Testing primordial non-Gaussianity: Perspectives beyond Planck

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Beyond19, Warsaw, 2019
Primordial non-Gaussianity. Measures interactions. Many inflationary scenarios (notably, multi-field Inflation) predict small, model-dependent deviations from Gaussianity. Additional information in 3-point (bispectrum) and 4-point (trispectrum) functions.

- Multi-field
- Curvaton
- Ekpyrotic/cyclic
- Non-canonical kinetic terms (K-inflation, DBI)
- Higher derivative terms (Ghost Inflation)
- Variants of non canonical
- Kinetic terms and higher derivatives
- EFT

M. Liguori, Testing primordial non-Gaussianity

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### Planck LEO constraints

<table>
<thead>
<tr>
<th>Shape and method</th>
<th>Independent</th>
<th>ISW-lensing subtracted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SMICA (T)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local</td>
<td>6.7 ± 5.6</td>
<td>−0.5 ± 5.6</td>
</tr>
<tr>
<td>Equilatral</td>
<td>4.0 ± 67</td>
<td>4.7 ± 67</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>−38 ± 37</td>
<td>−15 ± 37</td>
</tr>
<tr>
<td><strong>SMICA (T+E)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local</td>
<td>4.1 ± 5.1</td>
<td>−0.9 ± 5.1</td>
</tr>
<tr>
<td>Equilatral</td>
<td>−25 ± 47</td>
<td>−26 ± 47</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>−47 ± 24</td>
<td>−38 ± 24</td>
</tr>
</tbody>
</table>

Planck 2018 results. IX, arXiv:1905.05697
2018 analysis: polarization multipoles in the range $4 < l < 40$ added. Robustness of polarization results reassessed (and significantly improved)

EEE is noisy and has little weight in the final constraints. Nevertheless:
- Very useful to validate polarization-based results
- Constraining power of Planck EEE at the level of WMAP TTT
Comparison between estimators

Smica, T+E

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Comparison between maps: T+E

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Bispectrum reconstruction: modes

Fig. 13. Scatter plots of the 2001 Modal 2 coefficients for each combination of component separation methods, with the $R^2$ coefficient of determination. The figures on the left are for the temperature modes and those on the right for pure polarization modes (the modal 2 pipeline reconstructs the component of the $EEE$ bispectrum that is orthogonal to $TTT$, so this is not exactly the same as the $EEE$ bispectrum of the other estimators).

Fig. 14. Scatter plots of the bispectrum values in each bin-triplet ($13020$ for $TTT$ and $11221$ for $EEE$) for all the combinations of component separation methods, with the $R^2$ coefficient of determination. The figures on the left are for $TTT$ and those on the right for $EEE$.

In the test we have just described we generate uncorrelated extra-noise multipoles (with a non-white spectrum). On the other hand, we know that the estimator is most sensitive to couplings between large and small scales, which require a properly calibrated linear term correction. Therefore, we decide to also test the impact of a possible linear term mis-calibration of this type, by generating and studying an extra-noise component directly in pixel-space. In this case, $\ell$-space correlations between large and small scales arise, due to the spatially anisotropic distribution of the noise. We proceed as follows: after extracting the noise rms of the SMICA FFP10 polarization simulations, we rescale it by a fixed factor $A$, and we use this rescaled rms map to generate new Gaussian "extra-noise" realization in pixel-space, which we add to the starting noise maps. We consider different cases. Firstly, we take a rescaling factor $A_{TQ U} = 0.2$ for both temperature and polarization noise maps. We then perform a more detailed study of the effect on polarization maps only. For this, we leave the temperature noise unchanged and rescale the polarization rms noise by factors ranging from $A = 0.1$ up to $A = 0.3$.

We see again from the summary of results reported in Table 17 that the $f_{NL}$ error bar change is always very small. The same can be said of the standard deviation of the $f_{NL}$ scatter between realizations with and without extra noise, which reaches at most a value $f_{NL} \sim f_{NL}/3$, for a large $A = 0.3$. These results provide a good indication that a noise mismatch between simulations and data is not a concern for primordial NG estimation, unless the mismatch itself is well above the estimated percent...
Overall: large improvement in polarization bispectra. Consistent for different decompositions.
<table>
<thead>
<tr>
<th>Method</th>
<th>T</th>
<th>T+E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SMICA</td>
<td>SEVEM</td>
</tr>
<tr>
<td>Binned</td>
<td>0.64 ± 0.33</td>
<td>0.42 ± 0.33</td>
</tr>
<tr>
<td>Modal1</td>
<td>0.74 ± 0.33</td>
<td>0.59 ± 0.32</td>
</tr>
<tr>
<td>Modal2</td>
<td>0.73 ± 0.27</td>
<td>0.61 ± 0.27</td>
</tr>
</tbody>
</table>

T+E is systematically higher than T-only. Possible SZ contribution in T-only, but no counterpart in nlocal
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada. Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
Future goals

- It is generally accepted that the next sensitivity target should be $f_{NL} \sim 1$

- Local shape: $f_{NL} > 1$ would rule out single-field inflation. $f_{NL} < 1$ would rule out a large class of multi-field models ("spectator fields")

- Equilateral, Orthogonal: the $f_{NL} \sim 1$ threshold allows discriminating between the single-field slow-roll and non-slow-roll regimes.

<table>
<thead>
<tr>
<th>$f_{NL}^{eq, orth}$</th>
<th>$f_{NL}^{loc}$</th>
<th>$f_{NL}^{loc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{NL} \lesssim 1$</td>
<td>Single-field slow-roll</td>
<td>Multi-field</td>
</tr>
<tr>
<td>$f_{NL} \gtrsim 1$</td>
<td>Single-field non-slow-roll</td>
<td>Multi-field</td>
</tr>
</tbody>
</table>

(from Alvarez et al., arXiv:1412.4671)

- This talk is mostly focused on LEO shapes, but keep in mind that there are many interesting additional shapes (e.g. oscillatory features)
### LEO shapes: forecasts

<table>
<thead>
<tr>
<th></th>
<th>LiteCOre-120</th>
<th>CORE+</th>
<th>Planck 2015</th>
<th>LiteBird</th>
<th>ideal</th>
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<tbody>
<tr>
<td>T local</td>
<td>3.7</td>
<td>3.4</td>
<td>5.7</td>
<td>9.4</td>
<td>2.7</td>
</tr>
<tr>
<td>T equil.</td>
<td>59</td>
<td>56</td>
<td>70</td>
<td>92</td>
<td>46</td>
</tr>
<tr>
<td>T ortho.</td>
<td>25</td>
<td>25</td>
<td>33</td>
<td>58</td>
<td>20</td>
</tr>
<tr>
<td>E local</td>
<td>4.5</td>
<td>3.9</td>
<td>32</td>
<td>11</td>
<td>2.4</td>
</tr>
<tr>
<td>E equil.</td>
<td>46</td>
<td>43</td>
<td>141</td>
<td>76</td>
<td>31</td>
</tr>
<tr>
<td>E ortho.</td>
<td>21</td>
<td>19</td>
<td>72</td>
<td>42</td>
<td>13</td>
</tr>
<tr>
<td>T+E local</td>
<td>2.2</td>
<td><strong>1.9</strong></td>
<td><strong>5.0</strong></td>
<td><strong>5.6</strong></td>
<td>1.4</td>
</tr>
<tr>
<td>T+E equil.</td>
<td>22</td>
<td>20</td>
<td>43</td>
<td>40</td>
<td>15</td>
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<tr>
<td>T+E ortho.</td>
<td><strong>10</strong></td>
<td><strong>9.1</strong></td>
<td><strong>21</strong></td>
<td><strong>23</strong></td>
<td>6.7</td>
</tr>
</tbody>
</table>

- A cosmic variance dominated E-mode reconstruction up to \( l_{\text{max}} \sim 3000 \) (PRISM, CMBpol) allows an improvement in \( f_{\text{NL}} \) error bars by a factor \( \sim 2 \) for all shapes.
Tensor-Scalar-Scalar: forecasts

- Tensor-scalar-scalar correlations in slow-roll single-field models have, as usual, amplitude $\sim \varepsilon$.

- Tensor-scalar-scalar correlations, in a parity conserving Universe, source TTB bispectra with $l_1+l_2+l_3 = \text{odd}$

<table>
<thead>
<tr>
<th>Type</th>
<th>Planck</th>
<th>CMB-S4</th>
<th>Rel. improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>$\sigma(\sqrt{r} f_{NL}) = 15.2$</td>
<td>$\sigma(\sqrt{r} f_{NL}) = 0.3$</td>
<td>50.7</td>
</tr>
<tr>
<td>Equilateral</td>
<td>$\sigma(\sqrt{r} f_{NL}) = 200.5$</td>
<td>$\sigma(\sqrt{r} f_{NL}) = 7.4$</td>
<td>27.1</td>
</tr>
<tr>
<td>Local ($r = 0.01$)</td>
<td>$\sigma(\sqrt{r} f_{NL}) = 15.2$</td>
<td>$\sigma(\sqrt{r} f_{NL}) = 0.7$</td>
<td>25.3</td>
</tr>
<tr>
<td>Equilateral ($r = 0.01$)</td>
<td>$\sigma(\sqrt{r} f_{NL}) = 200.8$</td>
<td>$\sigma(\sqrt{r} f_{NL}) = 14.7$</td>
<td>13.7</td>
</tr>
</tbody>
</table>

Stage IV Science Book
Meerburg et al. 2016
Complex non-separable shape, but can be handled with modal methods
(Fergusson, ML, Shellard, 2010, 2012; Shiraishi, ML, Fergusson, 2018)

\[
B_{\ell_1 \ell_2 \ell_3}^{(tss)} = \frac{(8\pi)^{3/2}}{3} \sum_{\ell_1=|\ell_1\pm 2|, \ell_1} (-1)^{\sum_{n=1}^{3} \frac{L_n+\ell_n}{2}} h_{L_1 L_2 L_3} h_{\ell_1 \ell_2 \ell_3}^{20-2} h_{\ell_2 L_2 L_3} h_{\ell_3 L_3 L_3} \left\{ \ell_1 \ell_2 \ell_3 \right\} \left[ \frac{\ell_1 \ell_2 \ell_3}{2 1 1} \right] \]

\[
\int_0^\infty y^2 dy \frac{2}{\pi} \int_0^\infty k_1^2 dk_1 T^{(t)}_\ell(k_1 j L_1(k_1 y)) \left[ \prod_{n=2}^\infty \frac{2}{\pi} \int_0^\infty k_n^2 dk_n T^{(s)}_\ell(k_n j L_n(k_n y)) \right]
\]

M. Shiraishi, ML, J. Fergusson, 2018

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Future LSS data have in principle great potential to improve over CMB bounds.

- Power spectrum: scale dependent signal on large scales. Sensitive to squeezed limit

\[ \Delta b(k) = 2(b - 1)f_{NL}\delta_c\frac{3\Omega_m}{2a\, g(a)r_H^2k^2} \]

- Bispectrum = primordial + late time non-linear evolution

  Gravitational part ~ Primordial x 1000
In Karagiannis et al. (2018) we present PNG LSS forecasts, focusing on linear and quasi-linear scales, accounting for:

- Power spectrum and bispectrum constraints
- Gravitational contributions and bias
- Redshift space distortions
- Theoretical errors
- (to some extent) NG contributions to the bispectrum variance and off-diagonal covariance terms

Many previous papers on these issues (e.g. Sefusatti and Komatsu 2007, Jeong and Komatsu 2009, Giannantonio et al. 2011, Tellarini et al. 2016, Baldauf et al. 2016), but they are often treated separately

- We include all terms in a single forecast.
- Discussion beyond local shape
- Comparison between optical and radio.
Fisher matrix

\[
F_{\alpha \beta}^{P_s} = \sum_{\mu_1=0}^{1} \sum_{k=k_{\min}}^{k_{\max}} \frac{\partial P^s_g}{\partial p_\alpha} \frac{\partial P^s_g}{\partial p_\beta} \frac{1}{\Delta P^2} \quad \text{and} \quad F_{\alpha \beta}^{B_s} = \sum_{\mu_1=-1}^{1} \sum_{\phi=-\pi/2}^{\pi/2} \sum_{T} \frac{\partial B^s_g}{\partial p_\alpha} \frac{\partial B^s_g}{\partial p_\beta} \frac{1}{\Delta B^2}
\]

\[
p = \{ f_{NL}^X, b_1, b_2, b_{s2}, P_\varepsilon, P_{\varepsilon\varepsilon\delta}, B_\varepsilon, f, \sigma_v \} \quad k_{\max}(z) = 0.1/D(z) \ h/Mpc
\]

- Gaussian approximation for P and B variance, off-diagonal terms neglected, PB correlation neglected (effect estimated)
- Cosmological parameters fixed
- Single tracer
- Consider:
  - “Euclid-like” spectroscopic survey
  - “LSST-like” photometric survey
  - Radio-continuum surveys with different flux limits (clustering based determination of redshift, based on Kovetz et al. 2016)
B_{g}^{s}(k_{1},k_{2},k_{3},z) = \mathcal{D}_{FOG}^{B}(k_{1},k_{2},k_{3}) \left[ Z_{1}(k_{1})Z_{1}(k_{2})Z_{1}(k_{3})B_{I}(k_{1},k_{2},k_{3},z) \\ + \left( 2Z_{1}(k_{1})Z_{1}(k_{2})Z_{2}(k_{1},k_{2})P_{m}^{L}(k_{1},z)P_{m}^{L}(k_{2},z) \right) \\ + 2P_{\epsilon\epsilon\delta}(Z_{1}(k_{1})P_{m}^{L}(k_{1}) + 2 \text{ perm}) + B_{\epsilon} \right]
Bispectrum model

\[
B_g^s(k_1, k_2, k_3, z) = D_{\text{FOG}}^B(k_1, k_2, k_3) \left[ Z_1(k_1)Z_1(k_2)Z_1(k_3)B_1(k_1, k_2, k_3, z) \right. \\
+ \left( 2Z_1(k_1)Z_1(k_2)Z_2(k_1, k_2)P_m^L(k_1, z)P_m^L(k_2, z) \right) \\
+ 2P_{\varepsilon \varepsilon \delta}(Z_1(k_1)P_m^L(k_1) + 2 \text{ perm}) + B_e \left] 
\]

Redshift space PT kernels. Bias parameters

\[
Z_1(k_i) = b_1 + f \mu_i^2 + \frac{b_\psi k_i^\alpha}{M(k_i, z)} \\
Z_2(k_i, k_j) = b_1 F_2(k_i, k_j) + f \mu_i^2 G_2(k_i, k_j) + \frac{b_2}{2} + b_s Z_2(k_i, k_j) + \frac{f \mu_{ij} k_{ij}}{2} \left[ \frac{\mu_i}{k_i} Z_1(k_j) + \frac{\mu_j}{k_j} Z_1(k_i) \right] \\
+ \frac{1}{2} \left( \frac{(b_\psi \delta - b_\psi N_2(k_j, k_i)) k_i^\alpha}{M(k_i, z)} + \frac{(b_\psi \delta - b_\psi N_2(k_i, k_j)) k_j^\alpha}{M(k_j, z)} \right)
\]
Theoretical errors

Baldauf et al. 2016

- The LSS bispectrum allows in principle tight constraints also on non-local shapes e.g. equilateral
- Naive mode counting suggest $\sigma_{fNL} \sim 1$ for equilateral might be achievable by pushing $k_{\text{max}}$ high enough
- However, in the non-linear regime we have to model the gravitational bispectrum with high accuracy. Very challenging. Equilateral is more correlated than local to non-linear gravitational bispectrum, so bigger problem.
We follow Baldauf et al. (2016), where theoretical errors are defined as the difference between the true theory and the fiducial predictions.

The “true theory” is taken to be the model which includes at least one more perturbative order with respect to the fiducial one.

\[
C_{TT'} = \frac{(2\pi)^3}{V(z_i)} \frac{\pi s_{123} f_{sky}^{-1}}{d k_1 d k_2 d k_3} \frac{M}{k_1 k_2 k_3} \delta_{TT'} + (C_e)_{TT'}
\]

\[
C_{ij}^e = E_i \rho_{ij} E_j
\]

\[
\rho_{ij} = \begin{cases} 
\exp\left(-\frac{(k_i - k_j)^2}{2\Delta k^2}\right) & \text{P}, \\
\prod_{\alpha=1}^{3} \exp\left(-\frac{(k_{i,\alpha} - k_{j,\alpha})^2}{2\Delta k^2}\right) & \text{B}.
\end{cases}
\]

We also included 1-loop local-in-matter bias terms, besides 1-loop matter corrections.
Impact of theoretical errors

Figure 8. The effect of theoretical errors on the bias parameters and on the three $f_{NL}$ parameters per redshift bin (i.e. two times the value of $z$ in Table 1) for the 1 µJy radio continuum survey. The dashed lines represent our "idealised model", using a simplified monopole statistic for the bispectrum (see item iv in Sec. 5), without theoretical or redshift errors (i.e. the starting step of our analysis, as explained in the main text); for the power spectrum we used the linear predictions with PNG [Eq. (31)], while for the bispectrum of galaxies we used Eq. (32). The non-linear evolution is treated within the formalism of MPTbreeze. The solid lines represent the same model, but including theoretical errors, as described in Sec. 4.2. Forecasts for the power spectrum are plotted in blue, for the bispectrum in green and for both power spectrum and bispectrum in red, without taking into account their cross term in the covariance. The dotted grey line indicates the best constraints on the PNG amplitude, as given by Planck Collaboration et al. (2016b).

(vi) The effect of the theoretical errors on forecasts is shown as a function of redshift in Fig. 8 and 9 for the two radio continuum surveys considered here. The effect on the forecasts coming from the summed signal over all redshift bins is shown in Tables 4 and 9 for the radio and optical surveys respectively.

(vii) The third step is to move to redshift space and include the full RSD treatment up to second order. The galaxy power spectrum and bispectrum model in redshift space are given by Eqs. (26) and (27) respectively. Note that the trispectrum term in Eq. (27) is still excluded for now. Only the diagonal part of the theoretical error covariance is used in the redshift space models. As also mentioned just above, we argue in Sec. 6.1.1 that the effect of the off-diagonal part on the final $f_{NL}$ forecasts is small. Note, finally, that we are still not including redshift errors. Therefore our forecast up to this point are still unrealistic for optical photometric and for radio surveys, for which these errors are important. The goal, up to here, remains that of assessing the impact of each ingredient added at each new step of the analysis. Moreover, forecasts with no redshift errors included provide upper limits to the performance of realistic radio continuum surveys, eventually approachable by improving current techniques for redshift determination.

(viii) In addition to the RSD effect, we consider redshift uncertainties, which are modelled like Eqs. (29) and (30) for the power spectrum and bispectrum respectively (see Sec. 2.3.2 for a discussion). The effect of RSD, theoretical errors and redshift uncertainties to the $f_{NL}$ forecasts is shown in Tables 5, 6 and 11 for the radio and optical surveys respectively.

(ix) Finally, we take into account the trispectrum term in the galaxy bispectrum for both the idealised and the full RSD models (see Eqs. (22) and (27)). The effect of this trispectrum correction to the final PNG forecasts is shown, for the idealised case, in Tables 7 and 10 for the radio and optical surveys respectively. For the final "full" model (i.e. RSD+theoretical errors+redshift errors+trispectrum), the $f_{NL}$ forecast are shown in Tables 8 and 11 for the radio continuum and optical surveys respectively.
Figure 9. Same as in Fig. 8, but for the 10 µJy radio continuum survey.

Figure 10. Same as Fig. 8, where the relative difference between the theoretical errors (denoted in the plots with the upper index TE) and without is shown. The spikes observed in the expected forecasts, obtained when including the effect of theoretical errors can be attributed to the trade-off between the contributions coming from higher-order terms in the matter and bias expansions (see main text in Sec. 6.1.1 for a discussion).
Bispectrum variance: NG corrections

- Dominant contribution from 1-loop power spectrum
- Final constraints deteriorate by ~40% for local and ~20% for equil. When including NG corrections.

\[ \Delta B^2_{NL}(k_1, k_2, k_3, z) = \Delta B^2(k_1, k_2, k_3, z) + \frac{s_{123} \pi V_f}{k_1 k_2 k_3 \Delta k^3 \Delta \mu \Delta \phi} \]

\[ \times \left( P_{tot}(k_1) P_{tot}(k_2) (P^{{NL}}_g(k_3) - P_g(k_3) + \frac{1}{n_g}) + 2 \text{ perm} \right) , \]
“Bivariate term” gives the largest contribution. Decrease rapidly with increasing $k_{\text{min}}$. Complementarity between power spectrum and bispectrum (different scales) also important for robustness, besides S/N.
Theoretical errors: bias loop corrections are important

Bispectrum improves substantially over power spectrum

NG contributions to bispectrum variance and off-diagonal covariance terms need further work.

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<table>
<thead>
<tr>
<th></th>
<th>Planck</th>
<th>Radio continuum, 1 $\mu$Jy</th>
<th>Radio continuum, 10 $\mu$Jy</th>
<th>Spectroscopic</th>
<th>Photometric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>5.0</td>
<td>0.2</td>
<td>0.6</td>
<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Equilateral</td>
<td>43</td>
<td>244</td>
<td>274</td>
<td>57</td>
<td>184</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>21</td>
<td>18</td>
<td>29</td>
<td>18</td>
<td>38</td>
</tr>
</tbody>
</table>

Karagiannis, Lazanu, ML, Bartolo, Raccanelle, Verde, 2018
M. Liguori, Testing primordial non-Gaussianity

Beyond19, Warsaw, 2019
Oscillatory shapes

A variety of inflationary models (features in the potential, axion monodromy...) can produce oscillatory features in the bispectrum. We consider linear oscillations:

\[
P_\zeta(k) = P_{\zeta,0}(k) \left[ 1 + A_P \sin \left( \frac{2\pi k h}{3k_s^P} + \phi_P \right) \right], \quad B_\zeta(k_1, k_2, k_3) = f_{NL} \frac{6P^2_{\zeta,0}(k_p)}{k_1^2 k_2^2 k_3^2} \sin \left( \frac{2\pi K h}{3k_s^B} + \phi_B \right)
\]

- CMB+ LSS analysis. LSS can significantly improve over CMB
- Theoretical errors are much less correlated with these shapes

Karagiannis et al. in prep.
The largest and smallest available perpendicular scales are given by

\[ k_{\perp,\min} \]

Note that the smallest accessible scales are also limited by the specifications of each survey.

The non-linear scales are defined to be the linear, one-dimensional velocity dispersion, spectrum and bispectrum is valid, by cutting the maximum scales at

\[ k_{\perp,\max} \]

while we confine the analysis inside the linear/semi-linear regime, where the tree-level power

\[ P(k) \]

is used for the main forecasts of this work.

To treat the foregrounds we follow the wedge approach

\[ \text{wedge} \]

and Table 3

\[ \text{forefeud} \]

where all scales that satisfy,

and

Note that the smallest accessible scales are also limited by the specifications of each survey.

The PNG forecasts are presented in Fig.

\[ k_{\parallel,\min} \]

\[ k_{\parallel,\max} \]

\[ 0.01 \]

\[ 0.05 \]

\[ 0.01 \]

\[ 0.05 \]

\[ 0.01 \]

\[ 0.05 \]

\[ 0.01 \]

\[ 0.05 \]

\[ \text{ANSARI}\text{ET AL.,\text{ ARXIV: 1810.09572}} \]

Karagiannis, Slosar, ML, in prep.

Foregrounds: remove scales with \( k_{\parallel} < k_{\text{wedge}} k_{\perp} \) ("wedge")

\[
k_{\text{PB}} = \frac{rH(z)}{c(1+z)} \sin \left( N_w \frac{\theta_{\text{FOV}}}{2} \right)
\]
CIB power spectrum

- CIB power spectrum is integrated over a large volume. Ideal for scale dependent bias (Tucci, Desjacques, Kunz. 2016)
- Seriously contaminated by dust, but future full-sky satellite B-mode experiments with many (high-)frequency channels allows very accurate component separation.

(Tucci et al. 2016)
**Intensity mapping: 30 < z < 100**

**Table II. Fractional error and correlation coefficients to each other to high precision.**

<table>
<thead>
<tr>
<th>PNG type</th>
<th>$\sigma_{f_{NL}}$ (1 MHz)</th>
<th>$\sigma_{f_{NL}}$ (0.1 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>Equilateral</td>
<td>0.39</td>
<td>0.04</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>0.29</td>
<td>0.03</td>
</tr>
<tr>
<td>$J = 1$</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$J = 2$</td>
<td>0.33</td>
<td>0.05</td>
</tr>
<tr>
<td>$J = 3$</td>
<td>0.85</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Plots and results from Munoz, Haimoud, Kamionkowski, 2015

arXiv: 1506.04152
Squeezed bispectra generate couplings between large and small scales i.e., large scale modulation of small scale power

This modulation couples CMB temperature fluctuations on large scales to spectral distortions arising from acoustic wave dissipation at very small scales.

- Use $T_\mu$ to measure local $f_{\text{NL}}$ and $\tau_{\text{NL}}$ (Pajer and Zaldarriaga 2013)
- Further constraining power on $f_{\text{NL}}$ running (Biagetti et al. 2013, Emami et al. 2015)
- Large S/N increase for “super-squeezed “ shapes (Ganc and Komatsu 2013)
- Can measure also $g_{\text{NL}}$ from $TT_\mu$ bispectrum
M. Liguori, Testing primordial non-Gaussianity
the current error bars on relevant NG parameters which are much worse than what is achievable with... spectra, we assume... quantities – i.e. TT\mu – distortions is smaller than that for temperature anisotropies (i.e.,... as it is typical for this type of analysis, we... as shown in this figure, since the cosmic... might become better... For comparison, in... × 10^7... Planck (black lines) for a noiseless CMB survey, which are almost the same as the errors obtained in the... \Delta s_{NL}^g$ vs. $l_{\text{max}}$... 

**N. Bartolo, ML, M. Shiraishi (2015)***

M. Liguori, Testing primordial non-Gaussianity
Signals

The cross correlations with \( E \) are \( \approx 100 \) times smaller than those with \( T \), … WAIT TO SEE THE S/N!

Forecast results

- >3x improvement w.r.t. previous methods for \( y \)
- 20% improvement for \( \mu \)

**Forecast results**

- >3x improvement w.r.t. previous methods for \( y \)
- 20% improvement for \( \mu \)

**Overall factor ~ 16 improvement (PRISM)**

From masking + template cleaning + \( yE \)

20% improvement on \( \mu T \) when adding \( \mu E \) (see also Ota 2016)
Conclusions: PNG, beyond *Planck*

- The next challenge is $f_{\text{NL}} < 1$
- CMB bispectrum. Factors $\sim 2$ improvements possible for *all* shapes but local $f_{\text{NL}} \sim 1$ seems out of reach without additional datasets. TTB is interesting.
- Local $f_{\text{NL}} \sim 1$ seems achievable in the not too far future with LSS: Euclid, LSST, Spherex, SKA; also CIB measurements are interesting.
- Oscillatory shapes also look like a good target for forthcoming LSS surveys.
- Improvements for non-local shapes is hard. Theoretical errors in LSS bispectrum and redshift errors affect mostly equilateral.
- Next generation IM can achieve good constraints both on local and orthogonal/flat shapes.
- Futuristic. Large improvements possible with spectral distortions (local) and 21 cm brightness fluctuations from EoR (all)