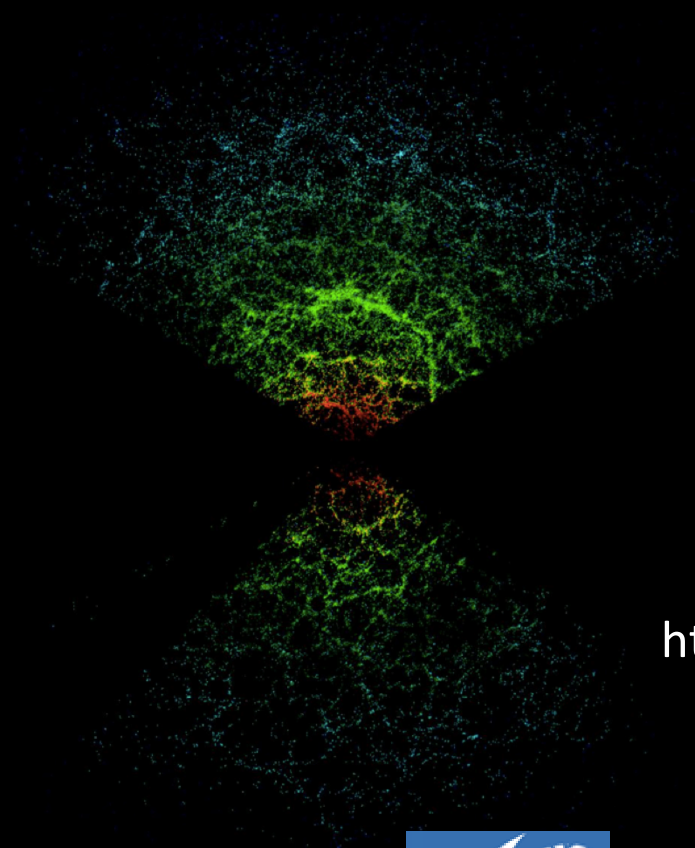
(Primordial) Non Gaussianity and large-scale structure



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Outline

Ideal

Real

Last Judgment, Vasari, Florence Duomo

Tools:

Bispectrum (or higher orders)

Abundance of rare events (peaks, massive halos, voids…)

(Topology)

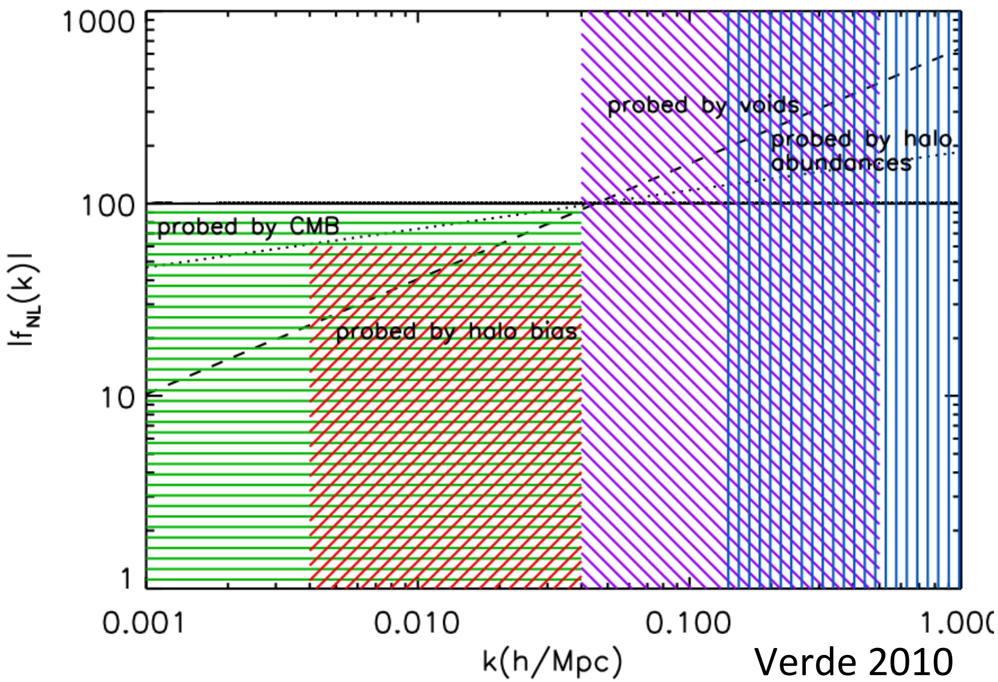
Clustering of peaks on large scales

Anything else???

Non-linearities always present in LSS: N-body simulations (at the very least)

Searching for non-Gaussianity with LSS: COMPLEMENTARITY

Each probe is affected by different systematics



Verde 2010

interesting: can probe smaller scales than CMB

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".

Bispectrum

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; Sefusatti,Komatsu 2007).

``Galaxy” Clustering

$$\langle\delta(\mathbf{r}_1)\delta(\mathbf{r}_2)\delta(\mathbf{r}_3)\rangle = \frac{1}{(2\pi)^6}\int d^3\mathbf{k}_1 d^3\mathbf{k}_2 d^3\mathbf{k}_3 B(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)e^{i(\mathbf{k}_1\cdot\mathbf{r}_1+\mathbf{k}_2\cdot\mathbf{r}_2+\mathbf{k}_3\cdot\mathbf{r}_3)}\delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)$$

Now this is the density!!!

$$\delta_{\mathbf{k}}(a) = \hat{M}(k;a)\Phi_{\mathbf{k}}$$

$$M(k,a) \equiv \frac{2}{3}\frac{D(a)}{H_o^2\Omega_m}k^2T(k).$$

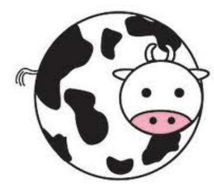
Additional complications:

- Non-linear gravity:

$$B(\mathbf{k_1},\mathbf{k_2},\mathbf{k_3}) = \mathcal{K}(\mathbf{k_1},\mathbf{k_2})P(k_1)P(k_2) + cyc.$$

- biasing

$$\delta(\mathbf{x}) = b_1\delta_m(\mathbf{x}) + \frac{1}{2}b_2\delta_m(\mathbf{x})^2$$



$$\mathcal{K}(\mathbf{k_1},\mathbf{k_2}) \longrightarrow \frac{\mathbf{1}}{\mathbf{b_1}}\mathcal{K}(\mathbf{k_1},\mathbf{k_2}) + \frac{\mathbf{b_2}}{\mathbf{b_1^2}}$$

Cf. with primordial (initial) bispectrum for LOCAL type:

$$B_\delta^I(k_1,k_2,k_3) = 2f_{\rm NL}\left(\frac{M(k_3)}{M(k_1)M(k_2)}P_\delta(k_1)P_\delta(k_2) + cyc.\right)$$

Why?

$$\Phi = \phi + \alpha(\phi^2 - \langle\phi^2\rangle)$$

$$B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \simeq$$
$$\left\{P(k_1)P(k_2)\left[\left(2\alpha\frac{\mathcal{M}_{k_3}}{\mathcal{M}_{k_1}\mathcal{M}_{k_2}}\right) + 2J(\mathbf{k}_1, \mathbf{k}_2)\right]\right\} + cyc.$$

fNL

gravity

$$\delta(k, z) = \mathcal{M}_k(z)\Phi(k), \text{ where } \mathcal{M}_k(z) = \frac{2k^2T(k)(1+z)}{3H_0^2}.$$

from Verde et al1999

In ‘99 did not take Λ seriously

!

In 1999 I did not think one could measure the galaxy bispectrum at z>0, and disentangle it from bias, but in the 21st century…

You can also think of 21 cm (e.g. Pillepich et al 06**)**

Could look for other type of NG

Must disentangle gravity (and biasing) first, these are **not small nor simple signals**

Model gravity first:

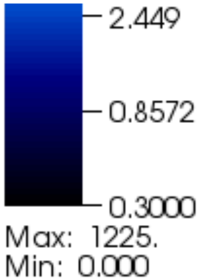
- Analytically
- Simulations
- fit

$$F_2^s(\mathbf{k}_i,\mathbf{k}_j) = \frac{5}{7} + \frac{1}{2}\cos(\theta_{ij})\left(\frac{k_i}{k_j} + \frac{k_j}{k_i}\right) + \frac{2}{7}\cos^2(\theta_{ij}),$$

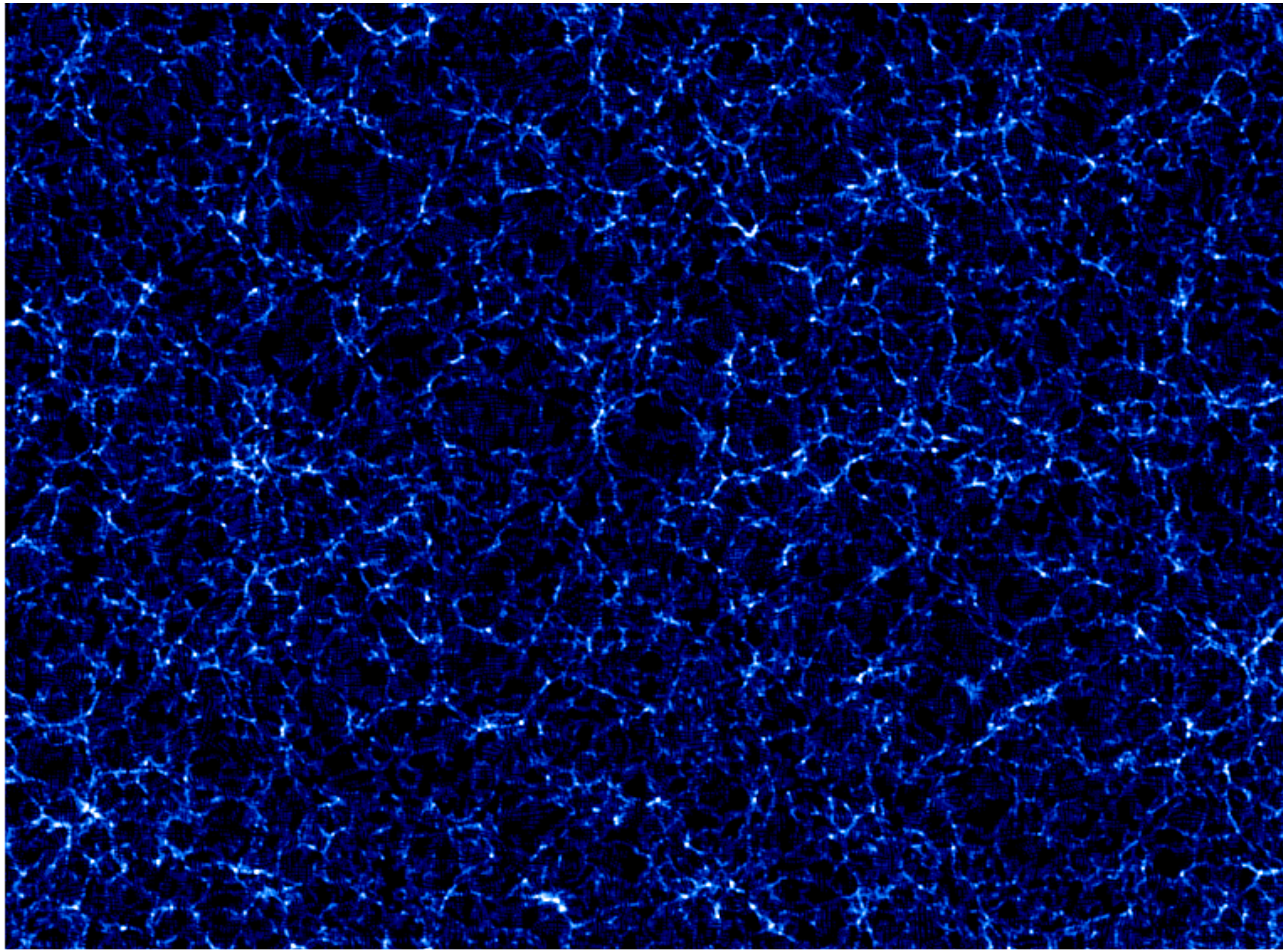
2OPT kernel

Scoccimarro Couchman 2001

$$\begin{aligned} F_2^{\rm eff}(\mathbf{k}_i,\mathbf{k}_j) &= \frac{5}{7}a(n_i,k_i)a(n_j,k_j) \\ &+ \frac{1}{2}\cos(\theta_{ij})\left(\frac{k_i}{k_j} + \frac{k_j}{k_i}\right) b(n_i,k_i)b(n_j,k_j) + \frac{2}{7}\cos^2(\theta_{ij})c(n_i,k_i)c(n_j,k_j), \end{aligned}$$



600x600x30 Mpc/h.



Courtesy of C. Wagner

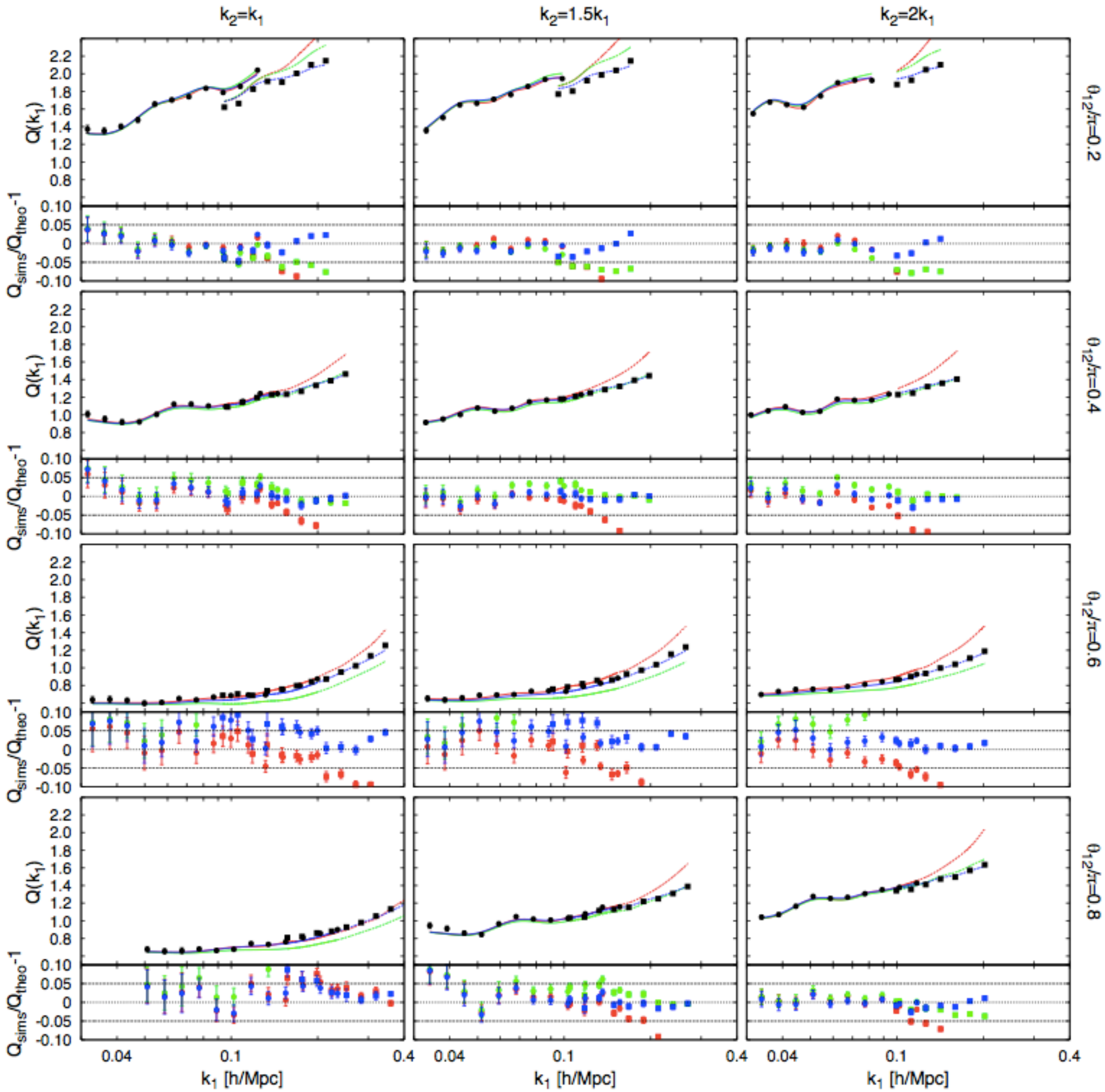
$$\frac{B(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)}{P(k_1)P(k_2)+P(k_1)P(k_3)+P(k_2)P(k_3)}$$

1loop SC01

This fit simulations

Fix BAO
Improve fit
Bigger sims

	A	B
L_b [Mpc/h]	2400	1875
N_p	768^3	1024^3
N_r	40	3
$k_N/4$ [h/Mpc]	0.25	0.43
softening ϵ [kpc/h]	90	40
PM grid	2048^3	2048^3
ErrTolForceAcc α	0.005	0.005
initial scale factor a_i	0.05	0.02
maximum $\Delta \log a$	0.025	0.025
ErrTolIntAccuracy η	0.025	0.025
# time steps	~ 1300	~ 2500



Gil-Marin, Wagner, Frakgoudi, Jimenez, LV, 2012 (arXiv1111.4477)

See also Schmittfull et al 2012

(Some) ISSUES for discussion :

- (How well) Do we know gravitational instability Bispectrum? (simulate/then fit e.g., Gil-Marin et al.2012; model, PT+++?)
- (How well) Do we know bias? (of what?, optimal weighting?)
- Do we *need* to work with galaxies/halos? (think of lensing)
- Can non-linearities be undone? (see reconstruction?, clipping?)
- How does bias interfere with non-gaussianity and vice versa

(can still simulate, work in rapid progress)

- How do you estimate confidence intervals? Is there an optimal estimator?
- How can you combine Power spectrum and Bispectrum measurements?

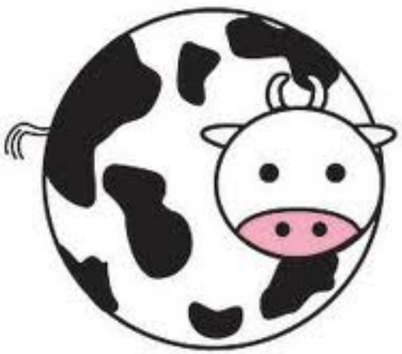
example: for a Gaussian field x, x and x^2 (or x^2 and x^3) are uncorrelated but NOT independent, so…..

- Different triangles are not independent nor necessarily uncorrelated
- Does one need a better likelihood than a chisquare? Does central limit theorem hold? (see e.g. Wandelt and collaborators work on CMB)
- What if it is not a simple f_{NL}?
- What about the LSS trispectrum?

Part of bigger picture: bispectrum of LSS is useful for other science as well…

small aside for Local non gaussianity

(with Alvarez-Gaume’, Heavens, Jimenez, Matarrese)

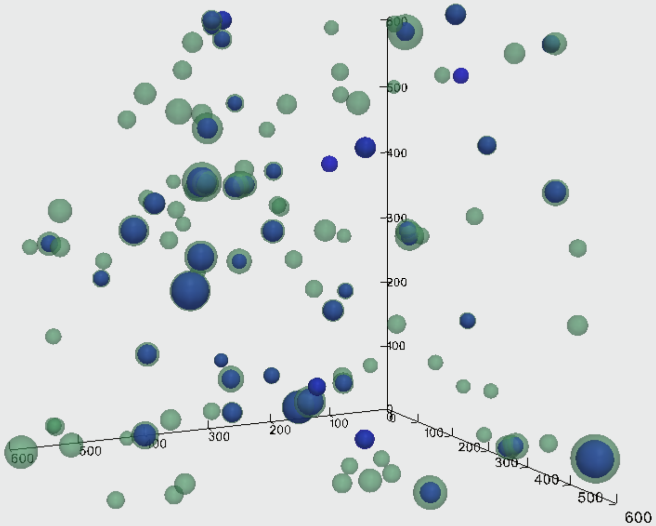


Local non-linear (non monotonic) transformation of a multi-variate Gaussian field Φ
Followed by linear operators, superposed with independent almost Gaussian processes

Must be possible to treat (analytically) exactly

How important is to obtain an **exact** formulation of the relevant statistics? E.g., tails

But why local only? E.g., other models, gravity, etc..



Credit: C. Wagner

Abundance of rare events

Massive halos (peaks)→ mass function

Extremely appealing in principle

Not space to report all the recent literature
massive revival on the past few years,
great progress.

	simulations	theory
	Can now go (well) beyond local fnl Check out: http://icc.ub.edu/~liciaverde/NGSCP.html	Modeling getting exquisite Excursion set Moving barrier Diffusing barrier
	Hard to get the tails, slow, expensive	What's a halo, really..

Need: interplay theory-simulations, generality (not just local NG)
Direct simulations comparison, can model the RATIO NG/G? Some "fudge" factor

simulations

Three approaches:

Wagner et al. 2011, 2012

$$\Phi_{\mathbf{k}} = \Phi^{\rm G}_{\mathbf{k}} + \Phi^{\rm NG}_{\mathbf{k}}.$$

$$\Phi^{NG}_{\mathbf{k}} = \frac{1}{2(2\pi)^3}\int d^3k' \frac{B_\Phi(k,k',|\mathbf{k}+\mathbf{k}'|)\Phi^{*G}_{\mathbf{k}'}\Phi^{G}_{\mathbf{k}+\mathbf{k}'}}{P_\Phi(k)P_\Phi(k')+P_\Phi(k')P_\Phi(|\mathbf{k}+\mathbf{k}'|)+P_\Phi(k)P_\Phi(|\mathbf{k}+\mathbf{k}'|)}$$

Which improves over

$$= \frac{1}{6(2\pi)^3}\int d^3k_2 B(k,k_2,|\mathbf{k}+\mathbf{k}_2|)\frac{\Phi^{*G}_{\mathbf{k}_2}}{P(k_2)}\frac{\Phi^{G}_{\mathbf{k}+\mathbf{k}_2}}{P(|\mathbf{k}+\mathbf{k}_2|)}$$

Scoccimarro et al 2012

$$\Phi_{\rm EQ} = \phi + f_{\rm NL}\Big[-3\phi^2 + 4\,\partial^{-1}(\phi\,\partial\phi) + 2\,\nabla^{-2}(\phi\,\nabla^2\phi) + 2\,\nabla^{-2}(\partial\phi)^2\Big],$$

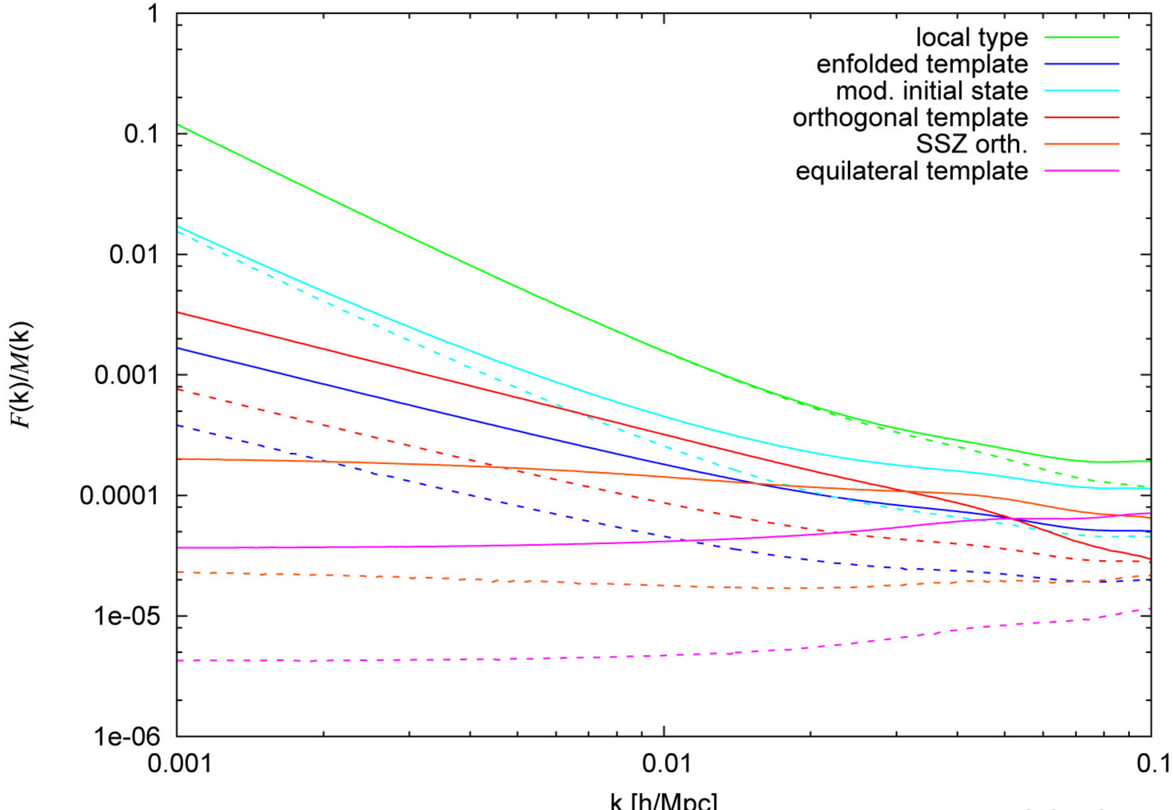
$$\Phi_{\rm ORT} = \phi + f_{\rm NL}\Big[-9\phi^2 + 10\,\partial^{-1}(\phi\,\partial\phi) + 8\,\nabla^{-2}(\phi\,\nabla^2\phi) + 8\,\nabla^{-2}(\partial\phi)^2\Big]$$

Regan et al 2012

$$\frac{B(k,k',k'')}{P(k)P(k')+P(k)P(k'')+P(k')P(k'')} = \sum_{rst}\alpha^{Q}_{rst}q_r(k)q_s(k')q_t(k''),$$

Expand that in separable basis

Beware:Templates vs. physical shapes



Wagner LV 2012

- **templates** approximate the physical bispectra over all triangle configurations and are **factorizable**
=> allows efficient computation

- however, for the **NG bias** the correct scaling in the **squeezed limit** is crucial

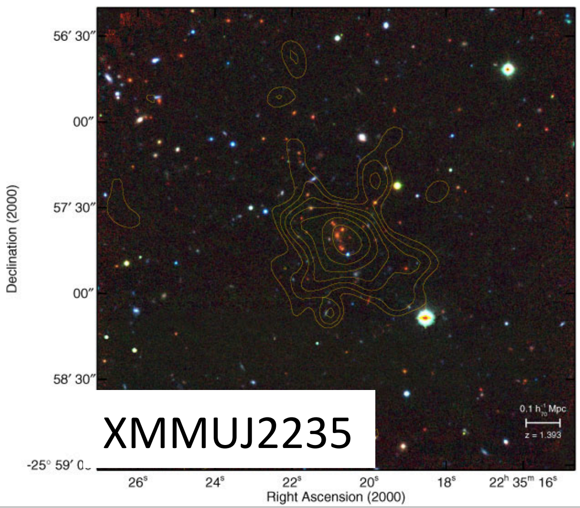
- modified initial state/ enfolded template template (Meerburg et al. 2009)

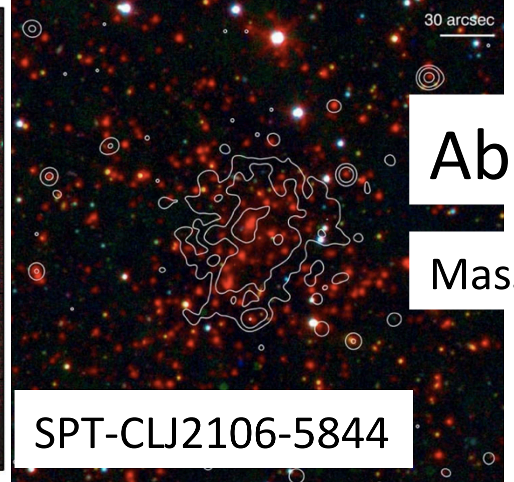
- orthogonal template (Senatore et al. 2010)

- these templates do **not** have the correct scaling in the squeezed limit

solid lines: $M_{halo} \sim 10^{14}\ M_{sun}/h$
dashed lines: $M_{halo} \sim 10^{11}\ M_{sun}/h$

What are the possible squeezed limit scalings?





Abundance of rare events

Massive halos (peaks)→ mass function

What are we really seeing????

Not space to report all the recent literature massive revival on the past few years, great progress.

For discussion:

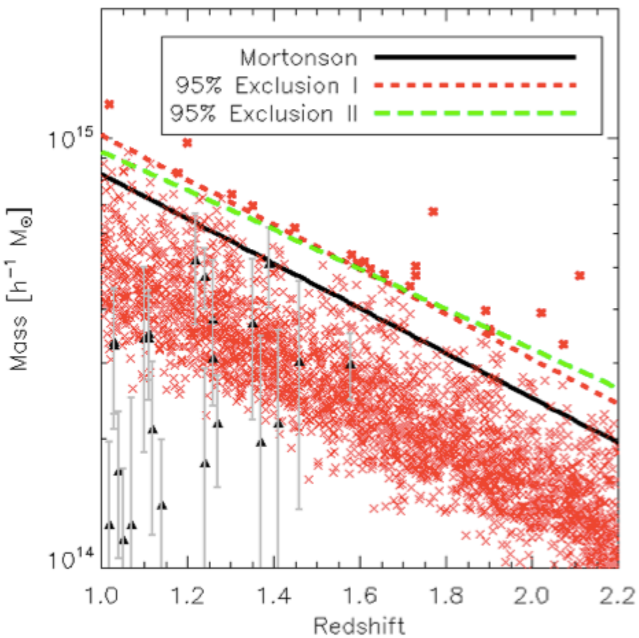
- If we are seeing rare events, how do we quantify tension with a given model?

(see e.g. discussion in Hoyle et al 2012, Hotchiss et al, Mortonson et al 2011. criterion valid for 1 object, exclusions regions might become ambiguous)

- What are wee seeing? is that a cluster? What's its mass?
- How dependent is a finding on the (observational) selection effects?
- Given that selection effects might not be well know, and that complete samples might not yet be available, what can be done?
- What happened to SZ clusters catalogs?

- What is the probability R that a cluster(s) can exist in a region of the >M >z plane?
- What level of tension with a model is caused by the existence of this cluster(s)

100 sq deg M> 7 10^{14} Msun, 1<z<2.2, Poisson sample this 425 times (Gaussian mass function)

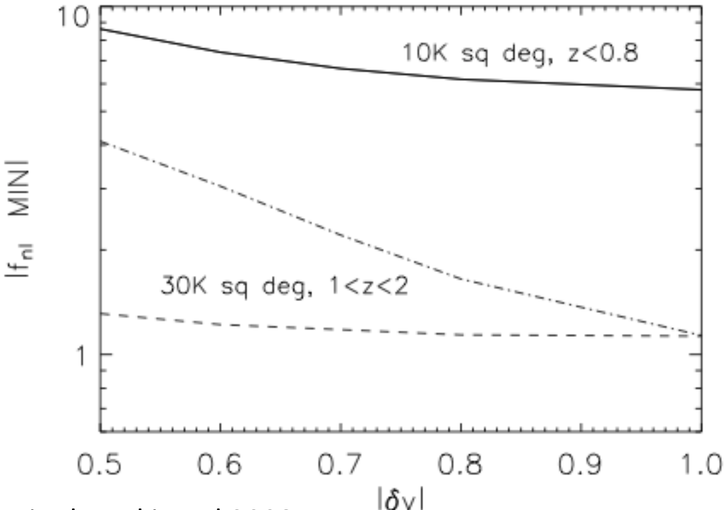


Least probable clusters
Typical (random) clusters

Rare clusters are "weird"
If they are the least probable clusters their mass distribution is consistent with LCDM
If they are random their redshift distribution is consistent with LCDM

Is there a nice and unique and reasonable way to define exclusion regions???

Hoyle et al 2012



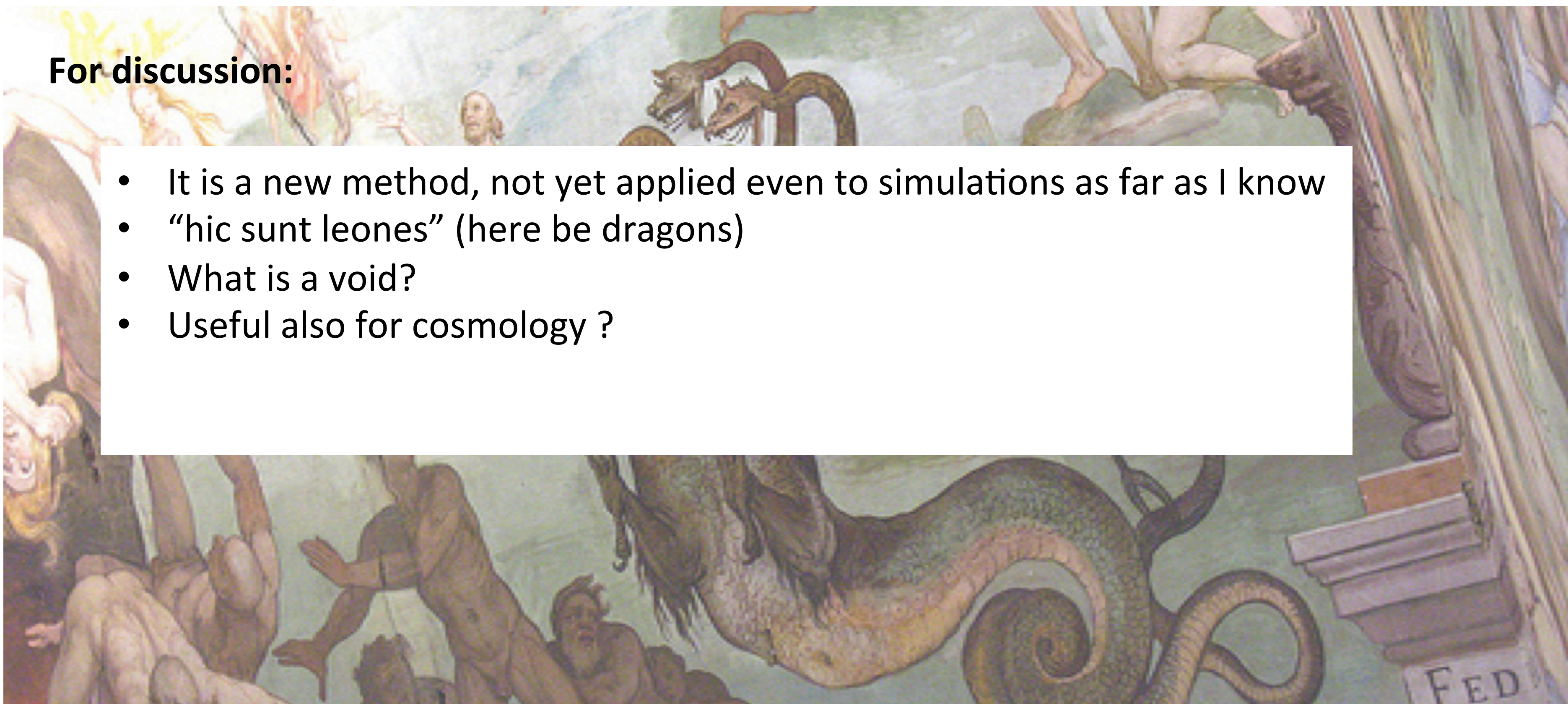
Kamionkowski et al 2008

Abundance of rare events

voids

Extremely appealing in principle

Can count them but also use shapes



For discussion:

- It is a new method, not yet applied even to simulations as far as I know
- “hic sunt leones” (here be dragons)
- What is a void?
- Useful also for cosmology ?

Clustering of peaks (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})

Clustering of peaks (Halo bias)

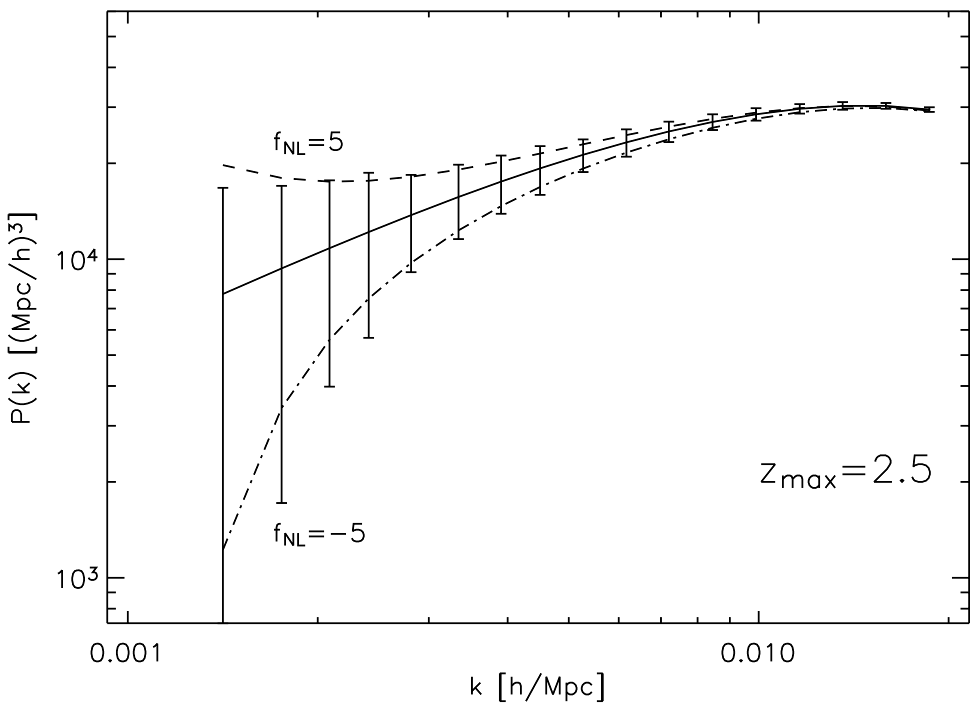
- Gaussian IC and a non-Gaussian IC can have the same P(k) for the dark matter
- For Gaussian IC the P(k) of massive halos is completely specified by the dark matter P(k)
- For Non Gaussian IC, however, the P(k) of the halos, depends on all higher order correlations (i.e. f_{NL})

In other words: in general a non-linear operation you do on a Gaussian field will give you a scale dependent halo bias (how big and on what scales really depends on the details)

Clustering of peaks (Halo bias)

Its own peculiar scale, redshift and halo mass dependence

Depend on the "shape"



``Effective" effect on LSST

Clustering of peaks (Halo bias)

Its own peculiar scale, redshift and halo mass dependence

Depend on the "shape"

$$\frac{\Delta b}{b^{L,G}} = \beta(k)\frac{\Delta_c(z)}{D(z)}$$

$$\delta(k) = \mathcal{M}_R(k)\Phi(k)$$

z dependence in here

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

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

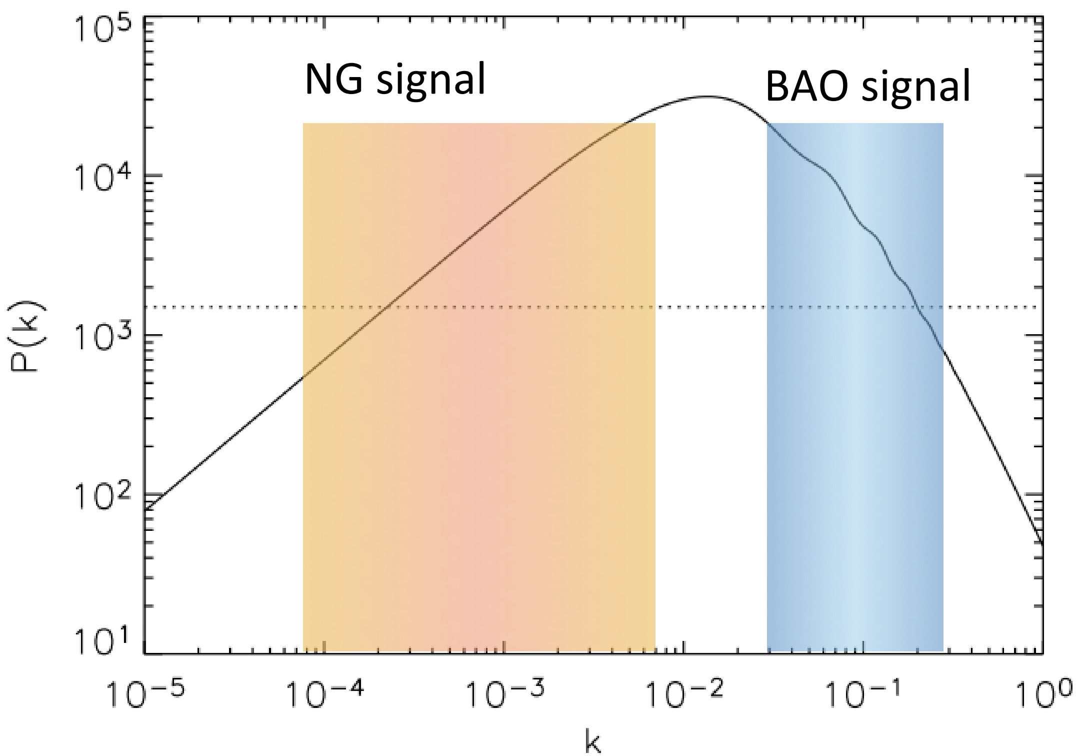
Spectro- vs photo- z's

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

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!

A lot more work done on this, but Fisherisms are limited…..

Inflationary-GR Intrinsic to LSS

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

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

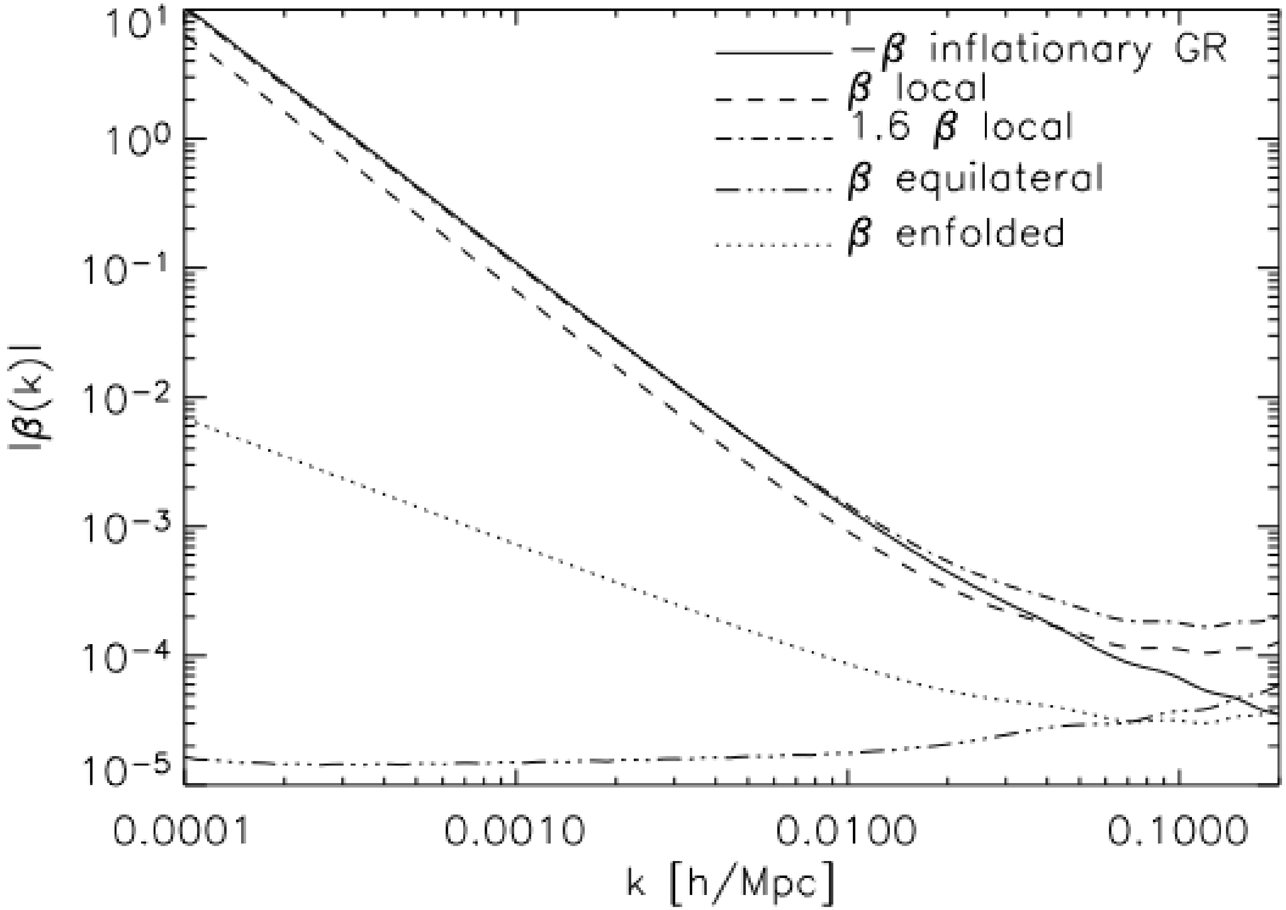
$$f_{\rm NL}^{\rm infl,GR}(k_i,k_j,k_k) = -\frac{5}{3}\left[1 - \frac{5}{2}\frac{k_i k_j cos\theta_{ij}}{k_k^2}\right]$$

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



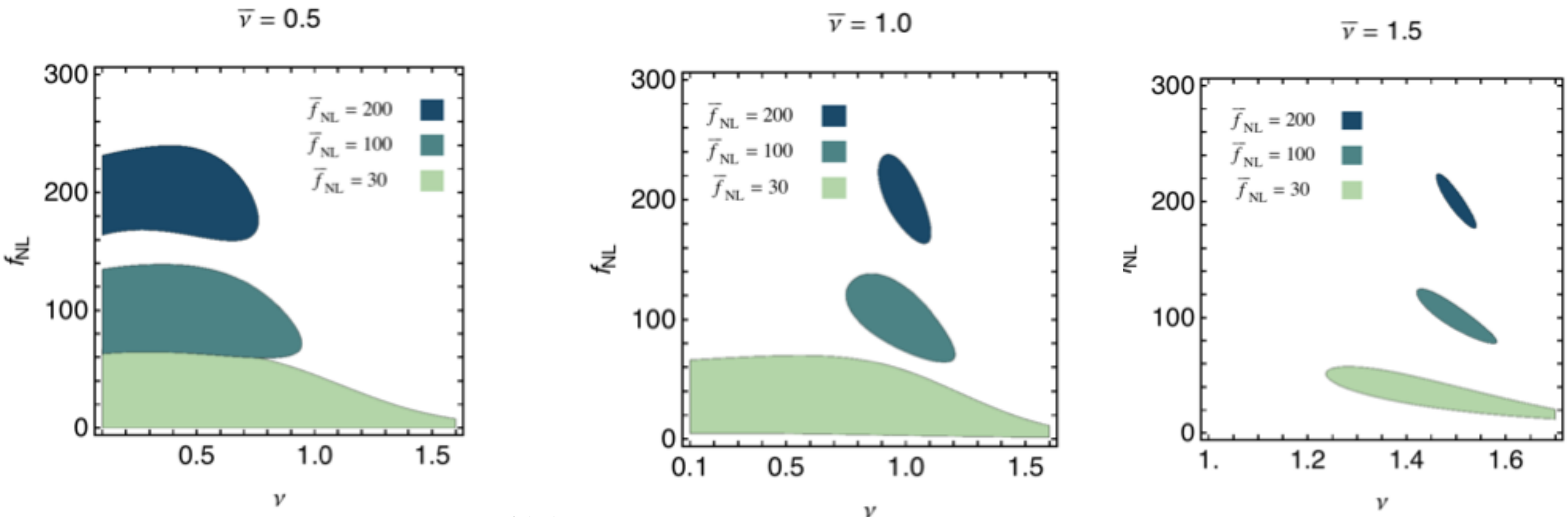
On horizon-scales Poisson equation gets quadratic corrections:
Needs IC set up of inflation, parallels the TE anti-correlation.

Verde & Matarrese 2009, ApJL

At a potentially detectable level!

Probing the squeezed limit

QSF (see Chen talk) $\nu \equiv \sqrt{9/4 - m^2/H^2}$ $\langle \zeta^3 \rangle \sim 1/q^{3/2+\nu}$



68% joint C. L.

~ orth. template

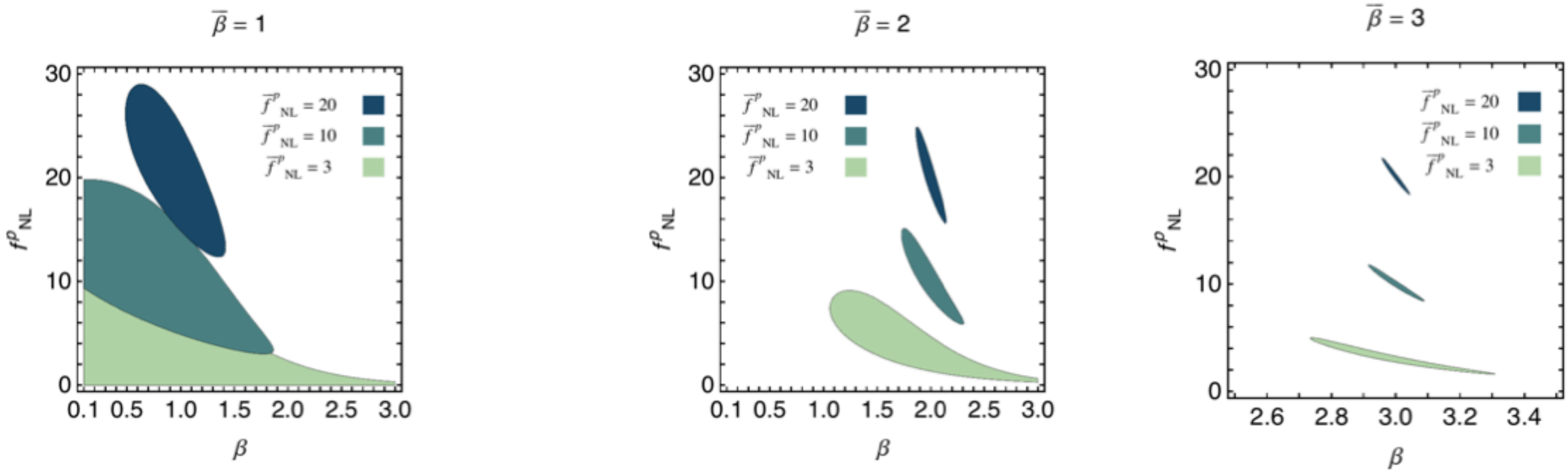
~Local

PS beware of Fisher!!!!

Norena LV, Barenboim, Bosh 2012

Probing the squeezed limit

Model-independent(phenomenological) $\Delta b(k, M) = f^{p}_{\rm NL} \frac{A(M)}{k^{\beta}}$ Agullo, Shandera 2012



$$f_{\rm NL}(\nu = 1.5) \sim 8 f^{p}_{\rm NL}(\beta = 2).$$

Norena LV, Barenboim, Bosh 2012

Creminelli et al 11: If a bispectrum with a squeezed limit that does not go like $1/q$ or $1/q^3$ is observed, it would signal the presence of heavy fields or other non-trivial dynamics during inflation.

Issues for discussion

- Of course why stop at the power spectrum? Halo bispectrum? (Baldauf et al.)
- SYSTEMATICS!!!   How to control?
- signals: SDSS, NVSS…
- How to combine with other measurements?
- Do we even want to combine?
- Relativistic corrections, how important, how well modeled?
- Beware: not just fnl gives a scale dependent halo bias!!! (e.g., Porciani et al) but non-linear bias itself!
- Can, in principle, reduce errors drastically by "reducing cosmic variance"; how about in practice?
- The role of lensing?

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

Galaxy bispectrum

few
10's

Discussion!!!

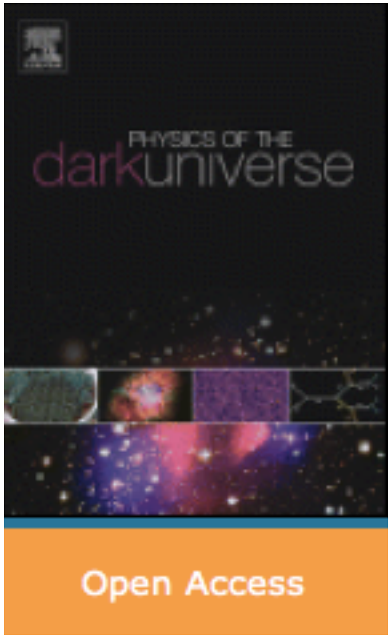
A) Yadav, Komatsu & Wandelt (2007) B) Carbone et al. (2008) C) Baumann et al. (2009); Sefusatti et al. (2009) E)Verde & Matarrese 2009
F) Mangilli & Verde 2009, Hanson et al. 2009, Junk& Komatsu, Lewis 2012

POSTDOCTORAL POSITIONS IN COSMOLOGY
at ICC Barcelona

The Physical Cosmology group at ICC-UB is expected to make one or more postdoctoral positions to work in Cosmology and in the areas of interest to the group. We are looking for researchers with a strong background in cosmology and in the analysis of large-scale structure surveys, but exceptional candidates in other areas of cosmology will also be considered.

The position will be guaranteed for two years, and could be extended depending on performance and availability of funding. The bulk of the funding comes from an IDEAS European Research Council Award to Licia Verde.
Applicants are asked to submit their curriculum vitae, publication list, a brief summary of their past research and a statement of research interests, and arrange for at least three letters of recommendation to be sent. Applications should be sent by e-mail to:
Licia Verde, liciaverde[at]icc.ub.edu.
The appointment may start as early as March and preferably no later than September 2013. Applications received before December 1, 2012 will receive full consideration.

Advertissment



Physics of the Dark Universe

Frontiers in Particle Astrophysics and Cosmology

Physics of the Dark Universe is a new and innovative online-only, fully open access journal. The journal offers rapid publication of peer-reviewed, original research articles considered of high scientific impact. The journal is focused on the understanding of the nature of Dark Matter and Dark Energy and covers all theoretical, experimental and phenomenological aspects of both Dark Matter and Dark Energy.

It encourages the submission of articles on the following subjects in this field:

- Nature of Particle Dark Matter
- Direct searches for Dark Matter
- Indirect searches for Dark Matter
- Collider searches for Dark Matter, including for example the Large Hadron Collider
- Theoretical investigations of the Physics of Dark Matter
- Investigations of New and Existing Models OF Dark Matter (e.g. SUSY, extra dimensions, axions, etc)
- Low mass WIMP searches
- Observations and experimental results related to the properties of Dark Energy
- New experiments, forecasts and methods for the observation of Dark Energy
- Models and theoretical properties of vacuum energy,quintessence, modified gravity, and in general of Dark Energy and its alternative explanations

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- Articles containing additional information, such as additional figures, interactive plots and database linking. Elsevier offers 700 MB of space to be used for each article for additional material. Each file has a suggested size limit of 50 MB, but larger files are possible (in this case please contact the Managing Editor).