How Improbable is our Universe?

The Uncorrelated Anomalies of the Cosmic Microwave Background

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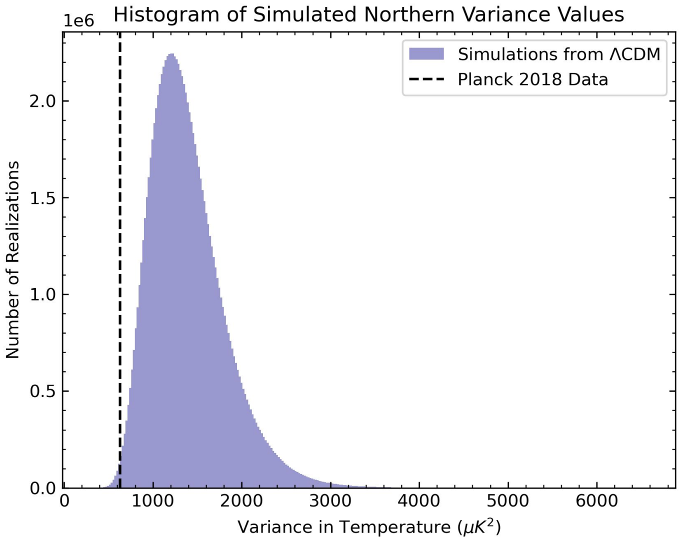
The large angle anomalies

- There are several strange large angle features in the CMB suggesting deviations from statistical isotropy



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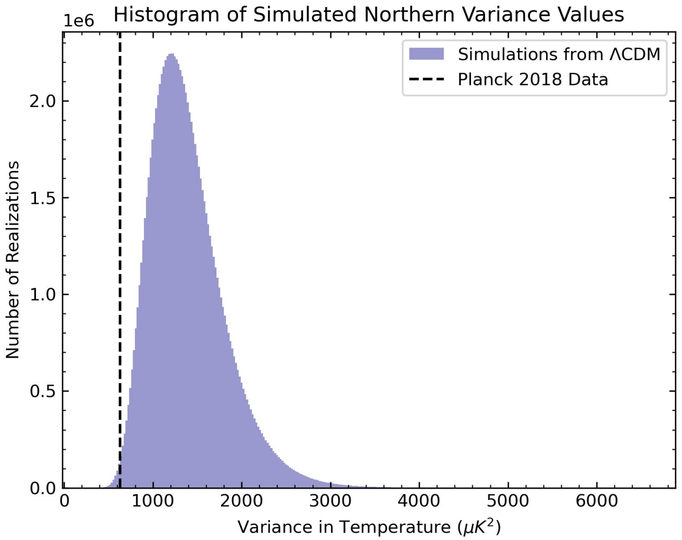

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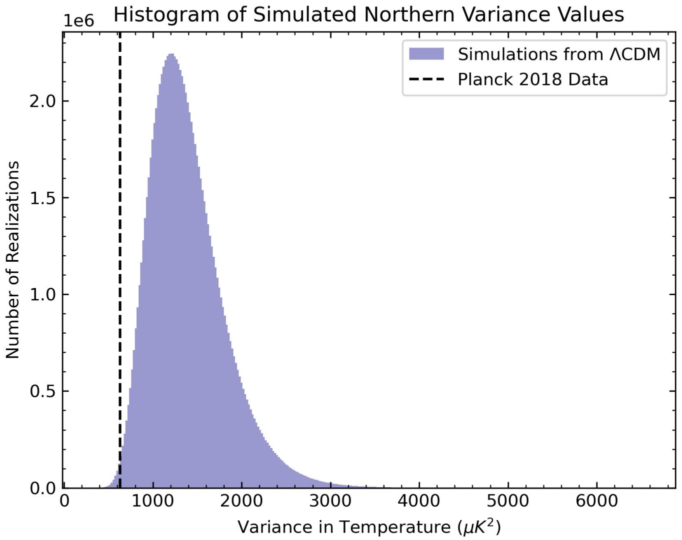

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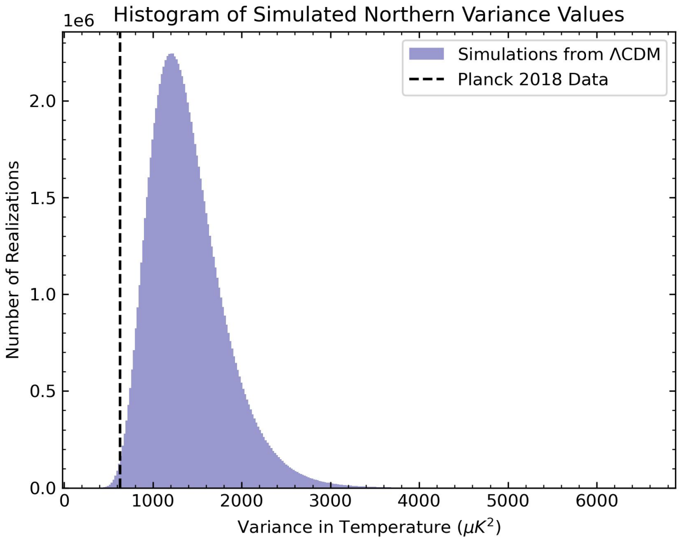
- First noted in COBE (1996) and WMAP (2003) data, still exist in Planck (2018)



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- Under LCDM, each anomaly has a small chance of occurring individually
- They are often **individually** excused as statistical flukes
- **What is the joint probability of all of the anomalies occurring in a LCDM Universe?**
- **Are they correlated?** Or is the joint p-value significant enough for us to seriously consider **LCDM with the assumption of statistical isotropy isn't working to describe the data?**

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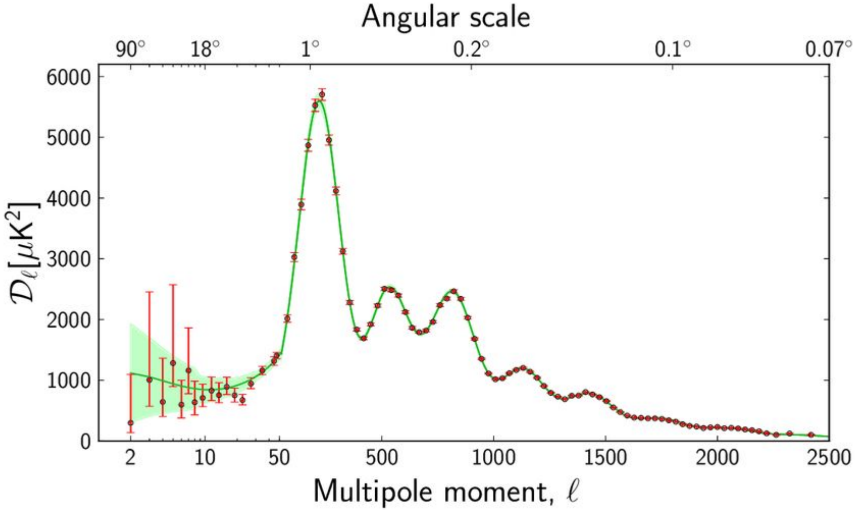

$$f(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm}Y_{lm}(\theta,\phi)$$

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

$$D_\ell \equiv C_\ell\,\ell(\ell+1)/(2\pi)$$

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- Utilize different Python packages (HEALPix (healpy), NaMaster (pymaster))
- We created 100,000,000 noise-free realizations

2nd step: calculating the anomalous statistics on the real and simulated data

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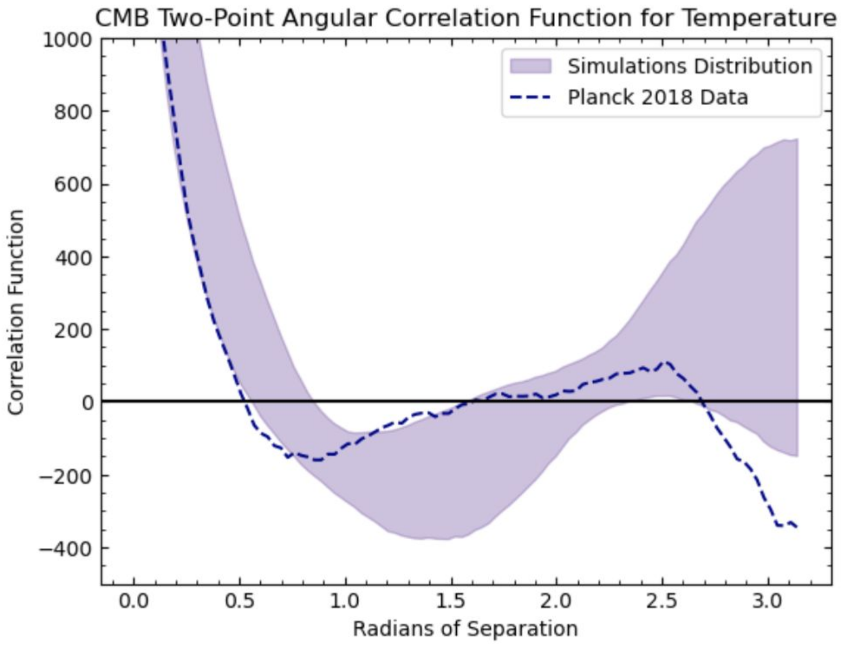
$$C(\theta) = \langle T(\hat{\mathbf{n}}_1) T(\hat{\mathbf{n}}_2) \rangle$$
$$= \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_\ell P_\ell(\cos\theta)$$



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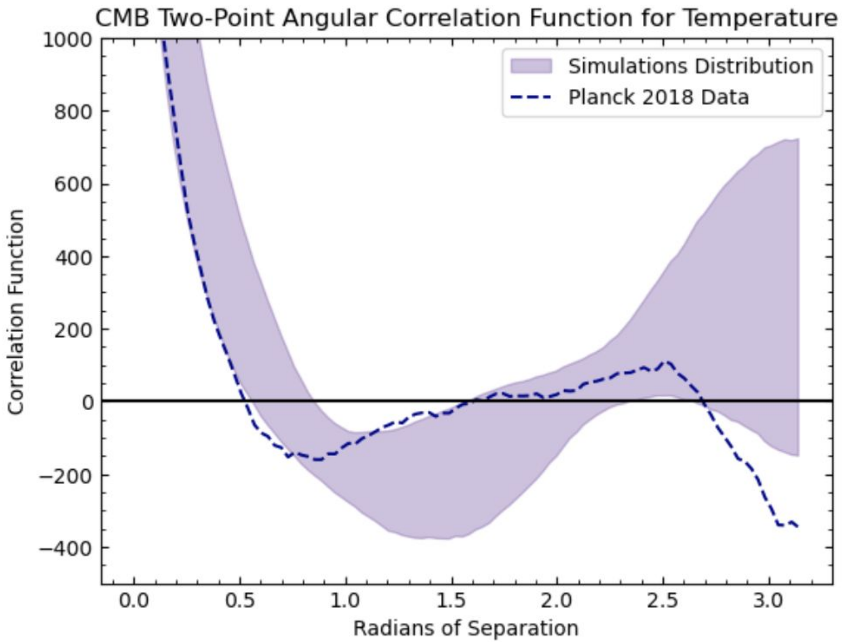

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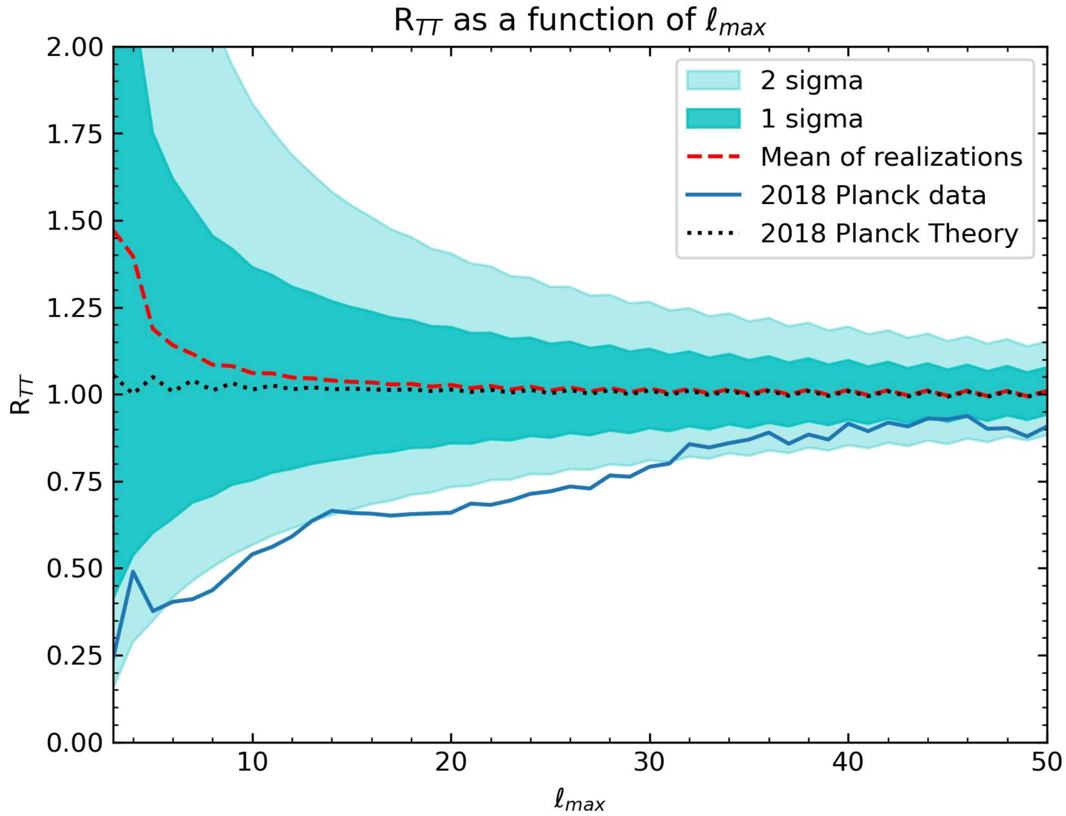

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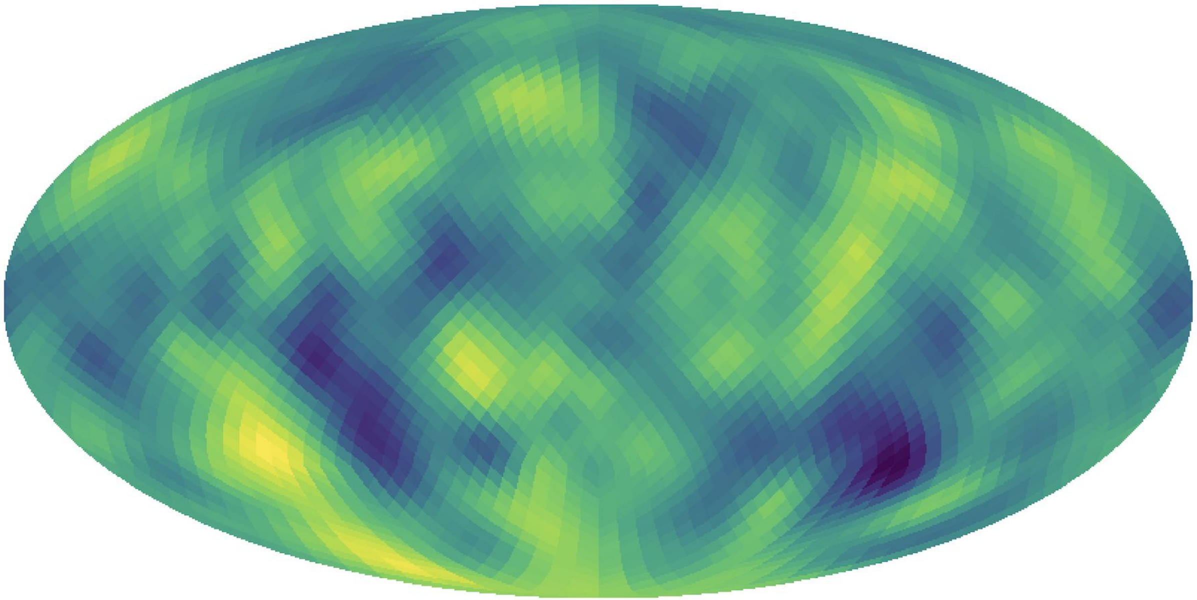

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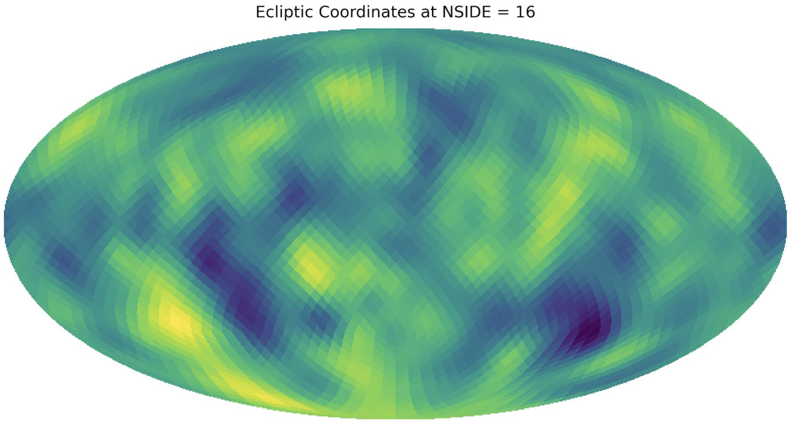

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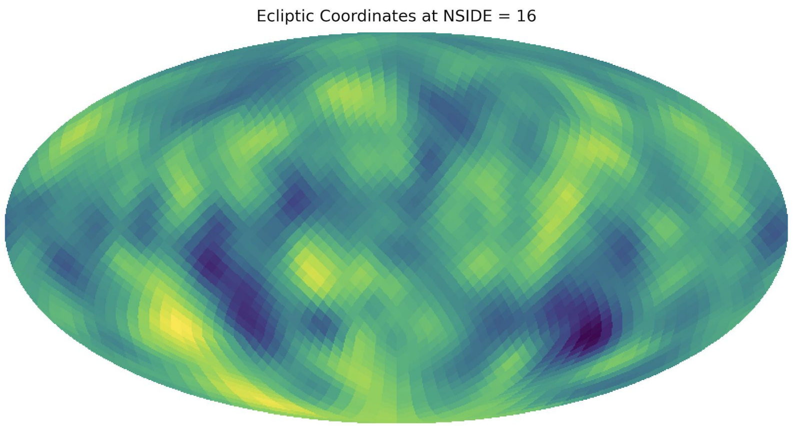
- **Only .4% of realizations have as low of a value as the data**



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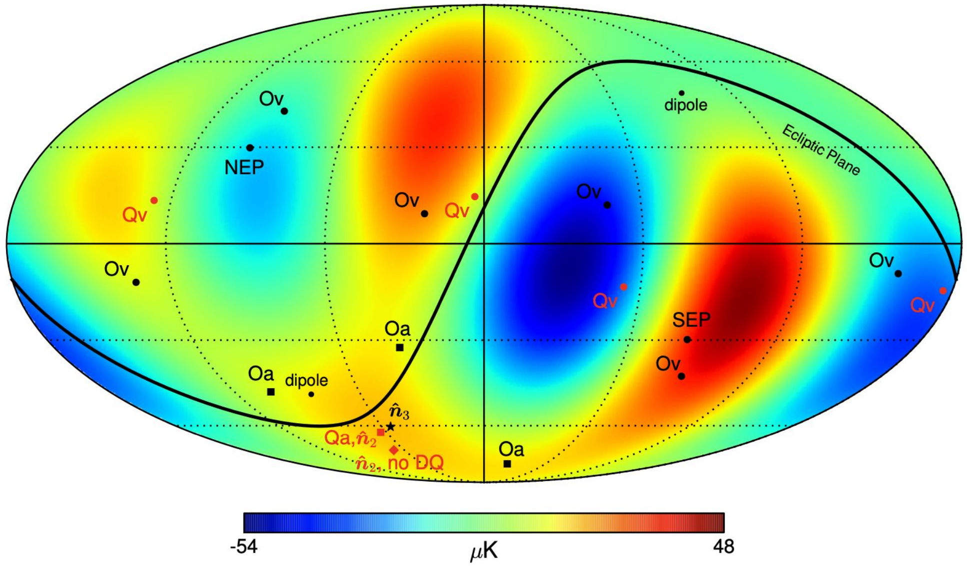

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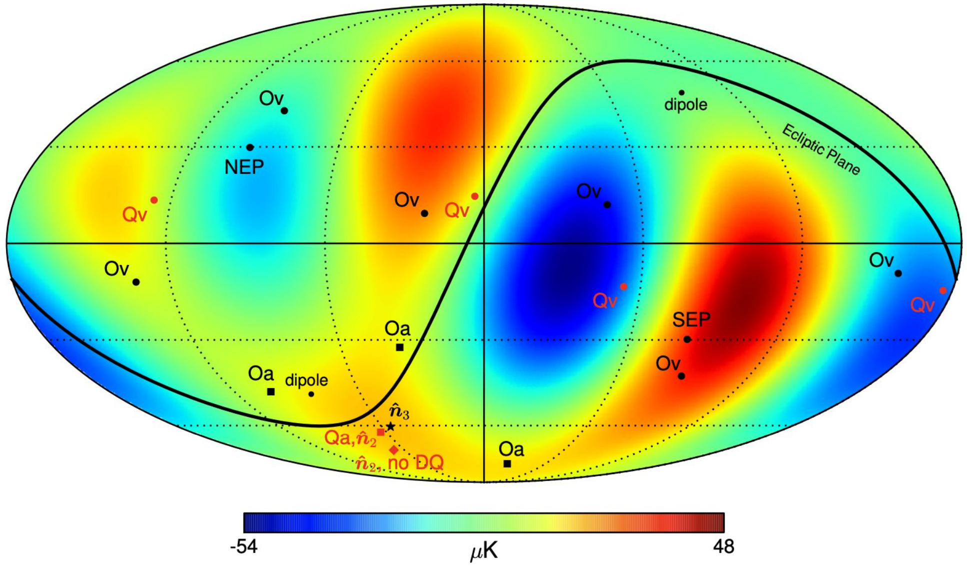

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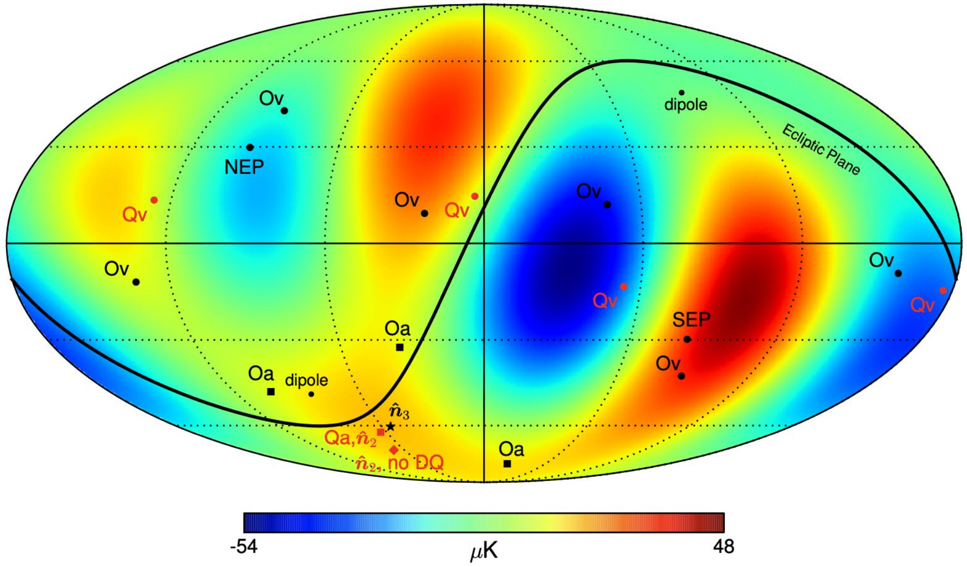
$$S_{QO} \equiv \frac{1}{3} \sum_{i=1}^{2} \sum_{j=i+1}^{3} \left| \boldsymbol{w}^{(2;1,2)} \cdot \boldsymbol{w}^{(3;i,j)} \right|$$



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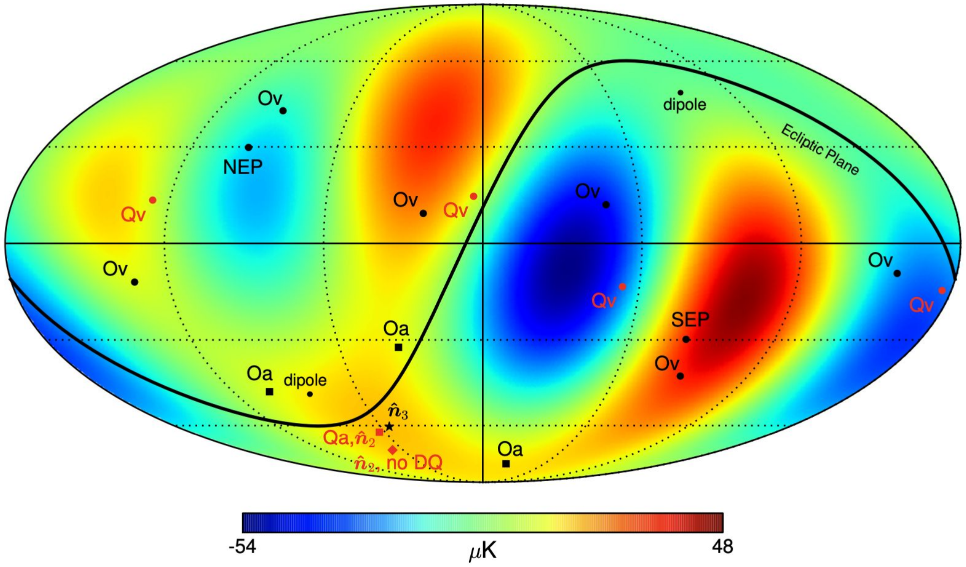
- **Only .1% of realizations have as high of an alignment as the data**



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To summarize:

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Are these results correlated? Or is their joint probability significantly lower?

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However, we are interested in the tails of the distributions

The tail end correlations may be quite different than the bulk of the distribution!

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Let’s look at this visually

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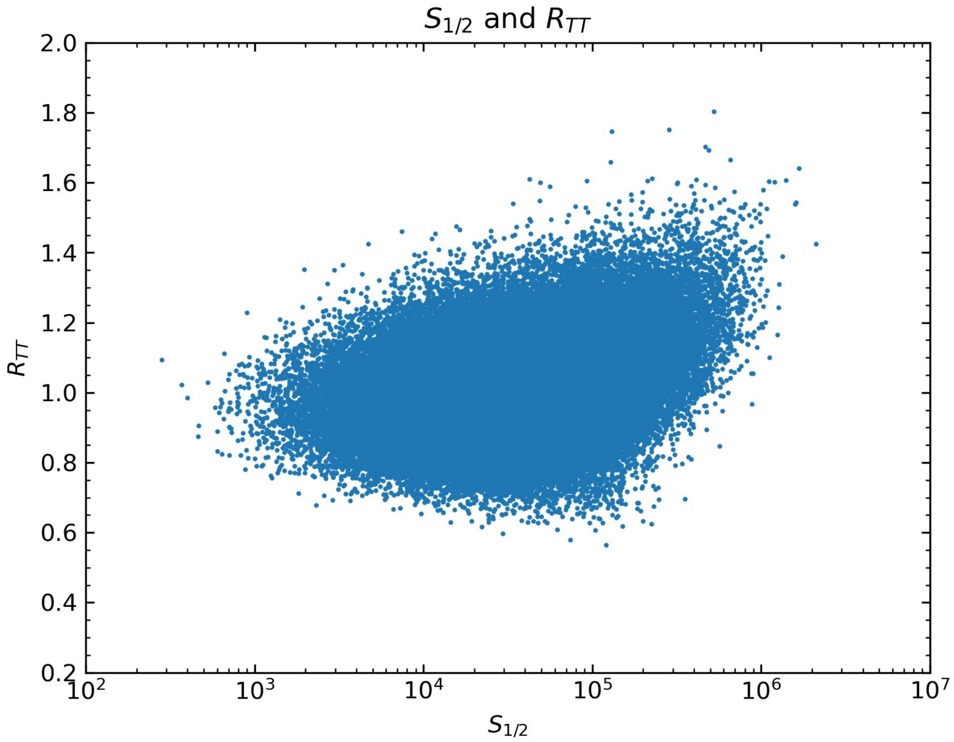

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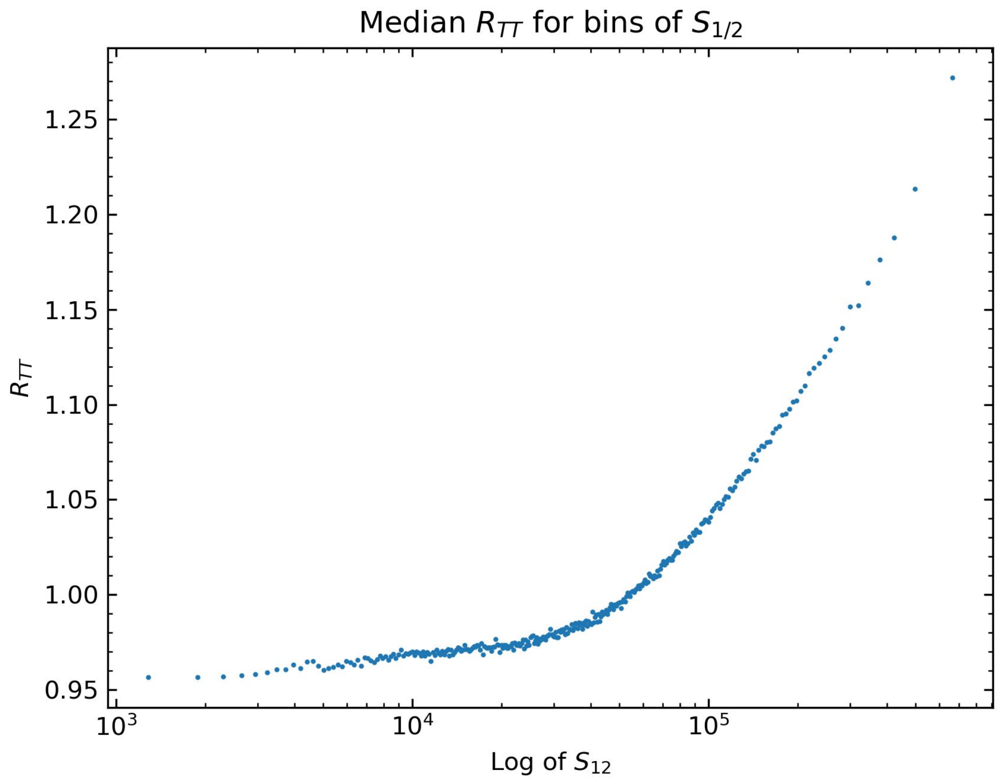

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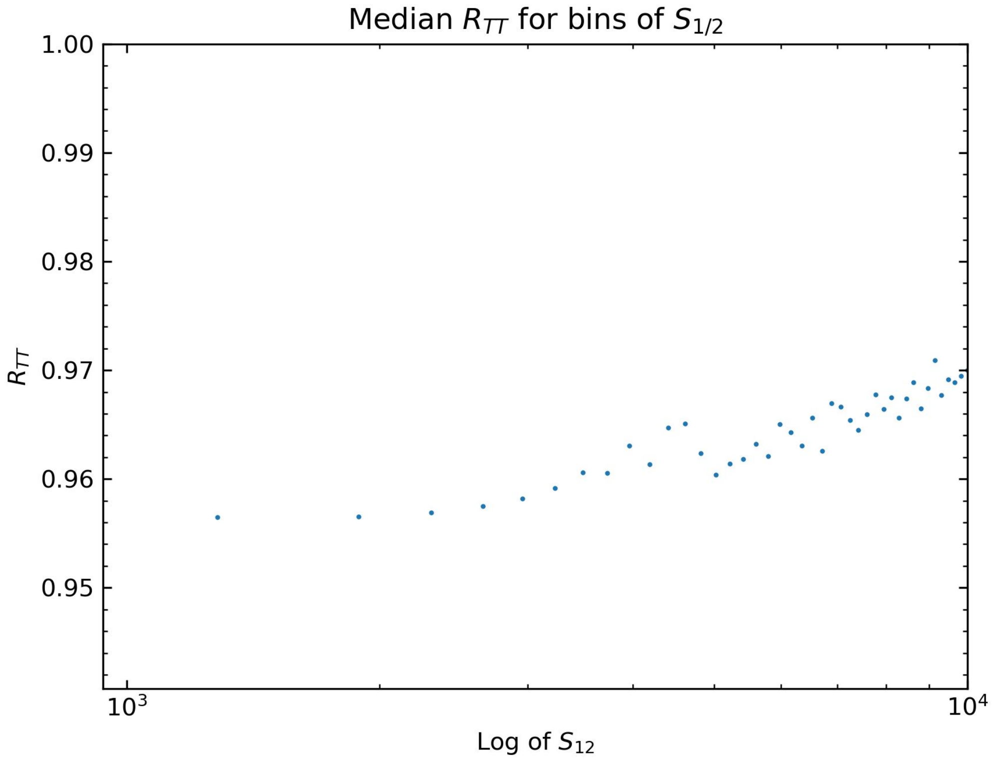

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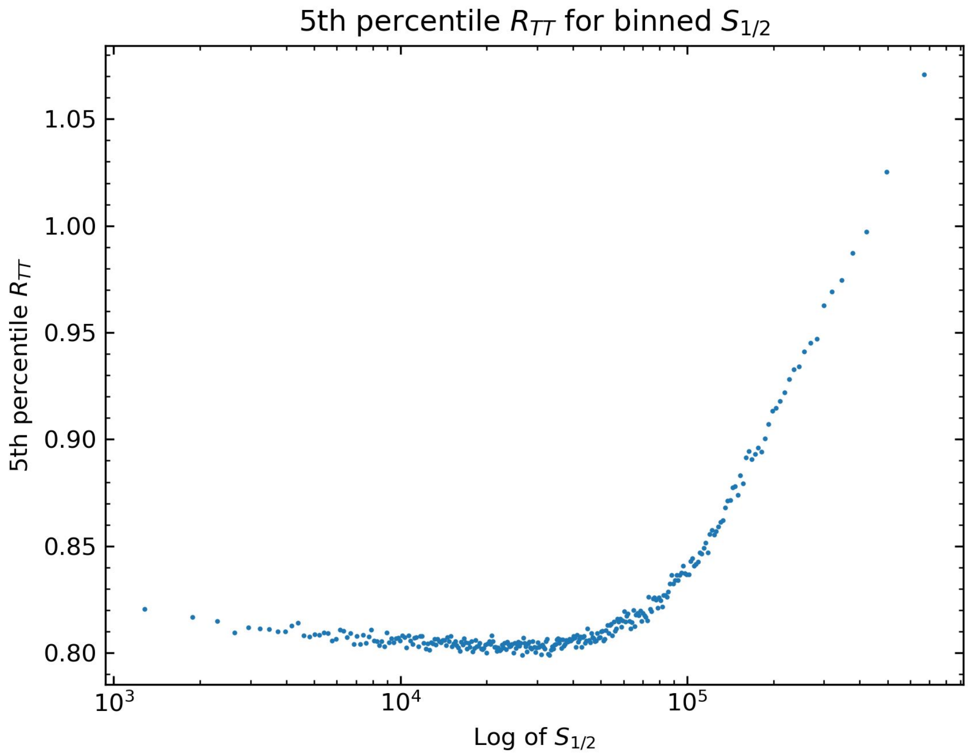

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$$p(S_A, S_B)/(p(S_A)p(S_B))$$

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			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_{16}^2	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}

(Jones, Copi, Starkman, Akrami, 2023, arXiv:2310.12859)

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P-value of all four anomalies occurring in a LCDM CMB:

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over a 5 sigma deviation!!!

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- We believe that our result still holds strong significance providing insight into the nature of the anomalies and their occurrence in LCDM

Thank you for listening!