Scale-dependent non-Gaussianity probes inflationary physics

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Based on arXiv:0911.2780, arXiv:1007.4277, arXiv:1102.0560,
with Byrnes, Gerstenlaurer, Hebecker, Nurmi, Wands.

Aims of this talk

- Theoretically analyse **scale-dependence** of **local non-Gaussianity**
  - ▷ Tools to further characterize properties of mechanism responsible for generating fluctuations
  - ▷ Examples in concrete models
  - ▷ Improve ansätze to apply to simulations/observations

Scale dependence of inflationary observables

- **Three point function**:

Bispectrum: $\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = (2\pi)^3 \, \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) \, B(k_1, k_2, k_3)$

$$\Rightarrow \quad B(k_1, k_2, k_3) \; = \; \tfrac{6}{5} f_{\rm NL}(k_1, k_2, k_3) \; [P(k_1) P(k_2) + \text{perms}]$$

Scale dependence: $n_{f_{\rm NL}} = d \ln |f_{\rm NL}| / d \ln k$

- Vary all momenta by same amount: the result is independent on the shape of the triangle
- If local $f_{\rm NL} \sim 50$, then $n_{f_{\rm NL}} \sim 0.1$ might be detectable with Planck [Sefusatti et al]
- $n_{f_{\rm NL}}$ at lower bound might be enough to get information on mechanism generating primordial fluctuations.

  Larger values might be needed in the future to reconcile LSS with CMB measurements.

Scale dependence of inflationary observables

- **Four point function**: Trispectrum [Byrnes-Sasaki-Wands]

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \zeta_{\mathbf{k}_4} \rangle = (2\pi)^3 \delta(\sum_{i=1}^{4} \mathbf{k}_i) \Big[\tau_{\rm NL}(k_1, k_2, k_3, k_4, k_{13}) \left(P(k_1) P(k_2) P(|\mathbf{k}_1 + \mathbf{k}_3|) + 11 \,\mathrm{perm} \right)$$
$$+ \frac{54}{25} g_{\rm NL}(k_1, k_2, k_3, k_4) \left(P(k_1) P(k_2) P(k_3) + 3 \,\mathrm{perm} \right) \Big] ,$$

Analogous definitions for $n_{g_{\rm NL}} = d\ln|g_{\rm NL}|/d\ln k$ and $n_{\tau_{\rm NL}} = d\ln|\tau_{\rm NL}|/d\ln k$.

No available forecasts

Local non-Gaussianity

- **Local Ansatz**: assume that ζ is combination of Gaussian quantities:

$$\zeta_{\mathbf{k}} = \zeta^{\mathrm{G}}_{\mathbf{k}} + \frac{3}{5} f_{\mathrm{NL}}(k)(\zeta^{\mathrm{G}} \star \zeta^{\mathrm{G}})_{\mathbf{k}} + \frac{9}{25} g_{\mathrm{NL}}(k)(\zeta^{\mathrm{G}} \star \zeta^{\mathrm{G}} \star \zeta^{\mathrm{G}})_{\mathbf{k}} + \cdots$$

Then it's particularly easy to extract connected n-point function.

- This Ansatz fits well with the results of δN-formalism. [Starobinsky, Sasaki-Stewart, Sasaki-Tanaka]

Consider a model of inflation with multiple scalar fields. At superhorizon scales

t_f after inflation ends ↑ ; Scalar fluctuations at horizon exit ↗

$$\zeta_{\vec{k}}(t_f) = \sum_a N_a(t_f, t_k)\, \delta\phi^a_{\vec{k}}(t_k) + \frac{1}{2} \sum_{ab} N_{ab}(t_f, t_k) \left(\delta\phi^a(t_k) \star \delta\phi^b(t_k)\right)_{\vec{k}}$$

↓ Derivatives of number of e-foldings: depends on background evolution

↓ time of horizon exit: $k = a(t_k) H(t_k)$

- It tells how perturbations classically evolve after horizon crossing.
- Assume $\delta\phi^a$ are Gaussian at horizon exit: non-Gaussianity has **local form** with $\zeta^G_{\vec{k}} \propto N_\phi\, \delta_{\vec{k}}\phi$

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$$f_{\mathrm{NL}} = \frac{\sum_{ab} N_{ab} N_a N_b}{(\sum_c N_c^2)^2}$$

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t_f after inflation ends $\uparrow$; Scalar fluctuations at horizon exit $\nearrow$

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$\downarrow$ Derivatives of number of e-foldings: depends on background evolution

$\downarrow$ time of horizon exit: $k = a(t_k)H(t_k)$

Then [Lyth-Rodriguez]

$$f_{\mathrm{NL}} = \frac{\sum_{ab} N_{ab} N_a N_b}{\left(\sum_c N_c^2\right)^2}$$

These quantities are **explicitly calculable**: depend on homogeneous cosmological evolution.

This method apply to **large class** of models.

Assume slow-roll at horizon exit: the **scale dependence** $n_{f_{\mathrm{NL}}}$ can then be derived by the dependence of N_a on t_k at leading order in slow-roll.

Results

Consider a set-up in which the potential is $W(\phi, \sigma) = U(\phi) + V(\sigma)$ (ϕ is inflaton)

$$\zeta(\mathbf{k}) = \zeta_{\mathbf{k}}^{G,\phi} + \zeta_{\mathbf{k}}^{G,\sigma} + f_\sigma(k)\left(\zeta^{G,\sigma} \star \zeta^{G,\sigma}\right)_{\mathbf{k}} + g_\sigma(k)(\zeta^{G,\sigma} \star \zeta^{G,\sigma} \star \zeta^{G,\sigma})_{\mathbf{k}}$$

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Then, we get (vary all the k's by the same amount)

$$f_{\rm NL} = \frac{5}{3} f_\sigma \qquad g_{\rm NL} = \frac{25}{9} g_\sigma$$

$$n_{f_{\rm NL}} \simeq \frac{5}{6 f_{\rm NL}} \sqrt{\frac{r_T}{8}}\, \frac{V'''}{3H^2} \qquad n_{g_{\rm NL}} = \frac{2 f_{\rm NL}^2}{g_{\rm NL}} n_{f_{\rm NL}} + \frac{25}{54}\,\frac{1}{g_{\rm NL}}\,\frac{V''''}{6\pi^2\,\mathcal{P}_\zeta}$$

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- Offer opportunities to test cubic (and quartic) **self-interactions** not probed by properties $\mathcal{P}_\zeta$

Concrete scenarios

Curvaton:

During radiation era σ-fluctuations converted into adiabatic curvature fluctuations

- In the pure curvaton limit, resulting observables depend on curvaton potential and relative energy density at decay

- For quartic potential $V(\sigma) = \frac{m^2}{2}\sigma^2 + \lambda\sigma^4$, we found $n_{f_{\rm NL}} \propto V''/H^2 \sim 10^{-2}$

- More general potentials need numerical treatment [Byrnes, Takahashi, Enqvist]

Concrete scenarios

Modulated reheating:

σ-fluctuations modulate decay rate of inflaton into radiation

- Results depend on efficiency of tranfer, functional dependence of decay rate $\Gamma(\sigma)$, modulaton field potential $V(\sigma)$

- Choose for definiteness $V(\sigma) = \frac{\lambda}{4!}\sigma^4$. Then [Suyama et al, Ichikawa et al]

$$f_{\rm NL} = 5\left(1 - \frac{\Gamma\Gamma_{\sigma\sigma}}{\Gamma_\sigma^2}\right) \qquad g_{\rm NL} = \frac{50}{3}\left(2 - 3\frac{\Gamma\Gamma_{\sigma\sigma}}{\Gamma_\sigma^2} + \frac{\Gamma^2\Gamma_{\sigma\sigma\sigma}}{\Gamma_\sigma^3}\right)$$

while for the running

$$n_{f_{\rm NL}} \simeq \frac{0.1\,\lambda^{\frac{3}{4}}}{f_{\rm NL}\mathcal{P}_\zeta^{\frac{1}{2}}} \sim \frac{600\,\lambda^{3/4}}{f_{\rm NL}} \qquad n_{g_{\rm NL}} \simeq \frac{2f_{\rm NL}^2}{g_{\rm NL}} n_{f_{\rm NL}} + 4\times 10^{-3}\,\frac{\lambda}{g_{\rm NL}\,\mathcal{P}_\zeta} \sim \frac{10^6\,\lambda}{g_{\rm NL}}$$

One can get $n_{f_{\rm NL}}$, $n_{g_{\rm NL}} \sim 0.1$: valuable model!

Concrete scenarios

Primordial fluctuations from loops!?

- With judicious choice of parameters (fine-tuning, symmetries) ζ is [Boubekeur-Lyth, Suyama-Takahashi]

$$\zeta \;=\; \zeta_\phi + \zeta_\sigma^2$$

with ϕ inflaton, σ responsible for generating fluctuations

- Loops give dominant contributions to non-G:

$$f_{\rm NL} \sim \frac{\mathcal{P}^3_{\zeta_\sigma}}{\mathcal{P}^2_\zeta} \ln kL$$

apply sharp cut-off to integrals from convolutions; choose $L \sim 1/H$ [Kumar et al]

$$n_{f_{\rm NL}} \sim \frac{1}{\ln kL} \;\sim\; 0.2$$

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- **To do**: Clarify these issues in the multiple field case

Shape dependence

Suppose now to vary *independently* the momenta: how does $f_{\rm NL}$ change?

- For single field source (as pure curvaton or modulated reheating)

$$f_{\rm NL} \,=\, f_{\rm NL}^{p}\,\frac{k_1^{3+n_{f_{\rm NL}}}+k_2^{3+n_{f_{\rm NL}}}+k_3^{3+n_{f_{\rm NL}}}}{k_1^3+k_2^3+k_3^3}$$

- *Not* of factorizable form $f_{\rm NL} \propto (k_1k_2k_3)^{n_{f_{\rm NL}}/3}$ used by [Sefusatti et al] to get forecasts.

  Nevertheless the bispectrum is combination of product separable terms

$$B_\zeta(k_1,k_2,k_3) \propto (k_1k_2)^{n_\zeta-4}k_3^{n_{f_{\rm NL}}} + 2 \text{ perms}$$

- In two-field inflation, different functional form: [Huterer et al]

Summary

- I presented a new approach, based on δN, to analyse scale-dep of local nonG.
  If non-G is large, its scale dependence might be detectable with Planck

- Parameters controlling scale-dep of non-Gaussianity depend on properties of the mechanism that generate primordial fluctuations (third and fourth derivatives of the potential) that can't be probed by other means

- Results usually depend by just one new parameter (e.g. $n_{f_{\rm NL}}$ for $f_{\rm NL}$)

- I applied general results to concrete models: modulated reheating with quartic potential for the modulon leads to potentially observable non-Gaussianity.

Outlook

- Can loop effects lead to large $n_{f_{\rm NL}}$ in two-field case? Still to get convinced!

- Generalize the formulae to a more general set-up, beyond slow-roll

- Apply a generalized Ansatz for scale dep $f_{\rm NL}$ to simulations of LSS.

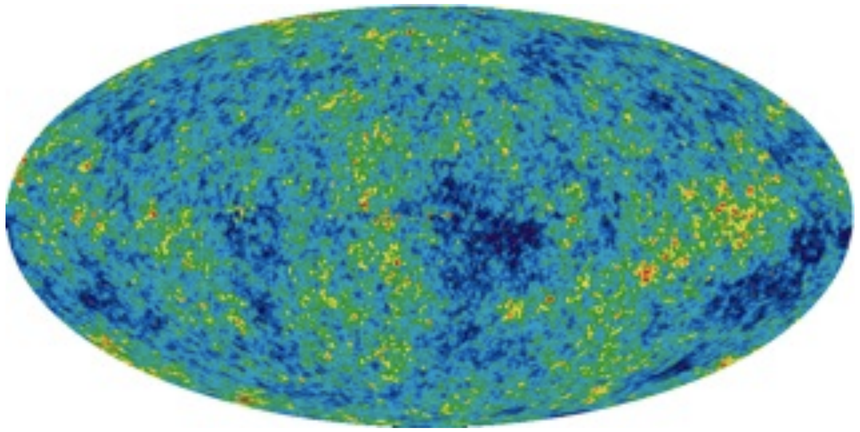
Inflation

Inflation solves basic problems of Standard Big-Bang Cosmology

▷ Short period of **quasi-exponential expansion**, driven by **dynamics of a scalar field**

It allows to understand CMB and LSS, providing a **mechanism** to generate **primordial density fluctuations** from **scalar perturbations**.

scalar fluctuations $\Rightarrow$ metric fluctuations $\Rightarrow$ density fluctuations of baryon-photon plasma



Predictions

▷ Nearly scale invariant spectrum of curvature fluctuations with almost Gaussian distribution

▷ Small contribution of gravitational waves

Non-Gaussianity

How to get information about primordial non-Gaussianity?

- ▷ Connected n-point functions ($n \geq 3$) of curvature perturbation ζ.

Why primordial non-Gaussianity has received so much attention?

- ▷ Because offers new opportunities to **distinguish** models of inflation

- ▷ Because Planck satellite will improve present bounds of a **factor 5**
  - – If no non-Gaussianity: simplest models of inflation favored
  - – If non-Gaussianity detected, other options have to be considered

- ▷ If Planck detects non-Gaussianity, the task is to **extract** as much information as possible from **data**.
  - – Subject at **interface** between theory and observations

Scale dependence of inflationary observables

- **Two point function**:

Power spectrum: $\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle = (2\pi)^3 \; \delta^3(\vec{k}_1 + \vec{k}_2)\, P(k_1)$ $\qquad$ $P(k_1) \,=\, \frac{2\pi^2\, \mathcal{P}(k_1)}{k_1^3}$

Spectral index: $n_\zeta - 1 \,=\, \left(\frac{d \ln \mathcal{P}_\zeta}{d \ln k} \right)_{|k=aH} \,=\, 0.963 \pm 0.012$