Quasi-Single Field Inflation
and
Critical Test of Multi-Field Inflation

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In the last paragraph of my review article on Non-Gaussianity (1002.1416):

“….., primordial non-Gaussianity – the collider in the very early universe – is one of the few hopes (to go beyond the ΛCDM standard model). …… We do not know which cards Nature is hiding from us, but we are hoping and preparing for the best.”

This is exactly we are doing here:

In this workshop, we are a bunch of OPTIMISTS.
**Working Assumption**

Planck observes some non-Gaussianity, e.g. the local $f_{NL}$, with more than $3\sigma$, or even $5\sigma$, confidence level.

**What does this imply and what shall we do next?**

Among many other things, … (to be discussed in this conference) …,

this will be **the official establishment** of ……
... the Emerging Field of

**Density Perturbation Phenomenology:**

-- Learning fundamental physics from density perturbation maps --

Scattering amplitudes in colliders: \( \text{out} \langle \mathbf{p}_1 \mathbf{p}_2 \cdots | \mathbf{k}_A | \mathbf{k}_B \rangle_{\text{in}} \)

Particle physics phenomenology

\[ \begin{aligned} \quad \end{aligned} \]

Density perturbation phenomenology

Correlation functions in maps: \( \text{in} \langle \frac{\delta \rho}{\rho} (x_1) \frac{\delta \rho}{\rho} (x_2) \cdots \rangle_{\text{in}} \)
In the previous working assumption, what we assumed to know, more precisely, is that, the non-G in data has a large local shape projection.

In this talk, **we probe the mass spectra of inflation models** by asking: **What is the more precise shape of this non-Gaussianity?**

➢ **A key formula:**

\[
\alpha = \frac{1}{2} - \sqrt{\frac{9}{4} - \frac{m^2}{H^2}} \quad \text{(X.C., Wang, 09)}
\]

- Shape of non-G
- Spectrum of inflation model

\[ S \rightarrow f_{NL} \left( \frac{p_L}{p_S} \right)^\alpha \]
Mass Spectra Define Several Classes of Inflation Models

- **Single Field**
- **Multi-Field**
- **Quasi-Single Field**
- **Quasi-Multi-Field**
What are the Observable Signatures of These Isocurvatons ($0 < m < \sim H$)?

A special kind of large non-Gaussianities
Large
A New Sector

Introducing coupling without spoiling the slow-roll conditions

\[ V'''' \sim H^2 \]
\[ V''' \text{ can be } H \]
\[ V'''' \text{ can be } 1, \text{ etc} \]

\[ V'' \sim \mathcal{O}(\epsilon) H^2 \]
\[ V'''' \sim \mathcal{O}(\epsilon^2) P_{\zeta}^{1/2} H \]
\[ < 10^{-9} H \]
Perturbation Method and Feynman Diagrams

Correction to 2pt

Perturbation theory:

\[
\left( \frac{\dot{\theta}}{H} \right)^2 \ll 1 , \quad \frac{V'''}{H} \ll 1 .
\]

But not model-building requirements
Special
Shapes of Bispectra

\[ \langle \zeta^3 \rangle \equiv S(k_1, k_2, k_3) \frac{1}{(k_1 k_2 k_3)^2} \tilde{P}_\zeta^2 (2\pi)^7 \delta^3 \left( \sum_{i=1}^{3} k_i \right) \]

\[ S(p_1, p_2, p_3) \xrightarrow{\text{scale-invariance}} S(1, p_2/p_1, p_3/p_1) \]
Shapes of Bispectra (X.C., Wang, 09)

Shapes of bispectrum (in squeezed limit) directly measure the mass

\[ \nu \equiv \sqrt{\frac{9}{4} - \frac{m^2}{H^2}} \]
Soft Limit

Squeezed-limit: \[ p_3 \ll p_1 = p_2 \]

Shape:
\[ S \rightarrow f_{NL} \left( \frac{p_3}{p_1} \right)^\alpha \]

\[ \alpha = \frac{1}{2} - \sqrt{\frac{9}{4} - \frac{m^2}{H^2}} \]

\[ m : 0 \rightarrow 3H/2 \quad S : \left( \frac{p_3}{p_1} \right)^{-1} \rightarrow \left( \frac{p_3}{p_1} \right)^{1/2} \]

Local shape
Underlying Physics

• **Quasi-local:** for lighter isocurvatons \( m < \sqrt{2}H \), i.e. \( 3/2 > \nu > 1/2 \)

  Fluctuations decay slower after horizon-exit

  Non-G gets generated and transferred at more super-horizon scale

  Closer to local shape.


• **Quasi-equilateral:** for heavier isocurvatons \( m > \sqrt{2}H \), i.e. \( \nu < 1/2 \)

  Fluctuations decay faster after horizon-exit

  Large interactions happens closer to the horizon scale

  Modes have comparable wavelengths

  Peaks at equilateral limit
Critical Test of Multi-Field Slow-Roll Inflation Models
Multi-Field Inflation

Isocurvatton mass: \[ m^2 = \mathcal{O}(0.01) H^2 \]

- Massless scalars fluctuations do not decay \[ \longrightarrow \text{span multifield space} \]
- Patches that are separated by horizon evolve independently (locally)

\[ \zeta(x) = \zeta_g(x) + f_{NL} \zeta_g^2(x) \]

(Sasaki, Stewart, 95; Lyth, Rodriguez, 05)

Local in position space \[ \Rightarrow \] Non-local in momentum space

From the above \( \delta N \) formalism: \[ S \propto \left( \frac{p_3}{p_1} \right)^{-1} \]

From in-in formalism:

\[ \alpha = \frac{1}{2} - \sqrt{\frac{9}{4} - \frac{m^2}{H^2}} \quad m \to 0 \quad \alpha \to -1 \]
Critical Test from the Soft Limit

- $\alpha > -1$ will rule out all multi-field (slow-roll) models as source of density perturbations. I.e., massive isocuvaton is necessary.
  (Including: multifield turning trajectory, curvaton model, inhomogeneous reheating, …)

- Some quasi-single field models are very degenerate with multi-field models

  E.g. $\alpha = -0.9 \iff m = 0.54H$

  Non-G is very close to local, but model is not multi-field slow-roll.

  So a detection of a local component could mean either multi-field or QSF.

- Important to see what the experimental sensitivities are
How do We Measure the Shapes in the Sky?

If a large non-Gaussianity \( f_{NL} \) is detected by Planck, how much can we refine our discovery to pin down the shapes \( \alpha \)?
Cosmic Microwave Background
Planck Forecast for Constraints on QSFI

(Sefusatti, Fergusson, X.C., Shellard, 12)

Constraint on $f_{NL}$ will be better than constraint on $\nu$

Lines: Fisher matrix
Shades: Monte Carlo

Normalization difference: $f_{NL}^{\nu=1} = 3.3 f_{NL}^{\text{loc}}$
Large Scale Structure Surveys

Euclid Satellite:
- 20,000 degree-squared
- 3D map, 0.4 < z < 2
- Launch in 2019

Denote as V1

LSST telescope:
- 30,000 degree-squared
- 3D map, 0.3 < z < 3.8
- Taking data in 2020

Denote as V2
Large Scale Structures

Halo Bias: \( b = \frac{\text{halo overdensity}}{\text{matter overdensity}} \)

Determined by the long wavelength modulation on short wavelength modes

For local shape: \( b \propto f_{NL} k^{-2} \)  \hspace{1cm} (Dalal, Dore, Huterer, Shirokov, 07)

For QSFI: \( b \propto f_{NL} k^{-1/2 - \nu} \)

(squeezed-limit of 3pt)

(Scoccimarro, Manera, Hui, Chan, 11; Emiliano, Fergusson, X.C., Shellard, 12; Norena, Verde, Barenbiom, Bosch, 12)
Large Scale Structure Forecast for QSFI

(Sefusatti, Fergusson, X.C., Shellard, 12; Norena, Verde, Barenbiom, Bosch, 12)

Halo bias is more sensitive to the shapes than the size of 3pt

\[ k_{\text{max}}(0) = 0.075 \, h \, \text{Mpc}^{-1} \]
Large Scale Structure Forecast for QSFI

(Sefusatti, Fergusson, X.C., Shellard, 12)

\[ f_{NL} = 100 \]
\[ \nu = 1 \]

\[ k_{max}(0) = 0.15 \, h \, \text{Mpc}^{-1} \]
An interesting Cosmic Complimentarity!

**CMB**: better at size of non-Gaussianity:
less differentiating away from squeezed limit.

**Halo bias**: better at the shapes at squeezed limit:
its physics entirely depends on squeezed limit shape
Combining CMB and LSS

\[ k_{\text{max}}(0) = 0.075 \, h \, \text{Mpc}^{-1} \]

\[ k_{\text{max}}(0) = 0.15 \, h \, \text{Mpc}^{-1} \]

We can also add: polarization data; LSS bispectra; beyond bispectra, …..
So, if $\alpha$ is not very close to -1, we can hope to separate two important classes of models, by measuring the mass spectrum, like in particle physics.

Establishment of such spectra will have important implications on fundamental physics, such as model building and supersymmetry.

(X.C., Wang, 09; Baumann, Green, 12, McAllister, Renaux-Petal, Xu, 12)
Thank You !