Learning about inflation from large scale structure

Sarah Shandera
Penn State University

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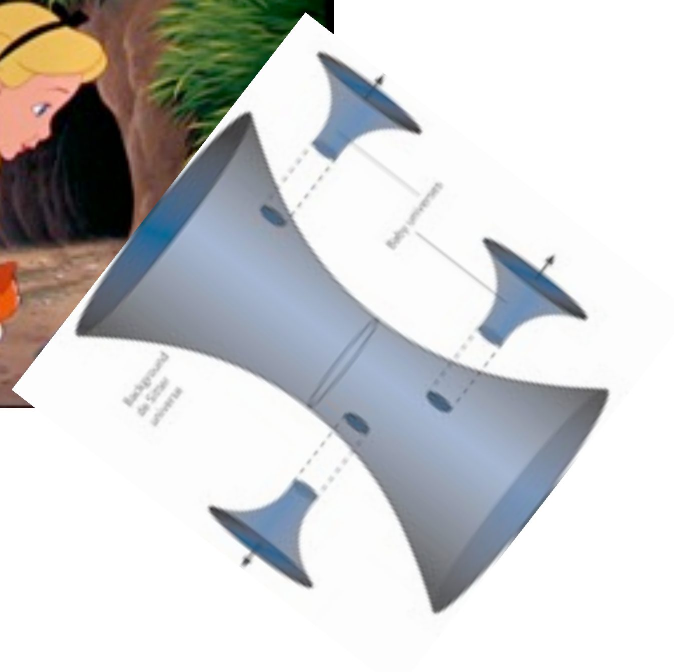
Better observations have theorists (re)asking:



(1) What particle physics is behind inflation?

(2) Is inflation right?

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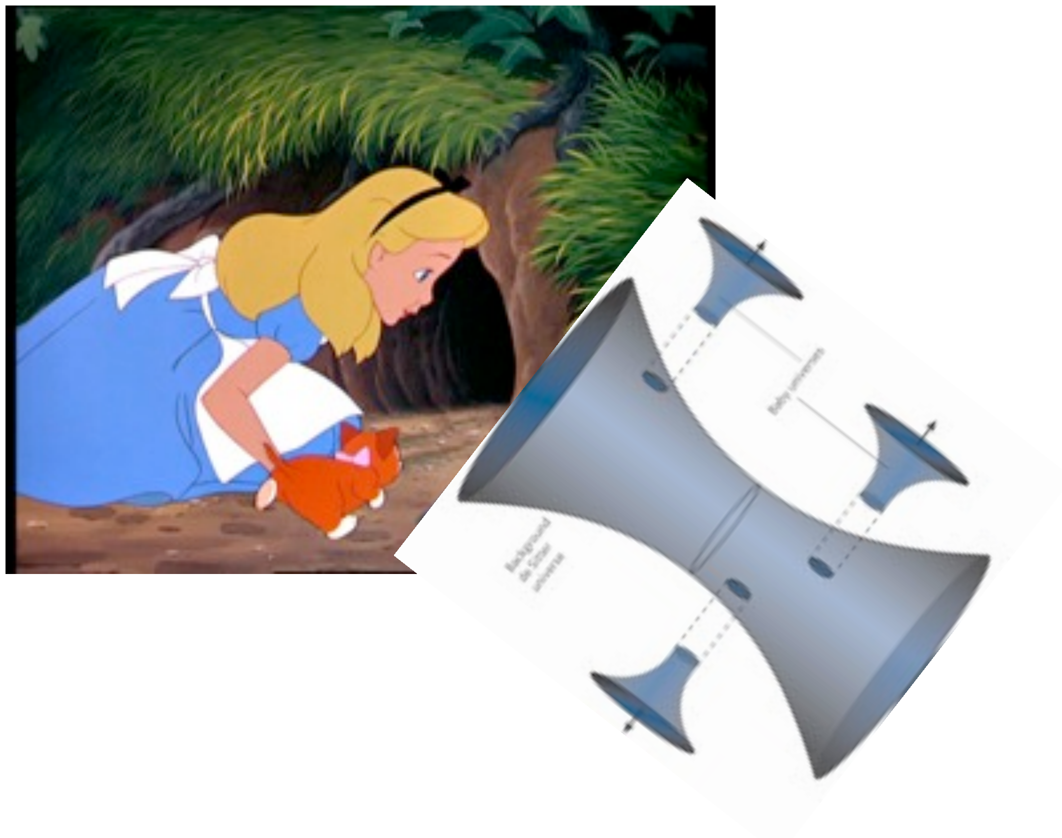

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Interactions
Non-Gaussianity

What has changed?

- Shift in consensus about what is ‘natural’ or likely for inflation theory
- New better, observations ⟷ more information! (Planck Satellite, LSS Surveys)
- New ideas from LSS about how to observe primordial NG

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The Plan

1. *Non-Gaussian toolkit*
2. *Example 1*: Theory driven
3. *Example 2*: Observation driven

I. The non-Gaussian toolkit

Example: the local ansatz

$$\zeta(x) = \zeta_g(x) + \frac{3}{5} f_{NL}[\zeta_g^2(x) - \langle\zeta_g^2(x)\rangle]$$

(Salopek, Bond; Komatsu, Spergel)

- Nearly Gaussian? $|f_{NL}| < 10^{9/2}$
- Positive skewness ($f_{NL} > 0$) means more structure
- One parameter describes all moments

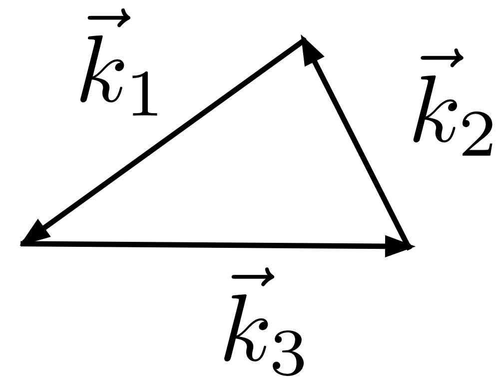
$$\frac{\langle\zeta^n\rangle_c}{(\langle\zeta^2\rangle)^{n/2}} \propto (f_{NL}\mathcal{P}_\zeta^{1/2})^{n-2}$$

More Generally...

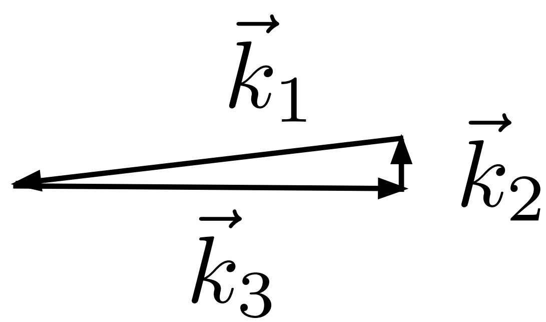
- Interactions that don't screw up inflation are allowed:
  - * Self-interactions with symmetry
  - * Multi-field inflation
  - * Interactions with spectator fields
- Different interactions $\Rightarrow$ Different shapes in bispectrum and beyond

A First Pass: 3-point triangles

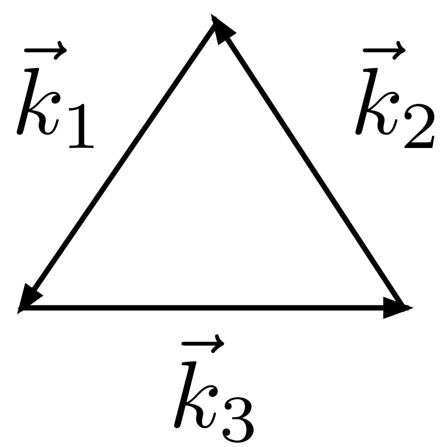
$$\delta_D^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \Rightarrow$$



- Squeezed



- Equilateral



Different Interactions,
Different Triangles.
But not 1-to-1 map!

(Babich, Creminelli, Zaldarriaga;)

Information in higher statistics

	Power Spectrum	Bispectrum	Beyond...
Information			
Amplitude			
Sign			
Scale Dependence			

Single Field Multi Field

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	Power Spectrum	Bispectrum		Beyond...
Information	$\frac{\lvert\vec{k}\rvert}{\quad}$			
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Single Field ↗ ↖ Multi Field

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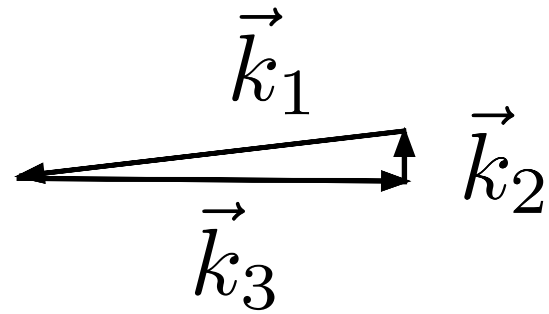
Information	$|\vec{k}|$		
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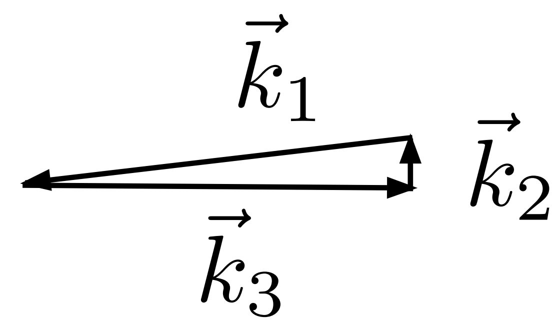
Information	$\|\vec{k}\|$			
Amplitude	$\frac{H^2}{\epsilon M_p^2}$	$\frac{H}{f} < 1$		
Sign	—			
Scale Dependence	$n_s - 1$ not exact de Sitter			

Single Field ↗ (bispectrum, left column)   ↖ Multi Field (bispectrum, right column)

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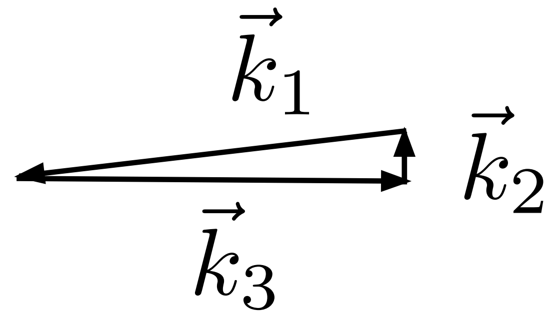
Information	$\vert\vec{k}\vert$ ——			
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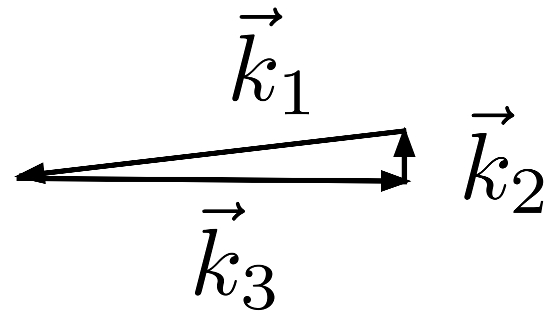
Information	$\frac{\lvert\vec{k}\rvert}{}$			
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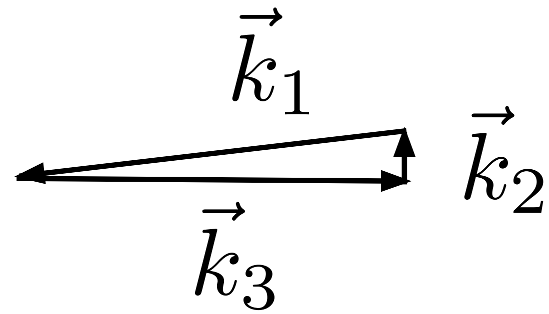
Information	$|\vec{k}|$			
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Single Field ↗ Multi Field ↖

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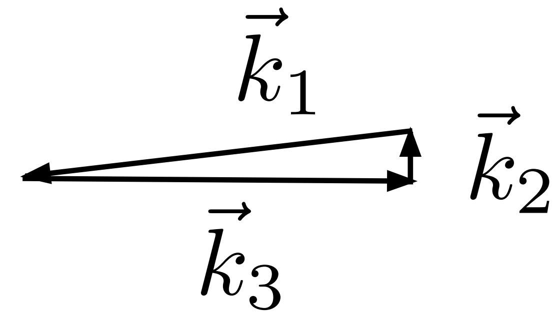
Information	$\underline{\lvert\vec{k}\rvert}$			
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↗ Single Field ↖ Multi Field

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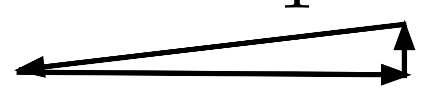
Information in higher statistics

	Power Spectrum	Bispectrum		Beyond...
Information	$\lvert\vec{k}\rvert$	$\vec{k}_1$  $\vec{k}_2$ $\vec{k}_3$		N-gon
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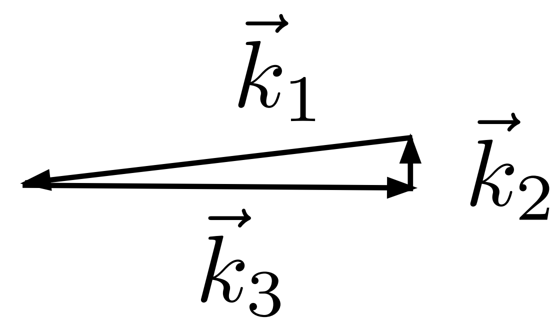
Information	$\lvert\vec{k}\rvert$			N-gon
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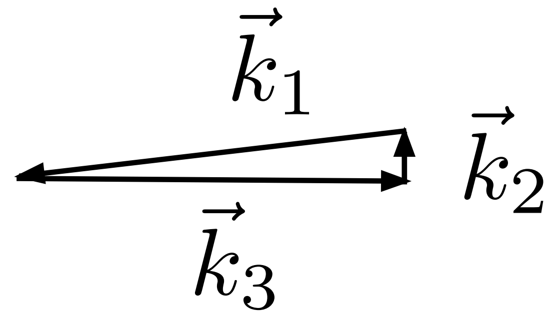
Information	$\|\vec{k}\|$	 $\vec{k}_1$ $\vec{k}_2$ $\vec{k}_3$	N-gon
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Scale Dependence	$n_s - 1$ not exact de Sitter	Scaling of interaction strength Difference between fields	?

Single Field ↗ Multi Field ↖

Non-Gaussian Statistics? Infinitely many!

Which cases are:

- Distinguishable
- Physical
- Natural
- Consistent with inflation
- Consistent with measured power spectrum?

} How much overlap?

(Elliot Nelson's talk)

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Excitement about NG:

Non-Gaussianity: More numbers
(eg, 3 point, triangles)!

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Can we gain something more?

Must go beyond three-point and see structure of NG

II. Theory Driven Example

Example: Symmetry for the Inflaton

* Inflaton with a shift symmetry: $\boxed{\phi \rightarrow \phi + c}$

(Freese; Silverstein, Westphal; Barnaby, Peloso; Anber, Sorbo; Chen et al; Flauger, Pajer; Leblond, Pajer; Adshead, Wyman...)

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Example: Symmetry for the Inflaton

* Inflaton with a shift symmetry: $\phi \to \phi + c$

Lesson from the Standard Model: Any allowed interactions appear....

- Derivative self-interactions
- Couplings to gauge fields
- Terms that break the symmetry slightly

(Freese; Silverstein, Westphal; Barnaby, Peloso; Anber, Sorbo; Chen et al; Flauger, Pajer; Leblond, Pajer; Adshead, Wyman...)

Shift symmetry continued

- Each family of terms generates a *family of correlation functions* for the fluctuations:

$$V(\phi) = \mu^4 \left[1 - b\,\mathrm{Cos}\left(\frac{\phi}{f}\right)\right] + \ldots$$

$$V(\phi_0) + V''|_{\phi_0}\delta\phi^2 + V^{(3)}|_{\phi_0}\delta\phi^3 + V^{(4)}|_{\phi_0}\delta\phi^4 + \ldots$$

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- New mass scale, *f*: amplitude of non-Gaussianity
- Patterns in the correlation functions

Each interaction has a different signature

Small Sound Speed

Resonant terms

Feeder field

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Small Sound Speed	* Equilateral Bispectrum
Resonant terms	* Bispectrum has oscillating amplitude
Feeder field	* Equilateral Bispectrum * Moments Scale Differently

(At least) Two equilateral types

(Barnaby, Shandera; 1109.2985)

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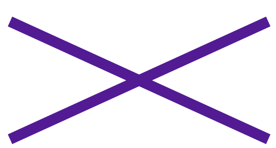

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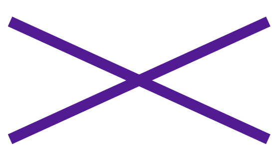

Hierarchical: $\mathcal{M}_n \propto \left(\mathcal{I} \mathcal{P}_{\Phi}^{1/2} \right)^{n-2}$

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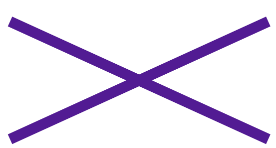

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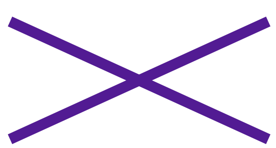

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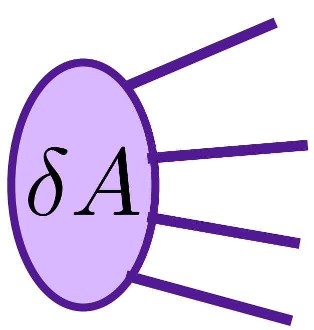

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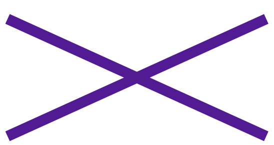

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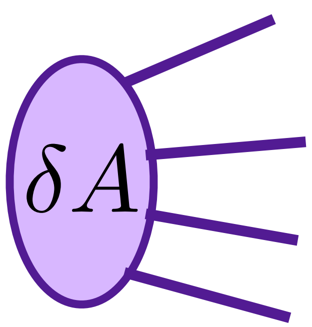
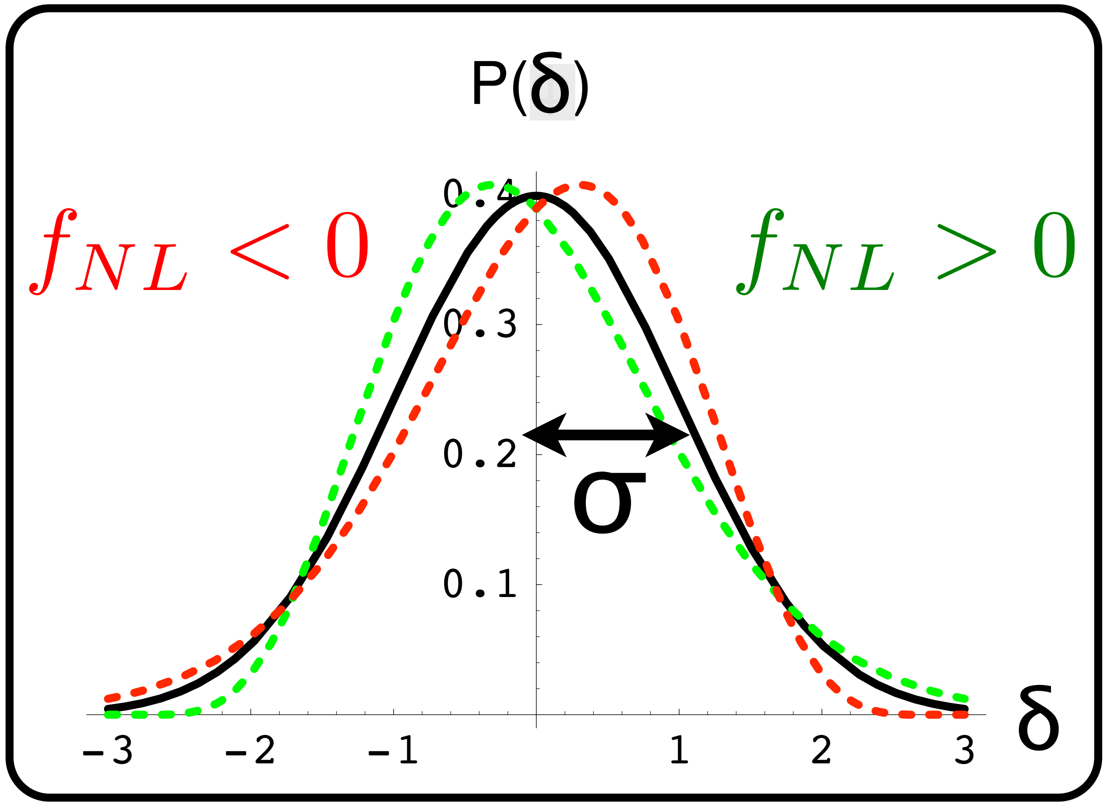


Feeder: $\mathcal{M}_n \propto \mathcal{I}^n$

(Barnaby, Shandera; 1109.2985)

Different Scaling?

- Relative importance of higher order moments is greater for *fixed amplitude* of three point
- Skewness isn't everything...



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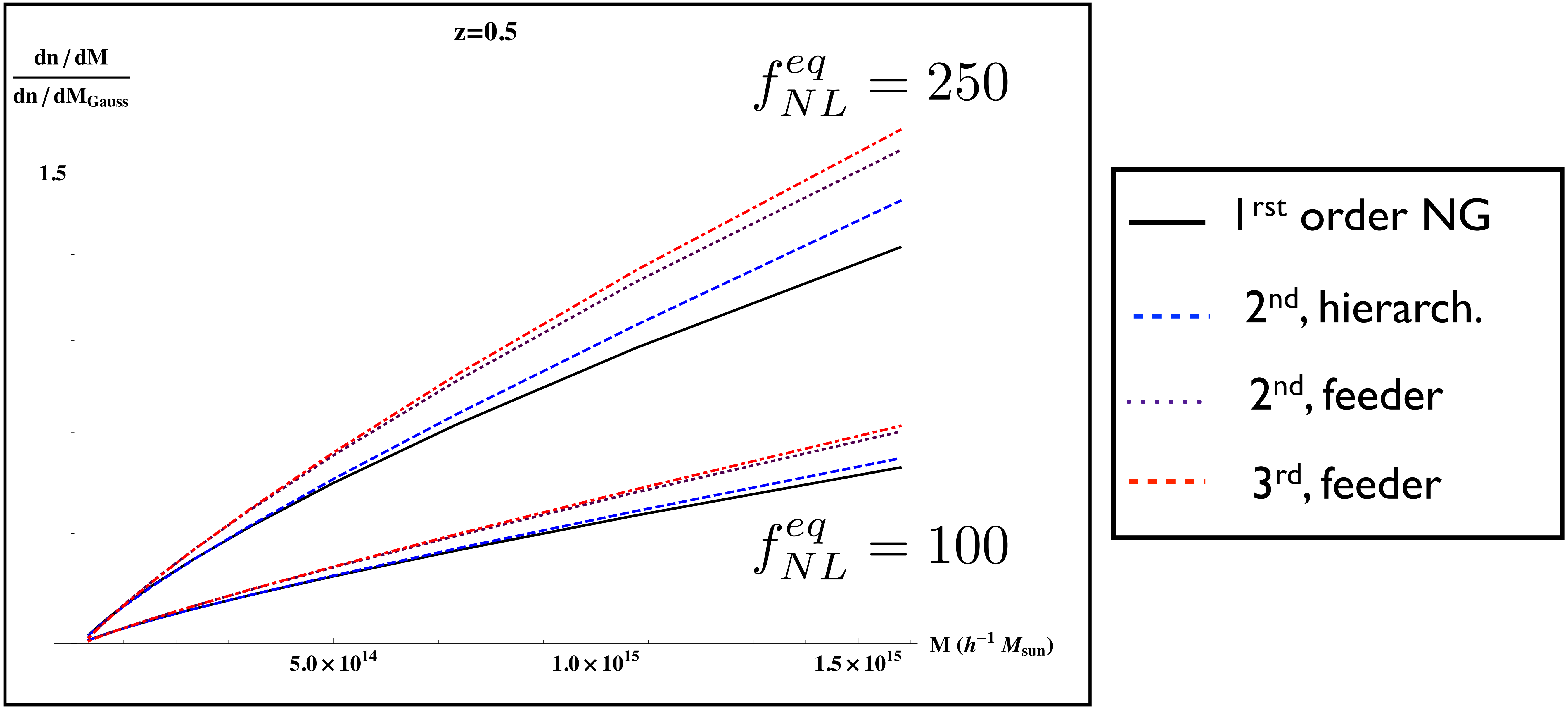
Is this Distinction Observable?

- Which measurements might have big signals from higher moments?
- Simulations in progress (w/ Saroj Adhikari, L. Book, N. Dalal)
- Encouraging tale of the galaxy bias...

NG Mass Function



* What can we learn from rare objects?

(Barnaby, Shandera 1109.2985;
With A. Mantz, D. Rapetti, X-ray cluster in progress
With A. Erickcek, P. Scott: Ultra Compact Mini Halos and Primordial Black Holes: difference more sig when more NG!)

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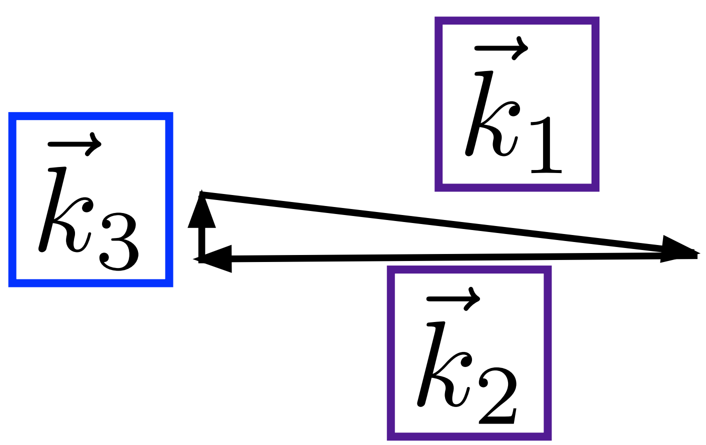
III. Observation Driven Example

Non-Gaussian Bias

- Effect was discovered in an N-body simulation: (Dalal et al 0710.4560)

$$\Phi(x) = \Phi_G(x) + f_{NL}[\Phi_G^2(x) - \langle\Phi_G^2(x)\rangle]$$

- Sensitive to a particular sort of correlation:



Bias and Local Non-Gaussianity

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$$P_{hm}(k) = b(M)P_{mm}(k)$$

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(Halo) x (Linear matter)

Linear matter

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$$P_{hm}(k) = b(M, f_{NL}, k) P_{mm}(k)$$

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Bias and Local Non-Gaussianity

$$P_{hm}(k) = b(M) P_{mm}(k)$$

(Halo) x (Linear matter)

"Bias"

Linear matter

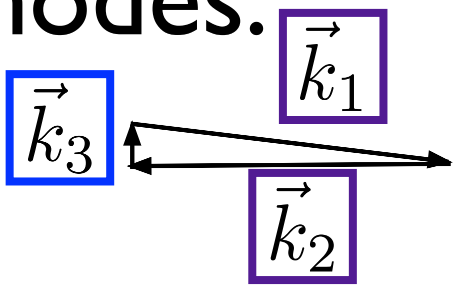
$$P_{hm}(k) = b(M, f_{NL}, k) P_{mm}(k)$$

$$P_{hm}(k) = [b_G(M) + \Delta b(f_{NL}, k, M)] P_{mm}(k)$$

"Non-Gaussian Bias"

Local Non-Gaussianity and bias

- *Correlation* between long and short modes: enhanced clustering



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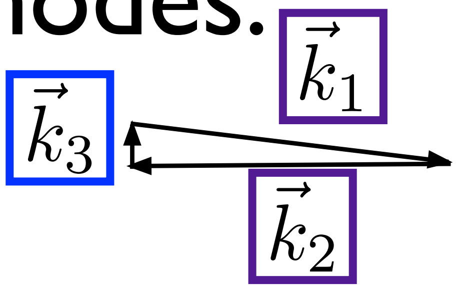

- Local density and local σ_8 determine where halos form

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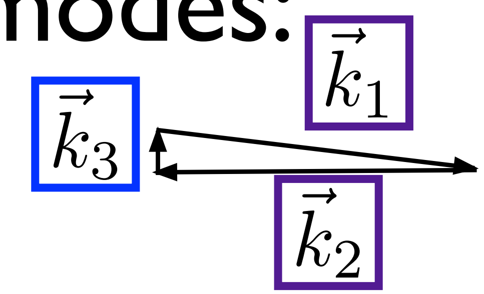

- Local density and local σ_8 determine where halos form

$$\Delta b_{NG}(k, M, f_{NL}) \propto \frac{f_{NL}}{k^2}$$

(Dalal et al 0710.4560)

A good constraint:

$$-57(-89) < f_{NL} < 69(90)$$
$$8 < f_{NL} < 88$$

(Slosar et al 2008)

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But....

- What does f_{NL} measure/constrain?
- What do inflation models actually predict?
- Are observations sensitive to those details?

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Which theories can look like the local ansatz?

- Single field $\not\longrightarrow$ Local Non-Gaussianity (near time-translation invariance; Maldacena; Senatore, Zaldarriaga; Creminelli et al; Hinterbichler et al)

$$B(k_\ell, k_s, k_s) \underset{k_\ell \to 0}{\longrightarrow} \mathcal{O}(n_s - 1)\frac{1}{k_\ell^3} + \mathcal{O}\left(\frac{1}{k_\ell}\right)$$

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- Multi-field: two degrees of freedom contribute to inflationary background and/or fluctuations IS local

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Distinguishing Multi-Field models

- Break correlation between background evolution and fluctuations
- Anything goes?
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Multi-field → Local shape → Halo Bias

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Beyond the local Ansatz

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Can use this even more generally....

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(Shandera, Dalal, Huterer 1010.3722)

NG bias, generalized

$$\Delta b_{NG}(k, M, f_{NL}) \propto \frac{f_{NL}}{k^2} \rightarrow \frac{f_{NL}^{eff}(M)}{k^{\alpha}}$$

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So far models give: $0 \leq \alpha \leq 3$

Standard Single field	$\alpha = 0$	
Multiple Light fields	$\alpha = 2 \pm \mathcal{O}(\epsilon, \eta)$	Byrnes et al; Seery et al;
Quasi Single field	$1/2 \leq \alpha \leq 2$	Chen, Wang;
Generalized Initial State	$\alpha \lesssim 3$	Agullo, Parker; Agullo, Shandera; Ganc, Komatsu
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}!

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Does an observation of local NG *really rule out* Single Field?

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- Consistency condition doesn't have to hold away from $k_\ell \to 0$
- Over what k-range can SF have local NG? (Small scale probes needed!)
- How divergent can the squeezed limit be?
- Easy out: more divergent is easier to test (in principle) (N. Agarwal's talk)
- Can soft limits of higher order correlation functions ever look (locally) local? (Smith et al; Roth, Porciani; E. Nelson's talk)

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Summary:

* LSS surveys are coming! They constrain initial conditions (maybe even initial conditions of inflation)

* If Planck + LSS shows evidence of local NG, pressure on single field

* Can we find observationally allowed NG that inflation cannot predict?