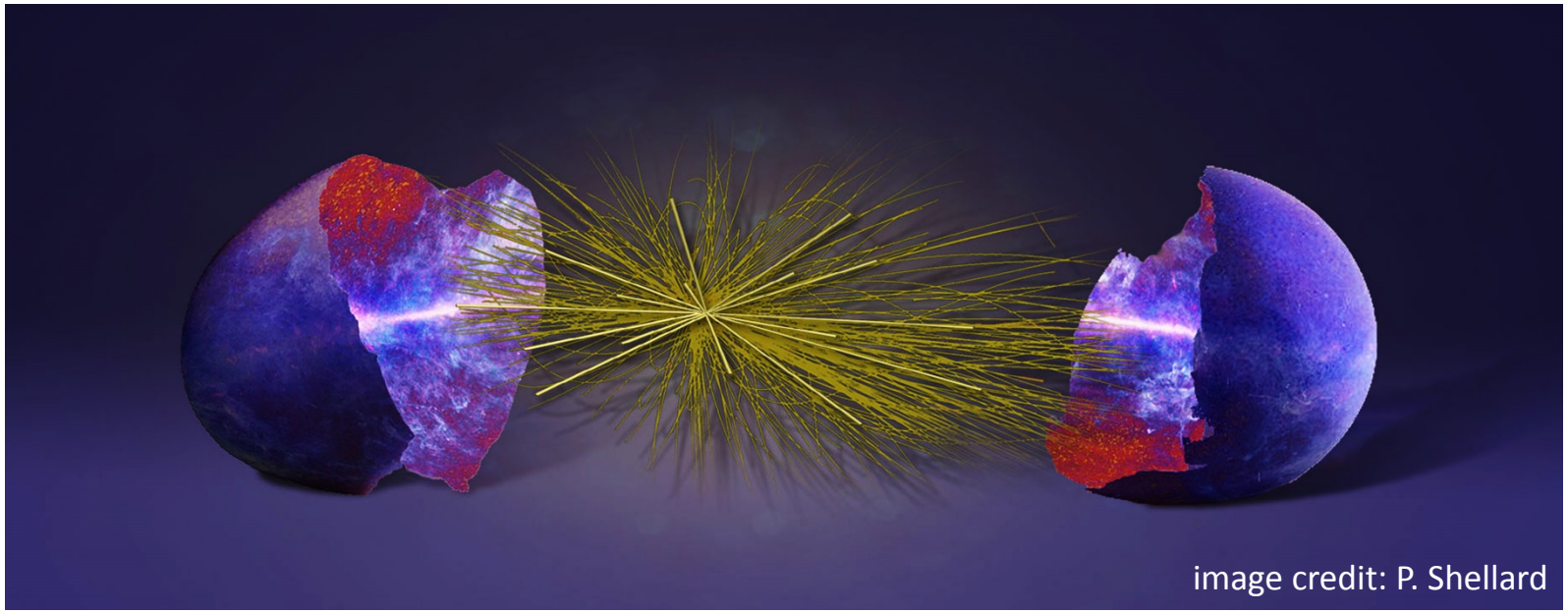
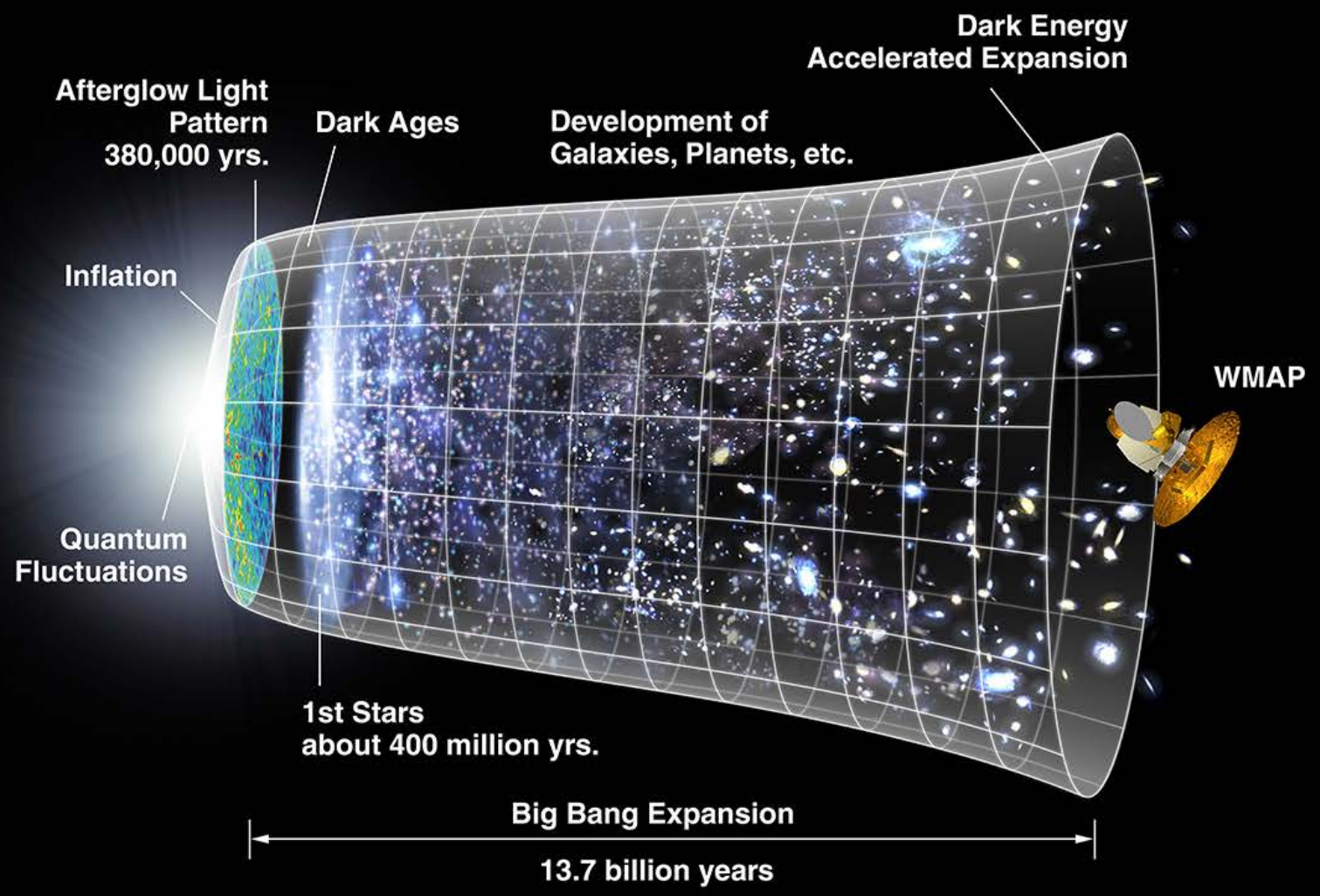
Theory of Primordial Non-Gaussianity and Primordial Feature

Xingang Chen

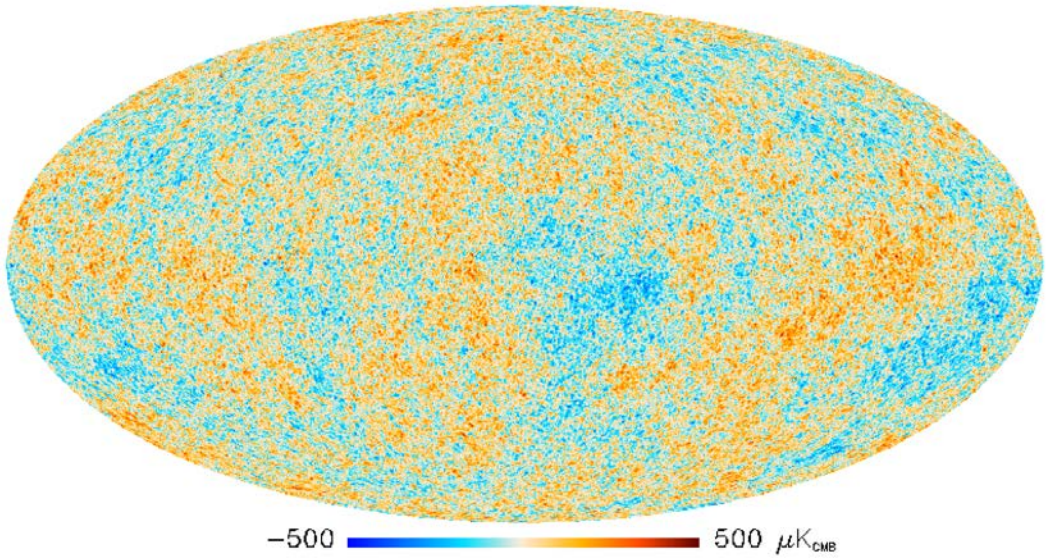
CfA, Harvard

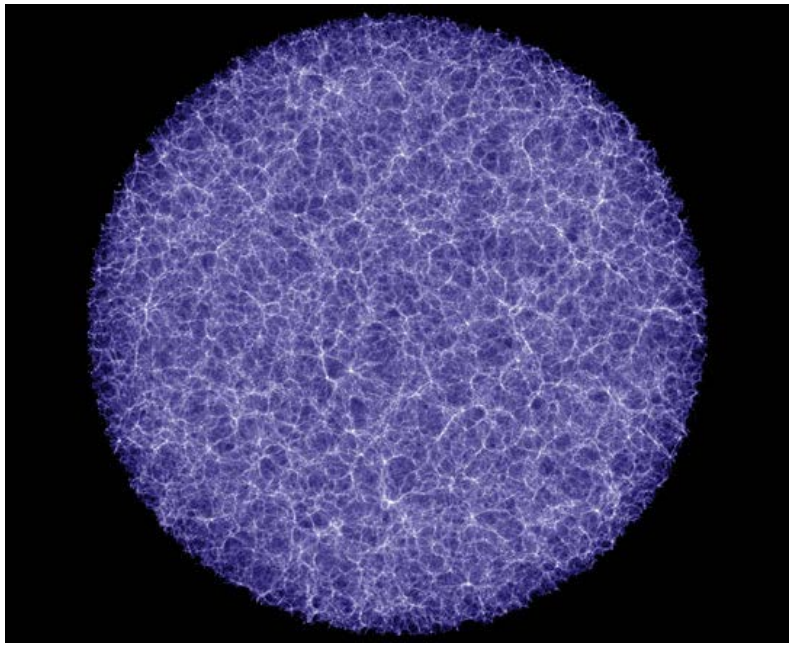


Origin of the Universe



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-proporgating →

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:

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

$$\delta\rho/\rho \quad \longleftrightarrow \quad \phi = \phi_0 + \delta\phi$$

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

$H \lesssim 10^{13}\mathrm{GeV}$ 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 → Properties of particle states involved: mass, spin

Bulk behavior → Properties of interactions

Comparison b.t. different configurations → Properties of parity

Single field inflation models with minimal self-interactions

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

→ Size of 3pt: $f_{NL} \sim \mathcal{O}(\epsilon) \lesssim \mathcal{O}(0.01)$ (Maldacena, 02; Acquaviva et al, 02)

In physical coordinates, the squeezed limit $f_{NL}^{\rm loc} = 0$

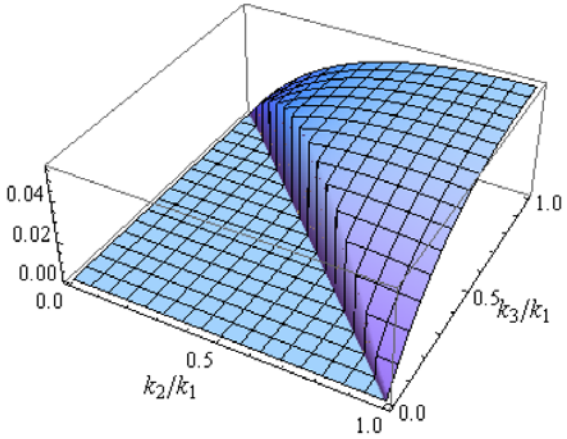
The leading order non-G is equilateral, and very small. (Tanaka, Urakawa, 11; Pajer, Schmidt, Zaldarriaga, 13. Cabass, Pajer, Schmidt, 16)

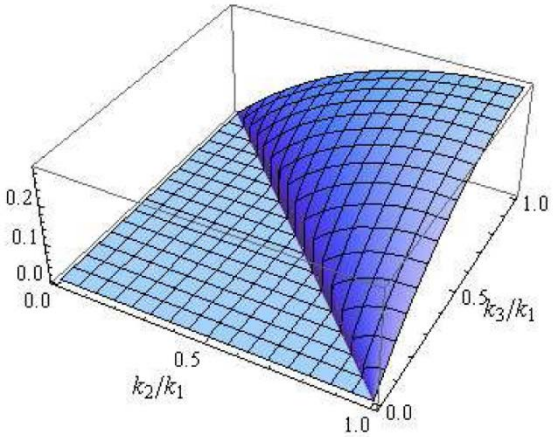
A clean background for signatures of new particles and interactions.

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



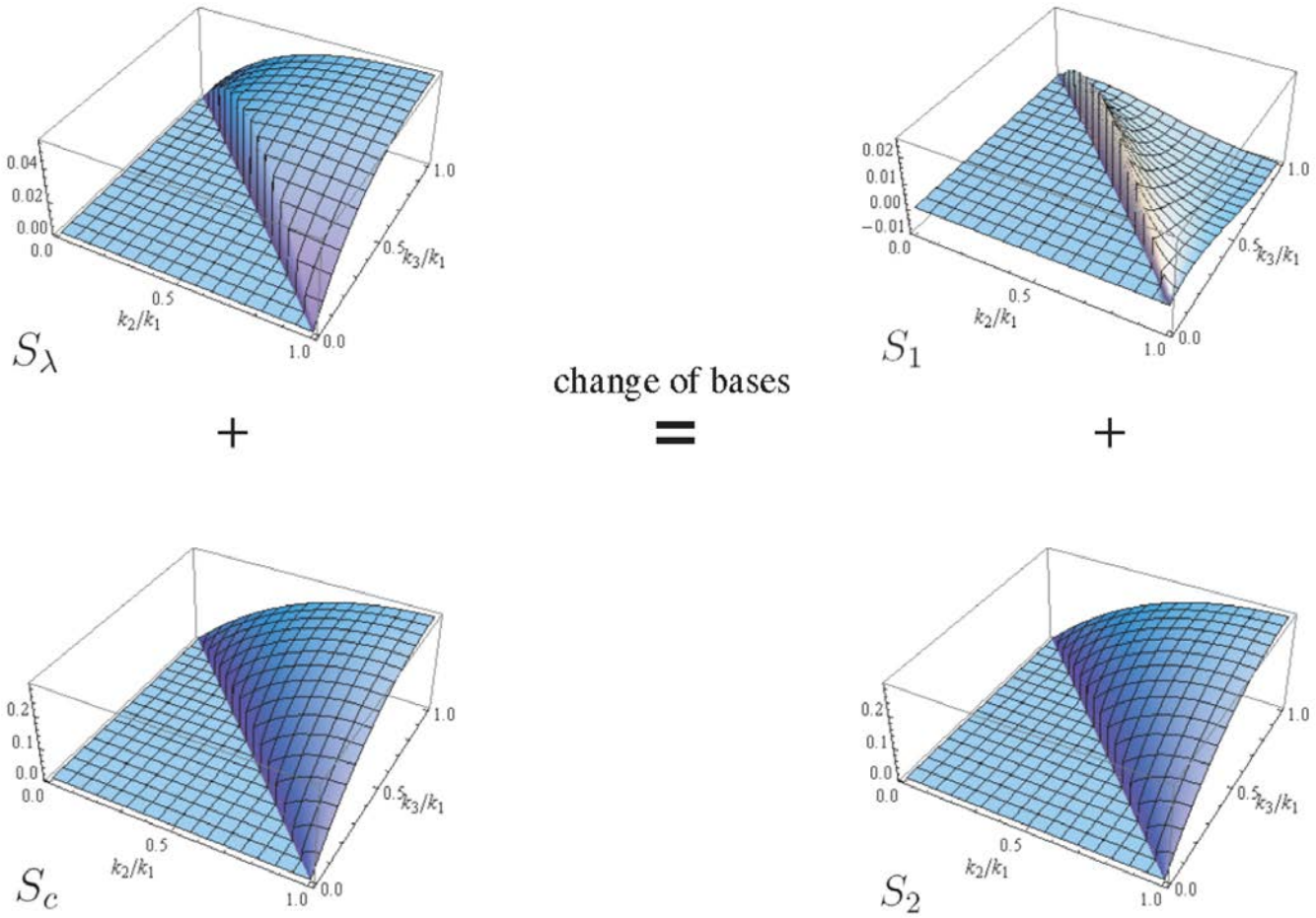


$$S_\lambda : \; f_{NL}^{\lambda} = \frac{5}{81}\left(\frac{1}{c_s^2} - 1 - \frac{2\lambda}{\Sigma}\right)$$

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

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

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



orthogonal shape

equilateral shape

(Smith, Senatore, Zaldarriaga, 09)

Non-standard vacuum → large folded non-Gaussianity

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

Non-attractor solution → large local non-Gaussianity

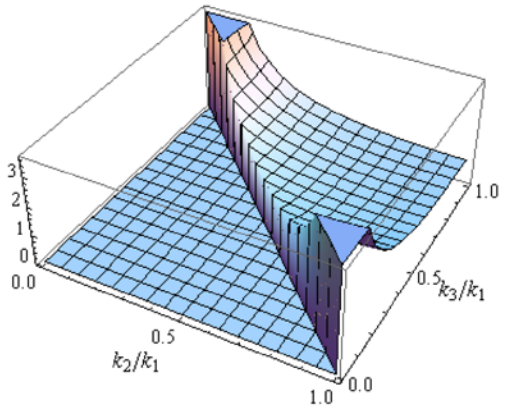
(Namjoo, Firouzjahi, Sasaki, 12, … …)

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

(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

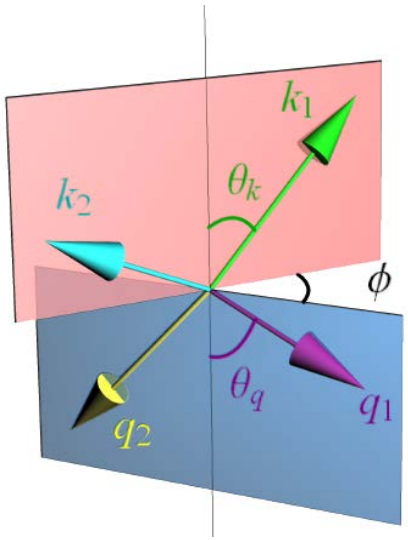
(XC, Wang, 09; Baumann, Green, 11; Noumi, Yamaguchi, Yokoyama, 12; Arkani-Hamed, Maldacena, 15)

E.g. **Squeezed limit bispectrum**

$$S \xrightarrow[\text{limit}]{\text{squeezed}} e^{-\pi\mu} \left(\frac{k_{\text{long}}}{k_{\text{short}}}\right)^{\frac{1}{2}\pm i\mu} P_s(\cos\theta) \qquad \mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

Boltzmann suppression

mass spin



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

$$\frac{\Delta P_\zeta}{P_{\zeta 0}} \propto 1 - \cos(2k/k_f) \qquad S \propto \sin(K/k_f + \phi)$$ 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

$$\frac{\Delta P_\zeta}{P_{\zeta 0}} \propto \sin(\Omega \log(2k) + \phi) \qquad S \propto \sin(\Omega \log(K) + \phi)$$

(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

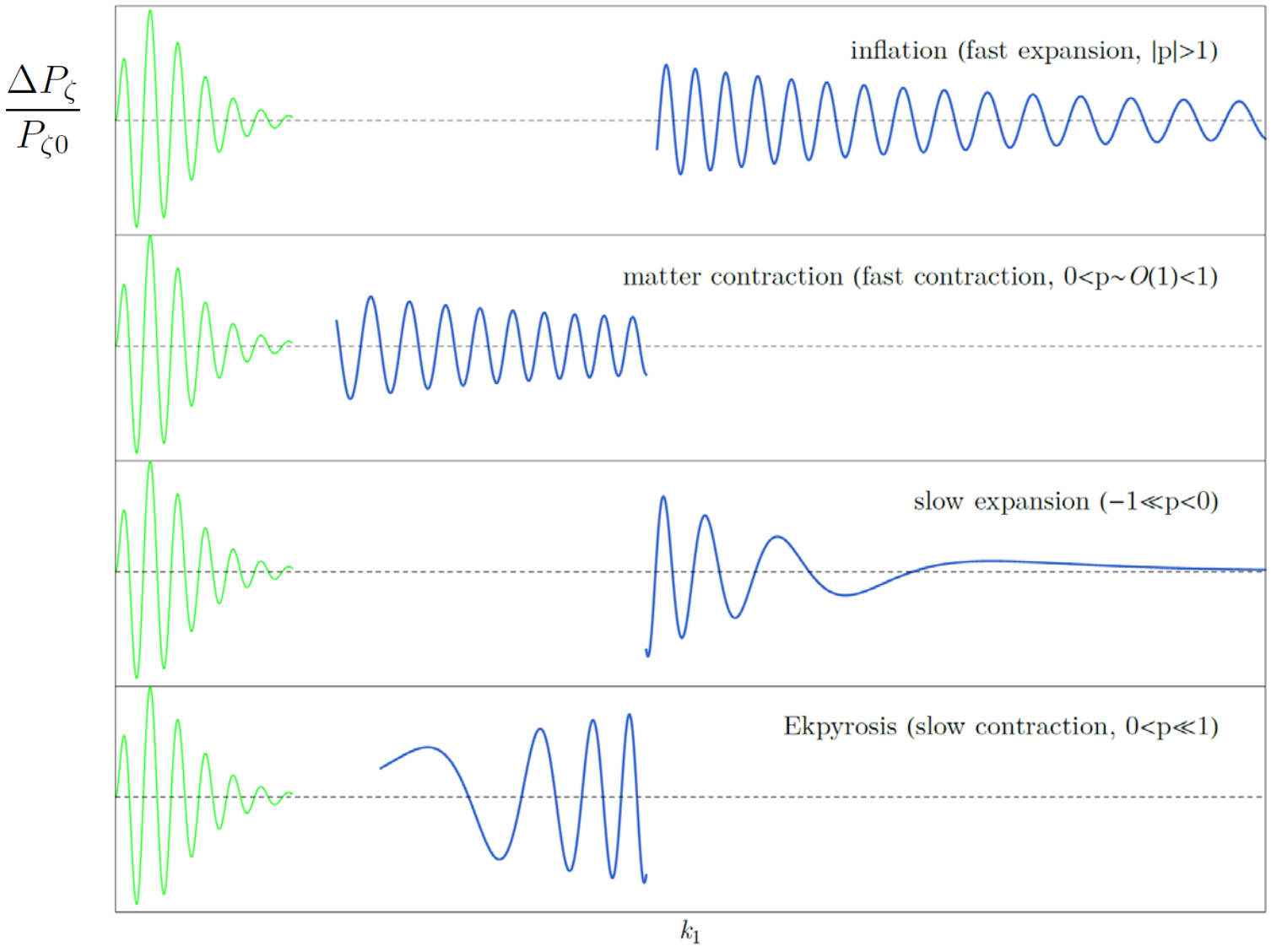
Massive: Mass larger than event-horizon scale of the primordial epoch

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

Oscillations of massive fields can be
- classical → requires a sharp feature
- quantum-mechanical → completely general

Oscillation/ticking of the massive field
induce patterns of ticks in density perturbations – "**Clock Signals**"

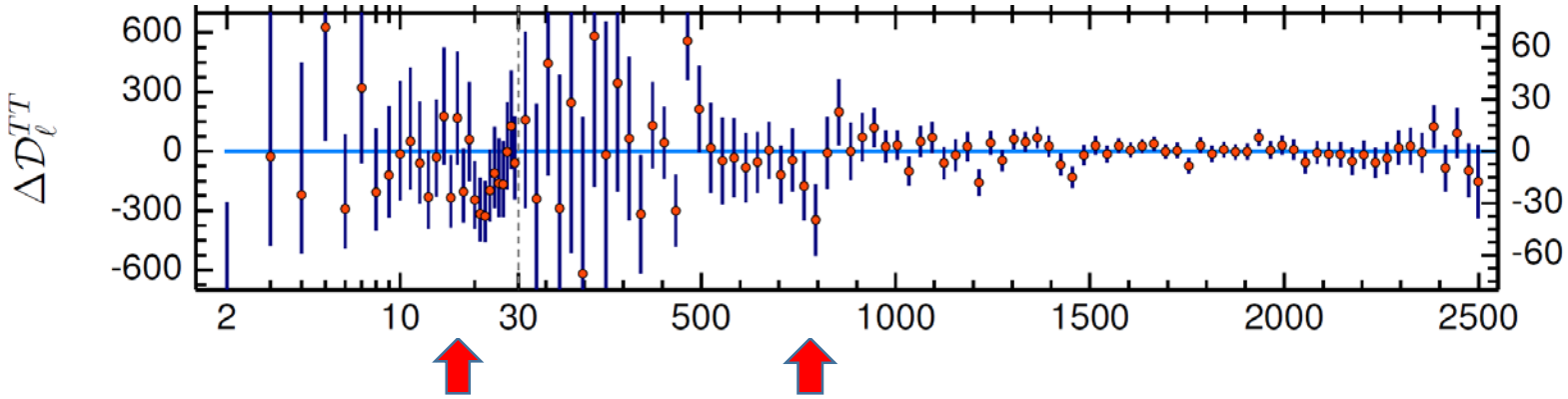
Fingerprints of Different Scenarios in Classical Clock Case



Oscillation phase as function of k is inverse function of a(t)

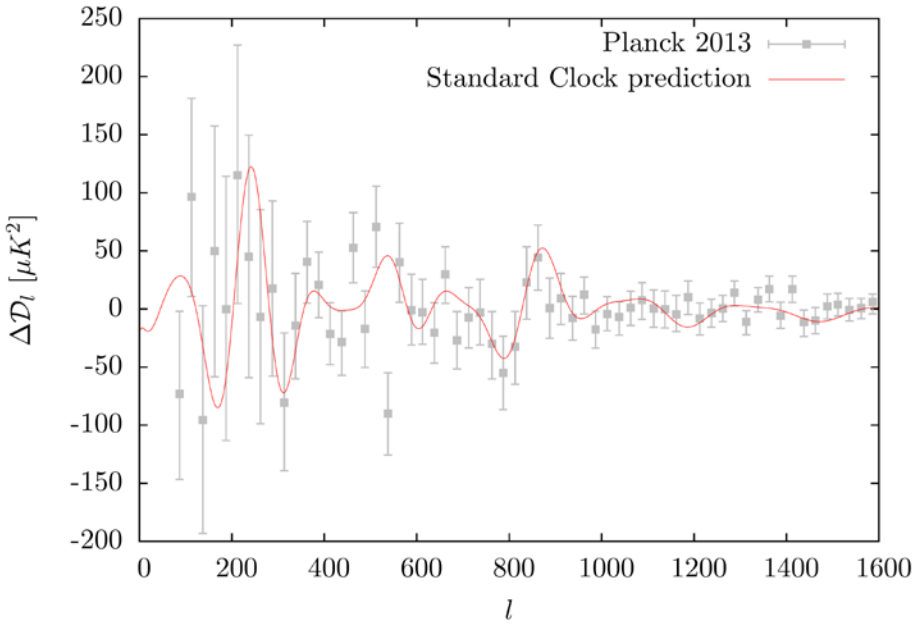
Have correlated signals in non-Gaussianities

Motivation from Data Analyses



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

A full model example:



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 separaable 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

$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1 \qquad f_{\rm NL}^{\rm equil} = -26 \pm 47 \qquad f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

(Planck 2018 results)

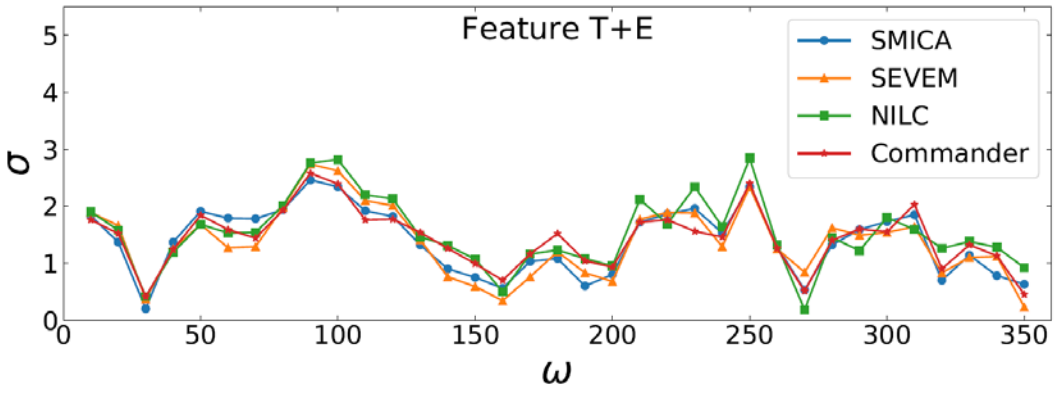
Future works: constrain many other shapes of non-G.

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
- … … …

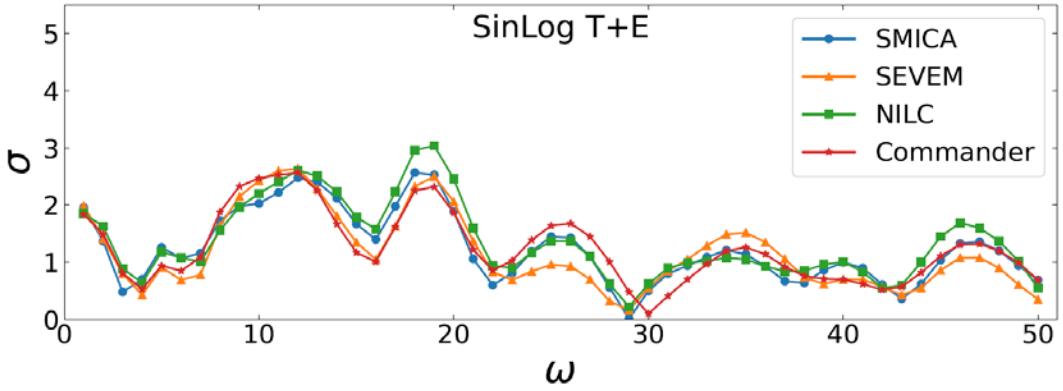
CMB Constraints: feature case

sharp feature



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

resonance feature



$$\sigma_{f_{NL}} \approx 40 \sim 150$$

(Planck 2018 results)

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 !