Title: Bispectrum signatures of modifications to the inflationary vacuum

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Abstract: Modifications of the initial-state of the inflaton field can induce a departure from Gaussianity and leave a testable imprint on the higher order correlations of the CMB and large scale structures in the Universe. I will discuss general vacuum state modifications in the case of a canonical single-field action, after adding a dimension 8 higher order derivative term, and DBI models of inflation. Observed bounds on local and equilateral non-Gaussianities, even though they correspond to template shapes that are far from optimal, can lead to constraints that are already competing to those derived from the power spectrum alone, due to enhancement effects. We emphasize that the construction and application of especially adapted templates could lead to significant improvements in the CMB bispectrum constraints on modified initial states.

Bispectrum signatures of modifications to the inflationary vacuum

Jan Pieter van der Schaar
KdVI/ITP, University of Amsterdam

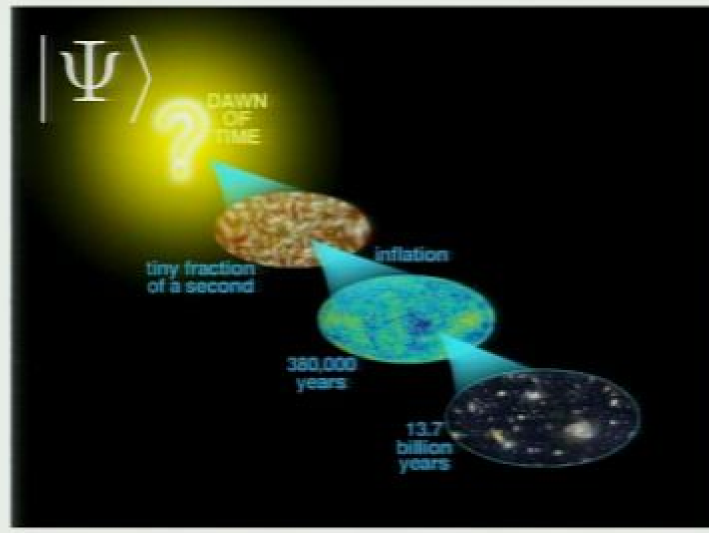
Based on arXiv:0901.4044 [hep-th] with Daan Meerburg and Pier-Stefano Corasaniti (and work in progress)

EFT's in Inflation, May 20, Perimeter Institute

Introduction

One cannot exclude
vacuum state corrections

- EFT: irrelevant operators
- Physics before inflation



Constraints:

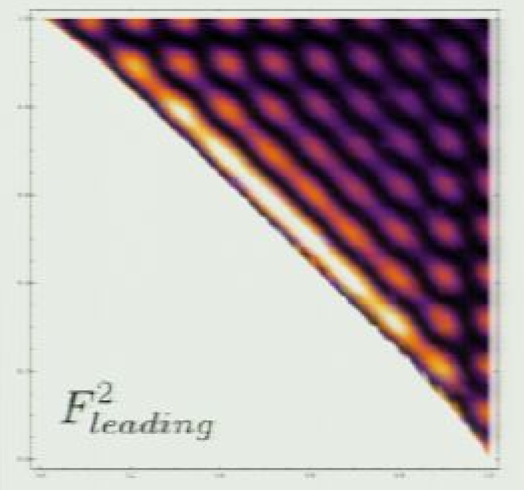
- Backreaction
- Power spectrum

Pragmatic, pheno, EFT point of view:
Allow small corrections to BD at scales
below some cut-off Λ and study signatures

$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle^{\mathrm{nBD}}$

The executive summary

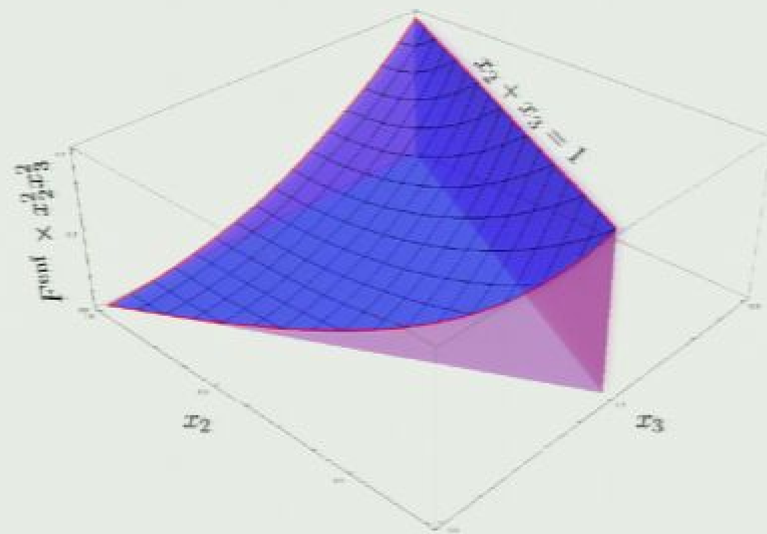
Bispectrum extremely sensitive to BD modifications



- Enhancement factors $|k_1\eta_0| = \frac{(|k_1/a_0|)}{H} = M/H$
- Typically localized
- Available templates inadequate $f_{\rm NL}^{\rm local}$ and $f_{\rm NL}^{\rm equil}$
- Oscillatory effects

Outline

- Bispectrum preliminaries
- Standard slow-roll calculation
- Higher derivative correction
- DBI inflation (preliminary)
- Conclusions



Preliminaries

$$\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_2}\rangle = A\cdot(2\pi)^3\delta\left(\sum_i \vec{k}_i\right)F(\vec{k}_1,\vec{k}_2,\vec{k}_3),$$

$$\hat{A} = \frac{\sum_{\vec{k}_i}\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_2}F(\vec{k}_1,\vec{k}_2,\vec{k}_3)/\left(\sigma^2_{\vec{k}_1}\sigma^2_{\vec{k}_2}\sigma^2_{\vec{k}_3}\right)}{\sum_{\vec{k}_i}F^2(\vec{k}_1,\vec{k}_2,\vec{k}_3)/\left(\sigma^2_{\vec{k}_1}\sigma^2_{\vec{k}_2}\sigma^2_{\vec{k}_3}\right)}.$$

"3d best estimator"

Perfect template: O = A |F|

$$F_X\cdot F_Y = \sum_{\vec{k}_i}\frac{F_X(\vec{k}_1,\vec{k}_2,\vec{k}_3)F_Y(\vec{k}_1,\vec{k}_2,\vec{k}_3)}{\sigma^2_{k_1}\sigma^2_{k_2}\sigma^2_{k_3}}.$$

$$\mathrm{Cos}(F_X,F_Y) \equiv \frac{F_X\cdot F_Y}{(F_X\cdot F_X)^{1/2}(F_Y\cdot F_Y)^{1/2}},$$

$$\Delta_F = \frac{F_Y\cdot F_X}{(F_X\cdot F_X)} = \mathrm{Cos}(F_X,F_Y)\left(\frac{F_Y\cdot F_Y}{F_X\cdot F_X}\right)^{1/2}.$$

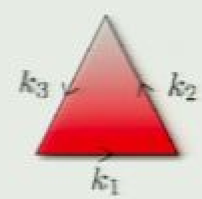
Scale invariance: $F \propto k_1^{-6}\tilde{F}(x_2,x_3)$

$$F_X\cdot F_Y \propto \int dx_2dx_3F_X(x_2,x_3)F_Y(x_2,x_3)x_2^4x_3^4.$$

$$x_2 \equiv k_2/k_1 \text{ and } x_3 \equiv k_3/k_1$$

$$k_1 \geq k_2 \geq k_1,\text{ giving } x_2 \leq 1 \quad x_3 \leq 1$$

$$1 - x_2 \leq x_3 \leq 1$$



Fudge factor: leakage of theoretical signal F_y into (observational) template F_x

D. Babich, P. Creminelli and M. Zaldarriaga, [arXiv:astro-ph/0405356]

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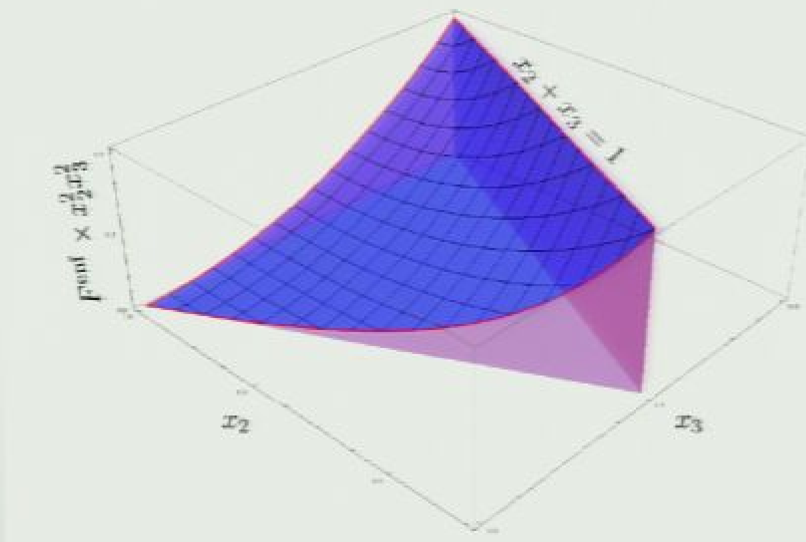

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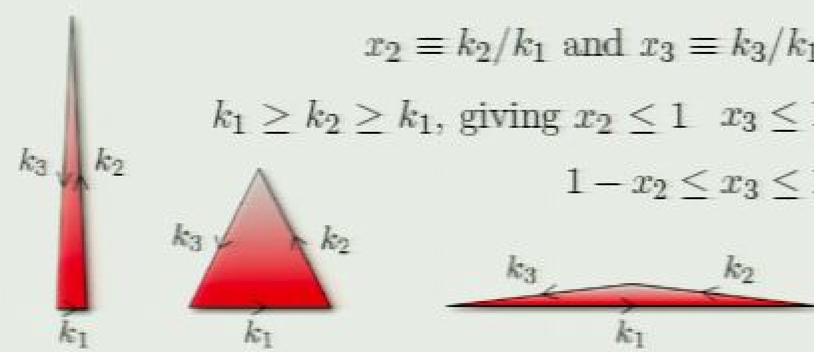

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Redefined amplitudes

$$A = (2\pi)^4 \left(-\frac{3}{5} f_{\rm NL}^{\rm local}\right) \frac{\Delta_\Phi^2}{k_1^6}, \qquad A = (2\pi)^4 \left(-\frac{3}{5} f_{\rm NL}^{\rm equil}\right) \frac{\Delta_\Phi^2}{k_1^6}.$$

$$F^{\rm equil}(x_2, x_3) = 6\left[-\frac{1}{x_2^3} - \frac{1}{x_3^3} - \frac{1}{x_2^3 x_3^3} - \frac{2}{x_2^2 x_3^2} + \left(\frac{1}{x_2^2 x_3^3} + 5 \text{ perm}\right)\right]$$

Factorizable templates

$$F^{\rm local}(x_2, x_3) = 2\left(\frac{1}{x_2^3} + \frac{1}{x_3^3} + \frac{1}{x_2^3 x_3^3}\right)$$

WMAP 5-yr results:

$$-9 < f_{\rm NL}^{\rm local} < 111$$
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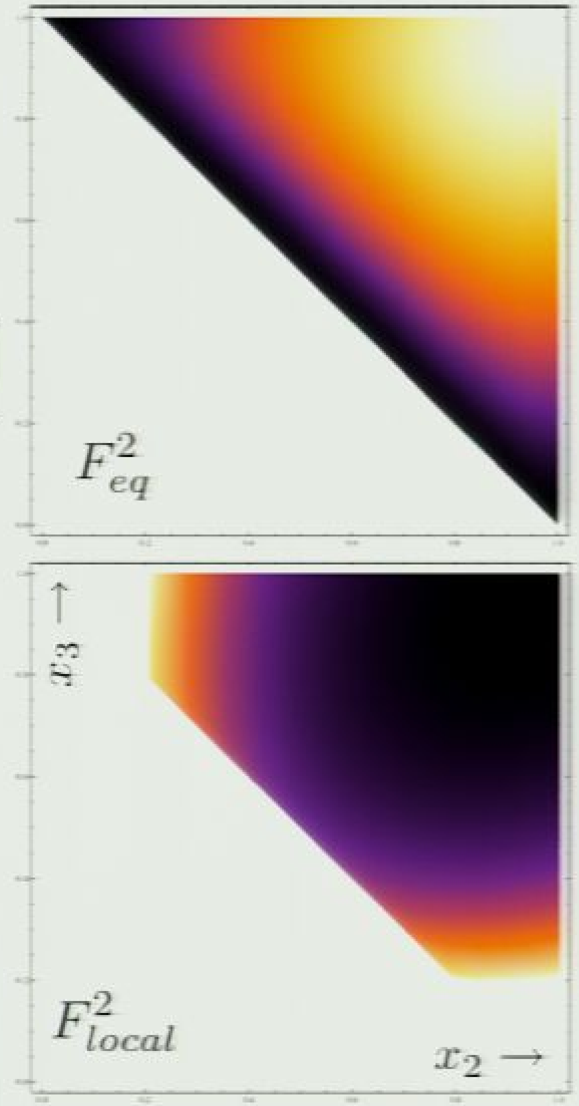

Slow-roll inflation

$$\langle\psi(\eta)|\zeta_{k_1}(\eta)\zeta_{k_2}(\eta)\zeta_{k_3}(\eta)|\psi(\eta)\rangle = \cancel{\langle\psi(\eta_0)|\zeta_{k_1}(\eta)\zeta_{k_2}(\eta)\zeta_{k_3}(\eta)|\psi(\eta_0)\rangle}$$

$|\psi(\eta_0)\rangle$: Gaussian

$$-i\int_{\eta_0}^{\eta} d\eta' \langle\psi(\eta_0)|[\zeta_{k_1}(\eta)\zeta_{k_2}(\eta)\zeta_{k_3}(\eta), H_I(\eta')]|\psi(\eta_0)\rangle + \mathcal{O}(H_I^2)$$

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$$k\,\eta_0(k) \equiv M/H$$

New Physics Hypersurface approach

$$v_k = \alpha_k u_k^{\mathrm{BD}} + \beta_k u_k^{\mathrm{BD}*}$$

First order in β

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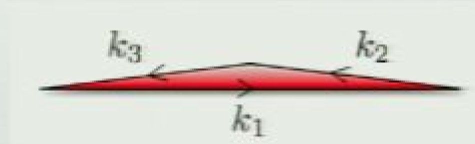
$$k_t = k_1+k_2+k_3 \quad \tilde{k}_j = k_t - 2k_j.$$

Maximizes in enfolded/collinear limit, $x_2 + x_3 = 1$



R. Holman and A. J. Tolley, [arXiv:0710.1302 [hep-th]]

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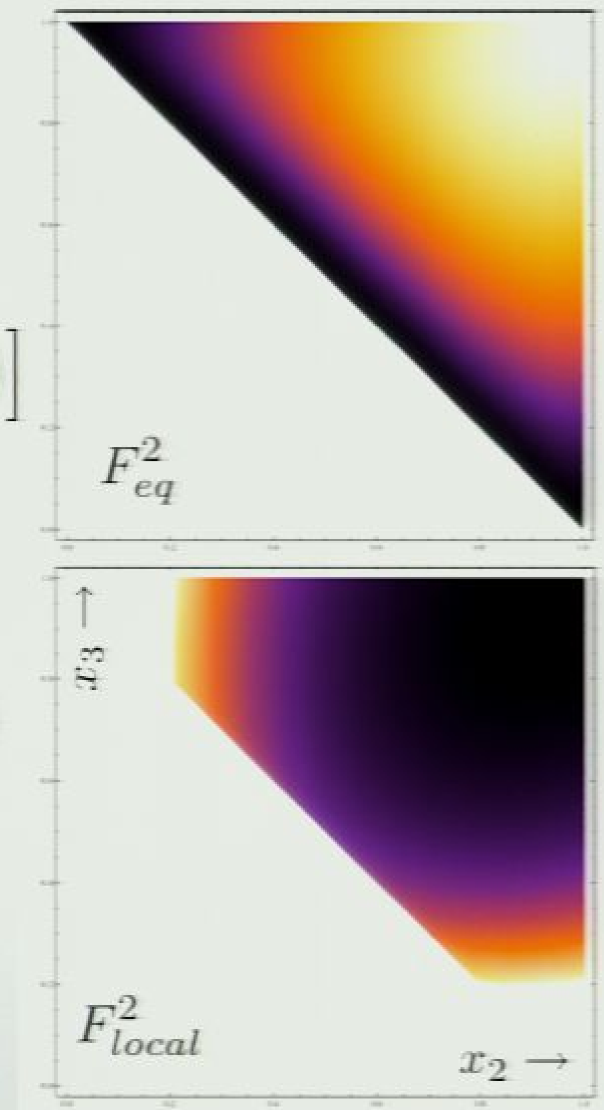

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Determine leakage into local and equilateral to put constraint

Or: develop enfolded template and compare to data

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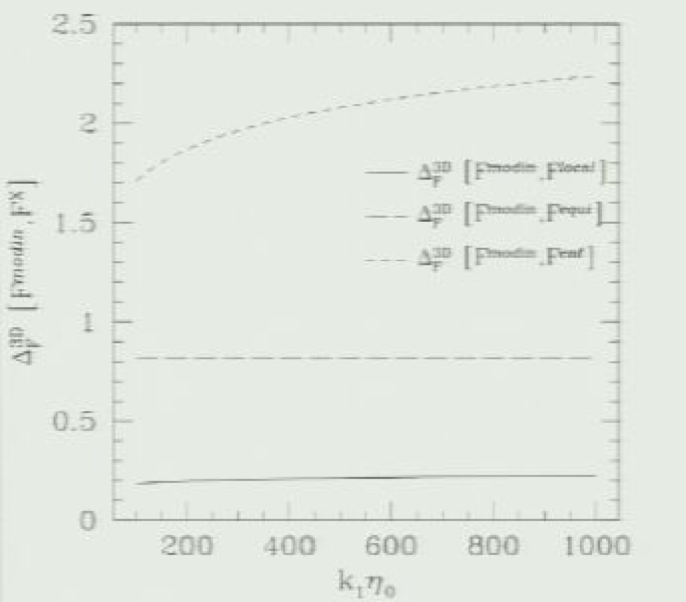
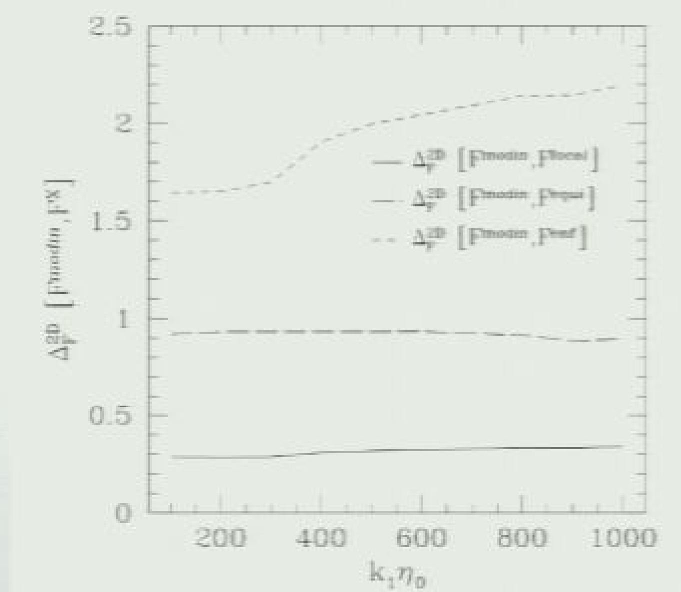


2d CMB sphere

CMBFAST, flat space limit



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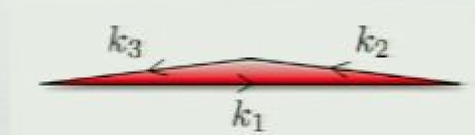

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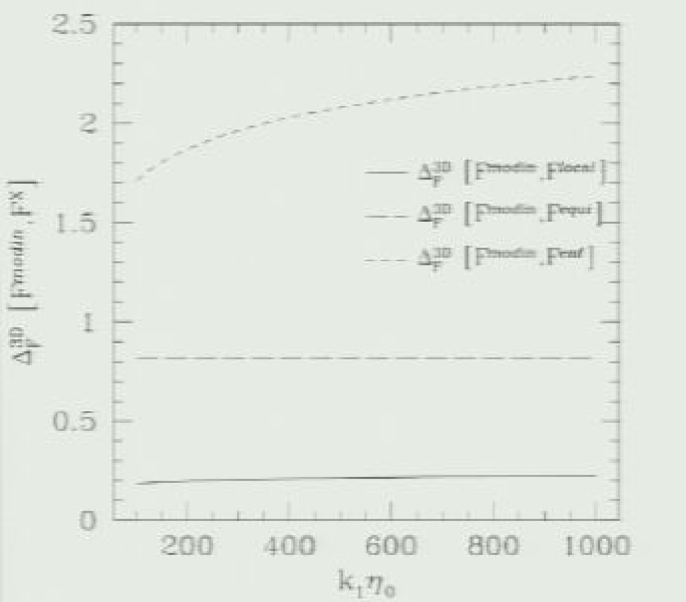

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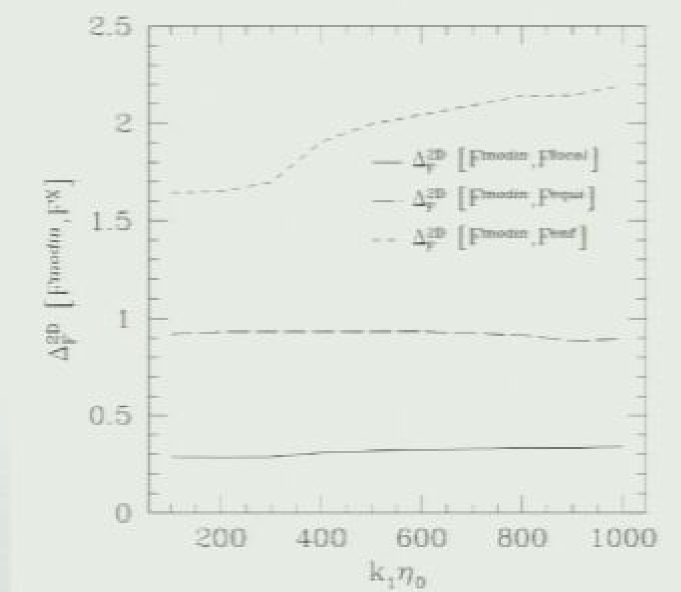

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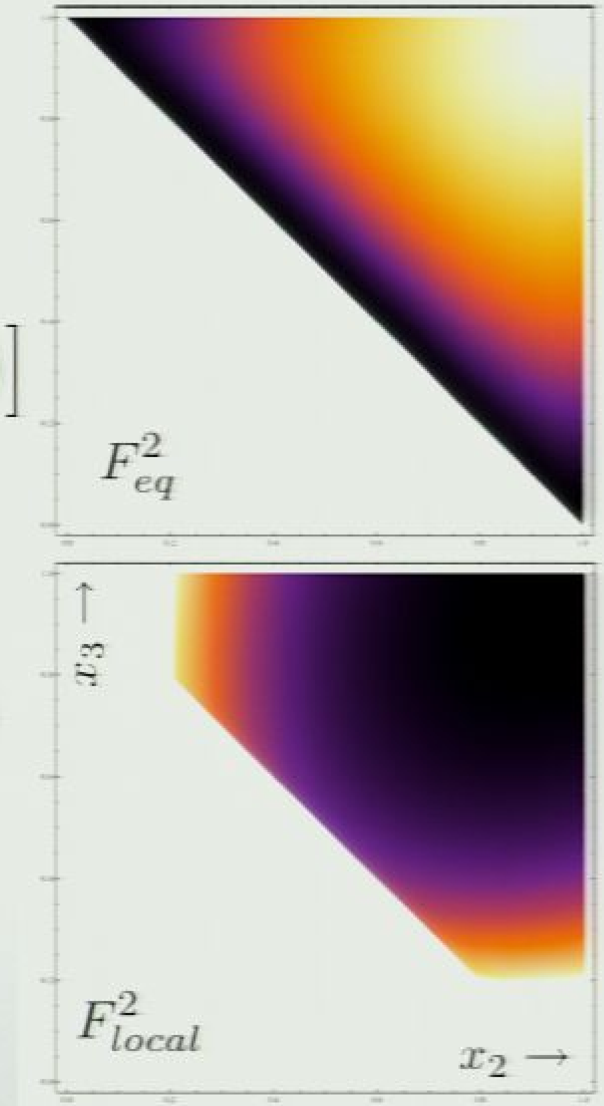

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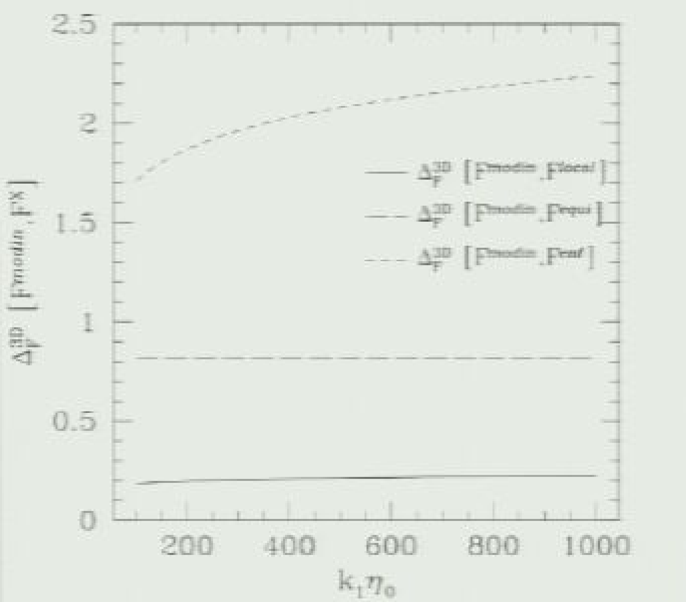

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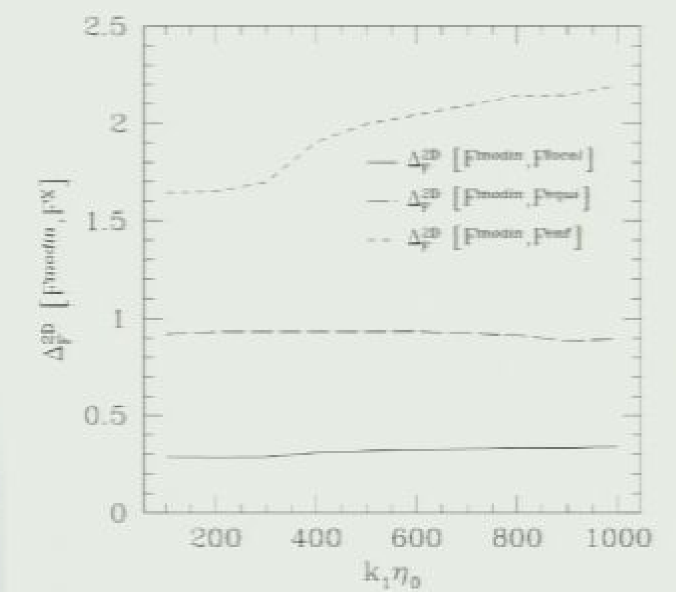

Slow-roll inflation

$$\langle\psi(\eta)|\zeta_{k_1}(\eta)\zeta_{k_2}(\eta)\zeta_{k_3}(\eta)|\psi(\eta)\rangle = \cancel{\langle\psi(\eta_0)|\zeta_{k_1}(\eta)\zeta_{k_2}(\eta)\zeta_{k_3}(\eta)|\psi(\eta_0)\rangle}$$

$|\psi(\eta_0)\rangle$: Gaussian

$$-i\int_{\eta_0}^{\eta} d\eta' \langle\psi(\eta_0)|[\zeta_{k_1}(\eta)\zeta_{k_2}(\eta)\zeta_{k_3}(\eta), H_I(\eta')]|\psi(\eta_0)\rangle + \mathcal{O}(H_I^2)$$

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$$k\,\eta_0(k) \equiv M/H$$

New Physics Hypersurface approach

$$v_k = \alpha_k u_k^{\mathrm{BD}} + \beta_k u_k^{\mathrm{BD}*}$$

First order in β

$$\mathrm{Re}\beta_k \sim \mathrm{Im}\beta_k \sim |\beta_k|$$

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$$\langle\zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle^{\mathrm{nBD}} = (2\pi)^3\delta^{(3)}\left(\sum\vec{k}_i\right)\frac{1}{M_p^2}\frac{4}{\prod(2k_i^3)}\frac{H^6}{\dot\phi^2}\sum_j\frac{3k_1^2k_2^2k_3^2}{k_j^2\tilde{k}_j}\mathcal{R}e(\beta_{k_j})\left(\cos(\tilde{k}_j\eta_0)-1\right)$$

$$k_t = k_1+k_2+k_3 \quad \tilde{k}_j = k_t - 2k_j.$$

Maximizes in enfolded/collinear limit, $x_2 + x_3 = 1$

R. Holman and A. J. Tolley, [arXiv:0710.1302 [hep-th]]

Redefined amplitudes

$$A = (2\pi)^4 \left(-\frac{3}{5} f_{\rm NL}^{\rm local}\right) \frac{\Delta_\Phi^2}{k_1^6}, \qquad A = (2\pi)^4 \left(-\frac{3}{5} f_{\rm NL}^{\rm equil}\right) \frac{\Delta_\Phi^2}{k_1^6}.$$

$$F^{\rm equil}(x_2, x_3) = 6\left[-\frac{1}{x_2^3} - \frac{1}{x_3^3} - \frac{1}{x_2^3 x_3^3} - \frac{2}{x_2^2 x_3^2} + \left(\frac{1}{x_2 x_3^3} + 5 \text{ perm}\right)\right]$$

Factorizable templates

$$F^{\rm local}(x_2, x_3) = 2\left(\frac{1}{x_2^3} + \frac{1}{x_3^3} + \frac{1}{x_2^3 x_3^3}\right)$$

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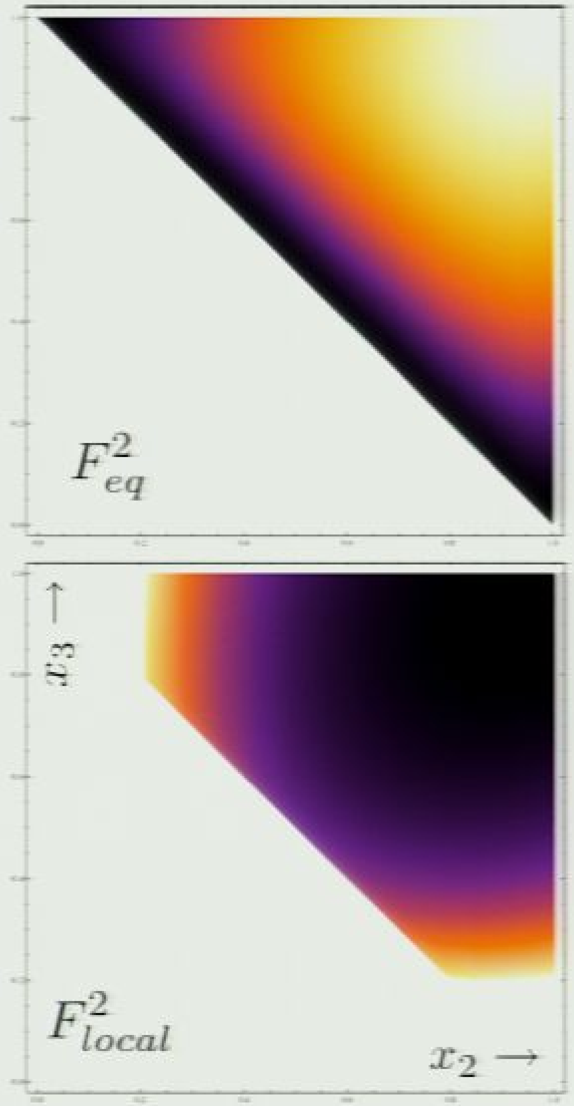

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$$A = (2\pi)^4 (3\epsilon|\beta|) \frac{\Delta_\Phi^2}{k_1^6}, \qquad F^{\rm modin}(k_1\eta_0, x_2, x_3) = \frac{1}{x_2 x_3}\left\{ \text{subleading} + \frac{1-\cos[k_1\eta_0(-1+x_2+x_3)]}{(-1+x_2+x_3)} \right\}$$

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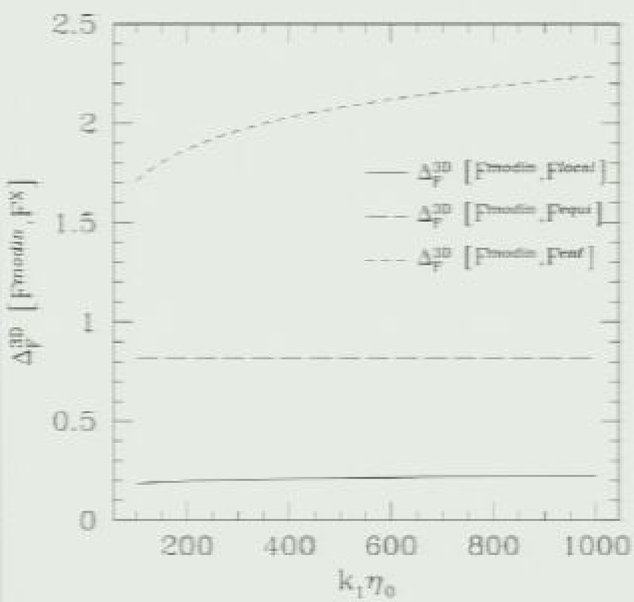

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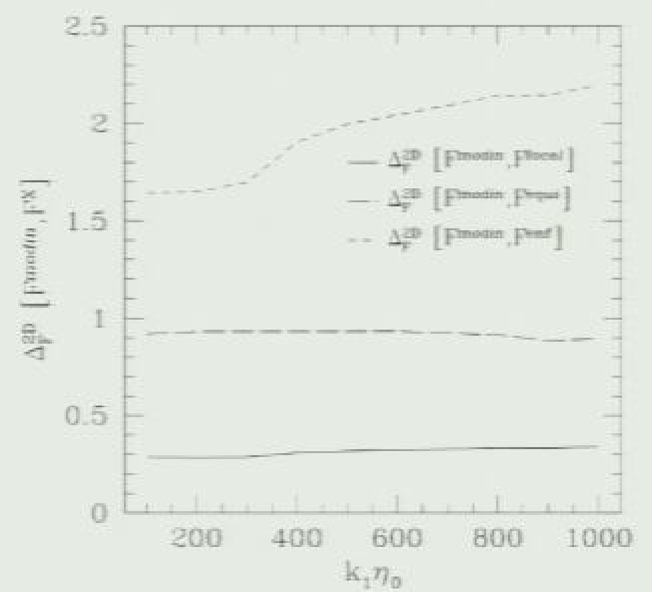

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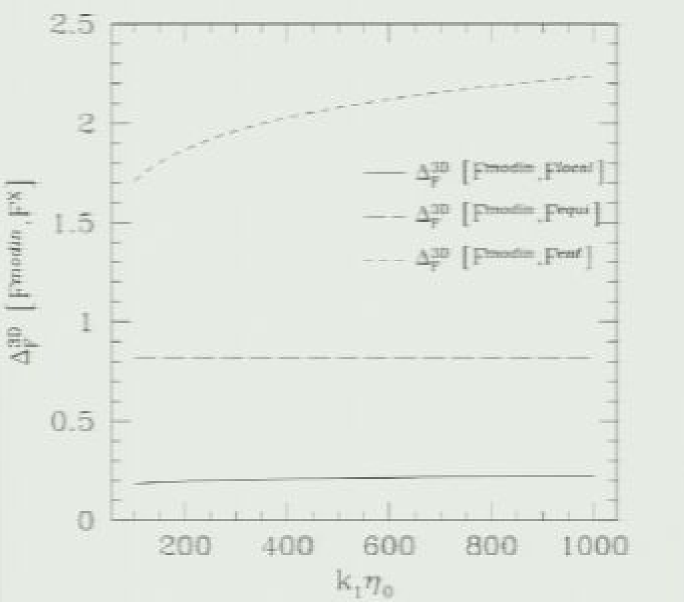

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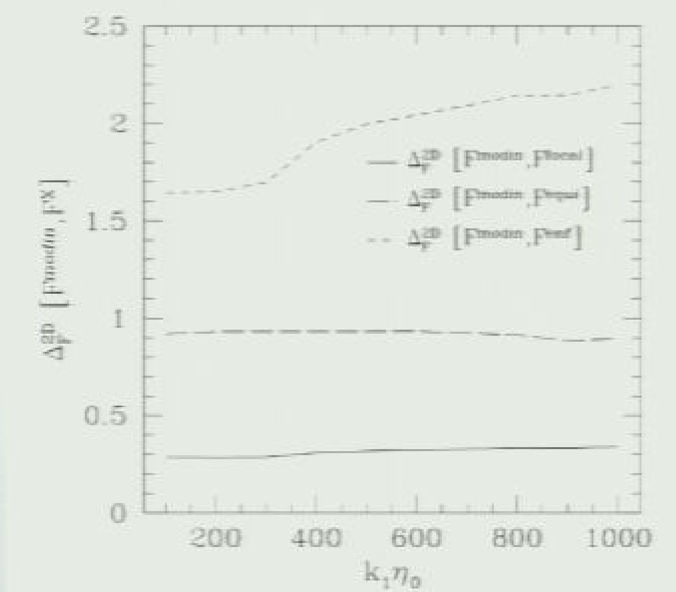

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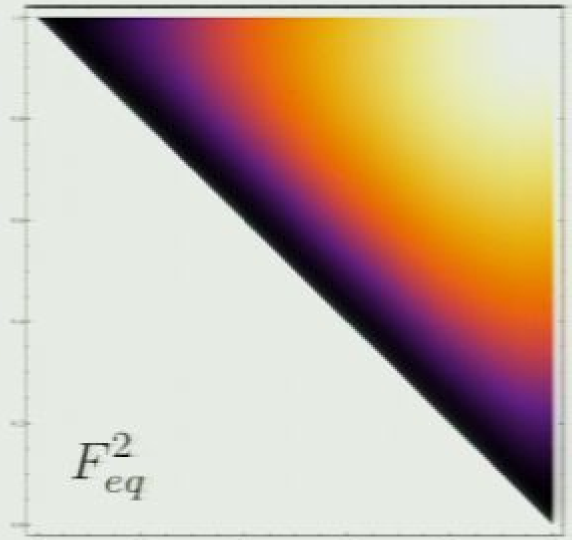

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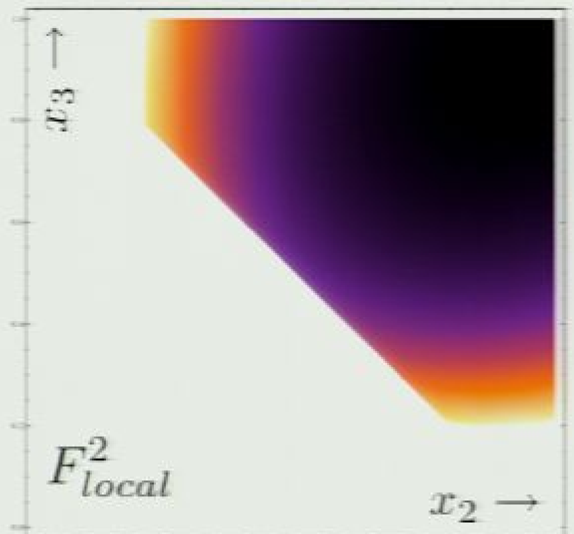

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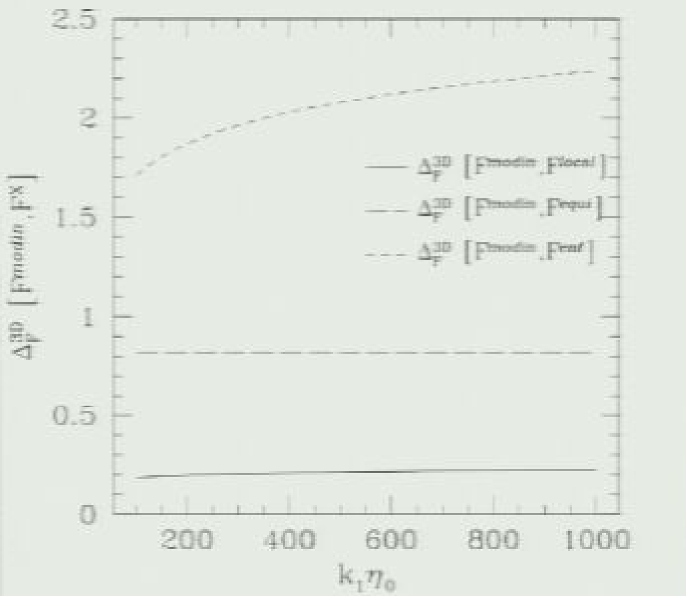

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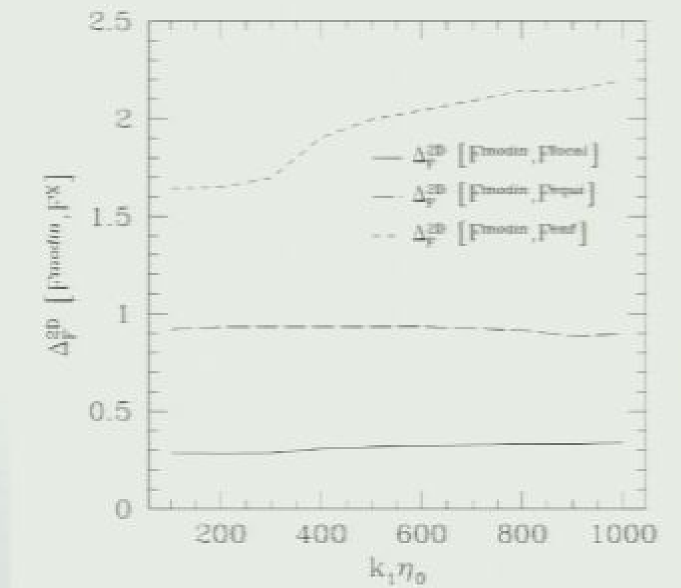

Adding a higher derivative correction

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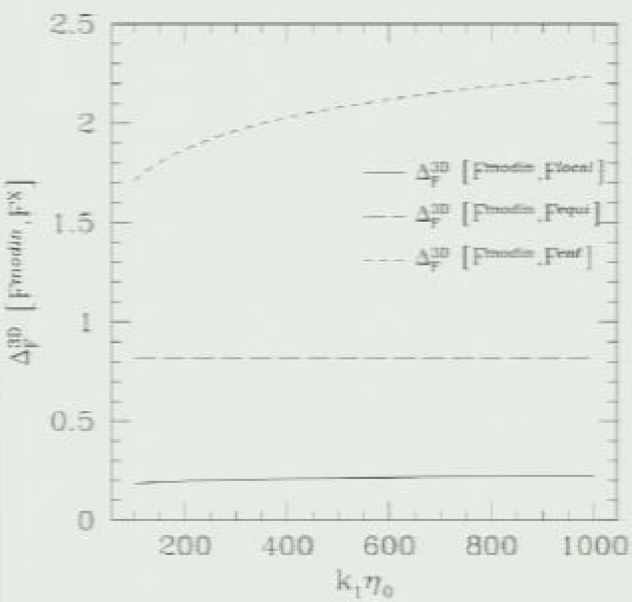

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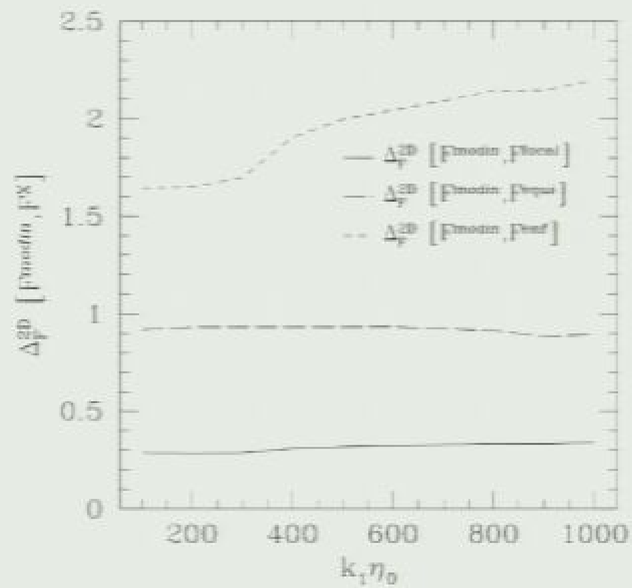

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- Sign difference reduces fudge factor
- Similar expression for equilateral
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$f_{\rm NL}^{\rm equil} \propto \left(\frac{M_{Pl}^2 H^2}{M^4}\right)\lambda\epsilon \lesssim 1$

$\beta\,(M/H)$ enhanced $\lesssim 10$

CMB bispectrum constraint

$$|\Delta f_{\rm NL}^{\rm local}| = \frac{5}{6}\epsilon|\beta|\left(\frac{M_{Pl}^2 H^2}{M^4}\right)|\Delta_F^{\rm 2D}|$$

Assume M/H=10^3 → $|\Delta_F^{\rm 2D}| \approx 6000$

ϵ can be replaced with $\frac{10^{10}}{8\pi^2}\frac{H^2}{M_{Pl}^2}$

$f_{\rm NL}^{\rm local} < 111$ → $4\cdot 10^3\,|\beta| < 111$

Comparable with powerspectrum constraint
Note: optimal template would deliver another factor of M/H

D. Meerburg, JPvdS, P.S. Corasaniti, arXiv:0901.4044 [hep-th]

Projections

All terms contribute, since the overall enhanced term changes sign

$$A = (2\pi)^4 \left(\frac{M_{Pl}^2 H^2}{M^4}\right) \frac{1}{2}\lambda\epsilon\,|\beta|\,\frac{\Delta_\Phi^2}{k_1^6}$$

$$\Delta_F\left[F^{\mathrm{HDmodin}}, F^{\mathrm{local}}\right] \approx 5.7\cdot 10^{-3}|k_1\eta_0|\,(-72+10\log|k_1\eta_0|)$$

- Neglected oscillatory contributions
- Sign difference reduces fudge factor
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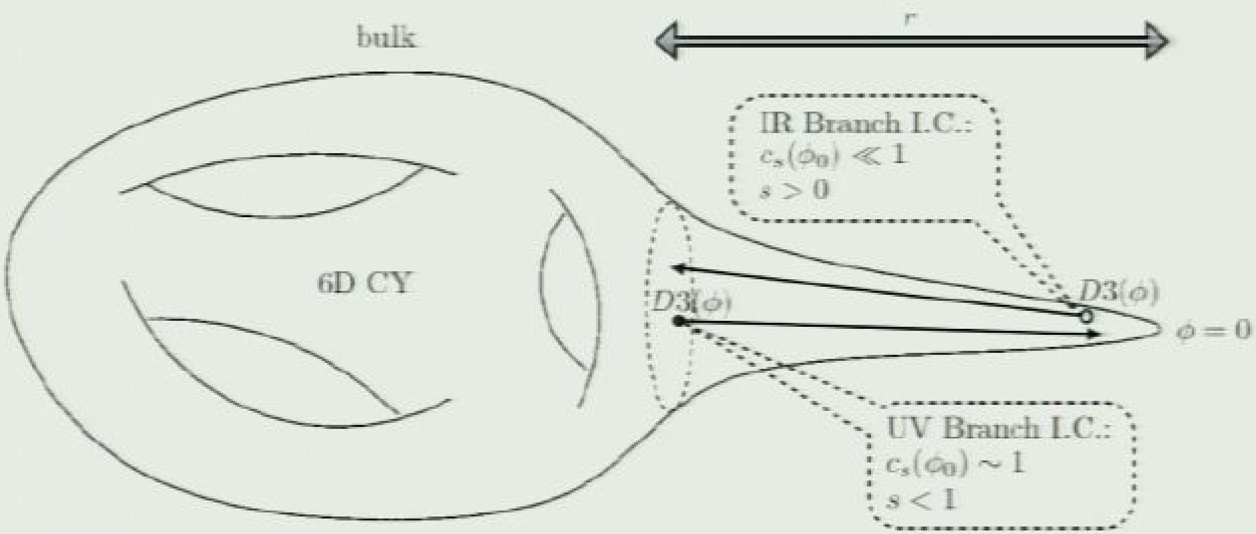
DBI inflationary vacuum

UV models : c_s decreasing
IR models: c_s increasing



BD state issues

- IR: shrinking sound horizon
- UV: upper limit on total number of e-folds from f_{NL}
- Strongly scale dependent scenarios

W. Kinney, K. Tzirakis, arXiv:0712.2043 [astro-ph]

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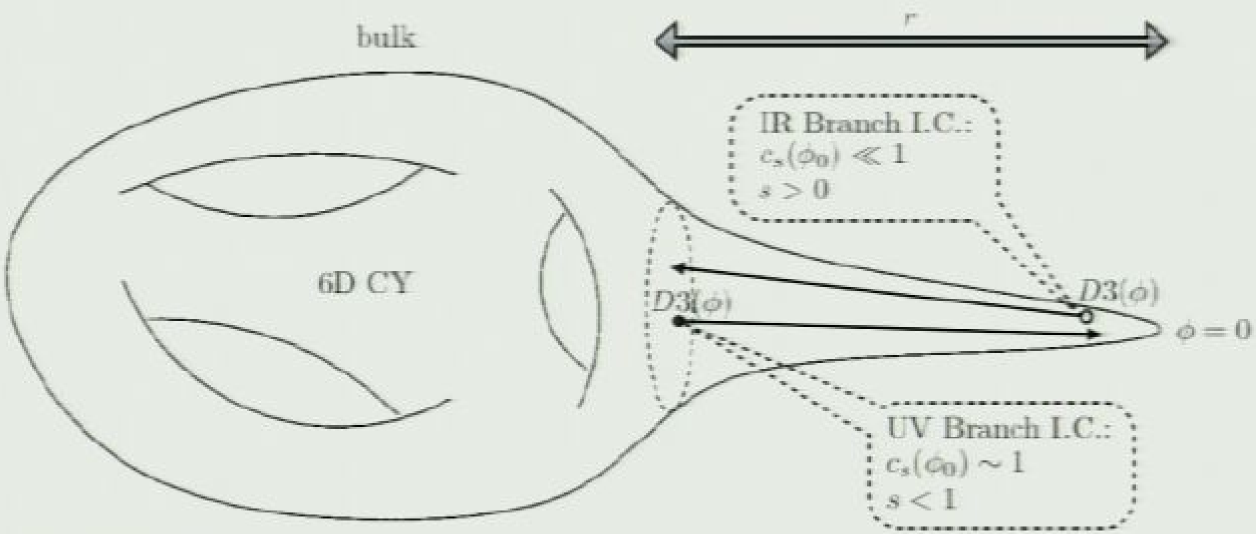

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DBI bispectrum

$$k_t = k_1 + k_2 + k_3$$

$$\tilde{k}_j = k_t - 2k_j.$$

$$\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle_{\text{nBD}(1)} = -\frac{1}{4}(2\pi)^3 \frac{H^4 \mathcal{R}e[\beta]}{\epsilon^2 c_s^4}(c_s^2 - 1 + \frac{2\lambda c_s^2}{\Sigma})\delta^{(3)}(\sum \vec{k}_i)\frac{1}{k_1 k_2 k_3}$$

$$\sum_j \left[\frac{c_s^2\eta_0^2}{2}\frac{\text{Cos}[\tilde{k}_j c_s \eta_0]}{\tilde{k}_j} - c_s\eta_0 \frac{\text{Sin}[\tilde{k}_j c_s\eta_0]}{\tilde{k}_j^2} + \frac{1-\text{Cos}[\tilde{k}_j c_s \eta_0]}{\tilde{k}_j^3}\right]$$

$$k_1 c_s \eta_0 \equiv M/H$$

- Leading terms
- Additional factor of localized enhancement!
- Speed of sound appearance
- Not singular (terms conspire)

Local contribution: $-\frac{5}{3}0.004|\beta|\left(\frac{M}{H}\right)^2\frac{1}{c_s^2}$ $\quad (c_s \ll 1)$

Preliminary, work in progress with Daan Meerburg and Mark Jackson

Conclusions/remarks

Nongaussianities are an excellent probe of (higher derivative) interactions and the initial state

- Assumed scale invariant NPH scenario
- Different analysis techniques necessary in a boundary effective field theory approach
- Produces scale dependent NGs (from scratch)
- Higher n-point functions