Theory of Primordial Non-Gaussianity and Primordial Feature

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Use maps of primordial fluctuations to probe the primordial Universe: CMB, LSS, 21cm
Quantum Fluctuations Become Seeds of LSS

Quantum fluctuations Evolve, exit horizon, non-propagating

Universe is populated through reheating, with curvature perturbations

Observed as correlations of fluctuations in CMB and LSS

In-In Formalism (Schwinger, 61; Weinberg, 05)

Expectation value of an operator in a time-dependent background:

\[ \langle Q(t) \rangle \equiv \langle 0 \mid \tilde{T} \exp \left( i \int_{t_0}^{t} H_I(t) dt \right) \mid Q^I(t) \mid T \exp \left( -i \int_{t_0}^{t} H_I(t) dt \right) \mid 0 \rangle \]

\[ \delta \rho / \rho \quad \Rightarrow \quad \phi = \phi_0 + \delta \phi \]

Density perturbations Fundamental fields
Non-Gaussianity as an ultimate probe of physics of primordial universe

Particle collider

- high energy collision
- new particle states
- decay to long-lived particles
- enter detectors
- measuring correlation functions

Primordial universe

- high energy background $H \lesssim 10^{13}\text{GeV}$ or energy scale of sharp feature
- new particle states
- (decay to) curvature perturbations, kept at super-horizon
- enter detectors
- measuring correlation functions

A Cosmological Collider
Outline (focus on inflation in this talk)

- Single field inflation model with minimal interaction
- Single field with more complicated interactions
- Additional fields in the final states
- Additional fields in the intermediate states

Soft limit behavior of non-G $\rightarrow$ Properties of particle states involved: mass, spin

Bulk behavior $\rightarrow$ Properties of interactions

Comparison b.t. different configurations $\rightarrow$ Properties of parity
Single field inflation models with minimal self-interactions

- Single field
- Canonical kinetic term
- Always slow-roll
- Bunch-Davies vacuum
- Einstein gravity

\[ f_{NL} \sim \mathcal{O}(\epsilon) \lesssim \mathcal{O}(0.01) \quad \text{(Maldacena, 02; Acquaviva et al, 02)} \]

In physical coordinates, the squeezed limit \( f^{\text{loc}}_{NL} = 0 \)

The leading order non-G is \textit{equilateral, and very small.} \quad \text{(Tanaka, Urakawa, 11; Pajer, Schmidt, Zaldarriaga, 13. Cabass, Pajer, Schmidt, 16)}

\textit{A clean background for signatures of new particles and interactions.}
Single Field Inflation Models with (1st) Derivative Interactions

(Creminelli, 03, Gruzinov, 04, Seery, Lidsey 05, XC, Huang, Kachru, Shiu, 06, Cheung et al, 08)

Two types of interaction terms: same squeezed limit, different bulk shapes

\[ S_\lambda : f_{NL}^\lambda = \frac{5}{81} \left( \frac{1}{c_s^2} - 1 - \frac{2\lambda}{\Sigma} \right) \]

\[ S_c : f_{NL}^c = -\frac{35}{108} \left( \frac{1}{c_s^2} - 1 \right) \]

If \( f_{NL}^{eq} < 1 \), inflation mechanism is still slow-roll; if \( f_{NL}^{eq} > 1 \), non-slow-roll inflation, e.g. DBI, k-inflation.

(Garriga, Mukhanov, 99; Silverstein, Tong, 03)
orthogonal shape

change of bases

equilateral shape

(Smith, Senatore, Zaldarriaga, 09)
Non-standard vacuum $\rightarrow$ large folded non-Gaussianity

(XC, Huang, Kachru, Shiu, 06, Holman, Tolley, 08, Meerburg, van der Schaar, Corasaniti, 09, ... ...)

Non-attractor solution $\rightarrow$ large local non-Gaussianity

(Namjoo, Firouzjahi, Sasaki, 12, ... ...)

Features $\rightarrow$ correlated scale-dependent signals in power spectrum and non-Gaussianities

(Will discuss later ... ...
Additional Fields in the Final State

- These fields need to be massless during inflation so they do not decay.
- Large local non-G may be generated by super-horizon evolution.

Patches that are separated by horizon evolve independently (locally):

$$\delta N = \delta N_g + f_{NL} (\delta N_g)^2$$  

(Starobinsky, 85; Sasaki, Stewart, 95; Lyth, Rodriguez, 05)

Local in position space

Examples: Curvaton models:

$$f_{NL}^{loc} = \frac{5}{4r} - \frac{5}{3} - \frac{5r}{6};$$

(Linde, Mukhanov, 96; Lyth, Wands, 01; Moroi, Takahashi, 01)

Modulated reheating (Dvali, Gruzinov, Zaldarriaga, 03; Kofman, 03)

Isocurvature non-G (Komatsu, 02; Bartolo, 02; Langlois et al, 08)
**Additional fields in the intermediate state**

Simplest case is intermediate *massless scalars*: turning trajectory in multifield inflation

- small amount of local non-Gaussianity, due to similar reason as the curvaton model case

  (Bartolo et al, 02; Vernizzi, Wands, 06; Rigopoulos, Shellard, van Tent, 06, ... ...)

At horizon scale, equilateral type non-G can be generated due to interactions / curved field space

(See Sebastien Renaux-Petel’s talk in this workshop)

Generally, intermediate particles can have any mass, spin and parity

**Question:** What are the observational signatures for all the particles present during inflation?
Cosmological Collider Physics

- Mass, spin and parity of intermediate state show up in various behavior non-G

\[(X, C, \text{Wang, 09; Baumann, Green, 11; Noumi, Yamaguchi, Yokoyama, 12; Arkani-Hamed, Maldacena, 15})\]

E.g. Squeezed limit bispectrum

\[S \xrightarrow{\text{squeezed limit}} e^{-\pi\mu \left( \frac{k_{\text{long}}}{k_{\text{short}}} \right)^{\frac{1}{2} \pm i\mu}} P_s(\cos \theta) \]

Boltzmann suppression mass spin

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

Parity from comparing mirror pair of scalar trispectra

\[(Liu, Tong, Wang, Xianyu, 19)\]

Also, tensor spectra

\[(Barnaby, Pajer, Peloso, 11; Cook, Sorbo, 13, Namba et al, 16)\]
Application of Cosmological Collider Physics

• Particle Physics Standard model signature in non-G
  (XC, Wang, Xianyu, 16, 17; Kumar, Sundrum, 17; Hook, Huang, Racco, 19)

• Intermediate fields in curvaton models
  (Lu, Wang, Xianyu, 19; Kumar, Sundrum, 19)

• Signature of higher dimensional Grand Unification Theory
  (Kumar, Sundrum, 18)

• Signature of higher spin fields
  (Arkani-Hamed, Maldacena, 15; Lee, Baumann, Pimental, 16; Bordin, Creminelli, Khmelnitsky, Senatore, 19)
  (See talks of Guilherme Pimental and Paolo Creminelli in this workshop)

• ... ... ...
Primordial Features

Small components that significantly depart from scale-invariance, in power spectrum or non-G

- **Sharp feature:** Deviation from attractor at some instant of evolution, due to a sharp feature

  \[
  \frac{\Delta P_\zeta}{P_{\zeta 0}} \propto 1 - \cos(2k/k_f) \quad S \propto \sin(K/k_f + \phi) \quad \text{with model-dependent envelop}
  \]
  
  (Staronbinsky, 92; Adams et al, 01; Bean et al, 08; Achucarro et al, 10; ...)

- **Resonant feature:** Background oscillations with frequency larger than horizon scale

  \[
  \frac{\Delta P_\zeta}{P_{\zeta 0}} \propto \sin(\log(2k) + \phi) \quad S \propto \sin(\log(K) + \phi)
  \]
  
  (XC, Easther, Lim, 08; Flauger et al, 09; Flauger, Pajer, 10)

  Mixing features with derivative interaction or multifield give more complicated variations

  (XC, 10; Behbahani, Dymarsky, Mirbabayi, Senatore, 11)

- **Primordial standard clocks**
**Primordial Standard Clocks**  
(XC, 11; XC, Namjoo, Wang, 14, 15; XC, Loeb, Xianyu, 18)

**Motivation:** Distinguish inflation and alternative-to-inflation scenarios model-independently by directly measuring $a(t)$ using massive fields

Massive: Mass larger than event-horizon scale of the primordial epoch

1) exist in any realistic models
2) oscillate in a standard way in any background

Oscillations of massive fields can be

- classical
- quantum-mechanical

requires a sharp feature

completely general

Oscillation/ticking of the massive field induce patterns of ticks in density perturbations – “Clock Signals”
Fingerprints of Different Scenarios in Classical Clock Case

- Inflation (fast expansion, $|p| > 1$)
- Matter contraction (fast contraction, $0 < p \sim O(1) < 1$)
- Slow expansion ($-1 \ll p < 0$)
- Ekpyrosis (slow contraction, $0 < p \ll 1$)

- Oscillation phase as function of $k$ is inverse function of $a(t)$
- Have correlated signals in non-Gaussianities
Motivation from Data Analyses

Two well-separated features in CMB may be connected by a classical Standard Clock

This PSC candidate so far only has marginal statistical significance; it nonetheless serves as an interesting example.

(XC, Namjoo, 14; XC, Namjoo, Wang, 14)

Future LSS data will tell.

(XC, Dvorkin, Huang, Namjoo, Verde, 16)
Comparing with CMB

• Construct separable templates for special types of non-G
  (Komatsu, Spergel, Wandelt, 05; Creminelli et al, 06; Senatore et al, 10)

• More generally, using method of modal decomposition
  Construct and constrain complete, orthogonal bases of separable bispectrum
  (Fergusson, Liguori, Shellard, 10, 12)

• For non-G that cannot be perturbatively expanded in poly-spectra, analyze full PDF
  (XC, Palma, Riquelme, Hitschfeld, Sypsas, 19, Palma, Hitschfeld, Sypsas, 19)

Examples of such models, such as landscape tomography
  (Bond et al, 09; Demozzi, Linde, Mukhanov, 10; Leblond, Pajer, 10; Flauger et al, 16; Palma, Riquelme, 17, Panagopoulos, Silverstein, 19, ......)

(See Gonzalo Palma’s talk in this workshop)
CMB Constraints: scale invariant case

\[ f_{\text{local}}^{\text{NL}} = -0.9 \pm 5.1 \quad f_{\text{equil}}^{\text{NL}} = -26 \pm 47 \quad f_{\text{ortho}}^{\text{NL}} = -38 \pm 24 \]

(Planck 2018 results)

Future works: constrain many other shapes of non-G.

Motivations for improvement and reach \( f_{NL} \lesssim 1 \)

• For local shape, can rule out most curvaton models (and some non-inflationary bounce models)

• For equilateral shape, can rule out non-slow-roll inflationary mechanism such as DBI, k-inflation

• Many particle physics signatures in cosmological collider may appear in this region

• ... ... ...
CMB Constraints: feature case

(Planck 2018 results)

sharp feature

resonance feature

$\sigma_{f_{NL}} \approx 30 \sim 100$

$\sigma_{f_{NL}} \approx 40 \sim 150$
Need more data digging in CMB ... ...

Future experiments: Polarization, LSS, 21cm, ... ...

See Azadeh Moredinezhad, Cora Dvorkin and Florian Beutler’s talk in this workshop
Thank You !