Constraints on Running of Non-Gaussianity from Large Scale Structure Probes

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Accepted 2019 November 4. Received 2019 October 28; in original form 2019 September 16

ABSTRACT

In this letter we present constraints on the scale-dependent “local” type primordial non-Gaussianity, which is described by non-Gaussianity’s spectral index n_{NG}, from the NRAO VLA Sky Survey and the quasar catalog of the Sloan Digital Sky Survey (SDSS) Data Release 6, together with the SDSS Data Release 12 photo-z sample. Here, we use the auto-correlation analyses of these three probes and their cross-correlation analyses with the cosmic microwave background (CMB) temperature map, and obtain the tight constraint on the spectral index: n_{NG} = 0.2^{+0.7}_{-1.0} (1σ C.L.), which shows the first competitive constraint on the running of non-Gaussianity from current large-scale structure clustering data. Furthermore, we also perform the forecast calculations and improve the limit of n_{NG} using the future Euclid mission, and obtain the standard deviation at 68% confidence level: Δn_{NG} = 1.74 when considering the fiducial value f_{NL} = 3, which provides the complementary constraining power to those from the CMB bispectrum information.

Key words: cosmology: theory – inflation – large-scale structure of universe

1 INTRODUCTION

The standard inflationary paradigm predicts a flat Universe perturbed by nearly Gaussian and scale invariant primordial perturbations. These predictions have been confirmed by the increasingly precise measurements of the CMB and the large-scale structure (LSS). Since the last decade, the Planck satellite has confirmed that the initial seeds of structure must have been close to Gaussian (Ade et al. 2016). However, it is difficult to discriminate between the vast array of inflationary scenarios since most of the present constraints on the Lagrangian of the inflaton field have been obtained from measurements of the two-point function, or power spectrum. Therefore, it is natural to study the non-Gaussianity signatures in higher order correlators.

Considering the non-Gaussianity, the bispectrum of gravitational potential Φ(k) is defined as,

\[ \langle Φ(k_1) Φ(k_2) Φ(k_3) \rangle \equiv (2π)^3 δ_0(k_{123}) B_Φ(k_1 k_2 k_3), \]

(1)

where δ_0(k_{123}) ≡ δ_0(k_1 + k_2 + k_3) is the Dirac delta function, and

\[ B_Φ(k_1 k_2 k_3) \equiv f_{NL} F(k_1 k_2 k_3), \]

(2)

where f_{NL} is the amplitude of bispectrum, and F encodes the functional dependence on the specific triangle configurations. Here, we mainly focus on the “local” shape which comes from the “squeezed” triangles dominantly \( k_3 \ll k_1, k_2 \).

As shown by Grossi et al. (2009) in numerical simulations with non-Gaussian initial conditions of the local kind, the large-scale halo bias can be greatly affected by relatively small values of f_{NL}, which provides another way to test the primordial non-Gaussianity using the properties of the LSS clustering data. Based on this point, many works used the auto-correlation power spectra or auto-correlation functions of high-redshift probes to constrain f_{NL} because the primordial non-Gaussianity can significantly enhance the clustering power at large scales (Xia et al. 2010a,b, 2011; Nikoloudakis et al. 2013; Karagiannis et al. 2014; Leistedt et al. 2014; Alvarez et al. 2014). These works obtained comparable results with the limits from the CMB bispectrum.

Even though a scale independent f_{NL} has been widely studied in recent works, a scale-dependent f_{NL} is still well-motivated by theoretical predictions of some inflationary models (Chen 2005; Khoury & Piazza 2009; Byrnes et al. 2010a,b, 2011; Riotto & Sloth 2011). To denote the running of f_{NL}, a non-Gaussianity’s spectral index n_{NG} is defined in analogy to the power spectrum spectral index. The first detailed forecasts on the running of non-Gaussianity were obtained by Sefusatti et al. (2009), and then by other works (Becker et al. 2012; Biagetti et al. 2013; Giannantonio et al. 2012), in which they performed the forecast analysis using the Fisher matrix method. Becker & Huterer (2012) took the first step and constrained the non-Gaussianity’s spectral in-
index using the WMAP bispectrum with KSW bispectrum estimator, \( r_{NG} = 0.3^{+0.4}_{-0.5} \) at 68% confidence level. Oppizzi et al. (2018) extended their work and included additional shapes and running models, and got \( r_{NG} = 0.4^{+0.9}_{-0.4} \) (1 \( \sigma \) C.L.) for the “local” shape considered in this letter. Recently, Planck collaboration published their new constraints on \( r_{NG} \) using the same method (Akrami et al. 2018), the results give a large error (\( 2\Delta r_{NG} \approx 2 \) for a constant prior) on this parameter because \( f_{NL} \) constrained by Planck is close to 0.

The main purpose of this letter is to constrain the running of the “local” type non-Gaussianity considering the clustering information of LSS probes. Following Byrnes et al. (2010b), we parameterize the initial bispectrum with the two scalar fields inflationary model, where both fields contribute to the generation of the perturbations.

\[
B_\Phi(k_1,k_2,k_3) = 2f_{NL} \times \left[ \frac{\sqrt{k_1^2 k_2^2}}{k_p} \right] R_\Phi(k_1) P_\Phi(k_2) + 2\text{Perm},
\]

where \( k_p \) is the pivot point, and \( P_\Phi \) is the primordial gravitational potential power spectrum. This kind of template arises, for example, from the mixed inflaton-curvature scenario.

In contrast to previous works (Sefusatti et al. 2009; Biagetti et al. 2013), we use the real LSS clustering data including radio sources from the NRAO VLBI Sky Survey (NVSS) (Condon et al. 1998) and the quasar catalogue of the Sloan Digital Sky Survey Release 6 (SDSS DR6 QSOs) (Richards et al. 2008), as well as the low redshift probe SDSS Data Release 12 photo-z sample (SDSS DR12 PZs) (Beck et al. 2016). We constrain on the running of the “local” type non-Gaussianity using the auto-correlation power spectra (ACPS) \( C_\ell^{\delta \delta} \) of these three LSS surveys, and their cross-correlation power spectra (CCPS) \( C_\ell^{\delta p} \) with the CMB temperature fluctuations from the Planck observation.

2 FORMALISM

We assume that the collapsed objects form in extreme peaks of the density field \( \delta(x) = \delta \rho/\rho \). The statistics of collapsed objects can be described by the statistics of the density perturbation smoothed on some mass scale \( M \). Following LoVerde et al. (2008), the non-Gaussianity probability density function can be obtained by the Edgeworth expansion (Bernardeau et al. 2002), where the non-Gaussianity mass function is

\[
N_{NG} = \frac{dn(M,z)}{dM} = \sqrt{\frac{2}{\pi}} \frac{d}{dM} \frac{d}{dM} \left[ \frac{d\ln \sigma_M}{dM} \right] \left( \frac{\delta_c}{\sigma_M} - \frac{S_3}{6} \frac{(\delta_c^4 - 2 \delta_c^2 \sigma_M^2 - \sigma_M^4 - 1)}{\sigma_M^4} \right).
\]

(4)

The redshift dependence is carried by the threshold for collapse \( \delta_c(z) = 1.686/D(z) \), with \( D(z) \) the growth factor. It worth noticing that we may replace \( \delta_c \) with \( \sqrt{q} \delta_c \) for ellipsoidal collapse, and the correlation \( q = 0.75 \) results from the N-body simulation (Grossi et al. 2000). \( \sigma_M \) is the variance of the smoothed density fluctuation, and \( S_3 \) is the skewness which defines as \( S_3 = \langle \delta_M^3 \rangle / \langle \delta_M^2 \rangle^3/2 \). Taking Eq. (3) into the above equation, we can calculate the correction on the Gaussianity mass function when considering the running non-Gaussianity model.

For the “local” type primordial non-Gaussianity, there are several theoretical expressions for the large-scale bias (Afshordi & Tolley 2008; Dalal et al. 2008; Matarrese & Verde 2008; Slosar et al. 2008; McDonald 2008; Desjacques et al. 2011a,b; Scocca et al. 2012). In our analysis, we use the accurate prediction for the scale dependent bias correction from primordial non-Gaussianity (Desjacques et al. 2011a).

\[
\Delta b(M; z, k) = 2 \frac{\mathcal{F}(M, k)}{W_M(k) M(k)} \left( b_L^2 \delta_c(z) + 1 \right) \frac{d \ln \mathcal{F}(M, k)}{d \ln \sigma_M} \frac{d \ln \mathcal{F}(M, k)}{d \ln M} \frac{d \ln \mathcal{F}(M, k)}{d \ln \sigma_M} \frac{d \ln \mathcal{F}(M, k)}{d \ln M} \frac{d \ln \mathcal{F}(M, k)}{d \ln \sigma_M}
\]

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where \( W_M \) is a top-hat windows function in Fourier space, and \( M(k) = 2k^2 T(k)/(3\Omega_m H^2_0) \), in which \( T(k) \) is the transfer function, \( \Omega_m \) is the current fraction of the matter energy density, and \( H_0 \) is the current Hubble constant. \( b_L \) is the Gaussian Lagrangian bias and the shape function \( \mathcal{F}(M, k) \) can be written as

\[
\mathcal{F}(M, k) = \frac{1}{4 \sigma_M^2 \Phi(k)} \int_{-q}^q \frac{d^q W_M(q) M(q) W_M(q)}{d \ln q} \times M(|k-q|) b_L(\delta_c, k, q - k) \sigma_M
\]

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which includes the dependence of \( f_{NL} \) and \( r_{NG} \). When setting \( r_{NG} = 0 \), \( \mathcal{F}(M, k) \) returns to the constant \( f_{NL} \) at large scales as expected. It worth noticing that Eq.(6) is applied to the two scalar fields inflationary model, instead of the single scalar field model discussed in Becker & Huterer (2012), because in the single scalar field model there is a very strong degeneracy between \( f_{NL} \) and \( r_{NG} \). Consequently, we cannot get obtain reasonable constraints on the latter from current LSS observations.

Making the standard assumption that halos move coherently with the underlying dark matter, the Lagrangian bias is related to the Eulerian one as \( b_L = 1 + b_{NL} \). We assume the large scale, linear halo bias for the Gaussian case is (Sheth & Tormen 1999)

\[
1 + b_{NL}^L = 1 + \frac{q \delta_c(z)}{\sigma_M} \left[ \frac{\delta_c(z)}{\sigma_M} - \frac{1}{\delta_c(z)} \right] + 2 \frac{p}{\sigma_M} \left[ \frac{\delta_c(z)}{\sigma_M} \right]^p - 1
\]

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where \( z_h \) is the halo formation redshift, and \( z_o \) is the halo observation redshift. As we are interested in massive halos, we expect that \( z_h \approx z_o \). Here, \( q = 0.75 \) and \( p = 0.3 \) account for non-spherical collapse and are a fit result from numerical simulations (Scoccimarro et al. 2001).

Finally, in order to get the effective bias, we need to integrate the halo mass in the given range relevant to our sources,

\[
b_{eff}(M_{\text{min}}, z, k) = \int_{M_{\text{min}}}^{M_{\text{max}}} b_{NG}(M, z, k) N_{NG}(M, z) dM
\]

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where \( b_{NG}(M, z, k) = 1 + b_{NL}^L(M, z) + \Delta b(M, z, k) \) is the scale-dependent bias. This effective bias is dependent on the minimal halo mass which differs for different sources.

2.1 Data Analysis

Since the Limber approximation is accurate below the
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3 FITTING RESULTS

In our calculations, we use the public software CosmoMC \(^\text{3}\) (Lewis & Brinle 2002), a Markov Chain Monte Carlo (MCMC) code to perform the global constraints on \(f_{\text{NL}}\) and \(n_{\text{NG}}\) from the ACPS and CCPS clustering data at scales \(10 < \ell < 500\) of three LSS surveys described above. Here, we abandon the very large scale data mainly for three reasons: 1) to avoid the deviation from accurate theory when we use Limber approximation. 2) to reduce the systematic error at very large scales. 3) to avoid the effects of gauge corrections on the power spectrum on very large scales (Yoo et al. 2009). A simple \(\chi^2\) is used for the fit in our analysis:

\[
\chi^2 = \sum_{\text{data}} \sum_{i} (\hat{C}_i - C_i)^T \Gamma_{i}^{-1} (\hat{C}_i - C_i),
\]

where \(\Gamma_i\) are the covariance matrixes output from PolSpice estimator and \(i\) means different ACPS or CCPS when we perform the joint analysis. \(\hat{C}_i\) and \(C_i\) represent the model and the measured power spectrum. Furthermore, we also constrain three minimal halo masses \(M_{\text{min}}\) for three LSS surveys, and the constraint results on \(M_{\text{min}}\) using their ACPS and CCPS are \(10^{12.2 \pm 0.04} h^{-1} M_\odot\) for NVSS, \(10^{10.92 \pm 0.04} h^{-1} M_\odot\) for SDSS DR6 QSOs and \(10^{11.64 \pm 0.02} h^{-1} M_\odot\) for SDSS DR12 QSOs, respectively (1 \(\sigma\) C.L.). In order to accelerate the calculation, we do not include the basic cosmological parameters. We admit there are degeneracies between some of the cosmological parameters with \(f_{\text{NL}}\), but they are constrained very tight by Planck. We have checked our work, and the results show these parameters have very little influence on the final constraints. Therefore, we assume the standard \(\Lambda\)CDM model, with purely adiabatic initial conditions and a flat Universe, and fix the six cosmological parameters as best fit values from the Planck measurement (Aghanim et al. 2018): \(\Omega_m h^2 = 0.0224, \Omega_b h^2 = 0.1201, 100\theta_{\text{MC}} = 1.0409, \tau = 0.0543, n_s = 0.9661, \ln(10^{10} A_s) = 3.0448\).

Oppizzi et al. (2018) showed the dependence of the likelihood on the pivot scale \(k_p\). As Becker & Huterer (2012)

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1 http://camb.info
2 http://www2.iap.fr/users/hivon/software/PolSpice/
3 http://cosmologist.info/cosmomc/
proposed, the true pivot scale favored by the data is the value of $k_p$ for which the errors in $f_{NL}$ and $n_{NG}$ are uncorrelated. In our analysis, we start with an arbitrary value of $k_p$, compute the likelihood and then rescale $k_p$ by (Shandera et al. 2011),

$$k_p = k_p^* \exp \left( - \frac{C_{f_{NL}, n_{NG}}}{f_{NL} C_{n_{NG}, n_{NG}}^{NL}} \right),$$

where $k_p^*$ is the arbitrary pivot used initially and $f_{NL}^{NG}$ is the constraint result using $k_p^*$. $C$ is the covariance matrix between $f_{NL}$ and $n_{NG}$. In practice, we find $k_p = 0.016 \text{Mpc}^{-1}$ is appropriate in our analysis, since the degeneracy between $f_{NL}$ and $n_{NG}$ we obtain is small enough if using this pivot scale.

We start with the NVSS catalog. In Tab. 1 we list constraints on $n_{NG}$ and $f_{NL}$ from NVSS. If only using the NVSS ACPS, we obtain the constraint: $f_{NL} = 51^{+55}_{-41}$ (1σ C.L.), which is consistent with the Gaussian case at 2σ confidence level, similar with previous works. The non-Gaussianity’s spectral index can also be constrained by the ACPS data: $n_{NG} = 0.8^{+1.9}_{-1.7}$ at 68% C.L., which is consistent with zero at 1σ confidence level, and implies that a positive value is slightly preferred, since in the analysis we find that there is a mild enhancement on the amplitudes of ACPS data points at scales $\ell < 30$. When we combine the ACPS and CCPS of NVSS together, the constraint on $n_{NG}$ is slightly tightened: $n_{NG} = 0.9^{+0.9}_{-1.6}$ at 1σ confidence level, as shown in the black dashed line in Fig. 2. Apparently, in this analysis the constraining power of ACPS is much stronger than the CCPS.

Then we move to the SDSS DR6 QSOs data. Similar with the NVSS result, using ACPS data alone the constraint of non-Gaussianity is consistent with zero safely: $f_{NL} = 43^{+65}_{-50}$ (1σ C.L.). This result is different from some previous works (Xia et al. 2011), which might due to the more conservative mask we use in the analysis. We also obtain the constraint on the non-Gaussianity’s spectral index: $n_{NG} = -0.7^{+1.4}_{-1.0}$ (1σ C.L.), which is also consistent with zero at 1σ confidence level. Unlike the NVSS constraint, the DR6 QSO sample slightly prefers a negative value of $n_{NG}$, since the ACPS data points at scales $10 < \ell < 100$ are slightly suppressed comparing with the non-running case. Again, we combine the ACPS and CCPS of SDSS DR6 QSOs, the blue dotted line shows that the constraint only has a very minor change: $n_{NG} = -0.6^{+1.2}_{-1.3}$ at 68% confidence level. The non-running case is still favored by the QSO data.

If we combine the ACPS and CCPS data of NVSS and SDSS DR6 QSOs samples together, we obtain tight constraint on the non-Gaussianity’s spectral index: $n_{NG} = 0.1^{+0.8}_{-1.0}$ (1σ C.L.), as shown in the green dash-dotted line, which shows a constraint competitive to previous work (Becker & Huterer 2012; Oppizzi et al. 2018) that used the CMB bispectrum to constrain the running non-Gaussianity. In the right panel of Fig. 2, we also show the two-dimensional contours between $f_{NL}$ and $n_{NG}$. Clearly we can see that now the degeneracy between them is not very strong, since we
set a proper scale $k_p$ in the calculations. Furthermore, we also see a long tail at lower values of $\Delta N_{\text{NG}}$, because in our calculations we only use the data points at $\ell > 10$. The effect of the negative $\Delta N_{\text{NG}}$ is smaller than that of the positive non-Gaussianity’s spectral index at scales $10 < \ell < 100$, as shown in Fig. 1. Therefore, the constraining power on the negative $\Delta N_{\text{NG}}$ will be weaker than that on the positive index. Finally, we add the ACPS and CCPS of SDSS DR12 PZs into the analysis, and obtain a tight constraint on the non-Gaussianity’s spectral index of the “local” type non-Gaussianity:

$$\Delta N_{\text{NG}} = \frac{0.2^{+0.7}_{-0.1}}{1 \, \text{C.L.}},$$

(13)

which clearly shows that the non-running case is supported by the current LSS clustering data.

Here we also preform a simple forecast using the future Euclid observation to estimate constraints on $\Delta N_{\text{NL}}$ and $\Delta N_{\text{NG}}$ based on the Fisher matrix technique. The Fisher matrix for the running non-Gaussianity parameters $f_{\text{NL}}$ and $\Delta N_{\text{NG}}$ is given by (Biagetti et al. 2013)

$$F_{ij} = \frac{\partial^2 P_k}{\partial \phi_i \partial \phi_j} \bigg|_{k=k_p} \frac{1}{V_{\text{sky}}} \int \frac{d^2 k}{(2\pi)^2} \frac{\partial P_k}{\partial \phi_i} \frac{\partial P_k}{\partial \phi_j},$$

(14)

where $\phi$ are $f_{\text{NL}}$ and $\Delta N_{\text{NG}}$, in our analysis, $V_{\text{sky}}$ is the surveyed volume, and $f_{\text{sky}}$ is the fraction of the sky observed. The integral over the momenta runs from $k_{\text{min}} = 2\pi/(\sqrt{V_{\text{sky}}} f_{\text{sky}})^{1/3}$ to $k_{\text{max}} = 0.03h \text{Mpc}^{-1}$, above which the non-Gaussian bias becomes negligible. Including shot-noise, the galaxy power spectrum $P_k(k)$ can be

$$P_k(k; z) = \frac{g^2_{\text{eff}}(k; z) P_k(k; z) + 1}{\eta},$$

(15)

where $\eta$ is the mean number density of the survey. In our analysis, we assume the fiducial values $f_{\text{NL}} = 3$ and $\Delta N_{\text{NG}} = 0$ ruled by Planck (Akrami et al. 2018). We also use the minimal halo mass $M_{\text{min}} = 10^{13} M_\odot$ and the pivot scale $k_p = 0.016h \text{Mpc}^{-1}$. We have adopted the specification from Euclid (Laureijs et al. 2011): $\delta_{\text{median}} = 0.9$, $f_{\text{sky}} = 0.48$, $V_{\text{sky}} = 190h^{-3} \text{Gpc}^3$, together with the number density of 30 galaxies per square arcminute. Finally, we obtain the standard deviations of the non-Gaussianity and its non-Gaussianity’s spectral index are $\Delta N_{\text{NG}} = 1.74$ and $\Delta N_{\text{NL}} = 4.2$. In the future, the LSS clustering data can also provide the complementarity constraining power on the non-Gaussianity’s spectral index.

4 CONCLUSIONS

In this letter, we analyze the effects of the running of “local” type non-Gaussianity, originated from the general two scalar fields model, on mass function, large scale halo bias and correlation angular power spectrum comprehensively. The non-Gaussianity’s spectral index $\Delta N_{\text{NG}}$ has effect on the LSS clustering data at large scale. Therefore, we use the current LSS data: NVSS and SDSS DR6 QSOs as high redshift probes, together with SDSS DR12 PZs as lower redshift probe to compute their ACPS and CCPS with CMB map. Combining all data together, we obtain the first tight constraint on the non-Gaussianity’s spectral index from the current LSS data: $\Delta N_{\text{NG}} = 0.2^{+0.7}_{-0.1} (1 \, \text{C.L.})$ at the pivot scale $k_p = 0.016h \text{Mpc}^{-1}$. We also perform a forecast for $\Delta N_{\text{NG}}$ using the future Euclid survey, which shows that the LSS clustering data can also useful on the estimation of the non-Gaussianity spectral index’s of “local” type non-Gaussianity.

ACKNOWLEDGEMENTS

J.-Q. Xia is supported by the National Science Foundation of China under grants No. U1931202, 11633001, and 11690023; the National Key R&D Program of China No. 2017YFA0402600; the National Youth Thousand Talents Program and the Fundamental Research Funds for the Central Universities, grant No. 2017YET01.

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