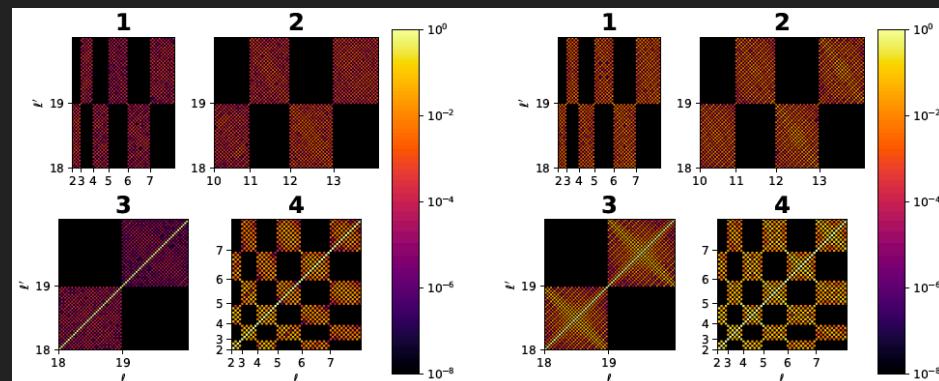
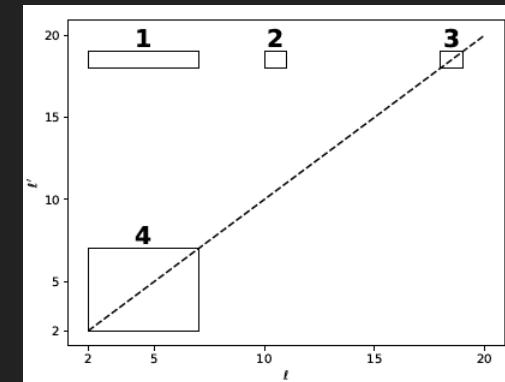
$$C_{\ell m \ell' m'}$$

It is very hard for microphysics to satisfy these conditions.

Our best bet: change boundary conditions \Rightarrow cosmic topology

Simplest topologies:

1. E^3 (flat): 18 topologies with ~ 10 free parameters each
2. S^3 (positively curved): (countably) infinite topologies
3. H^3 (negatively curved): (uncountably) infinite topologies



FUNDAMENTAL PHYSICS MODELS:

Requirements:

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

2. Affect scales that were causally disconnected until recently

$$C_{\ell m \ell' m'}$$

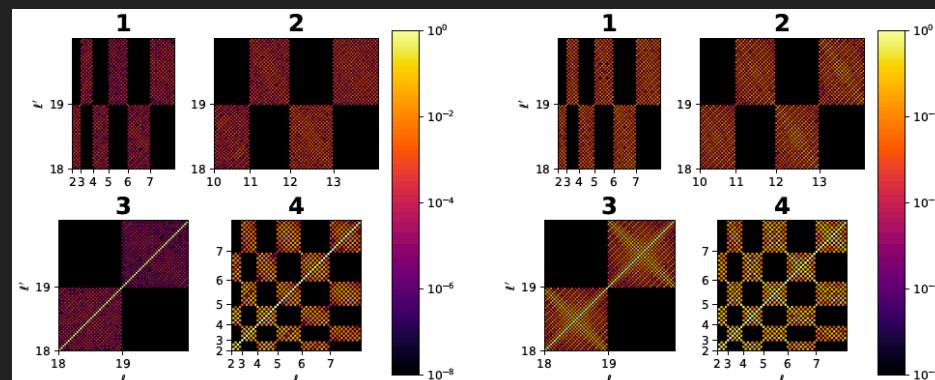
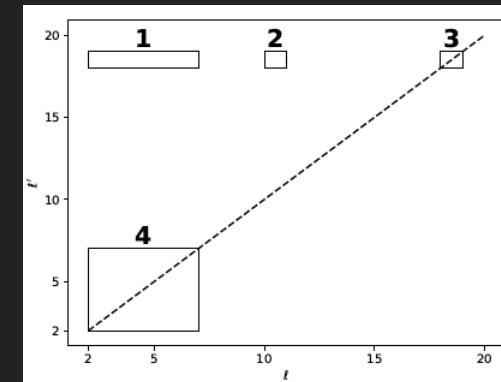
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- What has been explored/constrained so far is a set of **measure zero** in the space of possible cases and parameter values.
- Most of interesting/relevant cases **remain** to be explored/tested/constrained.
- Discovering nontrivial topology would 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 Λ CDM 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