The halo bispectrum in N-body simulations with non-Gaussian initial conditions

Critical Tests of Inflation Using Non-Gaussianity
@ MPA, Munich - November 7th, 2012

Emiliano SEFUSATTI - ICTP

in collaboration with Martin Crocce, Vincent Desjacques (ArXiv:1003.0007, ArXiv: 1111.6966)
+ Dani Figueroa, Toni Riotto & Filippo Vernizzi (ArXiv: 1205.2015)

The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

$$B_g(k_1, k_2, k_3) = b_1^3\, B(k_1, k_2, k_3) + b_1^2\, b_2\, P(k_1)\, P(k_2) + 2\ \mathrm{perm.} + ...$$

The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

$$B_g(k_1,k_2,k_3) = b_1^3\,B(k_1,k_2,k_3) + b_1^2\,b_2\,P(k_1)\,P(k_2) + 2\ \text{perm.} + \ldots$$

$$B = B_0 + B_G^{tree}[P_0] + B_G^{loop}[P_0] + B_{NG}^{loop}[P_0, B_0]$$

primordial component
(*large scales*)

The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

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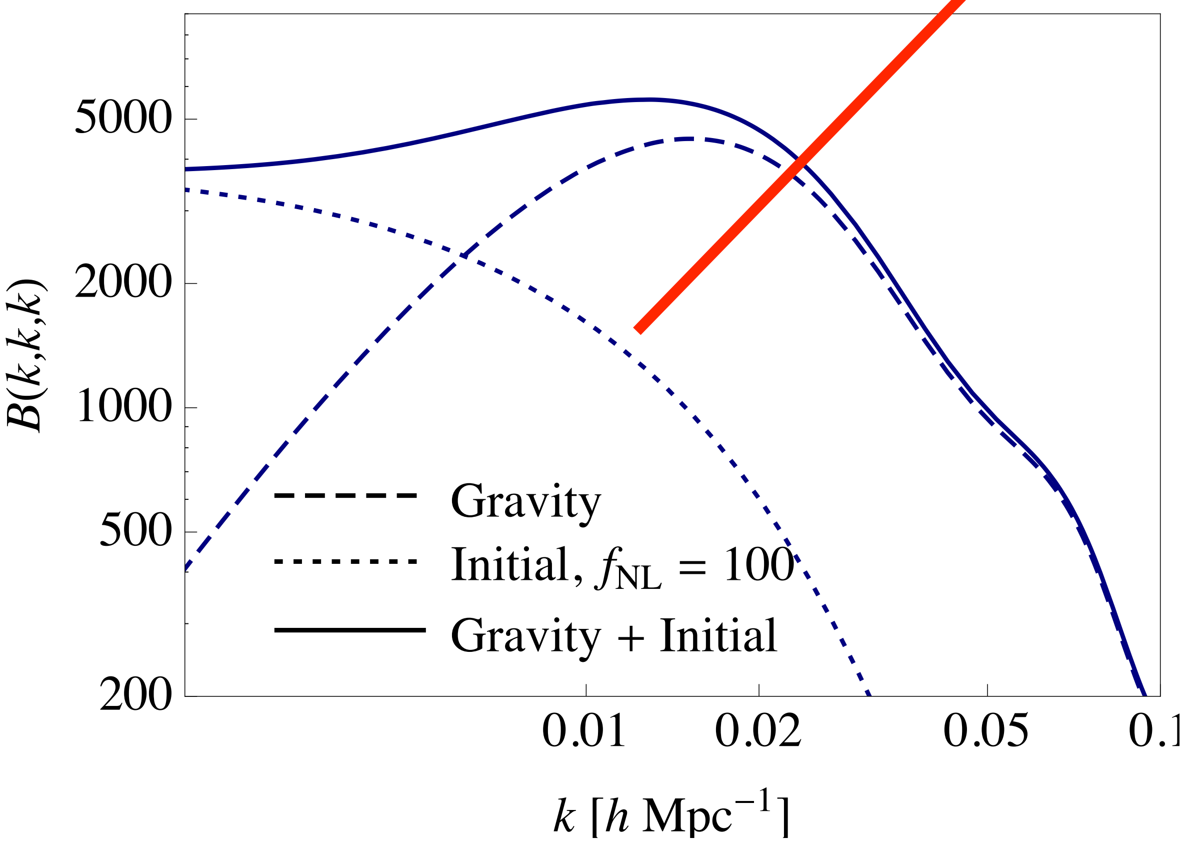

$$\frac{B_0(k,k,k)}{B_G^{tree}(k,k,k)} \overset{k\to 0}{\sim} \frac{f_{NL}}{D(z)k^2}$$

The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

$$B_g(k_1,k_2,k_3) = b_1^3\, B(k_1,k_2,k_3) + b_1^2\, b_2\, P(k_1)\, P(k_2) + 2 \text{ perm.} + \ldots$$

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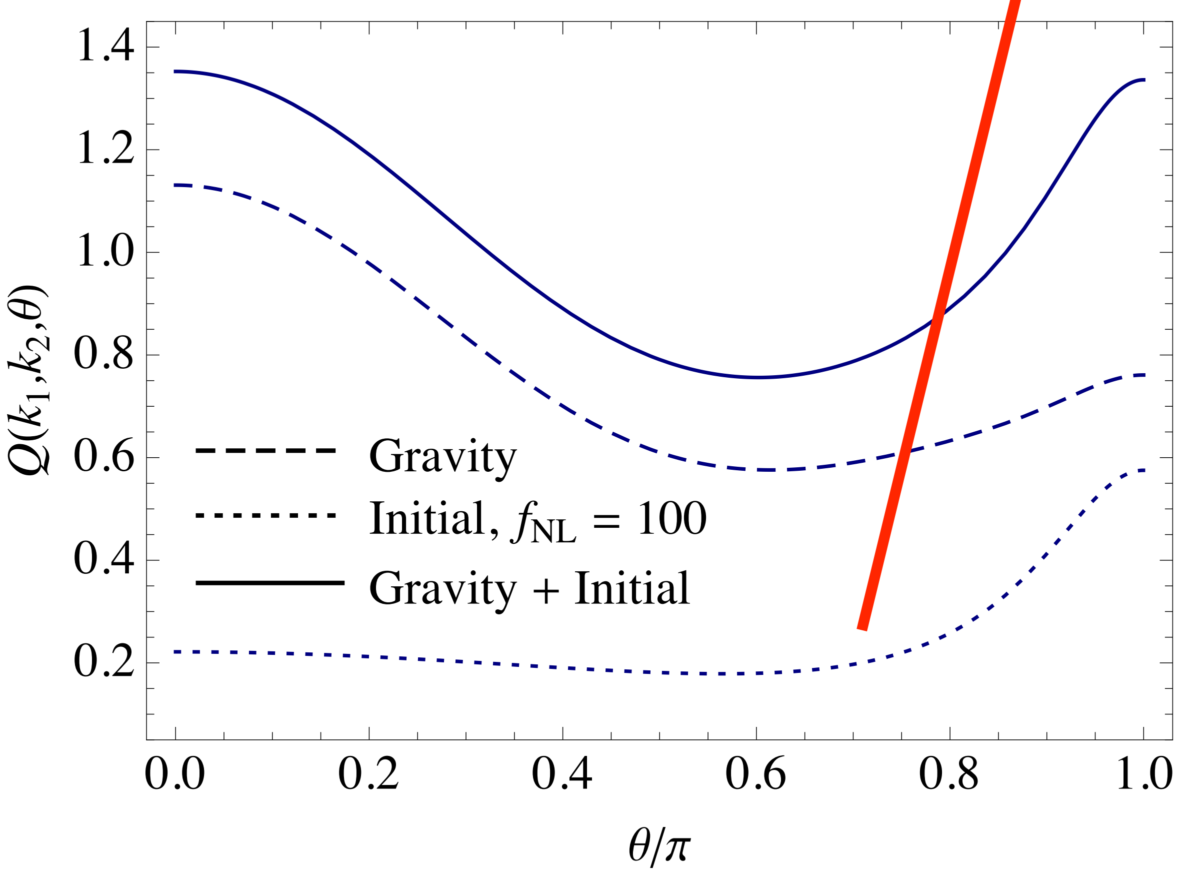

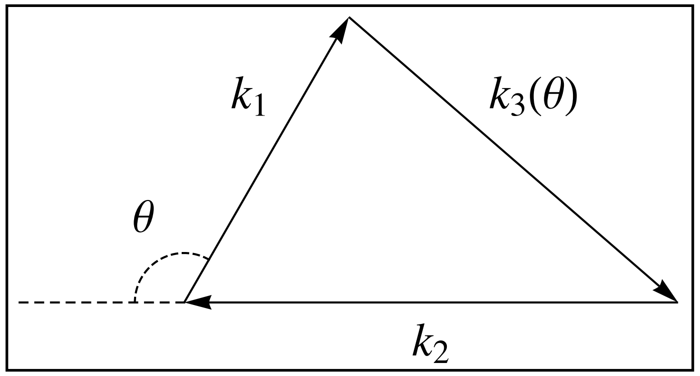

$$Q(k_1,k_2,k_3) = \frac{B(k_1,k_2,k_3)}{P(k_1)P(k_2)+P(k_1)P(k_3)+P(k_2)P(k_3)}$$

The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

$$B_g(k_1, k_2, k_3) = b_1^3\, B(k_1, k_2, k_3) + b_1^2\, b_2\, P(k_1)\, P(k_2) + 2 \text{ perm.} + \ldots$$

$$B = B_0 + B_G^{tree}[P_0] + B_G^{loop}[P_0] + B_{NG}^{loop}[P_0, B_0]$$

primordial component
(*large scales*)

If B_0 was the *only* **effect** of NG initial conditions on the LSS then future, large volume surveys (~100 Gpc^3) could provide:

$\Delta f_{NL}^{local} < 5$ and $\Delta f_{NL}^{eq} < 10$

Scoccimarro, ES & Zaldarriaga (2004), ES & Komatsu (2007)

The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

$$B_g(k_1, k_2, k_3) = b_1^3\, B(k_1, k_2, k_3) + b_1^2\, b_2\, P(k_1)\, P(k_2) + 2 \text{ perm.} + \ldots$$

$$P = P_0 + P_G^{loop}[P_0] + P_{NG}^{loop}[P_0, B_0]$$

$$B = B_0 + B_G^{tree}[P_0] + B_G^{loop}[P_0] + B_{NG}^{loop}[P_0, B_0]$$

primordial component
(*large scales*)

effect on nonlinear
evolution (*small scales*)

The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

$$b_{1,G} + \Delta b_{1,NG}(f_{NL}, k) \qquad b_{2,G} + \Delta b_{2,NG}(f_{NL}, \vec{k}_1, \vec{k}_2)$$

bias corrections

$$B_g(k_1, k_2, k_3) = b_1^3\, B(k_1, k_2, k_3) + b_1^2\, b_2\, P(k_1)\, P(k_2) + 2 \text{ perm.} + \ldots$$

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primordial component
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The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

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primordial component
(*large scales*)

effect on nonlinear
evolution (*small scales*)

$$\Delta b_{1,NG}(f_{NL}, \vec{k}) = \Delta b_{1,si}(f_{NL}) + \Delta b_{1,sd}(f_{NL}, b_{1,G}, \vec{k})$$

$$\Delta b_{2,NG}(f_{NL}, \vec{k}_1, \vec{k}_2) = \Delta b_{2,si}(f_{NL}) + \Delta b_{2,sd}(f_{NL}, b_{1,G}, b_{2,G}, \vec{k}_1, \vec{k}_2)$$

Giannantonio & Porciani (2010)
Baldauf, Seljak & Senatore (2010)

The **Galaxy Bispectrum**: *NG and nonlinear bias*

The galaxy bispectrum at large scales

$$b_{1,G} + \Delta b_{1,NG}(f_{NL}, k) \qquad b_{2,G} + \Delta b_{2,NG}(f_{NL}, \vec{k}_1, \vec{k}_2)$$

bias corrections

$$B_g(k_1, k_2, k_3) = b_1^3\, B(k_1, k_2, k_3) + b_1^2\, b_2\, P(k_1)\, P(k_2) + 2 \text{ perm.} + \ldots$$

$$P = P_0 + P_G^{loop}[P_0] + P_{NG}^{loop}[P_0, B_0]$$

$$B = B_0 + B_G^{tree}[P_0] + B_G^{loop}[P_0] + B_{NG}^{loop}[P_0, B_0]$$

primordial component (*large scales*)

effect on nonlinear evolution (*small scales*)

$$\Delta b_{1,NG}(f_{NL}, \vec{k}) = \Delta b_{1,si}(f_{NL}) + \Delta b_{1,sd}(f_{NL}, b_{1,G}, \vec{k})$$

$$\Delta b_{2,NG}(f_{NL}, \vec{k}_1, \vec{k}_2) = \Delta b_{2,si}(f_{NL}) + \Delta b_{2,sd}(f_{NL}, b_{1,G}, b_{2,G}, \vec{k}_1, \vec{k}_2)$$

Giannantonio & Porciani (2010)
Baldauf, Seljak & Senatore (2010)

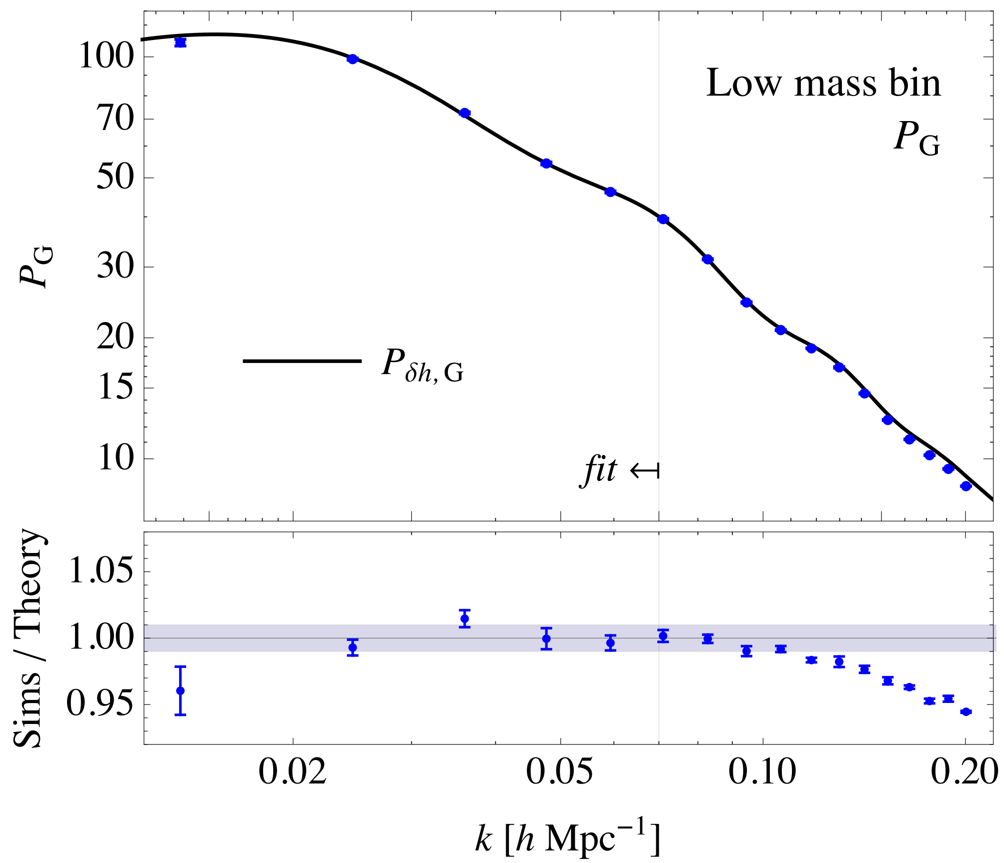
$$\Delta b_{2,sd,b}(k_1, k_2, f_{NL}) \;=\; 2\, f_{NL}\, \delta_c \left[b_{2,G} + \left(\frac{13}{21} - \frac{1}{\delta_c} \right) (b_{1,G} - 1) \right] \left[\frac{1}{M(k_1, z)} + \frac{1}{M(k_2, z)} \right]$$

We test this model in N-body simulations with local NG initial conditions

$$\langle \delta \delta \delta_h \rangle = \delta_D(\vec{k}_{123})\, B_{mmh}$$

$$\langle \delta_h \delta_h \delta_h \rangle = \delta_D(\vec{k}_{123})\, B_h$$

The **Halo Bispectrum**: *theory vs. simulations*



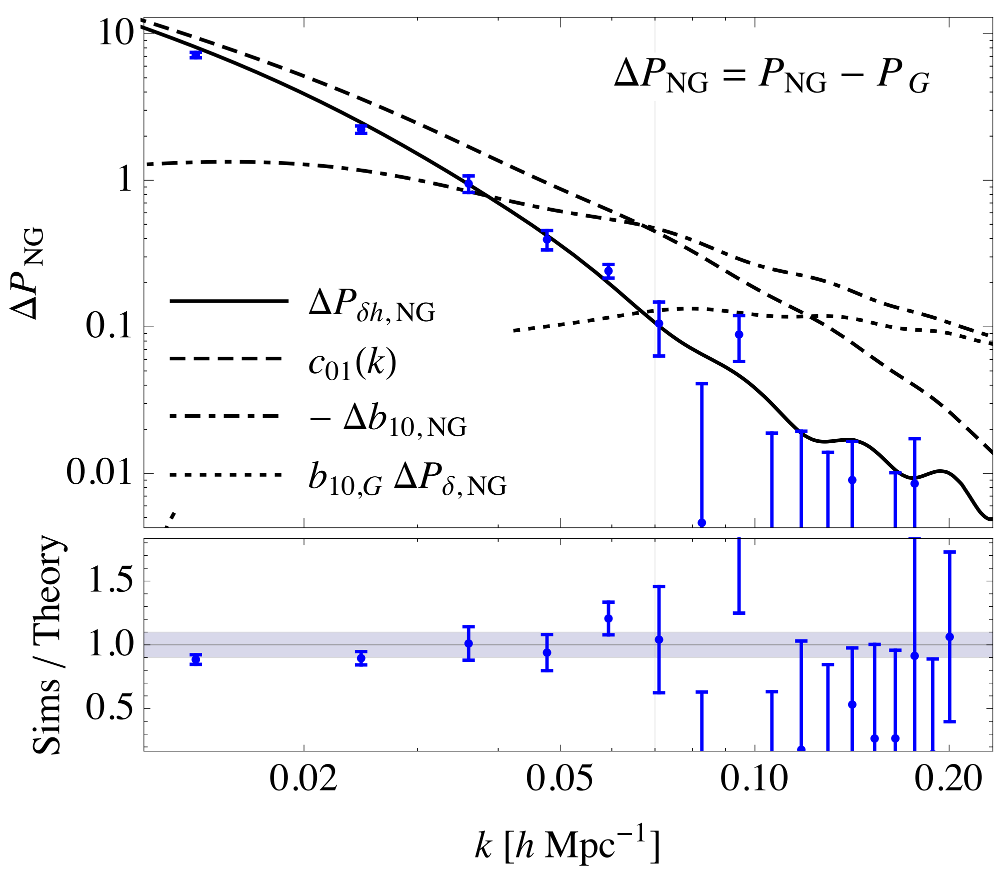
$$B_{mmh} = b_1\, B + b_2\, P\, P + \text{perm.}$$

$$b_1 = b_{1,G} + \Delta b_{1,si} + \Delta b_{1,sd}(b_{1,G}, \vec{k})$$

$$b_2 = b_{2,G} + \Delta b_{2,si} + \Delta b_{2,sd}(b_{1,G}, b_{2,G}, \vec{k}_1, \vec{k}_2)$$

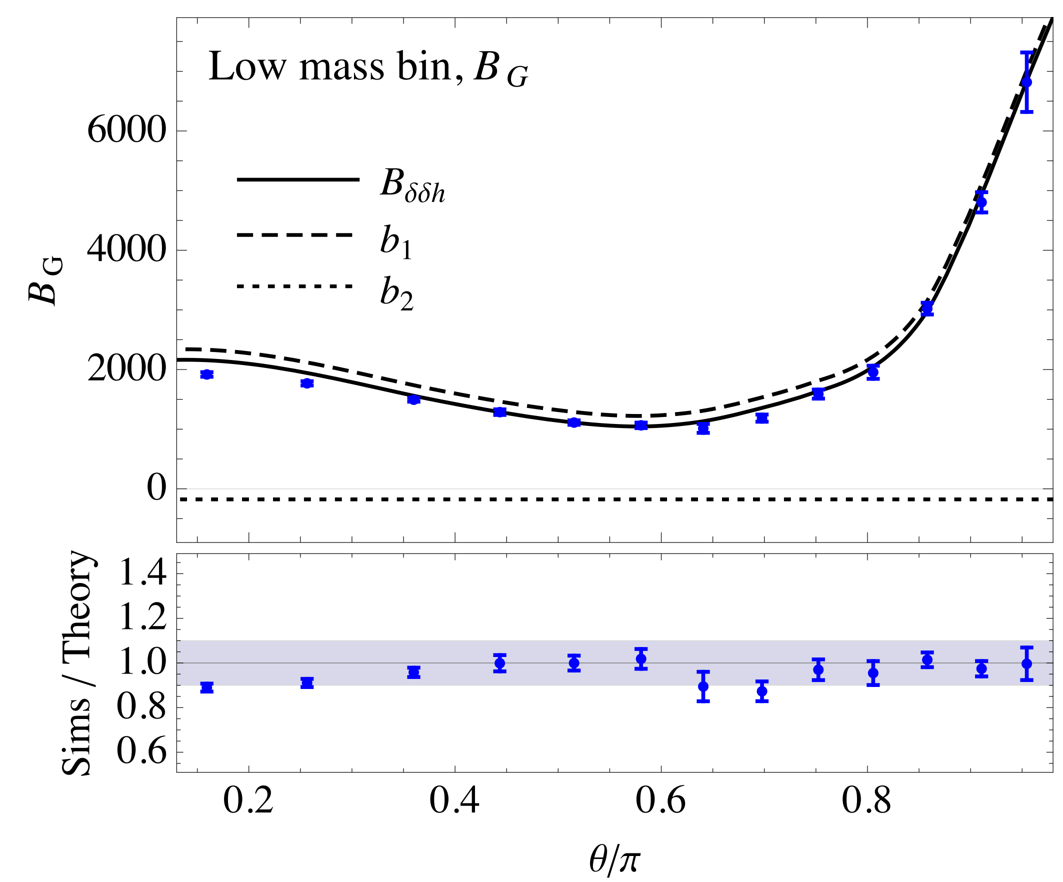
→ b_1

We fit for $b_{1,G}$, $b_{2,G}$, $\Delta b_{1,si}$ and $\Delta b_{2,si}$ ***all*** triangular configurations up to k = 0.07 h/Mpc



→ $\Delta b_{1,si}$

b_2 ←



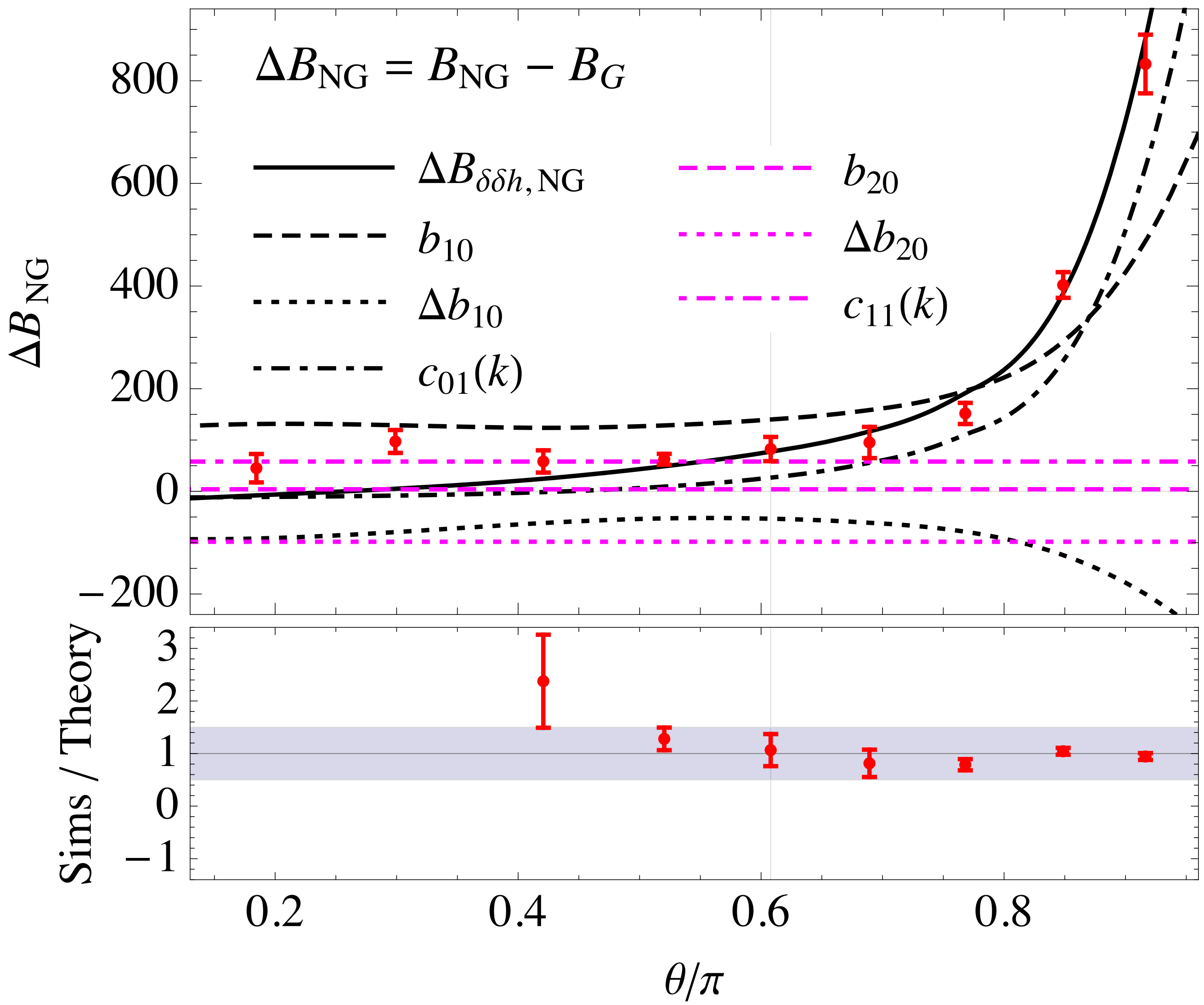
The **Halo Bispectrum**: *theory vs. simulations*

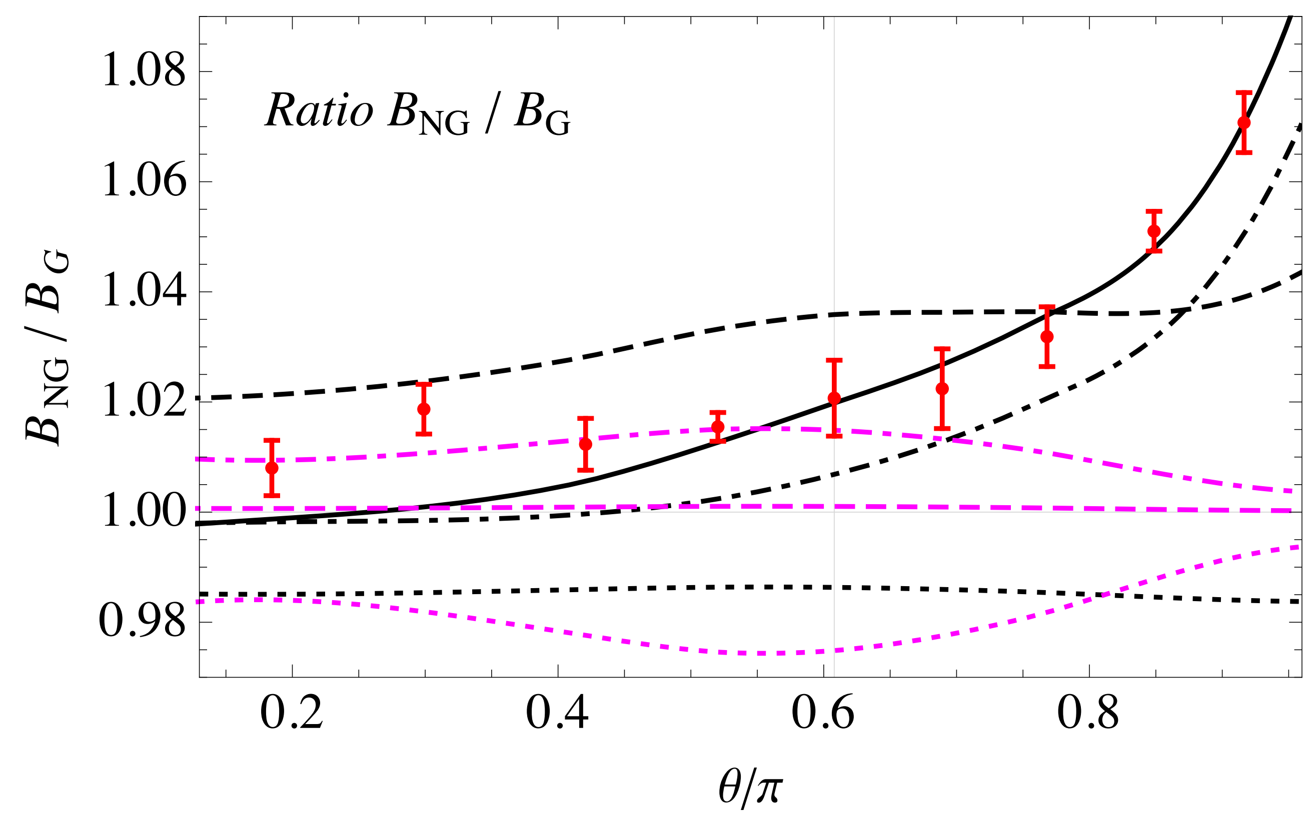
Matter-matter-halo bispectrum:

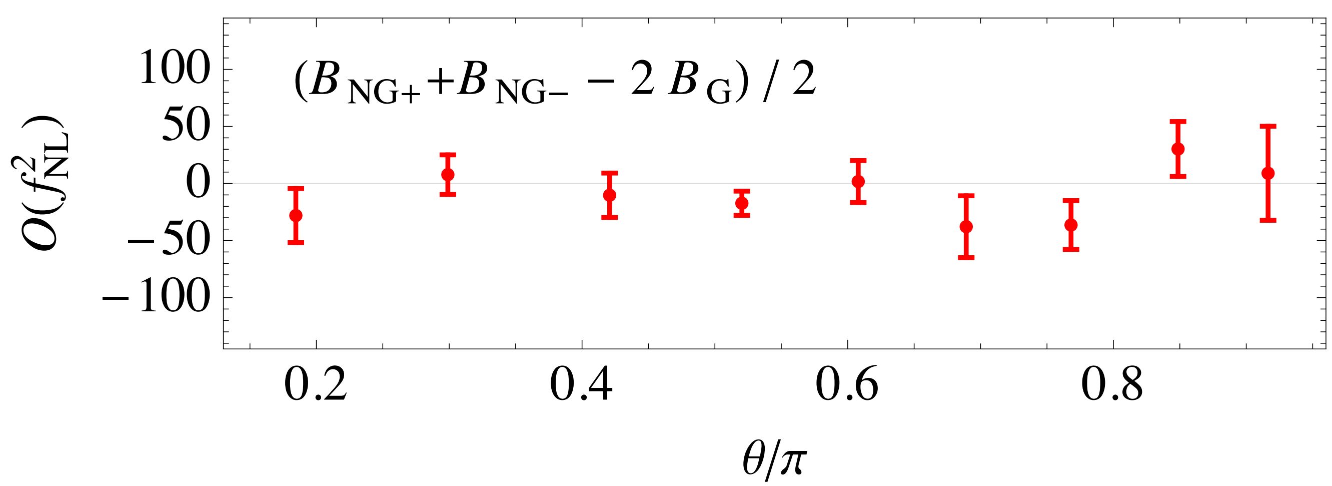
$$B_{mmh}(k_1, k_2; k_3) = b_1(f_{NL}, k)\, B(k_1, k_2, k_3) + b_2(f_{NL}, k_1, k_2)\, P(k_1)\, P(k_2)$$

$B(k_1, k_2, \theta)$ as a function of θ with k_1 = 0.05 h/Mpc, k_2 =0.07 h/Mpc

$M > 1.6 \times 10^{13}\, h^{-1}\, M_\odot$







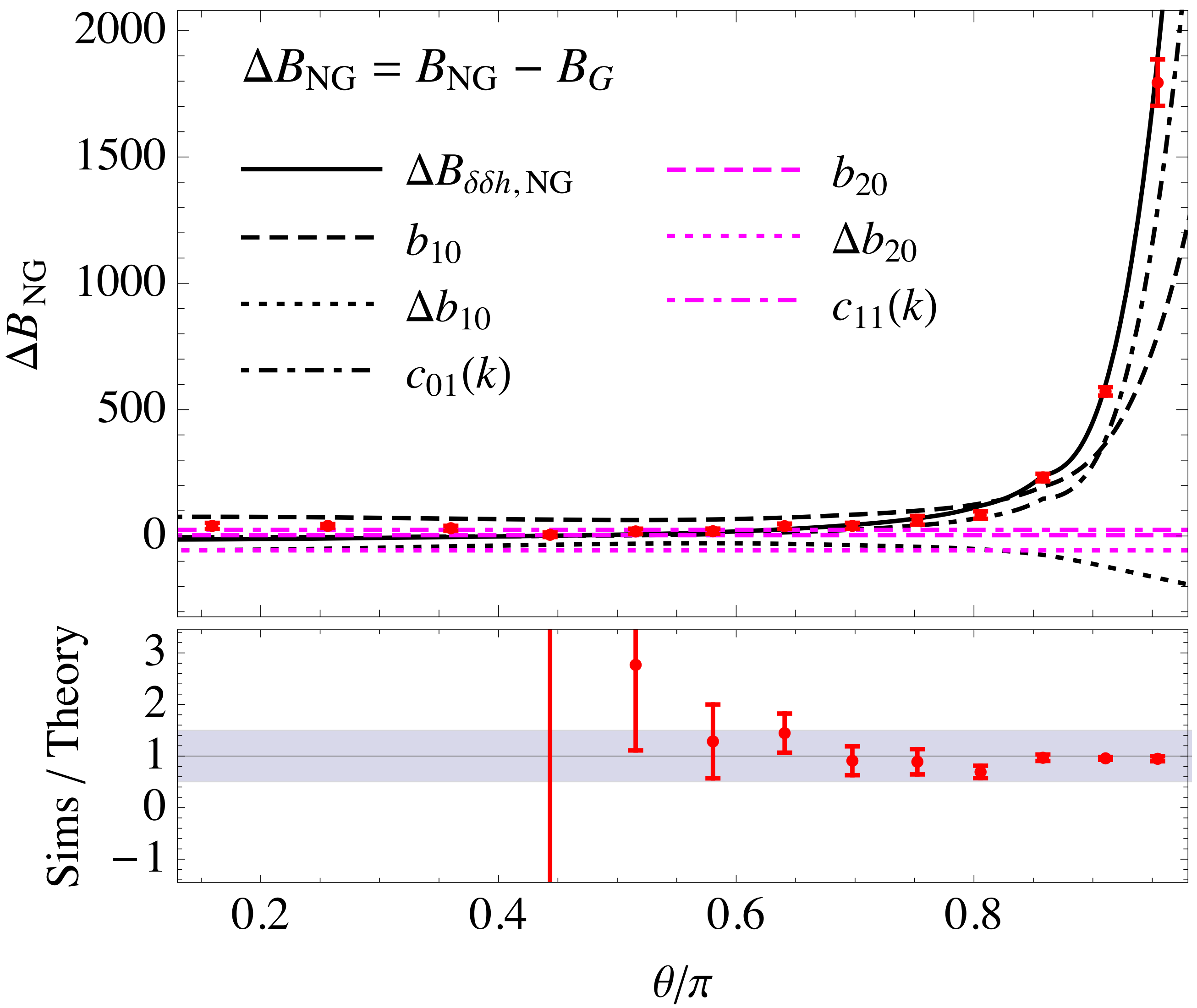
ES, Crocce & Desjacques (2011)

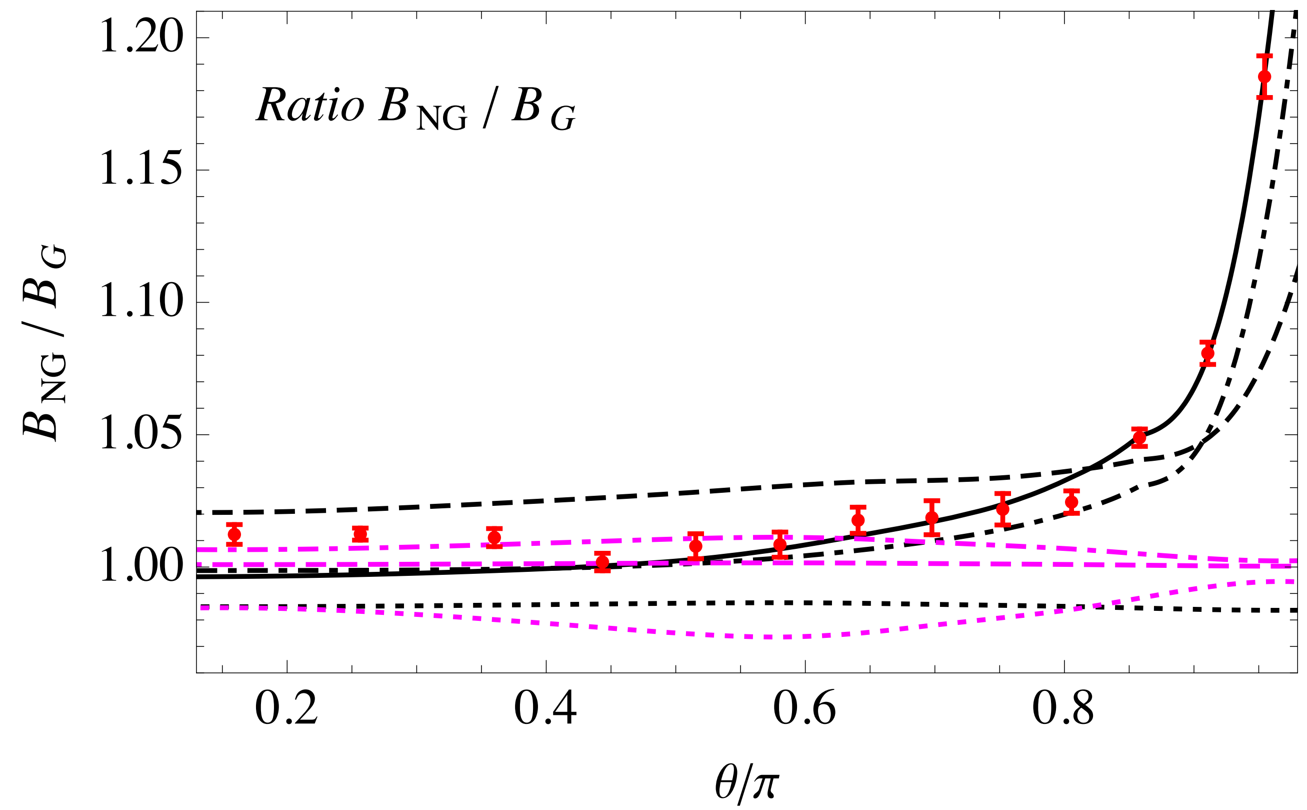
The **Halo Bispectrum**: *theory vs. simulations*

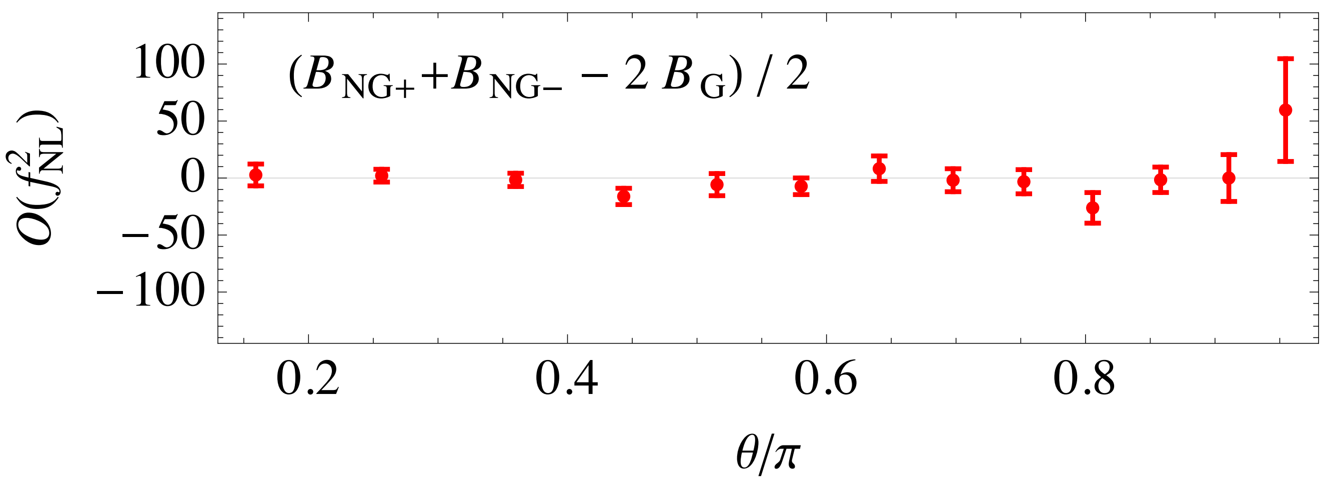
Matter-matter-halo bispectrum:

$$B_{mmh}(k_1, k_2; k_3) = b_1(f_{NL}, k)\, B(k_1, k_2, k_3) + b_2(f_{NL}, k_1, k_2)\, P(k_1)\, P(k_2)$$

B(k₁, k₂, θ) as a function of θ with k₁ = 0.07 h/Mpc, k₂ = 0.08 h/Mpc $M > 1.6 \times 10^{13}\, h^{-1}\, \mathrm{M}_\odot$







ES, Crocce & Desjacques (2011)

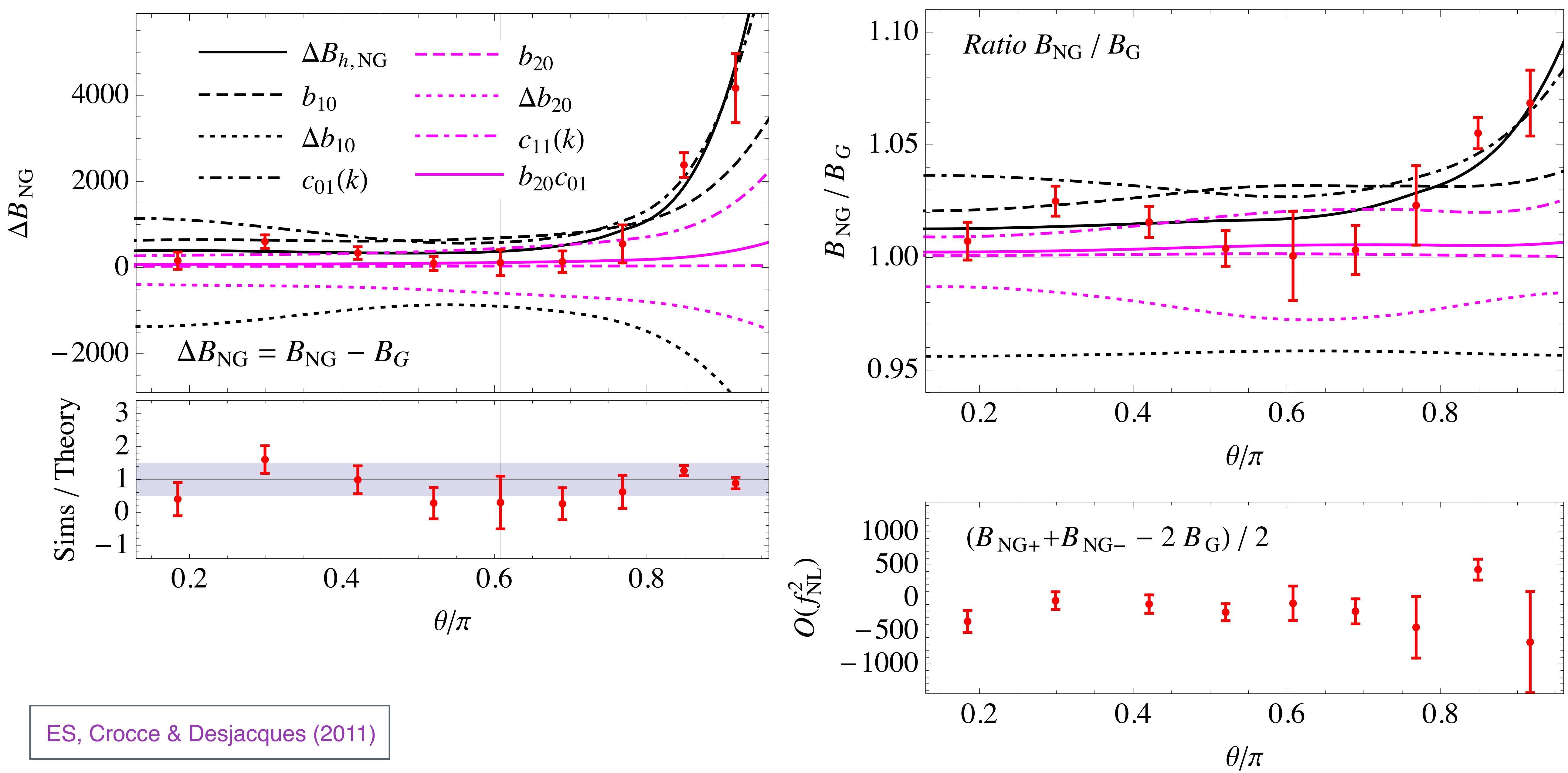
The **Halo Bispectrum**: *theory vs. simulations*

Halo bispectrum:

$$B_h(k_1,k_2,k_3) = b_1^3(f_{NL},k)\,B(k_1,k_2,k_3)$$
$$+b_1(f_{NL},k_1)b_1(f_{NL},k_2)b_2(f_{NL},k_1,k_2)\,P(k_1)\,P(k_2) + cyc.$$

$B(k_1, k_2, \theta)$ *as a function of* θ *with* $k_1 = 0.05\ h$/Mpc, $k_2 = 0.07\ h$/Mpc

$M > 1.6 \times 10^{13}\, h^{-1}\, \mathrm{M}_\odot$



ES, Crocce & Desjacques (2011)

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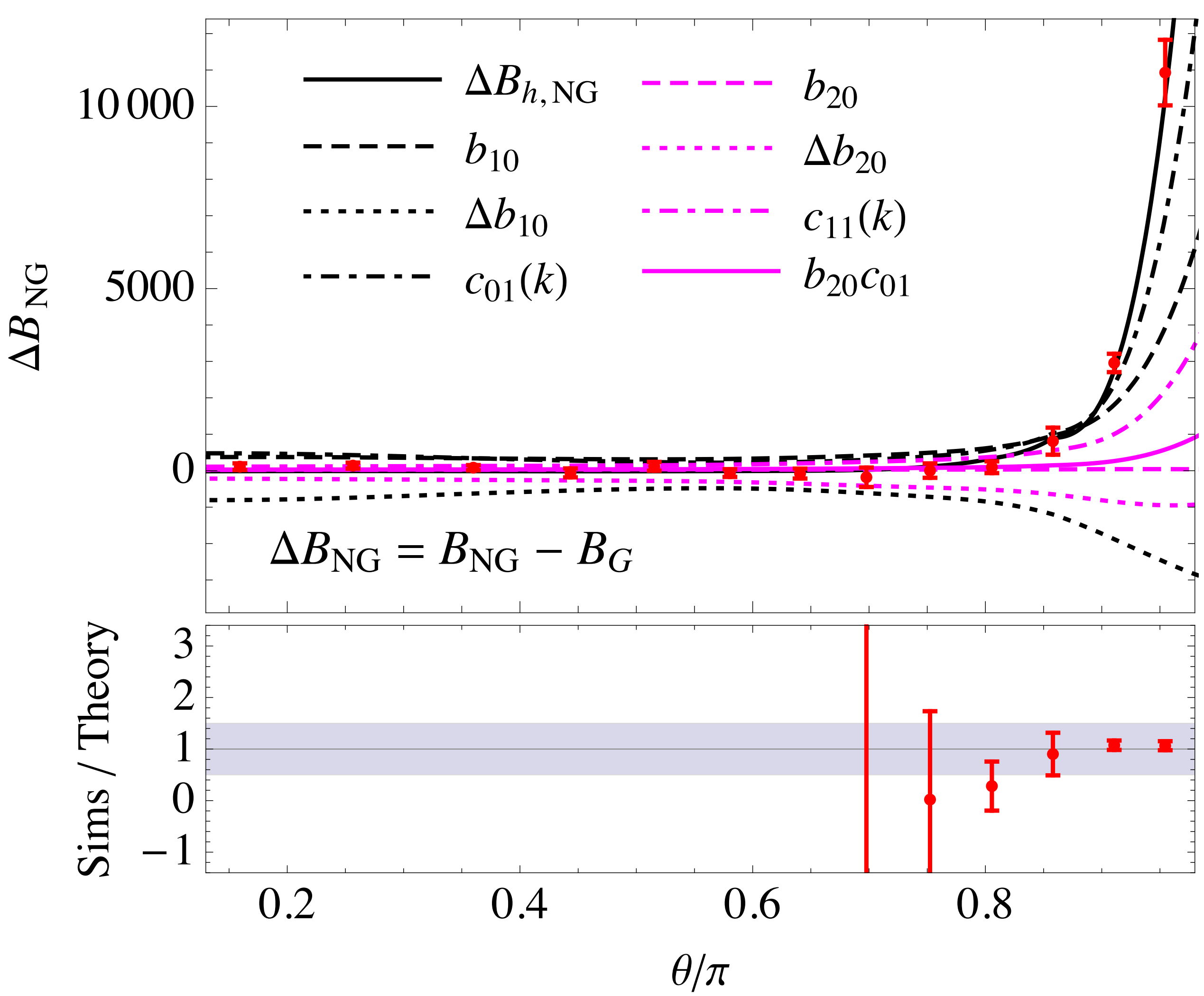
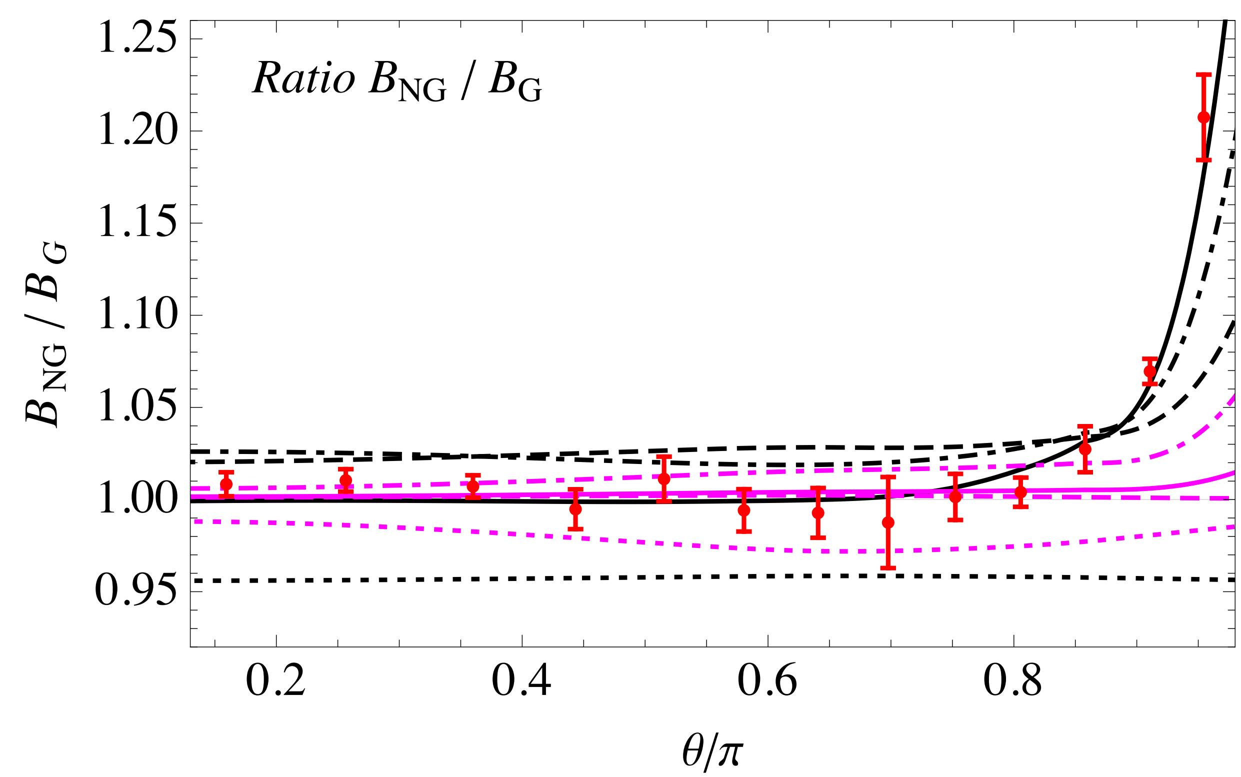
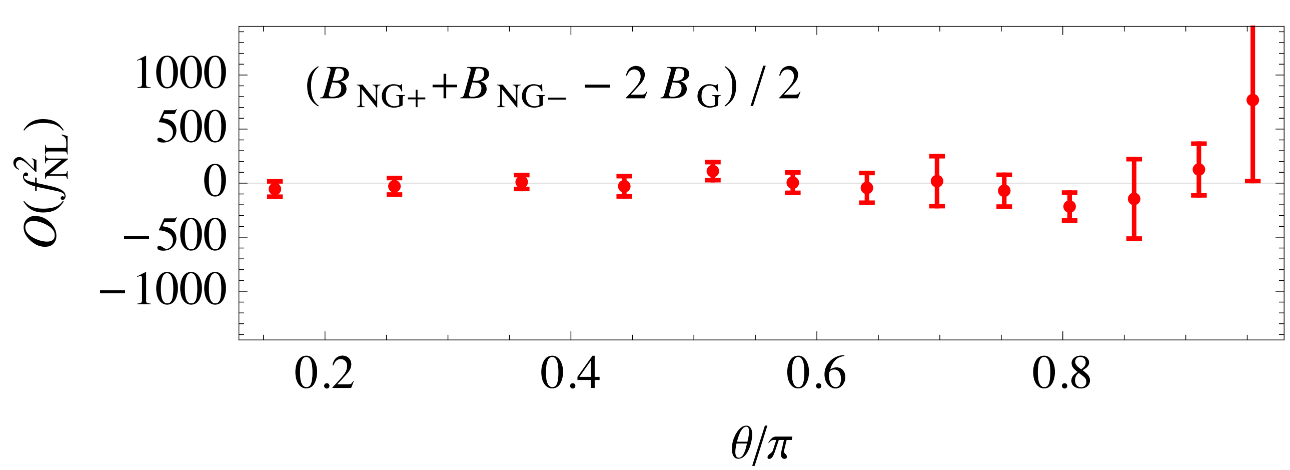


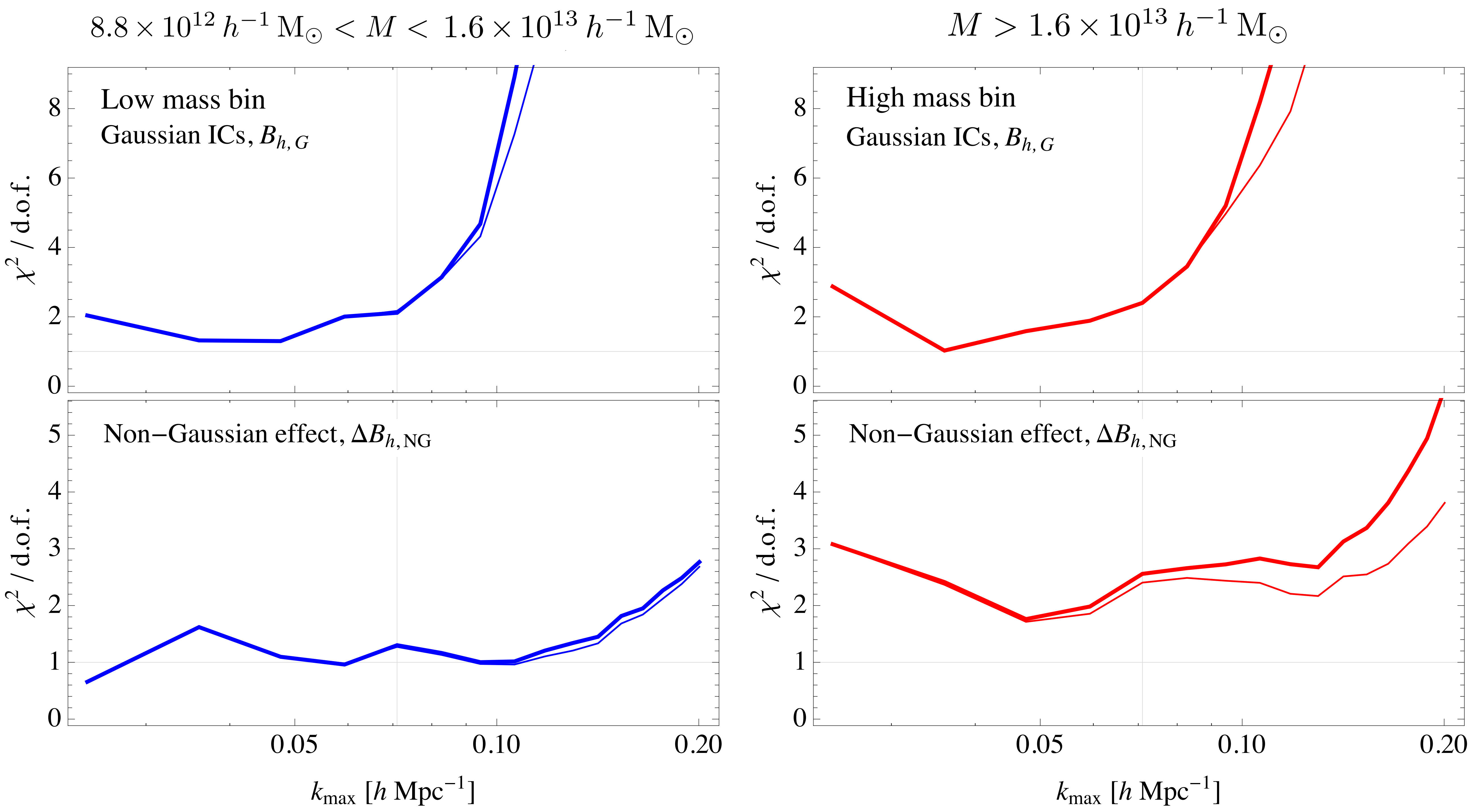




ES, Crocce & Desjacques (2011)

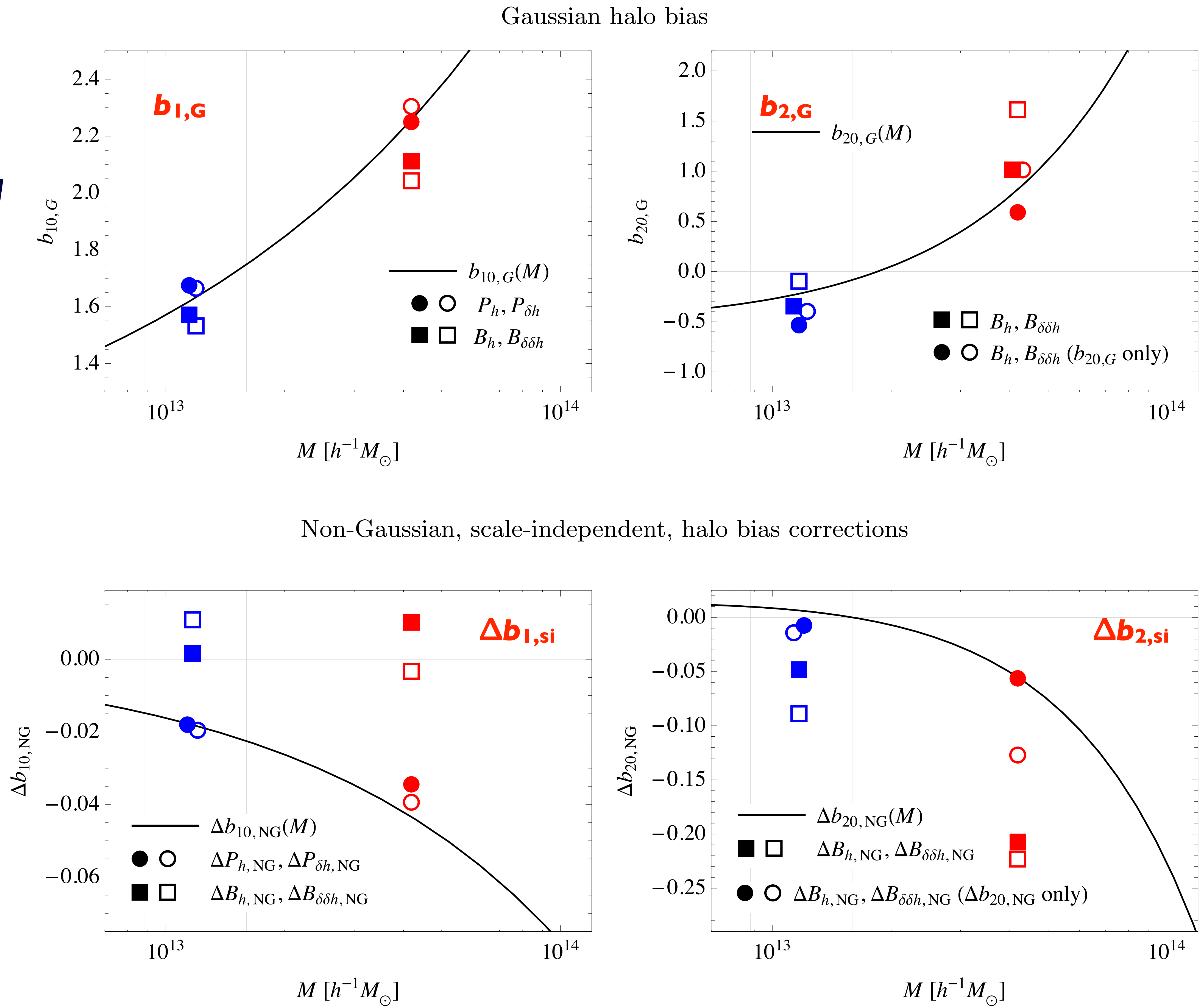
The **Halo Bispectrum**: *theory vs. simulations*

χ^2, *for all triangles*, as a function of k_{max}

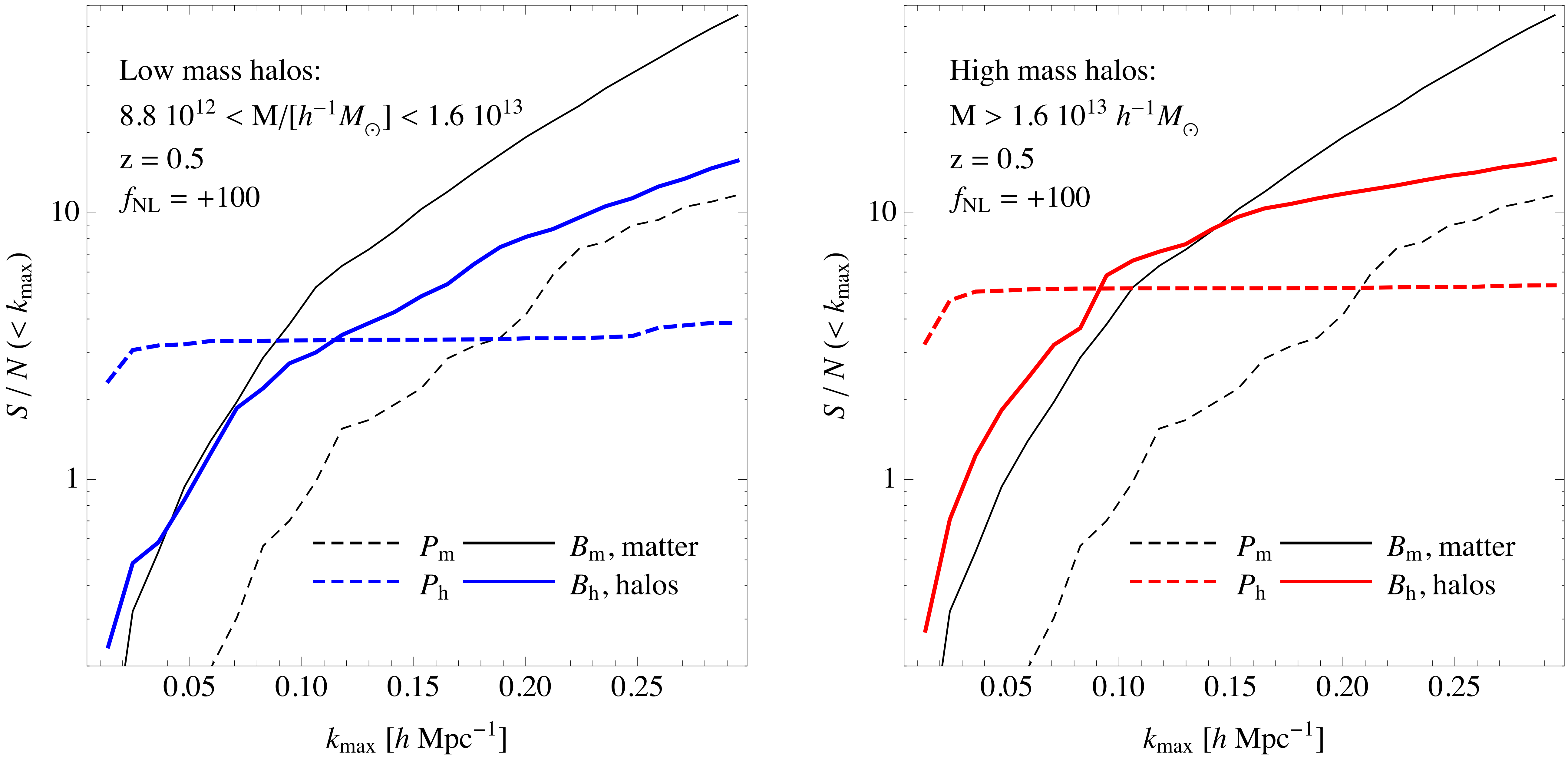


The **Halo Bispectrum**: *theory vs. simulations*

Best-fit bias parameters and their *peak-background split* predictions



Halo Power Spectrum vs. *Halo* Bispectrum



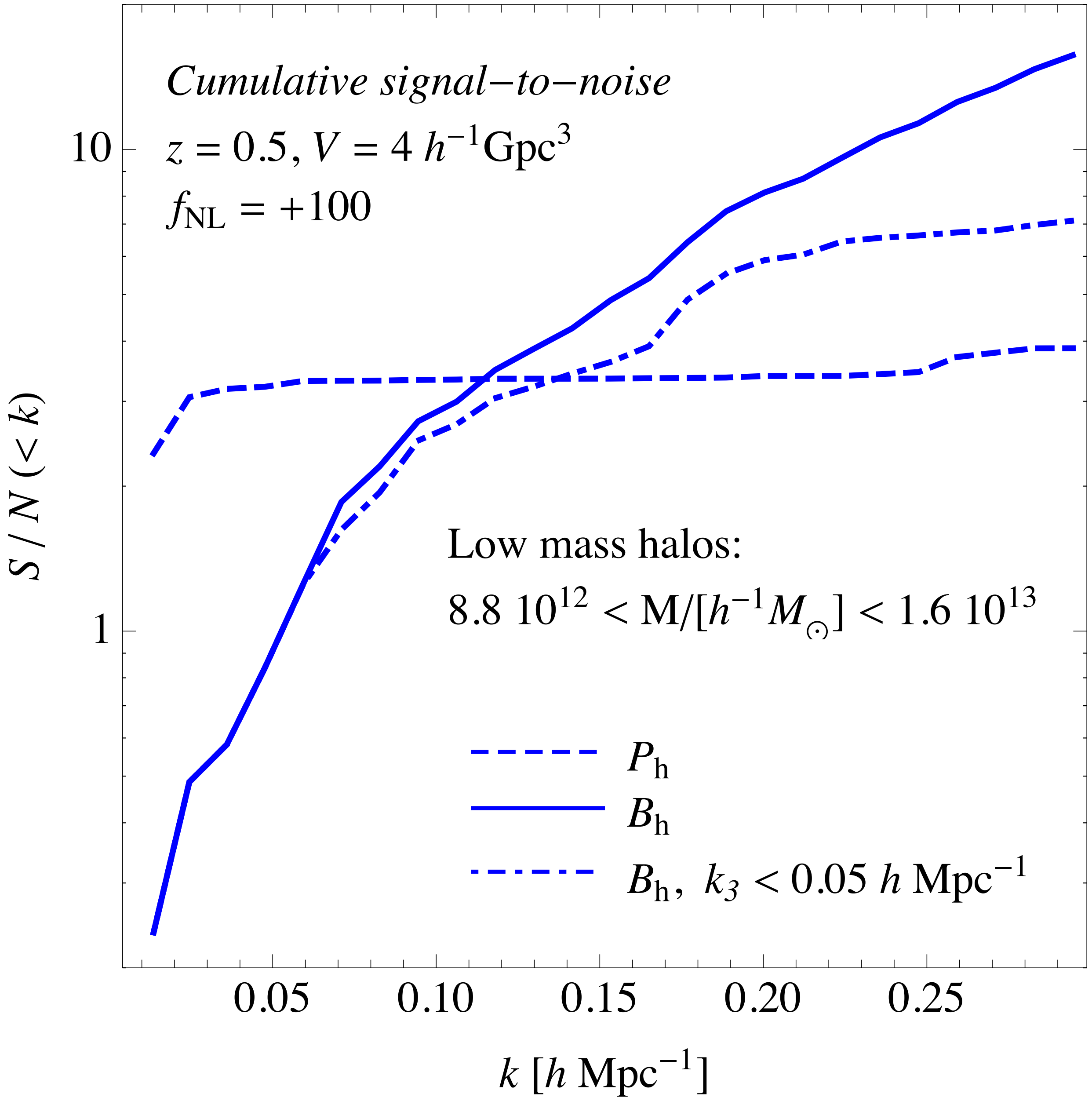
Cumulative signal-to-noise for the effect of NG initial conditions on matter and galaxy correlators (P & B)

Sum of all configurations up to k_{max}

$$\left(\frac{S}{N}\right)^2_P = \sum_k^{k_{max}} \frac{(P_{NG} - P_G)^2}{\Delta P^2} \qquad \left(\frac{S}{N}\right)^2_B = \sum_{k_1,k_2,k_3}^{k_{max}} \frac{(B_{NG} - B_G)^2}{\Delta B^2}$$

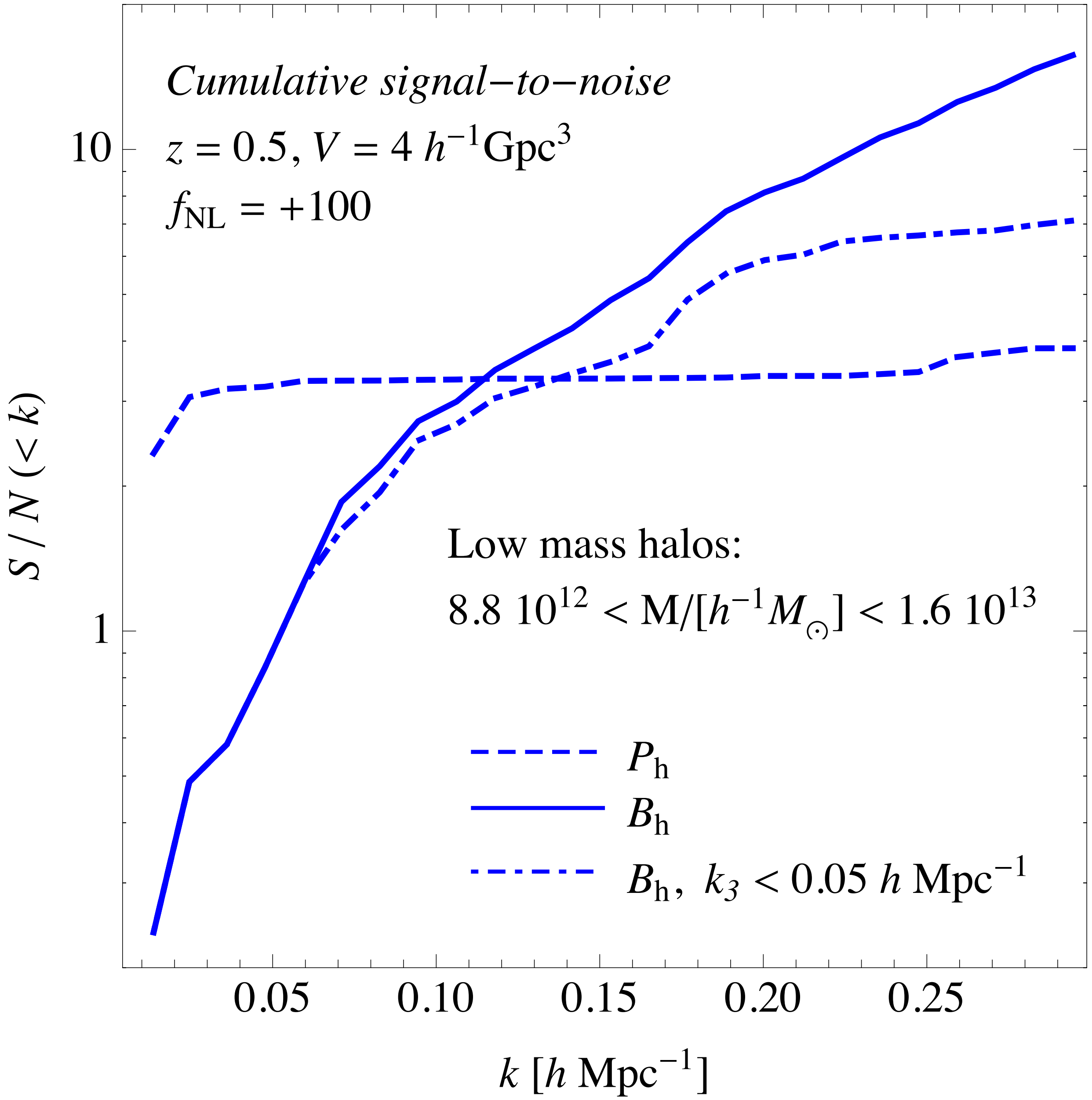
The cumulative NG effect is comparable at mildly nonlinear scales

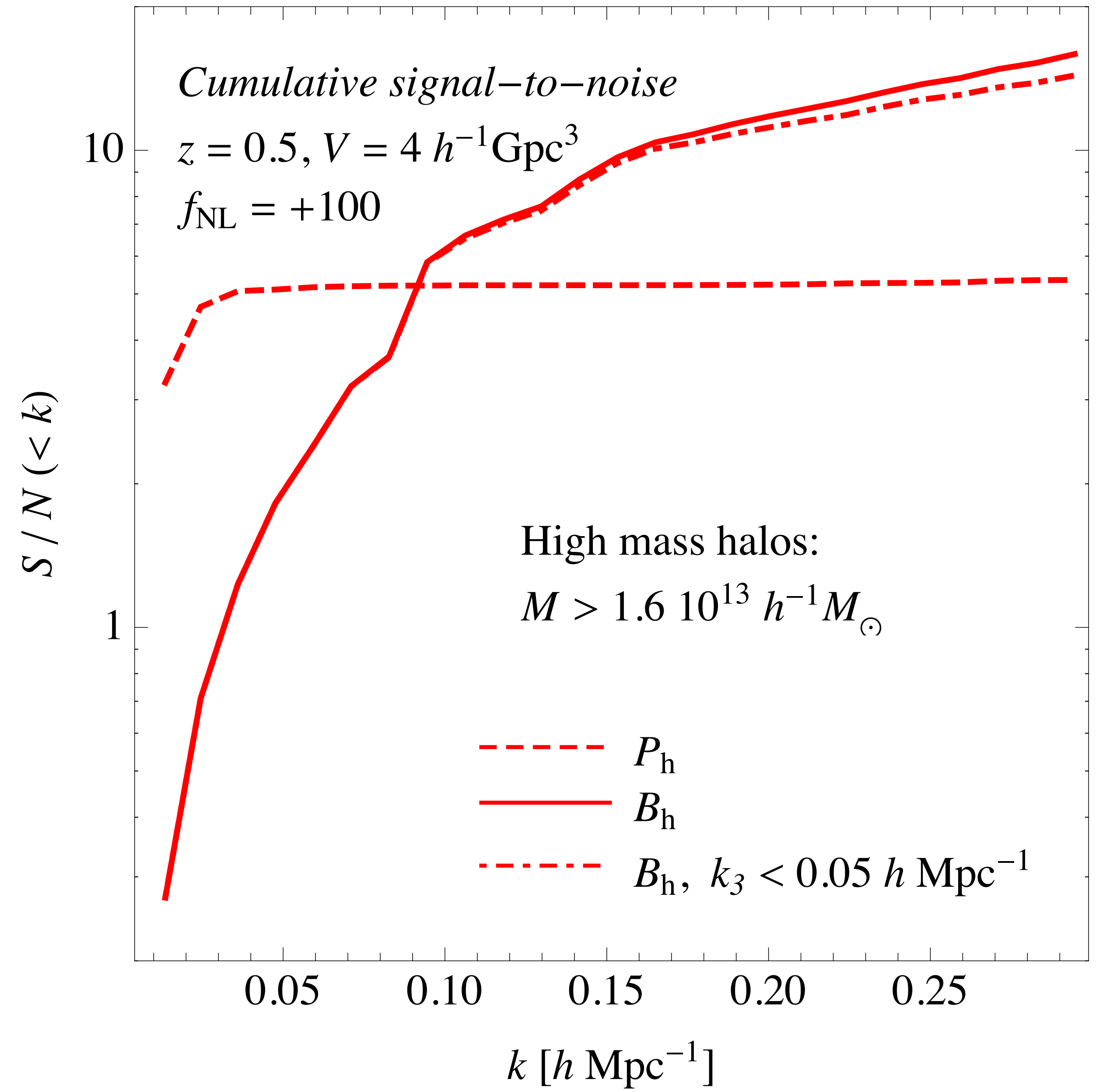
Halo Power Spectrum vs. *Halo* Bispectrum



What is the signal in squeezed configurations?

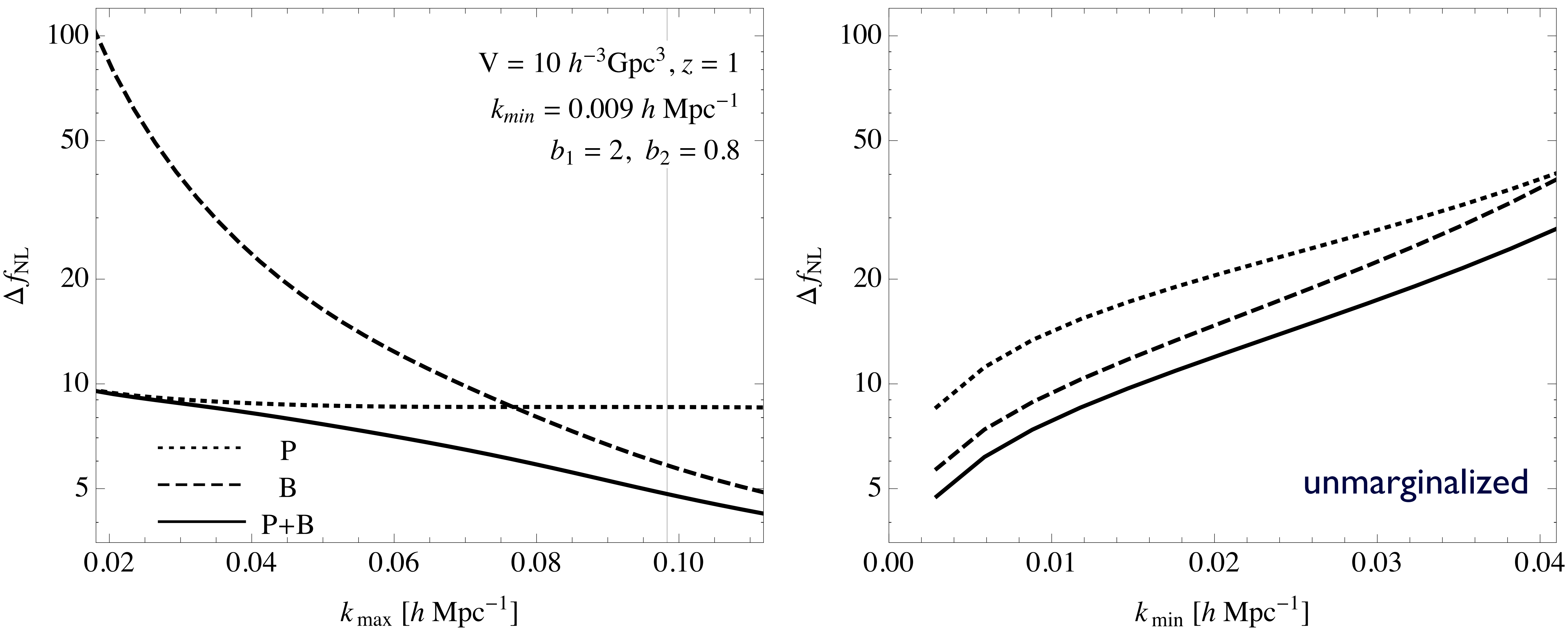
Halo Power Spectrum vs. *Halo* Bispectrum



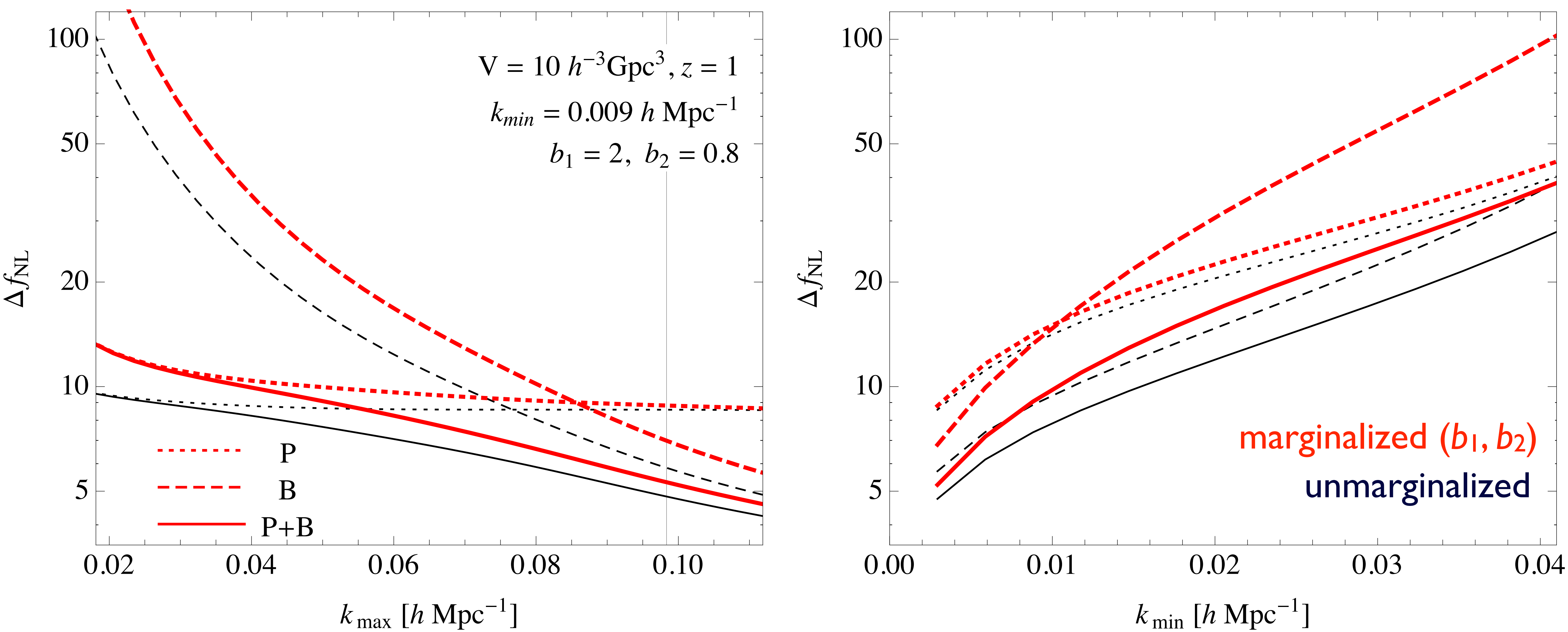


What is the signal in squeezed configurations?

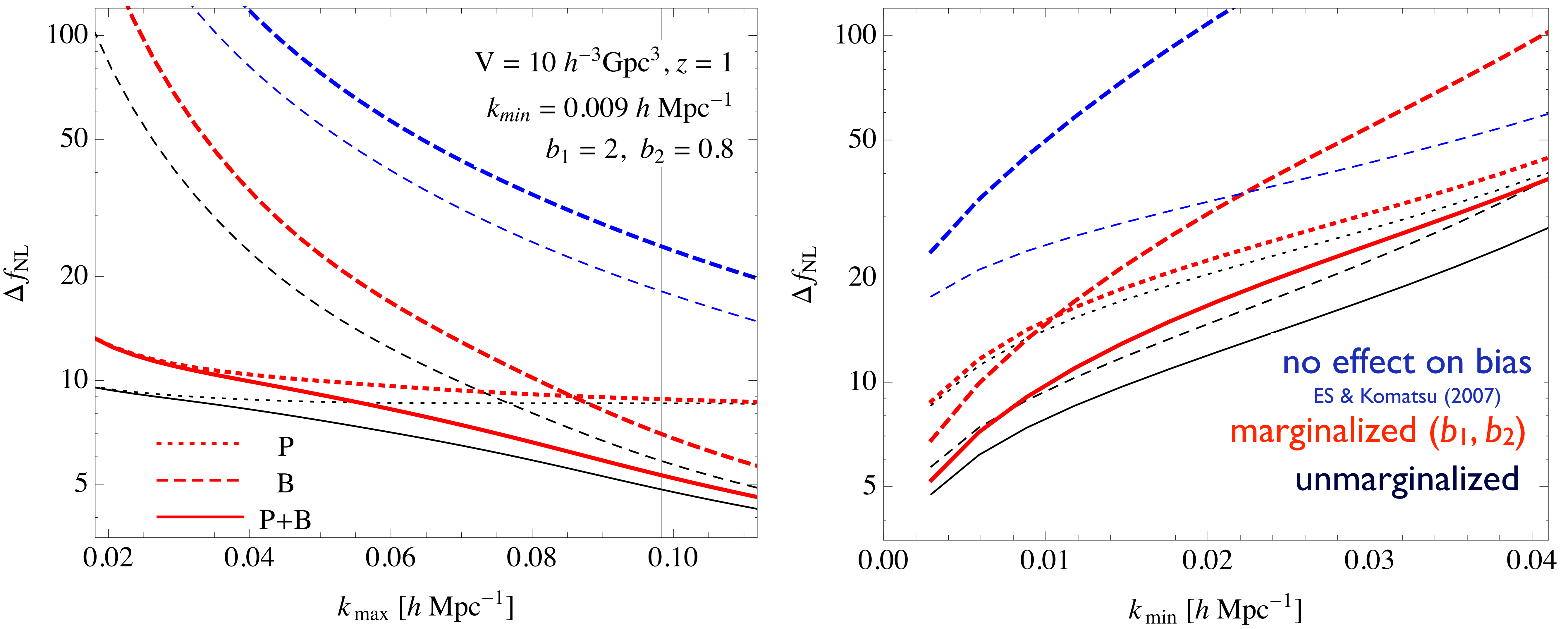
The uncertainty on f_{NL} (local) from Power Spectrum & Bispectrum (& both)



The uncertainty on f_{NL} (local) from Power Spectrum & Bispectrum (& both)



The uncertainty on f_{NL} (local) from Power Spectrum & Bispectrum (& both)



The matter bispectrum at small scales

Matter Power Spectrum

In Perturbation Theory ...

$$P = P_0 + P_G^{loop}[P_0] + P_{NG}^{loop}[P_0, B_0]$$

matter power spectrum

Linear power spectrum

Gravity-induced contributions (depending on P_0 alone)

Additional gravity-induced contributions present *only* for NG initial conditions (B_0)

Matter Power Spectrum

In Perturbation Theory ...

$$P = P_0 + P_G^{loop}[P_0] + P_{NG}^{loop}[P_0, B_0]$$

matter power spectrum

Linear power spectrum

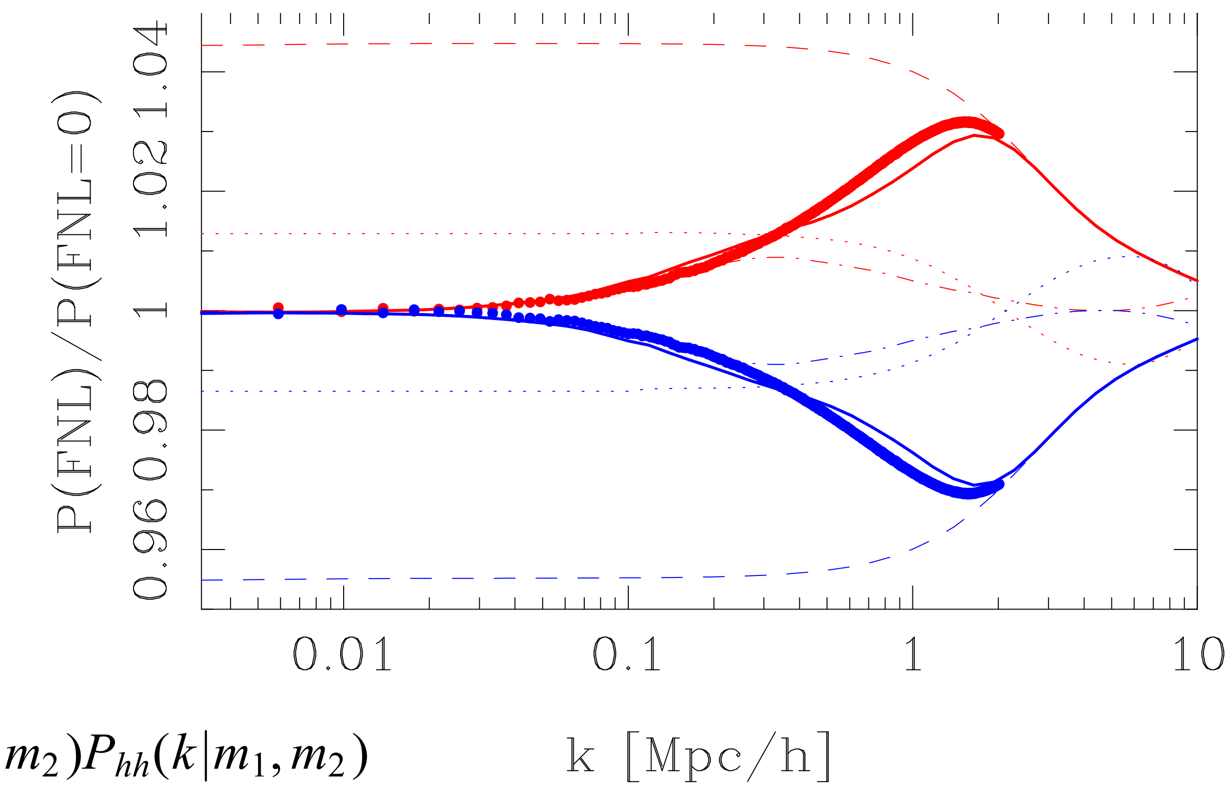
Gravity-induced contributions (depending on P_0 alone)

Additional gravity-induced contributions present *only* for NG initial conditions (B_0)

Few percent effect at small scales for allowed values of f_{NL}

Ratio of the non-Gaussian to the Gaussian power spectrum for f_{NL} = ±100 (local) at z = 1

Smith, Desjacques & Marian (2010)



In the Halo Model:

$$P(k) = P^{1h}(k) + P^{2h}(k), \quad \text{where}$$

$$P^{1h}(k) = \int dm\, n(m) \left(\frac{m}{\bar{\rho}}\right)^2 |u(k|m)|^2$$

$$P^{2h}(k) = \int dm_1 n(m_1) \left(\frac{m_1}{\bar{\rho}}\right) u(k|m_1) \int dm_2 n(m_2) \left(\frac{m_2}{\bar{\rho}}\right) u(k|m_2) P_{hh}(k|m_1, m_2)$$

The matter **bispectrum** and PNG: *small scales*

In Perturbation Theory ...

$$P = P_0 + P_G^{loop}[P_0] + P_{NG}^{loop}[P_0, B_0]$$

matter power spectrum

- P_0: Linear power spectrum
- $P_G^{loop}[P_0]$: Gravity-induced contributions (depending on P_0 alone)
- $P_{NG}^{loop}[P_0, B_0]$: **Additional** gravity-induced contributions present *only* for NG initial conditions (B_0)

$$B = B_0 + B_G^{tree}[P_0] + B_G^{loop}[P_0] + B_{NG}^{loop}[P_0, B_0]$$

& **bispectrum**

- B_0: **Primordial component**
- $B_G^{tree}[P_0]$, $B_G^{loop}[P_0]$: Gravity-induced contributions (depending on P_0 alone)
- $B_{NG}^{loop}[P_0, B_0]$: **Additional** gravity-induced contributions present *only* for NG initial conditions (B_0)

Nonlinear corrections are *also* affected by the initial conditions!

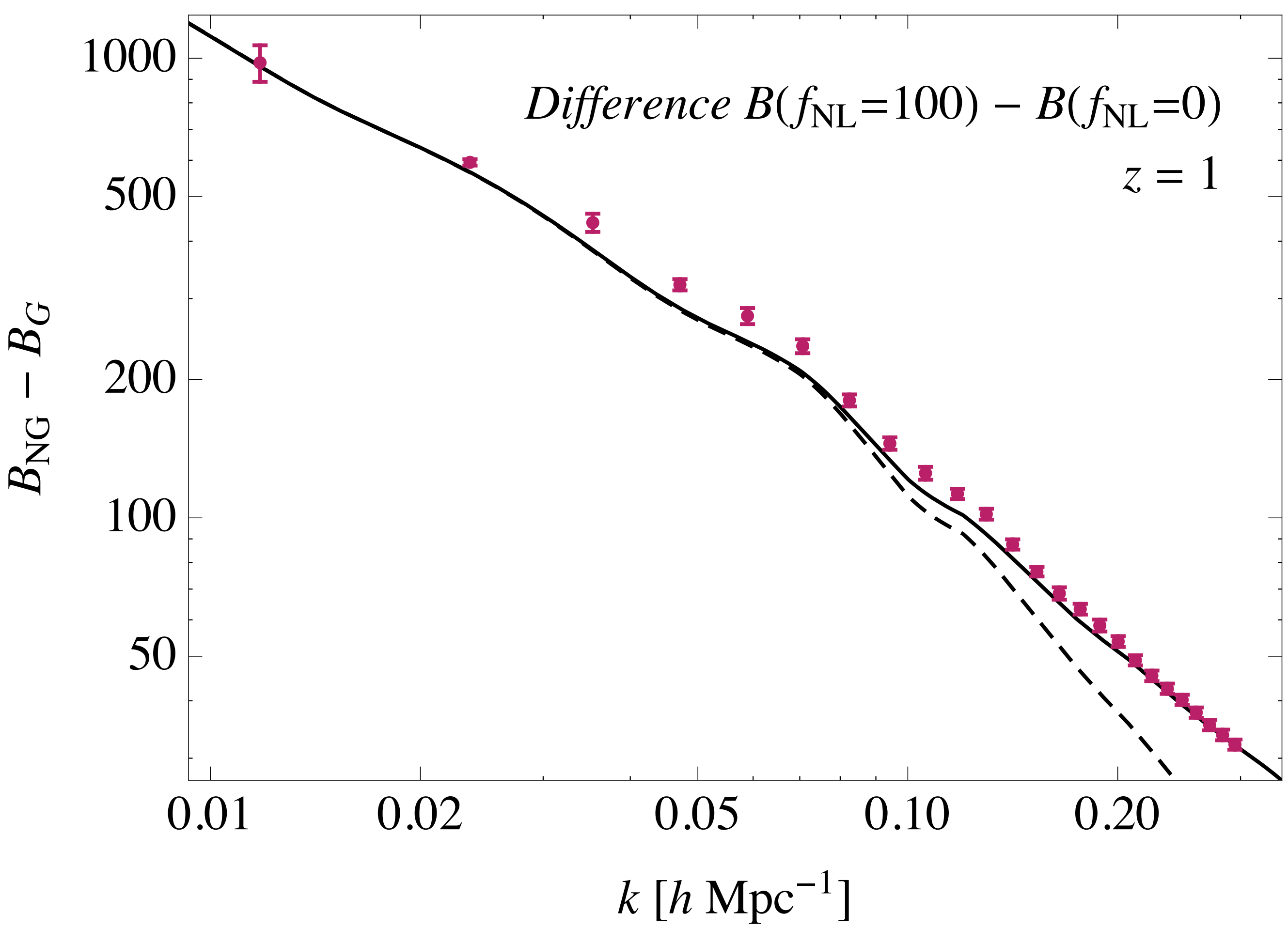
The matter **bispectrum** and PNG: *small scales*

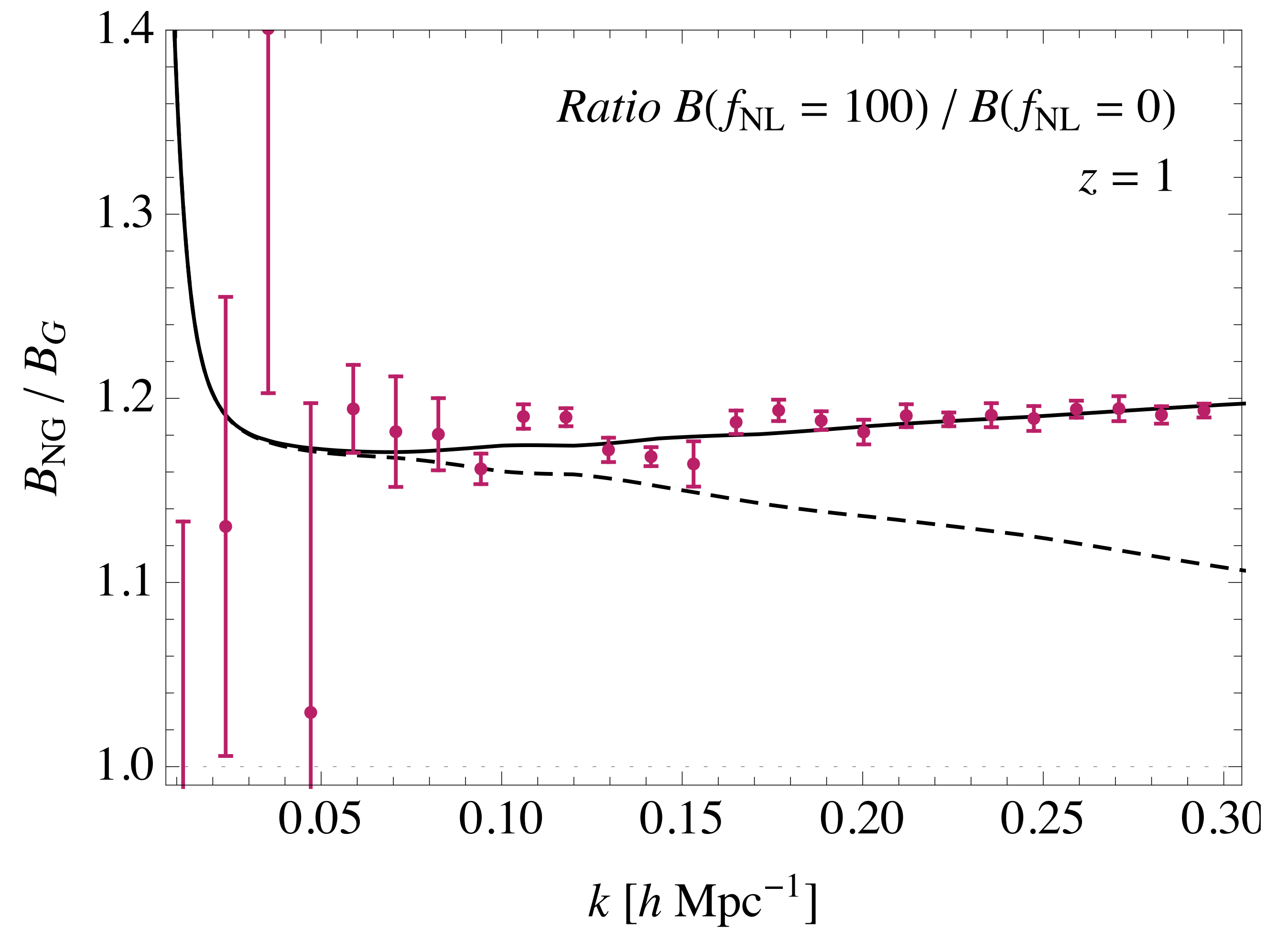
$$B = B_0 + B_G^{tree}[P_0] + B_G^{loop}[P_0] + B_{NG}^{loop}[P_0, B_0]$$

- B_0: Primordial component
- $B_G^{tree}[P_0]$, $B_G^{loop}[P_0]$: Gravity-induced contributions
- $B_{NG}^{loop}[P_0, B_0]$: **Additional** gravity-induced contributions present for NG initial conditions (B_0)

Squeezed configurations B(Δk, k, k) as a function of k with Δk = 0.01 h/Mpc

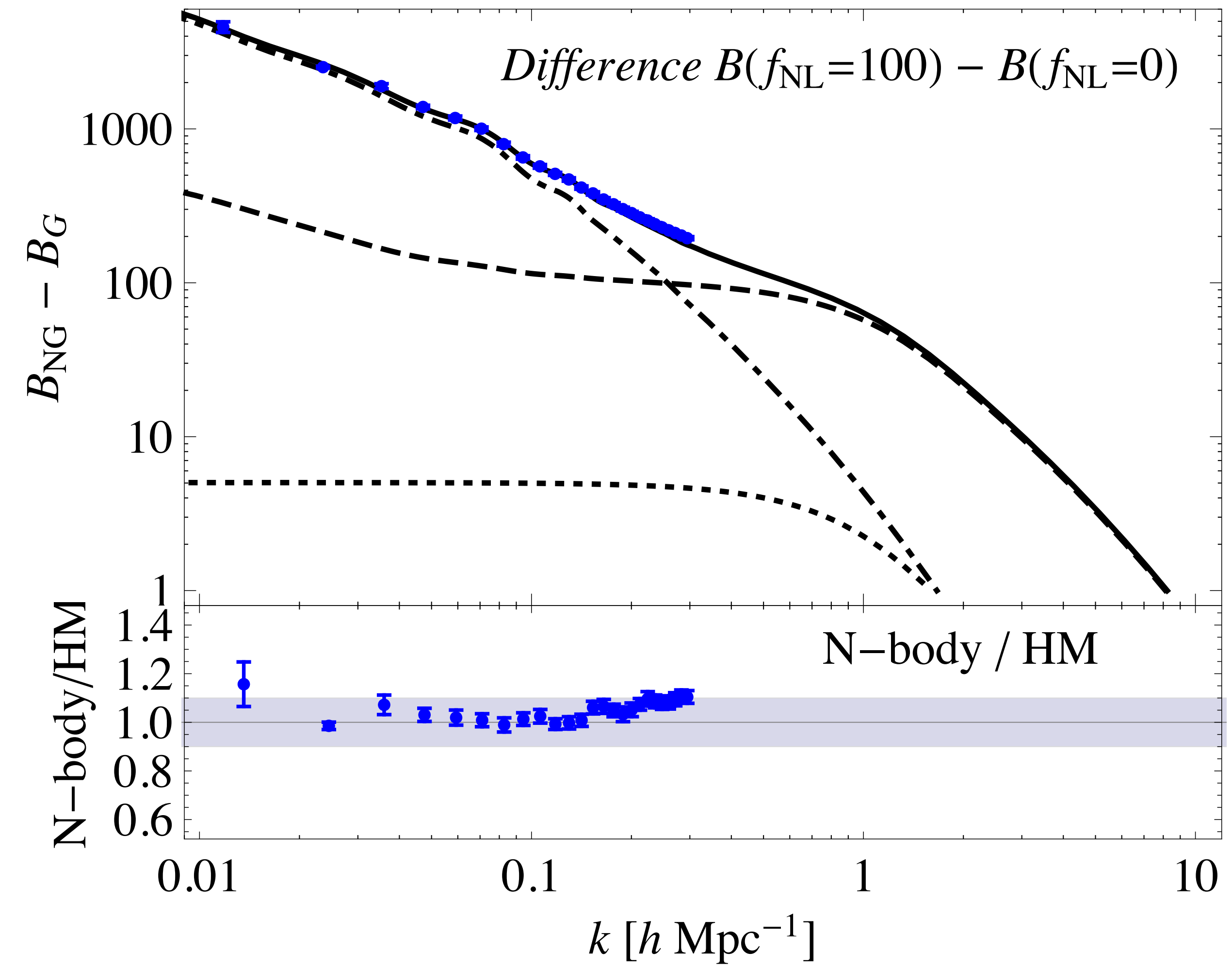
ES (2009)
ES, Crocce & Desjacques (2010)



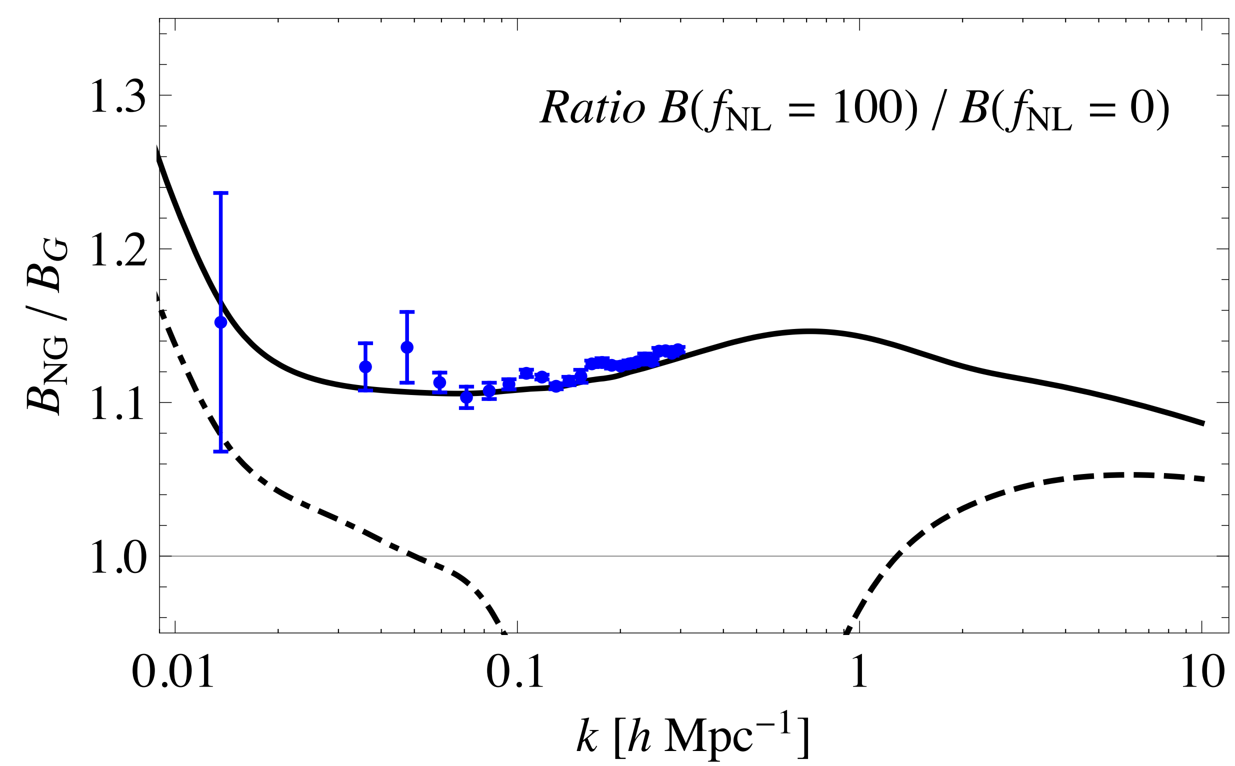


The matter **bispectrum** and PNG: ***even smaller scales***

Beyond PT: *The Halo Model*



There is a **significant effect** of NG initial conditions of about 5-15% on all triangles, at **small scales** and at **late times** for $f_{\rm NL}$ = 100



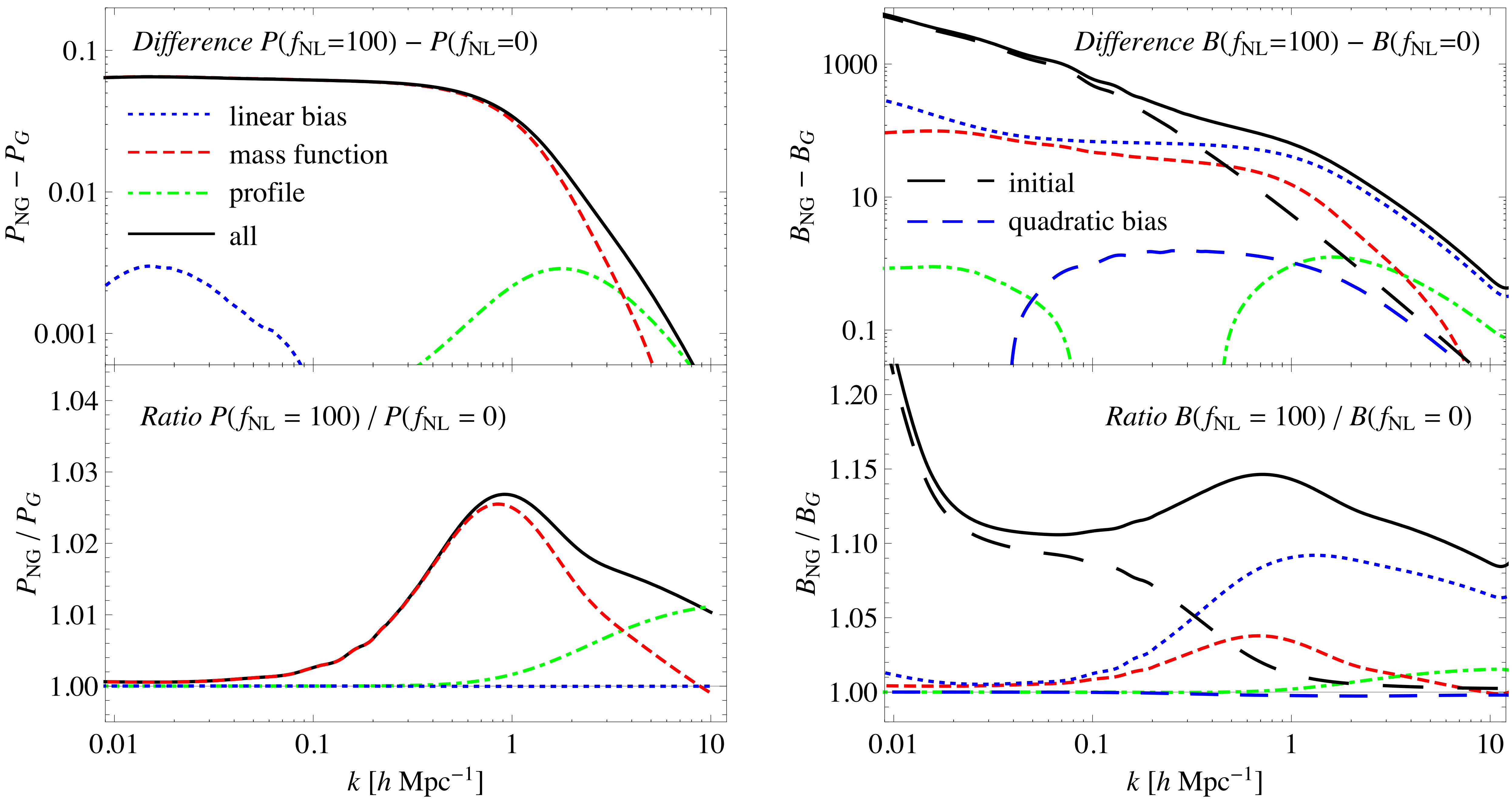
Squeezed configurations B(Δk, k, k)
as a function of k with Δk = 0.01 *h*/Mpc

Figueroa, ES, Riotto & Vernizzi (2012)

The matter **bispectrum** and PNG: ***even smaller scales***

Beyond PT: *The Halo Model*

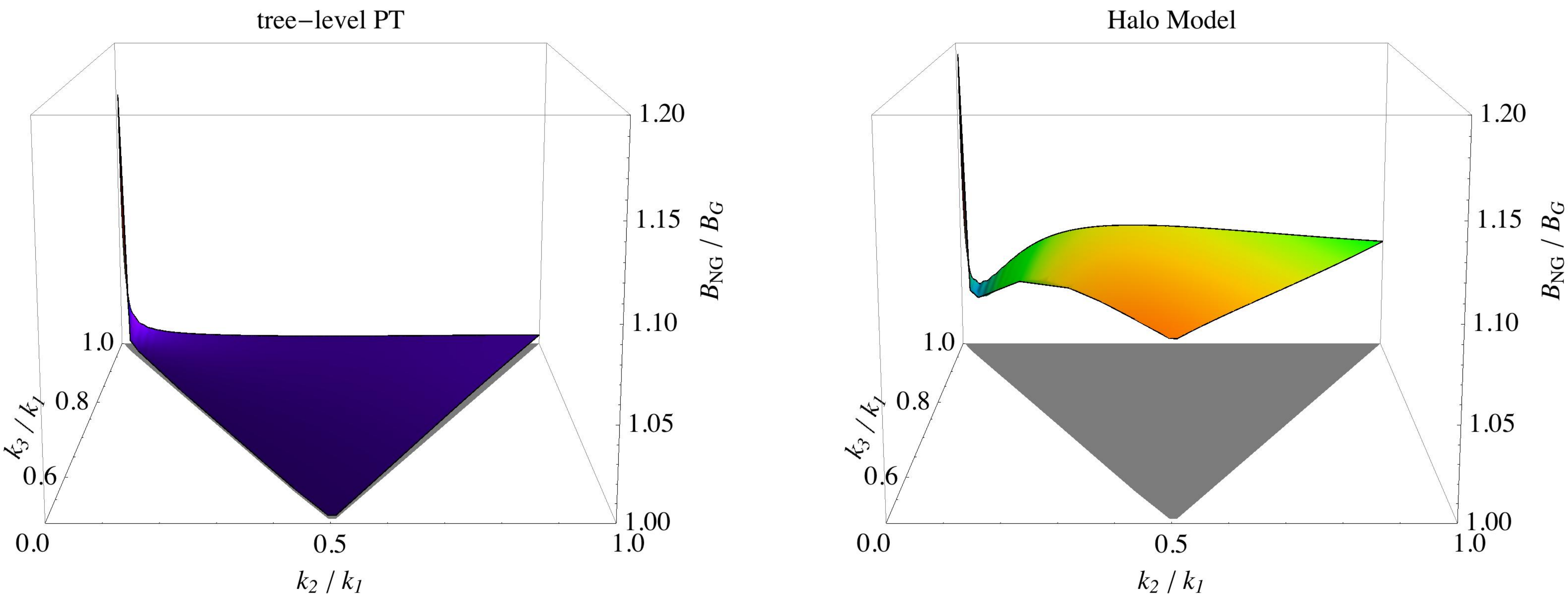
Squeezed configurations $B(\Delta k, k, k)$
as a function of k with Δk = 0.01 h/Mpc



Figueroa, ES, Riotto & Vernizzi (2012)

The matter **bispectrum** and PNG: ***even smaller scales***

Beyond PT: *The Halo Model*



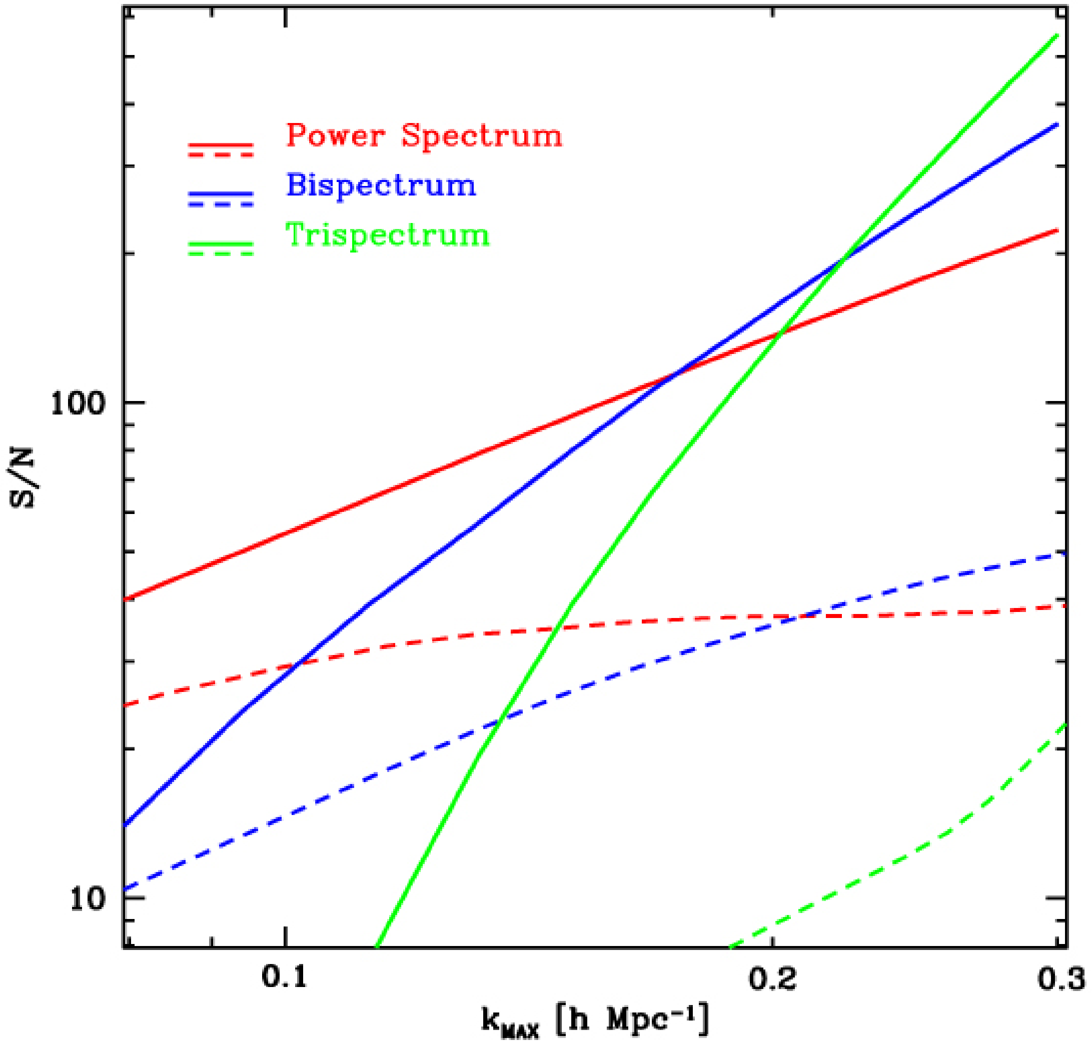
k_1 = 3 *h*/Mpc

Figueroa, ES, Riotto & Vernizzi (2012)

$f_{NL} = 0$

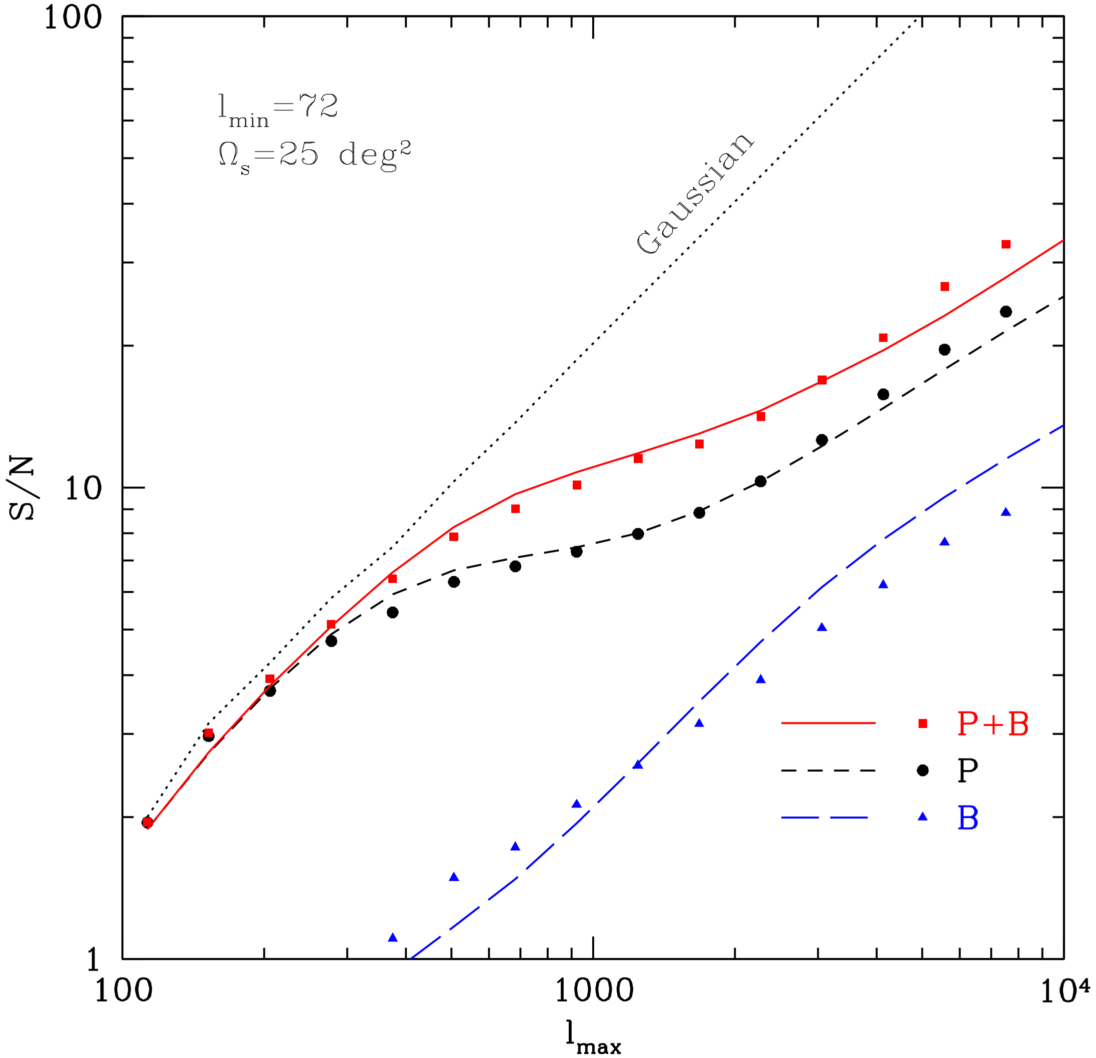
$f_{NL} = 0$

galaxies



ES & Scoccimarro (2005)

weak lensing



Kayo, Takada & Jain (2012)

Conclusions

- We do have a good understanding of the **multiple effects of PNG on the galaxy bispectrum** at large scales (with room for improvement!)
- The **impact of NG on nonlinear evolution of structure** is significant, particularly in terms of the **matter bispectrum**: can this be detected in weak lensing surveys?
- A **complete analysis of the large-scale structure** (e.g. galaxy power spectrum *and* bispectrum) **can do better than power spectrum alone**: smaller uncertainties on NG parameters **for** virtually **any model of non-Gaussianity**

Galaxy bias and the galaxy power spectrum

Dalal *et al.* (2008):

The bias of galaxies receives a significant *scale-dependent* correction for NG initial conditions of the *local* type

$$P_g(k) = [b_1 + \Delta b_1(f_{NL}, k)]^2 \, P(k)$$

"Gaussian" bias

Scale-dependent correction due to local non-Gaussianity

$$\Delta b_{1,NG}(f_{NL}, k) = \frac{2 f_{NL}(b_1 - 1)\delta_c}{M(k)}$$

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

Galaxy bias and the galaxy power spectrum

The bias of galaxies receives a *scale-dependent* correction for NG initial conditions of *any* type

Matarrese & Verde (2008)
Desjacques, Schmidt & Jeong (2011)
Scoccimarro *et al.* (2011)

$$P_g(k) = [b_1 + \Delta b_1(f_{NL}, k)]^2 \, P(k)$$

↓ "Gaussian" bias

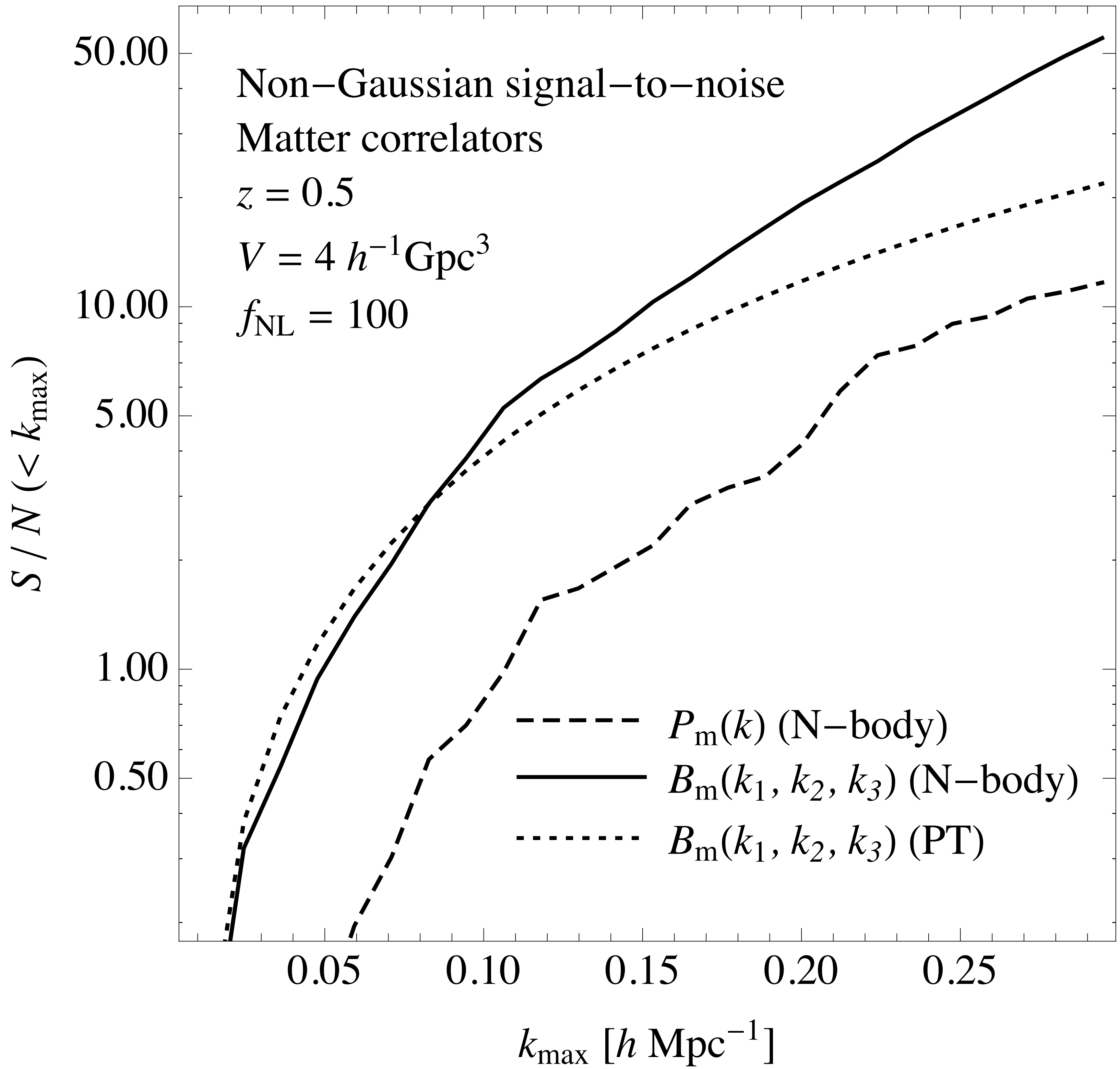
↘ Scale-dependent correction

$$\Delta b_{1,NG}(f_{NL}, k) = \frac{(b_1 - 1)\delta_c}{2M(k)} I(k,m) + \frac{1}{M(k,z)} \frac{\partial I(k,m)}{\partial \ln \sigma_m^2}$$

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

$$I(k,m) \sim \int d^3q [\ldots] B_\Phi(k, q, |\vec{k} - \vec{q}|)$$ → Initial bispectrum

Matter correlators with non-Gaussian initial conditions



Cumulative signal-to-noise for the effect of NG initial conditions

Sum of all configurations up to k_{max}

$$\left(\frac{S}{N}\right)^2_P = \sum_k^{k_{max}} \frac{(P_{NG} - P_G)^2}{\Delta P^2}$$

$$\left(\frac{S}{N}\right)^2_B = \sum_{k_1,k_2,k_3}^{k_{max}} \frac{(B_{NG} - B_G)^2}{\Delta B^2}$$

- *Both* the direct contribution of B_0 and its effect on the nonlinear corrections are important
- The effect of PNG on the *matter bispectrum* is *more significant* than on the power spectrum

ES, Crocce & Desjacques (2011)

The matter **bispectrum** and PNG: *small scales*

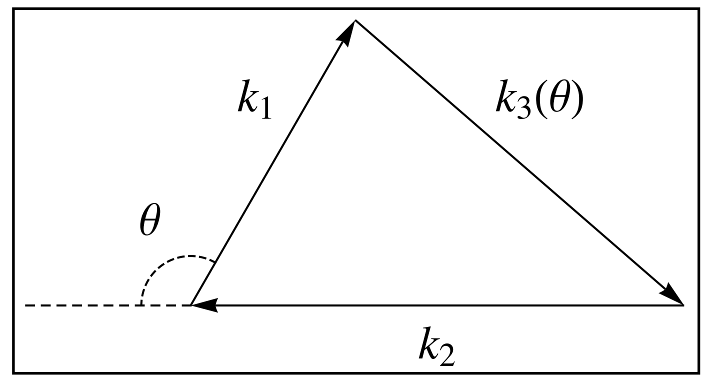
$$B = B_0 + B_G^{tree}[P_0] + B_G^{loop}[P_0] + B_{NG}^{loop}[P_0, B_0]$$

Primordial component

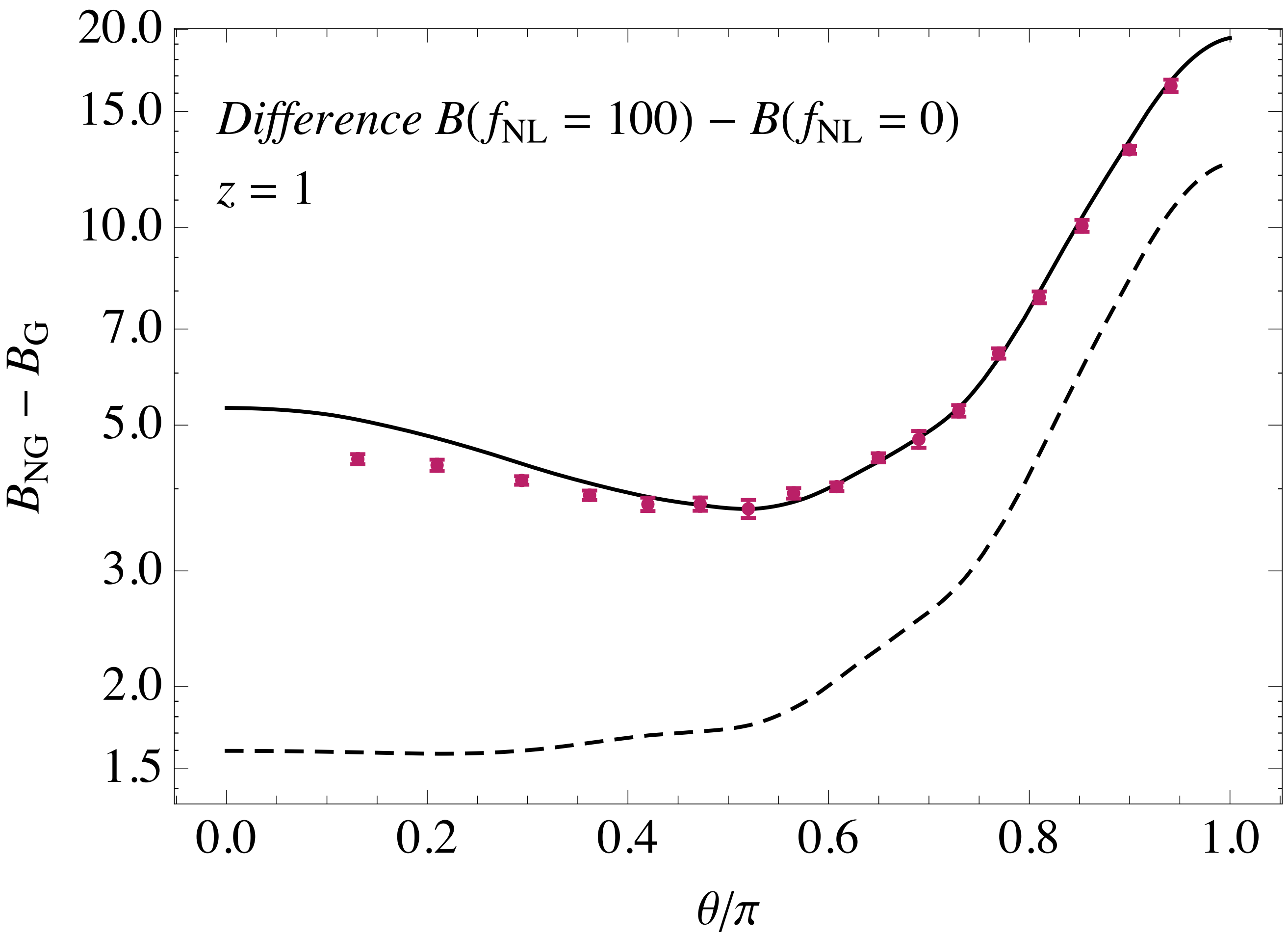
Gravity-induced contributions

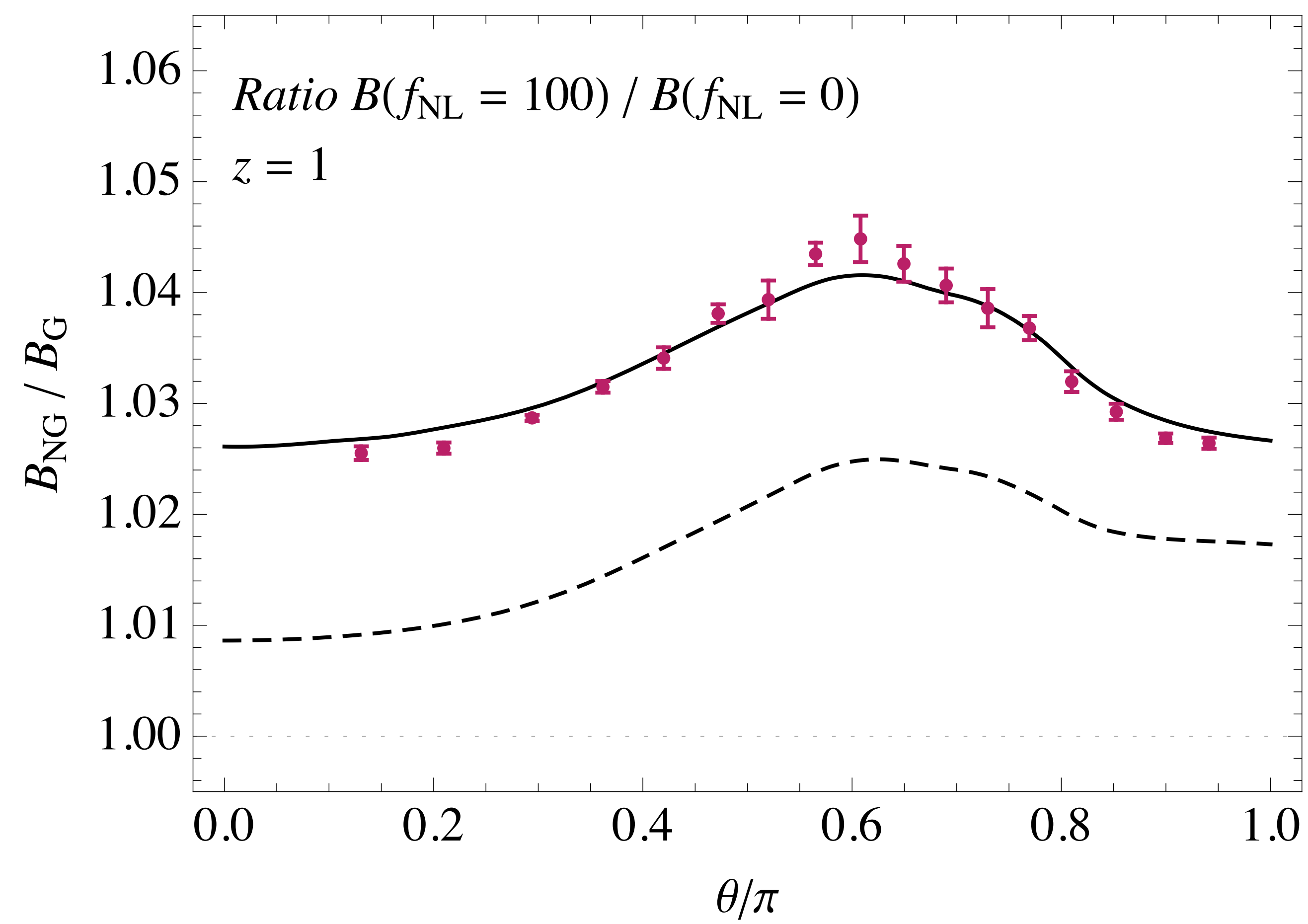
Additional gravity-induced contributions present for NG initial conditions (B_0)

Generic configurations $B(k_1, k_2, \theta)$
as a function of θ
with k_1 = 0.1 h/Mpc, k_2 =1.5 k_1



ES (2009)
ES, Crocce & Desjacques (2010)





The matter **bispectrum** and PNG: ***even smaller scales***

Beyond PT: *The Halo Model*

$$B(k_1,k_2,k_3) = B_{3h}(k_1,k_2,k_3) + B_{2h}(k_1,k_2,k_3) + B_{1h}(k_1,k_2,k_3)\,,$$

$$\begin{aligned}
B_{3h}(k_1,k_2,k_3,z) &= \frac{1}{\bar\rho^3}\left[\prod_{i=1}^{3}\int d\,m_i\, n(m_i,z)\,\hat\rho(m_i,z,k_i)\right] B_h(k_1,m_1;k_2,m_2;k_3,m_3;z)\,,\\
B_{2h}(k_1,k_2,k_3,z) &= \frac{1}{\bar\rho^3}\int d\,m\, n(m,z)\,\hat\rho(m,z,k_1)\int d\,m'\, n(m',z)\,\hat\rho(m',z,k_2)\,\hat\rho(m',z,k_3)\\
&\quad \times P_h(k_1,m,m',z) + \text{cyc.}\,,\\
B_{1h}(k_1,k_2,k_3,z) &= \frac{1}{\bar\rho^3}\int d\,m\, n(m,z)\,\hat\rho(k_1,m,z)\,\hat\rho(k_2,m,z)\,\hat\rho(k_3,m,z)\,.
\end{aligned}$$

$$\begin{aligned}
B_h(k_1,m_1;k_2,m_2;k_3,m_3;z) &= b_1(m_1)\,b_1(m_2)\,b_1(m_3)\,B(k_1,k_2,k_3)\\
&\quad + [b_1(m_1)\,b_1(m_2)\,b_2(m_3)\,P(k_1)\,P(k_2) + \text{cyc.}]
\end{aligned}$$

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$$P_g(k) = [b_1 + \Delta b_1(f_{NL}, k)]^2 \, P(k)$$

"Gaussian" bias

Scale-dependent correction due to local non-Gaussianity

QSOs+LRGs: **$-31 < f_{NL} < 70$** (95% CL)
[**Slosar *et al.* (2008)**]

AGNs+QSOs+LRGs: **$8 < f_{NL} < 88$** (95% CL)
[**Xia *et al.* (2011)**]

high-redshift sources: quasars & AGNs

CMB limits (95% CL): **$-10 < f_{NL} < 74$**
[**Komatsu *et al.* (2009)**]

Limits from LSS are already competitive with the CMB!

(at least for the local model ...)

From EUCLID we expect:
$\Delta f_{NL} \sim 5$
from the 3D power spectrum alone or better with multitracers
[*e.g.* Giannantonio *et al.* (2011), Seljak (2009) Hamaus *et al.* (2011)]