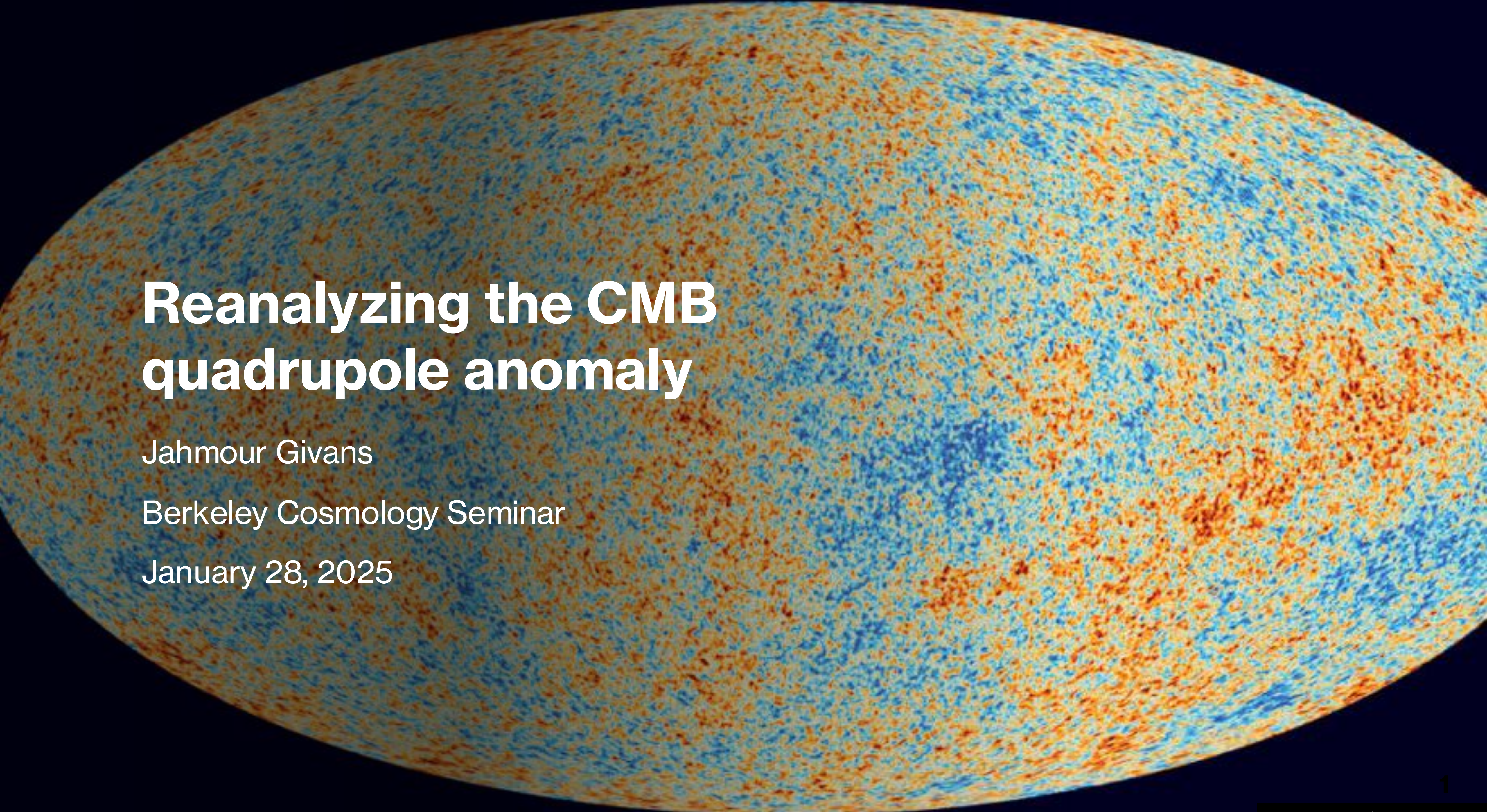

Credit: ESA/Planck Collaboration

Reanalyzing the CMB quadrupole anomaly

Jahmour Givans

Berkeley Cosmology Seminar

January 28, 2025

Ingredients of our cosmological model

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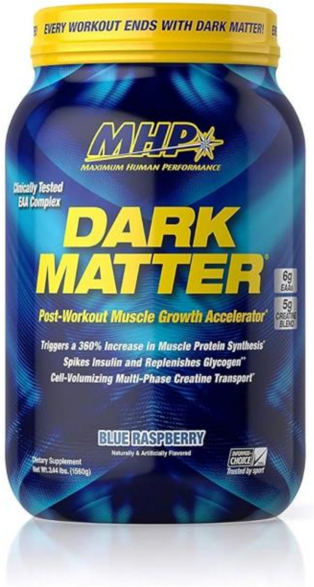

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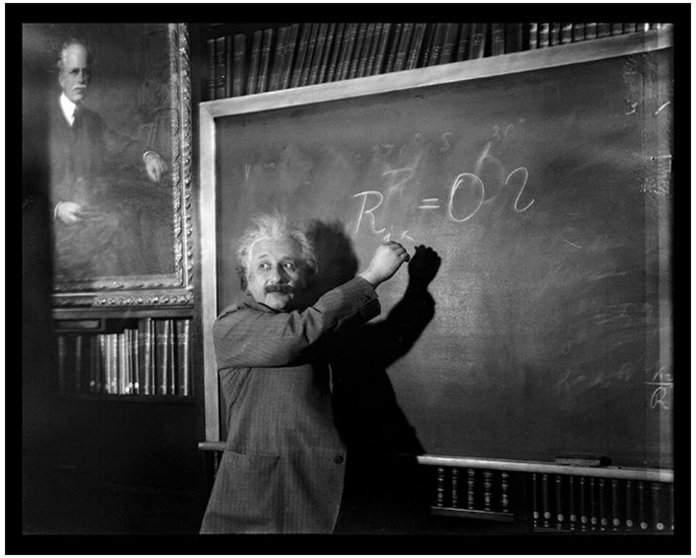

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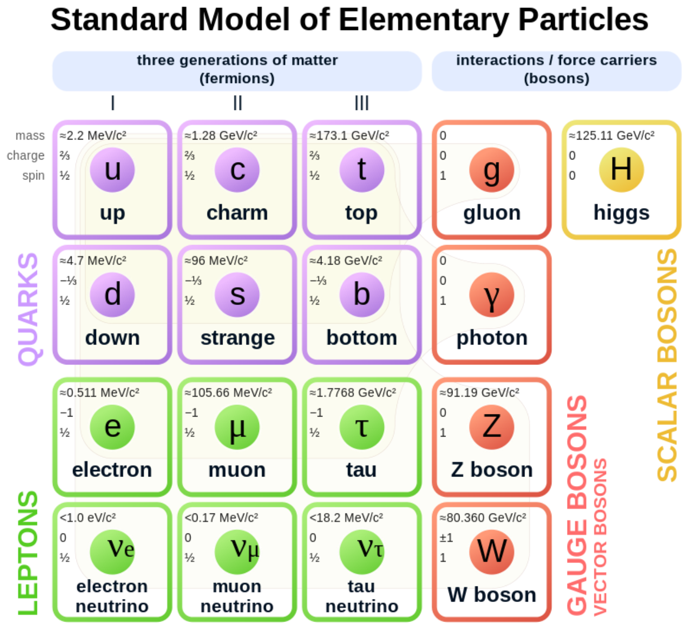
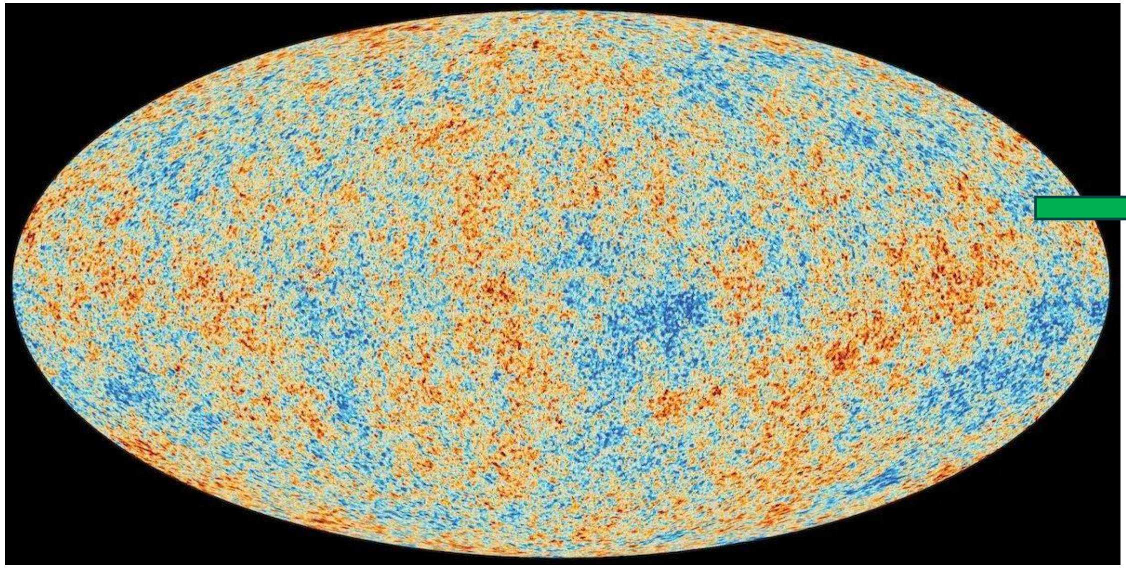
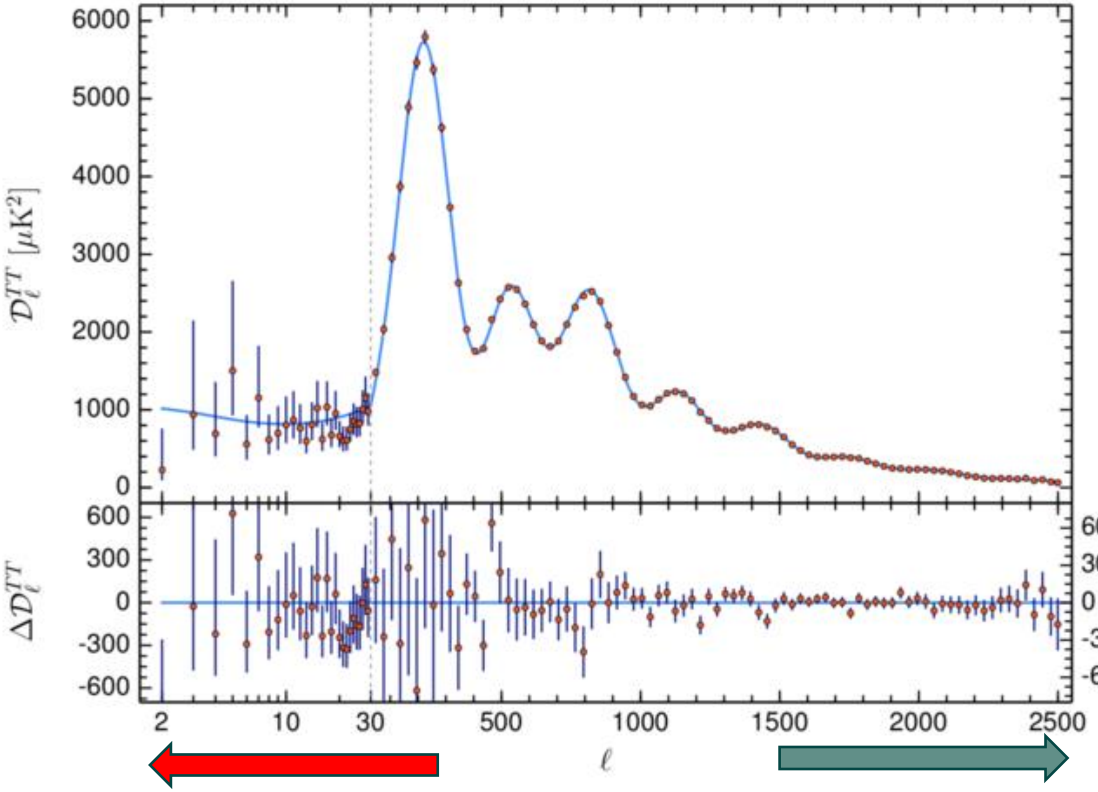


LCDM works*

- Six cosmological parameters can go a long way!
- CMB temperature power spectrum = variance in temperature fluctuations





Large scales

Small scales

Planck Collaboration VI 2020

LCDM is incomplete

- What is dark matter?
  - A mystery for over 90 years
  - Particles, macroscopic objects, or something else?
- What is dark energy?
  - Cosmological constant, scalar field, something dynamical?
- Details (and existence) of inflation are unknown

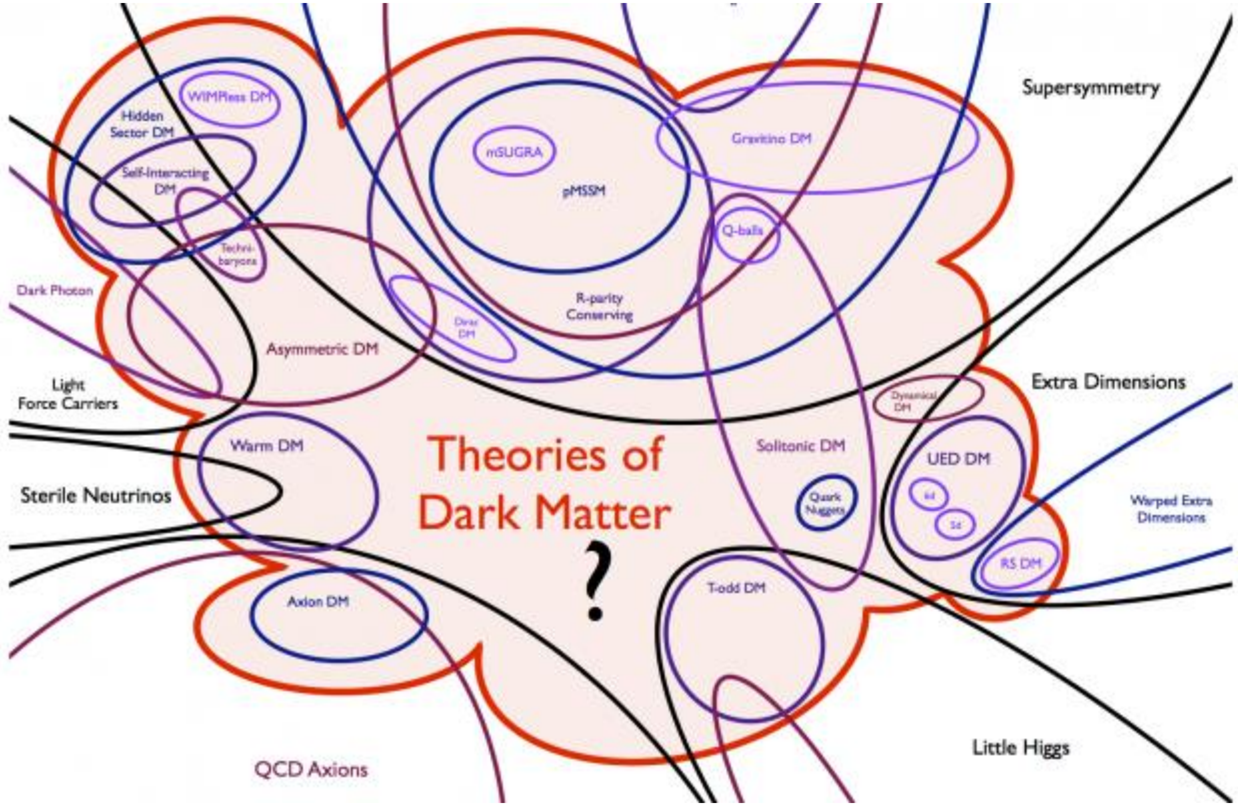
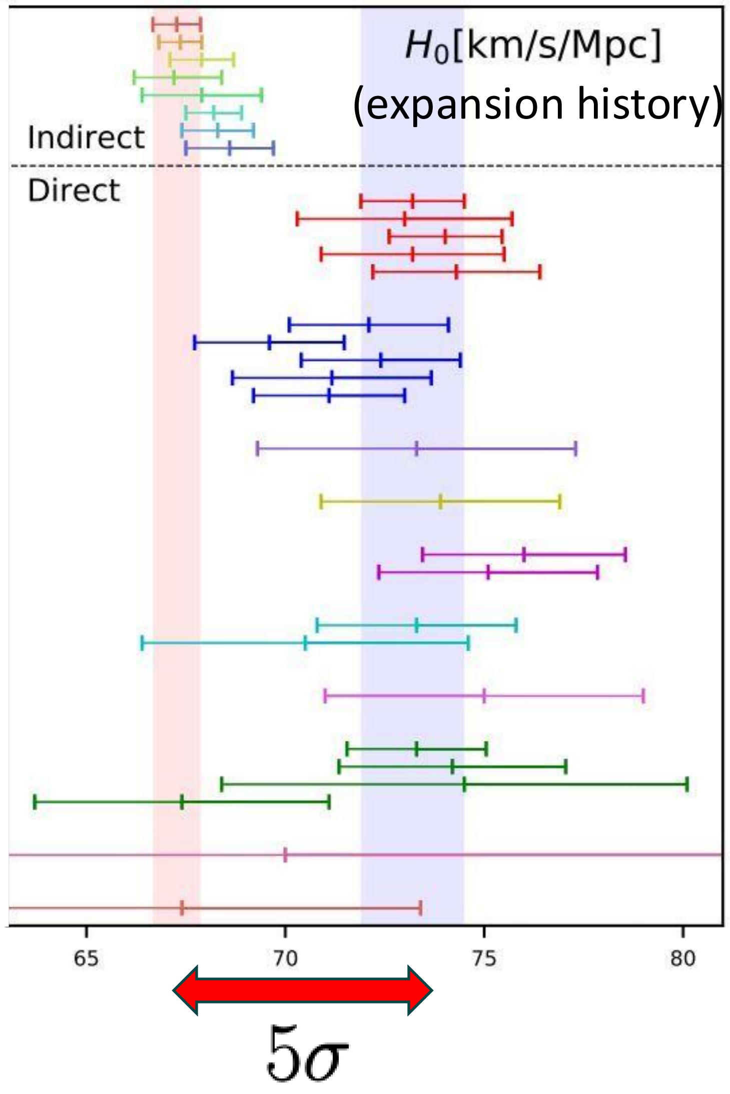


Image credit: Tim Tait

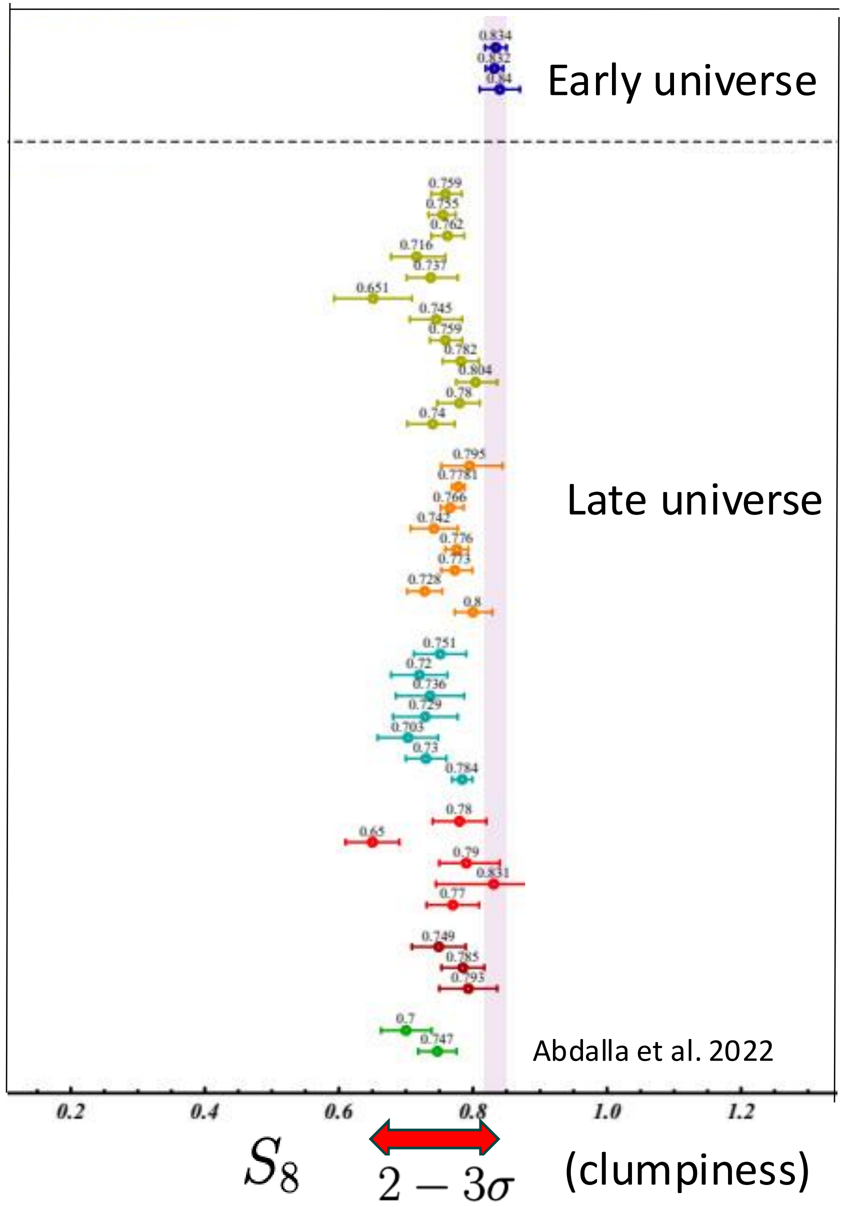
LCDM gets things wrong

Early universe

Late universe



Di Valentino et al. 2021

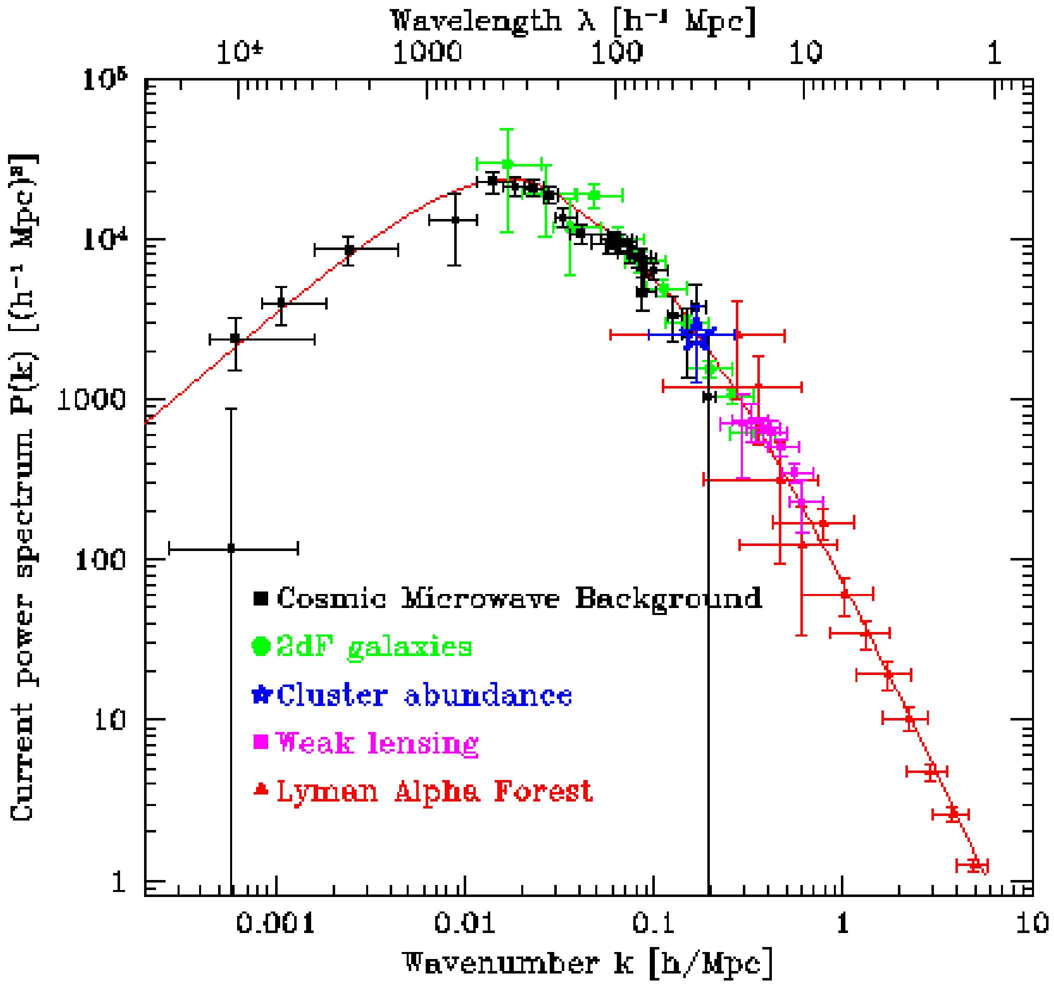


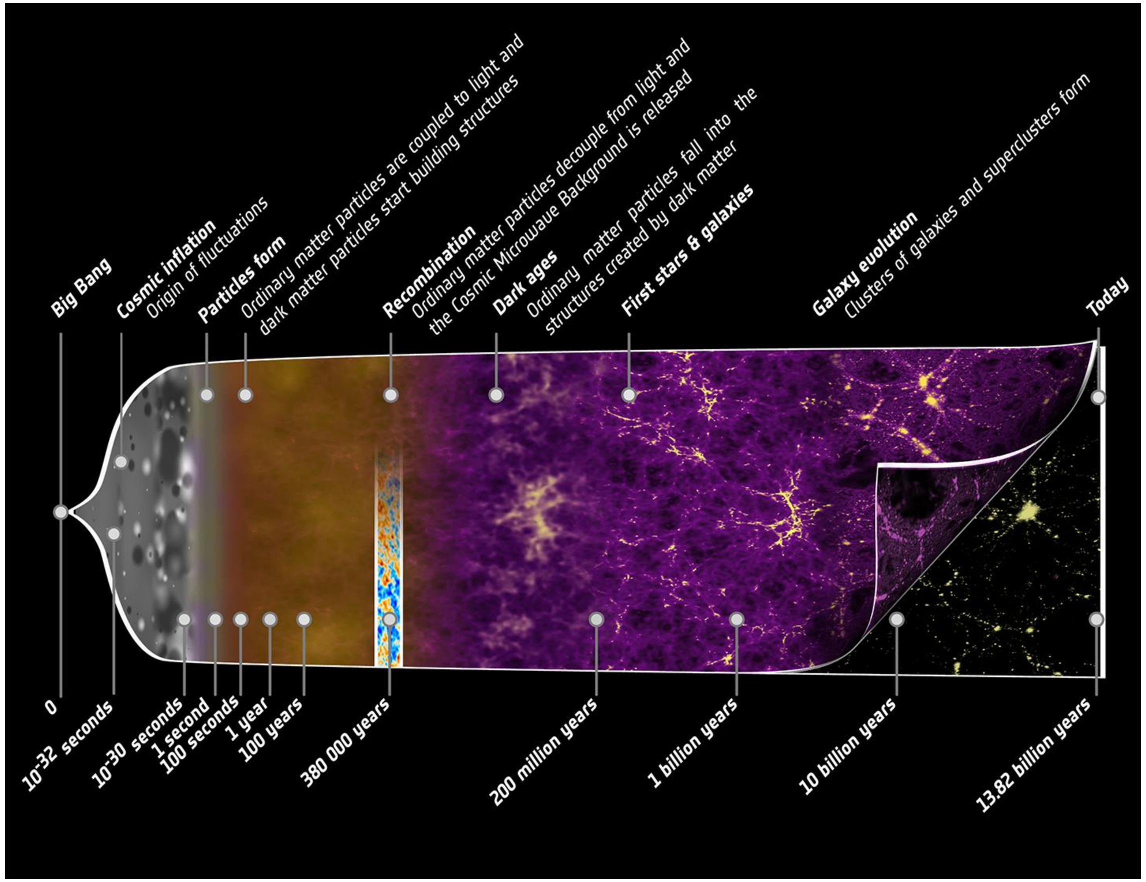
Principles of our cosmological model

- Copernican principle
- Statistically homogeneous
- Statistically isotropic
- Perturbations from inflation are:
  - Gaussian
  - Adiabatic (local state of matter = background + time shift)
  - Nearly scale-free (flat power spectrum)

Why the CMB? (1/2)

- Access to the largest observable scales
- Linear theory is sufficient





Why the CMB? (2/2)

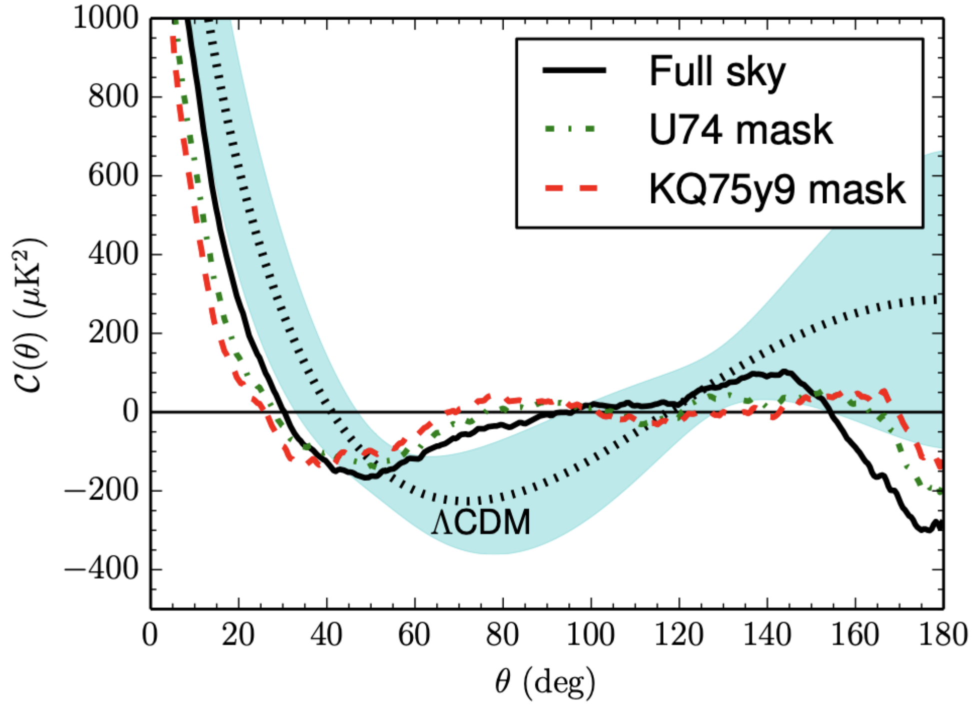
- Information from the earliest times
- (Almost) nothing else comes close

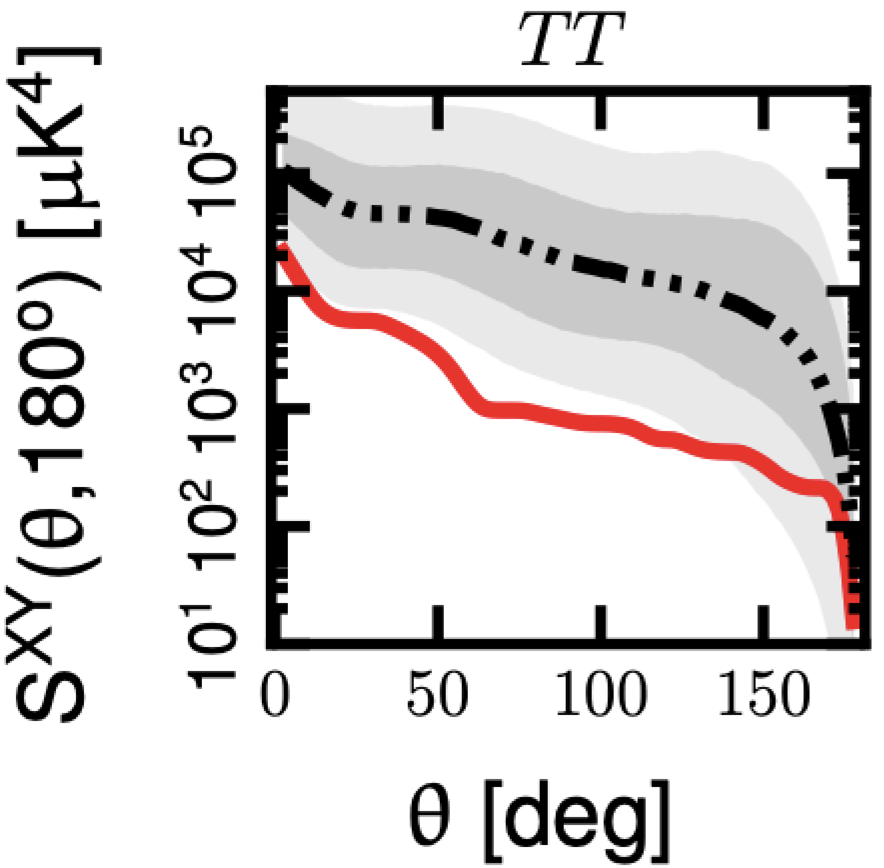
But first, what are other CMB anomalies

the following is an inexhaustive sample

Lack of large-angle correlations

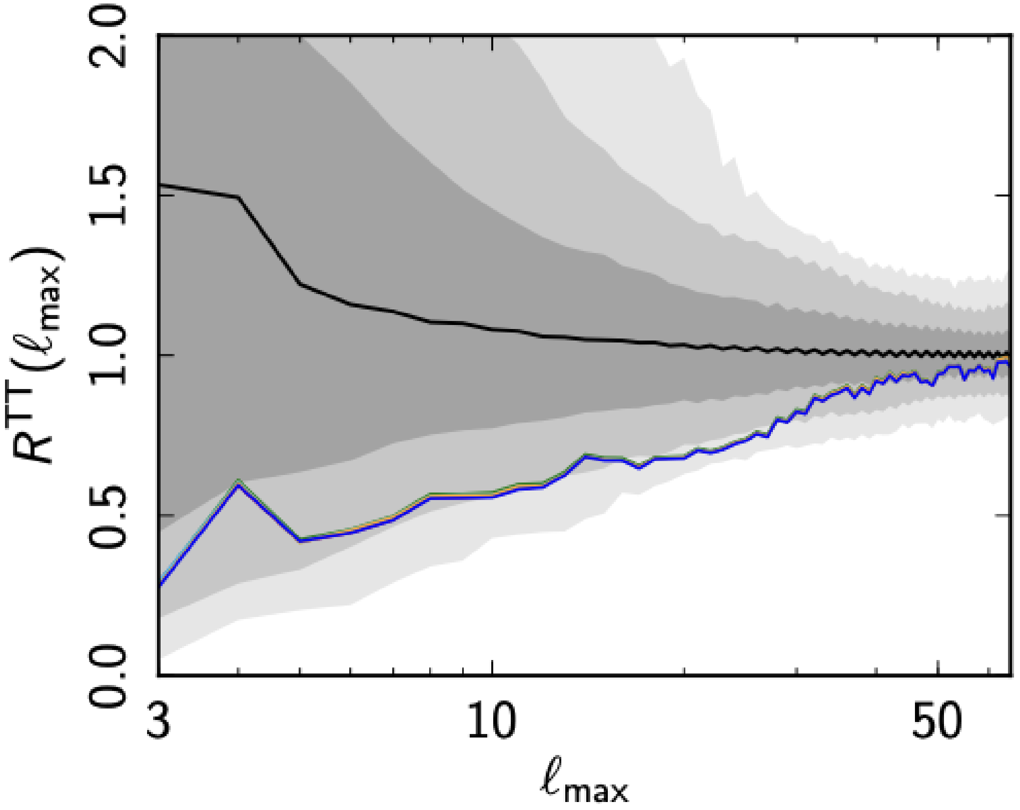
$$S^{XY}(\theta_1, \theta_2) = \int_{\cos\theta_2}^{\cos\theta_1} \left[\hat{C}_2^{XY}(\theta)\right]^2 \mathrm{d}(\cos\theta)$$

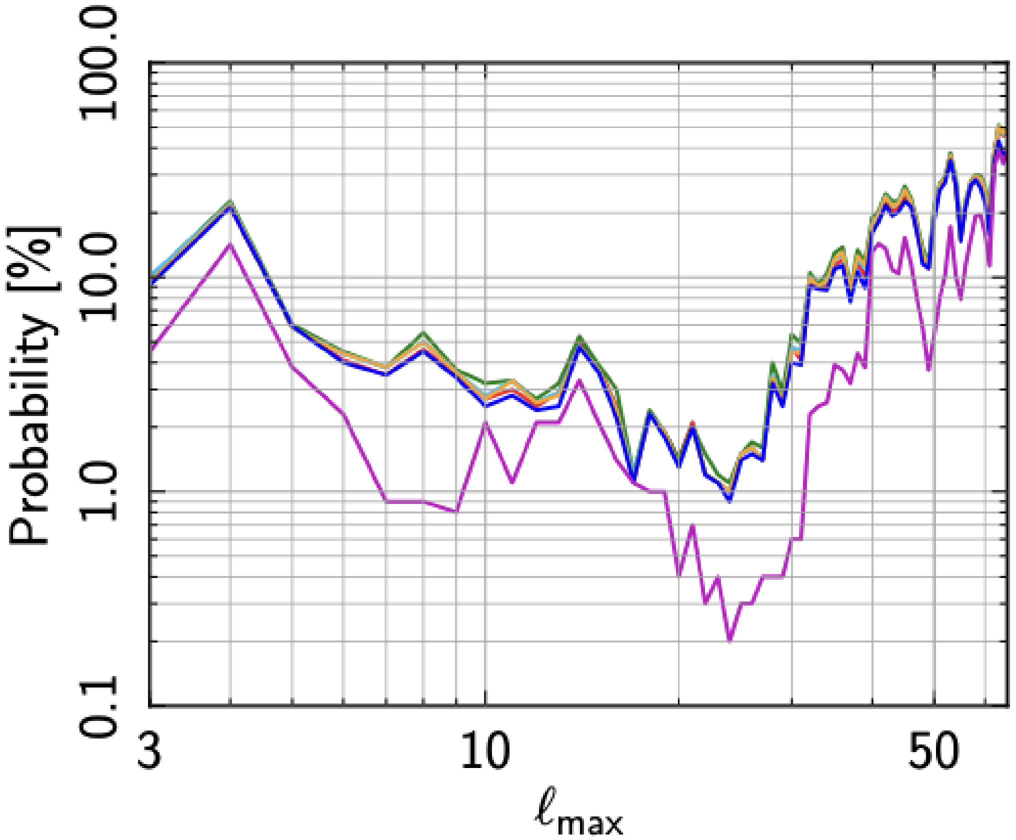




Parity asymmetry

$$R^{\mathrm{TT}}(\ell_{\max}) = \frac{C_{+}^{\mathrm{TT}}(\ell_{\max})}{C_{-}^{\mathrm{TT}}(\ell_{\max})}$$



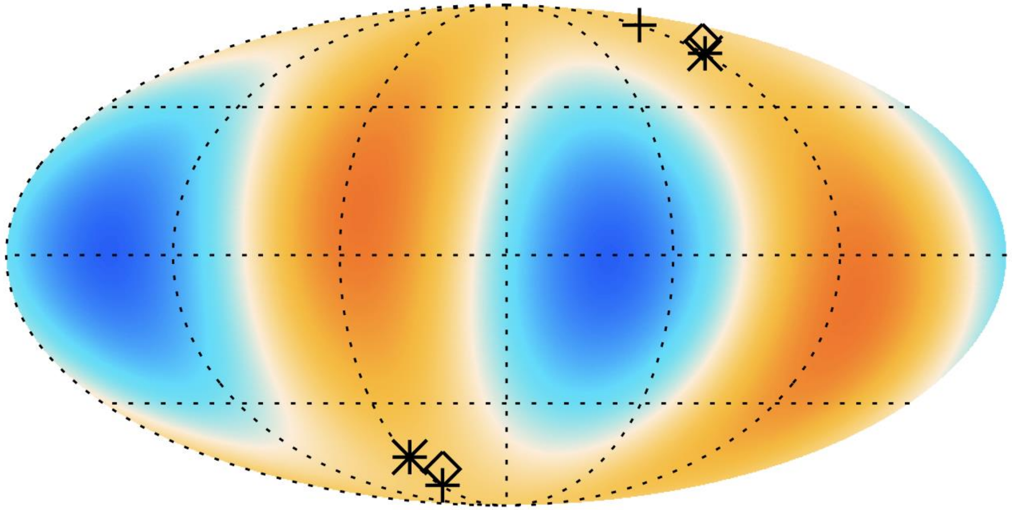


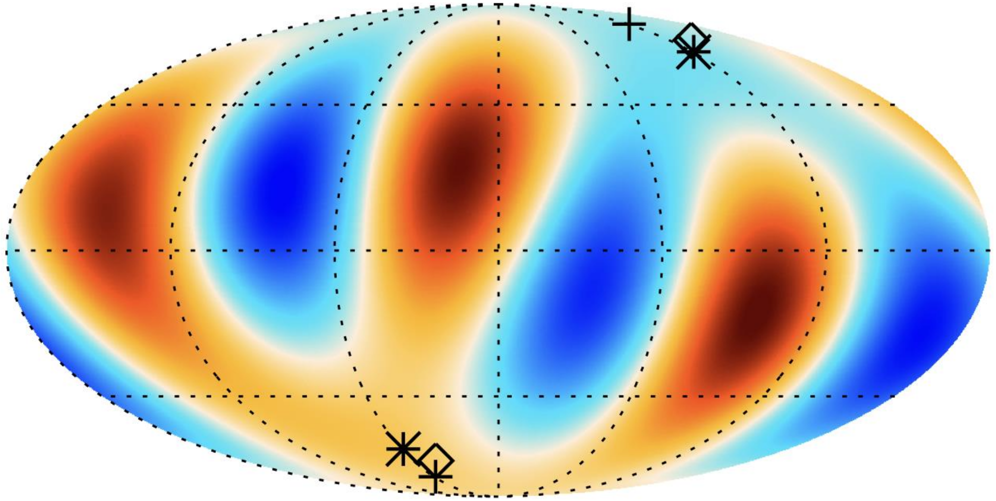
Hemispherical power asymmetry

Mask	Probability		
	Variance	Skewness	Kurtosis
U73, $f_{\rm sky} = 73\%$	0.017	0.189	0.419
CL58, $f_{\rm sky} = 58\%$	0.003	0.170	0.363
CL37, $f_{\rm sky} = 37\%$	0.030	0.314	0.266
Ecliptic North, $f_{\rm sky} = 36\%$	0.001	0.553	0.413
Ecliptic South, $f_{\rm sky} = 37\%$	0.483	0.077	0.556
Galactic North, $f_{\rm sky} = 37\%$	0.001	0.788	0.177
Galactic South, $f_{\rm sky} = 36\%$	0.592	0.145	0.428

Note the differences
between north and south!

Quadrupole-octopole alignment





Method	(*l*,*b*) quadrupole [°]	(*l*,*b*) octopole [°]	Ang. distance [°]	Scalar product	Probability
C-R	(228.2,60.3)	(246.1,66.0)	9.80	0.985	0.019
NILC	(241.3,77.3)	(241.7,64.2)	13.1	0.974	0.033
SEVEM	(242.4,73.8)	(245.6,64.8)	9.08	0.988	0.016
SMICA	(238.5,76.6)	(239.0,64.3)	12.3	0.977	0.032
NILC, KQ corrected . . .	(225.6,69.7)	(241.7,64.2)	8.35	0.989	0.011
SEVEM, KQ corrected. . .	(228.3,68.3)	(245.6,64.8)	7.69	0.991	0.009
SMICA, KQ corrected. . .	(224.2,69.2)	(239.0,64.3)	7.63	0.991	0.009

What if we combine them all?

The Universe is not statistically isotropic

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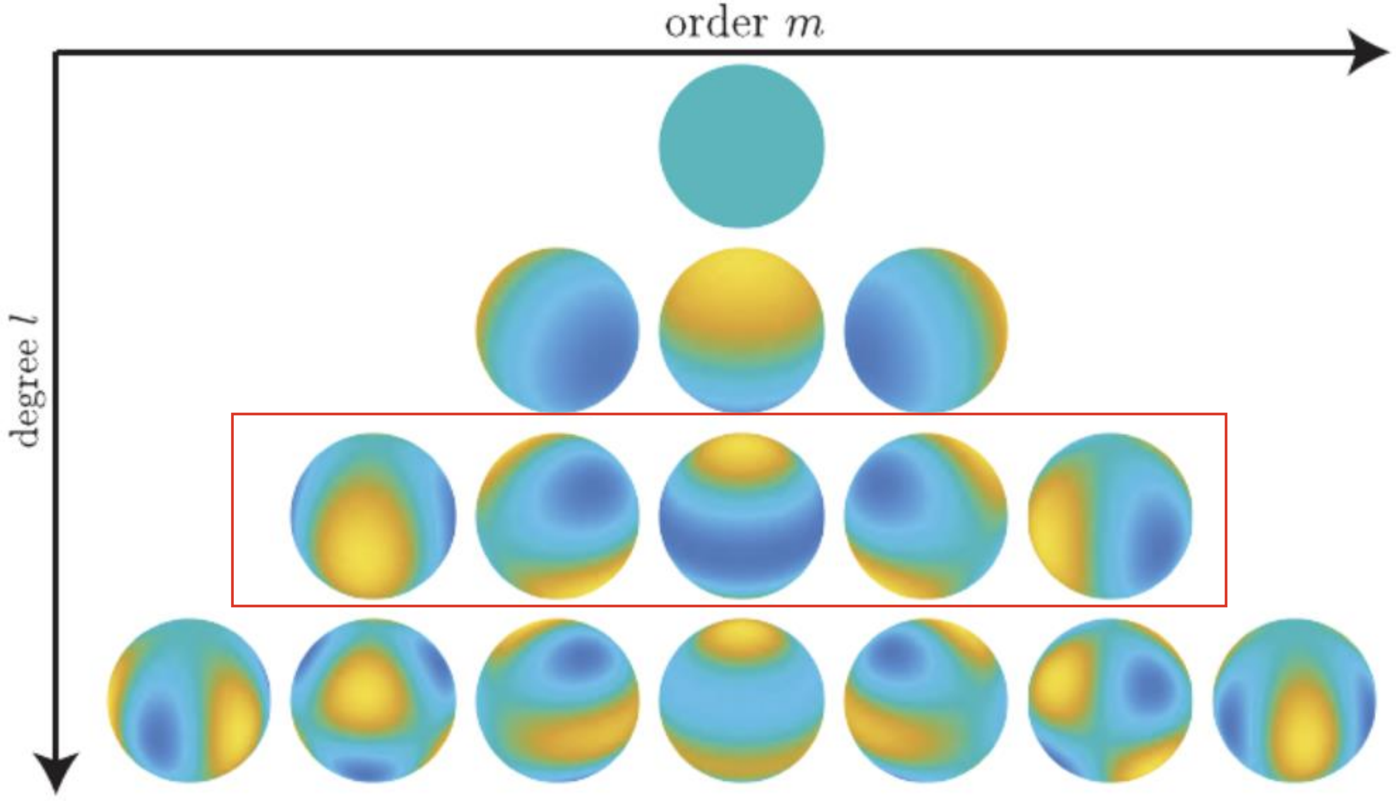
(Dated: October 20, 2023)

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.

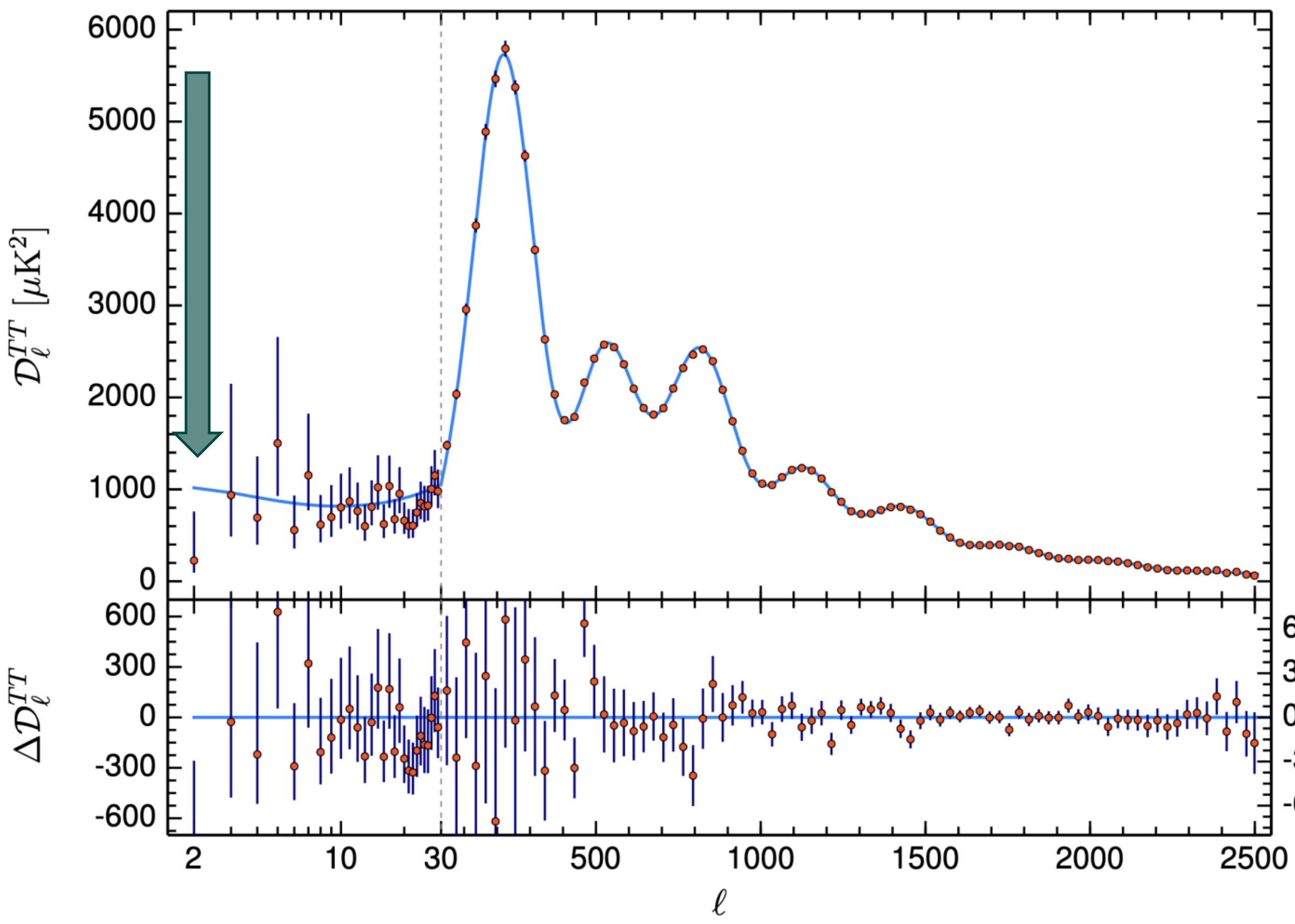
On to the quadrupoles!



Credit: Pfaff, Kurz, & Hanebeck 2017

What is the quadrupole anomaly

- It is low!
- Look-elsewhere effect
- Present in COBE, WMAP, and Planck
  - Instrumental effects, foregrounds unlikely
- Cosmic variance limits us



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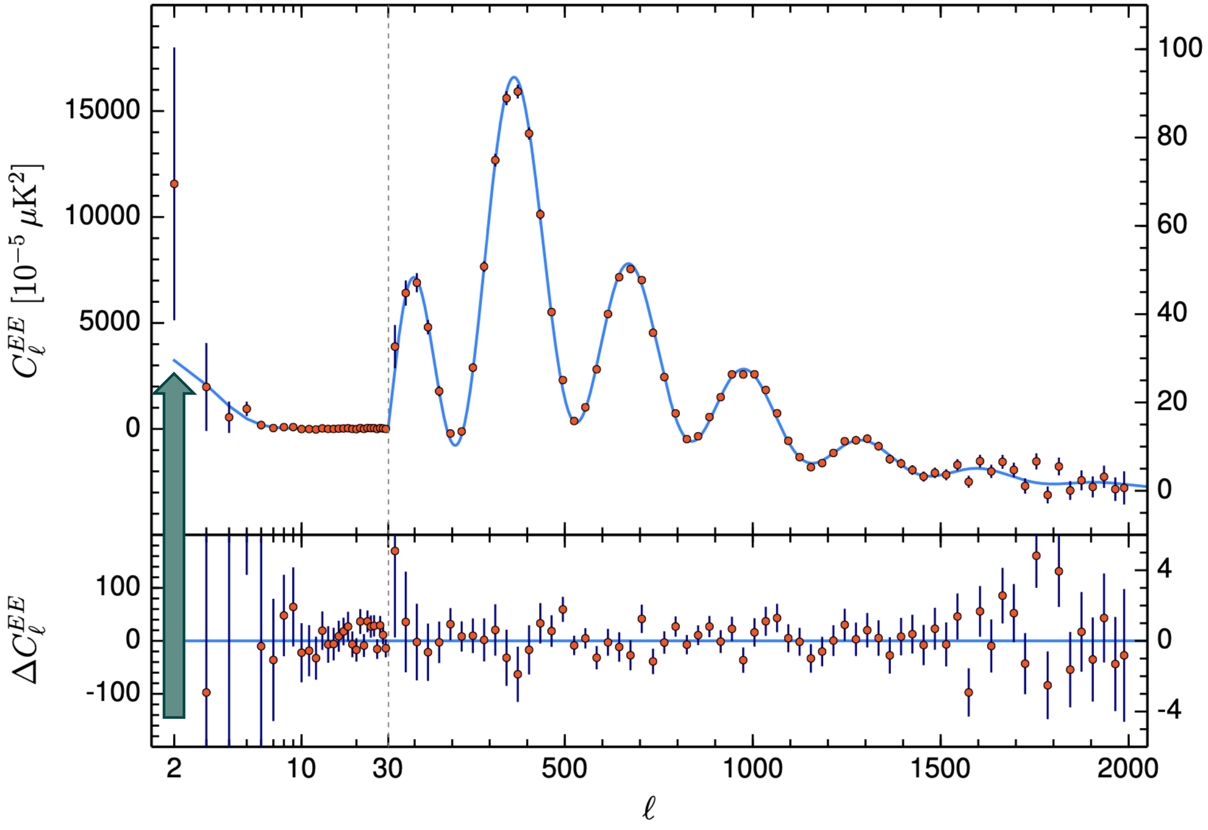


An interesting observation

- Polarization offers another window
  - Not independent, but "close enough"
- Data only got good enough with Planck
- It's high!

Quantifying the anomaly: the ideal case

- Full sky observations
- Instrumental systematics are ignored
- Assume perfect foreground subtraction
- Spherical harmonic coefficients drawn from a Gaussian
- Power spectra values are thus chi-squared-distributed

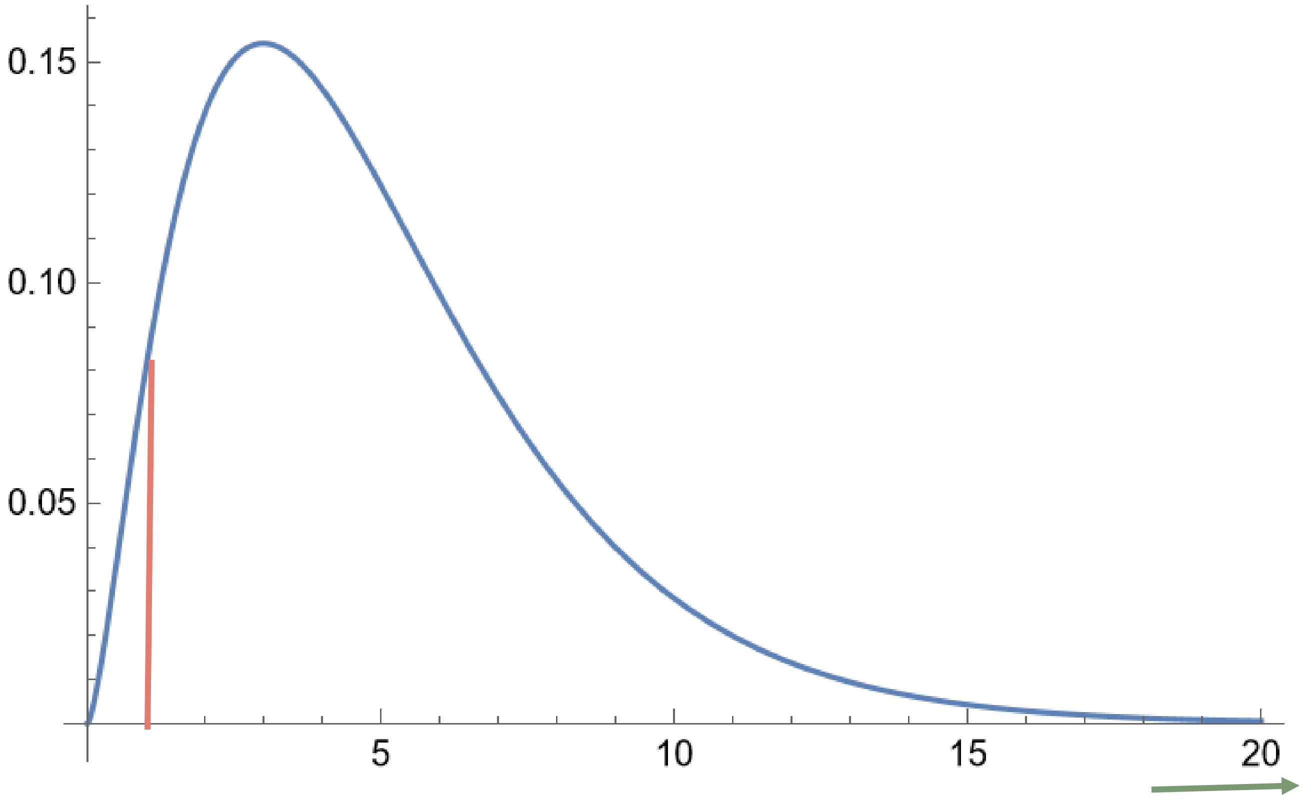
Individual probabilities

- Probability density function is a chi-squared with n = 5 d.o.f.
  - Follows from spherical harmonics: 2l + 1 independent modes
- Temperature

$$X = 5\,\frac{C_2^{TT,\mathrm{observed}}}{C_2^{TT,\mathrm{expected}}} = 1.1$$

- Polarization

$$Y = 5\,\frac{C_2^{EE,\mathrm{observed}}}{C_2^{EE,\mathrm{expected}}} = 18$$



2*p(X < 1.1) = 9%

2*p(Y > 18) = 0.7%

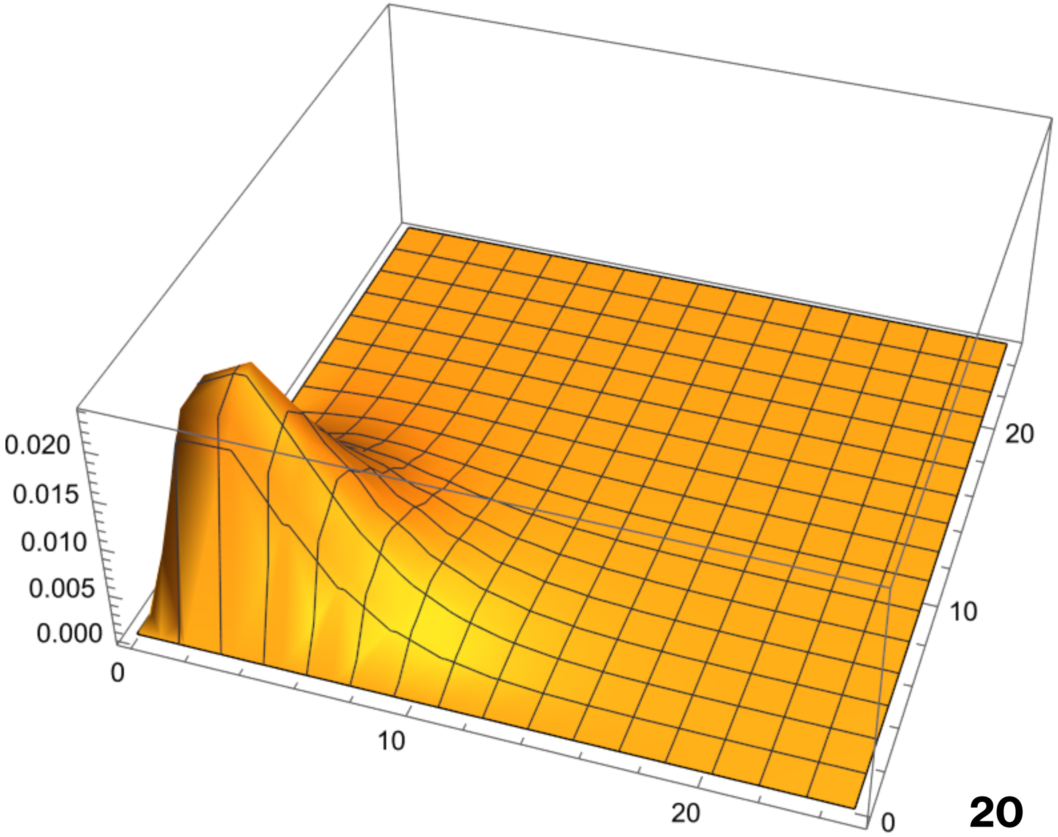
Joint probability

- Had to derive a correlated, bivariate chi-squared distribution

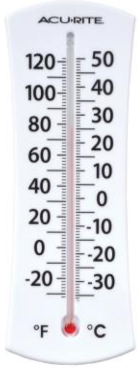
$$P_n(X,Y;\rho) = \frac{(XY)^{\frac{n}{2}-1}}{2^n(1-\rho^2)^{n/2}\,[\Gamma(n/2)]^2} \exp\left[-\frac{X+Y}{2(1-\rho^2)}\right] \times G_n\left(\frac{\rho\sqrt{XY}}{1-\rho^2}\right),$$

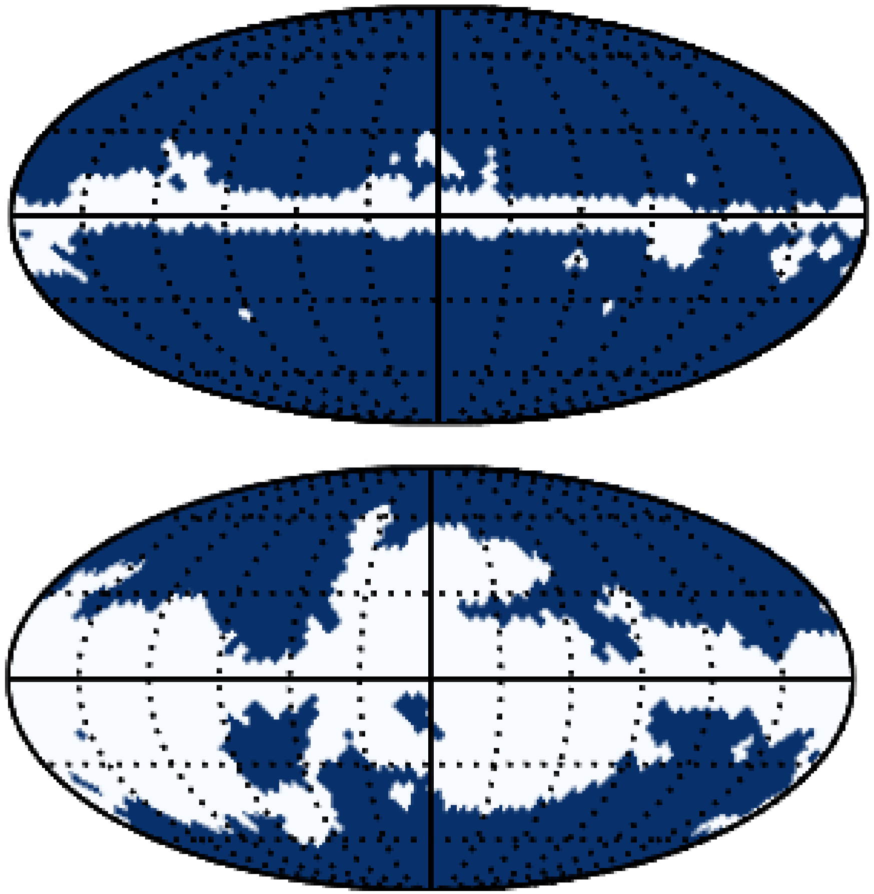
$$G_n(\alpha) \equiv \frac{1}{\sqrt{\pi}} \frac{\Gamma\left(\frac{n}{2}\right)}{\Gamma\left(\frac{n-1}{2}\right)} \int_{-1}^{1} d\mu\,(1-\mu^2)^{\frac{n}{2}-\frac{3}{2}} e^{\alpha\mu}$$

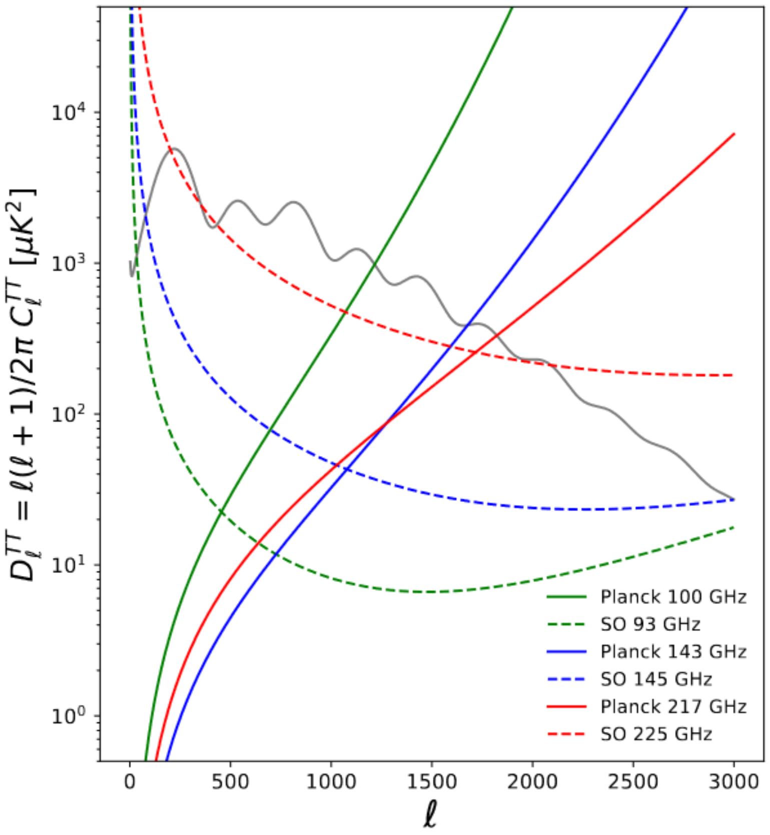
- Joint probability (two-tailed) is just 1/25,000!



Quantifying the anomaly: true observations





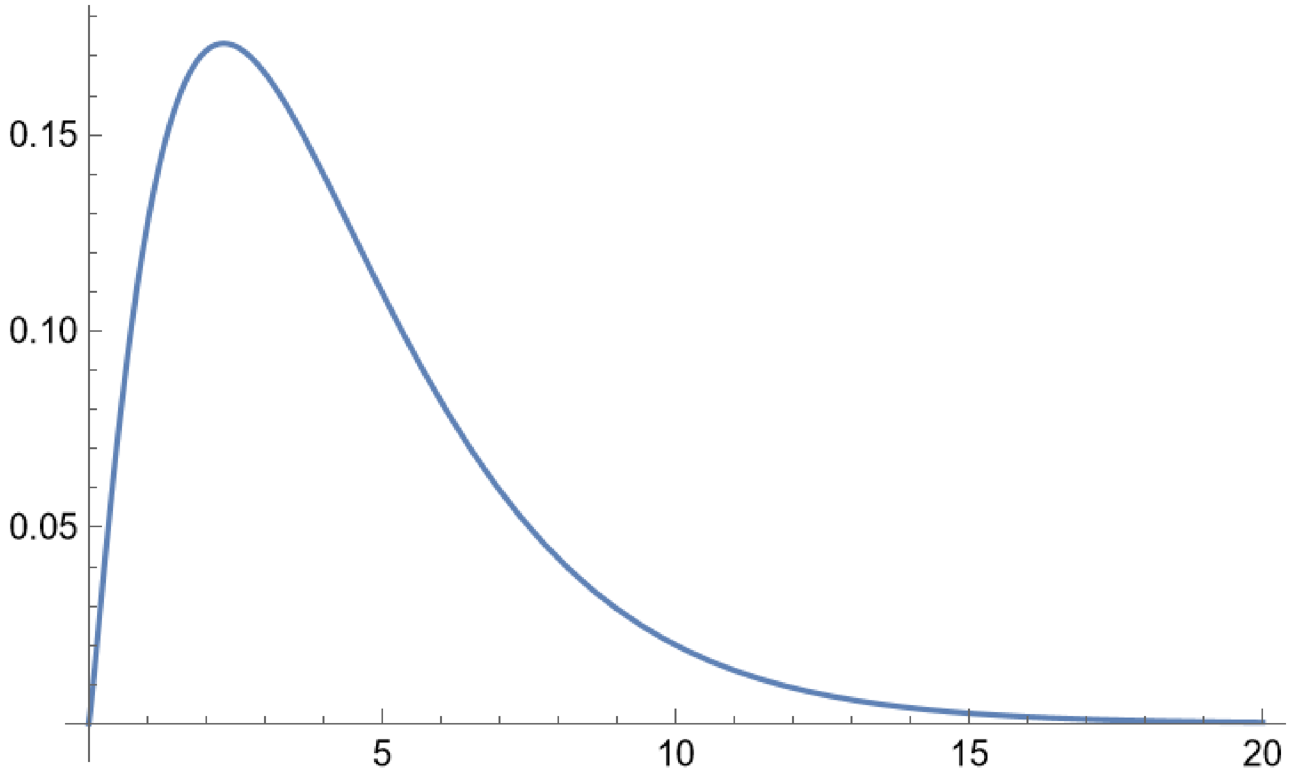


Temperature

- Measurement is cosmic-variance limited
- Chi-squared distribution now has 0.84*5 = 4.3 degrees of freedom

$$X = 4.3 \frac{C_2^{TT,\mathrm{observed}}}{C_2^{TT,\mathrm{expected}}} = 0.95$$

- Two-tailed probability is 12.8%



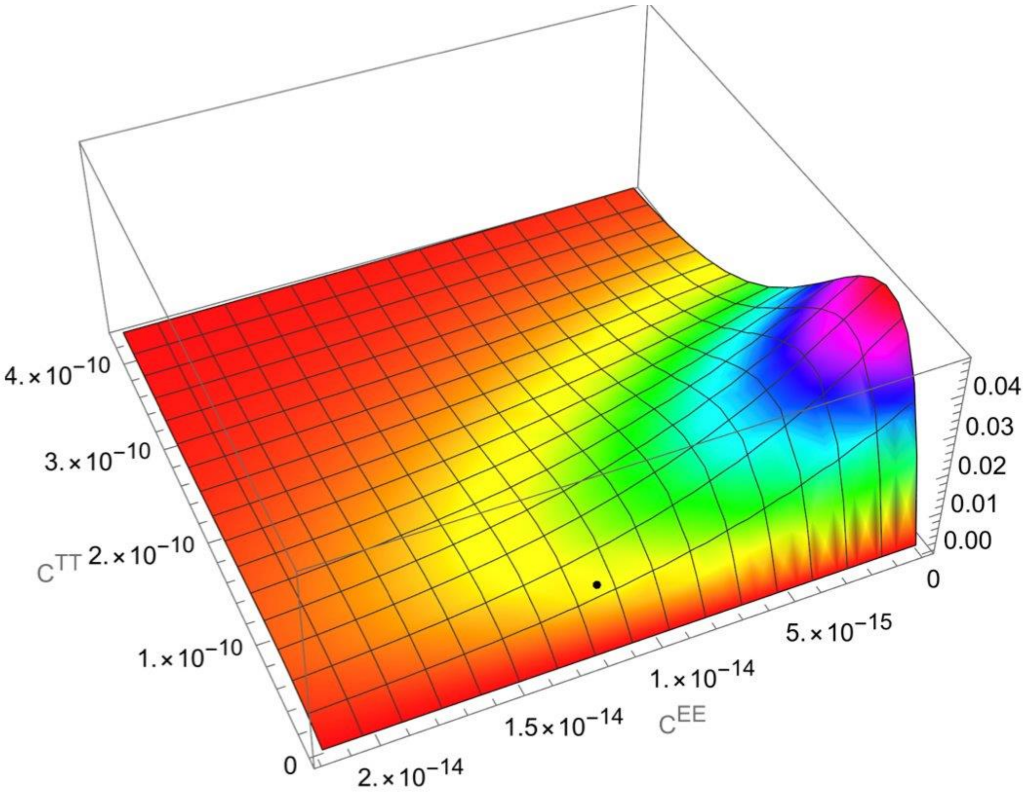
Polarization

- Significant instrumental noise
- Chi-squared distribution has 0.5*5 = 2.5 degrees of freedom
- Planck paper V (2018) gives probability as 29.6%.
- Can solve for noise power using

$$\int_Y^\infty \chi^2(5 f_{\rm sky}^E, Y)\, dY = 0.296/2 \qquad Y = 2.5\, \frac{C_2^{EE,\rm obs} + C_2^{EE,n}}{C_2^{EE} + C_2^{EE,n}}$$

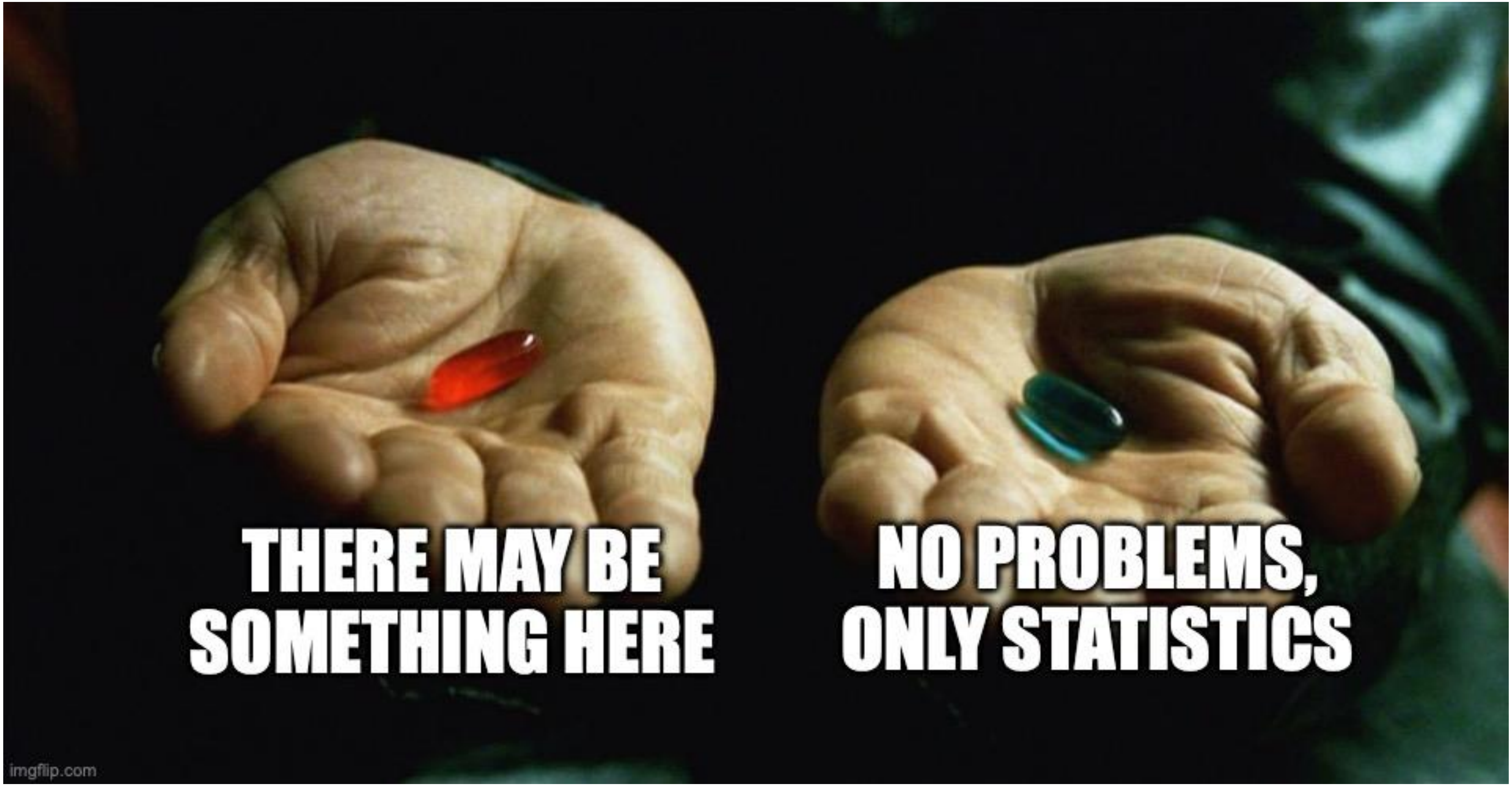
Joint probability: realistic case

- Degrees of freedom differ for T and E
  - Modified by sky fraction observed
- Noise errors are significant for polarization
- Use conditional probabilities to calculate joint
- After normalization, get probability of just 2.1%
  - Very close to product of probabilities



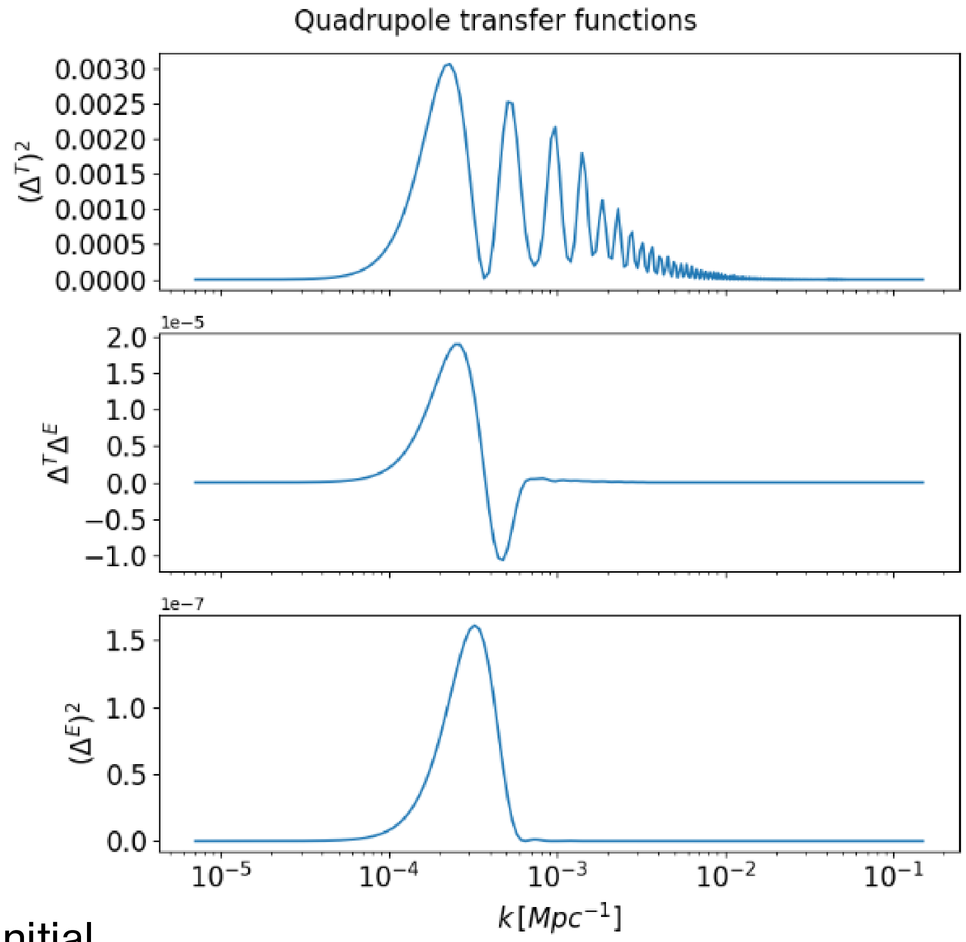
$$P(A \cap B) = P(A|B)P(B)$$

$$\frac{P_{5\,f_{\rm sky}^{T}}\left(5\,f_{\rm sky}^{T}C_2^{TT,{\rm obs}}/C_2^{TT,{\rm exp}}\right)}{P_{5\,f_{\rm sky}^{E}}\left(5\,f_{\rm sky}^{E}C_2^{TT,{\rm obs}}/C_2^{TT,{\rm exp}}\right)} P_{5\,f_{\rm sky}^{E}}\left(5\,f_{\rm sky}^{E}\frac{C_2^{TT,{\rm obs}}}{C_2^{TT,{\rm exp}}}, 5\,f_{\rm sky}^{E}\frac{C_2^{EE,{\rm obs}}+C_2^{EE,n}}{C_2^{EE,{\rm exp}}+C_2^{EE,n}}; \rho\right)$$


THERE MAY BE SOMETHING HERE
NO PROBLEMS, ONLY STATISTICS
imgflip.com

What can we do?

- Physics of transfer functions is well-understood
- Primordial power spectrum could still be changed
  - Recall, only CMB gives us such large scales
- Arbitrarily suppress or enhance primordial power
  - Scales of interest inferred from plot
  - Assume cosmological parameters are unchanged!



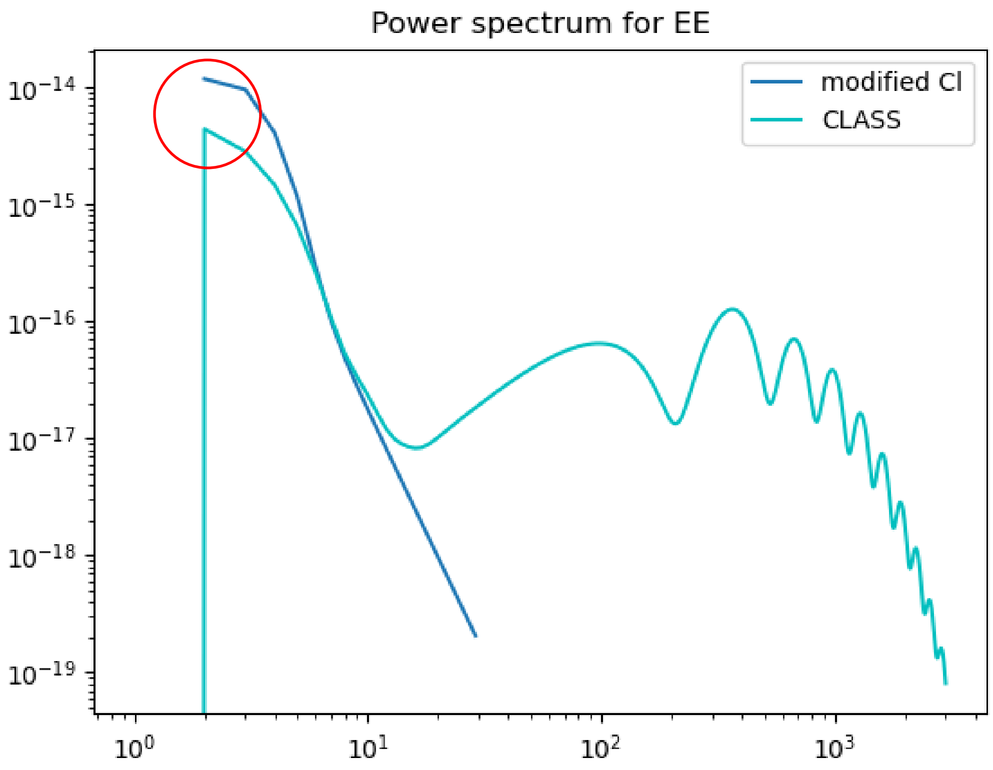
$$C_l^{XY} = 4\pi \int \frac{dk}{k} \mathcal{P}_\zeta(k) \Delta_l^X(k,\eta_0) \Delta_l^Y(k,\eta_0)$$

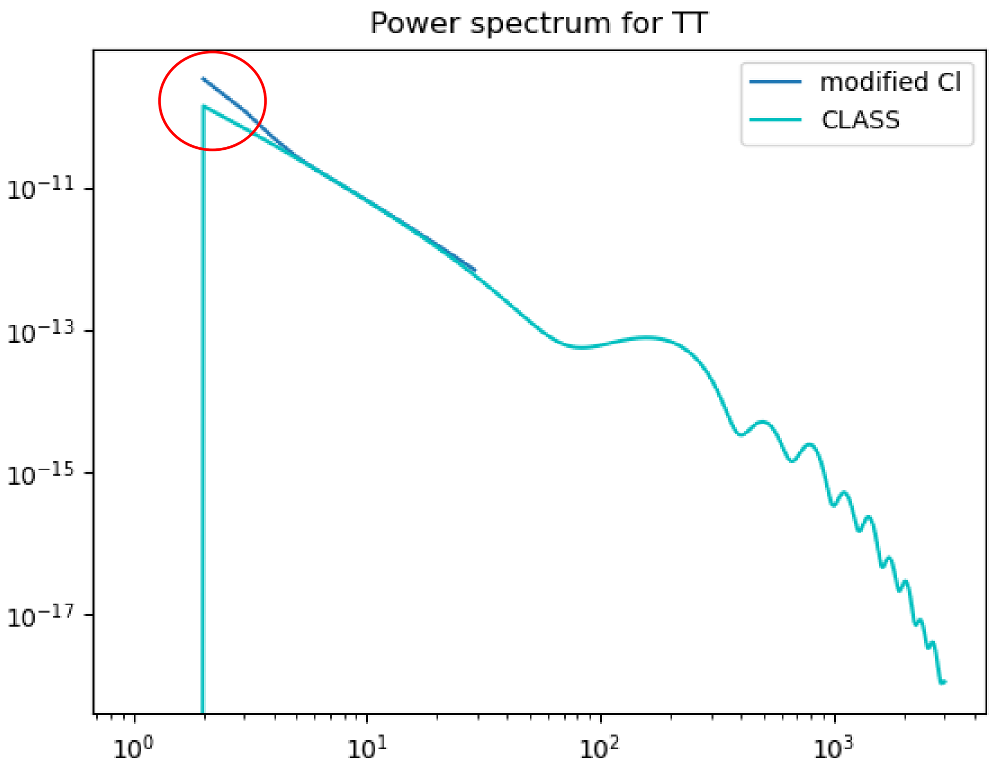
Power spectrum of initial perturbations from inflation. Some wiggle room to modify at large scales (small k)!

Explains how we go from initial conditions to CMB fluctuations. A well-understood quantity!

Impact on Cls – boosting power

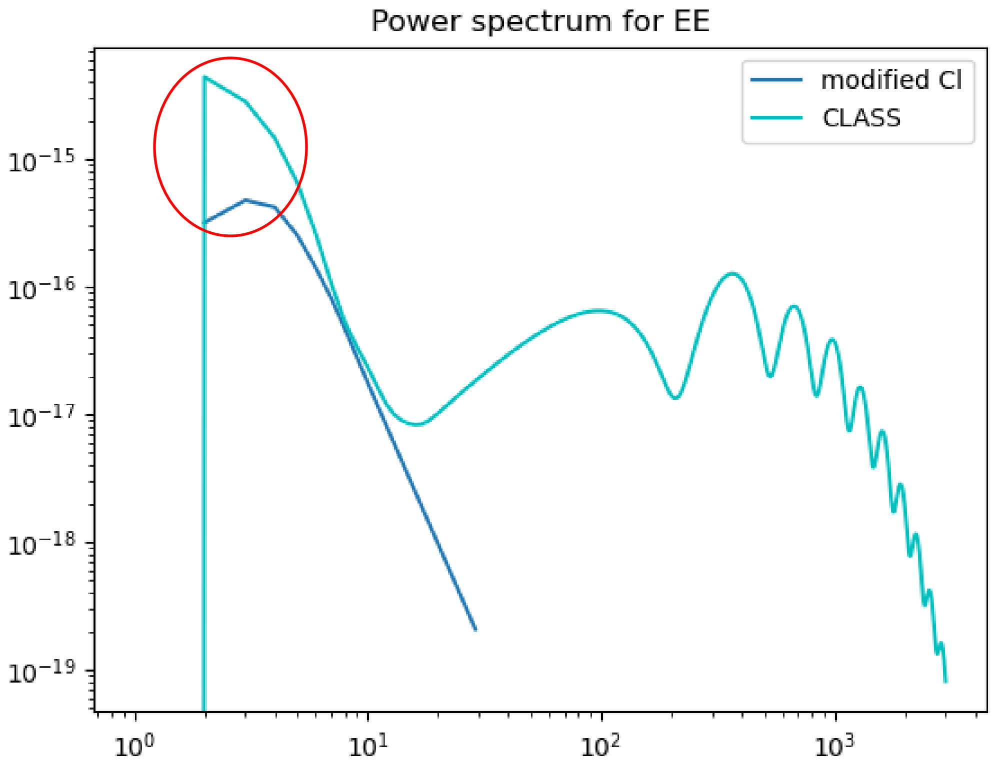
- Probability of recovering observed temperature is 2.6%

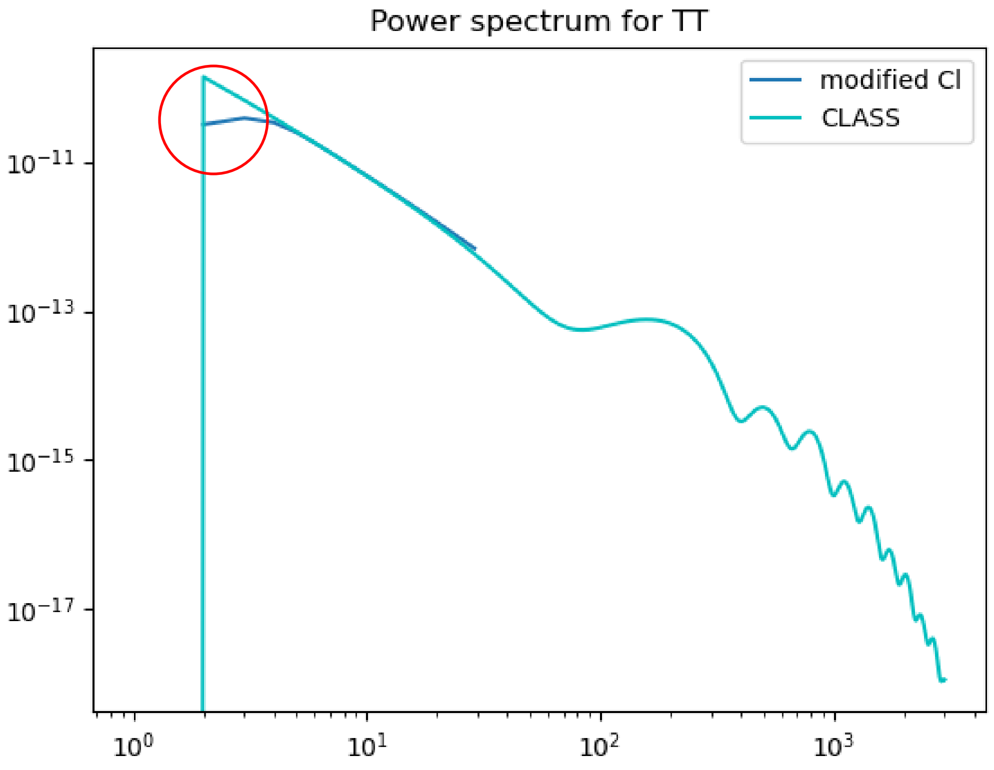




Impact on Cls – suppressing power

- Probability of recovering observed polarization is 4.1%





Should use newer maps

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Issue	A&A **Volume** 629, September 2019
Article Number	A38
Number of page(s)	19
Section	Astronomical instrumentation
DOI	https://doi.org/10.1051/0004-6361/201834882
Published online	02 September 2019

A&A 629, A38 (2019)

SRoll2: an improved mapmaking approach to reduce large-scale systematic effects in the *Planck* High Frequency Instrument legacy maps

J.-M. Delouis[1,2,3], L. Pagano[4,5,2,6], S. Mottet[2,3], J.-L. Puget[6,5,2] and L. Vibert[5,2]

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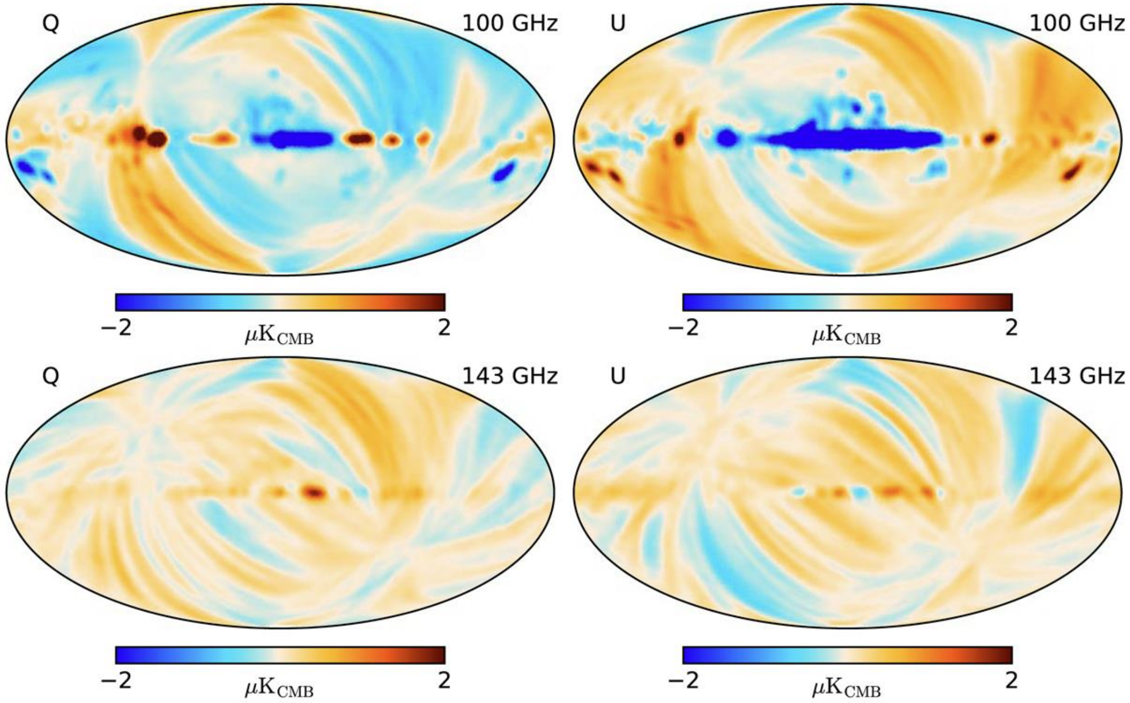
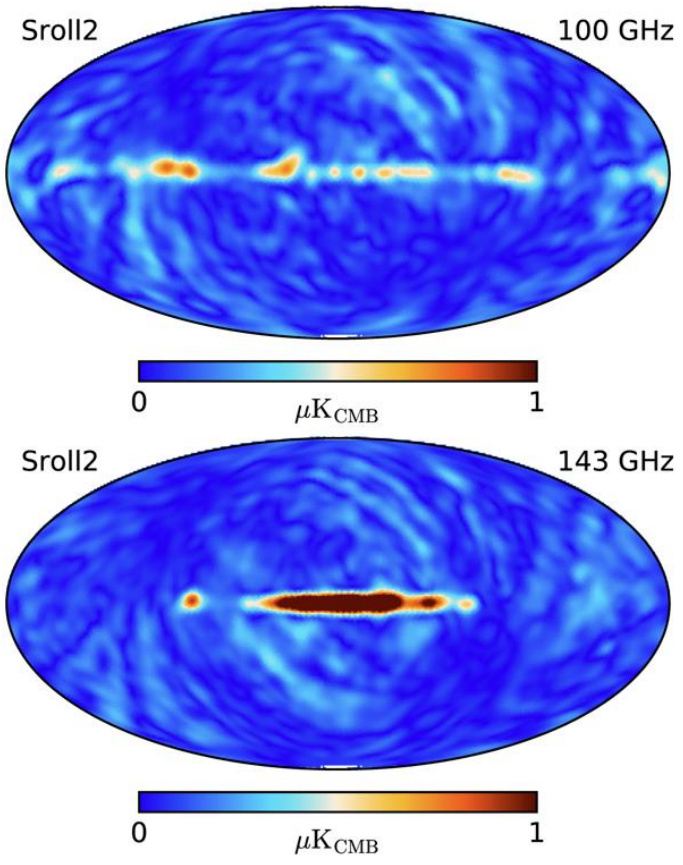
Received: 14 December 2018 | **Accepted:** 16 January 2019



PR3 - SRoll2

Simulations are paramount

- Difficult to analytically capture all the physics
  - Geometry of sky mask and degrees of freedom
  - Not easy to model systematics that go into errorbars
- Forward modeling would be more convincing
- SRoll2 simulations have what is needed built-in
  - Removal of ADCNL shown in figure



The look-elsewhere effect from a unified Bayesian and frequentist perspective

Adrian E. Bayer[1] and Uroš Seljak[1,2]

Published 2 October 2020 •

Journal of Cosmology and Astroparticle Physics, Volume 2020, October 2020

Citation Adrian E. Bayer and Uroš Seljak JCAP10(2020)009

DOI 10.1088/1475-7516/2020/10/009

Article PDF

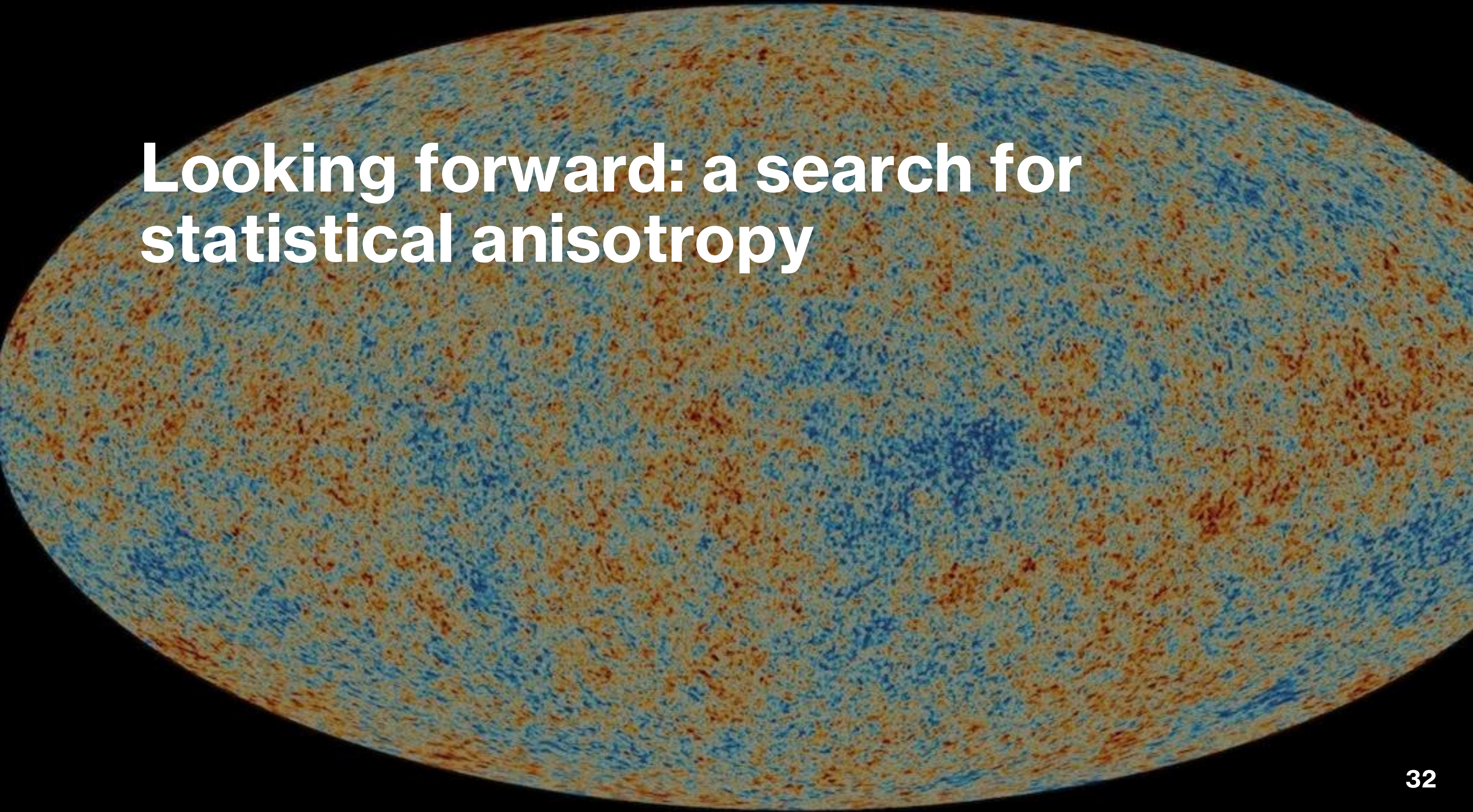
References

Article and author information

Abstract

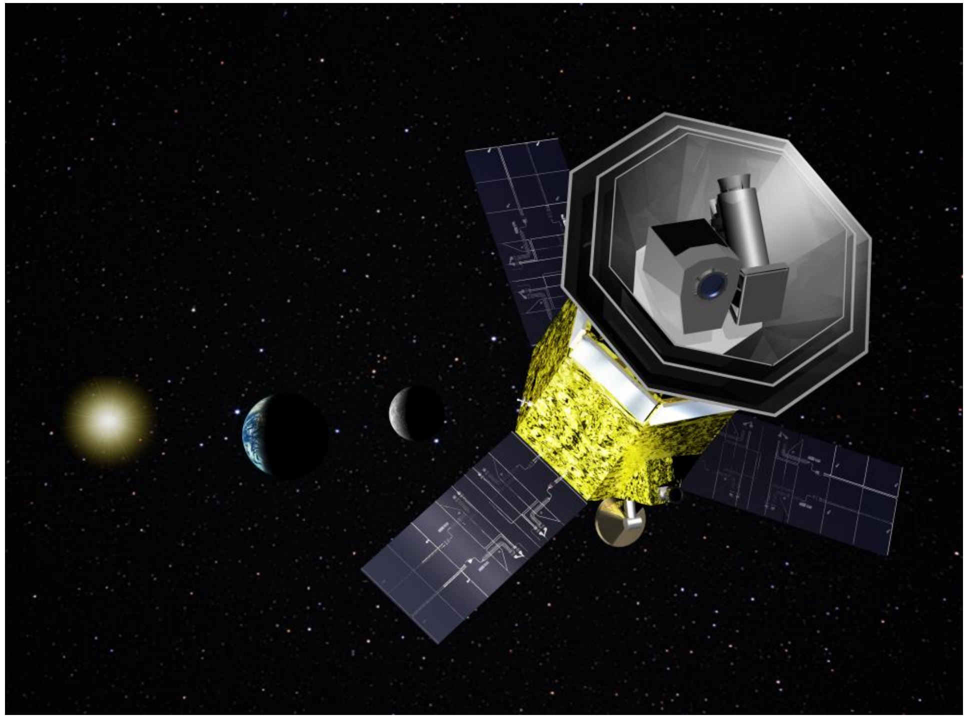
When searching over a large parameter space for anomalies such as events, peaks, objects, or particles, there is a large probability that spurious signals with seemingly high significance will be found. This is known as the look-elsewhere effect and is prevalent throughout cosmology, (astro)particle physics, and beyond. To avoid making false claims of detection, one must account for this effect when assigning the statistical significance of an anomaly. This is typically accomplished by considering the trials factor, which is generally computed numerically via potentially expensive simulations. In this paper we develop a continuous generalization of the Bonferroni and Šidák corrections by applying the Laplace approximation to evaluate the Bayes factor, and in turn relating the trials factor to the prior-to-posterior volume ratio. We use this to define a test statistic whose frequentist properties have a simple interpretation in terms of the global *p*-value, or statistical significance. We apply this method to various physics-based examples and show it to work well for the full range of *p*-values, i.e. in both the asymptotic and non-asymptotic regimes. We also show that this method naturally accounts for other model complexities such as additional degrees of freedom, generalizing Wilks' theorem. This provides a fast way to quantify statistical significance in light of the look-elsewhere effect, without resorting to expensive simulations.

Looking forward: a search for statistical anisotropy



Statistical anisotropy

- Consequences of observation would be tremendous
  - Universe would have interesting topology, not infinite-space and zero curvature
  - Drive an explosion of research into alternative cosmologies
- Must develop measures to quantify statistical anisotropy
  - Invoke ideas of symmetry, entropy, something else?
- Test against CMB and large-scale structure simulations
  - Compare performance of different measures
- Apply to data from current and future surveys
  - CMB: Planck, Simons Observatory, CMB-S4
  - LSS: Dark Energy Survey, Dark Energy Spectroscopic Instrument



Discussion

- Combination of quadrupoles is more anomalous than either one alone
  - Still not significant by most standards
- A simple, robust change in primordial power do little to fix this
- SRoll2 algorithm not tested, good for next steps
- Tie into broader picture of statistical anisotropy
- LiteBIRD should offer an additional window into these large scales