Non-Gaussian CMB & LSS Statistics Beyond Polyspectra

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@ COSMO19

Based on

1804.07315 (PRD), 1806.05202 (PRL), 1907.05332

in collaboration with:

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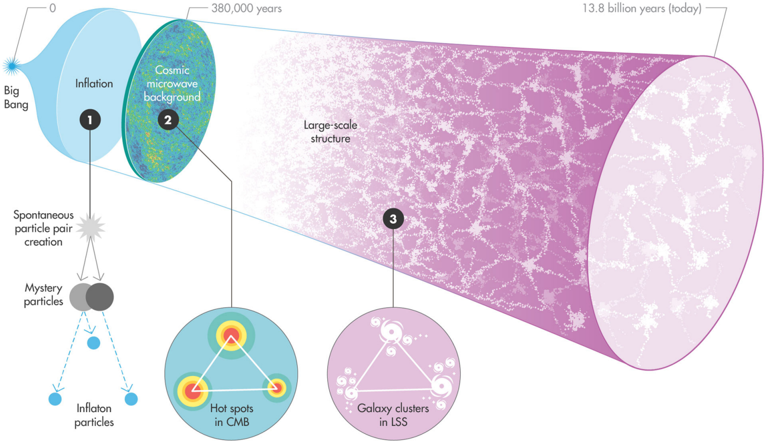
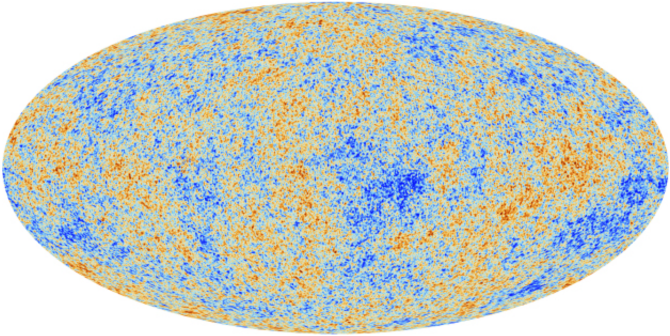
Outline

1. Intro
2. A bottom-up approach
   - Early time observables: CMB
   - Late time observables: LSS
3. Concluding remarks


0
380,000 years
13.8 billion years (today)
Big Bang
Inflation
Cosmic microwave background
Large-scale structure
1
2
3
Spontaneous particle pair creation
Mystery particles
Inflaton particles
Hot spots in CMB
Galaxy clusters in LSS



CMB Moments from Planck

⋆ Second moment (Power spectrum) **Measured!**

$$\langle\zeta\zeta\rangle \sim \frac{H^2}{M_{\rm Pl}^2\epsilon} = 10^{-10}$$

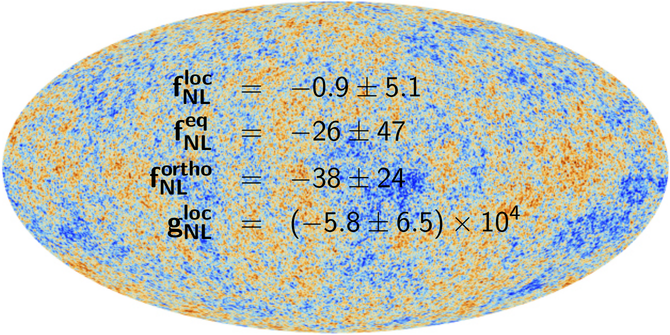
⋆ Third moment (Bispectrum) **Constrained!**

$$\langle\zeta(k_1)\zeta(k_2)\zeta(k_3)\rangle \sim f_{NL}(\epsilon)S(k_1,k_2,k_3)$$

⋆ Fourth moment (Trispectrum) **Constrained!**

$$\langle\zeta(k_1)\zeta(k_2)\zeta(k_3)\zeta(k_4)\rangle \sim g_{NL}(\epsilon)S(k_1,k_2,k_3,k_4)$$

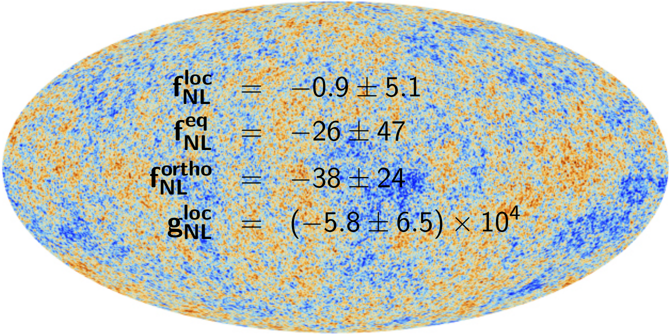
PLANCK 2018 @ 68% CL



$$f_{NL}^{loc} = -0.9 \pm 5.1$$
$$f_{NL}^{eq} = -26 \pm 47$$
$$f_{NL}^{ortho} = -38 \pm 24$$
$$g_{NL}^{loc} = (-5.8 \pm 6.5) \times 10^4$$

⋆ CMB temperature anisotropies follow nearly scale invariant, almost Gaussian statistics (Consistent with ΛCDM)

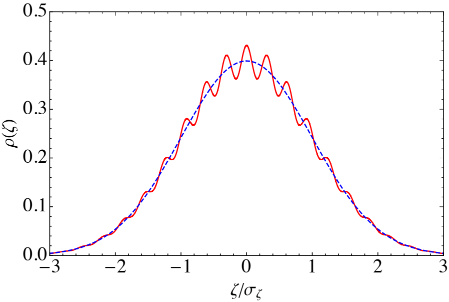
PLANCK 2018 @ 68% CL



$$
\begin{aligned}
\mathbf{f}_{\mathbf{NL}}^{\mathbf{loc}} &= -0.9 \pm 5.1 \\
\mathbf{f}_{\mathbf{NL}}^{\mathbf{eq}} &= -26 \pm 47 \\
\mathbf{f}_{\mathbf{NL}}^{\mathbf{ortho}} &= -38 \pm 24 \\
\mathbf{g}_{\mathbf{NL}}^{\mathbf{loc}} &= (-5.8 \pm 6.5) \times 10^4
\end{aligned}
$$

- ⋆ CMB temperature anisotropies follow nearly scale invariant, almost Gaussian statistics (Consistent with ΛCDM)
- ⋆ End of the story?

The PLANCK analysis is optimised for the search of nonzero moments of the PDF. What about this PDF for example?

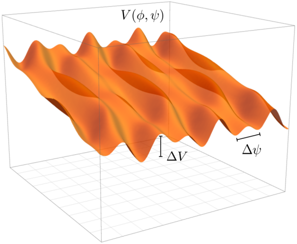


It is clearly non-Gaussian but has $f_{nl} = 0$

Can we get something like that?

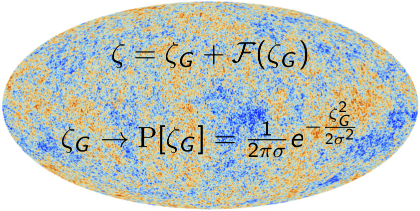
An example: Landscape Tomography

Chen, Palma, Riquelme, Scheihing, SS '18



$$\frac{\mathrm{P}(\zeta)-\mathrm{P}_G(\zeta)}{\mathrm{P}_G(\zeta)} \propto V'(\psi_\zeta)$$

The most general local NG



$$\zeta = \zeta_G + \mathcal{F}(\zeta_G)$$

$$\zeta_G \to \mathrm{P}[\zeta_G] = \frac{1}{2\pi\sigma} e^{-\frac{\zeta_G^2}{2\sigma^2}}$$

$$\langle \zeta(x_1) \cdots \zeta(x_n) \rangle = \int D[\zeta] \mathrm{P}[\zeta] \zeta(x_1) \cdots \zeta(x_n).$$

$$\mathrm{P}[\zeta] = \mathrm{P}_G[\zeta] \exp\left[-\frac{1}{2} \int_x \int_y \zeta(x) \Sigma^{-1}(x,y) \mathcal{F}[\zeta](y) - \int_x \ln\left\{ 1 + \frac{\mathrm{d}\mathcal{F}}{\mathrm{d}\zeta}(\zeta_G(x)) \right\} \right]$$

Matarrese, Verde, Jimenez '00; Palma, Scheihing, SS '19

1-pt statistics:

$$\mathrm{P}(\bar{\zeta};x) = \int D\zeta\, \mathrm{P}[\zeta]\, \delta[\zeta(x) - \bar{\zeta}],$$

$$\mathrm{P}(\zeta) = \frac{1}{\sqrt{2\pi\sigma_\zeta}} e^{-\frac{\zeta^2}{2\sigma_\zeta^2}} [1 + \Delta(\zeta)]$$

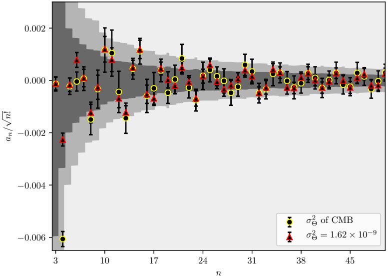
with

$$\Delta(\zeta) \propto \int_0^\infty \frac{\mathrm{d}x}{x} \mathcal{K}(x) \int_{-\infty}^{\infty} \mathrm{d}\bar{\zeta}\, \frac{\exp\left[-\frac{\left(\bar{\zeta}-\zeta(x)\right)^2}{2\sigma_\zeta^2(x)}\right]}{\sqrt{2\pi}\sigma_\zeta(x)} \times \left(\sigma_\zeta^2 \frac{\partial}{\partial\bar{\zeta}} - \bar{\zeta}\right) \mathcal{F}(\bar{\zeta})$$

Non-Gaussianity coefficients for 1-pt PDF:

$$\Delta(\Theta) = \sum_n \frac{a_n}{n!} \mathrm{He}_n\left(\frac{\Theta}{\sigma_\Theta}\right)$$

The a_n's characterise skewness, kurtosis, etc.



2-pt statistics:

$$\langle \zeta^n(x_1)\zeta^m(x_2)\rangle = \int \mathrm{d}\zeta_1 \mathrm{d}\zeta_2 \, \mathrm{P}(\zeta_1, \zeta_2; x_1, x_2)\zeta_1^n \zeta_2^m .$$

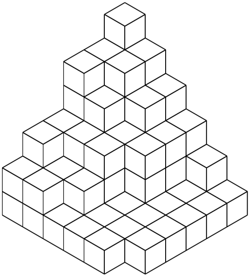
$$\mathrm{P}(\bar{\zeta}_1, \bar{\zeta}_2; r) = \int D\zeta \, \mathrm{P}[\zeta] \, \delta[\zeta(x) - \bar{\zeta}_1] \, \delta[\zeta(x+r) - \bar{\zeta}_2],$$

What is the probability to find a point with temperature $\delta T_2/T$, given a spot with $\delta T_1/T$ at distance r.
Scale information (CMB Anomalies, NG shapes)

Non-Gaussianity coefficients for 2-pt PDF:

$$\Delta(\Theta_1, \Theta_2; r) = \sum_n \frac{a_n}{n!} \mathrm{He}_n \left(\Theta_1, \Theta_2, \Sigma_\Theta(r)\right)$$

The a_n's characterise skewness, kurtosis, etc. of the 2-pt PDF



The halo mass function and number counts

We may also consider how this is transfered to LSS statistics:

$$\zeta_k \to T(k,z)\zeta_k = \delta_k$$

PS scheme: cumulative PDF $\Rightarrow$ halo mass function

$$\mu^{>}(M,z) = \int_{\delta_c(z)}^{\infty} \mathrm{d}\delta \; \mathrm{P}(\delta,\sigma) \quad \Rightarrow \quad \frac{\mathrm{d}n}{\mathrm{d}m}$$ [# of clusters of mass m at z]

$$\frac{\mathrm{d}n}{\mathrm{d}m} \propto \frac{\mathrm{d}\mu^{>}}{\mathrm{d}m} \propto \mathcal{D}_{z,m}\, \mathcal{F}$$

The scale dependent halo bias

Dalal et al. showed that for an f_{NL} cosmology, the bias inherits a scale dependent correction (enhanced signal at large scales)

$$\Delta b(k) \propto \frac{f_{\mathrm{NL}}}{k^2}.$$

However, in the generic case one finds

$$\Delta b(k) \propto \frac{1}{k^2} \sum_{m=1}^{\infty} \frac{\partial \log n}{\partial f_m} f_{m+1}.$$

A slope in the bias indicates a general local shape! No way to tell f_{NL} from any other NL parameter!

- ⋆ We have shown how a generic local ansatz alters the CMB, LSS statistics (PDFs).
- ⋆ Cluster counts and bias can be used to probe NG beyond polyspectra.

Message:

NG does not show up in 3-pt functions but there are good reasons to believe in it. Worth searching for NG signatures in the PDFs (CMB, LSS)

Leblond, Pajer '10
Flauger, Mirbabayi, Senatore, Silverstein '16
Chen, Palma, Scheihing, SS '18

Palma, Scheihing, SS '19

To do:

- ⋆ Nonlocal ansatz? e.g. what would yield equilateral correlators?
- ⋆ Number counts forecasts with this initial condition?
- ⋆ How does this affect PBH distribution?

Panagopoulos, Silverstein '19

Dankeschön!