The Scale-Dependent Signature of Primordial Non-Gaussianity in the Large-Scale Structure of Reionization

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D’Aloisio, Zhang, Shapiro, Mao (soon to be) submitted
Mao, D’Aloisio, Shapiro, Zhang, in prep.
Inflation: ICs for Structure Formation

- Why do we need Inflation?
  a) The horizon problem
  b) The flatness problem
  c) The exotic relics problem.

- QM fluctuations in field(s) generates initial distribution of random perturbations.

- Initial distribution characterized by correlation functions:
  \[ \xi_n(x_1, \ldots, x_n) \equiv \langle \delta(x_1) \ldots \delta(x_n) \rangle_c \]

where
  \[ \delta = \frac{\rho(x)}{\bar{\rho}_m} - 1 \]

- Probing PNG can yield new information about inflationary physics.
Primordial Non-Gaussianity: the Bispectrum

• Lowest order non-Gaussianity: bispectrum,
\[ \langle \tilde{\Phi}(k_1)\tilde{\Phi}(k_2)\tilde{\Phi}(k_3) \rangle = (2\pi)^3 B_\Phi(k_1, k_2, k_3) \delta_D(k_1 + k_2 + k_3) \]

• “Amplitude of non-Gaussianity: \( f_{NL} \)
\[ B_\Phi(k_1, k_2, k_3) = f_{NL} F(k_1, k_2, k_3) \]

• Phenomenological “templates”: e.g. local, equilateral, orthogonal

• Local (or squeezed) template, peaks when \( k_1 \ll k_2 \approx k_3 \)

• All single-field models of inflation with standard assumptions predict (Creminelli & Zaldarriaga 2004 and subsequent work):
\[ f_{NL}^{\text{local}} = \frac{5}{12} (n_s - 1) = 0.016 \text{ for } n_s = 0.96 \]
CMB Constraints on PNG

• WMAP9 (95% confidence limits, Bennett et al. 2012):

\[-3 < f_{NL}^{local} < 77\]

• First Planck results (68% confidence limits, Ade et al. 2013):

\[f_{NL}^{local} = 2.7 \pm 5.8\]

• Ideal -- no noise and infinitesimal beam width (Komatsu & Spergel, 2001; Babich & Zaldarriaga 2004):

\[\Delta f_{NL}^{local} = 1.6\]

• Probing lower fNL values will require other methods!
How Could PNG Affect Reionization?

1. Galactic halo abundance \((dn/dM)\)
2. Galactic halo clustering (bias)

Previous works on the impact of the above effects:
Crociani et. al. (2009); Joudaki et. al. (2011); Tashiro & Ho (2012);
Chongchitnan (2013)
How Could PNG Affect Reionization?

1. Galactic halo abundance (dn/dM)

2. Galactic halo clustering (bias)

\[ M = \bar{\rho}_m \frac{4\pi}{3} R^3 \]

\[ \delta(x, R) = \int d^3x' \, W_f (|x - x'|, R) \delta(x') \]

\[
\delta(x, R) = \frac{\rho(x, R)}{\bar{\rho}_m} - 1
\]

\[
M_{\text{min}} = 10^8 M_\odot
\]

*See D’Aloisio et al. (2013) (arXiv:1206.3305)
How Could PNG Affect Reionization?

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How Could PNG Affect Reionization?

1. Galactic halo abundance \((dn/dM)\)

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Non-Gaussian ICs continued:

\[\tilde{\delta}_h(k) = b_h(k) \tilde{\delta}(k)\]

e.g. local template:

\[\Delta b^\text{NG}_h(k) \propto f_{\text{NL}} \frac{(b^G_h - 1)}{D(z) k^2 T(k)}\]

Recent constraints from galaxy bias (Giannantonio et al. 2013):

\[-37 < f_{\text{NL}} < 25\quad \text{95\% C.L.}\]
Galactic halos source the radiation which creates these ionized patches in the IGM.

Abundance and clustering of galactic halos

“Patchiness” of reionization

Observations of IGM during reionization: another method for probing PNG

- “Ionized density” contrast:
  \[ \delta_{\rho_{\text{HII}}} = \frac{\rho_{\text{HII}}}{\bar{\rho}_{\text{HII}}} - 1 \]

- Define “ionized density bias”:
  \[ \tilde{\delta}_{\rho_{\text{HII}}}(k) = b_{\rho_{\text{HII}}}(k) \tilde{\delta}(k) \]

*Image from Iliev, Mellema, Shapiro, Pen, 2007
Methodology

• Calculate the **ionized density bias** for both Gaussian and non-Gaussian ICs

• Two methods:

  1. Extension of excursion-set model of reionization\(^1\) (ESMR) to include PNG\(^2\).
  2. Linear perturbation theory of reionization\(^3\) (LPTR)

<table>
<thead>
<tr>
<th>Model</th>
<th>C(_{\text{HII}})</th>
<th>C(_{\gamma H})</th>
<th>Emissivity</th>
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<td>LPTR1</td>
<td>C(_{\text{HII}}(z))</td>
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<td>A</td>
</tr>
<tr>
<td>LPTR2</td>
<td>2</td>
<td>1</td>
<td>A</td>
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<td>LPTR3</td>
<td>10</td>
<td>1</td>
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<td>LPTR4</td>
<td>C(_{\text{HII}}(z))</td>
<td>1</td>
<td>B</td>
</tr>
<tr>
<td>ESMR</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

A: \(j(r, \eta, \nu) \propto \frac{\partial}{\partial \eta} [n_H(r, \eta) f_{\text{coll}}]\)

B: \(j(r, \eta, \nu) \propto n_H(r, \eta) f_{\text{coll}}\)

\(^1\)Furlanetto, Zaldarriaga, Hernquist, 2004
\(^2\)D’Aloisio, Zhang, Jeong, Shapiro, 2013 (arXiv:1206.3305)
\(^3\)Zhang, Hui, Haiman, Hui, 2007
Results: the Mean Reionization History

\[ \tau_{es} = \sigma_T \int_{z_{rec}}^{0} \bar{n}_e(z) \frac{dt}{dz} \, dz \]
Results: Scale-Dependent Ionized Density Bias

General bispectra:
\[ \Delta b^{\text{NG}}_{\rho_{\text{HII}}}(k) = 2\delta_c (b^G_{\rho_{\text{HII}}} - 1) \frac{\mathcal{F}^{(3)}_\min(k)}{\mathcal{M}_\min(k)} \]

Local template:
\[ \Delta b^{\text{NG}}_{\rho_{\text{HII}}}(k) \propto f_{\text{NL}} \frac{(b^G_{\rho_{\text{HII}}} - 1)}{D(z)k^2\mathcal{T}(k)} \]
Results: Scale-Dependent Ionized Density Bias

Accurate (within ~ 10%) analytical mapping between $b^G_{\rho_{\text{HII}}}$ and $b^{NG}_{\rho_{\text{HII}}}$ in the LPTR models.

General bispectra:
$$\Delta b^{NG}_{\rho_{\text{HII}}} (k) = 2\delta_c(b^G_{\rho_{\text{HII}}} - 1) \frac{\mathcal{F}^{(3)}_{\min}(k)}{\mathcal{M}_{\min}(k)}$$

Local template:
$$\Delta b^{NG}_{\rho_{\text{HII}}} (k) \propto f_{NL} \frac{(b^G_{\rho_{\text{HII}}} - 1)}{D(z)k^2 \mathcal{T}(k)}$$
Implications: EoR 21cm Power Spectrum

On large scales (linear theory):

\[ P_{\Delta T}(k) \approx F[b_{\rho \text{HII}}(k), \bar{x}_i, \mu] \ P_{\delta \delta}(k) \quad \text{where} \quad \mu = \hat{k} \cdot \hat{n} \]