Detection of Cosmic Magnification via Galaxy Shear - Galaxy Number Density Correlation from HSC Survey Data

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We propose a novel method to detect cosmic magnification signals by cross-correlating foreground convergence fields constructed from galaxy shear measurements with background galaxy positional distributions, namely shear-number density correlation. We apply it to the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) survey data. With 27 non-independent data points and their full covariance, $\chi^2_0 \approx 34.1$ and $\chi^2_2 \approx 24.0$ with respect to the null and the cosmological model with the parameters from HSC shear correlation analyses in Hamana et al. [1], respectively. The Bayes factor of the two is $\log_{10} B_{02} \approx 2.2$ assuming equal model probabilities of null and HSC cosmology, showing a clear detection of the magnification signals. Theoretically, the ratio of the shear-number density and shear-shear correlations can provide a constraint on the effective multiplicative shear bias $\bar{m}$ using internal data themselves. We demonstrate the idea with the signals from our HSC-SSP mock simulations and rescaling the statistical uncertainties to a survey of 15000 deg$.^2$. For two-bin analyses with background galaxies brighter than $m_{\text{lim}} = 23$, the combined analyses lead to a forecasted constraint of $\sigma(\bar{m}) \sim 0.032$, 2.3 times tighter than that of using the shear-shear correlation alone. Correspondingly, $\sigma(S_3)$ with $S_3 = \sigma_3/(\Omega_m/0.3)^{0.5}$ is tightened by $\sim 2.1$ times. Importantly, the joint constraint on $\bar{m}$ is nearly independent of cosmological parameters. Our studies therefore point to the importance of including the shear-number density correlation in weak lensing analyses, which can provide valuable consistency tests of observational data, and thus to solidify the derived cosmological constraints.

1. INTRODUCTION

Weak gravitational lensing effects (WL), mainly consisting of cosmic shear and magnification, probe directly the matter distribution of the Universe, and are uniquely important in cosmological studies [2, 3, 4, 5, 6].

Cosmic shear induces tiny image distortions on distant galaxies. By accurately measuring their shapes, shear signals can be extracted statistically. This has been the main stream of current weak lensing studies. With large surveys, such as the on-going Dark Energy Survey [DES, 7], the Kilo-Degree Survey [KiDS, 8], and the Hyper Suprime-Cam Subaru Strategic Program survey [HSC-SSP, 9], the derived cosmological constraints are improving significantly [e.g., 10, 11, 12].

Cosmic magnification, on the other hand, leads to slight changes of the galaxy spatial distribution due both to the lensing magnification of galaxy flux and the lensing increase of solid angle [13, 14]. In principle, cosmic magnification can be extracted from photometric surveys without the need of shape measurements. There have been extensive theoretical investigations on the complementarity of cosmic magnification and shear and how to accurately reconstruct cosmic magnification power spectrum purely from the spatial distribution of galaxies [e.g., 15, 16, 17, 18, 19, 20], where the galaxy intrinsic clustering and the bias are the main concerns. Observational detections of cosmic magnification using galaxy distributions have been reported [e.g., 21, 22, 23].

Currently, most of the studies concentrate either on cosmic shear or on cosmic magnification. Combined analyses employing both sides of the signals are done for clusters of galaxies [24], but are still lacking on cosmic scales. In this paper, we put forward a method to cross-correlate foreground shear and background position of galaxies. This not only can lead to clean detections of cosmic magnification signals without being affected by galaxy bias, but also can, by combining with shear-shear correlation, provide important consistency tests of observational data themselves and further constrain the shear measurement bias. Validated by mock simulations, we apply the analyses to HSC-SSP data, and show cross-correlation signals with high significance. We also forecast the potential constraint on the multiplicative bias parameter $m$ of shear measurement from future large surveys.

The paper is organized as follows. In Sec. III we present our cross-correlation methodology theoretically. Sec. IV describes the HSC-SSP data used in our analyses. Sec. V contains details of the cross-correlation analyses. In Sec. VI we show the results measured from our HSC mock simulations and from observations. The cosmological potential of combining the shear-shear and shear-number density correlations is shown in Sec. VII. Summary and discussions are given in Sec. VIII.
II. METHOD

In our analyses, we cross-correlate the foreground convergence field constructed from the shear measurements and the spatial distribution of background galaxies (hereafter, shear-number density correlation). Specifically, we have

$$\omega_{ij}(\theta) = \langle \kappa_i(\mathbf{n}) \delta_j(\mathbf{n}^\prime, m_{lim}) \rangle_0,$$

where $\theta$ is the angular separation of the two directional vectors $\mathbf{n}$, $\mathbf{n}^\prime$, $\kappa_i$ is the foreground lensing convergence field from the galaxy shear measurements, and $\delta_j$ is the fluctuation field of background galaxy number count with the limiting magnitude $m_{lim}$. The latter is given by

$$\delta_j(\mathbf{n}^\prime, m_{lim}) = \delta_{ij}(\mathbf{n}^\prime, m_{lim}) + \delta_{ij}(\mathbf{n}^\prime, m_{lim}),$$

where $\delta_{ij}$ describes the intrinsic clustering of the galaxy sample, which is related to the density fluctuation field with a bias factor involved. The second term $\delta_{ij}$ is the fluctuation arising from the lensing magnification effect.

Assuming the foreground and the background are well separated, the intrinsic clustering term does not contribute to the correlation of Eqn. (1), and therefore eliminating the impact of the galaxy bias. For $\delta_{ij}$, it is [e.g., 2, 23]

$$\delta_{ij}(\mathbf{n}^\prime, m_{lim}) = \mu^\alpha(m_{lim})^{-1} - 1 \approx 2\kappa_j(\mathbf{n}^\prime)[\alpha(m_{lim}) - 1],$$

where $\alpha(m_{lim}) = 2.5d[\log_{10}N(m_{lim})]/dm_{lim}$ is the local slope of the galaxy cumulative number count $N(m_{lim})$ in log scale, and $\mu$ is the lensing magnification. The second expression in Eqn. (2) is the approximation in the weak lensing limit with $\kappa \ll 1$ and $\mu \approx 1 + 2\kappa$. Then we have

$$\omega_{ij}(\theta) = \langle 2[\alpha(m_{lim}) - 1] \kappa_i(\mathbf{n}) \kappa_j(\mathbf{n}^\prime) \rangle_0 = 2[\alpha(m_{lim}) - 1] \frac{1}{2\pi} \int_0^\infty \text{d}l P_{ij}^l(l) J_0(l\theta),$$

where $J_0$ is the zero-th order Bessel function and $P_{ij}^l$ is the convergence cross power spectrum between $i$ and $j$ given by

$$P_{ij}^l(l) = \int \text{d}w \frac{q_{ij}(w) q_{ij}(w)}{f_k^2(w)} P_\delta \left( \frac{l}{f_k(w)} w \right),$$

with

$$q_{ij}(w) = \frac{3H_0^2\Omega_m}{2\alpha(w)c^2} \int w \text{d}w^\prime p_{\delta}(w) \frac{f_k(w^\prime - w)}{f_k(w^\prime)}.$$  

Here $w$, $f_k(w)$, $P_\delta$ and $p_{\delta}(w)$ are the comoving radial distance, comoving angular diameter distance, 3-dimensional matter power spectrum, and the radial distribution calculated from the redshift distribution for $i$-th $(j$-th) redshift bin, respectively. $\Omega_m$, $H_0$, $a$ and $c$ are the present matter density parameter, Hubble constant, cosmic scale factor, and the speed of light, respectively. We note that the shear-number density correlation here is, in some sense, the inverse of the galaxy-galaxy lensing analyses which correlate foreground galaxy positions with background shear signals.

For the shear-shear correlation between $i$ and $j$, we have

$$\xi_{ij}(\theta) = \langle \gamma_i(\mathbf{n}) \gamma_j(\mathbf{n}^\prime) + \gamma_i(\mathbf{n}^\prime) \gamma_j(\mathbf{n}) \rangle_0 = \frac{1}{2\pi} \int_0^\infty \text{d}l P_{ij}^l(l) J_0(l\theta).$$

It is seen from Eqns. (4) and (7) that theoretically, $\omega_{ij}$ and $\xi_{ij}$ have exactly the same cosmology dependence with the ratio of the two being a constant $2[\alpha(m_{lim}) - 1]$, independent of $\theta$. Observationally, the shear measurements often involve a multiplicative bias and an additive bias. While the additive bias can be estimated from the data, the determination of the multiplicative bias $m$ needs extra calibrations. Assuming that we have no knowledge of $m$, then the two correlations calculated from the observational data should be, to a very good approximation, $\hat{\omega}_{ij} = (1 + \tilde{m}_i)\omega_{ij}$ and $\hat{\xi}_{ij} = (1 + \tilde{m}_i)(1 + \tilde{m}_j)\xi_{ij}$, where $\tilde{m}_i$ and $\tilde{m}_j$ are the effective multiplicative bias of the shear sample $i$ and shear sample $j$, respectively. Then

$$\hat{\omega}_{ij}(\theta) \hat{\xi}_{ij}(\theta) = 2[\alpha(m_{lim}) - 1]/(1 + \tilde{m}_j).$$

Thus the ratio of Eqn. (8) provides a means to calibrate $m$ in a cosmology-independent way using the observational data themselves if $\alpha$ can be determined accurately.

In the following, we apply the cross-correlation analyses to the HSC-SSP data.

III. OBSERVATIONAL DATA

HSC-SSP is a large imaging survey with weak lensing cosmology as a major science driver [9]. In our analyses, we use data from first and second data release PDR1 and PDR2 [25, 26], and the first-year shear catalog (S16A) [27].

To implement the cross correlation analyses, we divide galaxies into low- and high-redshift bins, with $0.2 \leq z_p \leq 0.7$ and $1.0 \leq z_p \leq 1.5$, respectively, where $z_p$ is the best-fit value of the photometric redshift (photo-$z$) of a galaxy [28, 29]. For the low-redshift bin, we use the S16A shear catalog to construct the convergence field, adopting the selection criteria listed in Table 4 of Mandelbaum et al. [27]. The sample’s redshift distribution is shown in blue in the left panel of Figure 1 by stacking the photo-$z$ distribution of individual galaxies.

For the high-redshift bin, we take the photometric data from PDR2. To ensure the data quality and avoid introducing significant photometric bias, besides the common flag criteria in Aihara et al. [25], two extra cuts are applied: the $i$-band flux signal-to-noise ($S/N$) ratio $\geq 5$ and iblendness_abs_flux, a measure of how strongly an object is blended, $\leq 10^{-0.375}$. We further take $i$ _extendedness_value $= 1$ at $i < 24.5$ to remove the impact of point sources [25]. In addition, we make a cross match in position between S16A and PDR2, and exclude those galaxies with a small position difference $(\leq 0.5$ arcsec) but a large magnitude difference $(\geq 0.5)$, which amount to $\sim 3\%$ of the whole sample. For magnification detections, we calculate the magnitude of each galaxy by $\text{mag} = \text{icmodel}_{\text{mag}} - a_i$ with $a_i$ the Galactic extinction correction in $i$-band given in the PDR2 catalog. The right panel of Figure 1 shows the magnitude distributions. By comparing with the HSC COSMOS
UltraDeep data [23], we find that the high-redshift sample is about 80% and 65% complete up to $m_{lim} \approx 23.5$ and 24.5, respectively. For magnification analyses, we then construct different subsamples with $m_{lim} \leq 22.5, 23.0, \text{ and } 23.5$, respectively. The impact of the incompleteness is tested with our mock simulations to be described later in the paper. The redshift distributions of these subsamples are shown in different colors in the left panel of Figure 1.

It is seen that the low- and high-redshift samples have only a small fraction of redshift overlap. We numerically check the contamination from the galaxy-convergence intrinsic correlation in the overlapped region. It is about 1–2% to $\omega_{ij}/[2(\alpha(m_{lim})–1)]$, negligible in the analyses here. For future high precision studies, we should investigate this contamination carefully.

To perform the analyses, we select 52 overlapped fields between S16A and PDR2, with 40 having an area of $1.5 \times 1.5 \text{ deg}^2$ each, and 12 with $1.0 \times 1.0 \text{ deg}^2$ each cropped from partially-overlapped tracts. The total area is $\sim 100 \text{ deg}^2$. For the low-redshift shear sample, the weighted number density is $n_g \sim 8.0 \text{ arcmin}^{-2}$. For the high-redshift PDR2 data, $n_g \sim 0.28, 0.77, \text{ and } 1.69 \text{ arcmin}^{-2}$, for $m_{lim} = 22.5, 23.0, \text{ and } 23.5$, respectively. We estimate the slope $\alpha$ by bootstrapping the 52 fields to generate 1000 sets of data. The average $\alpha$ for the three $m_{lim}$ is 2.48, 1.97, and 1.48 calculated with the interval of $\Delta m = 0.01$ around $m_{lim}$. The corresponding 1σ uncertainty is 0.052, 0.030, and 0.018. We test by using $\Delta m = 0.05$, and the $\alpha$ value differences are less than 1%.

For the corresponding shear-shear correlation analyses, S16A is used for both low- and high-redshift samples. We apply the same $m_{lim}$ to construct high-redshift shear subsamples. Their redshift distributions are nearly identical to the ones shown in the left panel of Figure 1.

IV. CROSS-CORRELATION ANALYSES

We first reconstruct the convergence fields from the low-redshift shear sample with the same procedures detailed in Liu et al. [30], which are summarized here. (1) The smoothed shear fields are calculated following Oguri et al. [31]. Specifically,

$$\langle \epsilon \rangle(\theta) = \frac{\sum_k w_k W_{\theta L}(\theta_k - \theta)e_k}{2 \sum_k w_k (1 - e_{\text{rms},k}^2)(1 + m_k)W_{\theta L}(\theta_k - \theta)} - \frac{\sum_k w_k W_{\theta L}(\theta_k - \theta)e_k}{\sum_k w_k (1 + m_k)W_{\theta L}(\theta_k - \theta)}$$

where $e_k$ is the two-component ellipticity of galaxy $k$, and $w_k$, $c_k$, $m_k$ and $e_{\text{rms},k}$ are the corresponding weight, additive and multiplicative biases of shear measurements, and the intrinsic ellipticity dispersion per component. We take the Gaussian smoothing kernel with $W_{\theta L}(\theta) = 1/(\pi \theta_G^2) \exp (-|\theta|^2/\theta_G^2)$ and $\theta_G = 1.5 \text{ arcmin}$. (2) From $\langle \epsilon \rangle(\theta)$, we reconstruct the convergence field $K_{\text{GRID}}$ sampled on $1024 \times 1024$ pixels for each of the 52 fields. (3) We generate smoothed filling-factor maps $f$ from the galaxy spatial distributions of the shear sample, and exclude regions with $f < 0.6$ [30]. The outermost $5\theta_G$ pixels in each of the four sides of a map are also removed to reduce the boundary effects. (4) We rotate each of the galaxies randomly, and reconstruct the noise part $N_{\text{GRID}}$ of the convergence fields following steps (1) and (2). In total, 30 sets of $N_{\text{GRID}}$ are generated for each field.

For the high-redshift galaxies from PDR2, we apply the same mask and boundary exclusion criteria as those of the foreground convergence fields. The remaining galaxies make up the background subsamples $G_B$ with different $m_{lim}$. We also generate 30 sets of random samples $G_R$ from the galaxies in each field by randomly populating them spatially.

An estimator for the shear-number density cross-correlation

FIG. 1. Left: Normalized redshift distributions of the foreground galaxy sample and background PDR2 galaxy subsamples with different magnitude cuts. Right: $i$-band differential galaxy number density of PDR2 wide (red) in comparison with that of HSC PDR1 COSMOS UltraDeep catalog (blue). Circles and squares are for the full and high redshift samples, respectively.
The calculations are done using Athena\textsuperscript{1}\cite{2005PASP..117..110R}. Considering the size of each selected field, a total of 9 bins with logarithmic bin-width of $\Delta \log_{10} \theta \sim 0.173$ are chosen with the central $\theta$ ranging from 1.21 to 29.65 arcmin. Note that in model calculations, the kernel $W_G$ applied to the foreground needs to be included in Eqn.(4) and also in Eqn.(7).

To estimate the shear-shear correlation between low- and high-redshift bins, we construct low-redshift shear fields $\Gamma_{\text{GRID}}$ on pixels directly from the smoothed shear fields $\langle \epsilon \rangle$. For high redshift part, we build shear subsamples $\gamma_j$ with $m_{\text{lim}} = 22.5, 23.0$, and 23.5 from S16A. The cosmic shear two-point correlations are then calculated over all preserved pixel-galaxy pairs $(ab)$ within some bin around $\theta$ using $\xi_{ij}(\theta) = \langle \Gamma_{\text{GRID}} \gamma_i(\theta) \rangle / \langle \mathcal{N}_{\text{GRID}} \gamma_j(\theta) \rangle$ = $\sum_{ab} w_b [\Gamma_{\text{GRID}}(\theta_a) \gamma_i(\theta_a) + \Gamma_{\text{GRID}}(\theta_b) \gamma_j(\theta_b)] / \sum_{ab} w_b$, where $\gamma_j(\theta_b) = (1 + \hat{m}) [e^b_2 R - c_b]$, with an ensemble correction of multiplicative bias $\hat{m}$ and reponsivity factor $R$ applied following\textsuperscript{27}.

V. HSC MOCK VALIDATION AND OBSERVATIONAL RESULTS

Before applying to data, we validate our analyses by building HSC-SSP mocks from ray-tracing simulations described in Liu et al.\textsuperscript{33}. We have 59 lensing-plane outputs between $z = 3$ and $z = 0$, and each consists of 96 maps of $3.5 \times 3.5$ deg$^2$ each.

With these lensing maps, we create HSC mocks as follows. (1) For high-redshift PDR2 mocks, the galaxy positions and magnitudes from PDR2 of the 52 fields are adopted. Because of the independence between the original HSC galaxy positions/magnitudes and our simulated lensing signals, we regard them as the unlensed quantities. The redshift $z_p$ is also kept. (2) For shear mocks, we preserve the position, magnitude, redshift $z_p$, and shear related quantities of each galaxy from S16A. We randomly rotate them to eliminate the original shear signals in the data. Otherwise the signals embedded in the HSC data will contaminate the mock simulation results of both shear-number density and shear-shear correlations. (3) We pad the mock galaxies into our simulated maps, and calculate the lensing signals at their positions by interpolating (in redshift and angular position) the grid signals on lensing maps. For high redshift PDR2 mocks, we obtain the deflection angle and magnification $\mu$ for each galaxy, and adjust

\textsuperscript{1}http://www.cosmostat.org/software/athena
its position and magnitude (adding a factor of $2.5\log_{10}(1/\mu)$) accordingly. For shear mocks, we follow the procedures of Oguri et al. [31] including the shear bias from S16A to our simulated lensing signal of each galaxy. (4) We do different paddings of (3), and generate 20 mocks for each of the 52 fields. (5) We randomly select one from the 20 for each field and compose one set of HSC mock with 52 fields. In total 200 sets of mock data are generated. (6) The same convergence reconstruction and correlation estimates are done as for the observational data. (7) The covariance matrices are estimated from the 200 mocks. The results are about the same as those calculated from 400 mocks.

In Figure 2, we show the results averaged over the 200 mocks. The blue and red symbols are for the shear-number density and shear-shear correlations, respectively. The solid and dashed lines are the corresponding model predictions with the listed $\alpha(m_{\text{lim}})$ values. The last panel shows $\tilde{\xi}_{ij}(\theta)$ or $\tilde{\xi}_{ij}(\theta)$ (1) with the theoretical expectation of 1:1 black line noting that we correct for the shear bias in calculating the correlations as shown in Eqns. (9) and (10) and $\tilde{\xi}_{ij}(\theta)$. The mock results agree well with that of the model, validating our analyses.

Our mock settings implicitly assume the completeness of the high-redshift PDR2 sample, which is not true for the real data. Ideally, to evaluate the effect of incompleteness, we should generate mock data from deeper surveys, and do analyses for the selected incomplete samples. This is infeasible here because of the small coverage of the HSC UltraDeep survey. We thus assess the impact by assuming an artificial incompleteness function to select galaxies from our high-redshift PDR2 mocks. Our results show, consistent with other studies, that the magnification signals from incomplete samples follow the predictions with $\alpha$ calculated from the underlying complete sample [34]. For our specific mocks, with the completeness fraction of $\sim 80\%$ and $\sim 70\%$, the $\alpha$ value estimated from the incomplete samples is lower by $\sim 4\%$ and $\sim 8\%$, respectively, than that from the complete sample. The effect of such changes on the shear-number density correlation is well within the statistical uncertainties here. In follow-up studies, we will investigate in detail the impact of incompleteness on future high precision analyses.

The results from the observational data are shown in Figure 3 with symbols and lines the same as those in Figure 2 except that the model is $\Omega_m = 0.346$ and $\sigma_8 = 0.749$ [1].

The observed shear-number density correlations follow the expected trend of varying $\alpha$, and are consistent with the theoretical predictions. With 27 non-independent data points and the full covariance, $\chi^2_T = 24.0$ and $\chi^2_0 = 34.1$ with respect to the model and to the null, respectively. The corresponding $p$-value of $p(\chi^2_T > \chi^2_0)$ is 0.63, four times higher than $p(\chi^2_0) = 0.16$. Assuming Gaussian likelihood and equal probability of the considered cosmological model and the null, the Bayes factor is $\log_{10} B_{T0} = \log_{10}\exp[-0.5(\chi^2_T - \chi^2_0)] \approx 2.2$, showing a solid detection of the signals [35].

**FIG. 3.** Correlation results from HSC-SSP observational data.
VI. COSMOLOGICAL POTENTIALS

With the shear multiplicative bias \( m \) corrected according to that given in S16A, we see from Figure 3 that \( \tilde{\omega}_{ij}/[2\alpha(m_{\text{lim}}) - 1] \) and \( \tilde{\xi}_{ij} \) follow each other well showing the consistency of the HSC shear and magnification signals, and the residual shear bias after correction is insignificant within the error bars.

Without the bias information (or it is incorrect), the ratio of the two correlations is given in Eqn. 5 containing the factor of \((1 + \tilde{m}_j)\). If \( \alpha(m_{\text{lim}}) \) can be well determined, the combination of the two can be used to calibrate \( \tilde{m}_j \) using observational data themselves, independent of cosmology. To demonstrate the idea, we perform a forecast of cosmological constraints by combining the shear-number density and shear-shear correlations in comparison with that using the shear-shear correlation alone.

To avoid the instability problem, we do not directly calculate the ratio. Instead, we perform analyses by combining the data vectors of \( \tilde{\omega}_{ij} \) and \( \tilde{\xi}_{ij} \). Specifically, we consider the same two redshift bins as we did for the HSC analyses, but scale the effective survey area from \( \sim 60 \text{deg}^2 \) to \( 15000 \text{deg}^2 \). For the high redshift bin, we use the subsample with \( m_{\text{lim}} = 23 \). How to combine different samples with different \( m_{\text{lim}} \) to enhance the constraining power will be our future tasks. The fiducial values of the correlation signals are taken from the mock results, and the covariance matrices are scaled by the considered area. The number densities of different galaxy samples are assumed to be the same as those of HSC analyses.

We consider three parameters \((\Omega_m, \sigma_8, \tilde{m})\) assuming the same \( \tilde{m} \) for low- and high-redshift shear samples. The value of \( \alpha(m_{\text{lim}}) = 1.96 \) from our mocks, and its uncertainty is estimated from the HSC data by bootstrap different fields and then scaled to \( 15000 \text{deg}^2 \), which gives \( \sigma_\alpha \approx 0.002 \).

The Fisher forecast results are shown in Figure 4 where the blue and red parts are for the case with \( \tilde{\xi}_{ij} \) only and that of combining \( \tilde{\omega}_{ij} \) and \( \tilde{\xi}_{ij} \), respectively. By including \( \tilde{\omega}_{ij} \), the constraint on \( \tilde{m} \) do improve significantly, and the degeneracies with \( \Omega_m \) and \( \sigma_8 \) are largely eliminated. Consequently, the constraints on the cosmological parameters are tightened, as presented in Table I. With SS and SP for shear-shear and shear-number density correlations and \( S_8 = \sigma_8(\Omega_m/0.3)^{0.5} \), the improvement on \( \tilde{m} \) and \( S_8 \) is 2.3 and 2.1 times, respectively.

The combination of the two correlations can also potentially reveal scale-dependent shear measurement bias or other systematics because then the ratio of the two should have a scale dependence. In the analyses here, because of the relatively large error bars, such a dependence is not seen clearly for HSC data. We will explore this potential in our follow-up studies with respect to future observations.

VII. SUMMARY AND DISCUSSION

In this study, we propose the shear-number density correlation analyses and apply to HSC data. The cosmic magnification signals are clearly detected with no galaxy bias involved. Combining with the shear-shear correlation allows us to check the data consistency internally. Our results show that the cosmic shear and magnification signals from HSC are consistent with each other within error bars. We further explore the potential of including shear-number density correlations in cosmological studies, revealing significant improvements of the constraints on \( \tilde{m} \) and \( S_8 \). Thus for future large weak lensing surveys, we advocate to include this information in addition to the shear-shear, galaxy clustering and galaxy-galaxy lensing analyses to enhance the cosmological gains. For that, this paper provides a proof of concept. We will carry out more detailed studies about different effects, such as sample incompleteness, dust effect, photo-z errors and intrinsic alignments. We will also investigate analyses methods to increase the signal-to-noise ratio of shear-number density correlations and how to include them in multi-bin tomographic studies.

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