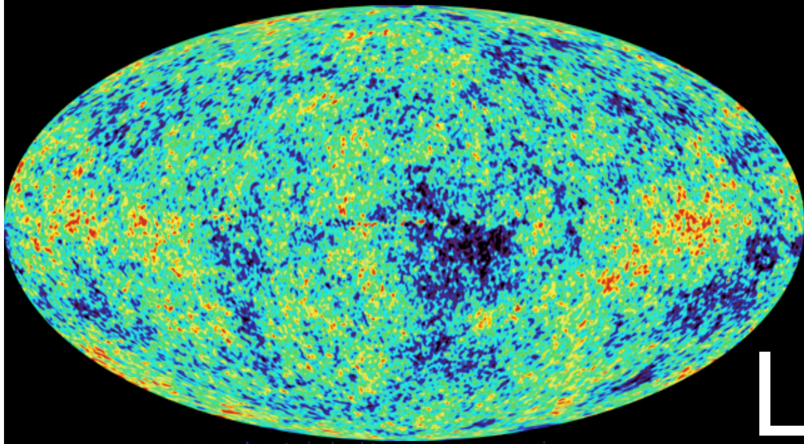
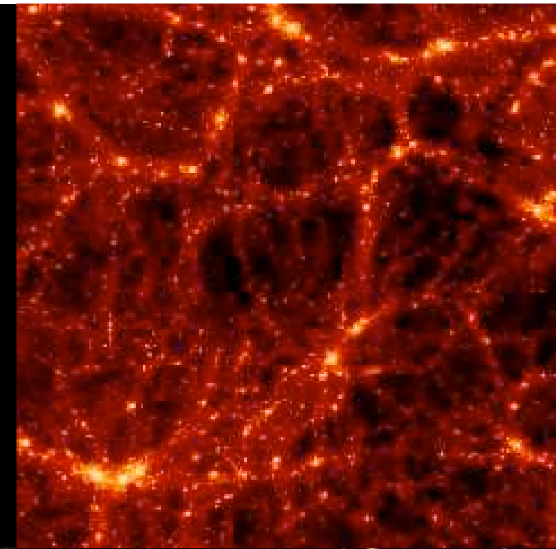
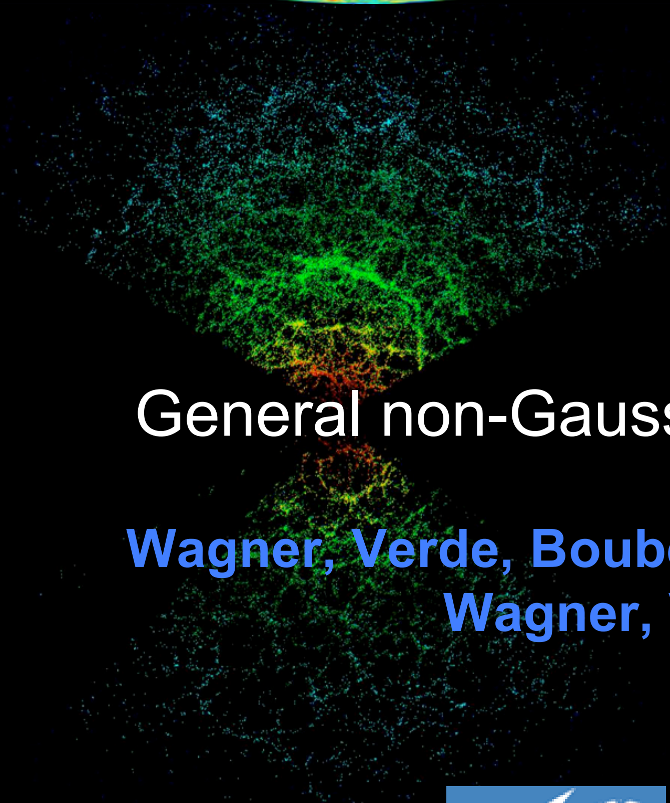


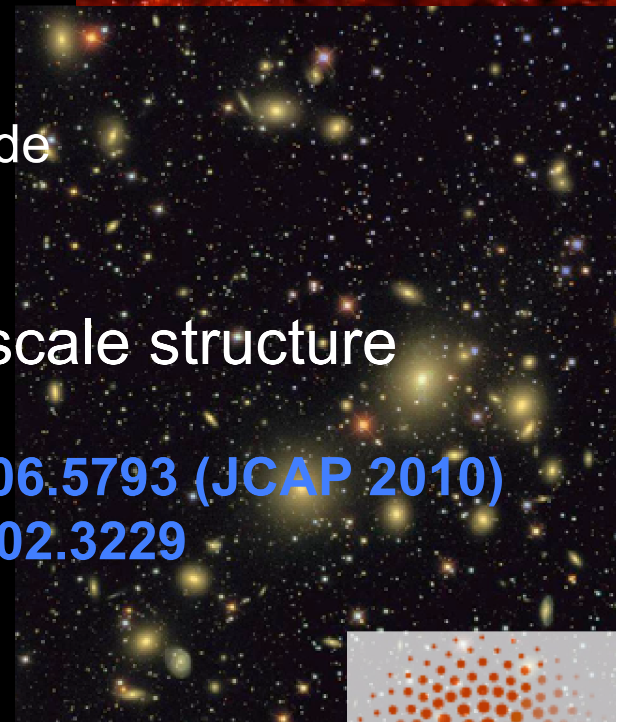


Licia Verde

ICC UB & ICREA

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





General non-Gaussian shapes in large-scale structure

Wagner, Verde, Boubekeur, Paper I: arXiv:1006.5793 (JCAP 2010)
Wagner, Verde Paper II: arXiv:1102.3229

*icrea Institució Catalana de Recerca i Estudis Avançats

ICCUB Institut de Ciències del Cosmos

UNIVERSITAT DE BARCELONA

erc

shapes

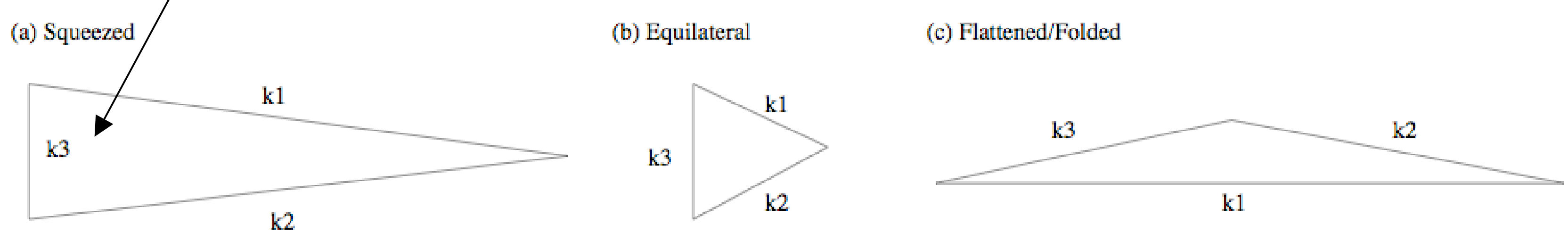
Simple inflationary model:

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

“Non-dog is my co-pilot”

Tools:

CMB: bispectrum, Topology

Large-scale structure:

Bispectrum (or higher orders)

Clustering of peaks on large scales ← new

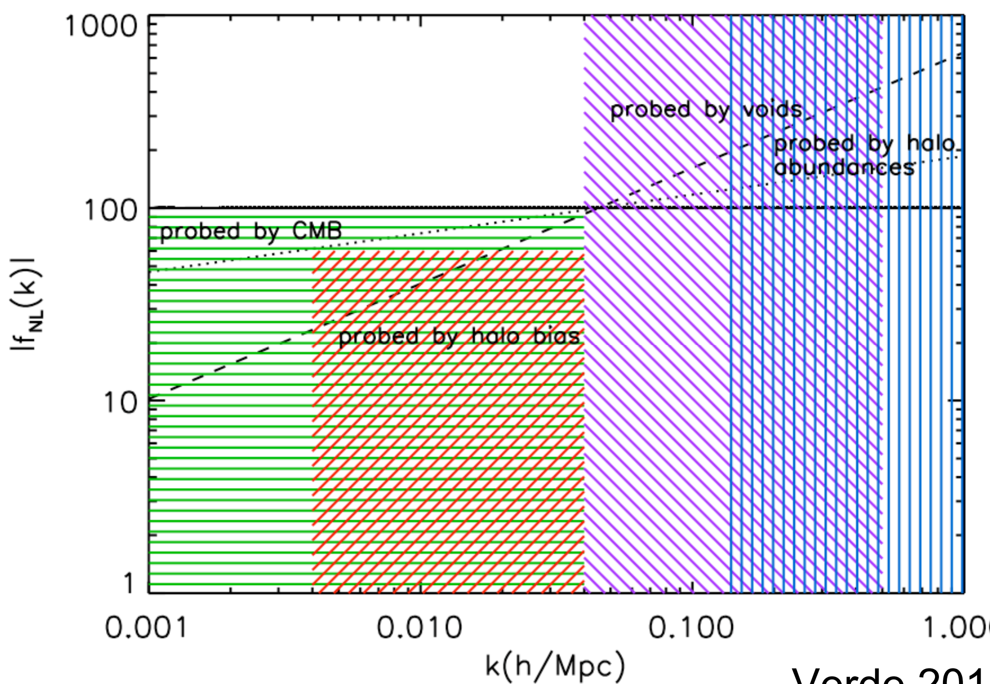
Abundance of rare events (peaks, massive halos…)

(Topology)

Non-linearities always present in LSS: N-body simulations

Searching for non-Gaussianity with LSS: COMPLEMENTARITY

Each probe is affected by different systematics



Verde 2010

In many cases the interpretation gets dirty and messy,

anyway interesting: can probe smaller scales than CMB

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 etc. etc.

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

The Effect

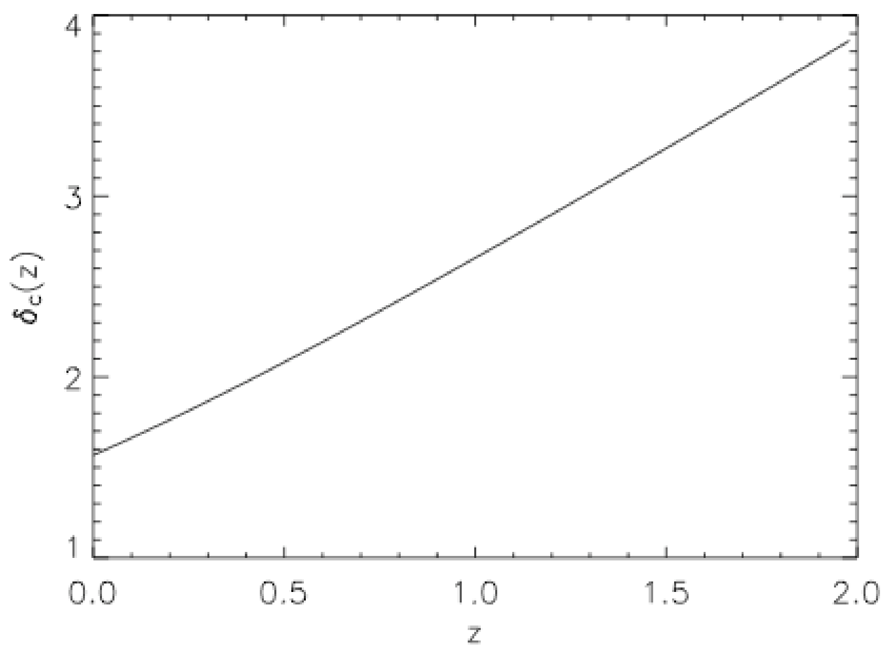
$$\frac{\Delta b}{b^{L,G}} = \beta(k)\frac{\Delta_c(z)}{D(z)}$$

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

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

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

Redshift dependence



Matarrese, Verde 2008

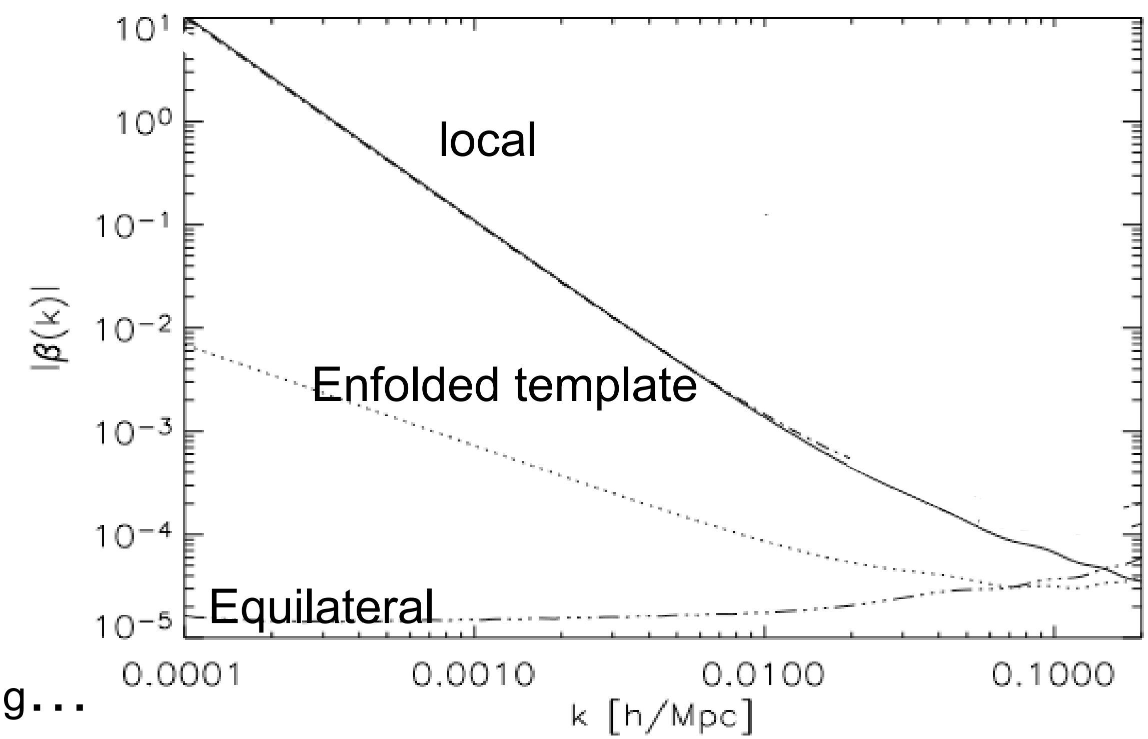
The Effect

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

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

Scale-dependence

Matarrese, Verde 08
Verde, Matarrese 09
Taruya et al 08



Interesting…

Verde, Matarrese 2009

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

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

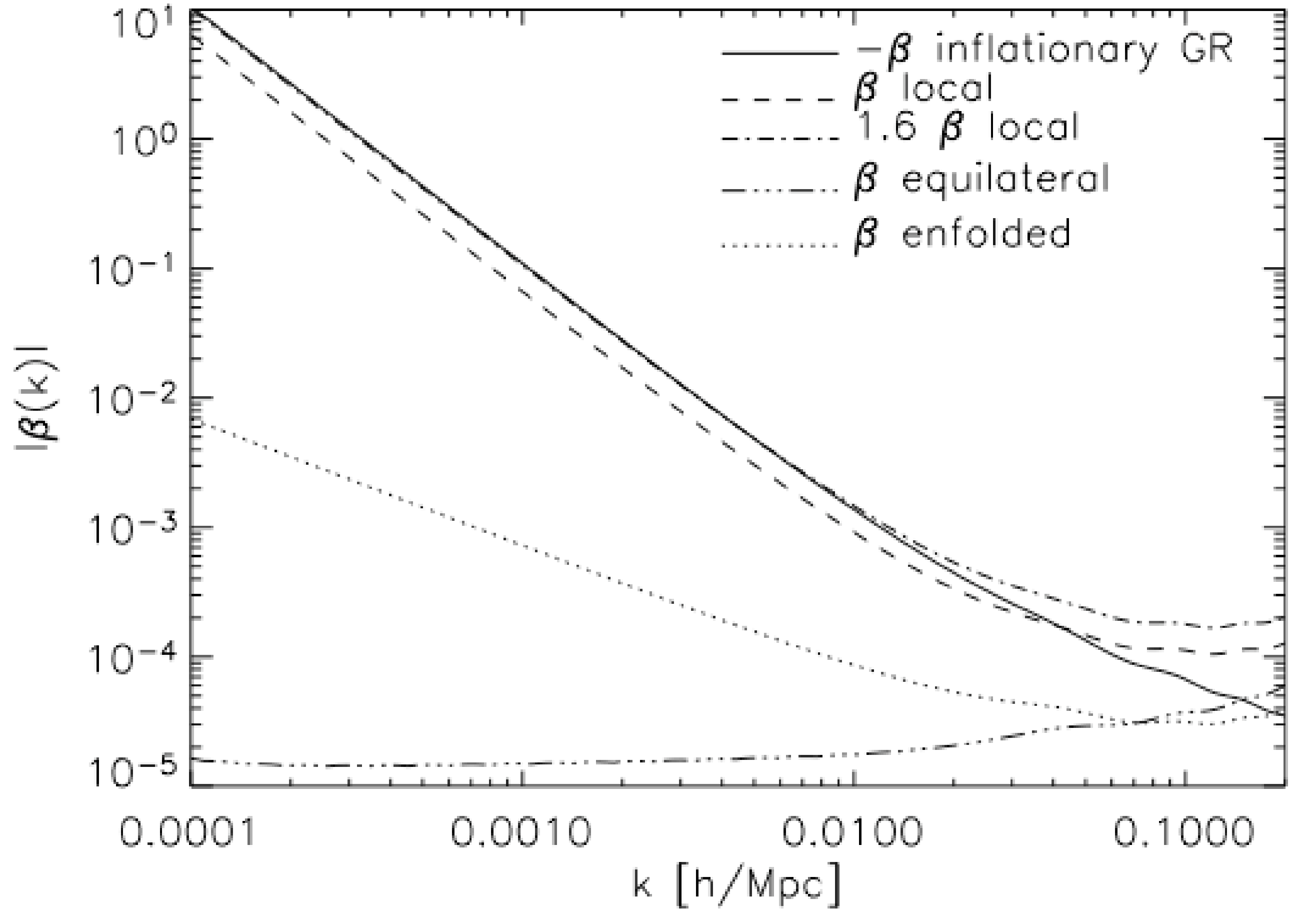
$$f_{\rm NL}^{\rm infl,GR}(k_i,k_j,k_k) = -\frac{5}{3}\left[1 - \frac{5}{2}\frac{k_i k_j cos\theta_{ij}}{k_k^2}\right]$$

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



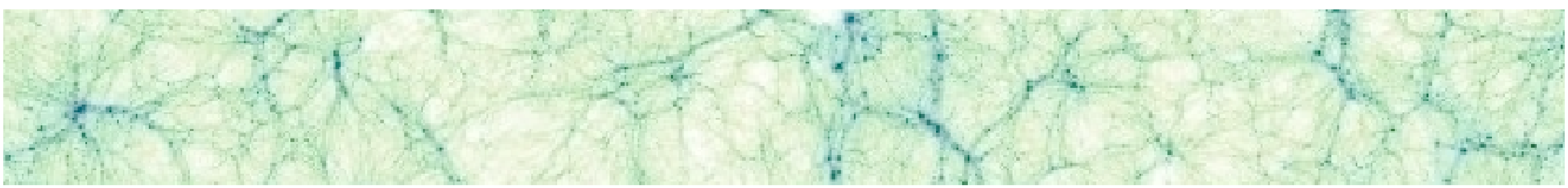
On horizon-scales Poisson equation gets quadratic corrections:
Needs IC set up of inflation, parallels the TE anti-correlation.

Verde & Matarrese 2009, ApJL

At a potentially detectable level!

N-body Simulations

- Halo formation is a highly non-linear process => N-body simulations
- Analytic predictions have been tested with N-body simulations by many groups
- Papers:
  - Dalal et al. 2008
  - Grossi et al. 2007 and 2010
  - Desjacques et al. 2009
  - Pillepich et al. 2010
  - …
- But up to very recently **only the local type** was simulated!



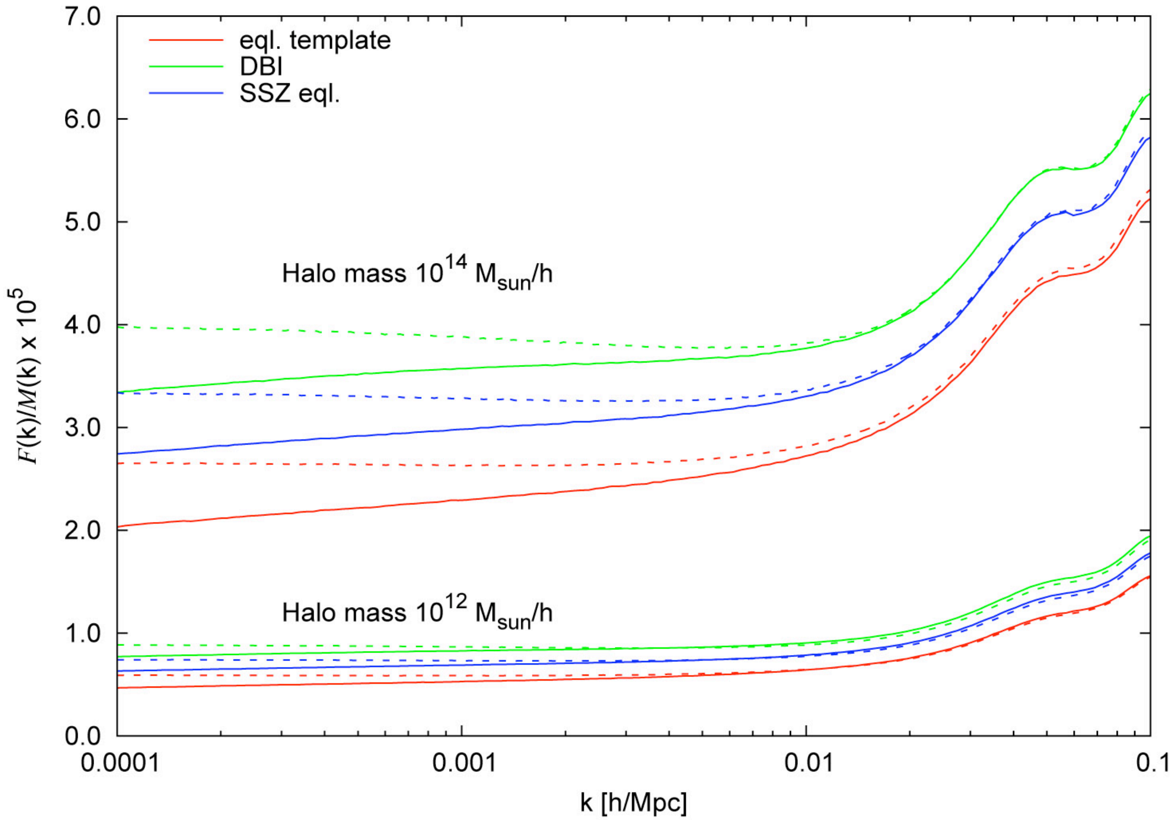
Need a big computer and somebody that can use it!

Christian Wagner

& a lieutenant of the navy to admin the machine and tune software vs hardware

Hipatia

Templates vs. physical shapes

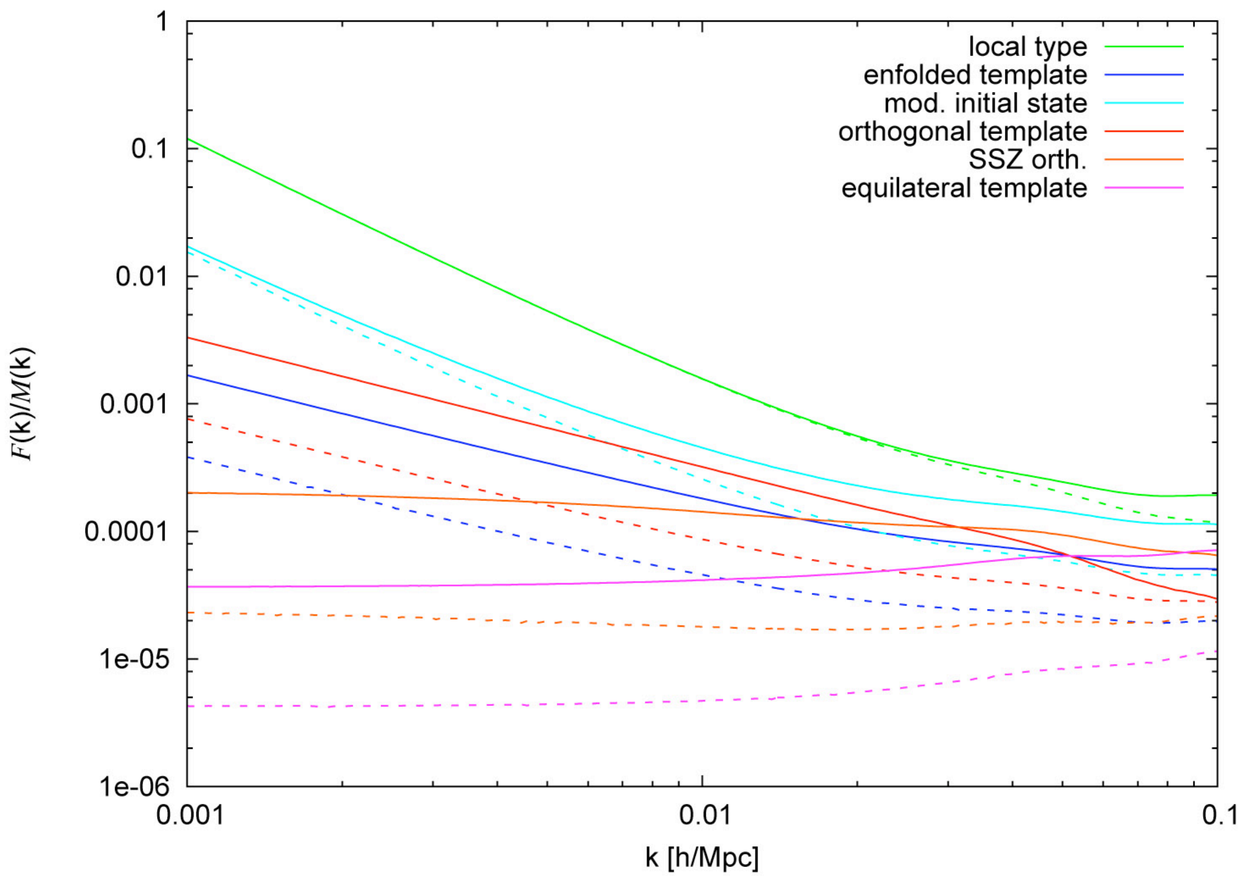


- **templates** approximate the physical bispectra over all triangle configurations and are **factorizable** => allows efficient computation

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

dashed lines: scale-invariant power spectrum
solid lines: spectral index n_s=0.95

Templates vs. physical shapes



- 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?

Initial Conditions

- Split the Potential into a Gaussian and a (small) non-Gaussian part

$$\Phi_{\mathbf{k}} = \Phi_{\mathbf{k}}^{G} + \Phi_{\mathbf{k}}^{NG}$$

- Generate a Gaussian Random field

  $\Phi^{G}_{\boldsymbol{k}} \sim N\{0, (P(k)/2)^{1/2}\} + i\, N\{0, (P(k)/2)^{1/2}\}$

  $P(k)=A\, k^{n-4}$ where n is the spectral index

- Add $\Phi^{NG}_{\boldsymbol{k}}$

- Poisson equation and CMB physics

$$\delta_{\mathbf{k}} = \frac{2}{3}\frac{k^2 T(k) D(z)}{\Omega_m H_0^2}\Phi_{\mathbf{k}}$$

- Use Zel'dovich Approximation or 2LPT to obtain particle positions and velocities

How to get ϕ^{NG}

- Ansatz for Φ^{NG} for a given bispectrum

  old (Paper I):
$$\Phi_{\mathbf{k}}^{NG} = \frac{1}{6(2\pi)^3}\int d^3k_2 B_\Phi(k, k_2, |\mathbf{k}+\mathbf{k}_2|)\frac{\Phi_{\mathbf{k}_2}^{*G}}{P(k_2)}\frac{\Phi_{\mathbf{k}+\mathbf{k}_2}^{G}}{P(|\mathbf{k}+\mathbf{k}_2|)}$$

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

- In both cases:
$$\langle \Phi_{k_1}^G \Phi_{k_2}^G \Phi_{k_3}^{NG} \rangle = \frac{1}{3}(2\pi)^3 B(k_1, k_2, k_3)\delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)$$

- The old ansatz sometimes gives rise to spurious divergences in the power spectrum, the new ansatz does not! ✓
- But computationally very expensive: cost ~ N_g^6

If the Bispectrum (or template or decomposition) is factorizable

$$B(k_1, k_2, k_3) \equiv \sum_i b_1^i(k_1) b_2^i(k_2) b_3^i(k_3)$$

- The old ansatz can be written as a sum of convolution
- Compute convolutions with the help of Fast Fourier Transforms => very significant speed up of the IC generation

$$\Phi_{\mathbf{k}}^{NG} = \frac{1}{6} \sum_i b_1^i(k) \int \frac{d^3 k_2}{(2\pi)^3} G^i(\mathbf{k}_2) Q^i(\mathbf{k} + \mathbf{k}_2)$$

$$G^i(\mathbf{k}) = b_2^i(k) \Phi_{\mathbf{k}}^{*G} / P(k)$$

$$Q^i(\mathbf{k}) = b_3(k) \Phi_{\mathbf{k}}^{G} / P(k)$$

- The new ansatz may also be factorized

$$\frac{k_1^3 k_2^3 k_3^3}{k_1^3 \ldots} \ldots + k_2^3 + k_3^3)$$

WORK IN PROGRESS

Using a smaller grid for ϕ_k^{NG}

- Initial ϕ_k^{NG} computation scales as ~ N_g^6
- Choose a grid size for ϕ_k^{NG} of 400 (computation takes 2 days on 256 cores)
- Gaussian grid size is 1024
- Box size 1875 Mpc/h

  => "NG resolution" 5 Mpc/h ~ 3 x 10^{13} M_{sun}/h
- One billion particles per simulation

  => Particle mass ~ 5 x 10^{11} M_{sun}/h
- Evolve simulation with Gadget-2 (takes 1 day on 256 cores)
- Numerical tests confirmed the expected lower mass limit of resolved halos to be **3 x 10^{13} M_{sun}/h**

Simulations

Table 1. N-body simulations. N_g denotes the size of the grid used for the non-Gaussian part of the potential. The size of the particle grid is identical to the size of the grid used for the Gaussian part of the potential and is given by N_p.

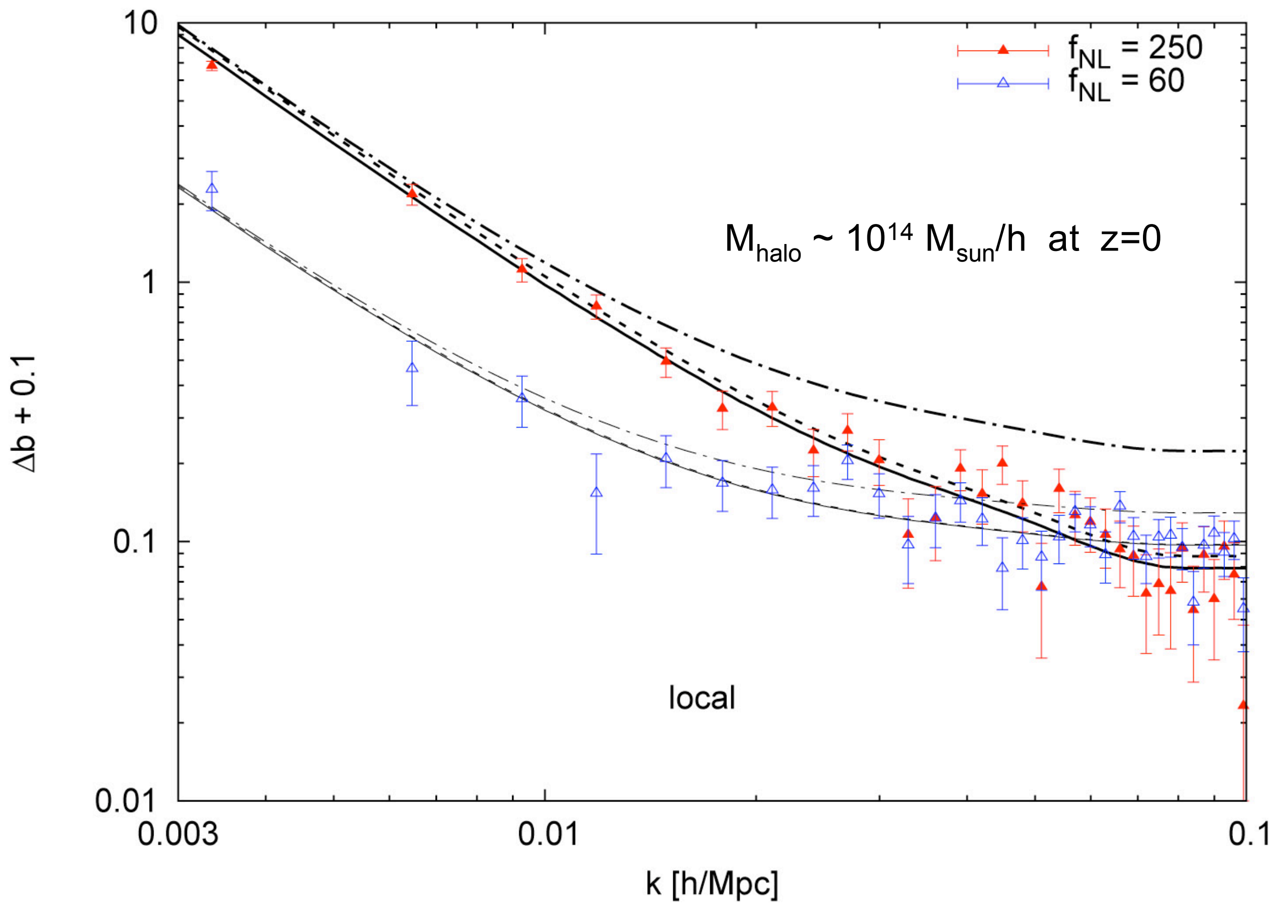
type of non-Gaussianity	$f_{\rm NL}$	N_g	N_p	# realizations
local	250	400	1024	1
local	250	1024	1024	2
local	60	1024	1024	3
equilateral template	1000	400	1024	2
equilateral template[a]	1000	1024	1024	1
orthogonal template	-1000	400	1024	2
orthogonal template	-250	400	1024	3
Gaussian	-	-	1024	3

[a] In this case, we use ansatz Eq. (4.5) for the non-Gaussian $\Phi^{NG}_{\mathbf{k}}$. The convolution is computed with an FFT in real space.

Simulation data is (or will be on request) publicly available at:
`http://icc.ub.edu/~liciaverde/NGSCP.html`

NG halo bias – local ~ k^{-3}

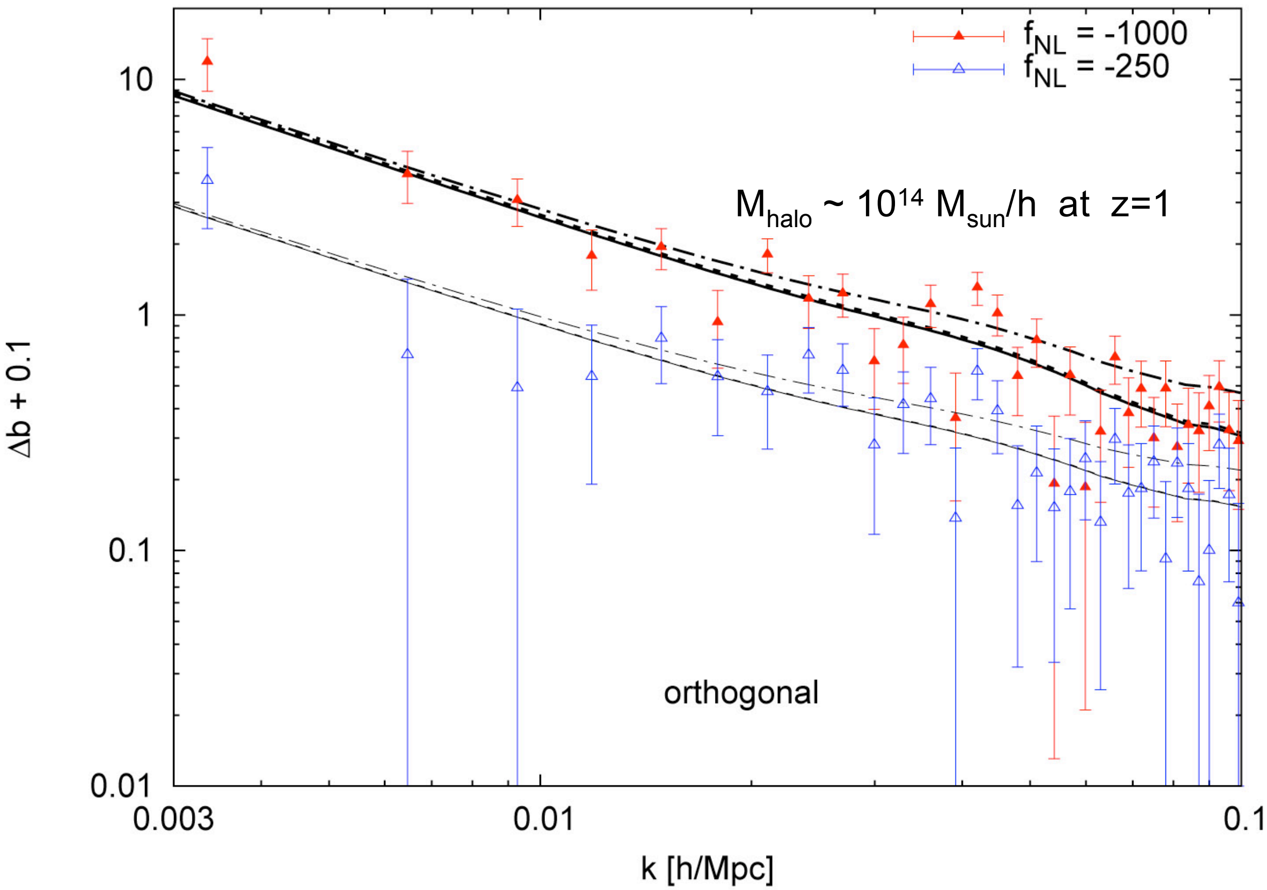
(squeezed limit)



$$\Delta b(k) = \Delta b_I + f_{\rm NL}\left[b_1^G + \Delta b_I - 1\right]\frac{q\delta_c}{D(z)}\frac{\mathcal{F}_M(k)}{\mathcal{M}_M(k)}$$

NG halo bias – “orthogonal” ~ k^{-2}

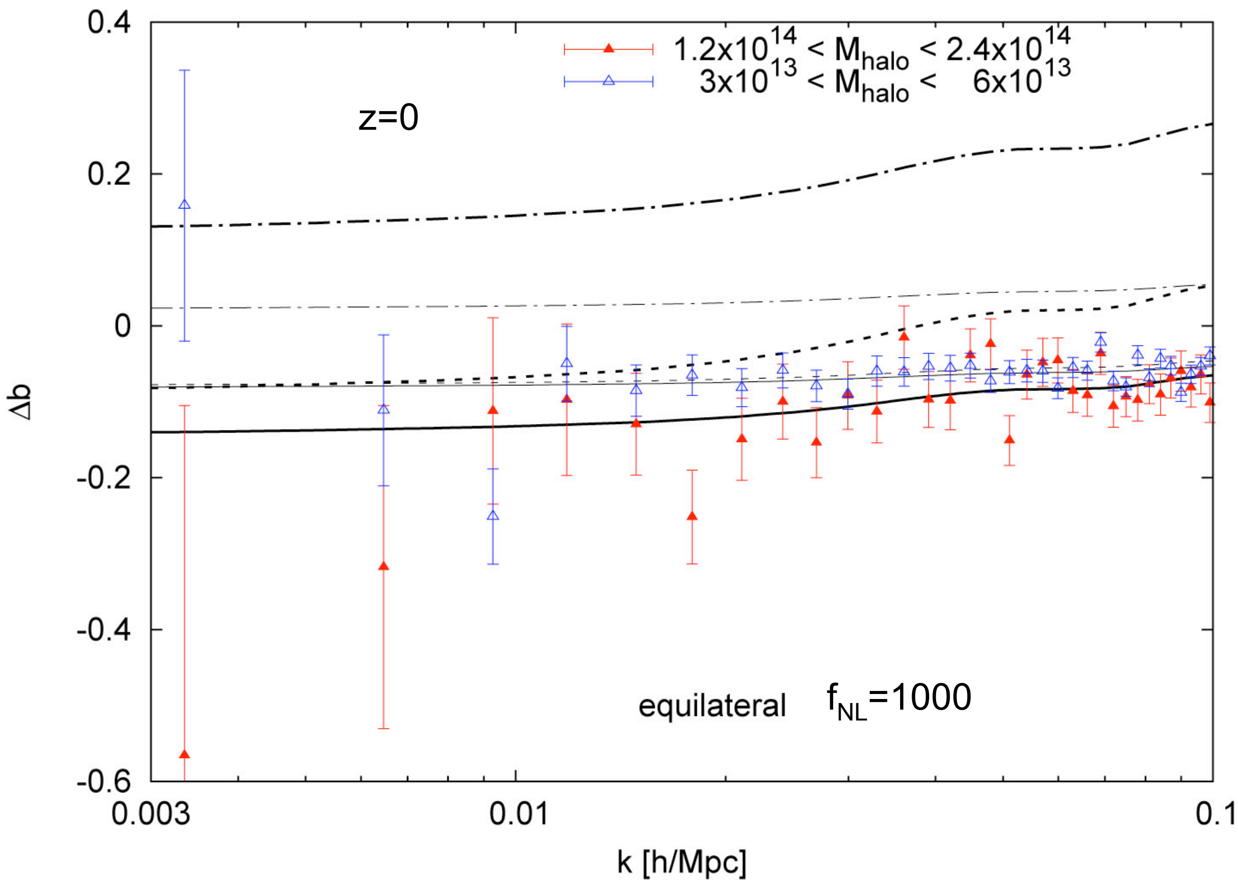
(squeezed limit)



$$\Delta b(k) = \Delta b_I + f_{\rm NL}\left[b_1^G + \Delta b_I - 1\right] \frac{q\delta_c}{D(z)} \frac{\mathcal{F}_M(k)}{\mathcal{M}_M(k)}$$

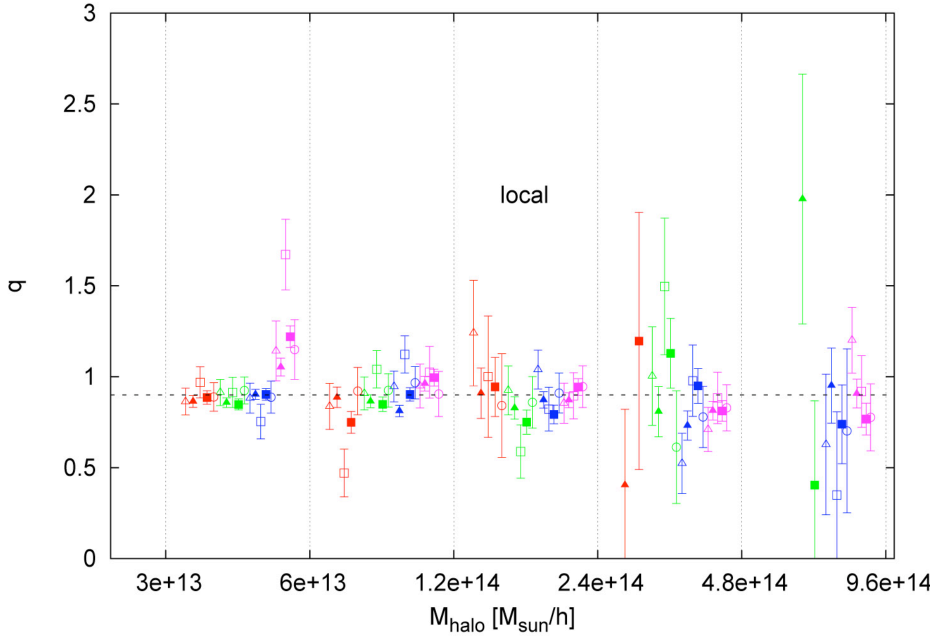
NG halo bias – equilateral ~ k^{-1}

(squeezed limit)



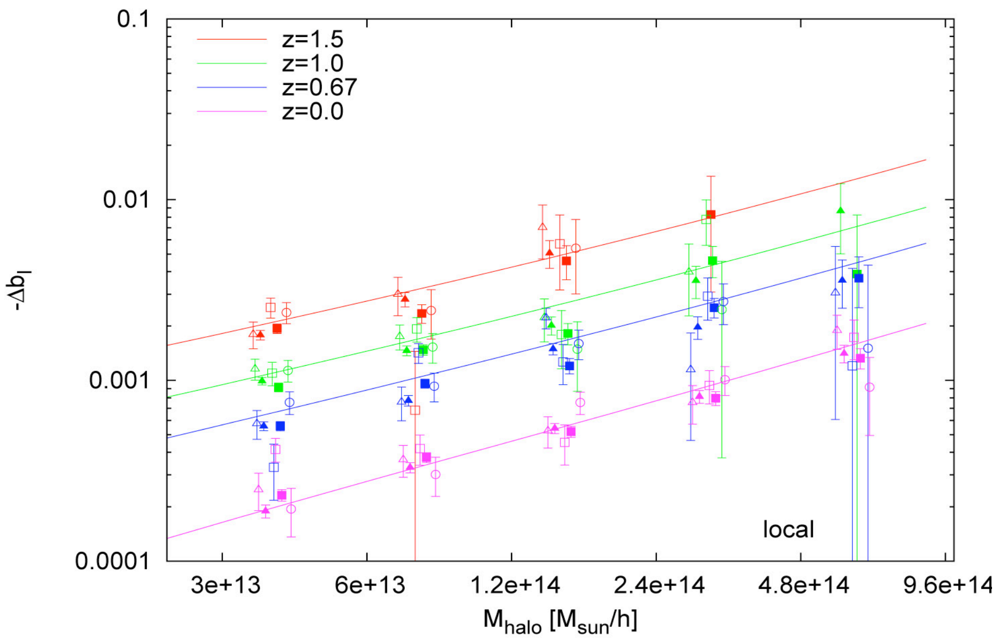
$$\Delta b(k) = \Delta b_I + f_{\rm NL}\left[b_1^G + \Delta b_I - 1\right]\frac{q\delta_c}{D(z)}\frac{\mathcal{F}_M(k)}{\mathcal{M}_M(k)}$$

Fitting results – local ~ k^{-3} (squeezed limit)



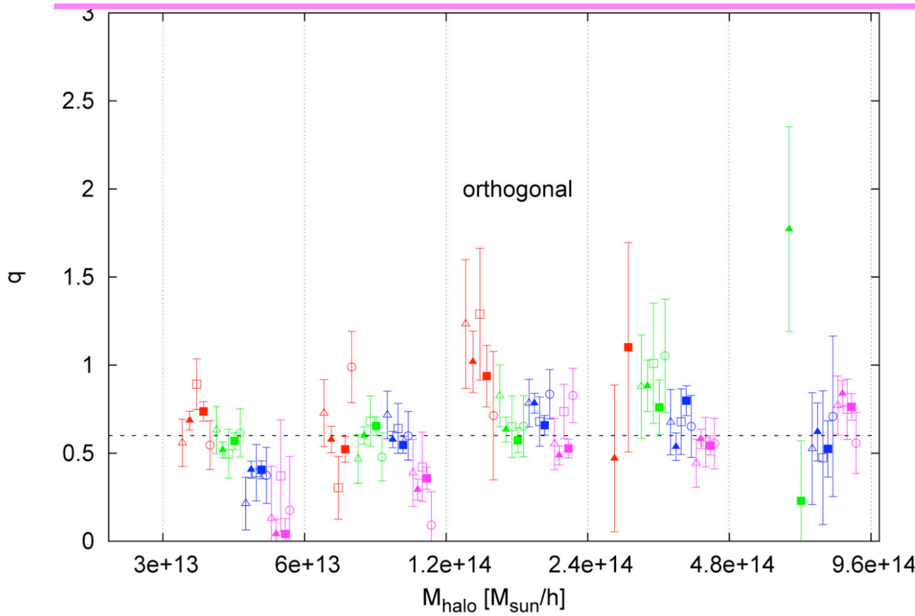
$$\Delta b(k) = \Delta b_I + f_{\rm NL}\left[b_1^G + \Delta b_I - 1\right]\frac{q\delta_c}{D(z)}\frac{\mathcal{F}_M(k)}{\mathcal{M}_M(k)}$$

For the local case, no significant mass or redshift dependence of the fudge factor q detectable



$$\Delta b_I = b_1^{NG} - b_1^G = -\frac{\partial \ln R^{NG}(M)}{\partial \delta_c}$$

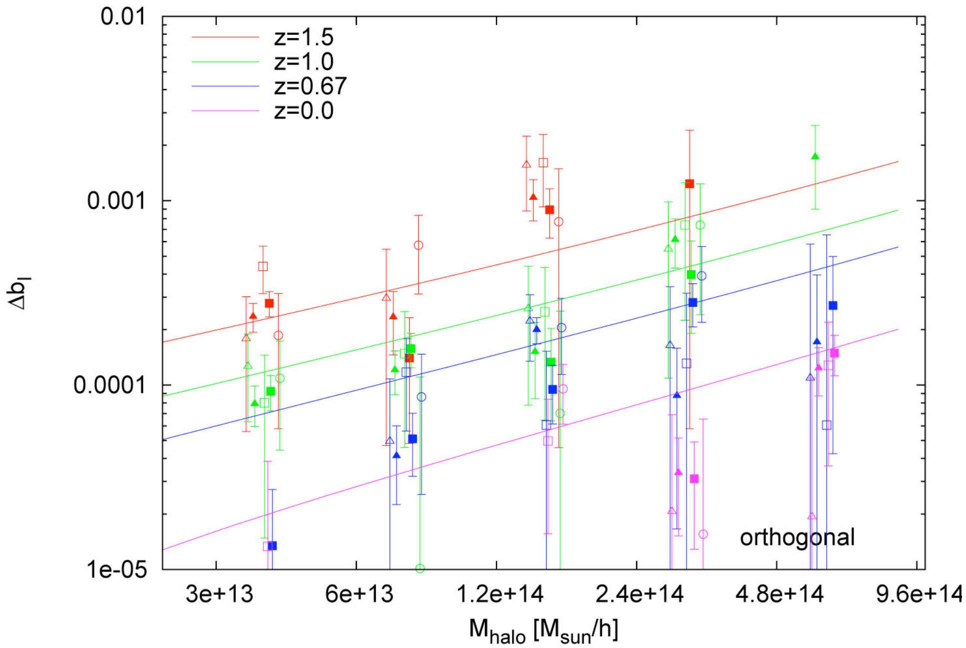
Fitting results – "orthogonal" ~ k^{-2} (squeezed limit)



$$\Delta b(k) = \Delta b_I + f_{\rm NL}\left[b_1^G + \Delta b_I - 1\right]\frac{q\delta_c}{D(z)}\frac{\mathcal{F}_M(k)}{\mathcal{M}_M(k)}$$

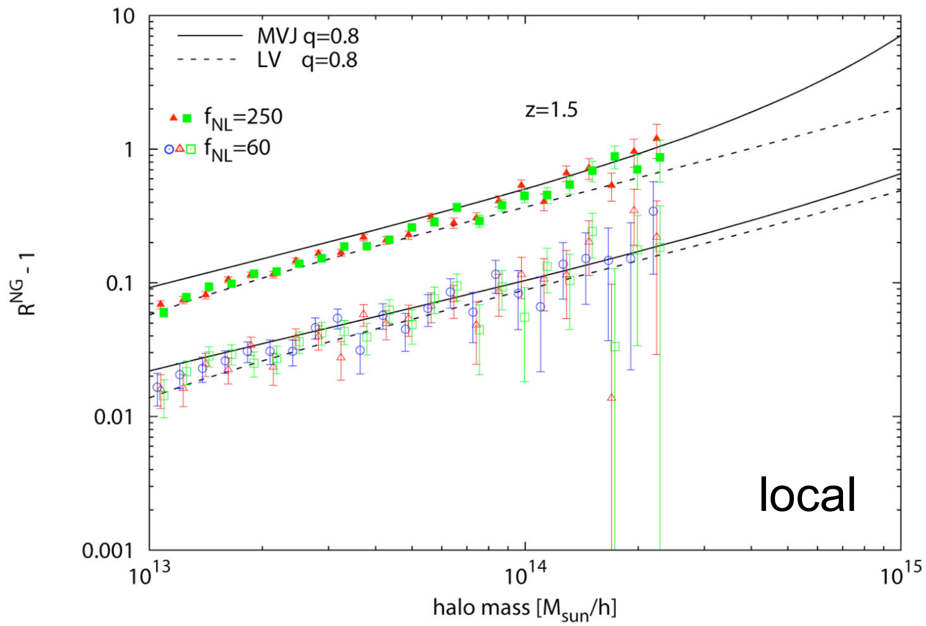
low q: ~0.6-0.8

There are hints for a mass and redshift dependence of the fudge factor q!

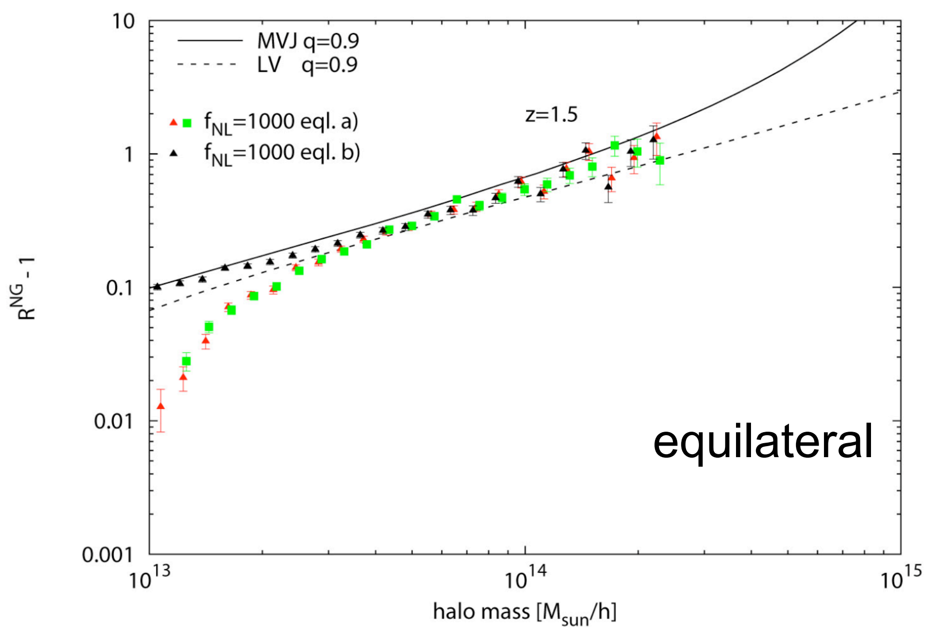


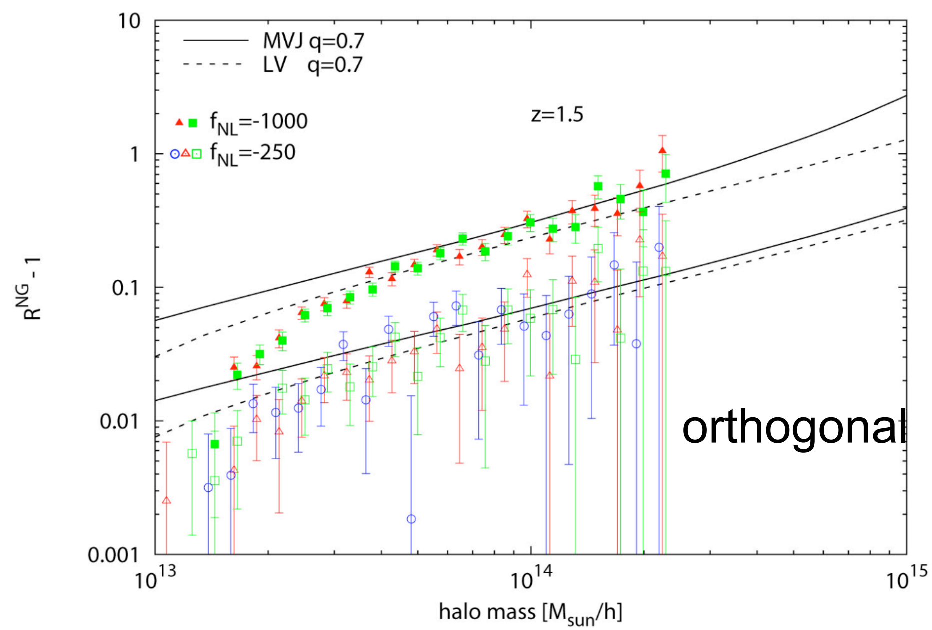
$$\Delta b_I = b_1^{NG} - b_1^G = -\frac{\partial \ln R^{NG}(M)}{\partial \delta_c}$$

Ratio of Mass function



Theoretical predictions fit the data well, if a shape-dependent fudge factor is taken into account.





Conclusions from sims

- Non-Gaussian initial condition for N-body simulations with generic bispectrum possible (but so far computationally expensive)
- N-body results for the (non)-local NG bias are consistent with theoretical predictions after the fudge factor q is calibrated
- This q-correction is shape-dependent and for some shapes q is redshift and mass dependent => **further modeling needed!**
- Interestingly, the fudge factors for the mass function and the halo bias predictions are consistent with each other. Probably more than a coincidence …
- **Advice:** Halo bias predictions need to be computed from the physical models not from templates

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

Too big, too early?

XMMUJ2235.3-2557 is not alone

B. Hoyle, R. Jimenez, LV, 2011, Phys.Rev.D

Cluster Name	Redshift	M_{200} $10^{14}M_\odot$
'WARPSJ1415.1+3612' +	1.02	$3.33^{+2.83}_{-1.80}$
'SPT-CLJ2341-5119' *	1.03	$5.40^{+2.80}_{-2.80}$
'ClJ1415.1+3612' *	1.03	$3.40^{+0.60}_{-0.50}$
'XLSSJ022403.9-041328' +	1.05	$1.66^{+1.15}_{-0.38}$
→'SPT-CLJ0546-5345' *	1.06	$10.0^{+6.00}_{-4.00}$
'SPT-CLJ2342-5411' *	1.08	$2.90^{+1.80}_{-1.80}$
'RDCSJ0910+5422' +	1.10	$6.28^{+3.70}_{-3.70}$
'RXJ1053.7+5735(West)' +	1.14	$2.00^{+1.00}_{-0.70}$
'XLSSJ022303.0043622' +	1.22	$1.10^{+0.60}_{-0.40}$
'RDCSJ1252.9-2927' +	1.23	$2.00^{+0.50}_{-0.50}$
'RXJ0849+4452' +	1.26	$3.70^{+1.90}_{-1.90}$
'RXJ0848+4453' +	1.27	$1.80^{+1.20}_{-1.20}$
→'XMMUJ2235.3+2557' +	1.39	$7.70^{+4.40}_{-3.10}$
'XMMXCSJ2215.9-1738' +	1.46	$4.10^{+3.40}_{-1.70}$
'SXDF-XCLJ0218-0510' +	1.62	$0.57^{+0.14}_{-0.14}$

These 15 objects should not be there

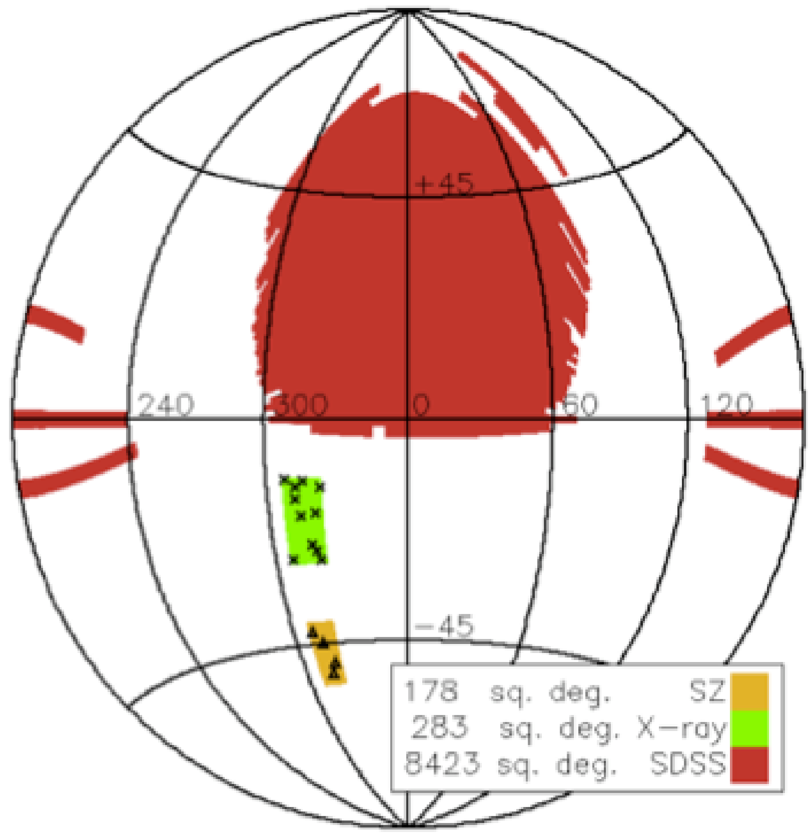
Conservative assumptions about

Mass estimates

Footprint

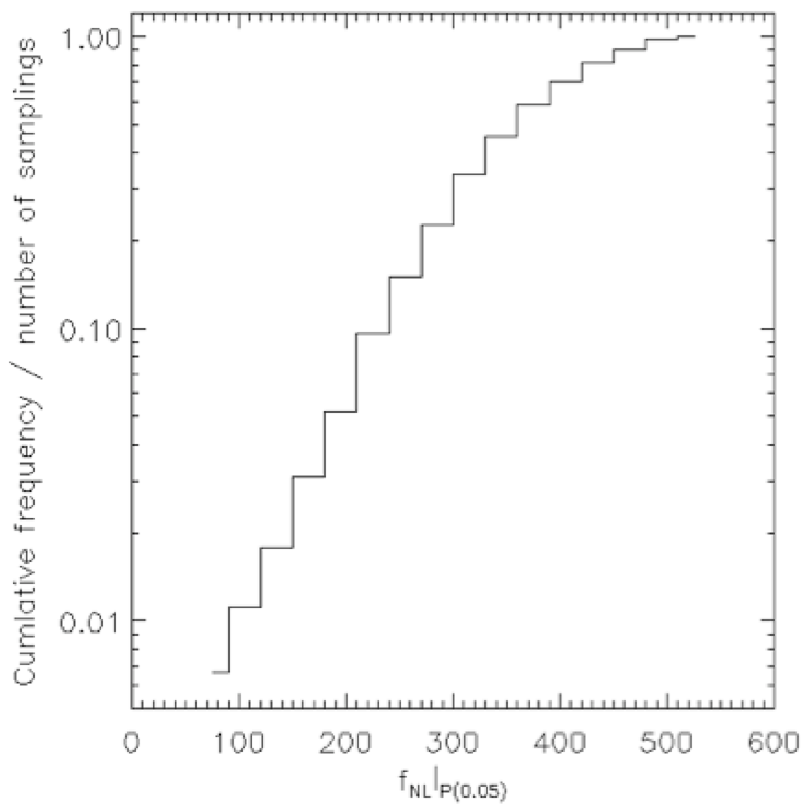
Survey volume

(and mass function adopted)



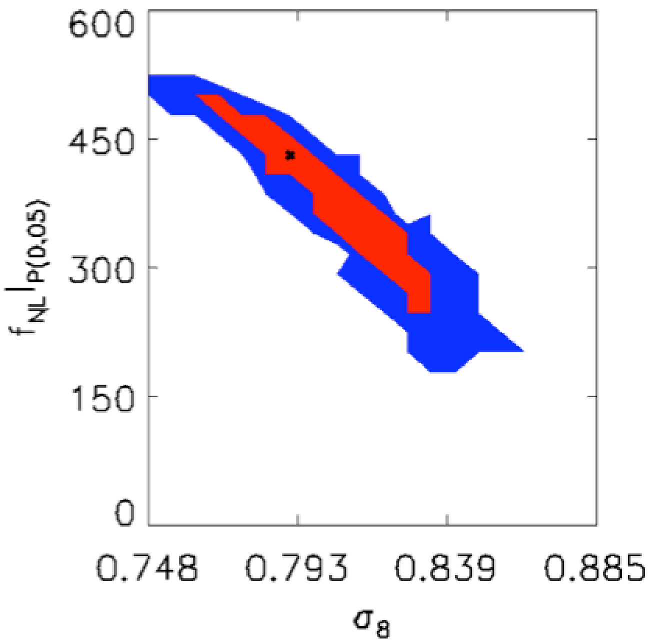
Not even marginalizing over WMAP cosmology…
Of course, if $f_{NL}>0$ is allowed….

Generalized
P-values



Distribution of the probability that they are allowed at 2-sigmas, as function of f_{NL}

What would one have to do to make f_{NL} go away?



Say that $\sigma_8 \simeq 0.90.$
And accept lower p-values

Such σ_8 is 4 σ higher than other cosmological probes measures

All cluster masses should have been systematically overestimated by 1.5 σ

RELIABLE GRAVITATIONAL LENSES MASSES ARE NEEDED!
Submitted HST proposal

Discussion…