We present forecast results for constraining the primordial non-Gaussianity from photometric surveys through a large-scale enhancement of the galaxy clustering amplitude. In photometric surveys, the distribution of observed galaxies at high redshifts suffers from the gravitational-lensing magnification, which systematically alters the number density for magnitude-limited galaxy samples. We estimate size of the systematic bias in the best-fit cosmological parameters caused by the magnification effect, particularly focusing on the primordial non-Gaussianity. For upcoming deep and/or wide photometric surveys like HSC, DES and LSST, the best-fit value of the non-Gaussian parameter, $f_{NL}$, obtained from the galaxy count data is highly biased, and the true values of $f_{NL}$ would typically go outside the 3-$\sigma$ error of the biased confidence region, if we ignore the magnification effect in the theoretical template of angular power spectrum. The additional information from cosmic shear data helps not only to improve the constraint, but also to reduce the systematic bias. As a result, the size of systematic bias on $f_{NL}$ would become small enough compared to the expected 1-$\sigma$ error for HSC and DES, but it would be still serious for deep surveys with $z_{m} \gtrsim 1.5$, like LSST. Tomographic technique improves the constraint on $f_{NL}$ by a factor of 2-3 compared to the one without tomography, but the systematic bias would increase.

I. INTRODUCTION

Any hints on primordial non-Gaussianity would be fruitful to clarify the generation mechanism for primordial density fluctuations in the early stage of the Universe. Since the single-field slow-roll inflationary scenario predicts nearly Gaussian fluctuations (e.g., [1–7]), a detection of large primordial non-Gaussianity will rule out the simplest inflationary model and provides us a new insight into the physics in the early universe.

Traditional and popular method to detect primordial non-Gaussianity is to measure the three-point correlations of statistical fields (e.g., [8–13]). This correlation vanishes in the Gaussian fields, and non-vanishing signals of the three-point correlations would provide information on primordial non-Gaussianity.

On the other hand, recent numerical and theoretical studies (e.g., [11, 14–25]) have revealed that the local-type non-Gaussianity, originating from the non-linear dynamics of scalar fields on super horizon scales, can induce a large-scale enhancement in the galaxy clustering amplitude. In the local-type non-Gaussianity, the primordial fluctuations characterized by the Bardeen potential, $\Phi(x)$, are described by the Taylor expansion of Gaussian field $\phi(x)$ as (e.g., [4, 8, 26, 27]):

$$\Phi(x) = \phi(x) + f_{NL} (\phi^2(x) - \langle \phi^2 \rangle).$$

The non-vanishing parameter, $f_{NL} \neq 0$, implies a departure from the Gaussian statistics, and even a small value of $f_{NL}$ has been found to produce a scale-dependent galaxy bias, which is prominent on large scales and at high redshifts. With a help of this property, the constraint on primordial non-Gaussianity has been obtained recently, combining photometric and spectroscopic surveys [28–30], and it turned out that the results are rather comparable to that from CMB observation. This constraint mainly comes from the quasar data obtained from photometric surveys, which are wider and deeper than spectroscopic surveys with a limited observation time. In this respect, wide and deep photometric surveys planned to start in the near future such as Subaru Hyper Suprime-Cam (HSC) survey [31], Dark Energy Survey (DES) [32], and Large Synaptic Survey Telescope (LSST) survey [33] would provide a more stringent constraint on primordial non-Gaussianity.

In those photometric surveys, the observed galaxy distribution at high redshifts often suffers from the magni-
fication effect due to the gravitational lensing, which apparently changes the number density of observed galaxies \[34, 36\]. As increasing redshift, since the amplitude of the density fluctuations becomes small and the observed angular separation between any pairs of two sources decreases, the galaxy auto-angular power spectrum is shifted to small scales with the amplitude decrease. On the other hand, the lensing contribution on the angular correlations become significant at higher redshifts. As a result, the contribution of the magnification effect on the galaxy auto correlations is expected to be significant not only at high redshifts, but also on large angular scales. We thus naively expect that the magnification effect can mimic the scale-dependent galaxy bias, and ignoring magnification effect in the theoretical template for angular correlations would lead to a biased estimation of primordial non-Gaussianity.

In this paper, we study the potential impacts of the magnification effect on constraining primordial non-Gaussianity from the upcoming photometric surveys. There are several studies forecasting constraints on primordial non-Gaussianity through the scale-dependent galaxy bias \(e.g., [24, 37–39]\). Here, we pay a particular attention to the magnification effect, and quantitatively evaluate the systematic biases arising from the incorrect treatment of the magnification effect in estimating the non-Gaussianity parameter \(f_{\text{NL}}\), which has never been considered in the previous forecast studies. Further, we discuss the role of the cross correlation statistics between galaxy number density and other observables such as cosmic shear. This has been also never investigated in previous works, since the cross correlation signals are basically insensitive to the primordial non-Gaussianity compared to the galaxy auto correlations. However, we found that the cosmic shear-galaxy count cross-correlations have large signal-to-noise ratios, and help not only to improve the constraint on \(f_{\text{NL}}\), but also to reduce the systematic bias.

This paper is organized as follows. In Sec II we briefly review the scale-dependent galaxy bias induced by the primordial non-Gaussianity, and describe how the magnification effect changes the number density of observed galaxies. We then give the formalism for the angular power spectra obtained from photometric galaxy surveys. In Sec III we explicitly compute the angular power spectra and calculate the signal-to-noise ratios for auto and cross power spectra of galaxy count and cosmic shear. In Sec IV based on the Fisher matrix formalism, we quantitatively estimate the impact of magnification effect on the detection of primordial non-Gaussianity, particularly focusing on three representative surveys, i.e., HSC, DES and LSST. Finally, Sec V is devoted to the summary and discussion.

Throughout the paper, all the angular power spectra are computed from the modified version of cosmological Boltzmann code, CAMB \[10\], with the following set of cosmological parameters assuming a flat Lambda-CDM model, which is consistent with WMAP7 results \[41\]:

\[
\Omega_b h^2 = 0.022, \Omega_m h^2 = 0.13, \Omega_{\Lambda} = 0.72, n_s = 0.96, A_s = 2.4 \times 10^{-9}, \tau = 0.086, \text{and } w = -1, \text{for the density parameters of baryon and matter, dark energy density, scalar spectral index, scalar amplitude at } k = 0.002 \text{ Mpc}^{-1}, \text{reionization optical depth, dark-energy equation-of-state parameter, respectively. Unless otherwise stated, non-Gaussian parameter is set to } f_{\text{NL}} = 0. \text{ The non-linear power spectrum is computed according to the fitting formula given in Ref.} [42].
\]

II. PROBING PRIMORDIAL NON-GAUSSIANITY FROM PHOTOMETRIC SURVEYS

A. Primordial non-Gaussianity imprinted on galaxy bias

In the presence of local-type primordial non-Gaussianity, recent numerical and theoretical studies on the clustering of halos/galaxies \(e.g., [14–23]\) show that there appears a scale-dependent enhancement of the clustering amplitude on very large scales. Theoretically, the scale-dependent property of the halo/galaxy bias can be explained by a tight correlation between long-wavelength and short-wavelength modes, which usually vanishes in the Gaussian case. Especially, the modulation of short-wavelength modes responsible for forming halos is induced by the Newton potential or Bardeen potential \(\Phi(x)\). This fact leads to a strong scale-dependence for the fluctuations of halo/galaxy number density on large scales, and in Fourier space, we obtain \[28, 43\]

\[
g(k, z) = [b_G + \Delta b(k, z)]\delta(k, z), \tag{2}
\]

where \(g(k, z)\) and \(\delta(k, z)\) are the fluctuations of galaxy number density and matter density fluctuations, respectively, and the quantity \(b_G\) implies the galaxy bias in the case of Gaussian initial condition. The function \(\Delta b(k, z)\) represents the non-Gaussian correction, which is given by \[28, 43\]

\[
\Delta b(k, z) = f_{\text{NL}} A_{\text{NG}} \frac{3\Omega_m H_0^2}{k^2 T(k)D(z)}. \tag{3}
\]

Here, the quantity \(\Omega_m\) is the matter energy density, \(H_0\) denotes the Hubble parameter at present, \(D(z)\) is the linear growth rate, and \(T(k)\) is the transfer function for linear matter density fluctuations, which is set to unity in the limit \(k \to 0\). Thus, in the large-scale limit \((k \to 0)\), the second term in Eq. (2) becomes dominant, and the enhancement of clustering amplitude is prominent in a scale-dependent way. Since this term is inversely proportional to the growth rate \(D(z)\), non-Gaussian correction becomes also significant at higher redshifts.

Assuming the universality of mass function, the quantity, \(A_{\text{NG}}\), gives \(\delta_c(b_G - 1)\) \[14, 28\], and the quantity \(\delta_c = 1.68\) is the critical density for a spherical collapse. As advocated by several papers, however, the quantity
\( A_{NG} \) would not be simply related to the halo mass function, but depends on the merger history of halo/galaxy samples [43]. In other words, we may have to determine \( A_{NG} \) from the observational data in practice. If this is the case, the non-Gaussian parameter \( f_{NL} \) would be completely degenerated with the quantity \( A_{NG} \), and we need additional information on \( f_{NL} \) like the galaxy bispectrum in order to break the degeneracy. Our primary focus here is to explore the impact of magnification effect on the non-Gaussian parameter, and we simply assume \( A_{NL} = 3\delta_c(b_\ell - 1) \) in the subsequent analysis. The influence of the magnification effect is a generic issue to constrain \( f_{NL} \) from the photometric surveys, and we expect that the results in the paper are also applicable to the case to combine other observations in breaking the degeneracy with \( A_{NG} \).

**B. Magnification effect on galaxy number density**

The number density of galaxies obtained from photometric surveys often suffers from the magnification effect by the weak gravitational lensing of the large-scale structure (e.g., [44–46]). Since the gravitational lensing changes the apparent magnitude and the area of the patch in the observed sky, it also changes the observed galaxy number density. Denoting the zero-mean fluctuations of the observed galaxy number density along a direction \( \theta \) at redshift \( z \) by \( n(\theta, z) \), we have [46]

\[
n(\theta, z) = g(\theta, z) + (5s(z) - 2)\kappa(\theta, z), \tag{4}
\]

where the quantity \( \kappa(\theta, z) \) is the lensing convergence at the position of source galaxy, and characterizes the change of the size of images. The convergence is given by [46]

\[
\kappa(\theta, z) = 3\Omega_m H_0^2 \frac{1}{2} \int_0^{\chi(z)} d\chi \frac{\chi(z) - \chi}{\chi(z)} \delta(\chi \theta, \chi), \tag{5}
\]

with the function \( \chi(z) \) being the comoving distance. The second \((5s(z)\kappa)\) and third term \((-2\kappa)\) in Eq. (4) arise from the modification of apparent magnitude and the area of the patch in the observed sky by lensing, respectively.

The magnitude of the lensing effect depends on the slope parameter, \( s(z) \). Denoting the number of galaxies at redshift \( z \), brighter than the magnitude \( m \) by \( N(z, < m) \), the quantity \( s(z) \) is defined by [46]

\[
s(z) = \frac{d\log_{10} N(z, < m)}{dm}. \tag{6}
\]

Note that in addition to the correction in Eq. (4), there exists another possible contribution related to the lensing effect, which has been addressed in Refs. [47,48]. That is, the observed galaxies are selected according not only to the magnitude cut, but also to the size cut, and the latter also alters the galaxy number density. Nevertheless, the effect of size cut is basically proportional to the lensing convergence, and can be incorporated into the expression [44], with a slight change of the meaning of slope index, \( s(z) \). In this respect, the results in the present paper is general, and applicable to the case taking account of the size cut.

**C. The angular power spectra**

The angular power spectra are the fundamental statistical quantity obtained from the photometric survey, and have a rich cosmological information. Here we write down the expressions for angular power spectra of galaxy number counts and cosmic shear obtained from photometric surveys.

The galaxy number density observed via photometric survey is projected onto the two-dimensional sky, and redshift information is obtained by dividing photometric galaxy samples into several subsamples binned with redshifts. With the redshift distribution of galaxies in \( i \)-th bin, \( N_i(z) \), the two-dimensional distribution of observed galaxies in \( i \)-th bin, \( n_i(\theta, z) \), are given by

\[
n_i(\theta, z) = \int dz \frac{N_i(z)}{N_i} n_i(\theta, z). \tag{7}
\]

The quantity \( \overline{N}_i \) is the average number density per square arcminute in \( i \)-th bin, defined by

\[
\overline{N}_i = \int_0^{\infty} dz s(z) N_i(z). \tag{8}
\]

On the other hand, the cosmic shear is measured from the ellipticity of each galaxy image. Using the photometric redshift information, we can also divide the estimated shear into several redshift bins. We denote the cosmic shear field in the \( i \)-th redshift bin by \( \gamma_i(\theta) \). Then, the angular power spectra between the observables, \( X \) and \( Y \) (\( X \) and \( Y \) are either of \( \gamma_i \) or \( n_j \)) are given by the following expression:

\[
C_{XY}^\ell = \frac{2}{\pi} \int \frac{dk}{k^2} P_{\text{init}}(k) \Delta^X(k) \Delta^Y(k), \tag{9}
\]

where \( P_{\text{init}}(k) \) is the matter power spectrum at an early time and \( k \) is the Fourier wave number. The functions \( \Delta^X(k) \) and \( \Delta^Y(k) \) are one of the following [43,51]:

\[
\Delta^X(k) = \sqrt{\frac{(\ell + 2)!}{(\ell - 2)!}} P_\ell(k; N_i(z)), \tag{10}
\]

\[
\Delta^Y(k) = k^2 \int dz [b_\ell + \Delta b(k, z)] \frac{N_i(z)}{N_i} D(z) j_\ell(k\chi(z)) + (5s_i - 2)\ell(\ell + 1)P_\ell(k; N_i(z)). \tag{11}
\]

The function \( j_\ell \) is the spherical Bessel function and
\( \mathcal{P}_\ell(k; N_i(z)) \) is defined by
\[
\mathcal{P}_\ell(k; N_i(z)) = \frac{3\Omega_m H_0^2}{2} \int_0^\infty dz_s \frac{N_i(z_s)}{N_i} \times \int_0^{\chi(z_s)} d\chi \frac{\chi(z_s) - \chi'(\chi(z))}{a(\chi)} \hat{J}_\ell(k\chi). 
\] (12)

The quantity \( s_i \) is the slope index in the \( i \)-th redshift bin. Although the slope index seems to have a strong redshift dependence [51, 52], we here assume the constant slope index within each redshift bin, and study the effect of time varying slope index.

Note that for the photometric redshift determination, the uncertainty arising from the photometric redshift error is crucial for the cosmological analysis [53]. To mimic this effect, we suppose that the photometric redshift estimates are distributed as a Gaussian with rms fluctuation \( \sigma(z) \). Then the actual redshift distribution for \( i \)-th galaxy subsamples over the range, \( z_{i-1} < z < z_i \), is related to the redshift distribution of galaxies, \( N(z) \), as [54]
\[
N_i(z) = \frac{1}{2} N(z) \left[ \text{erfc} \left( \frac{z_{i-1} - z}{\sqrt{2}\sigma(z)} \right) - \text{erfc} \left( \frac{z_i - z}{\sqrt{2}\sigma(z)} \right) \right], 
\] (13)
where the function \( \text{erfc}(x) \) is the complementary error function defined by
\[
\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty dz \exp(-z^2). 
\] (14)

### III. MAGNIFICATION EFFECT ON ANGULAR POWER SPECTRA AND SIGNAL-TO-NOISE RATIO

In this section, adopting a simple model of time evolution for bias parameter \( b_G \), we compute the angular power spectra, and show how the magnification effect changes the amplitude of angular power spectra. Also, based on the fiducial setup of future photometric surveys, we estimate the signal-to-noise ratios for auto- and cross-power spectra of galaxy counts and cosmic shear.

In Eq. (4), while the parameter \( b_G \) is assumed to be scale-independent on large-scales, it would manifest a strong time dependence. We characterize this by introducing the following function (e.g., [55, 57]):
\[
b_G = b_0 + \frac{b_z}{D(z)}. 
\] (15)
Here, we set \( b_0 = 1.5 \) and \( b_z = 2.0 \) for fiducial values of the galaxy bias parameters. Since the photometric redshift information is available for most of the photometric surveys, we employ the tomographic technique, and divide all the galaxy samples into the three redshift subsamples. The redshift ranges for each bin are chosen as, \( z < 0.739, 0.739 < z < 1.14, \) and \( 1.14 < z \), so that each redshift bin has the same number of galaxies. We assume the redshift distribution of galaxies \( N(z) \) as (e.g., [58])
\[
N(z) = N_g \frac{3z^2}{2(0.64z_m)^3} \exp \left[ -\left( \frac{z}{0.64z_m} \right)^{3/2} \right], 
\] (16)
where the quantities \( N_g \) and \( z_m \) are the total number of galaxies per square arcminute and mean redshift. As for typical values of the upcoming deep surveys, we set \( N_g \) to 35 arcmin\(^{-2}\) and \( z_m = 1.0 \). As for the photo-z error, we adopt the simple scaling relation [54]:
\[
\sigma(z) = 0.03 (1 + z). 
\] (17)

Finally, the influence of magnification effect on the angular power spectra depends on the slope parameter, for which we set \( s_1 = 0.5, s_2 = 1.0, \) and \( s_3 = 1.5 \), close to the recently estimated values from the observations [51, 52].

#### A. Magnification effect on angular power spectra

In the presence of the magnification effect, the galaxy auto-power spectra, \( C^g_{\ell i} \), and the shear-galaxy cross-power spectra, \( C^g_{\ell i} \), can be separately decomposed into several pieces:
\[
C^g_{\ell i} = C^g_{\ell i} + C^g_{\ell i} + C^g_{\ell i}, 
\] (18)
\[
C^g_{\ell i} = C^g_{\ell i} + C^g_{\ell i}, 
\] (19)
where the subscripts \( g_i \) and \( \mu_i \) respectively represent the contribution of the pure galaxy clustering and magnification, which are identified with the first and second terms in Eq. (11). That is, the power spectra involving \( g_i \) and \( \mu_i \) can be computed by simply neglecting the second and first terms in Eq. (11), respectively.

In Fig. 4, the galaxy auto and shear-galaxy cross angular power spectra \( C^g_{\ell i} \) and \( C^g_{\ell i} \) are shown. We plot the power spectra in the presence/absence of the magnification effect for the Gaussian initial condition (black solid/red dotted), and also show the power spectra in the absence of the magnification effect for the non-Gaussian case, \( f_{NL} = \pm 10 \) (magenta solid). Note that the power spectra plotted here are independent of \( N_g \) in Eq. (16) (see Eqs. (10)-(12)).

For the galaxy auto power spectra \( C^g_{\ell i} \), there appears two contributions of the magnification effect in Eq. (13), i.e., \( C^g_{\ell i} \) and \( C^g_{\ell i} \). As shown in the top panel of Fig. 4, the cross power spectrum between galaxy counts and the magnification, \( C^g_{\ell i} \) (green dotted), has similar angular dependence to \( C^g_{\ell i} \) (red dotted), and it slightly changes the overall amplitude of power spectra. The contribution of magnification auto-power spectra, \( C^g_{\ell i} \) (blue dotted), has also similar \( \ell \)-dependence, but the amplitude exceeds \( C^g_{\ell i} \) on large scales. This feature comes from the fact that the weak lensing effect is mainly attributed to the growth of structure at lower redshifts. In the same manner, in the bot-
fractional difference of the galaxy auto power spectra, we plot the angular power spectra in the presence/absence of the magnification effect (black solid/red dotted) for the Gaussian case, $f_{\text{NL}} = 0$, and also show the angular power spectra in the absence of the magnification effect in the non-Gaussian case, $f_{\text{NL}} = \pm 10$ (magenta solid). For comparison, we plot the contribution of the magnification effect ($2g_3\mu_3$, and $3\mu_3$ in the top and $3\mu_3$ in the bottom panel).

In Fig. 2, to elucidate the scale-dependent enhancement of the power spectra on large scales, we plot the fractional difference of the galaxy auto power spectra, $\delta C_\ell/C_\ell$, for galaxy auto and shear-galaxy cross spectra in the presence or absence of the magnification effect. We define the fractional difference of galaxy auto-power spectra, $\delta C_\ell/C_\ell$, which is given in two cases: $C_\ell^{i,j}(f_{\text{NL}} = 10)/C_\ell^{i,j}(f_{\text{NL}} = 0) - 1$ (magenta lines) and $C_\ell^{i,j}(f_{\text{NL}} = 0)/C_\ell^{i,j}(f_{\text{NL}} = 10) - 1$ (black lines). The solid, dashed and dotted lines represent $(i,j) = (1, 1), (2, 2)$ and $(3, 3)$ bin, respectively.

$\delta C_\ell/C_\ell$. Here, we examine the two cases: $C_\ell^{i,j}(f_{\text{NL}} = 10)/C_\ell^{i,j}(f_{\text{NL}} = 0) - 1$ (magenta lines) and $C_\ell^{i,j}(f_{\text{NL}} = 0)/C_\ell^{i,j}(f_{\text{NL}} = 10) - 1$ (black lines). As we expected, the impact of magnification effect is significant at higher redshift bins. This is because, as increasing the source redshifts, the gravitational lensing becomes significant and the amplitude of fluctuations $g$ conversely decreases. The contribution of primordial non-Gaussianity is also significant at higher redshifts, because the non-Gaussian correction in the scale-dependent galaxy bias is proportional to the inverse of growth function, $D(z)$ [see Eq. (3)]. Note, however, that the redshift dependence of the magnification effect (magenta lines) is rather different from that of the scale-dependent galaxy bias (black lines). This implies that the tomographic technique is useful to break the degeneracy between the effects of magnification and primordial non-Gaussianity.

**B. Signal-to-noise ratio**

Since the magnification effect enhances the amplitude of power spectra especially on large scales, the signal-to-noise ratio for angular power spectra would be changed. To estimate the size of this, in Fig. 3 we plot the signal-to-noise ratios for galaxy auto and shear-galaxy cross spectra in the presence or absence of the magnification effect. The signal-to-noise ratio, $S/N$, is defined by

$$\frac{S}{N} = \sqrt{\sum_{\ell=2}^{\ell_{\text{max}}} \left( \frac{C_{\ell}^{XY}}{\Delta C_{\ell}^{XY}} \right)^2},$$

(20)
where the quantity \( \Delta C_{\ell}^{XY} \) is the statistical error for each power spectra, given by

\[
(\Delta C_{\ell}^{XY})^2 = \frac{1}{(2\ell+1)f_{\text{sky}}} \left[ (C_{\ell}^{XY} + N_{\ell}^{XY})^2 + (C_{\ell}^{XX} + N_{\ell}^{XX})(C_{\ell}^{YY} + N_{\ell}^{YY})\right].
\] (21)

Here, the parameter \( f_{\text{sky}} \) is the sky coverage of photometric survey, and \( N_{\ell}^{XY} \) are the noise power spectra, which will be later given in Sec.IV [see Eqs. (24)–(26)]. In Fig. 3 the signal-to-noise ratios are computed with \( \ell_{\text{max}} = 1000 \), and are normalized by \( f_{\text{sky}} \).

For the cross power spectra which have primarily no statistical correlation i.e., \( C_{\ell,i}^{n,j} (i \neq j) \) and \( C_{\ell}^{n,n} (i < j) \) \( \delta \), the signal-to-noise ratios are significantly improved by the magnification effect. For example, the signal-to-noise ratio of \( C_{\ell,i}^{n,n} \) increases by a factor of \( \sim 115 \). This is because the magnification effect leads to a non-vanishing correlation between foreground galaxies and the background sources. On the other hand, the improvement of the signal-to-noise ratio is relatively small for the power spectra which have strong statistical correlation even in the absence of the magnification effect i.e., \( C_{\ell,i}^{n,n} (i = j) \), and \( C_{\ell}^{n,n} (i \geq j) \). Since the signals of these spectra are primarily very large enough to detect, the results indicate that the size of the constraint on \( f_{NL} \) would not be drastically changed even if the magnification effect is properly taken into account in the data analysis. We finally note that, even in the absence of the magnification effect, the signal-to-noise ratios of the shear-galaxy cross correlations \( [C_{\ell,i}^{n,n} (i \geq j)] \) are comparable to that of the galaxy auto correlations \( [C_{\ell,i}^{n,n} (i = j)] \). This implies that, the parameter \( f_{NL} \) would be constrained not only from the galaxy auto correlations, but also from the shear-galaxy cross correlations.

IV. MAGNIFICATION EFFECT ON THE DETECTION OF PRIMORDIAL NON-GAUSSIANSITY

In this section, based on the Fisher matrix formalism, we now present the forecast constraint on \( f_{NL} \) from photometric surveys, and estimate the size of systematic bias from the incorrect treatment of magnification effect in the theoretical template of angular power spectra. As representative upcoming experiments for wide and/or deep surveys, we consider HSC experiment for wide but narrow, DES for shallow but wide, and LSST for idealistically deep and wide surveys.

A. Fisher matrix formalism

Here, we summarize the Fisher matrix formalism used in the subsequent analysis, and describe the canonical survey setup for photometric galaxy surveys and CMB experiments.

Given the angular power spectra theoretically parametrized by a set of parameters \( p \), the Fisher matrix for the cosmological parameters is written as (e.g., \( \delta \)

\[
F_{ij} = \sum_{\ell=2}^{\ell_{\text{max}}} \frac{2\ell+1}{2} f_{\text{sky}} \times \text{Tr} \left( C_{\ell}^{-1}(p) \partial C_{\ell} \partial p_i \partial C_{\ell}^{-1}(p) \partial p_j \right) \bigg|_{p=p^{\text{fid}}},
\] (22)

where the quantity \( C_{\ell} \) represents the covariance matrix for the angular power spectra, \( p_i \) is a cosmological parameter which we want to estimate, and \( p^{\text{fid}} \) is the set of fiducial cosmological parameters.

In what follows, using a tomographic technique with the number of redshift bin, \( N_{\text{bin}} \), we consider the number density fluctuations \( n_1, \ldots, n_{N_{\text{bin}}} \) (or \( g_1, \ldots, g_{N_{\text{bin}}} \) when ignoring the magnification effect), and shear fields, \( \gamma_1, \ldots, \gamma_{N_{\text{bin}}} \), as observables obtained from the photometric surveys. Since these observables are rather sensitive to the late-time cosmic expansion and/or growth of structure, photometric surveys alone cannot give a tight constraint on all the cosmological parameters. To break the degeneracy between cosmological parameters and improve the constraints, we include the information obtained from the primary CMB anisotropies by Planck \( \delta \). To be specific, we use the temperature \( (\Theta) \) and (E-mode) polarization \( (E) \) data for primary CMB anisotropies. Denoting the noise power spectra by \( N_{\ell}^{XY} \), the full covariance matrix, \( C_{\ell} \), is written as

\[
[C_{\ell}]_{ij} = C_{\ell,i}^{X,X} + N_{\ell}^{X,j} \delta_{ij},
\] (23)

where \( X_i \) and \( X_j \) stand for \( n_1, \ldots, n_{N_{\text{bin}}} \) (or \( g_1, \ldots, g_{N_{\text{bin}}} \) in the absence of the magnification effect), \( \gamma_1, \ldots, \gamma_{N_{\text{bin}}} \),
The amplitude and shape of the noise spectra $N^{\gamma \gamma}_{XY}$ depends on the survey design which will be discussed below.

In the Fisher-matrix analysis, the forecast constraints depend on the properties of a photometric survey, characterized by the sky coverage, $f_{\text{sky}}$, the mean redshift, $z_m$, and the total number of galaxies per square arcminute, $N_g$. To show how the constraint on $f_{\text{NL}}$ depends on the survey design, we compute the Fisher matrix in the three representative photometric surveys; HSC for a deep survey ($f_{\text{sky}} = 0.05$, $z_m = 1.0$ and $N_g = 35$ arcmin$^{-2}$) and DES ($f_{\text{sky}} = 0.125$, $z_m = 0.5$ and $N_g = 12$ arcmin$^{-2}$) for a wide imaging surveys, and LSST ($f_{\text{sky}} = 0.5$, $z_m = 1.5$ and $N_g = 100$ arcmin$^{-2}$) as an idealistic survey, which is deeper and wider than the HSC and DES surveys. In Table I, we summarize the basic parameters of the survey design for three surveys used in the subsequent analysis.

Let us now consider the noise spectra for each data set. In a photometric survey, the main noise source for galaxy counts is the shot noise given by

$$N_i^{(n)} = \delta_{ij} \frac{1}{\hat{N}_i},$$

with the quantity $\hat{N}_i$ being the number density of galaxies per steradians in $i$-th redshift bin;

$$\hat{N}_i = 3600 \bar{N}_i \left( \frac{180}{\pi} \right)^2 \text{str}^{-1}. \quad (25)$$

On the other hand, the noise source for cosmic shear measurement mainly comes from the intrinsic ellipticity of galaxies, which is described by

$$N^{(\gamma \gamma)}_i = \delta_{ij} \frac{\langle \gamma_i^2 \rangle_{\text{int}}}{\bar{N}_i}. \quad (26)$$

The quantity $\langle \gamma_i^2 \rangle_{\text{int}}^{1/2}$ is the rms intrinsic ellipticity. We adopt the empirically derived value, $\langle \gamma_i^2 \rangle_{\text{int}}^{1/2} = 0.3$ [23]. In all surveys, the galaxy samples are divided into three redshift bins, and the ranges of redshift are chosen such that each redshift bin has same number of galaxies, $N_g/3$. The resultant redshift ranges are summarized in Table II for each mean redshift $z_m$. Note that the noise power spectra of CMB anisotropies, $N^{C^2}_{XY}$, and $N^{E E}_{XY}$, are computed according to Eq. (3.3) of Ref. [63], with the experimental specification for Planck [61].

From the Fisher matrix, the 1-$\sigma$ (68% C.L.) constraint on a cosmological parameter, $\sigma(p_i)$, marginalized over other parameters, is given by $\{F_{ii}^{-1}\}^{1/2}$. Number of free parameters in the subsequent Fisher analysis is, in total, 13, i.e., $\Omega_b h^2$, $\Omega_m h^2$, $\Omega_{\Lambda}$, $n_s$, $A_s$, $r$, $w$, $f_{\text{NL}}$, in addition to the galaxy bias parameters $(b_0$ and $b_2$) and slope indices $(\nu_2, \nu_3)$. Note that the number of free parameters is changed to 10 if we incorrectly neglect the magnification effect in the theoretical template of angular power spectra. The fiducial values of the parameters are the same as those in Sec. III and we assume that the photo-$z$ error and redshift distribution of galaxies are given in Eq. (17) and Eq. (19), respectively.

Using the Fisher matrix formalism, we also evaluate the systematic bias in the best-fit value of cosmological parameters, $\Delta p_i$, arising from the incorrect treatment of the magnification effect in the theoretical template. Assuming the Gaussian likelihood function, the bias of the best-fit value, $\Delta p_i$, can be estimated from [64]

$$\Delta p_i = \frac{1}{2} \sum_{k,j} \tilde{F}_{ij} \frac{2\ell + 1}{2} f_{\text{sky}}$$

$$\times \text{Tr} \left( \tilde{C}^{-1}(p_i) \frac{\partial \tilde{C}}{\partial p_i} (p_i) \tilde{C}^{-1}(p_i) (C(p_i) - \tilde{C}(p)) \right) \bigg|_{p = p^{\text{fid}}}, \quad (27)$$

where the covariance matrices $C$ and $\tilde{C}$ are computed with and without the magnification effect in the power spectra, respectively. The Fisher matrix $\tilde{F}_{ij}$ is computed by ignoring the magnification in angular power spectra.

### B. Results

#### 1. Estimation of primordial non-Gaussianity for representative surveys

Here we present forecast results for the constraint on primordial non-Gaussianity, especially focusing on the following cases:

- $+n$: using galaxy counts alone taking into account the magnification effect in the theoretical template $(C^{\gamma \gamma}_{\ell, n})$.

| Survey      | $f_{\text{sky}}$ | $z_m$ | $N_g$ [arcmin$^{-2}$] |
|-------------|------------------|------|------------------------|
| HSC         | 0.05             | 1.0  | 35                     |
| DES         | 0.125            | 0.5  | 12                     |
| LSST        | 0.5              | 1.5  | 100                    |

**Table II.** The relation between mean redshift, $z_m$, and the redshift ranges of $i$-th bin computed in the case with $N_{\text{bin}} = 3$. Using Eq. (13), the redshift ranges are determined such that each redshift bin has same number of galaxies.
TABLE III. The 1-σ constraints, \( \sigma(f_{NL}) \), and the systematic bias, \( \Delta f_{NL} \), on the primordial non-Gaussianity, in the case with/without the magnification effect in theoretical template. In each case, we show the resultant constraints obtained from galaxy number counts alone, and further including cosmic shear of galaxies. Note that CMB prior information from Planck is included in all cases. Information from the primary CMB is summed up to \( \ell = 3000 \), and other signals are included up to \( \ell_{\text{max}} = 1000 \). We also note that the fiducial values of the galaxy bias parameters and slope indices are chosen as \( b_0 = 1.5, b_1 = 2.0, s_1 = 0.5, s_2 = 1.0 \) and \( s_3 = 1.5 \).

\[
\begin{array}{c|c|c|c|c|c|c}
 & \text{HSC} & & \text{DES} & & \text{LSST} & \\
\hline
\sigma(f_{NL}) & \Delta f_{NL} & \sigma(f_{NL}) & \Delta f_{NL} & \sigma(f_{NL}) & \Delta f_{NL} \\
\hline
+\sigma & 4.8 & - & 9.8 & - & 0.86 & - \\
+g & 4.7 & 11 & 9.7 & 21 & 0.86 & 7.1 \\
+\sigma + \gamma & 3.5 & - & 8.2 & - & 0.49 & - \\
+g + \gamma & 3.5 & 0.19 & 8.2 & 1.7 & 0.49 & -0.76 \\
\end{array}
\]

- +\( g \): using galaxy counts alone neglecting the magnification effect in the theoretical template (\( C_{\ell}^{\theta \bar{\theta}} \)),

- +\( \sigma + \gamma \): combining galaxy counts, cosmic shear, and their cross-correlations taking into account the effect of magnification (\( C_{\ell}^{\bar{\theta} n_{i}} \), \( C_{\ell}^{\gamma n_{i}} \), \( C_{\ell}^{\gamma \gamma} \)),

- +\( g + \gamma \): combining galaxy counts, cosmic shear,

and their cross-correlations neglecting the effect of magnification, (\( C_{\ell}^{n_{i} n_{j}} \), \( C_{\ell}^{\gamma n_{i}} \), \( C_{\ell}^{\gamma \gamma} \)).

Note that, in all cases, we add the primary CMB information (i.e., \( C_{\ell}^{\bar{\theta} \bar{\theta}} \), \( C_{\ell}^{\theta E} \) and \( C_{\ell}^{E E} \) ) in the Fisher matrix. The primary CMB power spectra are used to estimate the cosmological parameters up to \( \ell = 3000 \). In Table III we show the forecast results of 1-σ constraints on \( f_{NL} \) for three representative surveys. Also, in Figs. 4-6 two-dimensional contours of 1-σ error on \( b_0 f_{NL} \), \( b_0 f_{NL} \) and \( b_0 - b_2 \) planes are plotted in the cases of HSC, DES and LSST taking into account or neglecting the magnifi-
cation effect.

Let us focus on the results from the galaxy counts alone, i.e., +n and +g (see red solid and dashed lines in Figs. 4-6). Naively, the statistical error on $f_{\text{NL}}$ is expected to be large if we properly take account of the magnification effect, because we need to specify the slope indices observationally and the number of parameters to be determined increases. As shown in Figs. 4-6, however, the statistical error on $f_{\text{NL}}$ does not change so much in all cases, and the fractional change is around a sub-percent level (see Table III). These figures also show that, as mentioned in Sec III, the degeneracy between $f_{\text{NL}}$ and the galaxy bias ($b_0$ and $b_z$) is weak (the correlation coefficient is $\sim 0.1$). On the other hand, the systematic bias on $f_{\text{NL}}$ arising from the incorrect treatment of the magnification effect is significant. As shown in Table III, the systematic bias is apparently very large for DES. Taking the ratio of the systematic bias to the statistical error, however, the largest value is obtained from the LSST case amongst the three surveys. That is, the systematic bias is rather serious for LSST than for HSC or DES.

Next discuss the importance of cosmic shear information, i.e., +n+γ and +g+γ (see green solid and dashed lines in Figs. 4-6). Compared to the cases with galaxy counts alone, the addition of cosmic shear data would not only improve the statistical error, but also reduce the systematic bias on $f_{\text{NL}}$, irrespective of the treatment of the magnification effect. These results basically come from the non-vanishing shear-galaxy correlations, which also carry the information on $f_{\text{NL}}$, through the scale-dependent galaxy bias, as shown in Fig. 1. Table III shows that compared to the results with galaxy counts alone, the improvement of the constraint is by a factor of $\sim 2$ for LSST and of $\sim 1.3 - 1.5$ for HSC and DES. The size of systematic bias on $f_{\text{NL}}$ is now well within the 1-σ statistical error for HST and DES, but it is still non-negligible for LSST.

2. Dependence on maximum multipole $\ell_{\max}$, mean redshift $z_m$, number of redshift bin $N_{\text{bin}}$, and slope $s_i$

To elucidate the results in Sec III in more details, we here consider the dependence of the systematic bias and statistical error on the various parameters, especially focusing on the LSST-like survey. Fig. 7 shows the systematic bias $\Delta f_{\text{NL}}$ using the tomographic technique with $N_{\text{bin}} = 3$, plotted against the maximum multipole used in the parameter estimation, $\ell_{\max}$. In each panel, the results obtained from a different survey depth are presented: $z_m = 0.5, 1.0, 1.5$ and $2.0$ (in each case, redshift ranges of each redshift bin are summarized in Table III). To infer the significance of the systematic bias, we also plot the 1-σ constraint on $f_{\text{NL}}$, $\sigma(f_{\text{NL}})$, taking a proper account of the magnification effect (shaded region). Fig. 8 also shows the same results as in Fig. 7, but, this time, we do not use the tomographic technique (i.e., $N_{\text{bin}} = 1$), and the slope index is simply set to $s_1 = 1.0$. Note that the systematic bias does not depend on $f_{\text{sky}}$, while the 1-σ constraint is proportional to $\sqrt{f_{\text{sky}}}$. Also, for a sufficiently large number density with $N_{g, \text{sky}} \geq 10$ arcmin$^{-2}$, the results are almost insensitive to the choice of $N_g$. Hence, the noise spectra are computed with fixed values of $f_{\text{sky}} = 0.5$ and $N_{g, \text{sky}} = 100$ arcmin$^{-2}$.

Let us consider the results using the galaxy counts alone with $N_{\text{bin}} = 3$ (see Fig. 7). As increasing $z_m$, the statistical error on $f_{\text{NL}}$ (the thin shaded region) becomes rather improved, and the systematic bias (the red dashed

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
$N_{\text{bin}}$ & $\sigma(f_{\text{NL}})$ & $\Delta f_{\text{NL}}$ \\
\hline
3 & $+n$ & $+g$ \\
\hline
100 [arcmin$^{-2}$] & $+n + \gamma$ & $+g + \gamma$ \\
\hline
\end{tabular}
\caption{Dependence on maximum multipole $\ell_{\max}$, mean redshift $z_m$, number of redshift bin $N_{\text{bin}}$, and slope $s_i$}
\end{table}
Fig. 9 shows the results in the case of the LSST survey. Here, the results are plotted against the shift of the slope index, $s$, defined by $s_i = s_{i,\text{fid}} + s$. The lines with different color indicate the systematic bias of $f_{\text{NL}}$ obtained by varying the different slope index. Note that the statistical errors depicted as shaded regions are evaluated specifically in the case varying the slope $s_3$.

Fig. 9 indicates that the systematic bias of $f_{\text{NL}}$ is insensitive to the variation of slope index in lower redshift bin, but rather sensitive to it at higher redshift bin. This result is quite reasonable because the magnification effect on high-$z$ bin is significant compared to low-$z$ bin (see Fig. 2). On the other hand, the statistical error on $f_{\text{NL}}$ is insensitive to the variation of slope index, as it is expected from Sec. III B. In this respect, depending on the value of slope indices at high redshifts, the magnification effect on constraining primordial non-Gaussianity may become even more serious, and again, should be properly taken into account in the theoretical template.

V. SUMMARY

In this paper, we studied the impact of magnification effect on the detection of $f_{\text{NL}}$ from photometric survey. As representative upcoming photometric surveys, we considered HSC for deep, and DES for wide, and LSST for an idealistically deep and wide survey. From the Fisher matrix analysis, we showed that, an incorrect treatment of the magnification effect on the theoretical template of angular power spectra leads to the systematic bias in the best-fit value of $f_{\text{NL}}$. Especially, using galaxy counts alone, the size of systematic bias is significant for all three surveys (HSC, DES and LSST), and true values of $f_{\text{NL}}$ would typically go outside the 3-$\sigma$ error of the biased confidence region. However, we found that additional information from the cosmic shear observations helps not only to improve the constraint, but also to reduce the systematic bias on $f_{\text{NL}}$. As a result, the systematic bias can become negligible for HSC and DES surveys, compared to their expected errors on $f_{\text{NL}}$. A proper account of the magnification effect does not increase the statistical error on $f_{\text{NL}}$ ($\lesssim 1\%$). Nevertheless, for LSST, a relative significance of the systematic bias still remains and the magnification effect should be correctly taken into account in the theoretical treatment.

We further explored the various cases by changing parameters characterizing the survey properties, and showed that the tomographic technique using photometric redshift information leads to a significant improvement on the statistical error on $f_{\text{NL}}$, but it does not help to reduce the systematic bias. In any case, high-$z$ observations are indispensable for tightly constraining primordial non-Gaussianity, but the influence of the magnification effect would be inevitable. This is particularly true for deep imaging surveys like LSST ($z_m \gtrsim 1.5$). A proper account of the magnification effect in the theoretical template is thus quite essential for an unbiased estimate of
primordial non-Gaussianity.

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