# Primordial non-Gaussianity in the Large-Scale Structure: <br> the galaxy power spectrum and beyond 

Theoretical methods for nonlinear cosmology @ CERN - September 6th, 2012

## Emiliano SEFUSATTI - ICTP

in collaboration with Xingang Chen, James Fergusson, Paul Shellard (ArXiv: 1204.6318)

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


## The power spectrum, first



## 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

$$
\begin{gathered}
P_{g}(k)=\left[b_{1}+\Delta b_{1}\left(f_{N L}, k\right)\right]^{2} P(k) \\
\underset{\text { "Gaussian" }}{\downarrow} \quad \begin{array}{l}
\text { Scale-dependent correction } \\
\text { bias }
\end{array} \\
\text { due to local non-Gaussianity }
\end{gathered}
$$



Measurements of the power spectrum of dark matter halos in N -body simulation with local NG initial conditions

$$
\Delta b_{1, N G}\left(f_{N L}, k\right) \sim \frac{f_{N L}}{D(z) k^{2}}
$$

## 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

$$
\begin{aligned}
& P_{g}(k)=\left[b_{1}+\Delta b_{1}\left(f_{N L}, k\right)\right]^{2} P(k) \\
& \text { "Gaussian" Scale-dependent correction } \\
& \text { bias due to local non-Gaussianity } \\
& \Delta b_{1, N G}\left(f_{N L}, k\right)=\frac{2 f_{N L}\left(b_{1}-1\right) \delta_{c}}{M(k)} \\
& M(k)=\frac{2}{3} \frac{D(z) T(k)}{\Omega_{m} H_{0}^{2}} k^{2}
\end{aligned}
$$

## Galaxy bias and the galaxy power spectrum

The bias of galaxies receives a correction for NG initial conditions of any type

$$
P_{g}(k)=\underset{\substack{\text { "Gaussian" } \\ \text { bias }}}{\left[b_{1}+\Delta b_{1}\left(f_{N L}, k\right)\right]^{2}} P \underset{\sim}{\downarrow} \quad \text { correction }
$$

$$
\begin{aligned}
& \Delta b_{1, N G}\left(f_{N L}, k\right)=\frac{\left(b_{1}-1\right) \delta_{c}}{2 M(k)} I(k, m)+\frac{1}{M(k, z)} \frac{\partial I(k, m)}{\partial \ln \sigma_{m}^{2}} \\
& M(k)=\frac{2}{3} \frac{D(z) T(k)}{\Omega_{m} H_{0}^{2}} k^{2} \\
& I(k, m) \sim \int d^{3} q[\ldots] B_{\Phi}(k, q,|\vec{k}-\vec{q}|) \rightarrow \text { Initial bispectrum }
\end{aligned}
$$

## What about other models?

The scale-dependence of bias can be different for other models, or not be there at all ...




## The interesting case of Quasi-Single Field Inflation

QSF inflation predicts a family of models parametrized by

$$
\nu \equiv \sqrt{\frac{9}{4}-\frac{m^{2}}{H^{2}}} \longrightarrow
$$

with intermediate "shapes" between the $m$ is the mass of the "isocurvaton" fields, i.e. field orthogonal to the inflaton trajectory in field-space
 equilateral and local


## The interesting case of Quasi-Single Field Inflation

The scale-dependent bias correction







## The interesting case of Quasi-Single Field Inflation

Given a positive detection of $f_{N L}$, how well can we constrain the parameter $v$, in future galaxy surveys?

Fisher matrix analysis of galaxy power spectrum measurements at $\mathrm{k}<\mathrm{k}_{\max }(\mathrm{z})$ $\mathrm{k}_{\max }(0)=0.075 \mathrm{~h} \mathrm{Mpc}^{-1}$


## The interesting case of Quasi-Single Field Inflation

What about the CMB?

QSF correlations with local and equilateral

QSF auto-correlations



## The interesting case of Quasi-Single Field Inflation

What about the CMB?

CMB Likelihood (Planck-like)










## The interesting case of Quasi-Single Field Inflation

What about the LSS and CMB?

$C M B+$ LSS Fisher matrix



## The interesting case of Quasi-Single Field Inflation

see also

LSS likelihood

$$
\bar{v}=0.5
$$


$\bar{v}=1.0$


$$
\bar{v}=1.5
$$



## Then the bispectrum

Nishimichi et al. (2011)


## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales

$$
B_{g}\left(k_{1}, k_{2}, k_{3}\right)=b_{1}^{3} B\left(k_{1}, k_{2}, k_{3}\right)+b_{1}^{2} b_{2} P\left(k_{1}\right) P\left(k_{2}\right)+2 \text { perm. }+\ldots
$$

## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales

$$
B_{g}\left(k_{1}, k_{2}, k_{3}\right)=b_{1}^{3} B\left(k_{1}, k_{2}, k_{3}\right)+b_{1}^{2} b_{2} P\left(k_{1}\right) P\left(k_{2}\right)+2 \text { perm. }+\ldots
$$

## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales


## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales

$$
B_{g}\left(k_{1}, k_{2}, k_{3}\right)=b_{1}^{3} B\left(k_{1}, k_{2}, k_{3}\right)+b_{1}^{2} b_{2} P\left(k_{1}\right) P\left(k_{2}\right)+2 \text { perm. }+\ldots
$$

If $B_{0}$ was the only effect of NG initial conditions on the LSS then future, large volume surveys ( $\sim 100 \mathrm{Gpc}^{3}$ ) could provide:

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

## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales

$$
\begin{array}{r}
B_{g}\left(k_{1}, k_{2}, k_{3}\right)=b_{1}^{3} B\left(k_{1}, k_{2}, k_{3}\right)+b_{1}^{2} b_{2} \underset{\downarrow}{P}\left(k_{1}\right) P\left(k_{2}\right)+2 \text { perm. }+\ldots \\
P=P_{0}+P_{G}^{\text {loop }}\left[P_{0}\right]+\begin{array}{l}
P_{N G}^{\text {loop }}\left[P_{0}, B_{0}\right] \\
B=B_{0}+B_{G}^{\text {tree }}\left[P_{0}\right]+B_{G}^{\text {loop }}\left[P_{0}\right]+B_{N G}^{\text {loop }}\left[P_{0}, B_{0}\right]
\end{array} \\
\begin{array}{c}
\text { Primordial component } \\
\text { (large scales) }
\end{array} \\
\begin{array}{c}
\text { Effect on nonlinear } \\
\text { evolution (small scales) }
\end{array}
\end{array}
$$

## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales


Primordial component (large scales)

Effect on nonlinear evolution (small scales)

## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales


Primordial component (large scales)
$\Delta b_{1, N G}\left(f_{N L}, \vec{k}\right)=\Delta b_{1, s i}\left(f_{N L}\right)+\Delta b_{1, s d}\left(f_{N L}, b_{1, G}, \vec{k}\right)$
$\Delta b_{2, N G}\left(f_{N L}, \vec{k}_{1}, \vec{k}_{2}\right)=\Delta b_{2, s i}\left(f_{N L}\right)+\Delta b_{2, s d}\left(f_{N L}, b_{1, G}, b_{2, G}, \vec{k}_{1}, \vec{k}_{2}\right)$

Effect on nonlinear evolution (small scales)

## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales


Primordial component (large scales)
$\Delta b_{1, N G}\left(f_{N L}, \vec{k}\right)=\Delta b_{1, s i}\left(f_{N L}\right)+\Delta b_{1, s d}\left(f_{N L}, b_{1, G}, \vec{k}\right)$
$\Delta b_{2, N G}\left(f_{N L}, \vec{k}_{1}, \vec{k}_{2}\right)=\Delta b_{2, s i}\left(f_{N L}\right)+\Delta b_{2, s d}\left(f_{N L}, b_{1, G}, b_{2, G}, \vec{k}_{1}, \vec{k}_{2}\right)$

$$
\Delta b_{2, s d, b}\left(k_{1}, k_{2}, f_{N L}\right)=2 f_{N L} \delta_{c}\left[b_{2, G}+\left(\frac{13}{21}-\frac{1}{\delta_{c}}\right)\left(b_{1, G}-1\right)\right]\left[\frac{1}{M\left(k_{1}, z\right)}+\frac{1}{M\left(k_{2}, z\right)}\right]
$$

## The Galaxy Bispectrum: NG and nonlinear bias

The galaxy bispectrum at large scales


Primordial component (large scales)
$\Delta b_{1, N G}\left(f_{N L}, \vec{k}\right)=\Delta b_{1, s i}\left(f_{N L}\right)+\Delta b_{1, s d}\left(f_{N L}, b_{1, G}, \vec{k}\right)$
$\Delta b_{2, N G}\left(f_{N L}, \vec{k}_{1}, \vec{k}_{2}\right)=\Delta b_{2, s i}\left(f_{N L}\right)+\Delta b_{2, s d}\left(f_{N L}, b_{1, G}, b_{2, G}, \vec{k}_{1}, \vec{k}_{2}\right)$

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

$$
\begin{gathered}
\left\langle\delta \delta \delta_{h}\right\rangle=\delta_{D}\left(\vec{k}_{123}\right) B_{m m h} \\
\left\langle\delta_{h} \delta_{h} \delta_{h}\right\rangle=\delta_{D}\left(\vec{k}_{123}\right) B_{h} \\
P_{h} \rightarrow b_{1, G}, \Delta b_{1, s i} \\
B_{h, G} \rightarrow b_{2, G} \\
\Delta B_{h, N G} \rightarrow \Delta b_{2, s i}
\end{gathered}
$$

## The Halo Bispectrum: theory vs. simulations

## Matter-matter-halo bispectrum:

$$
B_{m m h}\left(k_{1}, k_{2} ; k_{3}\right)=b_{1}\left(f_{N L}, k\right) B\left(k_{1}, k_{2}, k_{3}\right)+b_{2}\left(f_{N L}, k_{1}, k_{2}\right) P\left(k_{1}\right) P\left(k_{2}\right)
$$

$B\left(k_{1}, k_{2}, \theta\right)$ as a function of $\theta$ with $k_{1}=0.05 \mathrm{~h} / \mathrm{Mpc}, \mathrm{k}_{2}=0.07 \mathrm{~h} / \mathrm{Mpc}$

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



## The Halo Bispectrum: theory vs. simulations

## Matter-matter-halo bispectrum:

$$
B_{m m h}\left(k_{1}, k_{2} ; k_{3}\right)=b_{1}\left(f_{N L}, k\right) B\left(k_{1}, k_{2}, k_{3}\right)+b_{2}\left(f_{N L}, k_{1}, k_{2}\right) P\left(k_{1}\right) P\left(k_{2}\right)
$$

$B\left(k_{1}, k_{2}, \theta\right)$ as a function of $\theta$ with $k_{1}=0.07 \mathrm{~h} / \mathrm{Mpc}, \mathrm{k}_{2}=0.08 \mathrm{~h} / \mathrm{Mpc}$

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





## The Halo Bispectrum: theory vs. simulations

Halo bispectrum:

$$
\begin{aligned}
B_{h}\left(k_{1}, k_{2}, k_{3}\right)= & b_{1}^{3}\left(f_{N L}, k\right) B\left(k_{1}, k_{2}, k_{3}\right) \\
& +b_{1}\left(f_{N L}, k_{1}\right) b_{1}\left(f_{N L}, k_{2}\right) b_{2}\left(f_{N L}, k_{1}, k_{2}\right) P\left(k_{1}\right) P\left(k_{2}\right)+c y c .
\end{aligned}
$$

$B\left(k_{1}, k_{2}, \theta\right)$ as a function of $\theta$ with $k_{1}=0.05 \mathrm{~h} / \mathrm{Mpc}, k_{2}=0.07 \mathrm{~h} / \mathrm{Mpc}$


[^0]

## The Halo Bispectrum: theory vs. simulations

Halo bispectrum:

$$
\begin{aligned}
B_{h}\left(k_{1}, k_{2}, k_{3}\right)= & b_{1}^{3}\left(f_{N L}, k\right) B\left(k_{1}, k_{2}, k_{3}\right) \\
& +b_{1}\left(f_{N L}, k_{1}\right) b_{1}\left(f_{N L}, k_{2}\right) b_{2}\left(f_{N L}, k_{1}, k_{2}\right) P\left(k_{1}\right) P\left(k_{2}\right)+c y c .
\end{aligned}
$$

$B\left(k_{1}, k_{2}, \theta\right)$ as a function of $\theta$ with $k_{1}=0.07 \mathrm{~h} / \mathrm{Mpc}, \mathrm{k}_{2}=0.08 \mathrm{~h} / \mathrm{Mpc}$ $M>1.6 \times 10^{13} h^{-1} \mathrm{M}_{\odot}$


[^1]

## The Halo Bispectrum: theory vs. simulations

$\mathrm{X}^{2}$, for all triangles, as a function of $k_{\text {max }}$



## The Halo Bispectrum: theory vs. simulations

Gaussian halo bias
Best-fit bias parameters and their peak-background split predictions


fit all triangular configurations up to $\mathrm{k}=0.07 \mathrm{~h} / \mathrm{Mpc}$ for

Non-Gaussian, scale-independent, halo bias corrections
$b_{1, G}, b_{2, G}, \Delta b_{1, G}$ and $\Delta b_{2, G}$


## Halo Power Spectrum vs. Halo Bispectrum



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

Sum of all configurations up to $k_{\max }$

$$
\left(\frac{S}{N}\right)_{P}^{2}=\sum_{k}^{k_{\max }} \frac{\left(P_{N G}-P_{G}\right)^{2}}{\Delta P^{2}} \quad\left(\frac{S}{N}\right)_{B}^{2}=\sum_{k_{1}, k_{2}, k_{3}}^{k_{\max }} \frac{\left(B_{N G}-B_{G}\right)^{2}}{\Delta B^{2}}
$$

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?


Almost all signal is in squeezed configurations for massive halos!

## A Fisher matrix analysis for Galaxy correlators

The uncertainty on $f_{N L}$ (local) from Power Spectrum \& Bispectrum (\& both)



## The matter bispectrum

## Matter Power Spectrum

In Perturbation Theory ...


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 ...


## matter power spectrum

Additional gravity-induced contributions present only for NG initial conditions ( $B_{0}$ )

## Few percent effect at small scales

 for allowed values of $f^{\mathrm{N} L}$In the Halo Model:
$P(k)=P^{1 h}(k)+P^{2 h}(k), \quad$ where
$P^{1 h}(k)=\int \mathrm{d} m n(m)\left(\frac{m}{\bar{\rho}}\right)^{2}|u(k \mid m)|^{2}$
$P^{2 h}(k)=\int \mathrm{d} m_{1} n\left(m_{1}\right)\left(\frac{m_{1}}{\bar{\rho}}\right) u\left(k \mid m_{1}\right) \int \mathrm{d} m_{2} n\left(m_{2}\right)\left(\frac{m_{2}}{\bar{\rho}}\right) u\left(k \mid m_{2}\right) P_{h h}\left(k \mid m_{1}, m_{2}\right)$

## The matter bispectrum and PNG: small scales

In Perturbation Theory ...


## The matter bispectrum and PNG: small scales



Primordial Gravity-induced component
contributions

Additional gravity-induced contributions present for NG initial conditions ( $B_{0}$ )

## Squeezed configurations $B(\Delta k, k, k)$ as a function of $k$ with $\Delta k=0.01 \mathrm{~h} / \mathrm{Mpc}$

```
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 $f_{N L}=100$



## 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 $\Delta k=0.01 \mathrm{~h} / \mathrm{Mpc}$


## The matter bispectrum and PNG: even smaller scales

## Beyond PT: The Halo Model


$f_{N L}=0$

## $f_{N L}=0$

galaxies


ES \& Scoccimarro (2005)
weak lensing


## Conclusions

- Quasi-Single Field inflation provides very interesting predictions for scale-dependent bias: given a detection of $f_{N L}$ by Planck we could possibly learn something on the structure of the field-space in the early Universe.
- 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 nonGaussianity


[^0]:    ES, Crocce \& Desjacques (2011)

[^1]:    ES, Crocce \& Desjacques (2011)

