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# Modification of the halo mass function by kurtosis associated with primordial non-Gaussianity

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## ABSTRACT

We study the halo mass function in the presence of a kurtosis type of primordial non-Gaussianity. The kurtosis corresponds to the trispectrum as defined in Fourier space. The primordial trispectrum is commonly characterized by two parameters,  $\tau_{\text{NL}}$  and  $g_{\text{NL}}$ . We focus on  $\tau_{\text{NL}}$  which is an important parameter to test the physics of multifield inflation models. As applications of the derived non-Gaussian mass function, we consider the effects on the abundance of void structure, on early star formation and on formation of the most massive objects at high redshift. We show that by comparing the effects of primordial non-Gaussianity on cluster abundance with that on void abundance, we can distinguish between the skewness and the kurtosis types of primordial non-Gaussianity. As for early star formation, we show that the kurtosis type of primordial non-Gaussianity seems on the average not to affect the reionization history of the Universe. However, at high redshifts (up to  $z \simeq 20$ ) such non-Gaussianity does somewhat affect the early stages of reionization.

**Key words:** dark ages, reionization, first stars – inflation – large-scale structure of Universe.

## 1 INTRODUCTION

The inflation paradigm has been well known as a successful scenario for resolving several shortcomings of the standard big bang model, in particular the generation of primordial fluctuations which seed cosmic microwave background (CMB) fluctuations and structure formation of the Universe. In the standard inflationary scenario, the primordial density fluctuations are generated from quantum fluctuations of a scalar field, and they have almost Gaussian statistics. In recent years, it has been realized that studying the non-Gaussianity of the primordial density fluctuations can reveal valuable information about the dynamics of inflation (Komatsu & Spergel 2001; Bartolo et al. 2004; Bartolo, Matarrese & Riotto 2010; Komatsu 2010, and references therein). Thanks to significant progress in cosmological observations, most notably the CMB observations, we may expect that a meaningful measurement of this quantity will become observationally available in the near future and will thereby allow several inflation models to be tested.

In Komatsu & Spergel (2001), the authors have introduced a simple new parameter which describes the deviation from Gaussianity of the statistics of the primordial curvature fluctuations, the so-called non-linearity parameter  $f_{\text{NL}}$ , defined as (Salopek & Bond 1990; Gangui et al. 1994; Verde et al. 2000)

$$\zeta(\mathbf{x}) = \zeta_{\text{G}}(\mathbf{x}) + \frac{3}{5} f_{\text{NL}} [\zeta_{\text{G}}^2(\mathbf{x}) - \langle \zeta_{\text{G}}(\mathbf{x})^2 \rangle] + O[\zeta_{\text{G}}^3(\mathbf{x})], \quad (1)$$

where  $\zeta$  represents the primordial curvature fluctuations on a uniform energy density hypersurface and  $\zeta_{\text{G}}$  denotes the Gaussian part. In the probability density function (PDF) of the primordial fluctuations, the non-zero value of the non-linearity parameter  $f_{\text{NL}}$  may generate a non-zero value of the skewness (third-order moment), the kurtosis (fourth-order moment) and so on. Obviously, the skewness can be parametrized by the leading term using  $f_{\text{NL}}$ . However, the kurtosis can be affected not only by the  $f_{\text{NL}}$  term, but also by higher order terms, such as the  $\zeta_{\text{G}}^3(\mathbf{x})$  term in the above expression (1). In general, one needs two parameters in order to characterize the kurtosis in the PDF. These parameters are normally called  $\tau_{\text{NL}}$  and  $g_{\text{NL}}$ , where the first is usually (although not always) related to  $f_{\text{NL}}$  and the second is the parameter that characterizes the third moment of  $\zeta$ . Such kind of non-linearity is the so-called local type of non-Gaussianity. Recently, other types of

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non-Gaussianity have been discussed in the literature, e.g. equilateral and orthogonal types. Theoretically, the local type of non-Gaussianity can be generated from the superhorizon non-linear dynamics of primordial curvature perturbations. On the other hand, the equilateral and orthogonal types of non-Gaussianity can be generated when one considers a scalar field which has a non-canonical kinetic term or the higher order derivative correction terms. In this paper, we focus on the local type of non-Gaussianity and consider the case where the equilateral and orthogonal types are negligible.

In the case where the primordial curvature fluctuations were generated from single field stochastic fluctuations (single-sourced case), the primordial curvature fluctuations can be expressed as equation (1) and  $\tau_{\text{NL}}$  can be described only by  $f_{\text{NL}}$ . However, in general, e.g. if the primordial curvature fluctuations were generated from multistochastic fluctuations, then  $\tau_{\text{NL}}$  and  $f_{\text{NL}}$  have no universal relation any more (Suyama & Yamaguchi 2008; Suyama et al. 2010; Sugiyama, Komatsu & Futamase 2011). Hence, it seems to be important to investigate the observational consequences of  $\tau_{\text{NL}}$  independently of  $f_{\text{NL}}$ .

In this paper, we focus on the effects of the kurtosis type of primordial non-Gaussianity on the large-scale structure (LSS), in particular on the halo mass function. There are many studies on the effects of primordial non-Gaussianity on the LSS and also on the formulation of the non-Gaussian halo mass function (Matarrese, Verde & Jimenez 2000; Slosar et al. 2008; Maggiore & Riotto 2010a; Verde 2010; Wagner, Verde & Boubekur 2010; De Simone, Maggiore & Riotto 2011; D'Amico et al. 2011, and references therein), which focus not only on  $f_{\text{NL}}$  type, but also  $g_{\text{NL}}$  type (Chongchitnan & Silk 2010, 2011; Desjacques & Seljak 2010; Maggiore & Riotto 2010b; Enqvist, Hotchkiss & Taanila 2011). Here, we study the effects of kurtosis of the non-Gaussian primordial fluctuations whose non-linearity is parametrized by the two free parameters,  $g_{\text{NL}}$  and  $\tau_{\text{NL}}$ . Recently, a number of authors have studied non-Gaussian initial perturbations in two-field inflationary models (Smith & LoVerde 2010; Tselikhovich, Hirata & Slosar 2010). In these papers, the authors have considered the effect of non-Gaussianity on the halo bias. Although this type of primordial non-Gaussianity is similar to the one considered here, we study the effects on the halo mass function.

This paper is organized as follows. In the next section, we briefly review the kurtosis type of primordial non-Gaussianity considered here. In Section 3, we formulate halo mass functions with primordial non-Gaussianity, based on the Press–Schechter theory and Edgeworth expansion. In Section 4, we apply the non-Gaussian halo mass function to the formation of astrophysical objects. We consider three applications: early star formation, the most massive object at high redshift and the abundance of voids. Section 5 provides a discussion and summary of our results. We adopt throughout the best-fitting cosmological parameters taken from the 7-year *Wilkinson Microwave Anisotropy Probe* (WMAP) data.

## 2 TRISPECTRUM OF PRIMORDIAL NON-GAUSSIAN CURVATURE FLUCTUATIONS

Here, we focus on the local-type non-Gaussianity. Following the notation commonly used, in the single-sourced case, up to the third order, the primordial curvature fluctuations can be expressed as

$$\zeta = \zeta_{\text{G}} + \frac{3}{5} f_{\text{NL}} (\zeta_{\text{G}}^2 - \langle \zeta_{\text{G}}^2 \rangle) + \frac{9}{25} g_{\text{NL}} \zeta_{\text{G}}^3. \quad (2)$$

Based on this expression, the trispectrum of  $\zeta$  is given by

$$\langle \zeta(\mathbf{k}_1) \zeta(\mathbf{k}_2) \zeta(\mathbf{k}_3) \zeta(\mathbf{k}_4) \rangle = (2\pi)^3 T_{\zeta}(k_1, k_2, k_3, k_4) \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 + \mathbf{k}_4),$$

$$T_{\zeta}(k_1, k_2, k_3, k_4) = \tau_{\text{NL}} [P_{\zeta}(k_1) P_{\zeta}(k_2) P_{\zeta}(k_3) + 11 \text{ perms.}] + \frac{54}{25} g_{\text{NL}} [P_{\zeta}(k_1) P_{\zeta}(k_2) P_{\zeta}(k_3) + 3 \text{ perms.}], \quad (3)$$

where  $k_{13} = |\mathbf{k}_1 + \mathbf{k}_3|$  and  $P_{\zeta}(k_1)$  is a power spectrum of  $\zeta$  given by  $\langle \zeta(\mathbf{k}_1) \zeta(\mathbf{k}_2) \rangle = (2\pi)^3 P(k_1) \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2)$ . For the above definition of  $\tau_{\text{NL}}$  and the form of the non-linearity of the curvature perturbation (2),  $\tau_{\text{NL}}$  can be written in terms of the non-linearity parameter  $f_{\text{NL}}$  as

$$\tau_{\text{NL}} = \frac{36}{25} f_{\text{NL}}^2. \quad (4)$$

This consistency relation is satisfied only in the case where the primordial curvature fluctuations can be described by equation (2), namely the primordial curvature fluctuations are sourced only from the quantum fluctuations of a single scalar field, e.g. curvaton (Moroi & Takahashi 2001; Enqvist & Sloth 2002; Lyth & Wands 2002).

However, if there are multiple sources of the primordial curvature fluctuations, then the above consistency relation is not satisfied (Langlois & Vernizzi 2004; Ichikawa et al. 2008; Huang 2009; Byrnes & Choi 2010). In general, it has been known that there exists an inequality between the local type non-linearity parameters  $\tau_{\text{NL}}$  and  $f_{\text{NL}}$  given by (Suyama & Yamaguchi 2008; Suyama et al. 2010; Sugiyama et al. 2011)

$$\tau_{\text{NL}} > \frac{1}{2} \left( \frac{6}{5} f_{\text{NL}} \right)^2. \quad (5)$$

For example, let us consider the local-type non-Gaussianity given by

$$\zeta = \phi_{\text{G}} + \frac{3}{5} f_{\text{NL}} (\phi_{\text{G}}^2 - \langle \phi_{\text{G}}^2 \rangle) + t_{\text{NL}} \phi_{\text{G}} \psi_{\text{G}}, \quad (6)$$

where  $\phi_{\text{G}}$  and  $\psi_{\text{G}}$  are Gaussian fluctuations with  $\langle \phi_{\text{G}} \psi_{\text{G}} \rangle = 0$  and  $t_{\text{NL}}$  is a non-linearity parameter, which represents the non-linear coupling between  $\phi_{\text{G}}$  and  $\psi_{\text{G}}$  in  $\zeta_{\text{G}}$ . At leading order, the power spectrum of  $\zeta$  is given by that of the Gaussian part  $\phi_{\text{G}}$  as

$$\langle \zeta(\mathbf{k}) \zeta(\mathbf{k}') \rangle = \langle \phi_{\text{G}}(\mathbf{k}) \phi_{\text{G}}(\mathbf{k}') \rangle = (2\pi)^3 P_{\phi}(k) \delta^{(3)}(\mathbf{k} + \mathbf{k}'), \quad (7)$$

and the bispectrum is given only by  $f_{\text{NL}}$  as

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3) \rangle = (2\pi)^3 \frac{6}{5} f_{\text{NL}} [P_\phi(k_1)P_\phi(k_2) + 2 \text{ perms.}] \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3), \quad (8)$$

because of  $\langle \phi_G \psi_G \rangle = 0$ .

In the single-source case which corresponds to the case of  $t_{\text{NL}} = 0$ , as mentioned above, the trispectrum can be also parametrized only by  $f_{\text{NL}}$ . However, for the above type of curvature fluctuations, the trispectrum is given by

$$\begin{aligned} T_\zeta(k_1, k_2, k_3, k_4) = & \left( \frac{6}{5} f_{\text{NL}} \right)^2 [P_\phi(k_1)P_\phi(k_2)P_\phi(k_{13}) + 11 \text{ perms.}] \\ & + t_{\text{NL}}^2 (P_\phi(k_1)P_\phi(k_2)P_\psi(k_{13}) + P_\phi(k_1)P_\phi(k_2)P_\psi(k_{14}) + P_\phi(k_1)P_\phi(k_3)P_\psi(k_{12}) \\ & + P_\phi(k_1)P_\phi(k_3)P_\psi(k_{14}) + P_\phi(k_1)P_\phi(k_4)P_\psi(k_{12}) + P_\phi(k_1)P_\phi(k_4)P_\psi(k_{13}) \\ & + P_\phi(k_2)P_\phi(k_3)P_\psi(k_{12}) + P_\phi(k_2)P_\phi(k_3)P_\psi(k_{24}) + P_\phi(k_2)P_\phi(k_4)P_\psi(k_{12}) \\ & + P_\phi(k_2)P_\phi(k_4)P_\psi(k_{23}) + P_\phi(k_3)P_\phi(k_4)P_\psi(k_{13}) + P_\phi(k_3)P_\phi(k_4)P_\psi(k_{23})), \end{aligned} \quad (9)$$

where  $k_{13} = |\mathbf{k}_1 + \mathbf{k}_3|$ . We assume that the power spectra of random Gaussian fields  $\phi_G$  and  $\psi_G$  have only weak scale dependence, i.e. the power spectra are, respectively, given by

$$P_\phi(k) \equiv \frac{2\pi^2}{k^3} A_\phi \left( \frac{k}{k_0} \right)^{n_\phi - 1} \quad \text{and} \quad P_\psi(k) \equiv \frac{2\pi^2}{k^3} A_\psi \left( \frac{k}{k_0} \right)^{n_\psi - 1}, \quad (10)$$

where  $k_0$  is a pivot scale and  $|n_\phi - 1| \ll 1$  and  $|n_\psi - 1| \ll 1$ . In such a case, we can rewrite the power spectrum of  $\psi_G$  as

$$P_\psi(k) \simeq \alpha P_\phi(k), \quad \alpha \equiv A_\psi / A_\phi, \quad (11)$$

and then using the ratio of the amplitudes  $\alpha$ , the expression for the trispectrum can be reduced to

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4) \rangle \simeq (2\pi)^3 \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 + \mathbf{k}_4) \left( \frac{36}{25} f_{\text{NL}}^2 + \alpha t_{\text{NL}}^2 \right) [P_\phi(k_1)P_\phi(k_2)P_\phi(k_{13}) + 11 \text{ perms.}]. \quad (12)$$

From the above equation and equation (3), we easily find that the non-linearity parameter  $\tau_{\text{NL}}$  is

$$\tau_{\text{NL}} = \frac{36}{25} f_{\text{NL}}^2 + \alpha t_{\text{NL}}^2 \geq \frac{36}{25} f_{\text{NL}}^2. \quad (13)$$

Hence, in the following discussion, we consider  $\tau_{\text{NL}}$  independently of  $f_{\text{NL}}$ .

### 3 NON-GAUSSIAN MASS FUNCTION INDUCED FROM PRIMORDIAL NON-GAUSSIANITY

In the previous section, we have shown that there is a strong theoretical motivation for considering  $\tau_{\text{NL}}$  to be independent of  $f_{\text{NL}}$ . The parameter  $\tau_{\text{NL}}$  characterizes the amplitude of the trispectrum of primordial curvature fluctuations as well as  $g_{\text{NL}}$ . Here, we briefly review the formula for the halo mass function with not only the non-zero primordial bispectrum, but also the non-zero primordial trispectrum, based on Press–Schechter theory.

#### 3.1 Probability density function of the smoothed density field with primordial non-Gaussianity

The matter density linear fluctuations in Fourier space at redshift  $z$ ,  $\delta(\mathbf{k}, z)$ , are given by the primordial curvature perturbation on a uniform energy density hypersurface  $\zeta(\mathbf{k})$  as

$$\delta(\mathbf{k}, z) = \mathcal{M}(k) D(z) \zeta(\mathbf{k}), \quad (14)$$

$$\mathcal{M}(k) = \frac{2}{5} \frac{1}{\Omega_{\text{m}0}} \frac{k^2}{H_0^2} T(k), \quad (15)$$

where  $\Omega_{\text{m}0}$  is the present density parameter for total non-relativistic matter,  $H_0$  is the Hubble constant,  $D(z)$  is a linear growth function and  $T(k)$  is a transfer function. Using these expressions, we can obtain the linear matter power spectrum as

$$\langle \delta(\mathbf{k}, z) \delta(\mathbf{k}', z) \rangle \equiv (2\pi)^3 P_\delta(k, z) \delta^{(3)}(\mathbf{k} + \mathbf{k}'), \quad (16)$$

$$P_\delta(k, z) = \frac{2\pi^2}{k^3} \mathcal{M}(k)^2 D(z)^2 \mathcal{P}_\phi(k), \quad (17)$$

where  $\mathcal{P}_\phi(k) = k^3 P_\phi(k) / (2\pi^2)$ . Following the standard procedure, let us define the smoothed density fluctuation on a given length-scale,  $R$ , as

$$\delta_R = \int \frac{d^3 \mathbf{k}}{(2\pi)^3} W_R(k) \delta(\mathbf{k}, z), \quad (18)$$

where  $W_R(k)$  is the Fourier transform of a spherical top-hat window function given by

$$W_R(k) = 3 \left( \frac{\sin(kR)}{k^3 R^3} - \frac{\cos(kR)}{k^2 R^2} \right). \quad (19)$$

In order to take into account primordial non-Gaussianity in the smoothed density fluctuations, let us consider the PDF of  $\delta_R$ ,  $F(\delta_R)d\delta_R$ . The  $n$ th central moment for  $F(\delta_R)d\delta_R$  is defined as

$$\langle \delta_R^n \rangle \equiv \int_{-\infty}^{\infty} \delta_R^n F(\delta_R) d\delta_R, \quad (20)$$

and each reduced  $p$ th cumulant can be defined as

$$S_p(R) \equiv \frac{\langle \delta_R^p \rangle_c}{\langle \delta_R^2 \rangle_c^{p-1}}, \quad (21)$$

where a subscript  $c$  denotes the connected part of  $p$ -point function given by

$$\langle \delta_R \rangle_c = 0, \langle \delta_R^2 \rangle_c = \langle \delta_R^2 \rangle \equiv \sigma_R^2, \quad (22)$$

$$\langle \delta_R^3 \rangle_c = \langle \delta_R^3 \rangle, \langle \delta_R^4 \rangle_c = \langle \delta_R^4 \rangle - 3 \langle \delta_R^2 \rangle_c^2, \text{ etc.},$$

with zero mean density field. Here,  $\sigma_R^2$ ,  $S_3(R)$  and  $S_4(R)$  are the variance, the skewness and the kurtosis, respectively. Let us consider a non-Gaussian PDF of matter density fluctuations, based on the concept of the Edgeworth expansion. Here, we consider the expansion of the PDF of the density field  $F(v)dv$  with  $v \equiv \delta_R/\sigma_R$  in terms of the derivatives of the Gaussian PDF,  $F_G(v)$ , as (Juszkiewicz et al. 1995; LoVerde et al. 2008)

$$F(v)dv = dv \left[ c_0 F_G(v) + \sum_{m=1}^{\infty} \frac{c_m}{m!} F_G^{(m)}(v) \right], \quad (23)$$

with

$$F_G(v) \equiv (2\pi)^{-1/2} \exp(-v^2/2), \quad (24)$$

$$F_G^{(m)}(v) \equiv \frac{d^m}{dv^m} F_G(v) = (-1)^m H_m(v) F_G(v), \quad (25)$$

where  $H_m(v)$  is the Hermite polynomials:

$$H_1(v) = v, H_2(v) = v^2 - 1, H_3(v) = v^3 - 3v, \quad (26)$$

$$H_4(v) = v^4 - 6v^2 + 3, H_5(v) = v^5 - 10v^3 + 15v, \dots$$

From the above relation between the derivatives of the Gaussian PDF and the Hermite polynomials, we can regard expression (23) as a non-Gaussian PDF expanded in terms of the Hermite polynomials. Since the Hermite polynomials satisfy orthogonal relations,

$$\int_{-\infty}^{\infty} H_m(v) H_n(v) F_G(v) dv = \begin{cases} 0, & \text{if } m \neq n, \\ m!, & \text{if } m = n, \end{cases} \quad (27)$$

we can evaluate the coefficients as

$$c_m = (-1)^m \int_{-\infty}^{\infty} H_m(v) F(v) dv. \quad (28)$$

Then, we can obtain the expressions for the coefficients,  $c_m$ , in terms of the reduced cumulants (variance, skewness, kurtosis and so on) as

$$c_0 = 1, c_1 = c_2 = 0, c_3 = -S_3(R)\sigma_R, c_4 = S_4(R)\sigma_R^2, \quad (29)$$

$$c_5 = -S_5(R)\sigma_R^3, c_6 = 10S_3(R)^2\sigma_R^2 + S_6(R)\sigma_R^4, \dots,$$

and, as a result, the non-Gaussian PDF of the density field,  $F(v)dv$ , can be obtained as

$$F(v)dv = \frac{dv}{\sqrt{2\pi}} \exp(-v^2/2) \left[ 1 + \frac{S_3(R)\sigma_R}{6} H_3(v) + \frac{1}{2} \left( \frac{S_3(R)\sigma_R}{6} \right)^2 H_6(v) + \frac{1}{6} \left( \frac{S_3(R)\sigma_R}{6} \right)^3 H_9(v) \right. \\ \left. + \frac{S_4(R)\sigma_R^2}{24} H_4(v) + \frac{1}{2} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^2 H_8(v) + \frac{1}{6} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^3 H_{12}(v) + \dots \right], \quad (30)$$

up to the third-order terms in  $S_3(R)$  and  $S_4(R)$ , and neglect the contributions of the higher order cumulants:  $S_n(R)$  ( $n \geq 5$ ). This derivation of the non-Gaussian PDF is based on the so-called Edgeworth expansion. Of course, the non-zero non-linearity parameters  $f_{\text{NL}}$ ,  $\tau_{\text{NL}}$  and  $g_{\text{NL}}$  also generate non-zero higher order cumulants:  $S_n(R)$  ( $n \geq 5$ ). However, as far as considering the non-Gaussian curvature fluctuations given by equation (6) and current observational constraints on the non-linearity parameters (Fergusson, Regan & Shellard 2010; Komatsu et al. 2011), terms  $S_n(R)$  ( $n \geq 5$ ) are greatly suppressed (Enqvist et al. 2011). Hence, the assumption of neglecting the higher order cumulants seems to be reasonable.

### 3.2 Halo mass function with non-Gaussian corrections

Let us consider the halo mass function with non-Gaussian PDF of the smoothed density field as given in the previous subsection. Based on the spirit of the Press–Schechter formula, the halo mass function which gives the number density of collapsed structures (haloes) with the

mass between  $M$  ( $= 4\pi\bar{\rho}R^3/3$ , with  $\bar{\rho}$  the background matter density) and  $M + dM$  at a redshift  $z$ ,  $[dn(M, z)/dM]dM$  is given by (D'Amico et al. 2011)

$$\begin{aligned}
 \frac{dn}{dM}(M, z)dM &= -dM \frac{2\bar{\rho}}{M} \frac{d}{dM} \int_{\delta_c/\sigma_R}^{\infty} d\nu F(\nu) \\
 &= -dM \sqrt{\frac{2}{\pi}} \frac{\bar{\rho}}{M} \exp\left[-\frac{\nu_c^2}{2}\right] \left\{ \frac{d \ln \sigma_R}{dM} \nu_c \left[ 1 \right. \right. \\
 &\quad + \frac{S_3(R)\sigma_R}{6} H_3(\nu_c) + \frac{1}{2} \left( \frac{S_3(R)\sigma_R}{6} \right)^2 H_6(\nu_c) + \frac{1}{6} \left( \frac{S_3(R)\sigma_R}{6} \right)^3 H_9(\nu_c) \\
 &\quad \left. \left. + \frac{S_4(R)\sigma_R^2}{24} H_4(\nu_c) + \frac{1}{2} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^2 H_8(\nu_c) + \frac{1}{6} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^3 H_{12}(\nu_c) \right] \right. \\
 &\quad + \frac{d}{dM} \left( \frac{S_3(R)\sigma_R}{6} \right) H_2(\nu_c) + \frac{1}{2} \frac{d}{dM} \left( \frac{S_3(R)\sigma_R}{6} \right)^2 H_5(\nu_c) + \frac{1}{6} \frac{d}{dM} \left( \frac{S_3(R)\sigma_R}{6} \right)^3 H_8(\nu_c) \\
 &\quad \left. \left. + \frac{d}{dM} \left( \frac{S_4(R)\sigma_R^2}{24} \right) H_3(\nu_c) + \frac{1}{2} \frac{d}{dM} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^2 H_7(\nu_c) + \frac{1}{6} \frac{d}{dM} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^3 H_{11}(\nu_c) \right\} + \dots, \tag{31}
 \end{aligned}$$

where  $\nu_c = \delta_c/\sigma_R$  and  $\delta_c$  denotes the threshold for collapse which is originally given by  $\delta_c \approx 1.69$ . However, in Grossi et al. (2009), the authors have suggested that using the correction  $\delta_c \rightarrow \delta_c \sqrt{q}$  with  $q = 0.75$  puts the analytic predictions in good agreement with the numerical simulations. This is due to the more realistic case of ellipsoidal collapse. Hence,  $\delta_c = 1.69 \times \sqrt{q}$  is often referred to as the critical density of ellipsoidal collapse. Here we adopt this corrected density threshold  $\delta_c = 1.69 \times \sqrt{0.75}$ . In the following calculations, we use the above formula of the non-Gaussian mass functions up to the third order in terms of  $S_3$  and  $S_4$ .

For a Gaussian probability distribution, the mass function is given by

$$\frac{dn_G}{dM}(M, z)dM = -\sqrt{\frac{2}{\pi}} \frac{\bar{\rho}}{M} \exp\left[-\frac{\nu_c^2}{2}\right] \frac{d \ln \sigma_R}{dM} \nu_c dM, \tag{32}$$

and we define the ratio between the non-Gaussian mass function and the Gaussian one as<sup>1</sup>

$$\mathcal{R}_{\text{NG}}(M, z) \equiv \frac{dn(M, z)/dM}{dn_G(M, z)/dM}. \tag{34}$$

Let us focus on the redshift dependence of the above expression. From the definition of the reduced cumulants (21) and the fact that the redshift dependence of the density field is given by  $\delta_R \propto D(z)$ , we can easily find that  $\sigma^{p-2} S_p(R)$  has no redshift dependence. Hence, any remaining redshift dependence comes only from the term  $\frac{\delta_c}{\sigma_R}$ . Here, following the literature, the redshift dependence can be carried by  $\delta_c$  as  $\delta_c \rightarrow \delta_c(z) \propto D(z)^{-1}$  and then the variance  $\sigma_R$  has no redshift dependence. In the following discussion, we change the subscript  $R$  to  $M$  because  $R$  and  $M$  have a one-to-one correspondence through the equation  $M = 4\pi R^3 \bar{\rho}/3$ .

### 3.2.1 Variance, skewness and kurtosis

Let us consider the concrete expressions of the variance, skewness and kurtosis of the primordial curvature perturbations whose power-, bi- and tri-spectra are given by equations (7), (8) and (3), respectively. The variance is given by

$$\sigma_R^2 = \int \frac{dk}{k} W_R^2(k) \mathcal{M}(k)^2 \mathcal{P}_\phi(k), \tag{35}$$

<sup>1</sup> In Enqvist et al. (2011), Matarrese et al. (2000) and Verde et al. (2001), the authors introduced the MVJ convention for defining the ratio given by

$$\begin{aligned}
 \mathcal{R}_{\text{NG}}^{\text{MVJ}}(M, z) &= \exp\left[ \nu_c^3 \frac{S_3(R)\sigma_R}{6} + \nu_c^4 \frac{S_4(R)\sigma_R^2}{24} \right] \times \left[ \delta_3 + \frac{\nu_c}{\delta_3} \left( -\frac{S_3(R)\sigma_R}{6} \right) + \left( \frac{d \ln \sigma_R}{dM} \right)^{-1} \frac{d}{dM} \left( \frac{S_3(R)\sigma_R}{6} \right) \right] \\
 &\quad \times \left[ \delta_4 + \frac{\nu_c^2}{\delta_4} \left( -\frac{S_4(R)\sigma_R^2}{12} \right) + \left( \frac{d \ln \sigma_R}{dM} \right)^{-1} \frac{d}{dM} \left( \frac{S_4(R)\sigma_R^2}{24} \right) \right], \\
 \delta_3 &\equiv \left( 1 - \nu_c \frac{S_3(R)\sigma_R}{3} \right)^{1/2}, \quad \delta_4 \equiv \left( 1 - \nu_c^2 \frac{S_4(R)\sigma_R^2}{12} \right)^{1/2}, \tag{33}
 \end{aligned}$$

which is not based on the Edgeworth expansion. In our calculation, we have also checked the consistency between the above MVJ expression and equation (34). This issue is discussed in Appendix A.

the skewness is (Chongchitnan & Silk 2010)

$$S_3(R) \equiv \frac{6}{5} \frac{f_{\text{NL}}}{\sigma_R^4} \tilde{S}_3(R),$$

$$\tilde{S}_3(R) = \int \frac{dk_1}{k_1} W_R(k_1) \mathcal{M}(k_1) \mathcal{P}_\phi(k_1) \int \frac{dk_2}{k_2} W_R(k_2) \mathcal{M}(k_2) \mathcal{P}_\phi(k_2) \times \int \frac{d\mu_{12}}{2} W_R(k_{12}) \mathcal{M}(k_{12}) \left[ 1 + \frac{P_\phi(k_{12})}{P_\phi(k_1)} + \frac{P_\phi(k_{12})}{P_\phi(k_2)} \right], \quad (36)$$

where  $k_{12} = \sqrt{k_1^2 + k_2^2 + 2k_1k_2\mu_{12}}$  and  $\mu_{12} = \cos \theta_{12}$ , and the kurtosis which is proportional to the non-linearity parameter  $\tau_{\text{NL}}$  is given by  $S_4^r(R) \equiv \frac{\tau_{\text{NL}}}{\sigma_R^6} \tilde{S}_4^r(R)$ ,

$$\tilde{S}_4^r(R) = \int \frac{dk_1}{k_1} W_R(k_1) \mathcal{M}(k_1) \mathcal{P}_\phi(k_1) \int \frac{dk_2}{k_2} W_R(k_2) \mathcal{M}(k_2) \mathcal{P}_\phi(k_2) \int \frac{dk_3}{k_3} W_R(k_3) \mathcal{M}(k_3) \mathcal{P}_\phi(k_3) \times \int_{-1}^1 \frac{d\mu_{12}}{2} \int_{-1}^1 \frac{d\mu_{13}}{2} \int_0^{2\pi} \frac{d\varphi_{13}}{2\pi} W_R(k_{123}) \mathcal{M}(k_{123}) \times \left\{ P_\phi(k_{12}) \left[ \frac{1}{P_\phi(k_1)} + \frac{1}{P_\phi(k_2)} \right] \left[ 1 + \frac{P_\phi(k_{123})}{P_\phi(k_3)} \right] + P_\phi(k_{23}) \left[ \frac{1}{P_\phi(k_2)} + \frac{1}{P_\phi(k_3)} \right] \left[ 1 + \frac{P_\phi(k_{123})}{P_\phi(k_1)} \right] + P_\phi(k_{31}) \left[ \frac{1}{P_\phi(k_3)} + \frac{1}{P_\phi(k_1)} \right] \left[ 1 + \frac{P_\phi(k_{123})}{P_\phi(k_2)} \right] \right\}. \quad (37)$$

Here, we have fixed the three vectors,  $\mathbf{k}_1$ ,  $\mathbf{k}_2$  and  $\mathbf{k}_3$  that appear in the expression of the trispectrum, as shown in Fig. 1. Hence, using the angular variables,  $\theta_{12}$ ,  $\theta_{13}$  and  $\varphi_{13}$ , we have

$$k_{12} = \sqrt{k_1^2 + k_2^2 + 2k_1k_2\mu_{12}},$$

$$k_{23} = \sqrt{k_2^2 + k_3^2 + 2k_2k_3 \left( \sqrt{(1-\mu_{12}^2)(1-\mu_{13}^2)} \cos \varphi_{13} + \mu_{12}\mu_{13} \right)},$$

$$k_{13} = \sqrt{k_1^2 + k_3^2 + 2k_1k_3\mu_{13}}, \quad (38)$$

and

$$k_{123} = \sqrt{k_1^2 + k_2^2 + k_3^2 + 2k_1k_2\mu_{12} + 2k_1k_3\mu_{13} + 2k_2k_3 \left( \sqrt{(1-\mu_{12}^2)(1-\mu_{13}^2)} \cos \varphi_{13} + \mu_{12}\mu_{13} \right)}, \quad (39)$$

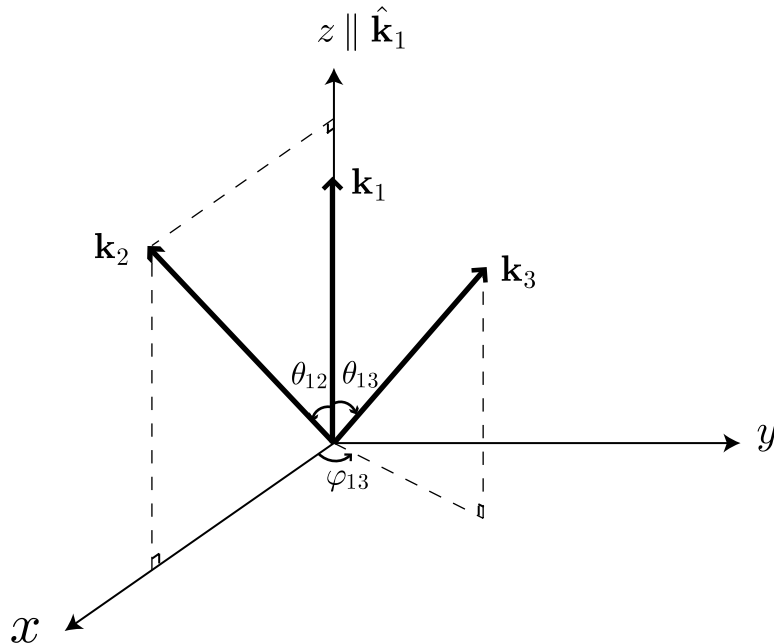


Figure 1. The three vectors,  $\mathbf{k}_1$ ,  $\mathbf{k}_2$  and  $\mathbf{k}_3$  in the trispectrum.

where  $\mu_{ij} \equiv \cos \theta_{ij}$ . In order to calculate the skewness more easily, let us consider the squeezed limit in momentum space, e.g.  $k_1 \ll k_2 \simeq k_3$ . In this limit, the equation for the skewness (36) can be reduced to

$$\tilde{S}_3 \Big|_{k_1 \ll k_2 \simeq k_3} \simeq 2\sigma_R^2 \int \frac{dk_1}{k_1} W_R(k_1) \mathcal{M}(k_1) \mathcal{P}_\phi(k_1), \quad (40)$$

and by considering other limiting cases, i.e.  $k_2 \rightarrow 0$  and  $k_3 \rightarrow 0$ , we obtain

$$\tilde{S}_3 \simeq 6\sigma_R^2 \int \frac{dk}{k} W_R(k) \mathcal{M}(k) \mathcal{P}_\phi(k). \quad (41)$$

Based on the above approximate expression, we find a simple formula:

$$\sigma_R S_3(R) = 4.3 \times 10^{-4} f_{\text{NL}} \times \sigma_R^{0.13} (10^{12} h^{-1} M_\odot < M < 2 \times 10^{15} h^{-1} M_\odot). \quad (42)$$

This result seems to be close to those given in De Simone et al. (2011) and Enqvist et al. (2011).<sup>2</sup> Hence, we adopt the above expression in the following discussion. In a similar way, from the expression of the kurtosis (37), we can easily find that the kurtosis induced from the non-linearity parameter  $\tau_{\text{NL}}$  becomes largest in the limit of  $k_i \rightarrow 0$  ( $i = 1, 2, 3, 4$ ) or  $k_{ij} \rightarrow 0$  ( $i \neq j = 1, 2, 3, 4$ ) (local type). Then, we have an approximate expression

$$\tilde{S}_4^r(R) \simeq 8 \int \frac{dk}{k} W_R(k) \mathcal{M}(k) \mathcal{P}_\phi(k) \times \tilde{S}_3(R) + 12A_\phi \sigma_R^4. \quad (43)$$

On the other hand, in the squeezed limit  $k_i \rightarrow 0$  ( $i = 1, 2, 3, 4$ ), the kurtosis which is proportional to the non-linearity parameter  $g_{\text{NL}}$  can be also reduced to (Chongchitnan & Silk 2010; Enqvist et al. 2011)

$$S_4^g \equiv \frac{54}{25} \frac{g_{\text{NL}}}{\sigma_R^6} \tilde{S}_4^g, \quad (44)$$

$$\tilde{S}_4^g \simeq 2 \int \frac{dk}{k} W_R(k) \mathcal{M}(k) \mathcal{P}_\phi(k) \times \tilde{S}_3(R).$$

From these approximate expressions, we, respectively, obtain simple formulae for the kurtosis in the form

$$\sigma_R^2 S_4^r(R) = 1.9 \times 10^{-7} \tau_{\text{NL}} \times \sigma_R^{0.25} (10^{12} h^{-1} M_\odot < M < 2 \times 10^{15} h^{-1} M_\odot),$$

$$\sigma_R^2 S_4^g(R) = 9.4 \times 10^{-8} g_{\text{NL}} \times \sigma_R^{0.27} (10^{12} h^{-1} M_\odot < M < 2 \times 10^{15} h^{-1} M_\odot). \quad (45)$$

The result for  $S_4^g(R)$  is also close to that obtained in Enqvist et al. (2011).<sup>3</sup> Hence in the following discussion, we also adopt the above expressions for the kurtosis as well as for the skewness.

### 3.2.2 Difference between the Gaussian and the non-Gaussian mass functions

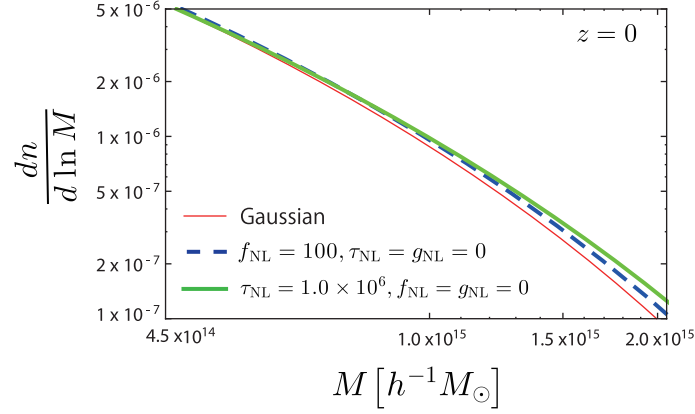
Based on the above calculations for the variance,  $\sigma_R^2$ , the skewness,  $S_3$ , and also the kurtosis,  $S_4$ , the mass function can now be calculated. In the following discussion, we take values of the non-linearity parameters as  $f_{\text{NL}} = 100$ ,  $\tau_{\text{NL}} = 10^6$  and  $g_{\text{NL}} = 0$ . This value of  $\tau_{\text{NL}}$  may be inconsistent with the observational constraint obtained by Smidt et al. (2010) as  $-0.6 < \tau_{\text{NL}}/10^4 < 3.3$  at 95 per cent confidence level. However, there might be a caveat since in Fergusson et al. (2010), the authors have claimed that the approach in Smidt et al. does not directly subtract the effect of anisotropic noise and other systematic effects which are important in obtaining an accurate and optimized result. None the less, in order to emphasize the differences between the Gaussian mass functions and the non-Gaussian mass functions with the non-zero  $f_{\text{NL}}$  and the non-zero  $\tau_{\text{NL}}$  cases, we take the above values.

In Fig. 2, we show that the mass function in the mass range between  $5.0 \times 10^{14}$  and  $2.0 \times 10^{15} h^{-1} M_\odot$  at the redshift  $z = 0$ . The red thin line shows the mass function with the Gaussian density fluctuations given by equation (32). The blue dashed and green thick lines show the non-Gaussian mass function given by equation (31) in the cases with  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$  and  $\tau_{\text{NL}} = 10^6$  and  $f_{\text{NL}} = g_{\text{NL}} = 0$ , respectively. From this figure, it is rather difficult to see the differences between the Gaussian and the non-Gaussian mass functions. In Fig. 3, we show the ratios between the Gaussian and the non-Gaussian mass functions defined by equation (34). The red dashed line shows  $\mathcal{R}_{\text{NG}}(M, 0)$  with  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$ , and the blue solid line shows the same with  $f_{\text{NL}} = g_{\text{NL}} = 0$  and  $\tau_{\text{NL}} = 10^6$ . The magenta dotted line is for the case with  $\tau_{\text{NL}} = g_{\text{NL}} = 0$  and  $f_{\text{NL}} = 30$ , which is corresponding to the mean value of the current *WMAP* data (Komatsu et al. 2011). The black dot-dashed line is for the case with  $f_{\text{NL}} = g_{\text{NL}} = 0$  and  $\tau_{\text{NL}} = 10^4$ , which is consistent with the maximum allowed value obtained by Smidt et al. (2010). From this figure, we infer that for both types of primordial non-Gaussianity, i.e. positive skewness and kurtosis, the mass functions can be systematically enhanced for more massive objects, as compared with the Gaussian case. The enhancement of the mass functions depends on the values of  $\tau_{\text{NL}}$  and  $g_{\text{NL}}$ . We find that for the cases with  $f_{\text{NL}} = 30$  and  $\tau_{\text{NL}} = 10^4$ , the  $\mathcal{R}_{\text{NG}}$  values are, respectively, 1.06 and 1.01 for  $M = 2 \times 10^{15} h^{-1} M_\odot$ . Hence, in both cases, the effects of the primordial non-Gaussianity on the mass functions seem to be too small to detect. We also find that the enhancement of the non-Gaussian mass function with the non-zero kurtosis

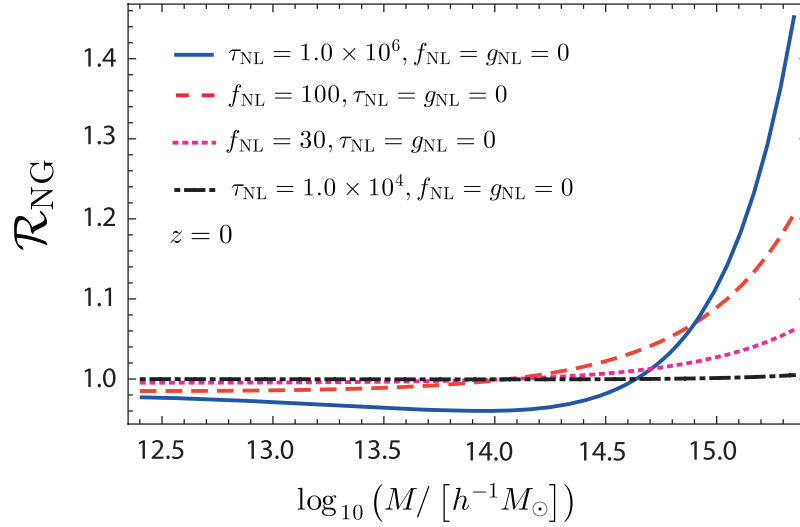
<sup>2</sup> As mentioned in Ref. (Enqvist et al. 2011), this result is different from that in the published version of Chongchitnan & Silk (2010). However, the authors in Chongchitnan & Silk (2010) have corrected the result in the arXiv version, and their new derivation is now close to our result (42).

<sup>3</sup> In addition to the expression derived for the skewness, the result for kurtosis in Chongchitnan & Silk (2010) has been corrected in the arXiv version, and this is also close to our result (45).





**Figure 2.** The mass function with the mass range between  $4.5 \times 10^{14}$  and  $2.0 \times 10^{15} h^{-1} M_{\odot}$  at the redshift  $z = 0$ . The red thin line shows the mass function with the Gaussian density fluctuations given by equation (32). The blue dashed and green thick lines show the non-Gaussian mass function given by equation (31) in the case with  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$  and the case with  $\tau_{\text{NL}} = 10^6$  and  $f_{\text{NL}} = g_{\text{NL}} = 0$ , respectively.

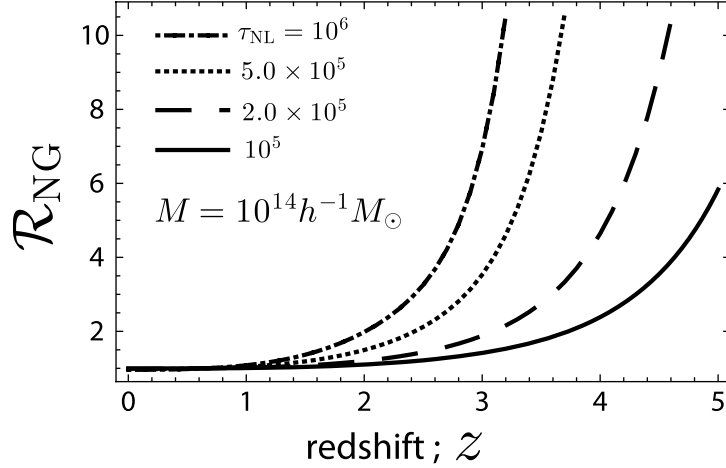


**Figure 3.** The ratio between the Gaussian and the non-Gaussian mass functions. The red dashed line shows  $\mathcal{R}_{\text{NG}}(M, 0)$  with  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$ , and the blue solid line shows the same with  $f_{\text{NL}} = g_{\text{NL}} = 0$  and  $\tau_{\text{NL}} = 10^6$ . The magenta dotted line is for the case with  $\tau_{\text{NL}} = g_{\text{NL}} = 0$  and  $f_{\text{NL}} = 30$  which is corresponding to the mean value of the current *WMAP* data (Komatsu et al. 2011). The black dot-dashed line is for the case with  $f_{\text{NL}} = g_{\text{NL}} = 0$  and  $\tau_{\text{NL}} = 10^4$ , which is consistent with the maximum allowed value obtained by Smidt et al. (2010).

type of primordial non-Gaussianity, i.e. non-zero  $\tau_{\text{NL}}$ , depends more strongly on the mass of the collapsed objects than the case with the non-zero skewness type of primordial non-Gaussianity. This is because in the expression for the non-Gaussian mass function (31), the  $\delta_c/\sigma_R$  dependence of the term related with the kurtosis  $S_4$  is stronger than that of the term related with the skewness  $S_3$ , namely  $S_4$ -term  $\propto (\delta_c/\sigma_R)^5$  and  $S_3$ -term  $\propto (\delta_c/\sigma_R)^4$ . As the collapsed objects become more massive, the variance  $\sigma_R$  becomes smaller and hence  $\delta_c/\sigma_R$  becomes larger. Thus, if we would detect the enhancement of the mass function for massive collapsed objects and find its scale dependence, then we might distinguish the kurtosis type of primordial non-Gaussianity from the skewness type. In Fig. 4, we show the redshift dependence of the ratio between the non-Gaussian mass function and the Gaussian mass function as we change the value of  $\tau_{\text{NL}}$ . Here we have fixed the mass of the halo as  $M = 10^{14} h^{-1} M_{\odot}$ . The solid line is for the case with  $\tau_{\text{NL}} = 10^5$ , the dashed line for  $2.0 \times 10^5$ , the dotted line for  $5.0 \times 10^5$  and the dot-dashed line for  $10^6$ . From this figure, we find that at higher redshift, the enhancement of the mass function for massive collapsed objects increases. This is because the critical density  $\delta_c(z) = \delta_c D(z)$  becomes much larger at larger redshifts due to the smaller linear growth function  $D(z)$ . Hence, in order to observationally test the kurtosis type of primordial non-Gaussianity, it will be useful to observe high-redshift rare objects.

#### 4 APPLICATIONS

In this section, we consider applications of the mass function with both skewness and kurtosis types of primordial non-Gaussianity. Here, we also take values of the non-linearity parameters to be  $f_{\text{NL}} = 100$ ,  $\tau_{\text{NL}} = 10^6$  and  $g_{\text{NL}} = 0$ .



**Figure 4.** The redshift dependence of the ratio between the non-Gaussian mass function and the Gaussian mass function with changing the value of  $\tau_{\text{NL}}$ . Here we have fixed the mass of halo as  $M = 10^{14} h^{-1} M_{\odot}$ . The solid line is for the case with  $\tau_{\text{NL}} = 10^5$ , dashed line for  $2.0 \times 10^5$ , dotted line for  $5.0 \times 10^5$  and dot-dashed line for  $10^6$ .

#### 4.1 Early star formation

Let us first investigate the effect of primordial non-Gaussianity on the epoch of reionization. As is well known, in order to understand the mechanism of reionization, it is important to estimate the number of photons from Population III (Pop III) stars. Following Somerville & Livio (2003), Somerville, Bullock & Livio (2003) and Sugiyama, Zaroubi & Silk (2004), the global star formation rate density denoted by  $\dot{\rho}_*$  can be written as

$$\dot{\rho}_* = e_* \rho_b \frac{d}{dt} F_h(M_{\text{vir}} > M > M_{\text{crit}}, t). \quad (46)$$

Here,  $\rho_b$  is the background baryon number density and  $e_*$  denotes the star formation efficiency usually taken to be 0.002 for  $200 M_{\odot}$  Pop III stars and 0.001 for  $100 M_{\odot}$ .  $F_h(M_{\text{vir}} > M > M_{\text{crit}}, t)$  represents the fraction of the total mass in collapsed objects (haloes) with masses greater than the minimum collapse mass scale  $M_{\text{crit}} = 10^6 h^{-1} M_{\odot}$  (Fuller & Couchman 2000; Yoshida et al. 2003) and lower than the virial mass  $M_{\text{vir}} = M(T_{\text{vir}} = 10^4 \text{ K})$ .

The relation between the mass and the virial temperature is given by (Barkana & Loeb 2001; Yoshida et al. 2003)

$$T_{\text{vir}} = 4.7 \times 10^3 \left( \frac{\mu}{0.6} \right) \left( \frac{M}{10^8 h^{-1} M_{\odot}} \right)^{2/3} \left( \frac{\Omega_{\text{m}0}}{0.24} \frac{\Delta_c(z)}{18\pi^2} \right)^{1/3} \left( \frac{1+z}{10} \right) \text{K}, \quad (47)$$

where  $\mu$  is the mean molecular weight and  $\Delta_c(z)$  is the final overdensity relative to the critical density, which is given by a fitting formula (Bryan & Norman 1998):

$$\Delta_c = 18\pi^2 + 82 [\Omega_{\text{m}}(z) - 1] - 39 [\Omega_{\text{m}}(z) - 1]^2, \quad (48)$$

where  $\Omega_{\text{m}}(z)$  is the density parameter of matter at redshift  $z$ :

$$\Omega_{\text{m}}(z) = \frac{\Omega_{\text{m}0}(1+z)^3}{\Omega_{\text{m}0}(1+z)^3 + \Omega_{\Lambda}}. \quad (49)$$

Assuming that the photon number production rate per  $M_{\odot}$  from Pop III stars is  $N_{\gamma} = 1.6 \times 10^{48} \text{ s}^{-1} M_{\odot}^{-1}$  and that the lifetime of Pop. III star is  $\tau_{\text{III}} = 3.0 \times 10^6 \text{ yr}$ , we can obtain the total production rate of ionizing photons at time  $t$  as

$$\frac{dn_{\gamma}}{dt}(t) = e_* \rho_b N_{\gamma} [F_h(t) - F_h(t - \tau_{\text{III}})]; \quad (50)$$

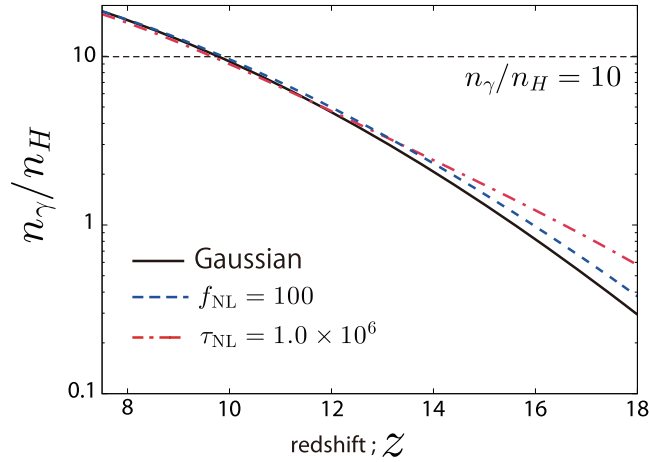
hence, the cumulative number of photons per H atom is

$$\frac{n_{\gamma}}{n_{\text{H}}}(z) \simeq \mu m_{\text{p}} e_* N_{\gamma} F_h(M_{\text{vir}} > M > M_{\text{crit}}, z) \tau_{\text{III}}, \quad (51)$$

with  $m_{\text{p}}$  the proton mass and  $n_{\text{H}}$  the hydrogen number density. In the above expression,  $F_h(M_{\text{vir}} > M > M_{\text{crit}}, z)$  is given by Press–Schechter theory as

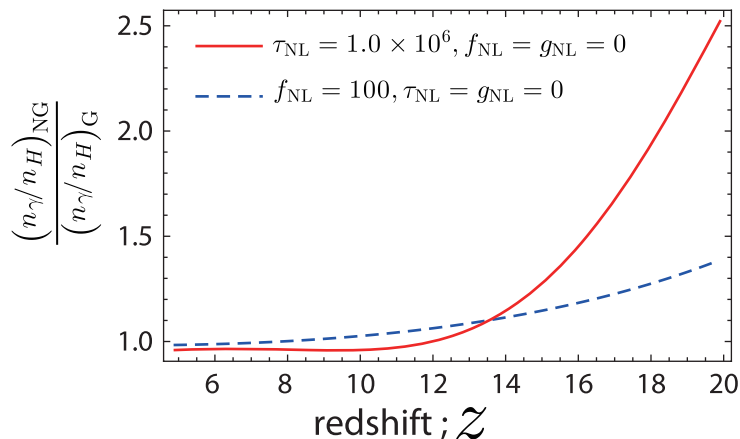
$$F_h(M_{\text{vir}} > M > M_{\text{crit}}, z) = \frac{1}{\bar{\rho}} \int_{M_{\text{crit}}}^{M_{\text{vir}}} M \frac{dn}{dM}(M, z) dM. \quad (52)$$

Substituting our expression (31) for the non-Gaussian mass function into the above equation, we can estimate the effect of primordial non-Gaussianity on the number of photons emitted from Pop III stars, which is one of the most important quantities during the epoch of reionization. In Fig. 5, we show the cumulative photon number per H atom given by equation (51) as a function of the redshift for



**Figure 5.** Cumulative photon number per H atom as a function of the redshift for  $8 < z < 18$ . The black solid line shows  $n_\gamma/n_H(z)$  for the case with the Gaussian fluctuations. The blue dashed line is for the case with the non-Gaussian fluctuations:  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$ . The red dot-dashed line is for the case with  $\tau_{\text{NL}} = 1.0 \times 10^6$  and  $f_{\text{NL}} = g_{\text{NL}} = 0$ . The thin black dashed line corresponds to  $n_\gamma/n_H = 10$  as a guide of the complete reionization on average.

$8 < z < 18$ . The black solid line shows  $n_\gamma/n_H(z)$  for the case with the Gaussian fluctuations, the blue dashed line is for the case with the non-Gaussian fluctuations,  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$ , and the red dot-dashed line is for the case with  $\tau_{\text{NL}} = 1.0 \times 10^6$  and  $f_{\text{NL}} = g_{\text{NL}} = 0$ . The thin black dashed line corresponds to  $n_\gamma/n_H = 10$  as a guide of the complete reionization on average. From this figure, we find that primordial non-Gaussianity seems not to affect the reionization history of the Universe on average which is characterized by the value of  $n_\gamma/n_H = 10$ . However, at higher redshift, the effect of primordial non-Gaussianity seems to be significant on the cumulative photon number density. We evaluate this effect in Fig. 6, where we plot the ratio between  $n_\gamma/n_H(z)$  in the pure Gaussian primordial fluctuation case and that in the non-Gaussian case. The blue dashed line is for the case with  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$  and the red solid line for the case with  $\tau_{\text{NL}} = 1.0 \times 10^6$  and  $f_{\text{NL}} = g_{\text{NL}} = 0$ . From this figure, we find that compared to the Gaussian case, the cumulative number of photons in the non-Gaussian case is larger at higher redshifts both in the non-zero  $S_3$  and the non-zero  $S_4$  cases. Moreover, as we have mentioned in the previous section, the kurtosis type of primordial non-Gaussianity affects the enhancement of the photon number density more significantly at high redshift. That is, there seems to be the possibility of dramatically changing the history of the early stage of reionization due to the kurtosis type of primordial non-Gaussianity even for values in the range of the current limits obtained from CMB observations. Of course, the above rough estimate is not precise enough to enable us to estimate the exact cumulative number of the ionizing photons. However, we consider here that, in view of the completely ad hoc nature of the amount of non-Gaussianity due to the absence of a compelling inflationary model, it suffices for us to focus on the deviation of the photon number based on the non-Gaussian mass function from that based on the Gaussian mass function.



**Figure 6.** We plot the ratio between  $n_\gamma(z)/n_H$  in the pure Gaussian primordial fluctuation case and that in the non-Gaussian case for  $5 < z < 20$ . The blue dashed line is for the case with  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$ , and the red solid line is for the case with  $\tau_{\text{NL}} = 1.0 \times 10^6$  and  $f_{\text{NL}} = g_{\text{NL}} = 0$ .

## 4.2 High-redshift massive clusters

Recently, the authors in Jee et al. (2009) and Rosati et al. (2009) have presented a weak lensing analysis of the galaxy cluster XMMU J2235.3–2557 which has a high redshift  $z \approx 1.4$  and whose mass is  $M_{324} = (6.4 \pm 1.2) \times 10^{14} M_{\odot}$ .<sup>4</sup> In  $\Lambda$  cold dark matter ( $\Lambda$ CDM) model, the formation of such a massive cluster at this redshift would be a rare event (at least  $3\sigma$ ).

In Cayon, Gordon & Silk (2011), the authors have considered the effects of primordial non-Gaussianity parametrized by the non-linearity parameter  $f_{\text{NL}}$ , which they found to be  $f_{\text{NL}} = 449 \pm 286$  at wavenumber of about  $0.4 \text{ Mpc}^{-1}$  in order to explain the existence of such a massive cluster at high redshift. Considering scale-invariant  $f_{\text{NL}}$ , this result contradicts the current CMB observational constraint  $f_{\text{NL}} < 100$ . Therefore, the authors remarked that one would need to invoke scale-dependent  $f_{\text{NL}}$ . In Enqvist et al. (2011), the authors have considered non-zero  $g_{\text{NL}}$  case and found that  $g_{\text{NL}} = O(10^6)$  could explain the existence of high-redshift massive clusters.

Here, instead of considering the scale dependence of  $f_{\text{NL}}$  or  $g_{\text{NL}}$ , let us consider the effect of the kurtosis induced from the  $\tau_{\text{NL}}$ -type primordial non-Gaussianity on the formation of massive clusters. Of course, for a more detailed analysis we need to calculate the probability of the massive clusters under the procedure done in Cayon et al. (2011). However, in order to give a naive estimation of the value of  $\tau_{\text{NL}}$  which can explain the existence of the massive cluster XMMU J2235.3–2557, we investigate the value of  $\tau_{\text{NL}}$ , which gives the same value as the non-Gaussian mass function does, namely  $\mathcal{R}_{\text{NG}}$  defined as equation (34), including the effect of kurtosis  $S_4$  on the corresponding scale at the corresponding redshift by including the effect of  $f_{\text{NL}}$ , i.e. skewness. Here, we adopt  $M_{\text{XMMU}} = 6.4 \times 10^{14} M_{\odot}$  and  $z_{\text{XMMU}} = 1.4$  as the mass and the redshift of the massive cluster XMMU J2235.3–255, respectively. For the value of  $f_{\text{NL}}$ , the best-fitting value derived in Cayon et al. (2011) is adopted. For these parameters, we also find that this value can be realized in the case with  $f_{\text{NL}} = g_{\text{NL}} = 0$  and  $\tau_{\text{NL}} = 1.7 \times 10^6$ . As we have mentioned in Section 3.2.2, this value may be ruled out by the result obtained by Smidt et al. (2010). Hence, if we believe this constraint, we need to consider possibilities such as scale-dependent  $\tau_{\text{NL}}$ .

## 4.3 Abundance of voids

As another example, we study the void abundance with primordial non-Gaussian corrections. In Kamionkowski, Verde & Jimenez (2009), the authors showed that the void distribution function can be derived in the same way as the halo mass function using Press–Schechter theory. This is done by replacing the critical ‘overdensity’ parameter,  $\delta_c$ , with the negative ‘underdensity’ parameter,  $\delta_v$ . The precise value of  $\delta_v$  depends on the definition of a void. For example, if the voids are regions having a density half of  $\bar{\rho}$ , then we can estimate the critical value of underdensity as  $\delta_v \simeq -0.7$  (Kamionkowski et al. 2009). There are also several numerical studies about the value of  $\delta_v$  which suggest  $\delta_v \approx -0.8$  (Shandarin et al. 2006; Park & Lee 2007; Colberg et al. 2008).

In any case, based on Press–Schechter theory, the abundance of voids which have radius between  $R$  and  $R + dR$  is given by (Kamionkowski et al. 2009)

$$\frac{dn^{\text{void}}(R)}{dR} dR = -dR \times \frac{6}{4\pi R^3} \frac{d}{dR} \int_{-\infty}^{\delta_v/\sigma_R} F(v) dv. \quad (53)$$

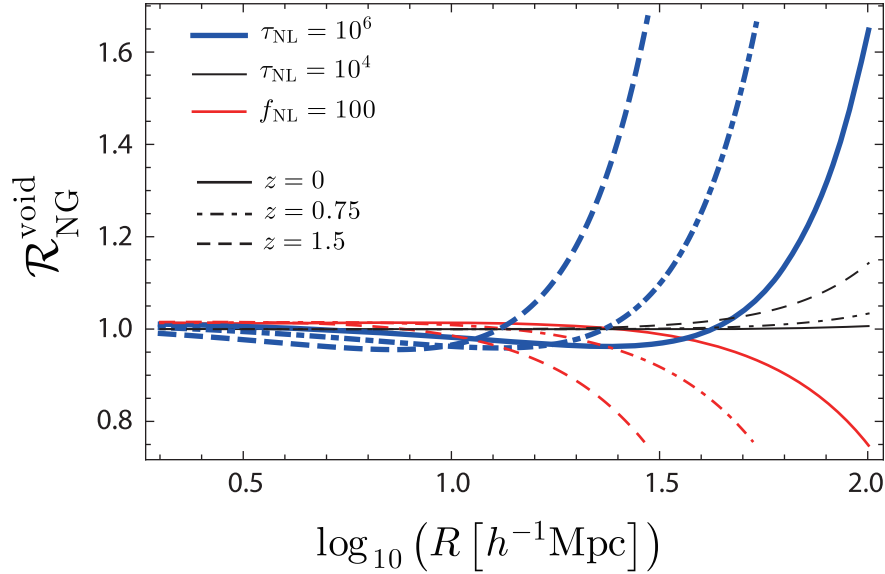
For pure Gaussian PDF, we have

$$\frac{dn_{\text{G}}^{\text{void}}(R)}{dR} = \sqrt{\frac{2}{\pi}} \frac{3}{4\pi R^4} \exp\left[-\frac{\delta_v^2}{2\sigma_R^2}\right] \frac{\delta_v}{\sigma_R} \frac{d \ln \sigma_R}{d \ln R}. \quad (54)$$

Up to the third order in terms of  $S_3$  and  $S_4$ , the void abundance with primordial non-Gaussian corrections is also given by

$$\begin{aligned} \frac{dn^{\text{void}}(R)}{dR} = & \sqrt{\frac{2}{\pi}} \frac{3}{4\pi R^4} \exp\left[-\frac{\delta_v^2}{2\sigma_R^2}\right] \left\{ \frac{d \ln \sigma_R}{d \ln R} \frac{\delta_v}{\sigma_R} \left[ 1 \right. \right. \\ & + \frac{S_3(R)\sigma_R}{6} H_3(\delta_v/\sigma_R) + \frac{1}{2} \left( \frac{S_3(R)\sigma_R}{6} \right)^2 H_6(\delta_v/\sigma_R) + \frac{1}{6} \left( \frac{S_3(R)\sigma_R}{6} \right)^3 H_9(\delta_v/\sigma_R) \\ & + \frac{S_4(R)\sigma_R^2}{24} H_4(\delta_v/\sigma_R) + \frac{1}{2} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^2 H_8(\delta_v/\sigma_R) + \frac{1}{6} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^3 H_{12}(\delta_v/\sigma_R) \left. \right] \\ & + \frac{d}{d \ln R} \left( \frac{S_3(R)\sigma_R}{6} \right) H_2(\delta_v/\sigma_R) + \frac{1}{2} \frac{d}{d \ln R} \left( \frac{S_3(R)\sigma_R}{6} \right)^2 H_5(\delta_v/\sigma_R) + \frac{1}{6} \frac{d}{d \ln R} \left( \frac{S_3(R)\sigma_R}{6} \right)^3 H_8(\delta_v/\sigma_R) \\ & + \frac{d}{d \ln R} \left( \frac{S_4(R)\sigma_R^2}{24} \right) H_3(\delta_v/\sigma_R) + \frac{1}{2} \frac{d}{d \ln R} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^2 H_7(\delta_v/\sigma_R) + \frac{1}{6} \frac{d}{d \ln R} \left( \frac{S_4(R)\sigma_R^2}{24} \right)^3 H_{11}(\delta_v/\sigma_R) \left. \right\}. \quad (55) \end{aligned}$$

<sup>4</sup> The halo is defined as a spherical overdense region whose density is 324 times the mean matter density of the Universe.



**Figure 7.** The ratio between the void abundance distribution function with non-zero primordial non-Gaussian correction and the Gaussian distribution function at redshifts  $z = 0.0, 0.75, 1.5$  given by equation (56). The red lines are for the case with  $f_{\text{NL}} = 100$  and  $\tau_{\text{NL}} = g_{\text{NL}} = 0$ , the blue thick lines for the case with  $\tau_{\text{NL}} = 10^6$  and  $f_{\text{NL}} = g_{\text{NL}} = 0$  and the black thin lines for the case with  $\tau_{\text{NL}} = 10^4$  and  $f_{\text{NL}} = g_{\text{NL}} = 0$ . The solid lines are for the case with  $z = 0.0$ , the dot-dashed lines for the case with  $z = 0.75$  and the dashed lines for the case with  $z = 1.5$ . Here we took  $\delta_v = -0.7$ .

Following the previous section, we define the ratio between the void abundance with the pure Gaussian PDF and that with the primordial non-Gaussian corrections as

$$\mathcal{R}_{\text{NG}}^{\text{void}} \equiv \frac{dn^{\text{void}}(R)/dR}{dn_{\text{G}}^{\text{void}}(R)/dR}. \quad (56)$$

In Fig. 7, we show  $\mathcal{R}_{\text{NG}}^{\text{void}}$  for the cases with  $f_{\text{NL}} = 100$ ,  $\tau_{\text{NL}} = g_{\text{NL}} = 0$  (red lines),  $\tau_{\text{NL}} = 10^6$ ,  $f_{\text{NL}} = g_{\text{NL}} = 0$  (blue thick lines) and  $\tau_{\text{NL}} = 10^4$ ,  $f_{\text{NL}} = g_{\text{NL}} = 0$  (black thin lines). We adopt  $\delta_v = -0.7$ . We also show the ratio with changing the redshift; the solid lines for the case with  $z = 0.0$ , the dot-dashed lines for the case with  $z = 0.75$  and the dashed lines for the case with  $z = 1.5$ . From this figure, we conclude that the non-Gaussian void abundance with non-zero  $\tau_{\text{NL}}$  becomes larger than the Gaussian one on relatively larger scales, whereas that with the non-zero  $f_{\text{NL}}$  becomes smaller. On the other hand, as seen in the previous section, the halo abundance becomes larger not only with non-zero  $\tau_{\text{NL}}$ , but also with non-zero  $f_{\text{NL}}$  in relatively more massive objects. Hence, from this discussion, we confirm that the non-Gaussian effects on both the halo and the void abundances allow us to distinguish the large kurtosis, i.e. large  $\tau_{\text{NL}}$ , case from the large skewness, i.e. large  $f_{\text{NL}}$  case (Chongchitnan & Silk 2010).

## 5 SUMMARY AND DISCUSSION

It has recently become clear that cosmological LSS and CMB observations could provide stringent constraints on the PDF of primordial adiabatic curvature fluctuations. In particular, the high-order moments of the PDF, such as its skewness and kurtosis, can give unique insights into the dynamics and conditions of the inflationary phase in the early Universe.

In this paper, we have investigated the effects of the  $\tau_{\text{NL}}$  type of primordial non-Gaussianity on the halo mass function. In particular, we have obtained a formula for the halo mass function with the non-Gaussian corrections coming from the kurtosis induced by the non-zero  $\tau_{\text{NL}}$ . We find that the deviations of the non-Gaussian mass function from the Gaussian one become larger for larger mass objects ( $M \gtrsim 10^{14} h^{-1} M_{\odot}$  for  $z \sim 0$ ) as well as at higher redshifts ( $z \gtrsim 1$  for  $M \approx 10^{14} h^{-1} M_{\odot}$ ) in the case with  $\tau_{\text{NL}} = O(10^6)$ . Such features are quite similar to those obtained from skewness-driven non-Gaussian corrections that are induced by the  $f_{\text{NL}}$  type of primordial non-Gaussianity.

As examples of applications of our formulae, we have considered the effects on early star formation, formation of the most massive objects at high redshift and the abundance of voids.

For early star formation, we applied our formula for the non-Gaussian halo mass function in order to estimate the redshift dependence of the cumulative number of photons emitted from Pop III stars, a crucial quantity in considerations of the reionization history of the Universe. We found that primordial non-Gaussianity does not affect the reionization history of the Universe on the average, but at high redshift ( $z \simeq 20$ ), namely the earliest stages of reionization, it is effective.

We have also obtained an estimate of the value of  $\tau_{\text{NL}}$  needed to naturally explain the existence of the galaxy cluster XMMU J2235.3–2557, namely  $\tau_{\text{NL}} = 1.7 \times 10^6$ . Hence, in light of the result of Smidt et al., we might need to consider a possibility such as scale-dependent  $\tau_{\text{NL}}$  in the case with non-zero  $f_{\text{NL}}$ . In Hoyle, Jimenez & Verde (2011), the authors have investigated 15 high-mass and high-redshift galaxy clusters and found that such objects are extremely rare in the standard  $\Lambda$ CDM model with Gaussian primordial fluctuations. They derived a constraint on  $f_{\text{NL}}$  in order to explain the mere existence of these objects as  $f_{\text{NL}} > 475$  at 95 per cent confidence level, with the other

cosmological parameters fixed to best-fitting values of the *WMAP* data. In Enqvist et al. (2011), the authors have extended the analysis of Hoyle et al. (2011) to the case with non-zero  $g_{\text{NL}}$ . It should clearly be of interest to derive a constraint on  $\tau_{\text{NL}}$  for these observed high-mass and high-redshift galaxy clusters. We will address this in future work.

As mentioned in Kamionkowski et al. (2009) and Chongchitnan & Silk (2010), the non-Gaussian correction coming from skewness reduces the abundance of voids on large scales when the non-linearity parameter  $f_{\text{NL}}$  is positive in contrast to the fact that positive  $f_{\text{NL}}$  enhances the number of more massive halo objects. On the other hand, the non-Gaussian correction coming from kurtosis enhances not only the numbers of more massive halo objects, but also the abundances of voids on large scales. Hence, if one could also measure the void abundance as well as the halo mass function more precisely, one could potentially distinguish between the  $f_{\text{NL}}$  and the  $\tau_{\text{NL}}$  types of primordial non-Gaussianity.

*NOTE.* During the time that we were preparing this manuscript, LoVerde & Smith (2011) appeared on the arXiv. In LoVerde & Smith (2011), they considered the same type of primordial non-Gaussianity as in our study and obtained a useful analytic formula for the halo mass function with the kurtosis type primordial non-Gaussianity using  $N$ -body simulations. We find that our formula (31) is in reasonably good agreement with their formula as far as the behaviour of the halo mass function with the kurtosis type of primordial non-Gaussianity is concerned.

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## APPENDIX A: MVJ EXPRESSION

In Matarrese et al. (2000), the authors have given a formula for the ratio between the non-Gaussian mass function and the Gaussian mass function as

$$\begin{aligned}
 R_{\text{NG}}^{\text{MVJ}}(M, z) = & \exp \left[ v_c^3 \frac{S_3(R)\sigma_R}{6} + v_c^4 \frac{S_4(R)\sigma_R^2}{24} \right] \times \left[ \delta_3 + \frac{v_c}{\delta_3} \left( -\frac{S_3(R)\sigma_R}{6} \right) + \left( \frac{d \ln \sigma_R}{dM} \right)^{-1} \frac{d}{dM} \left( \frac{S_3(R)\sigma_R}{6} \right) \right] \\
 & \times \left[ \delta_4 + \frac{v_c^2}{\delta_4} \left( -\frac{S_4(R)\sigma_R^2}{12} \right) + \left( \frac{d \ln \sigma_R}{dM} \right)^{-1} \frac{d}{dM} \left( \frac{S_4(R)\sigma_R^2}{24} \right) \right], \\
 \delta_3 \equiv & \left( 1 - v_c \frac{S_3(R)\sigma_R}{3} \right)^{1/2}, \quad \delta_4 \equiv \left( 1 - v_c^2 \frac{S_4(R)\sigma_R^2}{12} \right)^{1/2},
 \end{aligned} \tag{A1}$$

which was not derived based on the Edgeworth expansion as mentioned in Section 3. In Section 4, we have discussed some applications of the non-Gaussian halo mass function.

As for the discussion in Subsection 4.1 about early star formation, the redshift dependence of the critical value of the cumulative photon number per H atom ( $n_\gamma/n_H = 10$ ) is not so sensitive to primordial non-Gaussianity. In order to estimate more precisely how  $n_\gamma/n_H$  at high redshift is enhanced due to primordial non-Gaussianity, we should check which formula better describes the effect of primordial non-Gaussianity on the halo mass function. This is a future issue. In Subsection 4.3, we have discussed the void abundance and noted that the kurtosis type of primordial non-Gaussianity can enhance the abundance of the large voids as opposed to the skewness type of primordial non-Gaussianity. This is just qualitative discussion.

On the other hand, the discussion in Subsection 4.2 is so quantitative and hence we have investigated the difference of the estimated value of  $\tau_{\text{NL}}$  for the observation of XMMU J2235.3–2557 between the case with MVJ expression and that with equation (31) given in Section 3. Our naive estimated value of  $\tau_{\text{NL}}$  given in Subsection 4.2 is  $\tau_{\text{NL}} = 1.7 \times 10^6$ . For the case by making use of MVJ expression, we obtained  $\tau_{\text{NL}} = 1.1 \times 10^6$ . These values seem to be same order and hence the result does not extremely change.

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