Title: Constraining primordial non-Gaussianity with large-scale structure

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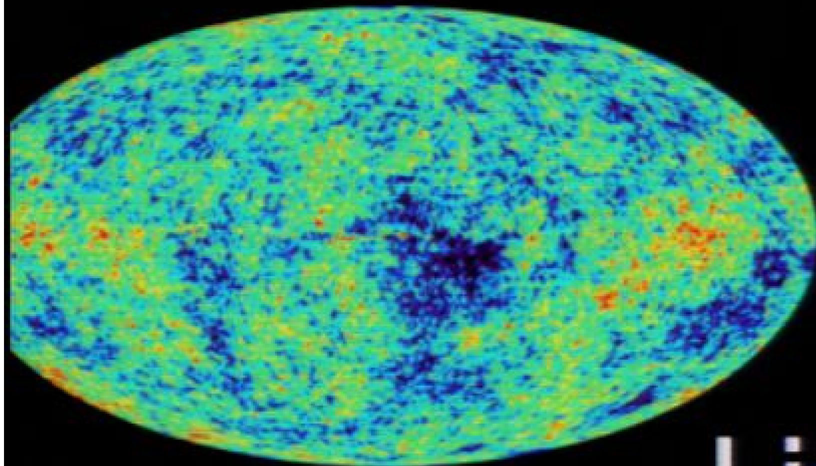
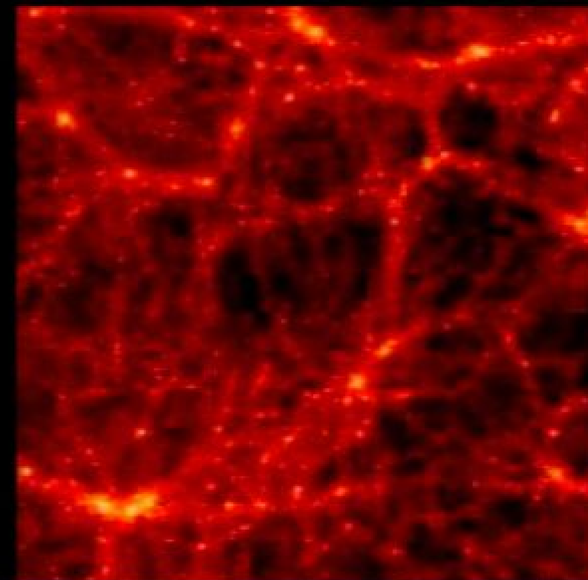
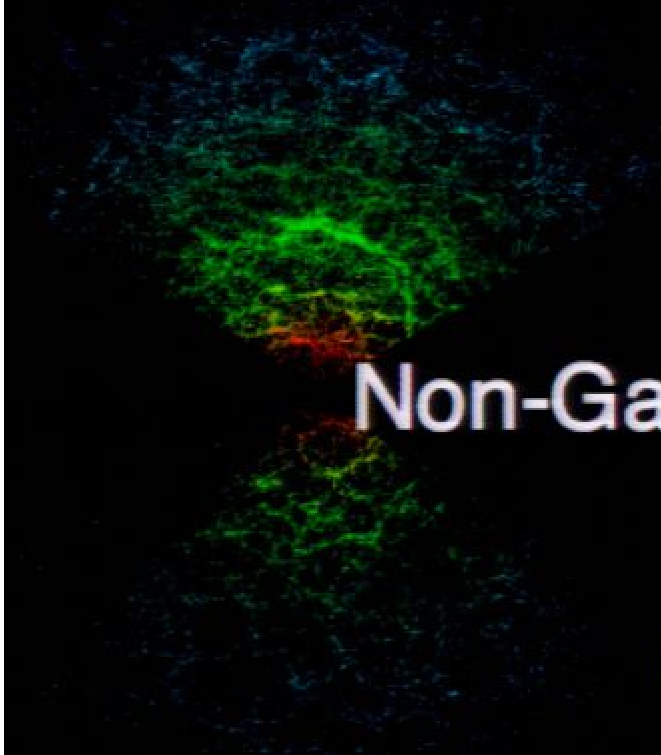
Abstract: Constraining primordial non-Gaussianity can offer a window into the early universe, and into testing the inflationary paradigm, which is fully complementary to the approach offered by Cosmic Microwave Background polarization.
Large-scale structure and galaxy surveys have recently received renewed attention as a way to constrain primordial non-Gaussianity. I will review the potential and the limitations of this approach and highlight its complementarity to Cosmic Microwave Background observations.





Licia Verde



Non-Gaussianity with large-scale structure

http://icc.ub.edu/~liciaverde

References

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Reid, Verde, Dolag, Matarrese, Moscardini, 2010, "Non-Gaussian halo assembly bias", arXiv:1004.1637

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Carbone, Mena, Verde, 2010. "Cosmological Parameters Degeneracies and Non-Gaussian Halo Bias", arXiv:1003.0456, in press

Jimenez, Verde, 2010, "Implications for Primordial Non-Gaussianity (fNL) from weak lensing masses of high-z galaxy clusters", PRD 80.127302

Xia, Viel, Baccigalupi, De Zotti, Matarrese, Verde,2010 "Primordial Non-Gaussianity and the NRAO VLA Sky Survey" ApJLett, 717 (2010) L17-L21, 2010.

BASIC MOTIVATION

see M. Zaldarriaga talk

Simplest inflationary models predict SMALL deviations from Gaussian initial conditions

How small is small? (How simple is simple?)
Can in some models "small" can be "detectable"?

There can always be non-standard models (strings, defects etc. yielding larger primordial non-Gaussianity)

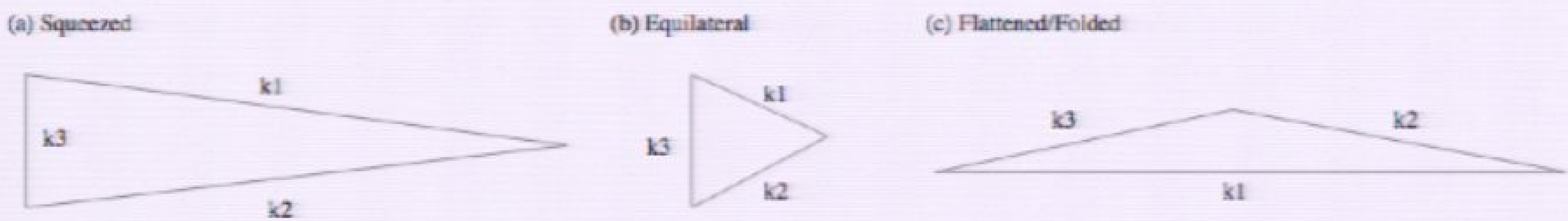
Fully complementary approach to looking for r (primordial tensor modes) in the CMB.

But for large-scale structure dedicated telescopes/surveys are not needed: the data will be gathered "anyway".

shapes

Simple inflationary model:
One field, canonical kinetic energy, slow roll, Bunch-Davies vacuum
→ Small LOCAL non-Gaussianity $\Phi = \phi + f_{NL}(\phi^2 - \langle\phi^2\rangle)$

Look at bispectrum



Violation of each of the above conditions leaves a unique signal with specific **shape**

From Komatsu et al. 2009, arxiv:0902.4759 & refs. there

The non-Gaussianity parameter f_{NL}:

f_{NL} Defined in Fourier space, through the bispectrum, and in general with complex dependence on k (vectors)

But many just say: $\Phi = \phi + \alpha\,(\phi^2 - <\phi^2>)$ Salopek Bond 1990; Gangui et al 1994; Verde et al 2000; Komatsu Spergel 2001

$\alpha \to f_{NL}$

f_{NL} Let's assume it is constant

This is called local model (Creminelli 03)
Typical of when non Gaussianity is generated outside the horizon

Defined on Gravitational potential
(actually Bardeen potential, important for sign)

Measuring fNL allows us to constraint inflationary models

Very very simple example: single field

Remember slow-roll parameters

$$\epsilon_* = \frac{m_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2, \quad \text{and} \quad \eta_* = \frac{m_{\rm Pl}^2}{8\pi}\left[\frac{V''}{V} - \frac{1}{2}\left(\frac{V'}{V}\right)^2\right]$$

The skewness is

$$S_{3,\Phi} = \frac{\langle \Phi^3 \rangle}{\langle \Phi^2 \rangle^2}$$

$$S_{3,\Phi} = 2 f_{NL} \times 3[1 + \gamma(n)]$$

Measuring fNL allows us to determine the shape of the inflaton potential

Relating the skewnness to the slow-roll parameters

$$f_{NL} = (5/2)\epsilon_* - (5/3)\eta_*$$

But the primordial slope is

$$n = 2\epsilon_* - 6\eta_* + 1$$

So a measurement of fNL gives you a measurement of the slow-roll parameters

$$\epsilon = 18/35 f_{NL} - n'/7$$

$$\eta = 6/35 f_{NL} - 3/14 n'$$

$$n' = n - 1$$

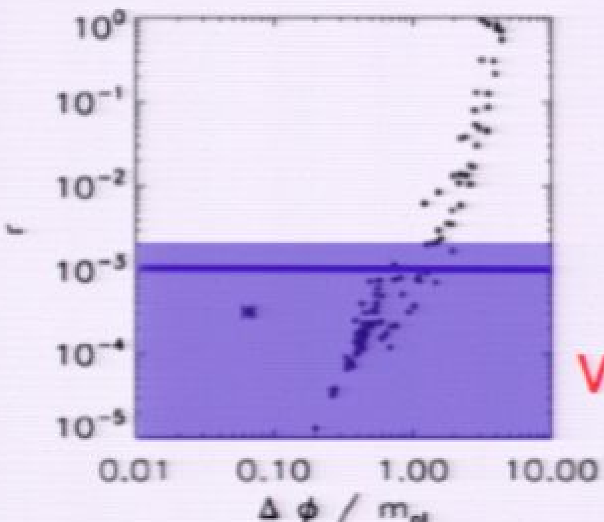
Verde, et al MNRAS 2001

And the scale of inflation…

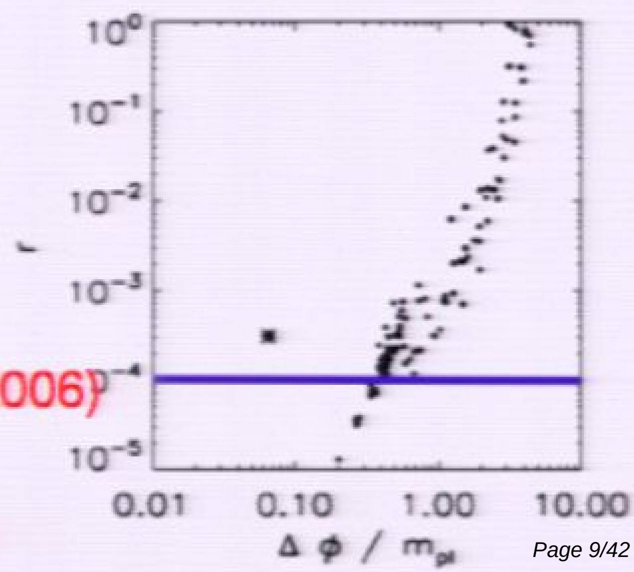
$$\Delta_R^2 = \frac{V/M_{pl}^4}{24\pi^2\epsilon}$$

Recall that CMB polarization detection
will be very challenging

What can be done



IDEAL EXPERIMENT



Verde, Peiris, Jimenez (2006)

Baumann et al 2009

(CMBPol working group)

Galaxy surveys:

Tools:

Bispectrum (or higher orders)

Clustering of peaks on large scales ← new

Abundance of rare events (peaks, massive halos…)

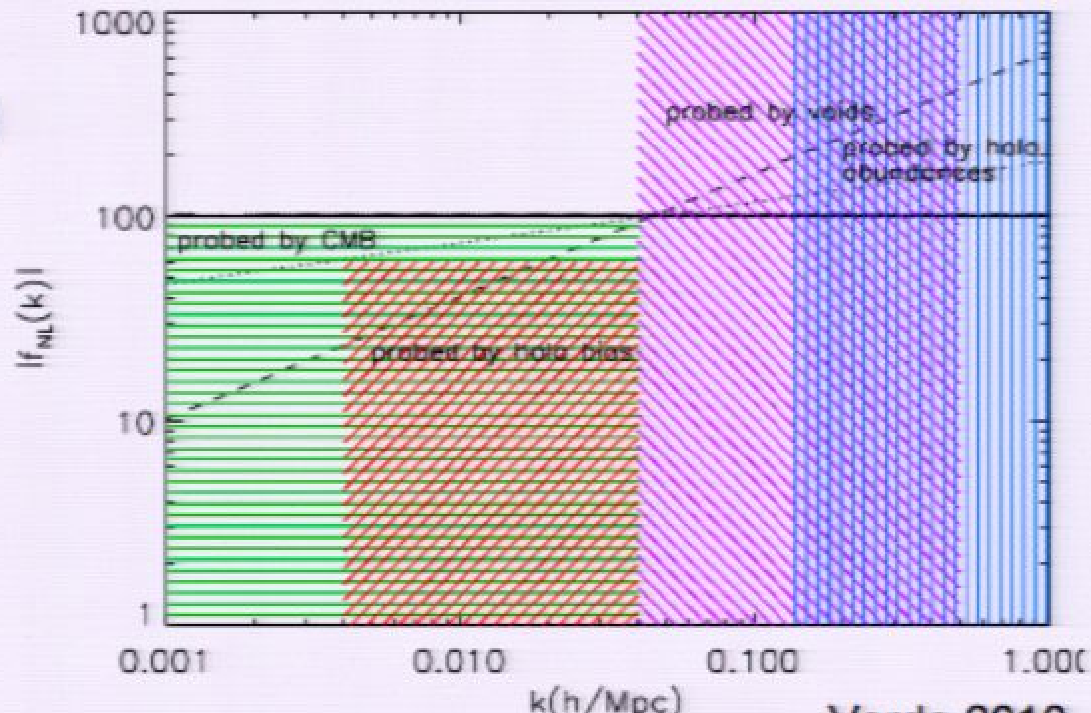
Topology

Searching for non-Gaussianity with LSS: COMPLEMENTARITY

Each probe is affected by different systematics

Clustering/spatial properties: Bispectrum, trispectrum, etc.
warning: gravity also generates NG
that's why trispectrum may be interesting (LV & Heavens 2001)

Abundance of rare events:
by looking at the tails of the halo mass function
warning: what's a halo and what's its mass?
What mass function?



Verde 2010

anyway interesting: can probe smaller scales than CMB

Searching for non-Gaussianity with LSS

Bispectrum, clustering; inflation-type

Verde et al. (1999) and Scoccimarro et al. (2004) showed that constraints on primordial NG in the gravitational potential from large redshift-surveys like 2dF and SDSS are not competitive with CMB ones : f_{NL} has to be larger than 10^2- 10^3 in order to be detected as a sort of non- linear bias in the galaxy-to-dark matter density relation. However LSS gives complementary constraints as it tests different scales than CMB.

Going to redshift z~2 can make LSS competitive (Sefusatti & Komatsu 2007). Going to higher z (e.g. through SZ cluster surveys or via 21-cm background anisotropies) helps, as the effective NG strength in the underlying CDM overdensity scales like (1+z) (LV et al 1999, Pillepich, Porciani & Matarrese 2006; Cooray 2006).

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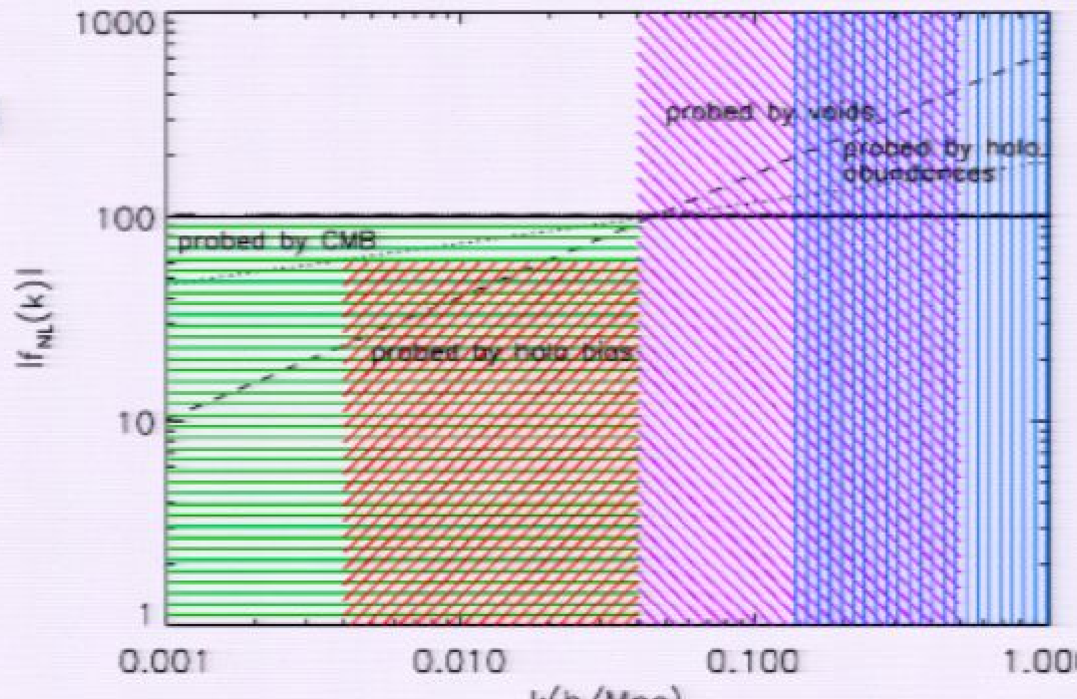

Verde 2010

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Abundance of 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!

Primordial non-Gaussianity also strongly affects the abundance of the first non-linear objects in the Universe, thereby modifying the reionization history.

- Matarrese LV & Jimenez (2000) and Verde, Jimenez, Kamionkowski & Matarrese showed that clusters at high redshift ($z>1$) can probe NG down to f_{NL} ~ few 10 which is, however, not competitive with future CMB (Planck) constraints (but probe different scales)
- Voids (rare events) may be competitive (Kamionkowski, Verde, Jimenez 2008)

MVJ(2000) mass function & improved formulae obtained by LoVerde, Miller, Shandera, Verde 2007, Grossi et al 09, Maggiore, Riotto 2009, D'Amico et al 2010

Abundance of Rare events

$$\frac{dn}{dM} = f\,\frac{\rho_b}{M}\left|\frac{dP(>\delta_c|z,M)}{dM}\right|$$

Press Schechter approach

Non-Gaussianity changes especially the tails

Note: this was derived in the Press-Schechter framework. PS fails at some point (spherical collapse etc.).

Recommended: use the ratio NG/G (compare this to observations normalized to numerically calibrated Gaussian predictions) $1+S_3\,\delta_c^3/(6\,\sigma_R^2)$

Must calibrate on N-body simulations.
(e.g., Grossi et al. 09, Desjaques et al 09, Pillepich et al 10)

Abundance of Rare events

A lightening fast history if the non-gaussian mass function!

Matarrese, LV & Jimenez (2001)

Derive the mass function for non-Gaussian fields using an approximation valid for rare events (MVJ) use a Press-Schecter-type approach

The resulting expressions should be used for fractional corrections

LoVerde, Miller, Shandera, Verde (2008)

Make different approximations, valid for not-so-rare events (LMSV,1&2)

Grossi, Verde et al (2009)

Calibrate on simulations, LMSV, MVJ work, need a factor $\sqrt{q}$ in front of δ_c

Riotto & Maggiore (2009)

Similar to LVMSV but improving over the Press-Schecter-type approach, giving the q factor (in the right place)

New: D'Amico, Musso, Norena, Paranjape

Get the best of three words: LVMSV2 not too shabby (in theory)!

Non-Gaussian halo bias

- A Gaussian field and a non-Gaussian field can have the same P(k)
- In a Gaussian field the P(k) of peaks is completely specified by the P(k)
- In a non-Gaussian field, however, the P(k) of the **peaks,** depends on all higher order correlations (i.e. f_{NL})

Non-Gaussian halo bias

- Gaussian IC and a non-Gaussian IC can have the same P(k) for the dark matter
- For Gaussian IC the P(k) of massive halos is completely specified by the dark matter P(k)
- For Non Gaussian IC, however, the P(k) of the halos, depends on all higher order correlations (i.e. f_{NL})

Non-Gaussian halo bias

For Gaussian initial conditions (known since the '80)

$$\xi_{h,M}(r) = \exp\left[\frac{\nu^2}{\sigma_R^2}\xi_R(r)\right] - 1 \simeq \frac{\nu^2}{\sigma_R^2}\xi_R(r)$$

$b_E = 1 + b_L$ "The Kaiser formula"

In the '90 this was improved (e.g. Mo & White 1996, Catelan et al 1998)

For Non-Gaussian initial conditions

Dalal et al. PRD 2008 7713514
Matarrese, Verde, ApJLett, 2008, 77:L77
Slosar et al 08
McDonald 08
Afshordi & Tolley 08
Valageas 2009

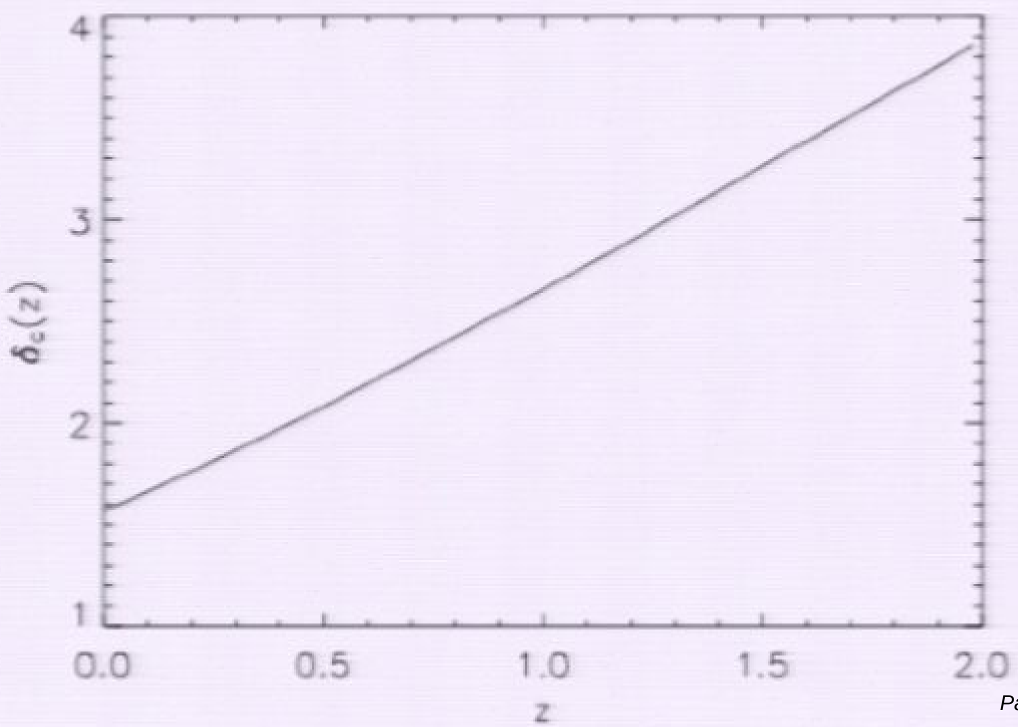
A scale-dependent bias!
(on top of the Gaussian one and proportional to it)

The Effect

$$\frac{\Delta b}{b^{L,G}} = \beta(k)\frac{\Delta_c(z)}{D(z)} \qquad \delta(k) = \mathcal{M}_R(k)\Phi(k) \qquad \alpha = k_1^2 + k^2 + 2k_1 k\mu$$

$$\beta(k) = \frac{1}{8\pi^2\sigma_R^2\mathcal{M}_R(k)}\int dk_1 k_1^2 \mathcal{M}_R(k_1)\int_{-1}^{1} d\mu \mathcal{M}_R\left(\sqrt{\alpha}\right)\frac{B_\phi(k_1,\sqrt{\alpha},k)}{P_\phi(k)}.$$

Redshift dependence



Matarrese, Verde 08, generalized to all bispectra

The Effect

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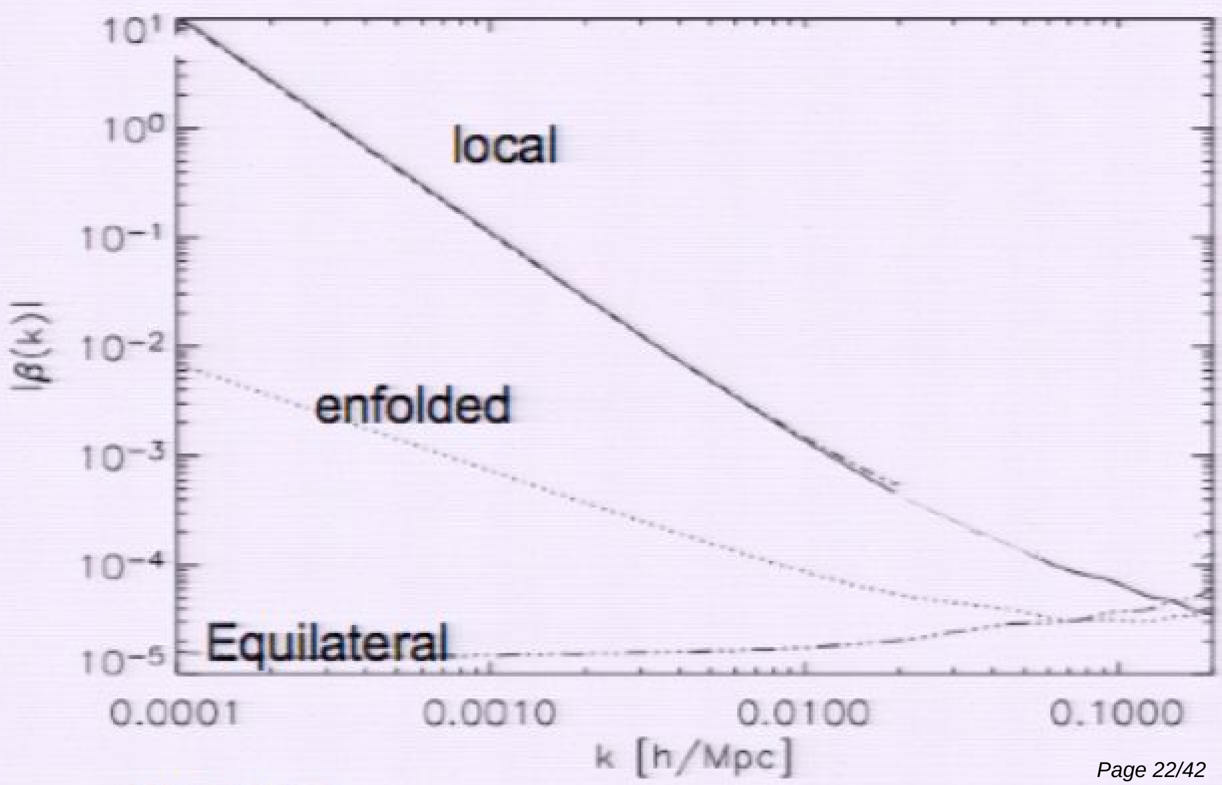
Scale-dependence



Matarrese, Verde 08
Verde, Matarrese 09

Interesting...

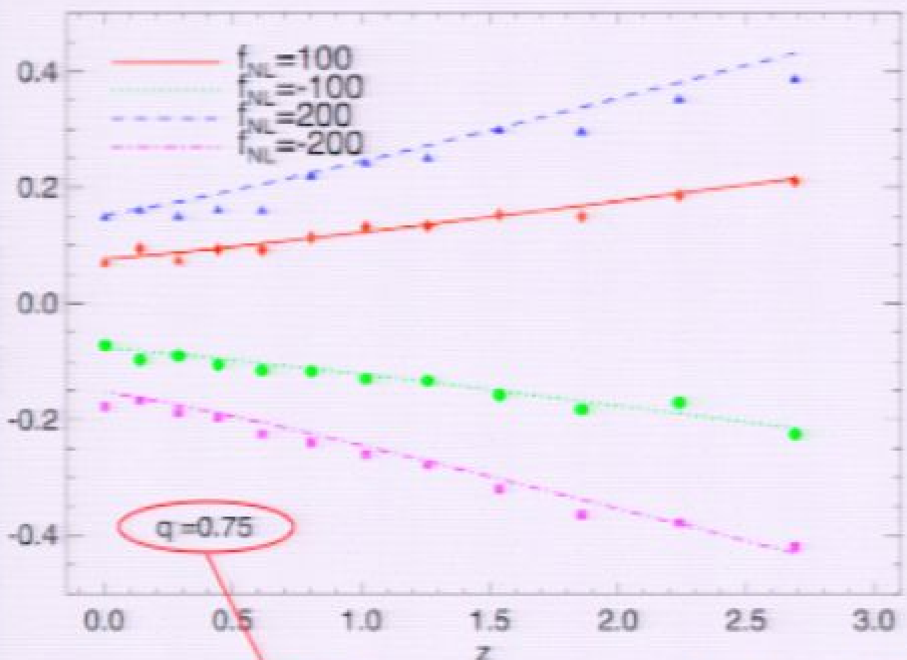
Calibration on simulations

e.g., Grossi, Verde, Carbone et al. 2009, MNRAS, 398, 321

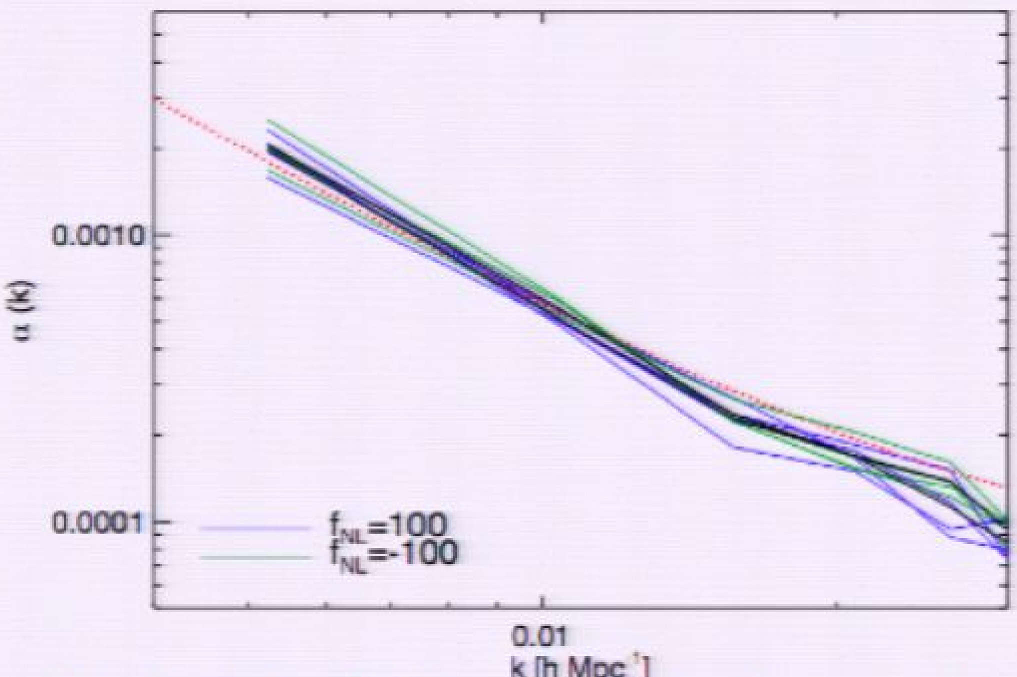
Volume: $(1.2\ \mathrm{Gpc}/h)^3$ 960^3 particles $m \approx 1.4 \times 10^{11} h^{-1} M_\odot$

Local non-gaussianity f_{NL}=0, -100, +100, -200, +200

Redshift dependence



Scale-dependence



Different interpretations: Grossi et al., Riotto& Maggiore, Desjaques etc.

Current constraints

Data/method	$f_{\rm NL}$	reference
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

Local-type only

CMB bispectrum (WMAP7 Komatsu et al 2010)

$$f_{\rm NL}^{\rm local} = 32 \pm 21 \ (68\% \ {\rm CL}) \qquad -10 < f_{\rm NL}^{\rm local} < 74.$$

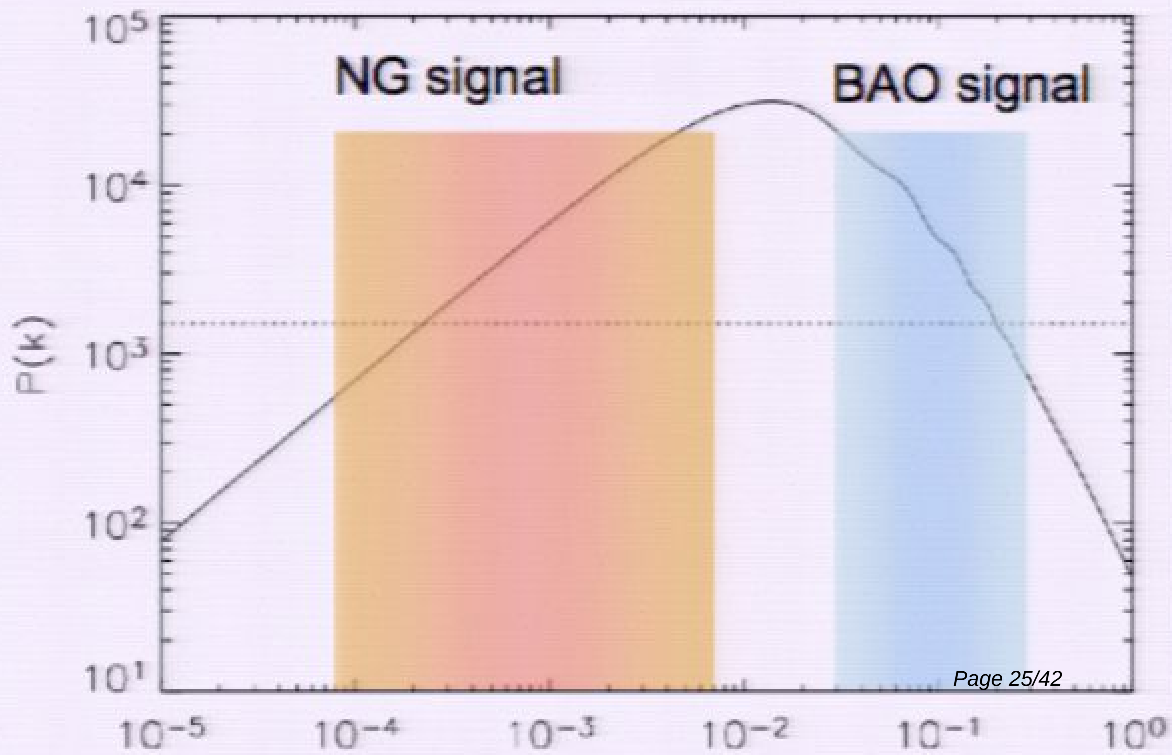
Interesting features

Spectro- vs photo- z's Smooth feature in k (this is not BAO)
Smooth behavior in z
Standard photo-z accuracy will suffice

BAO surveys well suited!

Large volumes
High-z
Appropriate shot noise

If nP~1 at k=0.2
Then nP~1 at k=10^{-4}



How well can this do? Local

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

Carbone, Verde, Matarrese 08

How well can this do? Local

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

Carbone, Verde, Matarrese 08

Carbone, Mena, Verde 2010:
there is no much degeneracy with cosmology!

Inflationary-GR Intrinsic to LSS

Bartolo, Matarrese, Riotto 2005, Bartolo et al 2006
Pillepich, Porciani, Matarrese, 2007

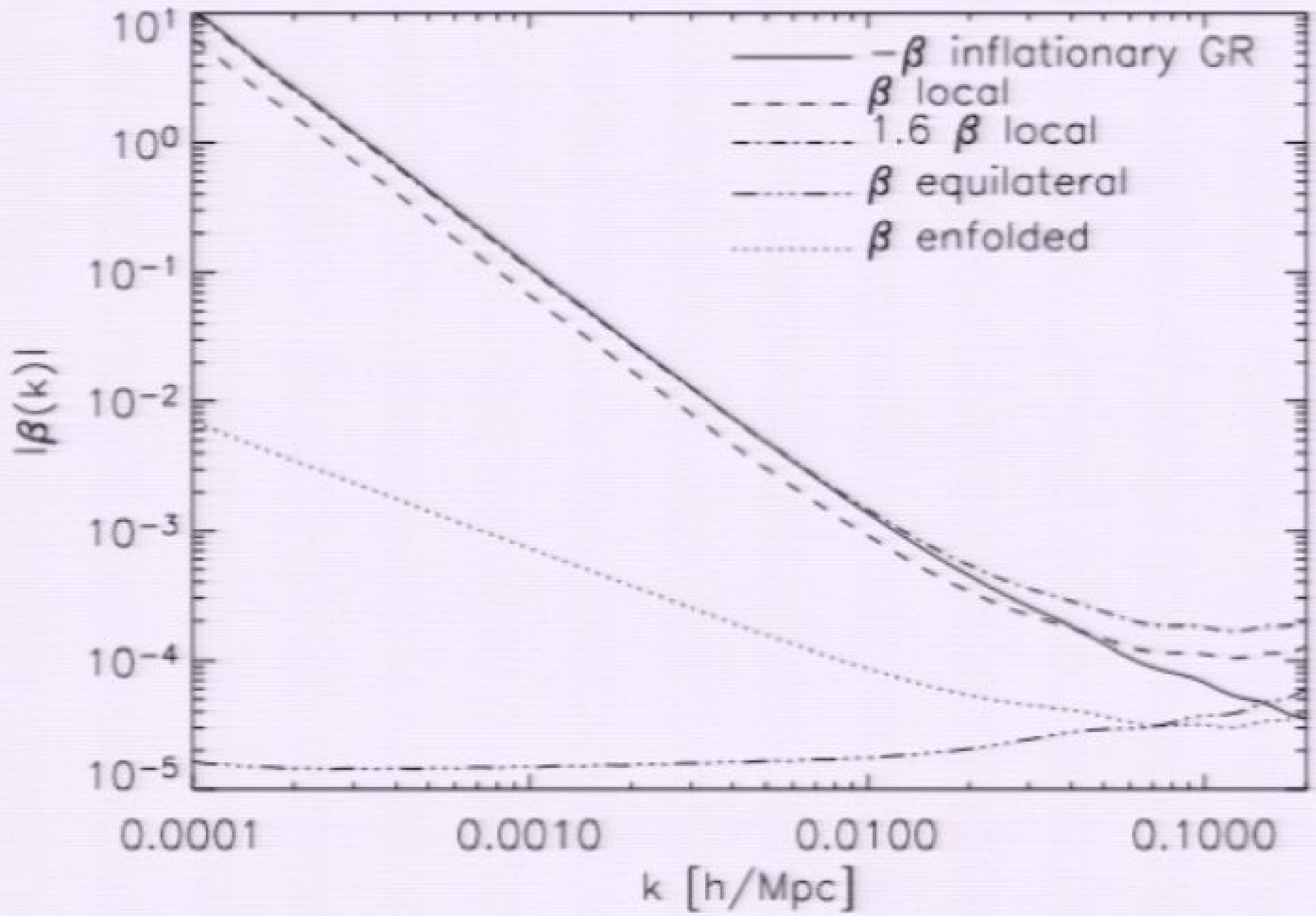
$$B_\Phi(k_1,k_2,k_3)=2\left[\frac{5}{3}(a_{\rm NL}-1)+f_{\rm NL}^{\rm infl,GR}(k_1,k_2,k_3)\right]P(k_1)P(k_2)+cyc.$$

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

On horizon-scales Poisson equation gets quadratic corrections:
Needs IC set up of inflation, parallels the TE anti-correlation.

Verde & Matarrese 2009, ApJL

Inflationary-GR Intrinsic to LSS



n horizon-scales Poisson equation gets quadratic corrections:
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Selection effects?

Assembly bias! (discussion on the gaussian case amplitude of the effect, Non-gaussian case effect expected to be larger…)

$$b_L^G = \bar{n}^{-1}\frac{\partial n}{\partial \delta_l} = \bar{n}^{-1}\frac{\partial n}{\partial \delta_c};$$

Peak Background split

Slosar et al 2008

Local case only

$$\Delta b_{\rm NG}(M,k,z_o) = \frac{2 f_{\rm NL}}{D(z_o)\mathcal{M}(k)}\frac{\partial \ln n(M,z_o)}{\partial \ln \sigma_8}$$

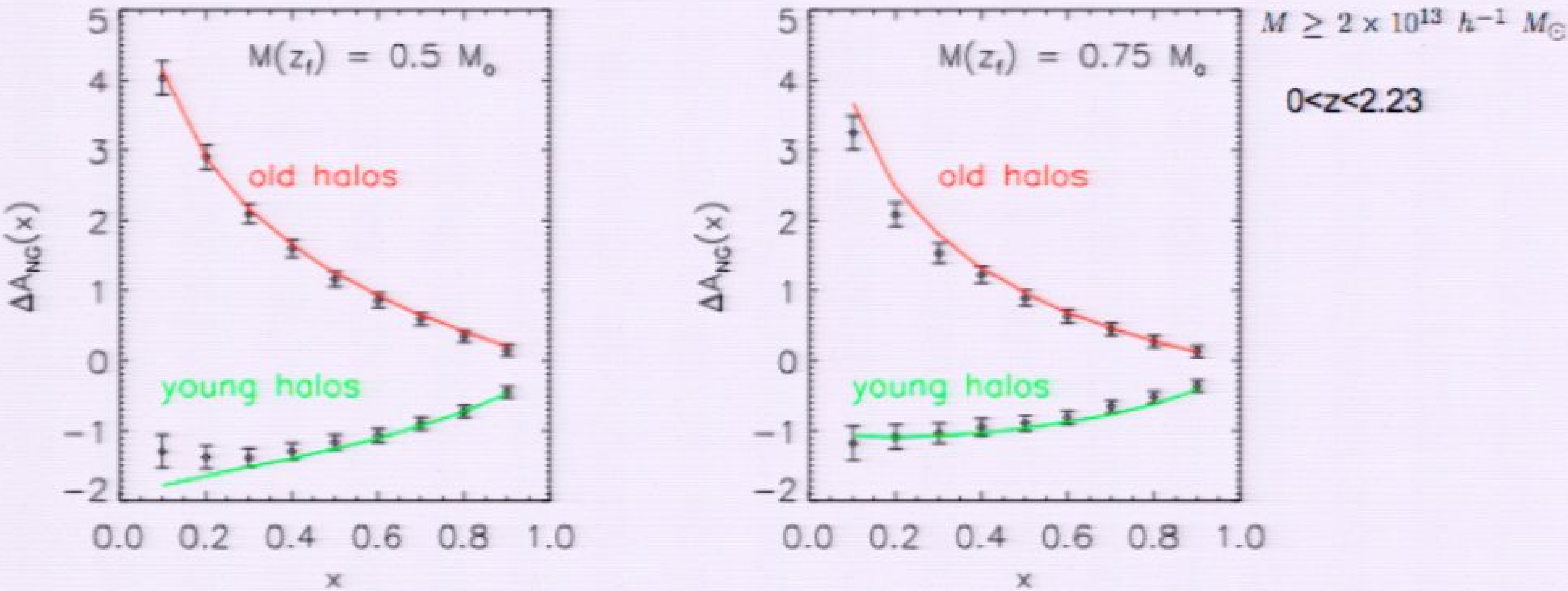
Reid et al. 2010, Extended PS approach:

$$\Delta b_{\rm NG}(M,k,z_o,z_f,f) = \frac{2 f_{\rm NL}}{D(z_o)\mathcal{M}(k)}\left(\frac{\partial \ln n(M,z_o)}{\partial \ln \sigma_8} + \frac{\partial \ln P_{z_f}(fM, z_f|M, z_0)}{\partial \ln \sigma_8}\right)$$

The proof of the pudding is in eating it

Dependence on halo formation time

$$\Delta A_{\rm NG} = \frac{\partial \ln P_{z_f}(fM, z_f | M, z_o)}{\partial \ln \sigma_8}$$



x is the fraction of halos with the highest (lowest) formation redshifts entering the sample

Points: simulations Grossi et al 2009

Line: ePS

$$\tilde{\omega}_f = \frac{\delta_c(z_f) - \delta(z_0)}{\sqrt{\sigma^2(fM) - \sigma^2(M)}}.$$

Is this worrying?

The effect is asymmetric between old and young halos. Even if the tracer population excludes only the 10% oldest halos, the value of the correction for the remaining 90% of the halos differs from the full sample by 0.44;
at z = 0, this amounts to a change of 40%.

Using the closest possible sample to recent major mergers
get -1: the ePS prediction derived in Slosar et al. 2008

Between theory and observations there is an ocean….

Go to Semi-analytic models

Non-Gaussian assembly bias in the Bertone et al. (2007) mock galaxy catalogs

$\bar{n}\ (h^{-1}\mathrm{Mpc})^{-3}$	selection criteria	$\Delta A_{\mathrm{NG}}^{\mathrm{gal}}$	b_G	$\delta_c(b_G-1)\approx A_{\mathrm{NG}}^{\mathrm{tot}}$	% change
4.5×10^{-4}	$\geq 8\times10^{10}\,h^{-1}\,M_\odot$	0.51	2.3	2.2	23%
4.5×10^{-4}	$\geq 24\,M_\odot/\mathrm{yr}$	0.24	1.3	0.51	48%

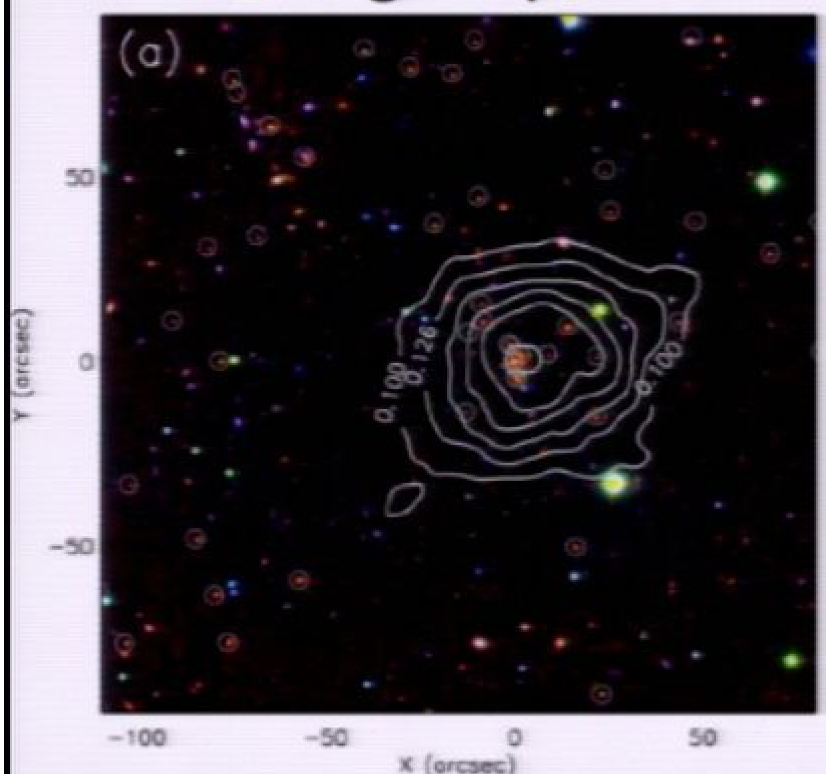
"observations" do not correlate well with halo formation time ????

Tantalizing hints
(this year only)

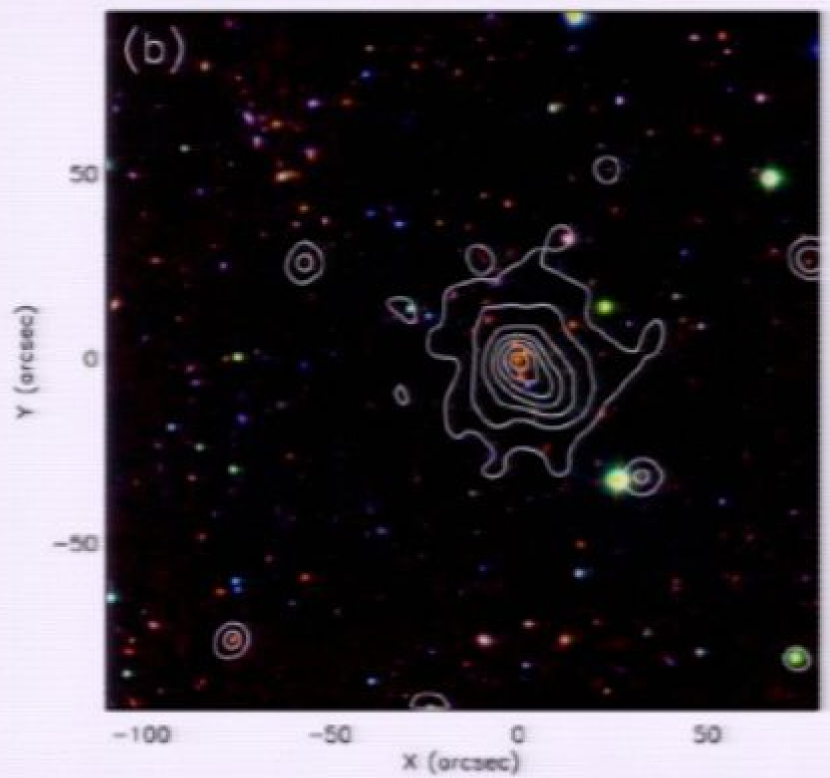
XMMUJ2235.3-2557

$(8.5 \pm 1.7) \times 10^{14} M_{\odot}$ z=1.4

Lensing + optical



X-ray + optical



Declared survey area: 11 sq deg

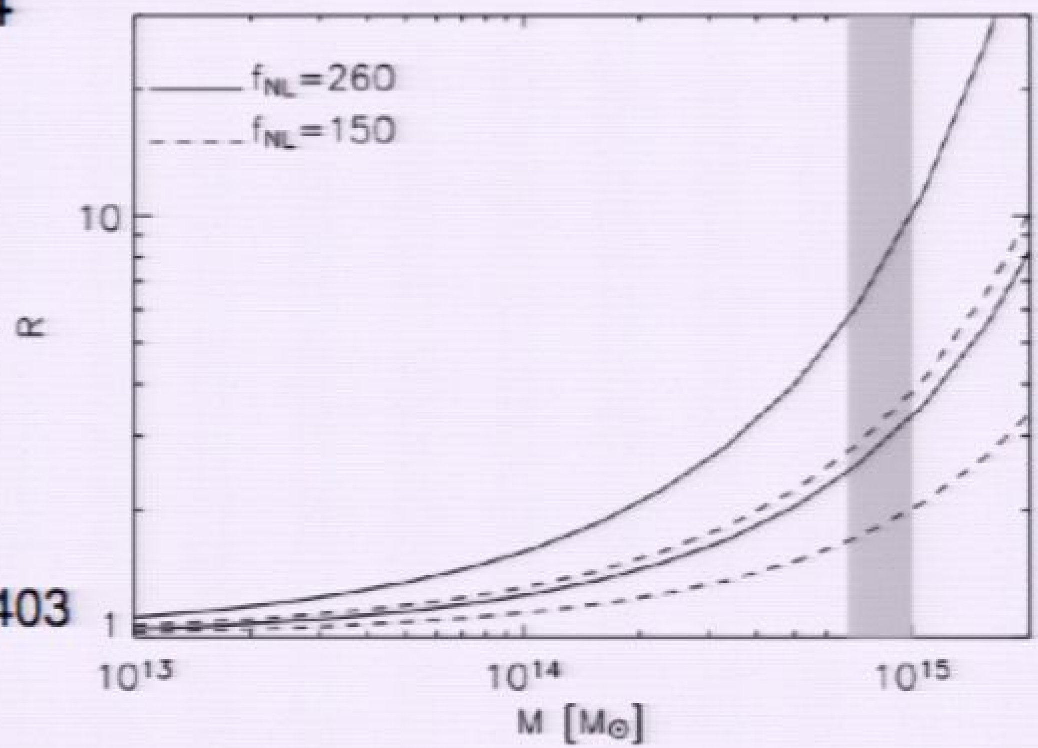
Jee, et al., 2009, ApJ, 704, 672, arXiv:0908.3897

XMMUJ2235.3-2557

$(8.5 \pm 1.7) \times 10^{14} M_\odot$ z=1.4

M> central estimate
expect ZERO in the 4π

M> lower estimate
expect 7 in the 4π

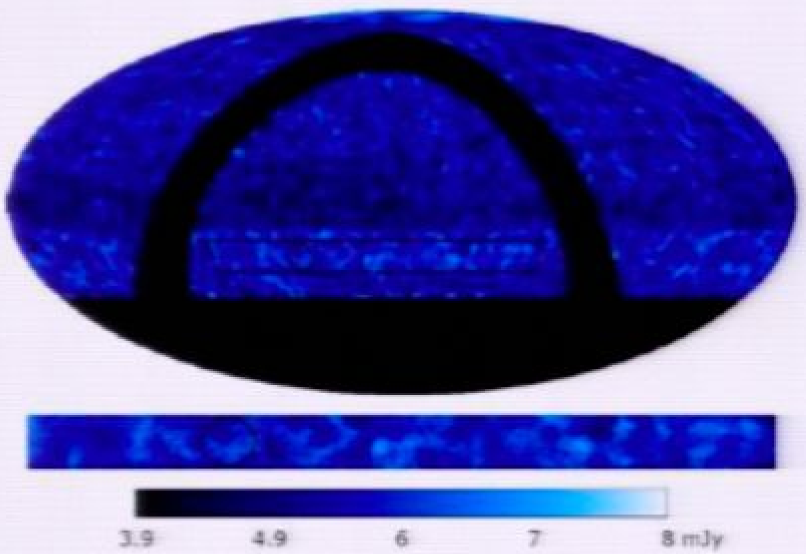


Jimenez, Verde, 2010 arXiv:0909.0403
Sartoris et al. arXiv:1003.0841
Holz, Perlmutter, arXiv:1004.5349
Cayon et al arXiv:1006.1950

NON-GAUSSIAN ENHANCEMENT

Weak lensing area 11 sq deg → P=0.005
XMM serendipitous survey area
in 2006: 165 sq deg → P=0.07
Now : 400 sq deg → P=0.17

NVSS correlation function



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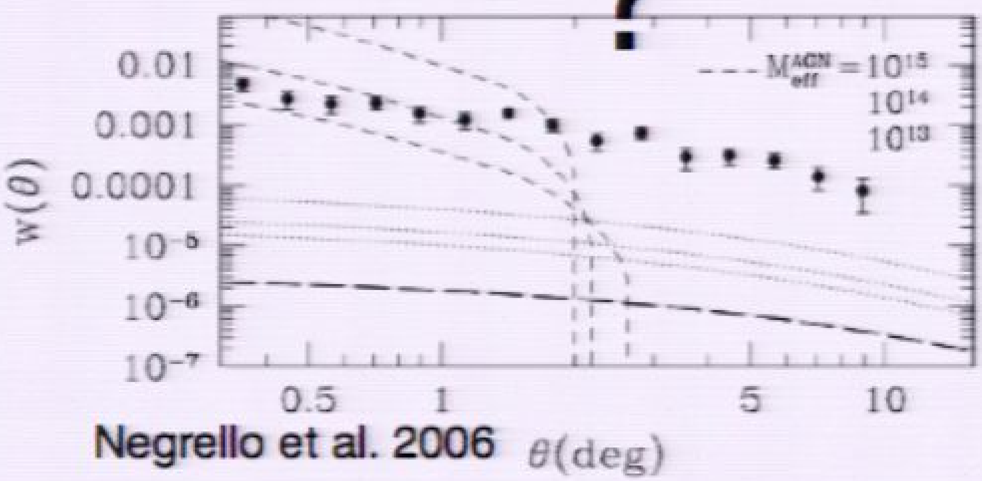


Negrello et al. 2006

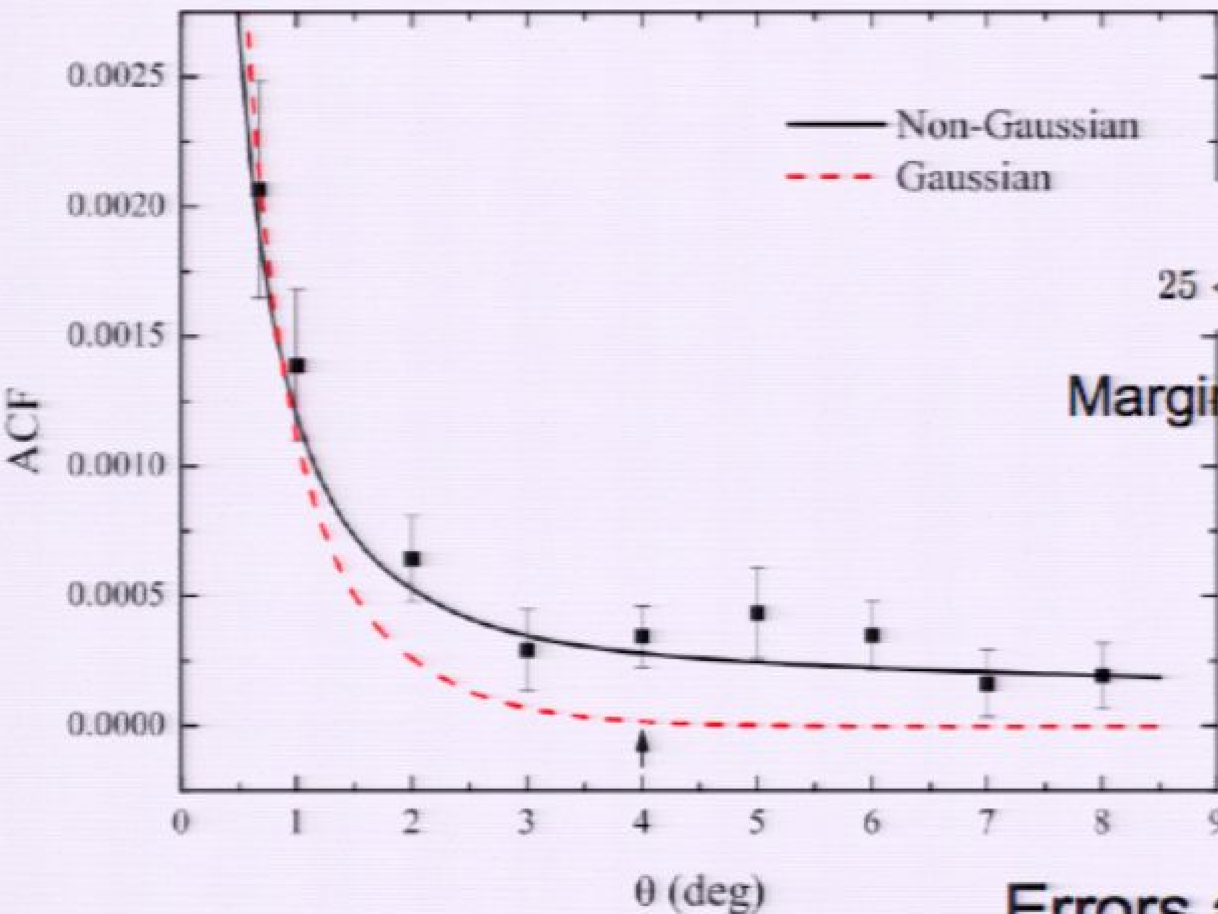
Explanations include:

Tinker with redshift distribution of sources…

Evolution of bias factor radically different from that of optical QSOs (e.g., Magliocchetti et al 1999, Negrello et al. 2006; Massardi et al. 2010….)

Could it be f_{NL}?

Xia, Viel, Baccigalupi, DeZotti, Matarrese, LV (2010)



$$f_{\rm NL} = 62 \pm 27 \ (1\,\sigma \ \ \text{C.L.}) \ ;$$

$$25 < f_{\rm NL} < 117(142) \ \ [95\% \ (99.7\%) \ \ \text{C.L.}],$$

Marginalizing over constant offset

$$f_{\rm NL} = 58 \pm 28 \ (1\sigma\,\text{C.L.})$$

Errors are jackknife-estimated (including full correlations)

My point being: if there is an fnl local ~few x 10 out there, today we have the capability of seeing it.

Extraordinary claims need extraordinary proofs

Complementarity

Putting it all together

Complementarity!

	CMB Bispectrum		Halo bias	
type NG	Planck	(CM)BPol	Euclid	LSST
		$1-\sigma$ 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

A) YADAV, KOMATSU & WANDELT (2007) B) CARBONE ET AL. (2008) C) BAUMANN ET AL. (2009); SEFUSATTI ET AL. (2009) E)Verde & Matarrese 2009 F) Mangilli & Verde 2009, Hanson et al. 2009

Conclusions
& future prospects

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* Constraining/detecting non-Gaussianity is a powerful tool to discriminate among competing scenarios for perturbation generation (*standard 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.

Conclusions & future prospects

* Constraining/detecting non-Gaussianity is a powerful tool to discriminate among competing scenarios for perturbation generation (*standard 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.

* Complementary approach to looking for primordial B models in CMB polarization

* Constraining non-Gaussianity in LSS allows to put independent limits on NG and on a different range of scales. Massive/high redshift objects (rare events) are most sensitive to primordial non-Gaussianity, both in their abundance and clustering (bias).

* Predicting/constraining non-Gaussianity is ready to become a branch of *Precision Cosmology:* this requires accurate analytical calculations, high-resolution numerical simulations.