Primordial Features

Testable structures in power spectrum and Non-Gaussianity from fundamental physics

General references include:

Scratches from the Past: Inflationary Archaeology through Features in the Power Spectrum of Primordial Fluctuations
Anze Slosar (Brookhaven), Kevork N. Abazajian (UC, Irvine), Muntazir Abidi (Cambridge U., DAMTP), Peter Adshead (Illinois U., Urbana), Zeeshan Ahmed (SLAC) et al. e-Print: 1903.09883 [astro-ph.CO] Bull.Am.Astron.Soc. 51 (2019) 3, 98

The Future of Primordial Features with Large-Scale Structure Surveys
Xingang Chen (Harvard-Smithsonian Ctr. Astrophys. and Texas U., Dallas), Cora Dvorkin (Harvard U.), Zhiqi Huang (Zhongshan U.), Mohammad Hossein Namjoo (Harvard-Smithsonian Ctr. Astrophys. and Texas U., Dallas), Licia Verde (ICC, Barcelona U. and ICREA, Barcelona and Radcliffe Coll. and Inst. Theor. Astrophys., Oslo) e-Print: 1605.09365 [astro-ph.CO] DOI: 10.1088/1475-7516/2016/11/014 JCAP 11 (2016), 014

Primordial Features from Linear to Nonlinear Scales
Florian Beutler (Portsmouth U., ICG and LBL, Berkeley), Matteo Biagetti (Amsterdam U.), Daniel Green (UC, San Diego), Anže Slosar (Brookhaven), Benjamin Wallisch (Princeton, Inst. Advanced Study and Cambridge U., DAMTP and Amsterdam U. and UC, San Diego)
e-Print: 1906.08758 [astro-ph.CO] DOI: 10.1103/PhysRevResearch.1.033209 Phys.Rev.Res. 1 (2019) 3, 033209

We are probing the probability distribution of primordial quantum fields

$$P(\zeta, \gamma) = \int \mathrm{D}\chi \, |\Psi[\zeta, \gamma, \chi]|^2$$

which can take many forms consistently with known constraints.

The type of observational signals and their amplitudes depend on field content and interactions.

We can aim for minimal assumptions (rather than an assumption of minimality). Test/discriminate broad classes of dynamics.

Features: anything going beyond approximately scale-invariant power spectrum

$$P_{\zeta 0} = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

and special low point correlators (N <~ 4)

$$f_{NL}^{local}, f_{NL}^{equilateral}, \ldots$$

These don't capture the signatures of generic early universe QFT consistent with inflation and known observational constraints. The physics is also UV sensitive, with string theory suggesting some particular signals of interest among a wide class of possibilities.

The EFT of Inflationary perturbations allows for features:

Cheung Creminelli Fitzpatrick Kaplan Senatore '07

$$S = \int d^4x \sqrt{-g} \Big[\frac{1}{2} M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2 (3H^2 + \dot{H}) + \frac{1}{2!} M_2(t)^4 (g^{00}+1)^2 + \frac{1}{3!} M_3(t)^4 (g^{00}+1)^3 + -\frac{\bar{M}_1(t)^3}{2}(g^{00}+1)\delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2}\delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2}\delta K^\mu{}_\nu \delta K^\nu{}_\mu + \dots \Big] . \quad (5.1)$$

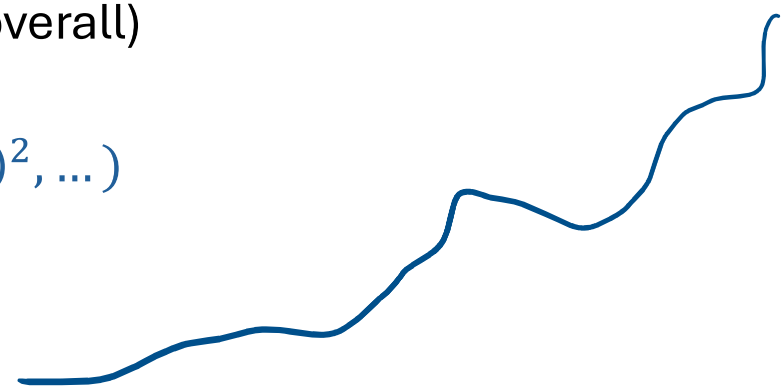
The coefficients here can be arbitrary functions of time.

$\Rightarrow$ The EFT of inflation is neutral (uninformative) on the question of features.

(A featureless distribution would arise from a special assumption of a continuous shift symmetry.)

Many QFTs are consistent with inflation ($\frac{\dot{H}}{H^2}, \frac{\ddot{H}}{H^3} \ll 1$ overall)

$$S = \int d^4x \sqrt{-g} L(\phi, (\partial\phi)^2, \dots)$$



Interactions with other fields, even heavy ones affect the effective inflaton Lagrangian $L(\phi, (\partial\phi)^2, \dots)$. Rather than presuming the existence of a continuous shift symmetry to eliminate generic couplings, let's include tests of their effects.

So what features are important to test? Possible organizing principles include

- EFT with discrete shift symmetry
- UV complete dynamics

) axions, heavy particles (generic)

- Multifield landscapes: back reaction of fields coupling to inflaton, phase transitions, particle production from inflaton-dependent masses and saddles, ...
  (a) Structured
  (b) Random

For LSS surveys, this is a natural target, these signals can be particularly robust against ordinary nonlinearities.

As a preview, for two classes of oscillatory signals:

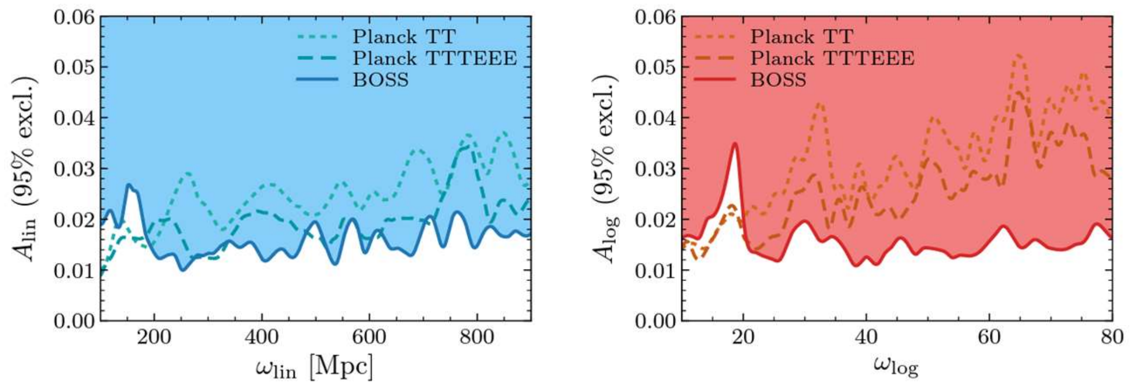


Figure 8: Comparison of the 95% upper limits on the feature amplitudes A_X, $X = \text{lin}, \log$, from LSS and the CMB for linear (*left*) and logarithmic features (*right*). The solid lines indicate our new BOSS-only results and are identical to the solid lines of Fig. 7. The bounds from Planck 2015 temperature (dotted) and temperature+polarization data (dashed) are for the first time displayed as a function of feature frequency as well. Beyond those frequencies which show a degeneracy with the standard BAO spectrum, the BOSS data are able to improve over the CMB.

Beutler Biagetti Green Slosar Wallisch '19: LSS already improves over CMB. **Ben's Talk**

A. Vasudevan, M. Ivanov, S. Sibiryakov, J. Lesgourgues; Chen Vlah White ...

One can postulate a feature in the inflaton action and determine its effect on the observables, e.g.

Spectrum of adiabatic perturbations in the universe when there are singularities in the inflaton potential

+Adams Cresswell Easther...

A. A. Starobinskiĭ

L. D. Landau Institute of Theoretical Physics, Russian Academy of Sciences, 117334, Moscow

(Submitted 9 April 1992)

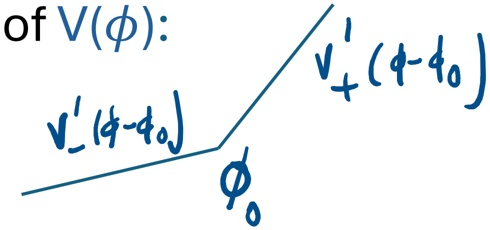
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No. 9, 477–482 (10 May 1992)

If the potential of the effective scalar which controls the de Sitter (inflationary) stage in the early universe has a singularity consisting of a rounded change in slope, a step of a universal form arises in the spectrum of adiabatic perturbations. Along with this step, there are superimposed modulations. If the singularity in the potential is instead a rounded jump, a hump appears in the spectrum.

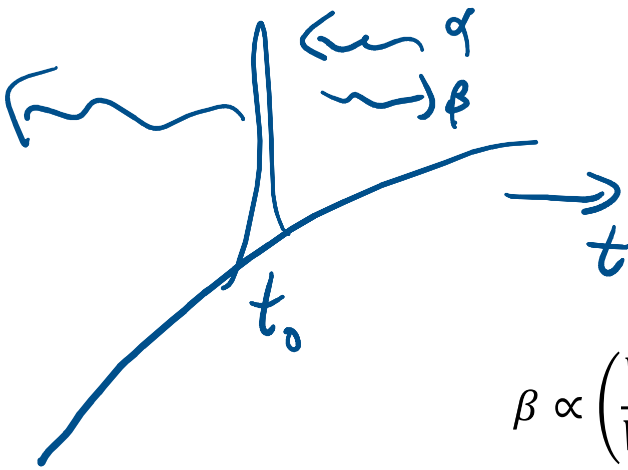
This could perhaps be motivated by rapid effects like phase transitions.

One possibility is a sharp feature such as a change in slope of V(ϕ):

Starobinsky '92; Adams Cresswell Easther '01…



$$-\delta\ddot{\phi} - 3\,H\delta\dot{\phi} - \left(\frac{k^2}{a^2} + V''(\phi)\right)\delta\phi = 0$$

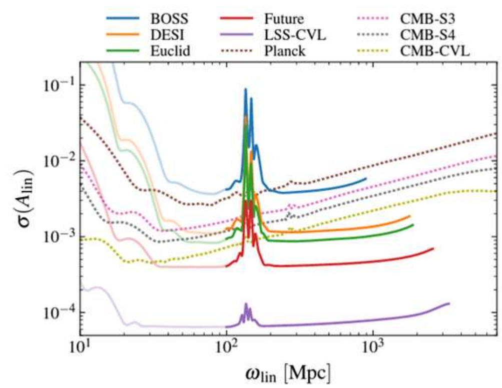


β

$(V'_+ - V'_-)\,\delta(\phi-\phi_0)$

$\frac{\delta(t-t_0)}{\dot{\phi}}$

$$\beta \propto \left(\frac{V'_-}{V'_+} - 1\right) e^{\frac{2ik}{a(t_0)H_0}}$$



Astro2020 `Scratches from the Past'; Beutler Biagetti Green Slosar Wallisch '19

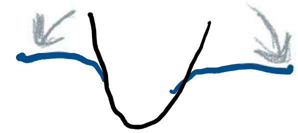
Leading to a template $P_\zeta(k) = P_{\zeta,0}(k)\,[1 + \delta P_\zeta(k)]$

$$\delta P_\zeta^{\rm lin}(k) = A_{\rm lin}^{\rm sin} \sin(\omega_{\rm lin}k) + A_{\rm lin}^{\rm cos} \cos(\omega_{\rm lin}k)$$
$$= A_{\rm lin} \sin(\omega_{\rm lin}k + \varphi_{\rm lin})\,,$$

Interactions with other fields generically affect the inflaton potential $V(\phi)$.

Even a super massive field flattens the slow roll potential as in the simple model:

$$V(\phi_L, \phi_H) = g^2\phi_L^2\phi_H^2 + m^2(\phi_H - \phi_0)^2 \quad \Rightarrow \quad V(\phi_L, \phi_{H,min}(\phi_L)) = \frac{g^2\phi_L^2}{g^2\phi_L^2 + m^2} m^2\phi_0^2$$

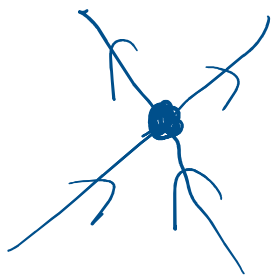


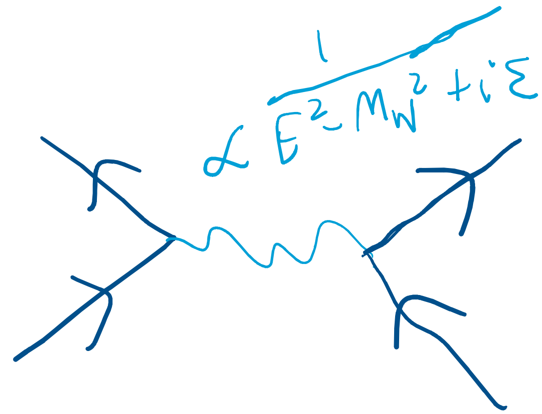
In general, the persistence and predictions of inflation depend on Planck-scale suppressed operators, even in minimal slow roll inflation:

$$\epsilon \equiv \frac{M_P V'}{V} \ll 1, \quad \eta \equiv M_P^2 \frac{V''}{V} \ll 1 \;\; \text{but} \;\; \Delta V = V_0(\phi)\frac{(\phi-\phi_0)^2}{M_P^2} \Rightarrow \eta \simeq 1$$

In string theory, as a candidate for quantum gravity (which gets black hole horizon entropy right, for example), one has a structured multidimensional landscape of heavy scalar fields and inflaton candidates. A particular type of feature signal is motivated by the genericity of axions.

As an analogy, recall Fermi Theory in advance of the discovery of the W and Z bosons and Higgs of the Standard Model





Effective coupling ~ $G_{Fermi}(Energy)^2$ UV-strong; UV completion: $G_{Fermi} \sim 1/M_W^2$

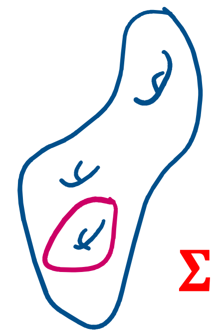
Weak interactions weakly coupled at EW scale ~ M_W.

Gravity: Effective coupling ~ $G_N(Energy)^2$ UV-strong; weakly coupled UV completion ?

- Might involve heavy fields similarly
- In string theory UV completion of gravity, there are massive degrees of freedom and weak coupling regimes. Also novel structures in the effective theory, some testable. Complex potential landscape (made of same stuff that accounts for horizon entropy).

Reduction of string theory to a 4d EFT yields generically heavy scalar fields parameterizing a generically negatively curved internal geometry, along with lighter **axions** from higher-dimensional higher-rank electromagnetic fields.

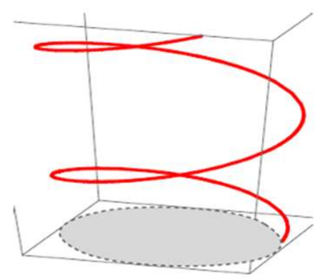
Potential field $\boldsymbol{A}$ plus topology leads to axion **a** $= \int_\Sigma \boldsymbol{A}$

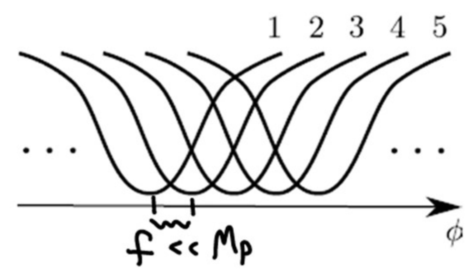


This axion couples to internal magnetic fields analogously to the low energy physics of superconductivity, where one has the gauge-invariant combination $\left(\partial_\mu A^{(0)} + A_\mu^{(1)}\right)^2$

Here we get $\left(dA^{(q)} + \boldsymbol{A}^{(p)} \wedge dA^{(q-p)}\right)^2$

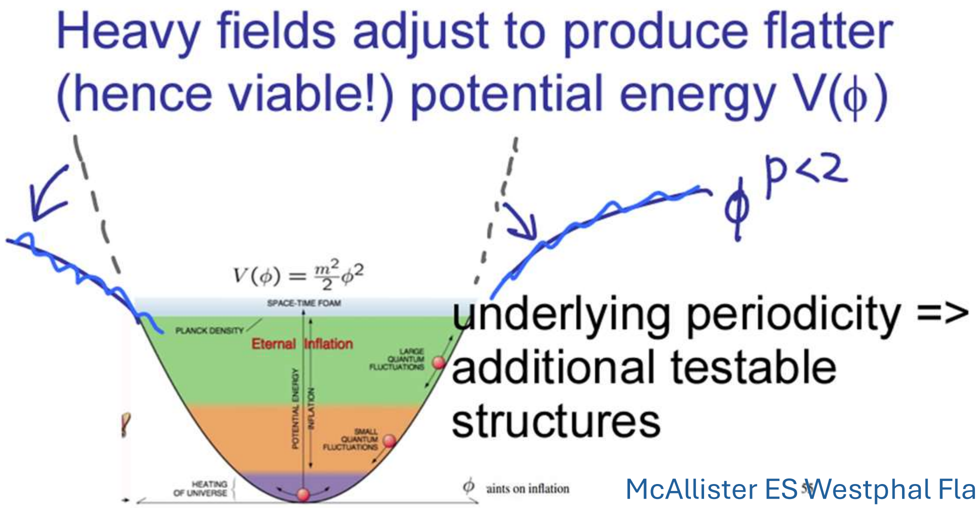
Quantized magnetic fluxes
$Vol(\Sigma) dA \sim Q$



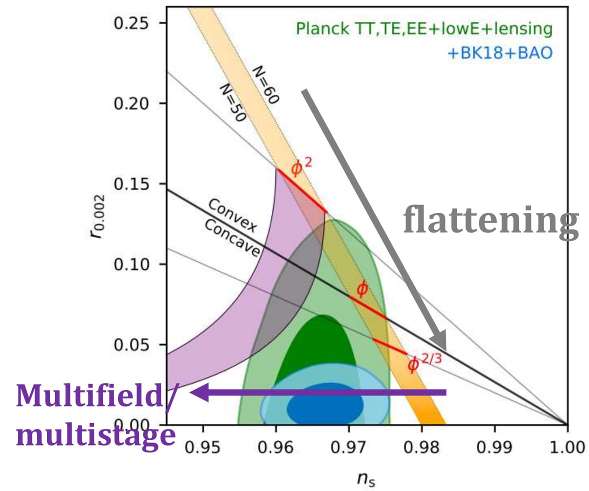


$(Q_1 + \boldsymbol{a}\, Q_2)^2 \times f(\{\phi_H\})$

ES Westphal'08 McAllister Flauger Wrase Kaloper Lawrence et al



McAllister ES Westphal Flauger
Pajer Xu Easther Peiris …



- From the EFT perspective, this is classified as a realization of a basic symmetry structure: a discrete shift symmetry.
  Wang Feng Li Chen Zhang ‘02, Pahud Kamionkowski Liddle’08; Behbahani Green Dymarsky Mirbabayi Senatore…
- A complication, however, is that the evolution of the massive fields also causes a drift in period.

Easther; Flauger ES McAllister Westphal

This case of axions in string theory, incorporated as a symmetry class in EFT, gives features approximately periodic in $\log(\frac{k}{k_*})$ due to the underlying periodicity in the inflaton ϕ,

$$\phi \sim \dot{\phi} t_{horizon-crossing} \sim \frac{\dot{\phi}}{H} \log\left(\frac{k_{horizon-crossing}}{a_* H}\right)$$

$$\cos\left(\frac{\phi}{f}\right) \Rightarrow \cos(\frac{\dot{\phi}}{fH} \log\left(\frac{k}{k_*}\right))$$

Examples include a modulated slow roll inflationary potential

$$V(\phi) = V_{slow}(\phi) + \Lambda_4 \cos(\frac{\phi}{f})$$

or periodic modulation of heavy particle masses (note non-derivative coupling)

$$m_{heavy}(\phi)^2 = \bar{m}^2 + g^2 f^2 cos\,(\frac{\phi}{f})$$

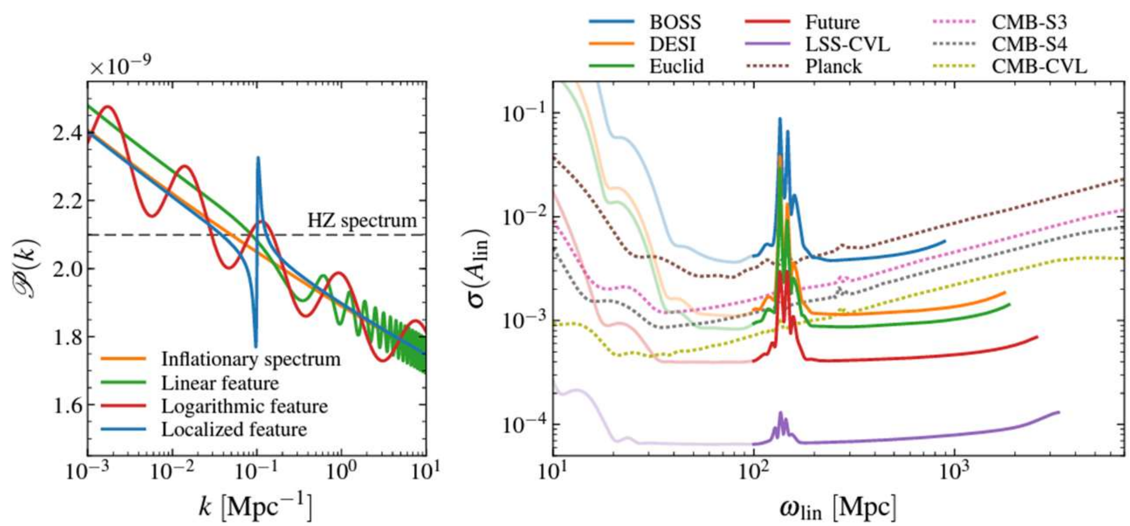
$$V(\phi) = V_{slow}(\phi) + \Lambda_4(\phi_H)\cos\left(\frac{\phi}{f}\right)$$

$$\ddot{\phi} + 3\,\mathrm{H}\dot{\phi} + \left(\frac{\mathrm{k}^2}{\mathrm{a}^2}\phi + \mathrm{V}'(\phi)\right) = 0$$

CMB & LSS power spectrum analysis e.g. with template

$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}\left(\frac{k}{k_\star}\right)^{n_s-1}\left(1+\delta n_s \cos\left[\Delta\varphi + \alpha\left(\ln(k/k_\star) + \sum_{n=1}^{2}\frac{c_n}{N_\star^n}\ln^{n+1}(k/k_\star)\right)\right]\right)$$

gives constraints $\delta n_s < O(10^{-2})$ for $\frac{f}{M_P} > O(10^{-3})$ (otherwise, weaker)



Astro2020 `Scratches from the Past'; Beutler Biagetti Green Slosar Wallisch '19

Easier to disentangle from ordinary nonlinear evolution than say f_{NL}^{eq}.

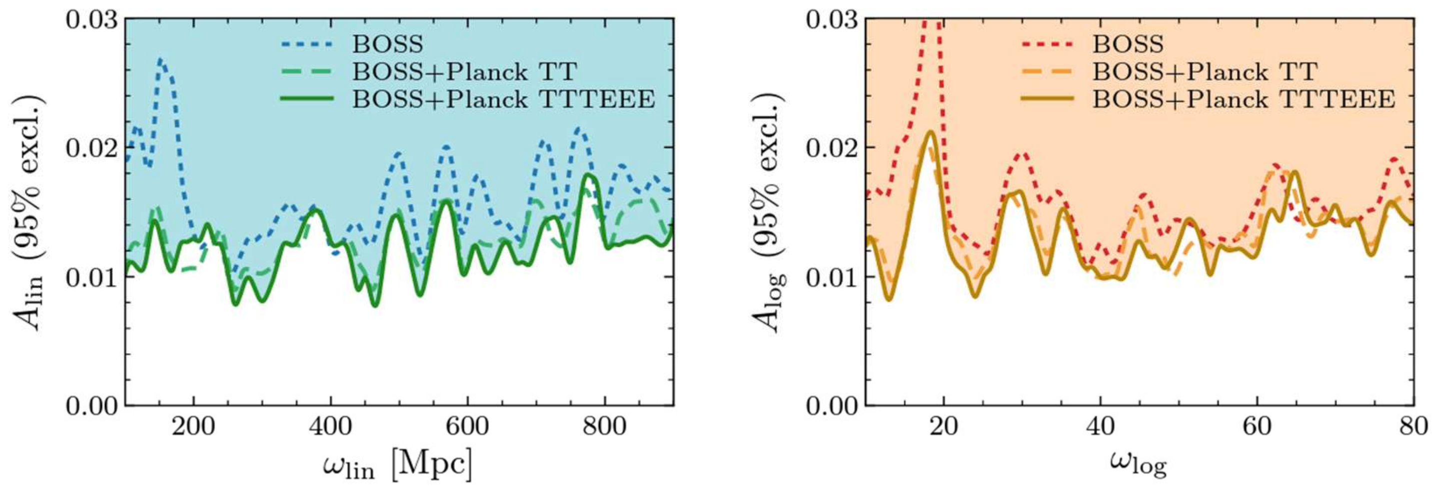
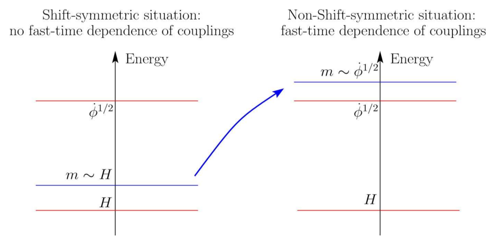


Figure 9: Joint BOSS and Planck upper limits at 95% c.l. on the linear (*left*) and logarithmic (*right*) feature amplitudes A_X, $X = \text{lin}, \text{log}$. The best current constraints come from a combination of BOSS DR12 and Planck 2015 TTTEEE data (solid). We also show the BOSS+Planck TT (dashed) results and include the BOSS-only bounds (dotted) for comparison.

Beutler Biagetti Green Slosar Wallisch '19: LSS (BOSS) alone already better than CMB alone. DESI?

A. Vasudevan, M. Ivanov, S. Sibiryakov, J. Lesgourgues; Chen Vlah White ...

Case with $m_{heavy}(\phi)^2 = \bar{m}^2 + g^2 f^2 cos\,(\frac{\phi}{f})$:



Production of particles with mass ~ 60 H can be detected/constrained. Optimal for the simplest shape (factorized in momentum space) is an N>3 point function (or resummed contributions from all N: position space features) Flauger, Mirbabayi, Senatore, ES;

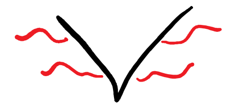
Munchmeyer, Smith: optimal estimator and (WMAP) analysis

Higher N-point function data analysis techniques for heavy particle production and WMAP results

Moritz Münchmeyer[1] and Kendrick M. Smith[1]

[1] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2L 2Y5, Canada*

We explore data analysis techniques for signatures from heavy particle production during inflation. Heavy particules can be produced by time dependent masses and couplings, which are ubiquitous in string theory. These localized excitations induce curvature perturbations with non-zero correlation functions at all orders. In particular, Ref. [1] has shown that the signal-to-noise as a function of the order N of the correlation function can peak for N of order $\mathcal{O}(1)$ to $\mathcal{O}(100)$ for an interesting space of models. As previous non-Gaussianity analyses have focused on $N = \{3, 4\}$, in principle this provides an unexplored data analysis window with new discovery potential. We derive estimators for arbitrary N-point functions in this model and discuss their properties and covariances. To lowest order, the heavy particle production phenomenology reduces to a classical Poisson process, which can be implemented as a search for spherically symmetric profiles in the curvature perturbations. We explicitly show how to recover this result from the N-point functions and their estimators. Our focus in this paper is on method development, but we provide an initial data analysis using WMAP data, which illustrates the particularities of higher N-point function searches.



$$\hat{h}(k\eta_n) = \int_{\eta_n}^{0} \frac{d\eta'}{\eta'} (\sin k\eta' - k\eta' \cos(k\eta')) \frac{\delta}{\delta\phi} m_\chi(\phi_0(\eta'))$$

$$\langle \delta\phi_{\mathbf{k}_1} \ldots \delta\phi_{\mathbf{k}_N} \rangle \sim$$

$$(2\pi)^3 \delta \left(\sum \mathbf{k}_i\right) \frac{\bar{n}_\chi}{H^3} H^{N+3} \sum_n (H\eta_n)^{-3} \prod_{i=1}^{N} \frac{\hat{h}(k_i\eta_n)}{k_i^3}$$

$$\hat{h}_b(k\eta_n) \sim c_b \sqrt{\frac{\omega}{H}} \cos\left(\frac{\omega}{H} \log(-k\eta_n) + \gamma\right)$$

$$\frac{(S/N)_3}{(S/N)_2} \sim c_b \sqrt{\alpha} = c_b \sqrt{\frac{\omega}{H}}$$

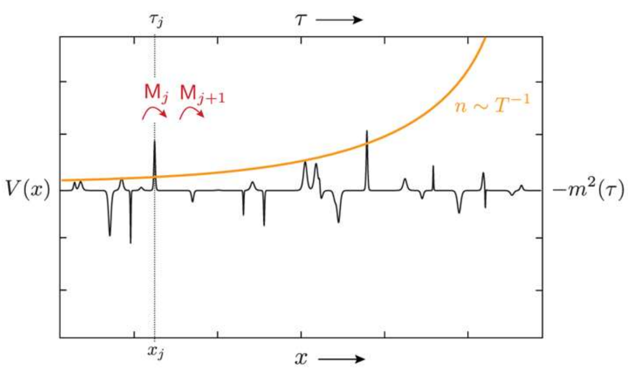
Predicts features in the Non-Gaussianity not captured by the scale-invariant templates and not captured by 2-4 point functions.

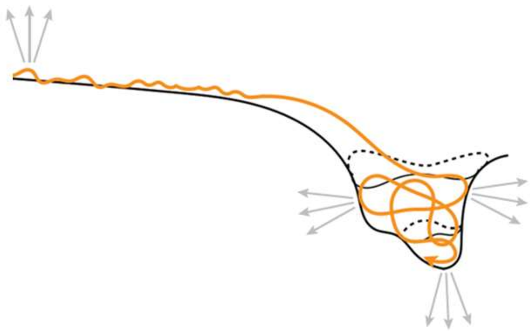
LSS analysis? Philcox et al?

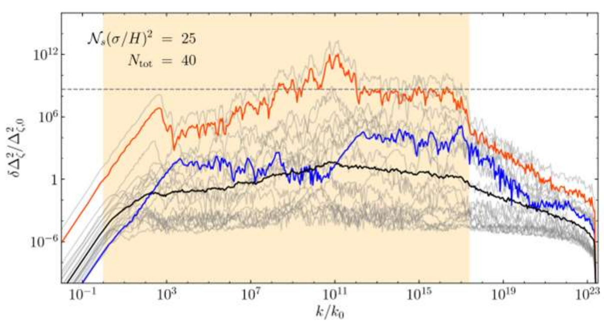
A complementary possibility motivated by the complexity of high dimensional landscapes is to consider a random, rather than regular, distribution of events.

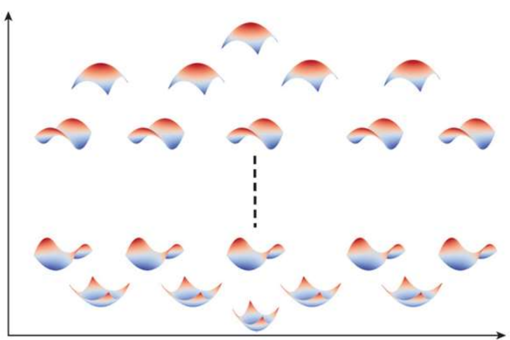
Amin, Baumann, Green et al;

Intermittent non-Gaussianity Bond, Braden et al









The mass distribution is on average scale invariant, but the dynamics breaks scale invariance through amplification of repeated production events.

Recent activity

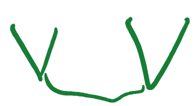
- Perturbative structure (amplitudes, bootstrap)

Arkani-Hamed, Maldacena, Baumann, Lee et al, Gorbenko et al, Pajer et al, Joyce et al,

e.g.

Proofs of bulk unitarity at level of late-time correlators

Elegant formulas for correlators assuming derivative couplings or at least discrete shift symmetry

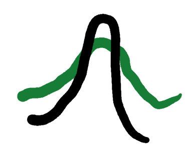


Quasi-single-field with derivative couplings also yields log oscillations, with small amplitude [Chen/Wang, Baumann/Green, Arkani-Hamed Maldacena…]

Minimality/symmetry of couplings

- Non-perturbative Non-Gaussianity: tails of the distribution

Bond et al
Flauger et al '16
Chen Palma Riquelme Hitschfeld
Sypsas '18
Baumgart/Sundrum '19
Panagopoulos ES '19,
Gorbenko-Senatore '19,
Mirbabayi '19
Creminelli et al '21, '23
Cohen Green Premkumar '21



e.g.

Stochastic Inflation from QFT

Calculations of shape of tails as a function of $\zeta \gg 1$ in various models

Massive particle production: highest S/N beyond 3pf, sensitivity to mass >> Hubble.

Hyperbolic field space $Exp(-\log(\zeta)^2)$ heavy non-Gaussian tail.

LSS: Philcox Slepian Hou Warner Eisenstein (Npf), Chudaykin Ivanov Kaurov Sibiryakov (counts in cells)

Genericity of couplings

Feature searches offer the potential to test various classes of primordial dynamics.

- Linear and Logarithmic oscillations

- More general templates can be motivated by notions of random landscapes with emergent scale dependence, non-Gaussian tails, …

These have the advantage of being easier to disentangle from ordinary nonlinear evolution than scale-invariant templates (also of interest).

The amplitude is model-dependent. We don't **currently** have a sharp threshold for them similar to the Planck field range for r or the scale of equilateral NG discriminating slow roll from interacting inflation models.