Anomalies in the CMB from a cosmic bounce

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Standard cosmology at the threshold of change?

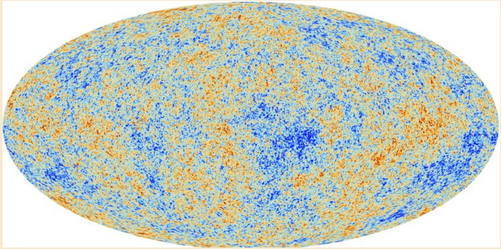
Aristotle University of Thessaloniki, 6 June 2024

In collaboration with I. Agullo, V. Sreenath

Main references:

- I. Agullo, D. Kranas, V. Sreenath, "Large scale anomalies in the CMB and non-Gaussianity in bouncing cosmologies", *Class. Quant. Grav.*, vol. 38, no. 6, p. 065010, 2021.
- I. Agullo, D. Kranas, V. Sreenath, "Anomalies in the CMB from a cosmic bounce", *Gen. Rel. Grav.*, vol. 53, no. 2, p. 17, 2021.
- I. Agullo, D. Kranas, V. Sreenath, "Anomalies in the cosmic microwave background and their non-gaussian origin in loop quantum cosmology", *Frontiers in Astronomy and Space Sciences*, vol. 8, p. 130, 2021, ISSN: 2296-987X.

Anomalies in the CMB



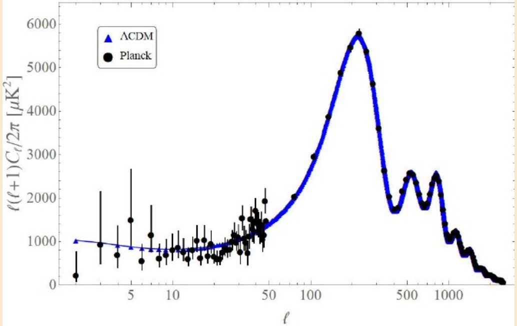
P.A.R. Ade et al, *Planck 2015* results, A&A, 594, A16, 2016.

N. Aghanim et al, *Planck 2018 results*, A&A 641, A7, 2020.

- Power suppression at angles $\theta \geq 60^o$.
- Scale-dependent dipolar modulation of the temperature spectrum.
- Preference for odd-parity correlations.
- Tension in the lensing amplitude A_L.

Power spectrum suppression

Power suppression



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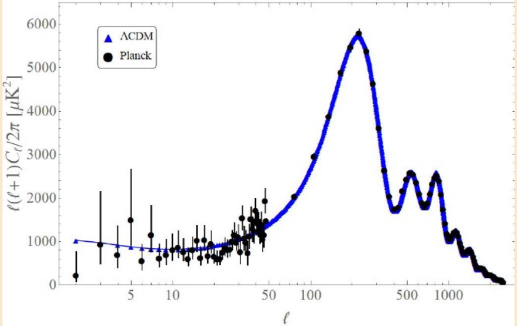

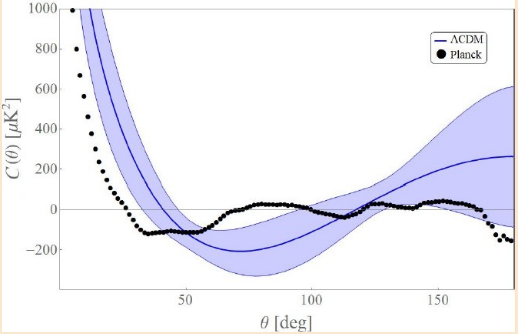

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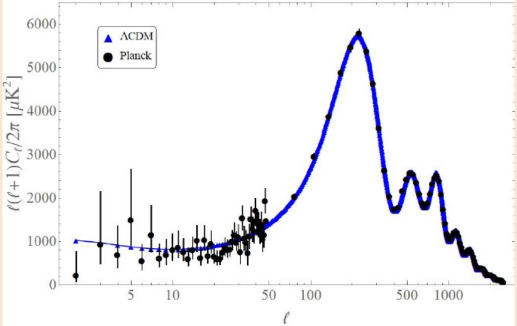

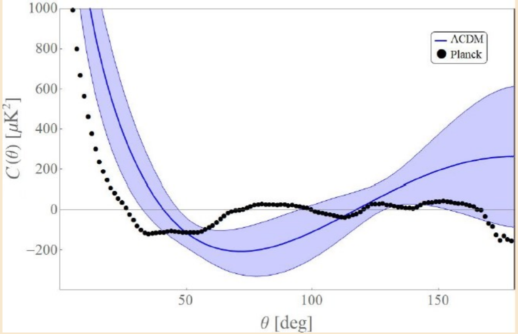

Main message: Observations reveal an absence of correlations at high angles; a feature that seems improbable according to ΛCDM.

Power suppression

Estimator to quantify total correlations in $\theta \in [60^o, 180^o]$:

$$S_{1/2} = \int_{-1}^{1/2} [C(\theta)]^2 d(\cos\theta).$$

$S_{1/2}^{\Lambda CDM} \approx 45000 \mu K^4$, $S_{1/2}^{obs} \approx 1500 \mu K^4 \longrightarrow p$-value$< 1\%$.

Dipolar modulation

- Observations show a **scale-dependent** hemispherical asymmetry in the CMB (after subtraction of the Doppler shift).
- This feature is observed at **large-angular scales** (small ℓ values).
- It is sourced from correlations between ℓ and $\ell + 1$ modes.
- It is a feature not predicted by the ΛCDM model as it is associated with the break of isotropy.

The p-value

- p-**value**: the probability of a realization to be at least as extreme as the observation, given a theoretical model.
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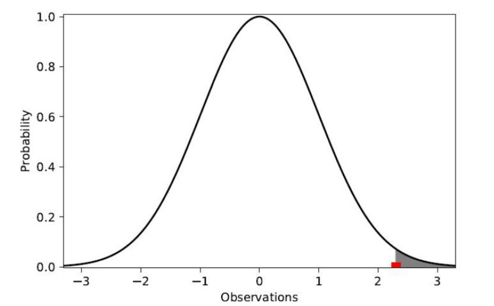

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Planck 2018 results. I.
Overview and the cosmological legacy of *Planck*

It is worth stressing that none of these so-called anomalies are strongly inconsistent with the assumption of statistical isotropy and Gaussianity, once one marginalises over a set of similar tests. It would nevertheless be premature to completely dismiss all the CMB anomalies as simple fluctuations of a pure ΛCDM cosmology, since if any of the anomalies have a primordial origin, then their large-scale nature would suggest an explanation rooted in fundamental physics. Thus it is worth exploring any models that might explain an anomaly (or even better, multiple anomalies) naturally, or with very few free parameters. Given a theoretical prediction, new probes of independent modes on similar scales (obtained through more sensitive polarization measurements, lensing, Ly α, or 21-cm studies for example) would increase the significance of existing anomalies and allow us to develop novel probes of early Universe physics. So far the simplest models explaining a single anomaly are not favoured over ΛCDM (see Planck Collaboration X 2018, and references therein). Further investigation of these anomalies will need to proceed on a case-by-case basis, and will be the subject of future work.

The bouncing model

- **Matter**: Scalar field
- **Geometry**: FLRW flat geometry

Around the bounce:

$$a(t) = a_{\mathrm{B}} \left(1 + \frac{R_B}{12n}\right)^n$$

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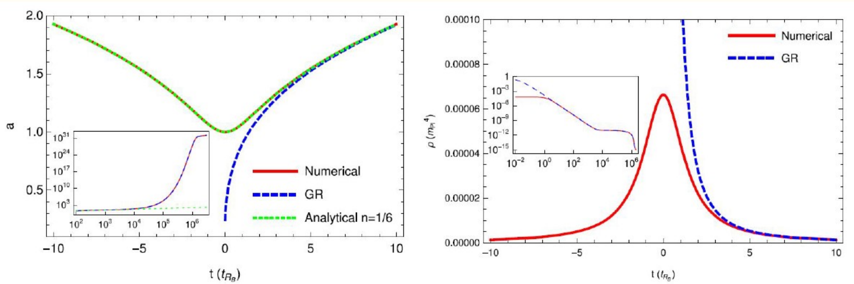
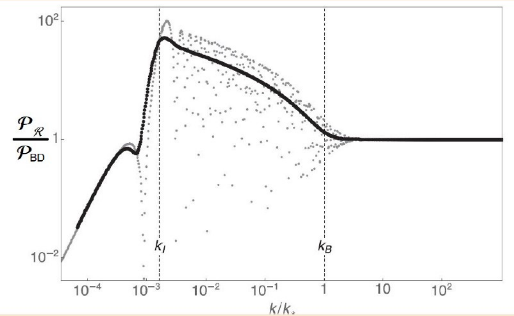


Primordial power spectrum

- Mode-evolution: $\frac{d^2 \hat{v}_k(\eta)}{d\eta^2} + \left(k^2 - a^2(\eta)\frac{R(\eta)}{6}\right)\hat{v}_k(\eta) = 0.$

$$P_{\mathcal{R}} \approx \begin{cases} A_S (k/k_B)^{n_S - 1}, & k > k_B \\ A_S (k/k_B)^{q}, & k_I < k \leq k_B \\ A_S (k_I/k_B)^{q} (k/k_I)^2, & k \leq k_I \end{cases}$$



- Modes of energy scale $k \leq k_B \equiv a_B \sqrt{R_B/6}$ are amplified by the cosmic bounce.

Non-Gaussianity

$$\Phi(\boldsymbol{x}, t) = \phi^{\mathrm{G}}(\boldsymbol{x}, t) + \frac{1}{2}\int d^3y d^3z F_{\mathrm{NL}}(\boldsymbol{y}, \boldsymbol{z})\phi^{\mathrm{G}}(\boldsymbol{x} + \boldsymbol{y}, t)\phi^{\mathrm{G}}(\boldsymbol{x}, \boldsymbol{z}, t)$$

$$\Phi_{\boldsymbol{k}}(t) = \phi^{\mathrm{G}}_{\boldsymbol{k}}(t) + \frac{1}{2}\int \frac{d^3q}{(2\pi)^3} f_{\mathrm{NL}}(\boldsymbol{q}, \boldsymbol{k} - \boldsymbol{q})\phi^{\mathrm{G}}_{\boldsymbol{q}}(t)\phi^{\mathrm{G}}_{\boldsymbol{k}-\boldsymbol{q}}(t)$$

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- Due to statistical homogeneity and isotropy: $f_{\mathrm{NL}}(\boldsymbol{k}_1,\boldsymbol{k}_2) = f_{\mathrm{NL}}(k_1,k_2,\hat{k}_1\cdot\hat{k}_2)$.
- Non-Gaussianities generate three-point functions: $\langle \Phi_{\boldsymbol{k}_1}\Phi_{\boldsymbol{k}_2}\Phi_{\boldsymbol{k}_3}\rangle = (2\pi)^3\delta(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B_\Phi(\boldsymbol{k}_1,\boldsymbol{k}_2)$.
- Bispectrum: $B_\Phi(\boldsymbol{k}_1,\boldsymbol{k}_2) = f_{\mathrm{NL}}(\boldsymbol{k}_1,\boldsymbol{k}_2)\left[P_{\phi^{\mathrm{G}}}(\boldsymbol{k}_1)P_{\phi^{\mathrm{G}}}(\boldsymbol{k}_2) + 1\longleftrightarrow 3 + 2\longleftrightarrow 3\right]$.

Non-Gaussianity

- Modified two-point functions:
$\langle \Phi_{\boldsymbol{k}_1} \Phi^*_{\boldsymbol{k}_2} \rangle = (2\pi)^3 \delta^{(3)}(\boldsymbol{k}_2 - \boldsymbol{k}_1) P_{\phi^{\mathsf{G}}}(\boldsymbol{k}_1) + f_{\mathsf{NL}}(\boldsymbol{k}_1, -\boldsymbol{k}_2) \frac{1}{2} \left[P_{\phi^{\mathsf{G}}}(\boldsymbol{k}_1) + P_{\phi^{\mathsf{G}}}(\boldsymbol{k}_2) \right] \phi_{\boldsymbol{q}^{\mathsf{G}}}$.

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- Temperature correlations and cosmological perturbations:
  $a_{\ell,m} = 4\pi \int \frac{d^3k}{(2\pi)^3} (-1)^\ell \Delta_\ell(k) Y^*_{\ell m}(\hat{k}) \Phi_{\boldsymbol{k}}$, recall $\delta T(\hat{n}) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\hat{n})$.

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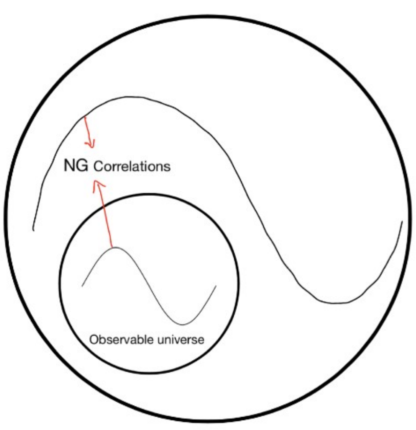
- $L = 0$: monopolar modulation, $L = 1$: dipolar modulation, $L = 2$: quadrupolar modulation.

Non-Gaussianity



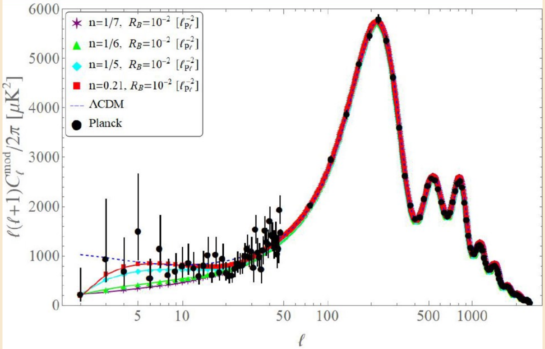
Our strategy

- Consider a profile $f_{\mathrm{NL}}(k_1, k_2, k_3) = f_{\mathrm{NL},o}\, e^{-\alpha(k_1+k_2+k_3)/k_{\mathrm{B}}}$ and fix $f_{\mathrm{NL},o}$ such that $S_{1/2}^{\mathrm{obs}}$ has a $p-$value$= 20\%$.
- Now explore how such an f_{NL} affects $\langle a_{\ell m} a_{\ell m}^* \rangle$, and, consequently the anomalous features.

Power suppression

Power suppression

$$C_\ell^{\text{mod}} = C_\ell \delta_{\ell\ell'} \delta_{mm'} + (-1)^{m'} \sum_{L,M} A_{\ell\ell'}^{LM} C_{\ell,m,\ell',-m'}$$



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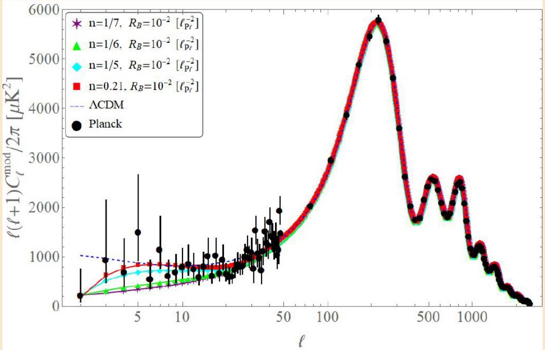

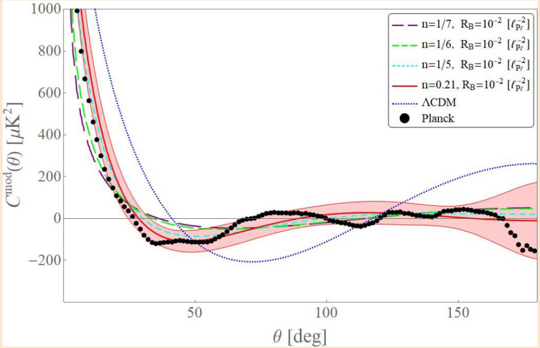

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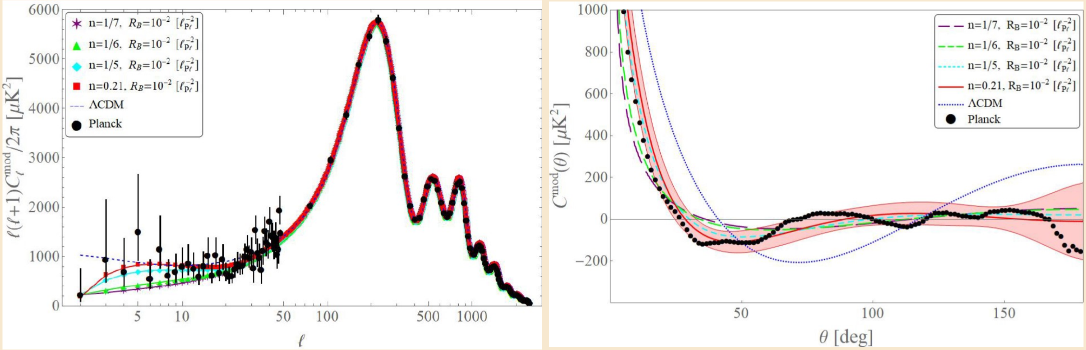

Main message: Power suppression at larger angles is a more likely feature of the modulated correlations.

Preference for odd-parity multipoles

Parity-correlations

$$R^{\mathrm{TT}}(\ell_{\mathrm{max}}) = \frac{D_{\mathrm{even}}}{D_{\mathrm{odd}}}, \quad D_{\mathrm{even,odd}}(\ell_{\mathrm{max}}) = \frac{1}{\ell_{\mathrm{tot}}} \sum_{\ell \in [2, \ell_{\mathrm{max}}]}^{\mathrm{even,odd}} \frac{\ell(\ell+1)}{2\pi} C_\ell .$$

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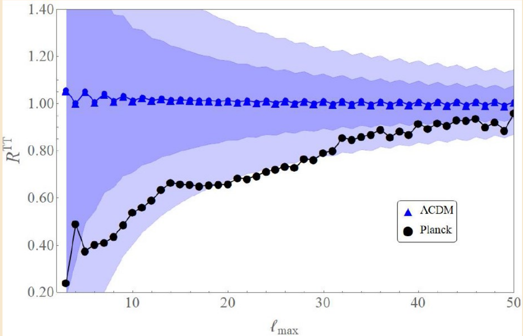

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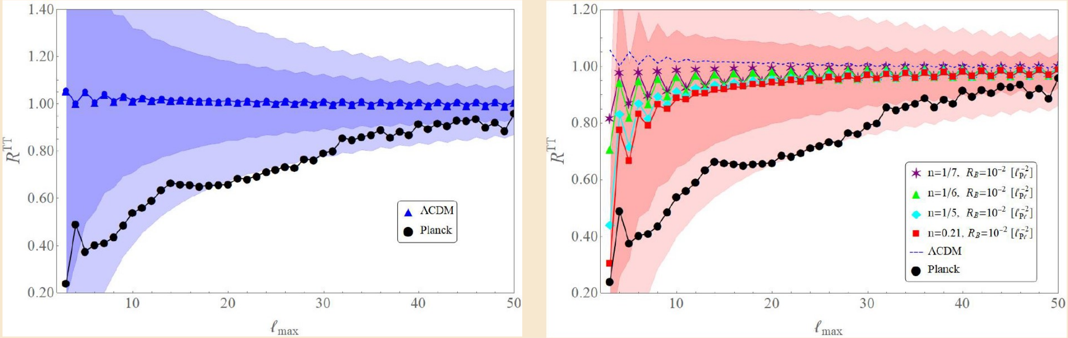

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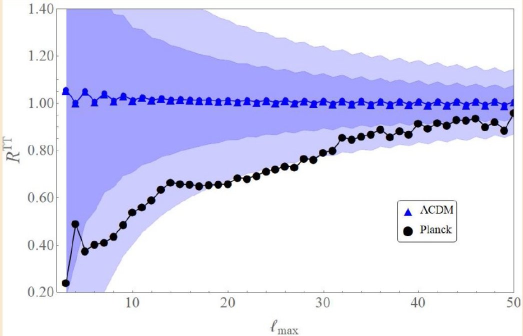

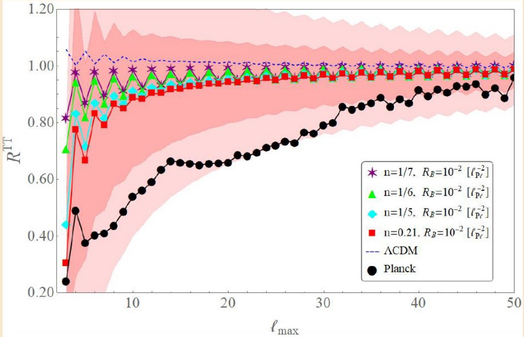

Main message: Preference for odd-parity correlations is a more likely feature of the modulated spectrum.

Dipolar modulation

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$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \delta_{\ell\ell'} \delta_{mm'} + (-1)^{m'} \sum_{L,M} A^{LM}_{\ell\ell'} C_{\ell,m,\ell',-m'} .$$

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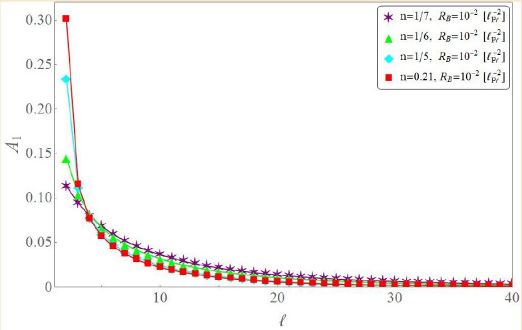

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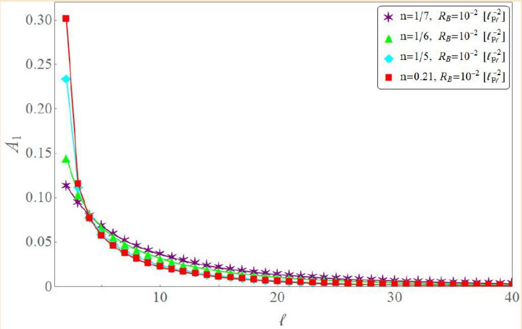

Main message: The modulated spectrum can generate a scale-dependent dipole in the sky.

Constraints on Bispectrum?

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[Delgado, Durrer, Pinto-Neto (2021)], [van Tent, Delgado, Durrer (2023)]

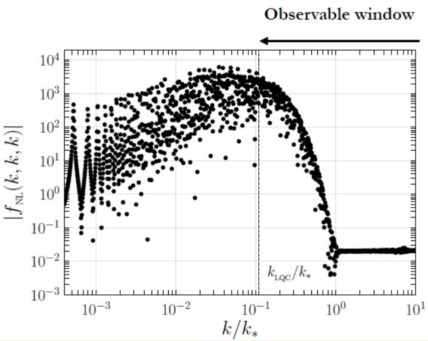
$$B_{\ell_1\ell_2\ell_3} = \left(\frac{2}{\pi}\right)^3 \int_0^\infty dx x^2 \int_0^\infty dk_1 \int_0^\infty dk_2 \int_0^\infty dk_3 \left[\prod_{j=1}^{3} \Delta_{\ell_j}(k_j) j_{\ell_j}(k_j x)\right] (k_1 k_2 k_3)^3 B(k_1, k_2, k_3).$$

Result of the analysis

The non-Gaussian profile $f_{\rm NL}(k_1, k_2, k_3) = f_{{\rm NL},o}\, e^{-\alpha(k_1+k_2+k_3)/k_{\rm B}}$, with $f_{{\rm NL},o} \sim 10^3$ is excluded by Planck data (by more than 5σ).

However...

Bouncing models produce oscillations in $f_{NL}(k_1, k_2, k_3)$ **[Agullo-Boilet-Sreenath (2018)]**.



which suppress significantly the projected bispectrum $B(\ell_1, \ell_2, \ell_3)$ making it compatible with Planck data **[Roshna-Sreenath (2023)]**.

Take-home messages

- A cosmic bounce preceding the inflationary era can generate non-Gaussian correlations between super-Hubble modes and modes at the longest wavelengths in the CMB.

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Observing the "Planck" physics in the Planck data is a mind-blowing possibility!

Additional Slides

Temperature correlations

‘

$$\delta T(\hat{n}) = \frac{T(\hat{n}) - \bar{T}}{\bar{T}} = \sum_{\ell,m} a_{\ell,m} Y_{\ell,m}, \qquad \langle a_{\ell,m} a^*_{\ell',m'} \rangle = C_\ell \delta_{\ell'} \delta_{m'm}.$$

$$C_\ell = \frac{2}{\pi} \int dk k^2 \Delta_\ell(k) P_\phi(k)$$

$$C(\theta) \equiv \langle \delta T(\hat{n}) \delta T(\hat{n}') \rangle = \frac{1}{4\pi} \sum_\ell (2\ell + 1) C_\ell P_\ell(\cos\theta), \theta \approx \frac{\pi}{\ell}.$$

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- **[B. van Tent, P. C. M. Delgado, R. Drurer]**:
  "These models can help to mitigate the large-scale anomalies of the CMB by considering substantial non-Gaussianities on very large scales, which **decay exponentially on sub-horizon scales**... In this letter we show that bouncing models with parameters such that they can significantly mitigate the large-scale anomalies of the CMB are excluded by the Planck data with high significance of, depending on the specific model, 5.4, 6.4 or 14 standard deviations."