Primordial non-Gaussianity and the large-scale structure of the universe

Cristiano Porciani
Identity crisis

...you theorists...

...you observers...
The talk of a phenomenologist

• There are lots of ideas regarding the early universe and the generation of primordial non-Gaussianity (PNG)

• Many experimental efforts are being developed/planned mainly driven by the quest for dark energy

• What will they be able to say about PNG?
The CMB future

- The Planck satellite has been launched on May 14 2009 and is currently acquiring data

- For PNG of the local type, the expected Cramér-Rao limit is $\Delta f_{NL} \approx 5$ from temperature anisotropies (Komatsu & Spergel 2001)

- This reduces to $\Delta f_{NL} \approx 3$ from the joint analysis of temperature and polarization maps (Yadav, Komatsu & Wandelt 2007)
Are there other probes of primordial non-Gaussianity beyond the CMB?

- Abundance of dark-matter halos
- Abundance of voids
- Topology of the LSS
- Clustering of the matter distribution
- Clustering of dark-matter halos
The large-scale structure

$P_{\text{NL}} = 0$

$250 \, h^{-1} \, \text{Mpc}$

$P_{\text{NL}} = 750$

Pillepich, CP & Hahn 2010
Zooming in

$160 \, h^{-1} \text{Mpc}$

$f_{NL} = 0$

$f_{NL} = 750$
A massive galaxy cluster

$f_{NL} = 0$

$f_{NL} = 750$

$40 \, h^{-1} \text{Mpc}$
Matter power spectrum (large scales)

Good agreement with perturbation theory on large scales

Taruya, Koyama & Matsubara 2008
Bartolo et al. 2010 (TRG, see S. Matarrese talk)
Matter power spectrum (small scales)

Halo model can predict it to 10-15% accuracy

Giannantonio, CP et al. 2011
Fedeli & Moscardini 2010
Halo mass function

- A positive local $f_{NL}$ enhances the formation of most massive halos at the expenses of the less massive ones.


- Excursion set + path integral (Maggiore & Riotto 2010)

- Fitting formulae (Pillepich, Porciani & Hahn 2010)
Halo mass function

- Models have been tested against N-body simulations (Grossi et al. 2007, 2009, Desjacques et al. 2009, Pillepich et al. 2010, Giannantonio & Porciani 2010, Wagner et al. 2010)

- Good agreement for the ratio between the mass functions in Gaussian and non-Gaussian models

- Model parameters need to be fine tuned depending on the adopted definition of dark-matter halo. What is \( q \) for galaxies?

Desjacques & Seljak 2010
Halo mass function

But you need to make sure that also your Gaussian mass function is accurate!

Giannantonio & Porciani 2010
Non-Gaussianity from galaxy clustering?

- It would be important to cross-check CMB results against probes with different systematics.

- What about the large-scale structure? e.g. the galaxy bispectrum?

- Unfortunately the non-linear growth of perturbations superimposes a much stronger non-Gaussian signal onto the primordial one that is then difficult to disentangle and recover.

Back to life in 2008

- The large-scale clustering of collapsed objects (galaxies, galaxy clusters) as measured by the power spectrum depends linearly on $f_{NL}$.

- An approximated model based on linear theory captures all the relevant physics

![Graph showing P(k) and b(k,fNL)/b(k,0)](Dalal et al. 2008)
Do halos form at linear density peaks?

Ludlow & Porciani 2010a
(do they form at peaks?)

Ludlow & Porciani 2010b
(do they collapse according to the ellipsoidal model?
Do all peaks above threshold make halos?)
Scale-dependent bias
(to 1-loop in PT)
Scale-dependent bias

\[ b_{\text{eff}}(k, f_{NL}) = \frac{P_{hm}(k, f_{NL})}{P_{mn}(k, f_{NL})} \]

\[ \Delta b(k, f_{NL}) = b_{\text{eff}}(k, f_{NL}) - b_{\text{eff}}(k, 0) \]

\[ \Delta b(k, f_{NL}) = b_{10}(f_{NL}) - b_{10}(0) + 2 \frac{f_{NL}}{\alpha(k)} \delta_c [b_{10}(f_{NL}) - 1] \]

\[ \alpha(k) = \frac{2c^2 k^2 T(k) D(z) g(0)}{3 \Omega_m H_0^2 g(\infty)} \]

For other shapes of PNG see Schmidt & Kamionkowski (2010) and F. Schmidt talk.
A non-local biasing scheme

• Using the peak-background split, we have shown that, in general (Giannantonio & Porciani 2010):

$$\delta_h(x) = F[\delta_m(x), \phi(x), [\nabla \phi(x)]^2]$$

• Since the potential and the density field are linked by the Poisson equation, this generates a non-local biasing scheme in terms of the mass density

• When $f_{NL} \neq 0$, this is not compatible with the standard local, deterministic biasing scheme by Fry & Gaztañaga (1993)
The bias expansion

For galaxy and cluster sized halos, we can expand the halo overdensity as:

\[
\delta_h(x) = b_0 + b_{10} \delta + b_{01} \varphi + \\
\frac{1}{2!} \left( b_{20} \delta^2 + 2 b_{11} \delta \varphi + b_{02} \varphi^2 \right) + \\
\frac{1}{3!} \left( b_{30} \delta^3 + 3 b_{21} \delta^2 \varphi + 3 b_{12} \delta \varphi^2 + b_{03} \varphi^3 \right),
\]

This term generates the leading order scale-dependence in the bias

and we provide explicit expressions for the bias coefficients as a function of \( f_{NL} \) and \( g_{NL} \). (see also talk by K. Smith)

All terms including the Gaussian potential vanish when \( f_{NL} = 0 \)
and the bias reduces to the model by Fry & Gaztañaga (1993).
Halo-matter cross spectrum

Solid lines: perturbative calculations (up to second next to leading order) by Giannantonio & Porciani 2010.

Points with errorbars: N-body simulations by Pillepich, Porciani & Hahn 2010.

The model is not a fit to the data!
Competitive with CMB!

• Fitting the best datasets for galaxy clustering with this model, gives:

\[-29 < f_{\text{NL}} < 70\] at 95% CL

• This is competitive with the WMAP 5yr results!

• Combined CMB+LSS:

\[0 < f_{\text{NL}} < 69\]

For a more recent analysis see Xia et al. 2011 and S. Matarrese talk
Generalisation to other shapes

• Local:
  \[ \Delta b \sim 1/k^2 \text{ as } k \to 0 \]
  Schmidt & Kamionkowski 2010
  Wagner et al. 2010

• Orthogonal:
  \[ \Delta b \sim 1/k \]

• Equilateral:
  \[ \Delta b \sim \text{constant} \]
## From theory to observations

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experiment</th>
<th>Systematics</th>
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<tr>
<td>Matter power spectrum</td>
<td>Weak lensing surveys</td>
<td>Dynamic non-linearities, intrinsic alignments, effect of baryons</td>
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<tr>
<td>Galaxy power spectrum or bispectrum</td>
<td>Galaxy redshift/photometric surveys</td>
<td>Galaxy biasing, non-linearities, shot noise, redshift-space distortions</td>
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<tr>
<td>Cluster abundance</td>
<td>X-ray, SZ surveys</td>
<td>Mapping observables to masses, accurate models for the mass function, effect of baryons</td>
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<tr>
<td>Void abundance</td>
<td>Galaxy redshift surveys</td>
<td>Galaxy biasing, definitions</td>
</tr>
<tr>
<td>Topology of LSS</td>
<td>Galaxy redshift surveys</td>
<td>Galaxy biasing, definitions</td>
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</table>
eROSITA

extended Roentgen Survey with an Imaging Telescope Array

• Primary instrument onboard the Russian Spectrum-Roentgen-Gamma satellite (SRG)

• German-Russian mission. Launched from Baikonur in 2012 (leased by Kazakhstan to Russia)

• L2 orbit

• First all-sky imaging survey in the medium energy X-ray band up to 10 keV with unprecedented spectra and angular resolution

• 7 Wolter-1 mirror modules (containing 54 shells each), special detectors
eROSITA science goals

- Detect the hot intergalactic medium of $10^5$ galaxy clusters and groups for studies of structure formation and cosmology
- Detect all obscured accreting black holes in nearby galaxies
- Study galactic X-ray sources

Pillepich, CP & Reiprich 2011
# Forecasted marginal constraints

(Fisher matrix with many cosmo + nuisance ICM parameters)

<table>
<thead>
<tr>
<th></th>
<th>$f_{\text{NL}}$</th>
<th>$n_s$</th>
<th>$\sigma_8$</th>
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<tbody>
<tr>
<td>I: Counts</td>
<td>7600</td>
<td>2.3</td>
<td>1.6</td>
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<tr>
<td>II: Counts +photoz</td>
<td>248</td>
<td>0.402</td>
<td>0.084</td>
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<tr>
<td>III: Angular Clustering</td>
<td>22</td>
<td>0.378</td>
<td>0.136</td>
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<tr>
<td>IV: Tomography</td>
<td>6.6</td>
<td>0.185</td>
<td>0.135</td>
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<tr>
<td>I + III</td>
<td>21</td>
<td>0.288</td>
<td>0.071</td>
</tr>
<tr>
<td>II+IV</td>
<td>6.1</td>
<td>0.071</td>
<td>0.034</td>
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<tr>
<td>I+III+Planck $C_i$</td>
<td>18</td>
<td>0.022</td>
<td>0.006</td>
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<tr>
<td>II + IV + Planck $C_i$</td>
<td>5.1</td>
<td>0.006</td>
<td>0.002</td>
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PNG of the local type

Pillepich, CP & Reiprich 2011
The EUCLID mission

- M-class mission within the Cosmic Vision program of the European Space Agency

- “High-precision survey mission to map the geometry of the dark universe”

- Now in the competitive Definition Phase, launch expected in 2018

- >200 people, 30 Institutions, 7 countries
The EUCLID concept

The EUCLID mission is being optimized for two complementary cosmological probes

- Weak gravitational lensing
- Baryonic acoustic oscillations
- Full extragalactic sky survey with 1.2m telescope at L2
- Additional probes: galaxy clusters, redshift-space distortions, integrated Sachs-Wolfe effect
- Legacy science for a wide range of areas in astronomy
EUCLID imaging surveys

**Wide survey (20,000 deg²)**

- Galaxy shape measurements in the visible band to $R_{IZ AB} < 24.5$ (10σ) yielding 30-40 resolved galaxies/arcmin² with a median redshift of 0.9
- Near-infrared photometry yielding photometric redshift errors of 0.03-0.05 (1+z) with ground-based complements (DES, PanStarrs)

**Deep survey (40 deg²):**

- 2 mag deeper for both visible and NIR data
EUCLID spectroscopic survey

- 20,000 deg$^2$ in 5 yr
- Slitless spectroscopy with spectral resolution $R=500$ (1-2 μm) in the near infrared
- $F_{H\alpha}>4\times10^{-16}$ erg s$^{-1}$ cm$^{-2}$ (star-forming galaxies)
- $\sigma_z<0.001(1+z)$
- Spectroscopic completeness >0.35 for a total of 70 million galaxy redshifts
Impact of EUCLID on PNG

Giannantonio, Porciani et al. 2011

PNG of the local type
### Impact of EUCLID on PNG

Giannantonio, Porciani et al. 2011 (preliminary)

<table>
<thead>
<tr>
<th>Probe</th>
<th>$\Delta f_{NL}$ Local</th>
<th>$\Delta f_{NL}$ equilateral</th>
<th>$\Delta f_{NL}$ orthogonal</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUCLID + Planck</td>
<td>EUCLID + Planck</td>
<td>EUCLID + Planck</td>
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<td>Weak lensing</td>
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<td></td>
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<td>2D clustering</td>
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<td>3D clustering</td>
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<td>1.3</td>
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<tr>
<td></td>
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<td>4.4</td>
<td>2.1</td>
</tr>
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</table>

For the simplest scale-dependent models (in the local case): $\Delta n_{f_{nl}}=0.05$ (Interesting!!!! See C. Byrnes and S. Shandera talks)

1. This is only from 2-point statistics!!!
2. Fiducial model assumes $f_{NL}=0$ (slightly worse forecasts for the alternative case)
3. In the non-local cases signal comes mainly from lensing, we need to test the halo model is accurate enough against N-body simulations.
Next frontier: the dark side of the Moon!

- Constraints from the 21-cm background in the dark ages (bispectrum)

- Tomography of HI distribution between $30 < z < 100$ would give: $\Delta f_{NL} \ll 1$

- This would require better modeling of GR and second order effects

Credit: NASA

Pillepich, CP & Matarrese (2007)
Cooray (2007)
Conclusions

• Primordial non-Gaussianity is fertile land for both theorists and observers.

• Near future missions will be able to constrain $f_{NL}$ with a statistical error of $\sim 3$ and $n_{f_{NL}}$ to 0.05.

• To make this possible we have to work hard on the systematics, especially modeling galaxy biasing and dynamical non-linearities.