Non-Gaussianity ... Planck, COrE

Benasque, February 13-19 2011

Unsolved Problems in Astrophysics
and Cosmology

Sabino Matarrese
Physics Dept. “Galileo Galilei”
University of Padova, Italy

Primordial non-Gaussianity as a new route to falsify Inflation

→ Historical remarks

- Groth and Peebles 1977 (3-pt function)
- Strongly non-Gaussian initial conditions studied in the eighties
- Determination of bispectrum for PSCz galaxies (Fedman et al. 2001) 2dF galaxies (Verde et al. 2002)
- New era with f_{NL} models from inflation (Salopek & Bond 1991; Gangui et al. 1994: $f_{NL} \sim 10^{-2}$; Verde et al. 1999; Komatsu & Spergel 2001; Acquaviva et al. 2002; Maldacena 2002; + many models with higher f_{NL}).
- Primordial NG emerged as a new "smoking gun" of (non-standard) inflation models, which will very soon complement the search for primordial GW

… and to test the physics of the Early Universe

- The NG amplitude and shape measures deviations from standard inflation, perturbation generating processes after inflation, initial state before inflation, … Inflation models which would yield the same predictions for scalar spectral index and tensor-to-scalar ratio might be distuinguishable in terms of NG features.

- Can we aim at "reconstructing" the inflationary action, starting from measurements of a few observables (like n_S, r, n_T, f_{NL}, g_{NL}, etc. …), just like in the nineties we were aiming at a reconstruction of the inflationary potential?

Simple-minded NG model

- Many primordial (inflationary) models of non-Gaussianity can be represented in configuration space by the simple formula (Salopek & Bond 1990; Gangui et al. 1994; Verde et al. 1999; Komatsu & Spergel 2001)

$$\Phi = \phi_L + f_{NL} * (\phi_L^2 - \langle\phi_L^2\rangle) + g_{NL} * (\phi_L^3 - \langle\phi_L^2\rangle \phi_L) + \ldots$$

where Φ is the large-scale gravitational potential, ϕ_L its linear Gaussian contribution and f_{NL} is the dimensionless *non-linearity parameter* (or more generally *non-linearity function*). The percent of non-Gaussianity in CMB data implied by this model is

$$\text{NG \%} \sim 10^{-5} \; |f_{NL}|$$

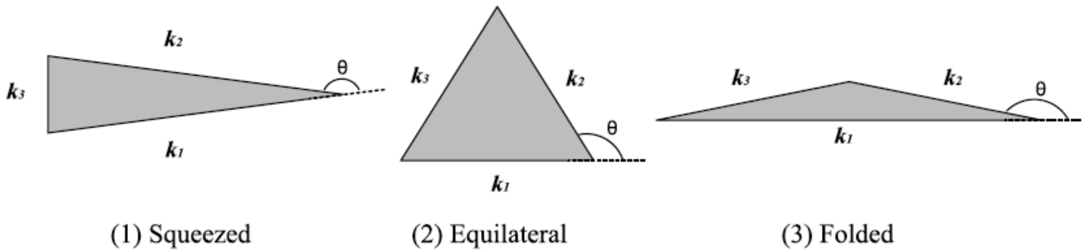
< 10^{-4} from CMB & LSS

$$\sim 10^{-10} \; |g_{NL}|$$

< 10^{-4} from CMB & LSS

Non-Gaussianity in the initial conditions

there are more shapes of non-Gaussianity from inflation than … stars in the sky



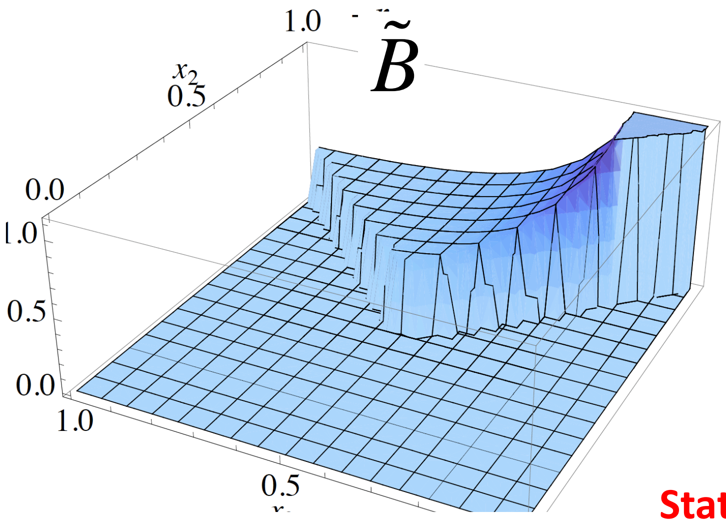
- The local shape of NG (→ squeezed triangles in k-space) typically arises in multi-field inflation models (e.g. curvaton, inhomogeneous reheating, etc...)

- Large NG with equilateral, flattened (folded) shapes, etc.. are typical of (non-standard) single-field inflation (Bartolo, Fasiello, Matarrese & Riotto 2010) → *no need for exotic initial states to get flattened shape!*

- General (non-separable) CMB bispectra can be expanded in terms of “separable” bispectra (Fergusson, Liguori & Shellard 2010) → general analyis

- Statistical anisotropic NG typically arises if (non-)Abelian vector field are present during inflation (see review by Dimastrogiovanni et al. 2010)

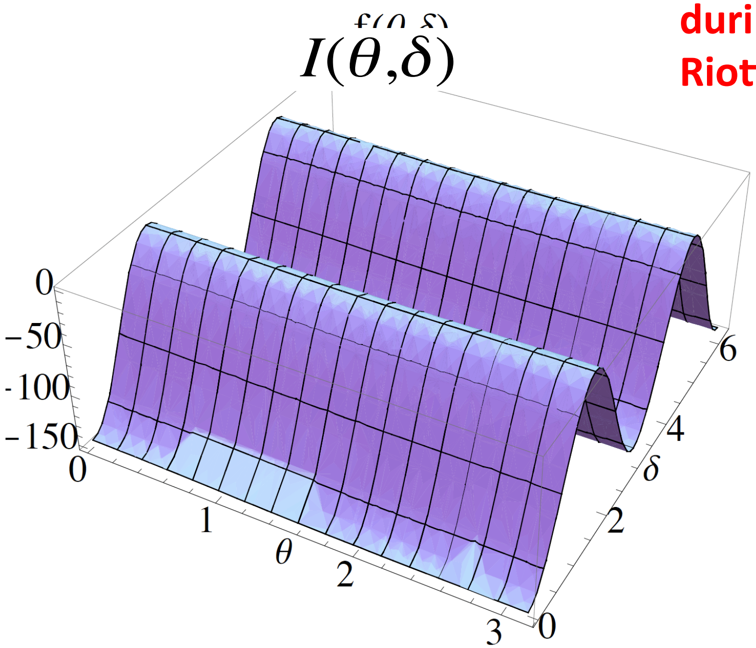
NG & Statistical anisotropy from non-Abelian vector fields



Isotropic contribution to the bispectrum

$$B(\vec{\mathbf{k}}_1,\vec{\mathbf{k}}_2,\vec{\mathbf{k}}_1) \sim \mathbf{I}(\vec{n}_i \bullet \vec{k}_i)\ \tilde{B}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

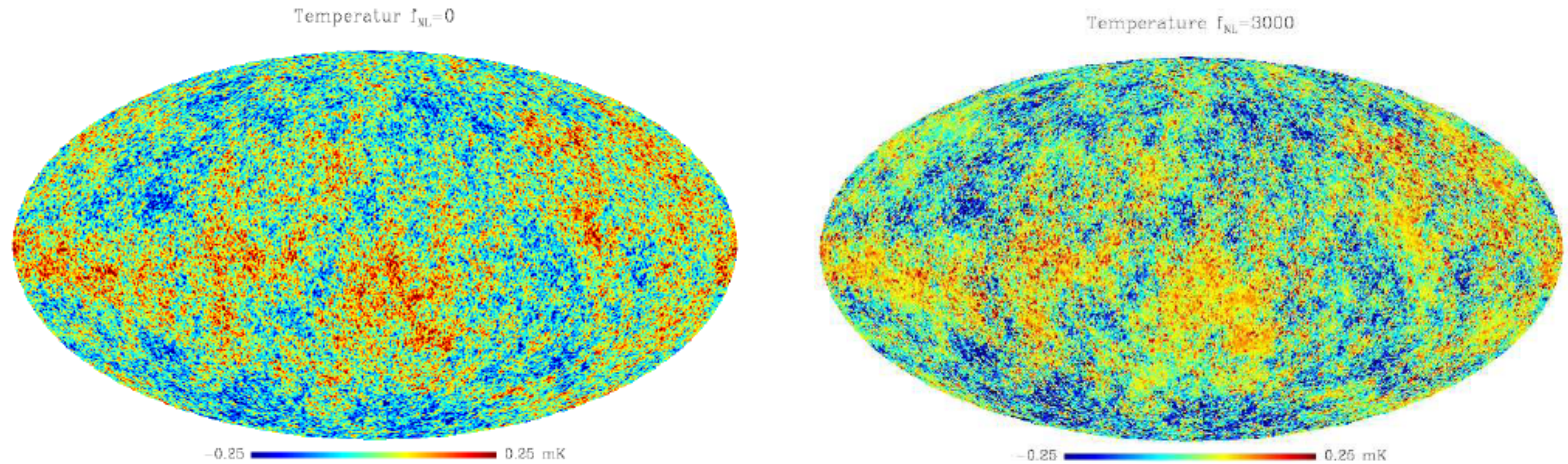
Statistically anisotropic NG from non-Abelian vector fields during inflation (Bartolo, Dimastrogiovanni, Matarrese & Riotto, 2009, 2010)



Modulation dependent on the preferred directions

Non-Gaussianity & the CMB

NG CMB simulated maps



Liguori, Yadav, Hansen, Komatsu, Matarrese & Wandelt 2007

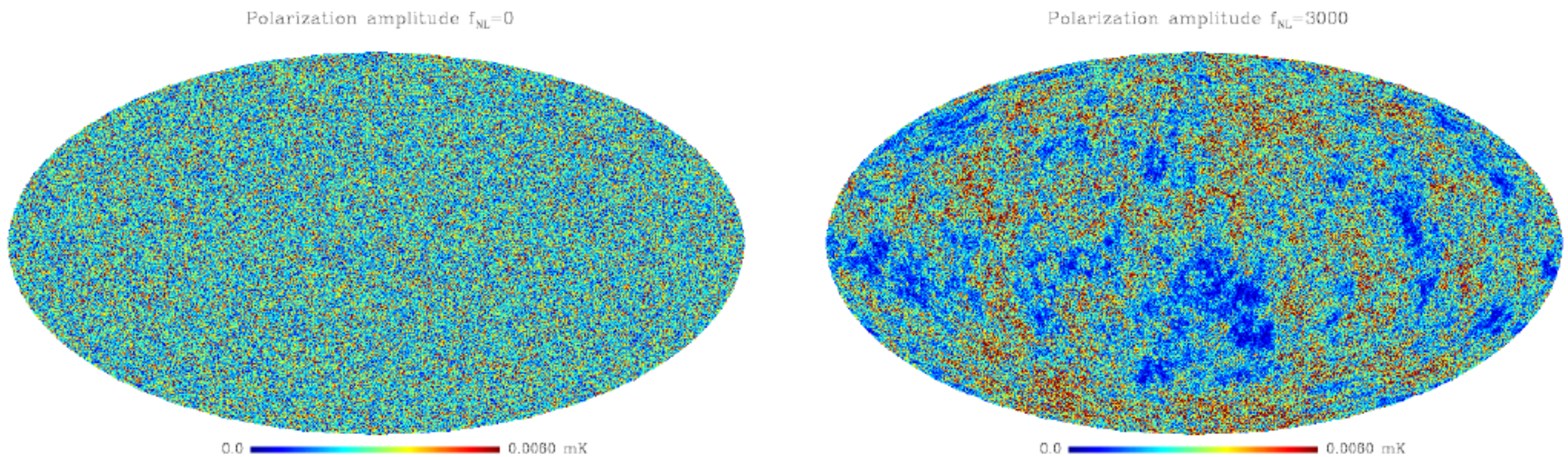


FIG. 8: Left column: temperature and polarization intensity Gaussian CMB simulations obtained from our algorithm. Polarization intensity is defined as $I \equiv \sqrt{Q^2 + U^2}$ where Q and U are the Stokes parameters. Right column: temperature and polarization non-Gaussian maps with the same Gaussian seed as in the left column and $f_{\rm NL} = 3000$. The reason for the choice of such a large $f_{\rm NL}$ is that we wanted to make non-Gaussian effects visible by eye in the figures. The cosmological model adopted for this plots is characterized by: $\Omega_b = 0.042$, $\Omega_{cdm} = 0.239$, $\Omega_L = 0.719$, $h = 0.73$, $n = 1$, $\tau = 0.09$. Temperatures are in mK.

Latest theoretical developments

Assessment of NG induced by secondary (second-order) anisotropies:

- Nitta, Komatsu, Bartolo, Matarrese & Riotto 2009: no (previously unknown) 2^{nd} order anisotropies (coming made of products of 1^{st} x 1^{st} order terms) can contaminate (local) NG at detectable level (good news!); Pitrou et al. 2010 f_{NL}~ 5 (local) from second-order effects at recombination (being cross-checked)

- Largest signal: cross-correlation of **lensing/ISW(RS)**: equivalent to local f_{NL}~10 (Hanson et al. 2009; Mangilli & Verde 2009). We can subtract it (or use *constrained* N-body simulations to map it).

CMB Constraints on local f_{NL}

Constraints (95%CL)	Method	Experiment	Paper
$-10 < f_{nl} < +74$	Bispectrum	WMAP-7	Komatsu et al. (2010)
$+11 < f_{nl} < +135$	Needlets	WMAP-5	Rudjord et al. (2009)
$-18 < f_{nl} < +80$	SMHW	WMAP-5	Curto et al. (2009)
$-4 < f_{nl} < +80$	Bispectrum	WMAP-5	Smith et al. (2009)
$-920 < f_{nl} < +1075$	Minkowski	Archeops	Curto et al. (2008)
$-8 < f_{nl} < +111$	SMHW	WMAP-5	Curto et al. (2008)
$-9 < f_{nl} < +111$	Bispectrum	WMAP-5	Komatsu et al.(2009)
$+27 < f_{nl} < +147$	Bispectrum	WMAP-3	Yadav & Wandelt (2008)
$-180 < f_{nl} < +170$	Local curvature & wavelets	WMAP-1	Cabella et al. (2005)
$-178 < f_{nl} < +64$	Minkowski	WMAP-5	Komatsu et al. (2009)
$-800 < f_{nl} < +1050$	Minkowski	BOOMERANG	De Troia et al. (2007)

credits: Andres Curto 2010

WMAP constraints

	WMAP 7-yrs	WMAP 5-yrs
Local	$-10 < f_{NL} < 74$	$-4 < f_{NL} < 80$
Equilateral	$-214 < f_{NL} < 266$	$-125 < f_{NL} < 435$
Orthogonal	$-410 < f_{NL} < 6$	$-369 < f_{NL} < 71$

WMAP 7-yr: Komatsu et al. 2010

(95% c.l)

Forecasts on f_{NL}

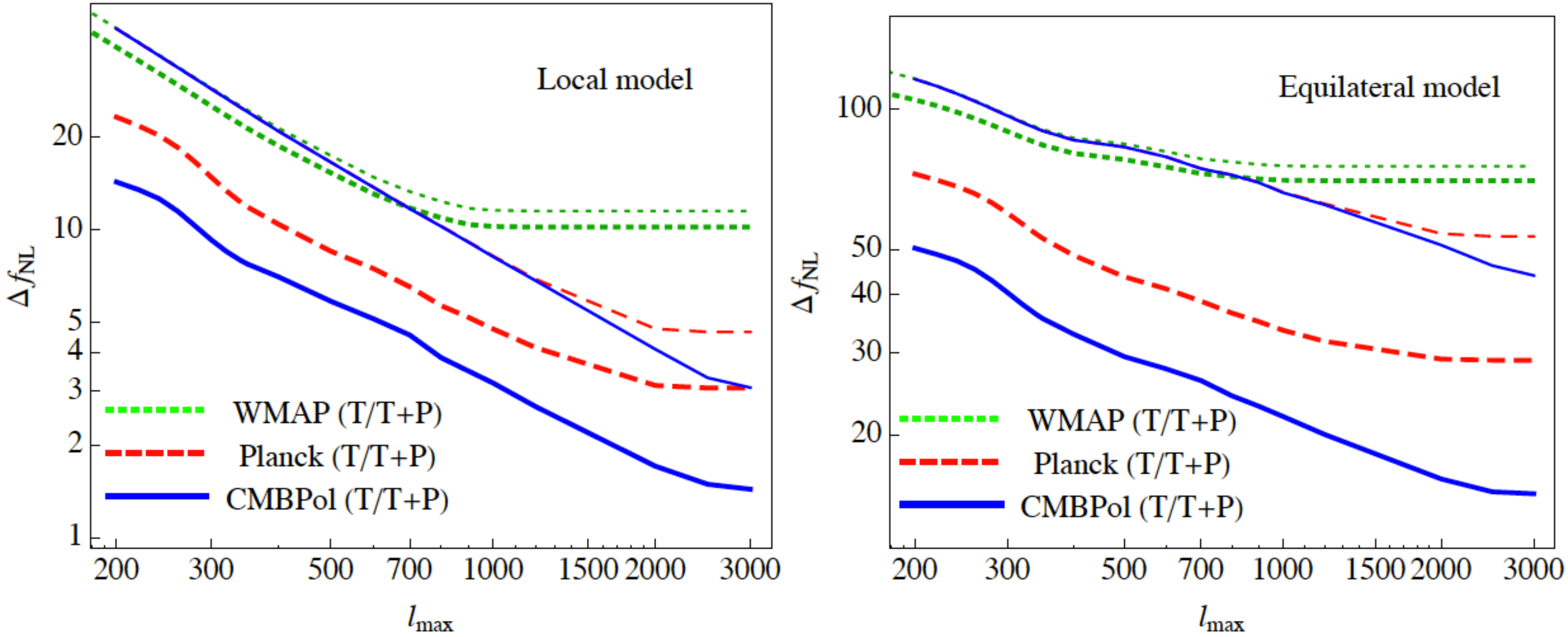


FIG. 11 Fisher matrix forecasts on Δf_{NL}, featured for different experiments: WMAP (*green, dotted lines*), Planck (*red, dashed lines*) and the proposed CMBpol (Baumann *et al.*, 2008) survey (*blue, solid lines*). The left panel shows results for the local shape, while the right panel refers to the equilateral shape. Thin lines are obtained from temperature data only, and thick lines show the improvement in the error bars coming from adding polarization datasets to the analysis for the various experiment.

from Liguori et al. 2010

Perspects with COrE (Bucher's talk)

- improve (by factor of a few) limits on f_{NL} → improve knowledge of shapes
- constrain g_{NL} and τ_{NL} (Δ <10^4), which is important for models with negligible f_{NL} , strings, ...
-
- see COrE white paper

(arXiv:1102.2181)

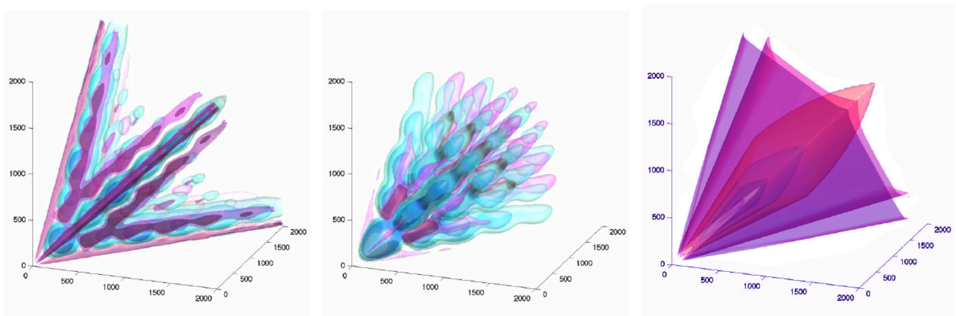


Figure 8: **Theoretical predictions for CMB bispectrum shape.** The primordial CMB bispectrum depends on three multipole numbers ℓ_1, ℓ_2, ℓ_3 subject to a triangle inequality constraint as opposed to the standard 'Gaussian' power spectrum $P(\ell)$ (which depends on only one multipole number). Hence the bispectrum contains rich shape information that can be exploited to confront observations with theoretical models and to probe the self-consistency of a possible detection. Here the CMB bispectra $B(\ell_1, \ell_2, \ell_3)$ from three theoretical models are plotted with positive (cyan) and negative (magenta) isocontours [109, 81]. The plots show (from left to right) the 'local' model (e.g., multifield inflation), equilateral model (e.g., DBI inflation) and non-Gaussianity generated by cosmic strings, which are inherently highly nonlinear.

Non-Gaussianity & the LSS

(= primordial NG + NG from gravitational instability)

NG and LSS

- ✓ NG in LSS (to make contact with the CMB definition) can be defined through a potential Φ defined starting from the DM density fluctuation δ through Poisson's equation (use comoving gauge for density fluctuation, Bardeen 1980)

$$\delta = -\left(\frac{3}{2}\Omega_m H^2\right)^{-1} \nabla^2 \Phi$$

- ✓ Many primordial (inflationary) models of non-Gaussianity can be represented in configuration space by the simple formula

$$\Phi = \phi_L + f_{NL}(\phi_L^2 - \langle\phi_L^2\rangle) + g_{NL}(\phi_L^3 - \langle\phi_L^2\rangle\phi_L) + \ldots$$

Φ on sub-horizon scales reduces to minus the large-scale gravitational potential, ϕ_L is the linear Gaussian contribution and f_{NL} and g_{NL} are dimensionless <u>non-linearity parameters</u> (or more generally <u>non-linearity functions</u>). CMB and LSS conventions differ by a factor 1.3 for f_{NL}, $(1.3)^2$ for g_{NL}

NG effects in LSS

- Bartolo, Matarrese & Riotto (2005) computed the effects of NG in the dark matter density fluctuations in a matter-dominated universe. Only for high values of f_{NL} (~10) the standard parameterization is valid. For smaller primordial NG strength non-Newtonian gravitational terms shift f_{NL} by a term ~ - 1.6 (see Verde & Matarrese 2010). On small scales stagnation effects during radiation dominance have to be taken into account up to second order. (Bartolo, Matarrese & Riotto 2007; Senatore et al. 2009).

- Sefusatti & Komatsu (2007) show that LSS becomes competitive with CMB at z > 2; Jeong & Komatsu (2009) and Sefusatti (2009) compute one-loop bispectrum of biased objects. ...

NG effects on the matter PS: local shape

Calculation based on Renormalization Group (RG) (Matarrese & Pietroni 2007; Pietroni 2008) technique

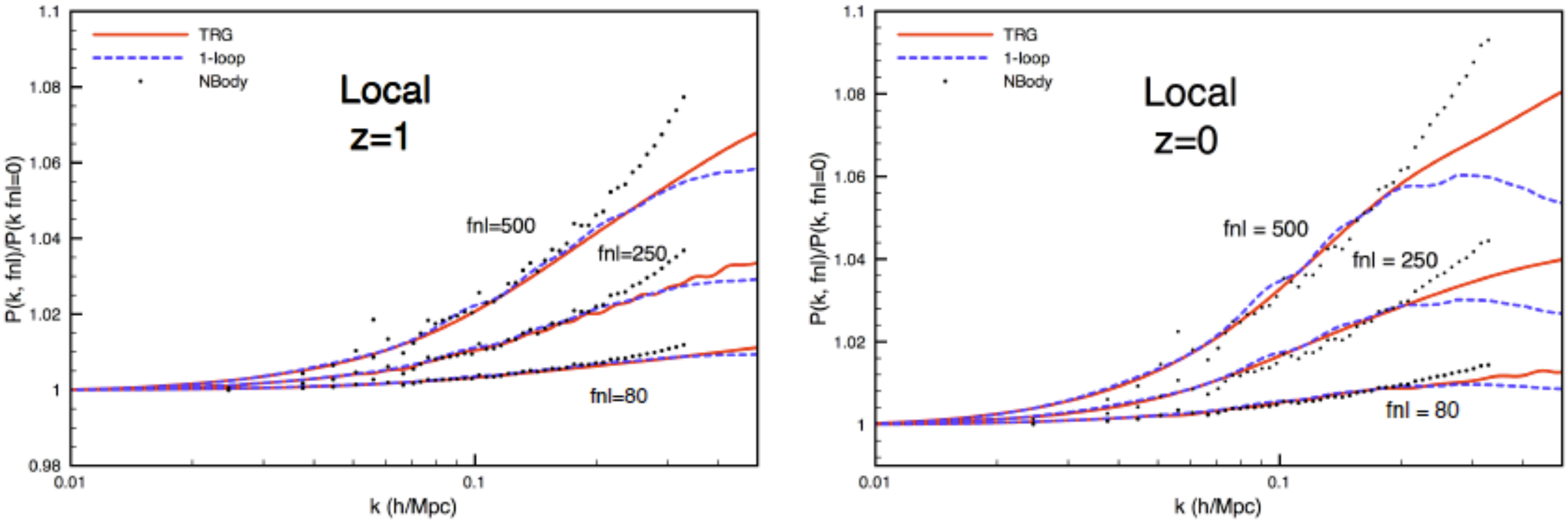


Figure 5. Ratio of the non-Gaussian to Gaussian power spectrum for several values of $f_{\rm NL}$ in the local model. The dots correspond to the data from the N-body simulations of [54]. The red (continuous) line is the TRG result of this paper and the blue (dashed) line is the one-loop result.

Bartolo, Beltrán Almeida, Matarrese, Pietroni & Riotto 2010

NG effects on the matter PS: equilateral and folded shapes

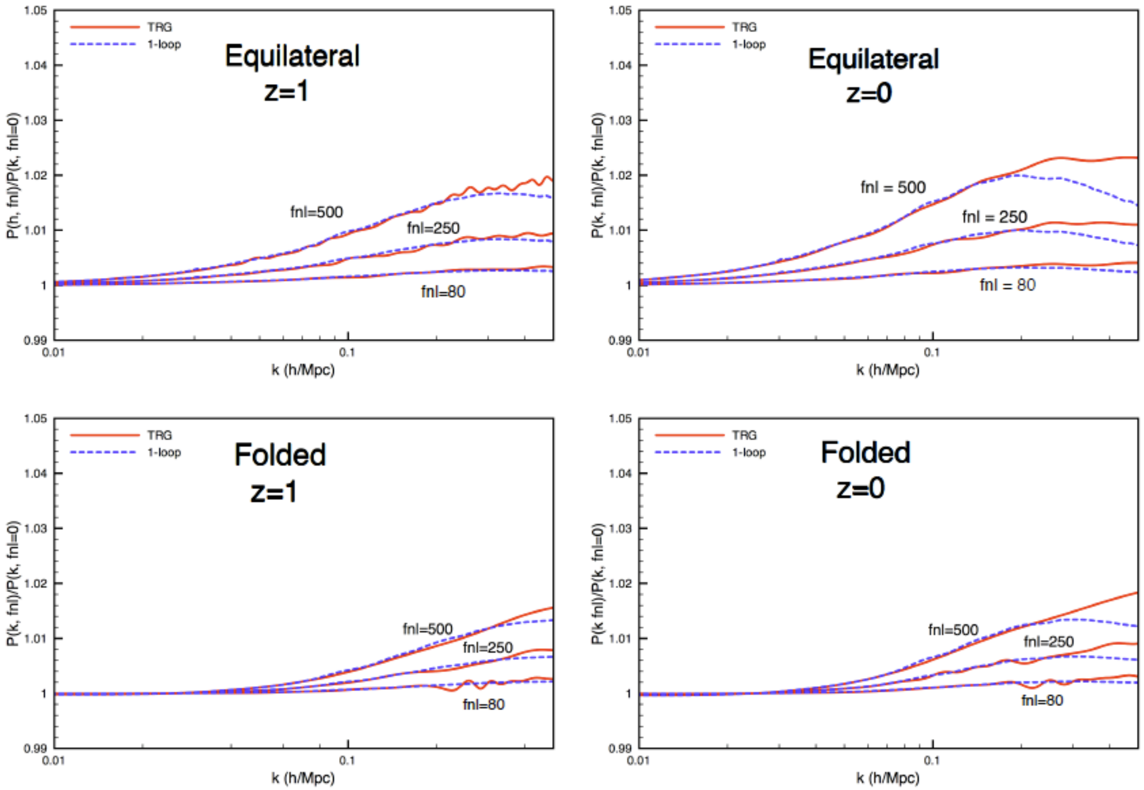
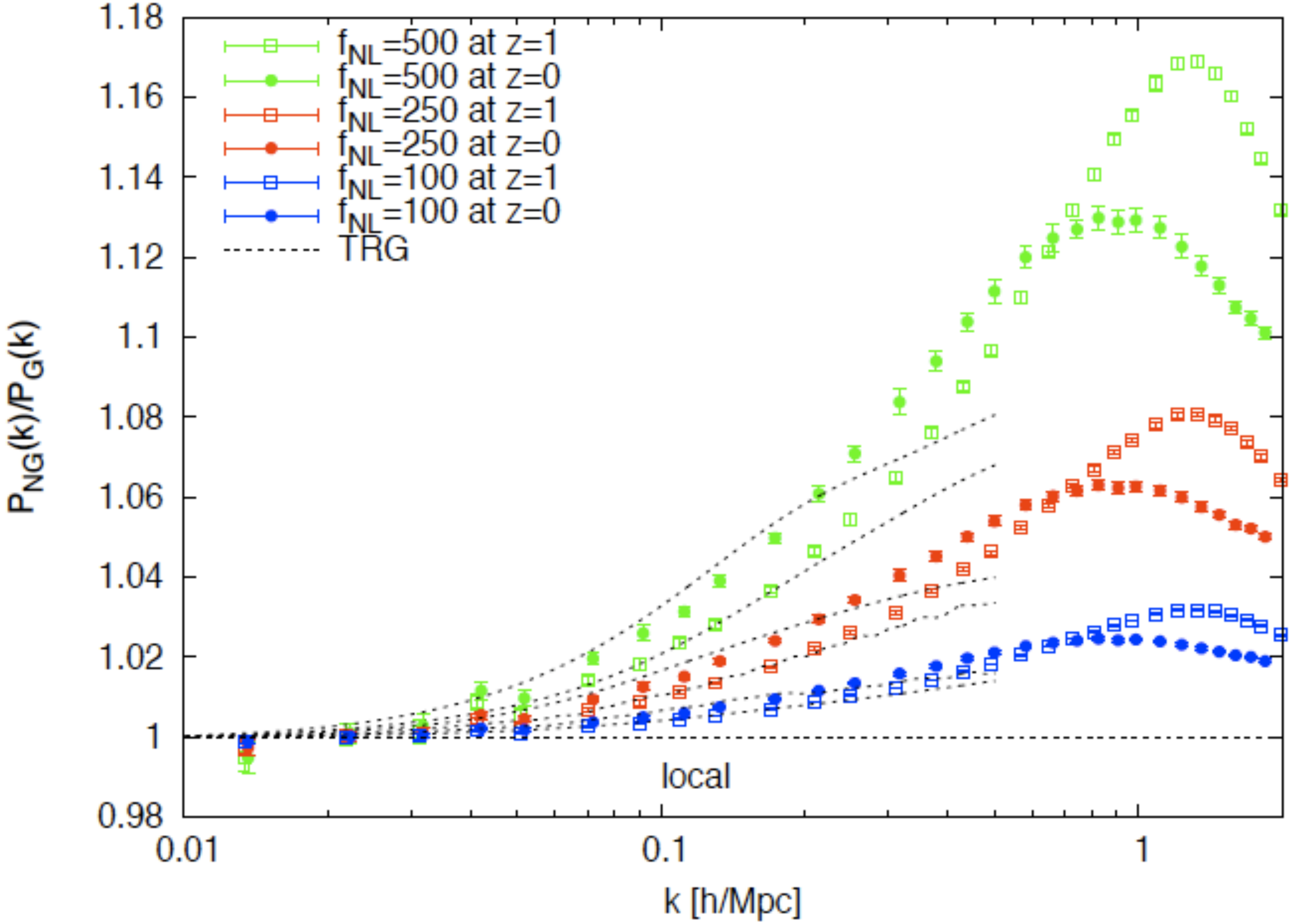


Figure 6. Ratio of the non-Gaussian to Gaussian power spectrum for several values of $f_{\rm NL}$ in the equilateral (top panels) and folded (bottom panels) models. The red (continuous) lines are the TRG result of this paper and the blue (dashed) lines are the one-loop result.

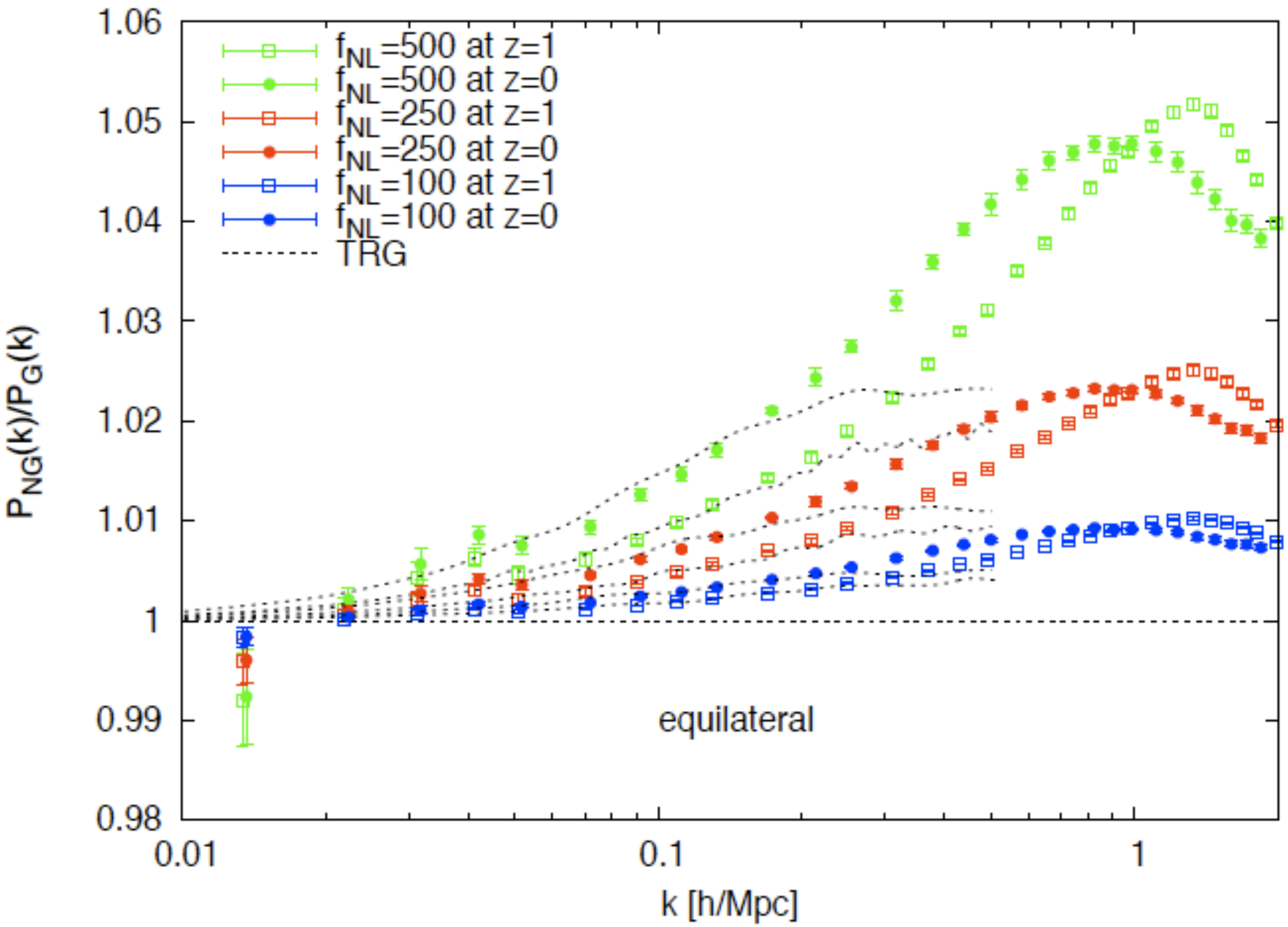
Bartolo, Beltrán Almeida, Matarrese, Pietroni & Riotto 2010

Comparison of RG with N-body simulations (local case)



from: Wagner, Verde & Boubekeur 2010

Comparison of RG with N-body simulations (equilateral case)



from: Wagner, Verde & Boubekeur 2010

Searching for non-Gaussianity with rare events

- Besides using standard statistical estimators, like bispectrum, trispectrum, three and four-point function, skewness, etc. …, one can look at the tails of the distribution, i.e. at rare events.

- Rare events have the advantage that they often maximize deviations from what predicted by a Gaussian distribution, but have the obvious disadvantage of being rare! But remember that, according to Press-Schechter-like schemes, all collapsed DM halos correspond to (rare) peaks of the underlying density field.

- Matarrese, Verde & Jimenez (2000) and Verde, Jimenez, Kamionkowski & Matarrese showed that clusters at high redshift (z>1) can probe NG down to $f_{NL} \sim 10^2$

- Alternative approach by LoVerde et al. (2007). Determination of mass function using stochastic approach (first-crossing of a diffusive barrier) Maggiore & Riotto 2009. Ellispsoidal collapse used by Lam & Sheth 2009. Saddle-point + diffusive barrier (Paranjape et al. 2010). Log-Edgeworth expantion: LoVerde & Smith 2011.

- Excellent agreement of analytical formulae with N-body simulations found by Grossi et al. 2009 ... and many others.

Different approaches to the NG halo mass function

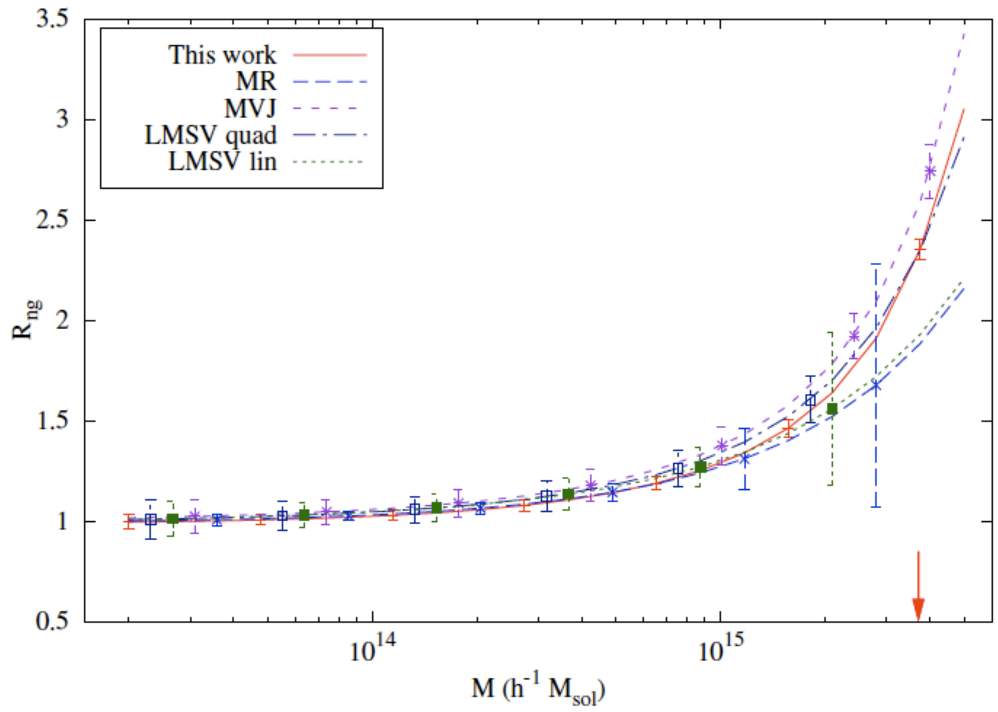


Figure 6: Same as Fig. 5, but including filter effects. These affect only the error bars for MVJ and LMSV, and they affect both the curve and the error bars for MR and our result. For MR and our result, the Gaussian mass function used to construct the ratio $R_{\rm ng}$, is taken as the non-Gaussian result at $f_{\rm NL} = 0$, and hence includes filter effects.

Paranjape et al. 2010

NG vs. Halo Mass Function

- Relevant effects:
  - non-Markovianity, already there in Gaussian case, unavoidable in NG case
  - non-spherical collapse
  - connecting random walks w. DM halos
  - diffusive collapse threshold?
- Dealing with rare events i.e. tails of NG distribution
- Validation with N-body simulations crucial (although very rare events/tails not probed by finite number of realizations → analytical treatments welcome!)
- Understanding/definition of connection between analytical/numerical quantities and real observables → to what level is this affecting NG (e.g. f_{NL}) measurements?

NG & high-z clusters

- Matarrese, Verde & Jimenez 2000

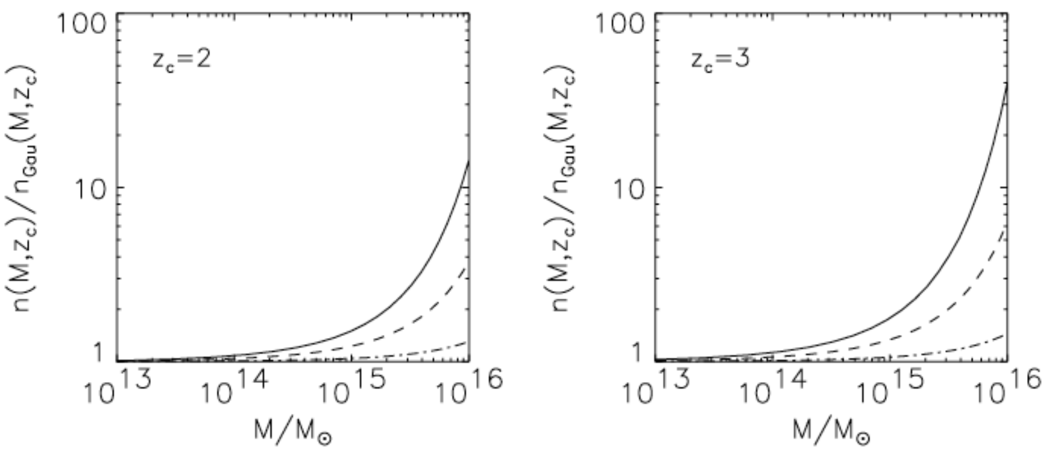
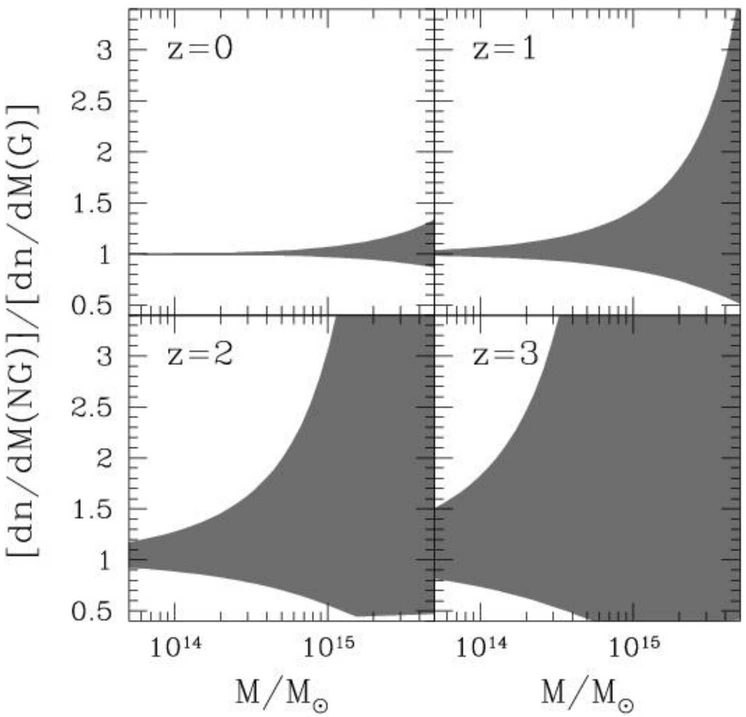


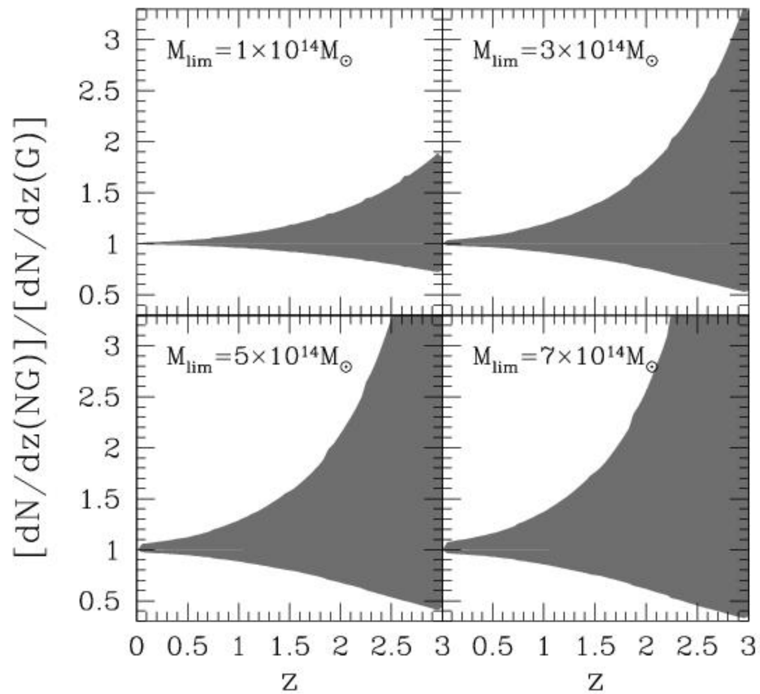
FIG. 8.—Model B: Non-Gaussian effect on the mass function on clusters scales. For two different redshift of collapse ($z_c = 1$, *left*; and $z_c = 2$, ***right***) the ratio of the mass function for model B to the mass function for a Gaussian field [$n(M, z_c)/n_G(M, z_c)$] is plotted as a function of mass. The choice for the ϵ parameter is, from top to bottom, $\epsilon = -100, -50, -10$. It is clear that for high masses one is probing the tail of the distribution, which is most sensitive to departures from Gaussianity.

Searching for NG with rare events

mass-function of massive haloes



number-counts of massive haloes



Komatsu et al. 2003 (assuming NG constraints from WMAP 1-yr)

DM halo clustering as (the most stringent?) constraint on NG

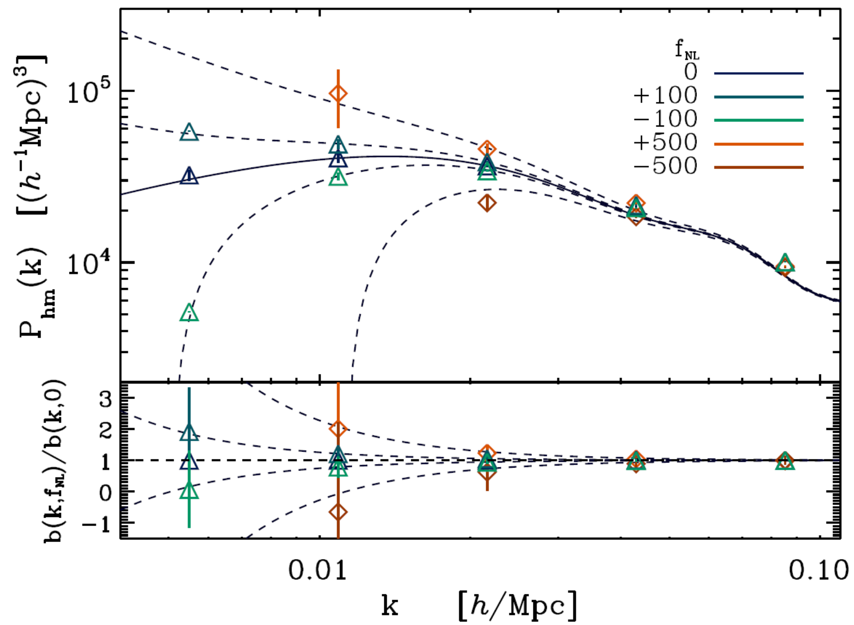
$$\delta_{halo} = b\ \delta_{matter}$$

Dalal et al. (2007) have shown that halo bias is sensitive to primordial non-Gaussianity through a scale-dependent correction term

$$\Delta b(k)/b \ \alpha\ 2 f_{NL}\delta_c / k^2$$

This opens interesting prospects for constraining or measuring NG in LSS but demands for an accurate evaluation of the effects of (general) NG on halo biasing.

Dalal, Dore', Huterer & Shirokov 2007



Clustering of peaks (DM halos) of NG density field

Start from results obtained in the 80's by

Grinstein & Wise 1986, ApJ, 310, 19

Matarrese, Lucchin & Bonometto 1986, ApJ, 310, L21

giving the general expression for the peak 2-point function as a function of N-point connected correlation functions of the background linear (i.e. Lagrangian) mass-density field

$$\xi_{h,M}(|\mathbf{x}_1 - \mathbf{x}_2|) = -1 +$$

$$\exp\left\{\sum_{N=2}^{\infty}\sum_{j=1}^{N-1}\frac{\nu^N\sigma_R^{-N}}{j!(N-1)!}\xi^{(N)}\begin{bmatrix}\mathbf{x}_1,\ldots,\mathbf{x}_1, & \mathbf{x}_2,\ldots\ldots\ldots,\mathbf{x}_2\\ j\,times & (N-j)\,times\end{bmatrix}\right\}$$

(requires use of path-integral, cluster expansion, multinomial theorem and asymptotic expansion). The analysis of NG models was motivated by a paper by Vittorio, Juszkiewicz and Davis (1986) on bulk flows.

THE ASTROPHYSICAL JOURNAL, 310:L21–L26, 1986 November 1

A PATH-INTEGRAL APPROACH TO LARGE-SCALE MATTER DISTRIBUTION ORIGINATED BY NON-GAUSSIAN FLUCTUATIONS

SABINO MATARRESE
International School for Advanced Studies, Trieste, Italy
FRANCESCO LUCCHIN
Dipartimento di Fisica G. Galilei, Padova, Italy
AND
SILVIO A. BONOMETTO
International School for Advanced Studies, Trieste, Italy; Dipartimento di Fisica G. Galilei, Padova, Italy; and INFN, Sezione di Padova
Received 1986 July 7; accepted 1986 August 1

ABSTRACT

The possibility that, in the framework of a biased theory of galaxy clustering, the underlying matter distribution be non-Gaussian itself, because of the very mechanisms generating its present status, is explored. We show that a number of contradictory results, seemingly present in large-scale data, in principle can recover full coherence, once the requirement that the underlying matter distribution be Gaussian is dropped. For example, in the present framework the requirement that the two-point correlation functions vanish at the same scale (for different kinds of objects) is overcome. A general formula, showing the effects of a non-Gaussian background on the expression of three-point correlations in terms of two-point correlations, is given.
Subject heading: galaxies: clustering

THE ASTROPHYSICAL JOURNAL, 310:19–22, 1986 November 1

NON-GAUSSIAN FLUCTUATIONS AND THE CORRELATIONS OF GALAXIES OR RICH CLUSTERS OF GALAXIES[1]

BENJAMIN GRINSTEIN[2] AND MARK B. WISE[3]
California Institute of Technology
Received 1986 March 6; accepted 1986 April 18

ABSTRACT

Natural primordial mass density fluctuations are those for which the probability distribution, for mass density fluctuations averaged over the horizon volume, is independent of time. This criterion determines that the two-point correlation of mass density fluctuations has a Zeldovich power spectrum (i.e., a power spectrum proportional to k at small wavenumbers) but allows for many types of reduced (connected) higher correlations. Assuming galaxies or rich clusters of galaxies arise wherever suitably averaged natural mass density fluctuations are unusually large, we show that the two-point correlation of galaxies or rich clusters of galaxies can have significantly more power at small wavenumbers (e.g., a power spectrum proportional to $1/k$ at small wavenumbers) than the Zeldovich spectrum. This behavior is caused by the non-Gaussian part of the probability distribution for the primordial mass density fluctuations.
Subject headings: cosmology — galaxies: clustering

Halo bias in NG models

- Matarrese & Verde 2008 applied this relation to the case of NG of the gravitational potential, obtaining the power-spectrum of dark matter halos modeled as high "peaks" (up-crossing regions) of height $\nu=\delta_c/\sigma_R$ of the underlying mass density field (Kaiser's model). Here $\delta_c(z)$ is the critical overdensity for collapse (at redshift a) and σ_R is the *rms* mass fluctuation on scale R ($M \sim R^3$).

- Account for motion of peaks (going from Lagrangian to Eulerian space), which implies (Catelan et al. 1998)

$$1+\delta_h(\mathbf{x}_{\mathrm{Eulerian}}) = (1+\delta_h(\mathbf{x}_{\mathrm{Lagrangian}}))(1+\delta_R(\mathbf{x}_{\mathrm{Eulerian}}))$$

and (to linear order) $b=1+b_L$ (Mo & White 1996) to get the scale-dependent halo bias in the presence of NG initial conditions. *Corrections may arise from second-order bias and GR terms.*

- Alternative approaches (e.g. based on 1-loop calculations) by Taruya et al. 2008; Matsubara 2009; Jeong & Komatsu 2009. Giannantonio & Porciani 2010 improve fit to N-body simulations by assuming dependence on gravitational potential) → extension to bispectrum by Baldauf et al. 2011

Halo bias in NG models

- Extension to general (scale and configuration dependent) NG is straightforward
- In full generality write the ϕ bispectrum as $B_\phi(k_1,k_2,k_3)$. The relative NG correction to the halo bias is

$$\frac{\Delta b_h}{b_h} = \frac{\Delta_c(z)}{D(z)} \frac{1}{8\pi^2\sigma_R^2} \int dk_1 k_1^2 \mathcal{M}_R(k_1) \times$$
$$\int_{-1}^{1} d\mu \mathcal{M}_R\left(\sqrt{\alpha}\right) \frac{B_\phi(k_1, \sqrt{\alpha}, k)}{P_\phi(k)} \times \frac{1}{M_R(k)}$$

$$\alpha = k_1^2 + k^2 + 2k_1 k\mu$$

- It also applies to non-local (e.g. "equilateral") NG (DBI, ghost inflation, etc..) and universal NG term!! (→ see also Schmidt & Kamionkowski 2010).
- Calibrated to N-body simulations by Grossi et al. (2009), Desjacques et al. 2009; Pillepich et al. 2009; ...

Observational status

Data/method	f_{NL} (local-type 95% CL)	reference **ad ref to bibl**
Photometric LRG - bias	$63^{+54+101}_{-85-331}$	Slosar et al. 2008
Spectroscopic LRG- bias	$70^{+74+139}_{-83-191}$	Slosar et al. 2008
QSO - bias	8^{+26+47}_{-37-77}	Slosar et al. 2008
combined	28^{+23+42}_{-24-57}	Slosar et al. 2008
NVSS–ISW	$105^{+647+755}_{-337-1157}$	Slosar et al. 2008
NVSS–ISW	$236 \pm 127(2-\sigma)$	Afshordi&Tolley 2008
NVSS-ACF (bias + ISW)	$10 < f_{NL} < 106$	Xia et al. 2010
SDSS DR6 QSOs (bias + ISW)	58 ± 24 (1 sigma)	Xia et al. 2010

positive NG @ more than 95% CL

Xia et al. (in prep.) analysis in terms of C_l

Xia, Bonaldi, Baccigalupi, De Zotti, Matarrese, Verde, Viel 2010

TABLE I: $1, 2\,\sigma$ constraints on the primordial non-Gaussianity from different data combinations.

Datasets	Non-Gaussianity $f_{\rm NL}$	
WMAP7+BAO+SN	$1\,\sigma$ C. L.	$2\,\sigma$ C. L.
NVSS Radio Sources		
+ACF	58 ± 28	$[16, 114]$
+CCF	29 ± 48	$[-50, 145]$
+ACF+CCF	53 ± 25	$[10, 106]$
SDSS DR6 Quasars		
+ACF	34 ± 22	$[-13, 63]$
+CCF	60 ± 42	$[-20, 145]$
+ACF+CCF	47 ± 21	$[10, 73]$

Observational prospects

On these large scales only the "two halo" term counts

Fisher matrix approach (Carbone, Verde & Matarrese 08;
see also Carbone, Mena & Verde 2010):

survey	z range	sq deg	mean galaxy density $(h/Mpc)^3$	$\Delta f_{\rm NL}/q'$ LSS
SDSS LRG's	$0.16 < z < 0.47$	7.6×10^3	1.36×10^{-4}	40
BOSS	$0 < z < 0.7$	10^4	2.66×10^{-4}	18
WFMOS low z	$0.5 < z < 1.3$	2×10^3	4.88×10^{-4}	15
WFMOS high z	$2.3 < z < 3.3$	3×10^2	4.55×10^{-4}	17
ADEPT	$1 < z < 2$	2.8×10^4	9.37×10^{-4}	1.5
EUCLID	$0 < z < 2$	2×10^4	1.56×10^{-3}	1.7
DES	$0.2 < z < 1.3$	5×10^3	1.85×10^{-3}	8
PanSTARRS	$0 < z < 1.2$	3×10^4	1.72×10^{-3}	3.5
LSST	$0.3 < z < 3.6$	3×10^4	2.77×10^{-3}	0.7

Observational prospects

Data/method	$\Delta f_{\rm NL}$ $(1-\sigma)$	reference
BOSS–bias	18	Carbone et al 2008
ADEPT/Euclid–bias	1.5	Carbone et al 2008
PANNStarrs –bias	3.5	Carbone et al 2008
LSST–bias	0.7	Carbone et al 2008
LSST-ISW	7	Afshordi& Tolley 2008
BOSS–bispectrum	35	Sefusatti & Komatsu 2008
ADEPT/Euclid –bispectrum	3.6	Sefusatti & Komatsu 2008
Planck-Bispectrum	3	Yadav et al . 2007
BPOL-Bispectrum	2	Yadav et al . 2007

The bispectrum sees the “shape”, the halo bias does not

Can we test standard single-field inflation NG?

- GR contributions to f_{NL} are universally present and can be seen through their effect on halo biasing (Verde & Matarrese 2009)

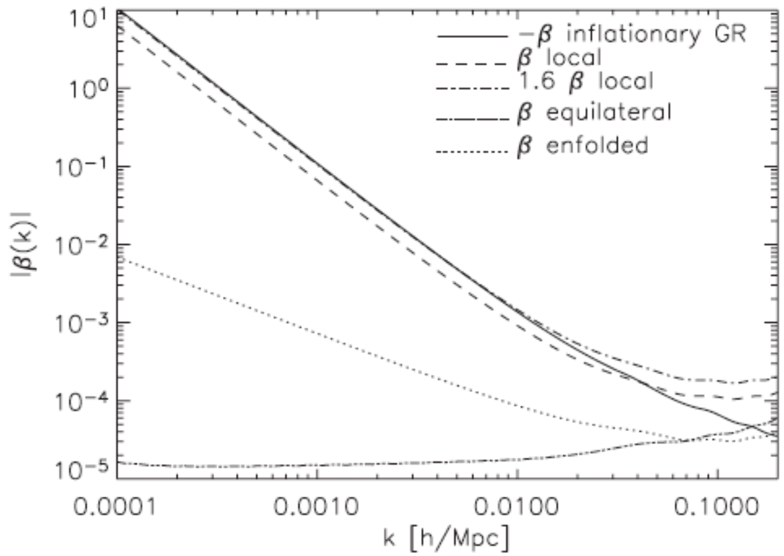


Figure 1. Scale dependence of the large-scale halo bias induced by a non-zero bispectrum, indicated by the β function of Equation (3) for the four types of non-Gaussianity discussed in the text. The solid line shows the absolute value of β for the inflationary, GR correction large-scale structure bispectrum. Note that the quantity is actually negative. The dashed line shows β for the local type of primordial non-Gaussianity for $f_{\rm NL}^{\rm loc} = 1$ (the quantity is positive). It is clear that the scale-dependent bias effect due to the inflationary bispectrum mimics a local primordial non-Gaussianity with effective $f_{\rm NL} \sim -1$ at $k > 0.02H$/Mpc and ~ -1.6 for $k < 0.01h$/Mpc. The dot-dot-dot-dashed line shows the effect of equilateral non-Gaussianity for $f_{\rm NL}^{\rm eq} = 1$ and the dotted line shows the enfolded type with $f_{\rm NL}^{\rm enf} = 1$.

$$f_{\rm NL}^{\rm infl,GR}(k_i, k_j, k_k) = -\frac{5}{3}\left[1 - \frac{5}{2}\frac{k_i k_j \cos\theta_{ij}}{k_k^2}\right]$$

Table 1
Forecasted Non-Gaussianity Constraints

Type NG	CMB Bispectrum		Halo Bias	
	Planck	(CM)BPol	Euclid	LSST
	1σ errors			
Local	$3^{(A)}$	$2^{(A)}$	$1.5^{(B)}$	$0.7^{(B)}$
Equilateral	$25^{(C)}$	$14^{(C)}$	...	...
Enfolded	$\mathcal{O}10$	$\mathcal{O}10$	$39^{(E)}$	$18^{(E)}$
	$\#\sigma$ Detection			
GR	N/A	N/A	$1^{(E)}$	$2^{(E)}$
Secondaries	$3^{(F)}$	$5^{(F)}$	N/A	N/A

References. (1) Yadav et al. 2007, (2) Carbone et al. 2008, (3) Baumann et al. 2009; Sefusatti et al. 2009, (4) this work, (5) e.g., Mangilli & Verde 2009.

Conclusions

☞ Contrary to earlier naive expectations, some level of non-Gaussianity is generically present in *all inflation models*. The level of non-Gaussianity predicted in the simplest (single-field, slow-roll) inflation is slightly below the minimum value detectable by *Planck* and at reach of future galaxy surveys.

☞ Constraining/detecting non-Gaussianity is a powerful tool to discriminate among competing scenarios for perturbation generation (*standard slow-roll inflation, curvaton, modulated-reheating, DBI, ghost inflation, multi-field, etc. …*) some of which imply large non-Gaussianity. Non-Gaussianity will soon become the *smoking-gun* for non-standard inflation models.

☞ The *Planck* mission (*in combination with future galaxy surveys*) will soon open a new window to the physics of the early Universe. COrE will provide further insight on NG shapes, cosmic strings ...

LSS evolution in GR