Separating the Intrinsic Alignment Signal and the Lensing Signal using Self-Calibration in Photo-z Surveys with KiDS450 and KV450 Data

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ABSTRACT

To reach the full potential for the next generation of weak lensing surveys, it is necessary to mitigate the contamination of intrinsic alignments (IA) of galaxies in the observed cosmic shear signal. The self calibration (SC) of intrinsic alignments provides an independent method to measure the IA signal from the survey data and the photometric redshift information. It operates differently from the marginalization method based on IA modeling. In this work, we present the first application of SC to the KiDS450 data and the KV450 data, to split directly the intrinsic shape – galaxy density (Ig) correlation signal and the gravitational shear – galaxy density (Gg) correlation signal, using the information from photometric redshift (photo-z). We achieved a clear separation of the two signals and performed several validation tests. Our measured signals are found to be in general agreement with the KiDS450 cosmic shear best-fit cosmology, for both lensing and IA measurements. For KV450, we use partial (high-z) data, and our lensing measurements are also in good agreement with KV450 cosmic shear best-fit, however, our IA signal suggests a larger IA amplitude. We discussed the impact of photo-z quality on IA detection and several other potential systematic biases. Finally, we discuss the potential application of the information extracted for both the lensing signal and the IA signal in future surveys.

Key words: cosmology, gravitational lensing; weak, observations, large-scale structure of the universe, galaxy

1 INTRODUCTION

As the era of precision cosmology is moving forward, systematic effects have become the center of focus of cosmological studies. Cosmic shear is one of the primary probes to put constraints on cosmological models and to test gravity theories at cosmological scales (Kaiser 1992; Hu & Tegmark 1999; Heavens et al. 2000; Bacon et al. 2001; Ishak 2005, 2007; Joudaki et al. 2009; Weinberg et al. 2013; Ishak et al. 2006; Linder & Cahn 2007; Heavens 2009; Dossett et al. 2011; Dossett & Ishak 2012, 2013). Unfortunately, cosmic shear suffers from serious systematic effects (Erben et al. 2001; Bacon et al. 2001; Bernstein & Jarvis 2002; Hirata & Seljak 2003; Heymans et al. 2004; Ishak et al. 2004; Bridle & King 2007; Faltenbacher et al. 2009), which require detailed studies in regards to their impacts on cosmology and also methods to remove them. Moreover, some tension persists between current cosmic shear surveys, i.e. KiDS (Kilo Degree Survey, Hildebrandt et al. (2017, 2018)), DES (Dark Energy Survey, Troxel et al. (2017)), and HSC (Hyper Suprime-Cam, Hamana et al. (2019); Hikage et al. (2019)), and CMB experiment Planck (Planck Collaboration et al. 2018) which manifests itself as a discordance in the value of the amplitude of matter fluctuations. To understand if this tension
comes from some systematic effects or new physics beyond the current standard ΛCDM cosmological model, all the systematics need to be dealt with carefully.

Intrinsic alignment (IA) of galaxies constitutes one of the most important systematic effects in cosmic shear studies. Because of the non-random orientations of galaxies due to local effects, such as the tidal gravitational field or the tidal torqueing with angular momentum, there are additional non-vanishing correlations from the intrinsic galactic alignments that contaminate the cosmic shear measurements. For 2-point correlations, the contamination includes the GI-type of IA (which denotes to a correlation between a tangentially lensed background galaxy and an intrinsically aligned foreground galaxy Hirata & Seljak (2003)) and the II-type of IA (which denotes to a correlation between a tangentially aligned toward the same matter structure), see for example (Catelan et al. 2001; Hirata & Seljak 2003; King 2005; Mandelbaum et al. 2006; Hirata et al. 2007). For more information on this topic and some more recent developments on the IA problem, we refer the reader to the following reviews or papers (Troxel & Ishak 2015; Kiessling et al. 2015; Kirk et al. 2015; Joachimi et al. 2015; Kilbinger 2015; Blazek et al. 2017; Troxel et al. 2017; Mandelbaum 2018).

To solve this IA contamination problem and obtain a cleaner signal of cosmic shear, multiple models of IA have been proposed. Such models take into consideration the local tidal field and angular momentum, redshift evolution, luminosity and type of galaxies, see for example (Hirata & Seljak 2004; Bridle & King 2007; Okumura et al. 2009; Joachimi et al. 2013; dosSantos & Ishak 2013; Joachimi et al. 2015; Krause et al. 2016; Blazek et al. 2015, 2017; Chisari et al. 2017). These models introduce IA nuisance parameters that are included along with the cosmological parameters to be constrained by cosmic shear data. This is referred to as the marginalization method, and is widely used in current cosmic shear studies, see for example (Heymans et al. 2013; Hildebrandt et al. 2017; Troxel et al. 2017; Hildebrandt et al. 2018; Hikage et al. 2019; Hamana et al. 2019). An alternative approach for IA mitigation is the Self-Calibration (SC) method for the 2-point IA Zhang (2010b,a) which was also extended to the 3-points Troxel & Ishak (2012a,c,b). The SC method does not put strong assumptions on the underlying IA model. It uses extra observables from the same galaxy survey to statistically separate IA-related correlation signal from the lensing signal, then uses mathematical approximations to propagate and subtract the measured IA signal in the cosmic shear measurement, see further description on this process and some recent forecasts for cosmic shear surveys in Yao et al. (2017, 2019).

In a previous work (Yao et al. 2017), we quantified the improvement one can obtain by using the original SC2008 (Zhang 2010b) for the IA mitigation. It can significantly reduce the GI type of IA contamination resulting in a more accurate estimation of the best-fit cosmological parameters. The very first step of the SC2008 process is the separation of the $C_{fg}$ IA signal in a “galaxy-galaxy lensing”-like approach (here it means the method is carried out within the same survey and same photo-z bin, without requiring the application of spectroscopic redshift). With such a measurement, the GI signal can be obtained in a way that is independent of the IA model. The application of this $C_{fg}$ measurement can also be used in another SC2010 (Zhang 2010a) method to self-calibrate the II type of IA signal. This method has also been applied in theoretical predictions in (Yao et al. 2019) as well as verification with simulations (Meng et al. 2018). Moreover, it can also be used in CMB lensing to clean the IA contamination (Troxel & Ishak 2014). Therefore, the extraction of the $C_{fg}$ signal is very important.

In this work, we present the separation between the IA-galaxy density ($I_g$) signal and the gravitational lensing-galaxy density ($G_g$) signal by applying the SC to the KiDS450 (Hildebrandt et al. 2017) and KV450 (Hildebrandt et al. 2018) data. We perform a theoretical analysis of how to apply SC to a galaxy shear catalog. We numerically calculate the key ingredient for IA separation, $Q_i(f)$ of photo-z. We take into account several bias corrections to the lensing catalog as discussed in Hildebrandt et al. (2017, 2018), and measure the two 2-points correlation functions introduced by the SC method, as extra observables, and they show a clear separation. After achieving the separation of the lensing signal and IA signal, we discuss how these different types of extra cosmological information can help future cosmological studies. A separate Letter reporting the specific detection of the gravitational shear – intrinsic shape correlation (GI) and related work can be found in Pedersen et al. (2019). Some extensions on the future usage of the separated signal are included in the Appendix.

2 METHODS

2.1 Self Calibration - the scaling relation

The intrinsic alignment of galaxies will lead to an additional IA term in observed galaxy shapes, besides the cosmic shear and the shot noise, i.e., $γ_{obs} = γ^G + γ^N + γ^I$. When cross-correlating the galaxy shapes, the shot noise will only correlate with itself, however, there will exist GI and II types of IA contamination in the correlation. In terms of power spectra, it can be written as (Bridle & King 2007):

$$ C_{ij}^{(gG)}(f) = C_{ij}^{GG}(f) + C_{ij}^{GI}(f) + C_{ij}^{GI}(f) + C_{ij}^{II}(f) + δ_{ij}C_{ii}^{GG,N} $$

where $C_{ij}^{(gG)}$ denotes the cross shape-shape power spectrum between redshift bin $i$ and redshift bin $j$. $G, I, N$ denotes to gravitational lensing, intrinsic alignment, and noise, respectively.

Because of symmetry, a choice of $i < j$ can be applied. We note that the SC2008 method (Zhang 2010b) doesn’t apply to auto-spectra with $i \neq j$. By using only cross-spectra, the impact of $C_{ij}^{GI}$ and $C_{ij}^{II}$ is minimized, as they are mainly local effects and are only significant at small physical separations. This is because the intrinsic alignment of galaxies is caused by local effects, such as tidal alignment (Bridle & King 2007) or tidal torqueing (Blazek et al. 2017). As a result, the II correlation will only exist within small separations, and the strength of GI correlation will depend on the ordering of the redshift bins.

In order to extract the IG contamination using the observable $C_{ii}^{IG}$, a scaling relation is derived (Zhang 2010b) under small-bin approximation, $C_{ij}^{IG}(f) \approx W_{ij}\Delta_i C_{ii}^{IS}(f)$,

$$ C_{ij}^{IG}(f) \approx \frac{W_{ij}\Delta_i}{b_i(f)} C_{ii}^{IS}(f), $$

where $W_{ij}$ is the weight of the bin.
where $W_{ij}$ is the weighted lensing kernel, defined as:

$$W_{ij} = \int_0^{\infty} dz_L \int_0^{\infty} dz_S [W_L(z_L, z_S) n(z_L) n(j)]_L.$$  

(3a)

$\Delta_i$ is an effective width of $i^{th}$ redshift bin, defined as:

$$\Delta_i^{-1} = \int_0^{\infty} n_i^2(z) \frac{dz}{dz_i}.$$  

(3b)

and $b_i(z)$ is the galaxy bias averaged over the redshift bin. It can be inferred from the following relation:

$$C_{ii}^{\Delta^2}(f) = b_i^2(t) C_{ii}^{\text{true}}(f).$$  

(3c)

In Eqs. (3a), (3b) and (3c), $W_L$ is the lensing kernel; $z_L$ and $z_S$ are the redshift of the lens and source, respectively; $n(z)$ is the true redshift distribution of the $i^{th}$ tomographic bin; $\chi$ is the comoving distance; $C_{ii}^{\text{true}}$ is the fiducial matter power spectrum; and $C_{ii}^{\Delta^2}$ is the observed galaxy-galaxy clustering power spectrum. Therefore, the task of measuring $C_{ii}^G$ is converted to that of measuring $C_{ii}^L$, the IA-galaxy correlation. In CMB lensing, a scaling relation similar to Eq. (2) can be obtained, see Ref. Troxel & Ishak (2014).

### 2.2 Self Calibration - the separation of $C_{ii}^G$

Here we review the separation of the $C_{ii}^G$ signal from the lensing signal $C_{ii}^G$ in the shape-galaxy correlation $C_{ii}^G$. This is not only important in terms of the IA information extracted using SC, as explained in the previous subsection, but is also potentially useful in future galaxy-galaxy lensing analysis with the separated $C_{ii}^G$ signal. In this subsection, we reiterate the separation method, which was first derived in Zhang (2010b).

The separation of $C_{ii}^G$ from $C_{ii}^G$ is done by the virtue of their distinct dependencies on the relative position of galaxies in a pair. In a pair of galaxies, let us denote the photo-z of the galaxy used for shape measurement as $z_{\text{Pho}}$ and that of the galaxy used for number density measurement as $z_{\text{G}}$. The $l - g$ correlation does not depend on the ordering of galaxies in a pair along the line of sight as long as the physical distance between them is fixed. Therefore, $C_{ii}^G$ remains the same for galaxy pairs with $z_{\text{Pho}} > z_{\text{G}}$ and $z_{\text{Pho}} < z_{\text{G}}$; given that the separation $|z_{\text{Pho}} - z_{\text{G}}|$ does not change. However, on account of the geometry dependence of lensing, $C_{ii}^G$ is statistically smaller for a pair with $z_{\text{Pho}} > z_{\text{G}}$ than for the pair with $z_{\text{Pho}} < z_{\text{G}}$. We can, then, construct the following two observables:

$$C_{ii}^{G_i} = C_{ii}^G + C_{ii}^{\Delta^2},$$  

(4a)

$$C_{ii}^{\Delta^2} = C_{ii}^{G_i} + C_{ii}^{G_i} |_{S},$$  

(4b)

where "$S$" denotes only correlating the pairs with $z_{\text{Pho}} < z_{\text{G}}$. Due to the fact that, unlike the lensing signal, the IA signal does not depend on the ordering of the source-lens pair, we can write $C_{ii}^{\Delta^2} |_{S} = C_{ii}^{\Delta^2}$, however, $C_{ii}^{G_i} |_{S} < C_{ii}^{G_i}$.

This drop in the lensing signal is captured by the quantity $Q_i(t)$, defined as:

$$Q_i(t) = \frac{C_{ii}^{\Delta^2} |_{S}(t)}{C_{ii}^{\Delta^2}(t)}.$$  

(5)

which can be calculated using only the redshift distribution, including the observed photo-z distribution and the estimated true redshift distribution, of the survey. The value of $Q_i$ can roughly represent the photo-z quality in the $i^{th}$ redshift bin. Based on the definition, the range will be $0 < Q_i < 1$, in which $Q_i = 1$ stands for very good photo-z quality, and $Q_i = 0$ means spectroscopic-level photo-z quality.

By combining Eq. (4a), (4b) and (5), the separation of $C_{ii}^G$ can be achieved (Zhang 2010b):

$$C_{ii}^G(t) = \frac{C_{ii}^{G_i} |_{S}(t) - Q_i(t) C_{ii}^{\Delta^2}(t)}{1 - Q_i(t)}.$$  

(6)

In this work, we use KiDS450 and KV450 data to detect the differences in Eq. (4a) and (4b), and show that SC can separate these two observables due to the physical differences between lensing and IA. Then the direct detection of Eq. (6) in configuration space is also achievable. We discuss the robustness of the signal separation, and the usage of the information from the separated lensing signal and the IA signal. The generalized SC signal to cosmic shear or CMB lensing is left for future studies.

### 2.3 $Q_i$ measurements

According to Eq. (6), the estimation of $Q_i$ plays an important role in the IA signal separation. Theoretically, $Q_i$ is calculated using Eq. (5), in which

$$C_{ii}^{G_i} |_{S}(t) = \int_0^{\infty} W_i(\chi) n_i(\chi) b_i P_{S_k}(k) \frac{\chi}{\mu} d\chi,$$  

(7a)

$$C_{ii}^{\Delta^2}(t) = \int_0^{\infty} W_i(\chi) n_i(\chi) b_i P_{S_k}(k) \frac{\chi}{\mu} n_i(\chi) d\chi.$$  

(7b)

Here $W_i$ is the lensing efficiency function, defined as:

$$W_i(\chi) = \frac{3}{2} \Omega_m H_0^2 c^2 (1 + z_L) \int_{\chi_L}^{\infty} n_i(\chi_S)(\chi_S - \chi_L) \chi_S \chi_L d\chi_S.$$

(8)

where, $n_i(\chi)$ is the true redshift galaxy distribution in the $i^{th}$ redshift bin; $\chi$ is the comoving distance; $b_i$ is the galaxy bias; $P_{S_k}$ is the matter power spectrum. Based on the definition, the "$i^{th}$" sign denotes only correlating the $\gamma - g$ pairs with $z_{\text{Pho}} < z_{\text{G}}$. To fulfill this definition, a quantity $n_i(z) = n_i(z_L = z_G = z)$ for the $i^{th}$ tomographic bin is defined in Zhang (2010b) as: Eq. (10) and (11) shown on the next page.

in which $z_L$ and $z_G$ denote to the redshifts of the lens, the galaxy count, and the shear source; $z_{\text{Pho}}$ is the true redshift; $z_{\text{Pho}}^{\text{min}}$ and $z_{\text{Pho}}^{\text{max}}$ are the minimum and maximum photo-z in the $i^{th}$ tomographic bin; $W_L$ is the lensing kernel:

$$W_L(z_L, z_S) = \left\{ \begin{array}{ll} \frac{3}{2} \Omega_m H_0^2 c^2 (1 + z_L) \chi_L (1 - \frac{z_S}{\chi_S}) & \text{for } z_L < z_S; \\ 0 & \text{otherwise} \end{array} \right.$$  

(12)

$p(z_{\text{Pho}})$ is the probability distribution function (PDF), which is assumed to be Gaussian, as in our previous works (Zhang 2010b; Yao et al. 2017):

$$p(z_{\text{Pho}}) = \frac{1}{\sqrt{2\pi}s_\text{Pho}(1+z)} \exp \left[ \frac{(z - z_{\text{Pho}} - \Delta z_i)^2}{2(s_\text{Pho}(1+z))^2} \right].$$  

(13)
theoretically calculated the according to Eqs. (4a) and (4b), we can not only separate the $\gamma_{\text{SG}}$ which is the lensing-galaxy signal within the same $w$, $\bar{J}_G$ where, the superscripts $G_{\gamma}$, $P_{\gamma}$, $S_{\gamma}$ for $0$ otherwise.

The front factor of $2$ in equation (10) is according to (Zhang 2010b) given by equation (11).

From the expressions above, one can see that to calculate $Q(t)$, the values we need are the photo-z distribution $n_f^P(z^P)$, the true redshift distribution $n_f^P(z^P)$, the lensing signal $\gamma_{\text{SG}}$, the lensing theory (for example, in Eq. (8)), and a fiducial cosmology (for example, $P_8$ in Eq. (7a)). In Ref. Yao et al. (2017), we theoretically calculated the $Q(t)$ using the steps above for LSST. We showed that the value of $Q(t)$ is almost scale-independent, and we discussed that its measurement uncertainty is negligible for a survey with photo-z quality like LSST.

## 2.4 Two-point statistics

In this section, we present the analysis of the correlation functions we need for the separation of the lensing signal and the IA signal using SC. First, we transform the target correlations $C^{G\gamma}_S(t)$ and $C^{G\gamma}_R(t)$ from $t$-space to $w^{G\gamma}(\theta)$ and $w^{I\gamma}(\theta)$ respectively, in real space. This is done using a Hankel transformation (Joudaki et al. 2018):

$$w^{(G\gamma,I\gamma)}(\theta) = \frac{1}{2\pi} \int dt \ |C^{G\gamma,I\gamma}(t)| J_2(t\theta)$$  \hspace{1cm} (15)

where, the superscripts $G\gamma$ and $I\gamma$ mean shear-galaxy and IA-galaxy correlation functions respectively; and $J_2(x)$ is the Bessel function of the first kind and order 2.

As we have shown in Figs. 1 and 2 here and in previous work Yao et al. (2019), the value of $Q_1(t)$ remains almost constant and can be approximated to its mean value $\bar{Q}_1$. Then, using Eq. (15) in Eq. (6) gives us:

$$w^{I\gamma}(\theta) = \frac{\bar{w}^{I\gamma}(\theta) - \bar{Q}_1 \bar{w}^{I\gamma}(\theta)}{1 - \bar{Q}_1},$$  \hspace{1cm} (16)

where, $\bar{w}^{I\gamma} = w^{I\gamma} + w^{G\gamma}$ is the observed shape-galaxy correlation, in which $\gamma$ represents the observed galaxy shape $\gamma_{\text{obs}} = \gamma^G + \gamma^I + \gamma^N$ as discussed earlier. Nevertheless, according to Eqs. (4a) and (4b), we can not only separate the IA signal, but also the lensing signal:

$$w^{G\gamma}(\theta) = \frac{\bar{w}^{I\gamma}(\theta) - \bar{Q}_1 \bar{w}^{I\gamma}(\theta)}{1 - \bar{Q}_1},$$  \hspace{1cm} (17)

which is the lensing-galaxy signal within the same $t$th redshift bin. This is different from the conventional galaxy-galaxy lensing as: (1) it correlates the lens and source within the same redshift bin in the same survey; (2) it doesn’t require spectroscopy. We will discuss this more later.

In Eq. (16) the observables are $w^{I\gamma}$ and $w^{G\gamma}$. Therefore we need to calculate these correlation functions from the KiDS450 shear catalog. We use the following estimator (Mandelbaum et al. 2006) for this purpose:

$$w^{I\gamma} = \frac{\sum_{j=1}^{N} w_{ij} \gamma_j}{\sum_{j=1}^{N} (1 + m_j) \gamma_j} - \frac{\sum_{j=1}^{N} w_{ij} \gamma_j}{\sum_{j=1}^{N} (1 + m_j) \gamma_j}.$$  \hspace{1cm} (18)

where $\sum_{j=1}^{N} w_{ij} \gamma_j$ means summing over all the tangential ellipticity (E) - galaxy count in the data (D) pairs, $\sum_{j=1}^{N} (1 + m_j) \gamma_j$ means summing over all the tangential ellipticity (E) - galaxy count in the random catalog (R) pairs. After normalization with the number of galaxies, $\sum_{j=1}^{N} (1 + m_j) \gamma_j$ in the random catalog are quite similar in the large scale structure we are interested in, as the boost factor (the ratio of these two) is 1 (Mandelbaum et al. 2005; Singh et al. 2017).

For the second pipeline, we make use of Treecorr’s (Jarvis et al. 2004) built-in functionality to have the correlation estimator become

$$w^{I\gamma} = NG - RG,$$  \hspace{1cm} (19)

Where the $NG$ refers to the number count-shape correlation for the same catalog and bin. While $RG$ is the number count-shape correlation between the random catalog and the same catalog and bin as for the shape in $NG$, while the shape calibration for the magnification bias $m$ in the second pipeline is included in the individual galaxy shape.

The random catalog is generated using the KiDS450 footprint mask (Hildebrandt et al. 2017), aiming to subtract the selection bias in the correlation function from the shape of the footprint of the survey. The size of the random catalog used in pipeline one is 9 times the size of the whole KiDS450 catalog. Because the analysis is approached in 4 different redshift bins, the size of the random catalog is approximately 36 times the associated KiDS catalog in a single bin. The large random catalog is aimed to reduce the measurement uncertainty caused by the 2nd term in the RHS of Eq. (18).

In the second pipeline, the random catalog generated

Table 1. A list of our fiducial cosmological models, using the best-fit cosmology from different observations (Hildebrandt et al. 2017, 2018; Planck Collaboration et al. 2018). They are used to produce the theoretical predictions in our results.

| Survey     | $h_0$ | $\Omega_0 h^2$ | $\Omega_m h^2$ | $n_s$ | $\sigma_8$ | $w$ |
|------------|-------|----------------|----------------|-------|------------|-----|
| KiDS450    | 0.75  | 0.0223         | 0.193          | 1.02  | 0.826      | -1.0|
| KV450      | 0.745 | 0.0222         | 0.118          | 1.021 | 0.836      | -1.0|
| Planck2018 | 0.6732| 0.022383       | 0.12011        | 0.96605| 0.812      | -1.0|
using the KiDS450 footprint mask is of a fixed size (in our case $10^6$ objects) generated using healpix util\(^1\), for each bin.

Moreover, $w_j$ denotes the lensfit Miller et al. (2013) weight for the galaxy shape measurement; $\gamma^i_j$ is the tangential ellipticity for the $j^{th}$ galaxy; $(1 + m_j)$ is a term used in the calibration correction for the shear measurement (Hilbrandt et al. 2017):

$$\gamma^\text{obs}_j = (1 + m_j)\gamma^\text{true}_j + c_j,$$

where the true shape of the $j^{th}$ galaxy $\gamma^\text{true}_j$ is affected by a multiplicative bias $(1 + m_j)$ and an additive bias $c_j$, and appears as the observed shape $\gamma^\text{obs}_j$.

Different from pipeline one of this work, in the second pipeline with KiDS450 data, we handle the multiplicative bias by instead calculating the weighted average multiplicative bias for each bin, and dividing by it.

In cosmic shear studies, the shear-shear correlation requires subtraction of the additive bias, which can be acquired by averaging the observed ellipticity $c_j = \langle \gamma^\text{obs}_j \rangle$ (Hilbrandt et al. 2017). This is not necessary for this work as in Eq. (18) the additive bias is already corrected with the random catalog.

### 2.5 (Extrapolated) Theoretical Predictions

In this section, we briefly describe how the theoretical values of $w^G$ and $w^I$ are calculated. The comparison between these theoretical values and the measurements from data will be presented in sections 3.4 and 3.5.

The two target correlation functions are calculated from the Hankel transformation described in Eq. (15), in which the lensing-galaxy correlation $C^{Gg}$ is given in Eq. (7a), and the IA-galaxy correlation $C^{Ig}$ is given by

$$C^{Ig}_i(\ell) = \int_{0}^{\chi_{\text{crit}}} \frac{n_i(\chi) n_i(\chi)}{\chi^2} b_g P_{\delta g,i}(k = \ell / \chi; \chi) d\chi.$$  

(21)

The related 3-D matter-IA power spectrum $P_{\delta,\gamma,i}$ depends on the IA model being used. In this work, we use the tidal alignment model (Hirata & Seljak 2004; Bridle & King 2007) for the purpose of theoretical modeling. It is the default IA model for KiDS450 (Hilbrandt et al. 2017) and is commonly used in the other stage III surveys (Hilbrandt et al. 2018; Troxel et al. 2017; Hikage et al. 2019; Hamana et al. 2019; Chang et al. 2019). The form is as follows:

$$P_{\delta,\gamma,i} = -A_{\text{IA}}(L, \gamma, z) \frac{C_1 \rho_{m,0} D_z(z)}{D_{z}(z)} P_g(k; \chi),$$

(22)

where $\rho_{m,0} = \rho_{c,0} \Omega_{m,0}$ is the mean matter density of the universe at $z = 0$, $C_1 = 5 \times 10^{-34} \left(h^2 M_{\text{sun}} / \text{Mpc}^{-2}\right)$ was used in Bridle & King (2007). We use $C_1 \rho_{c,0} \approx 0.0134$ as in Krause et al. (2016). $D_z(z)$ is the normalized growth factor. $A_{\text{IA}}(L, \gamma, z)$ is IA amplitude parameter, which is expected to be luminosity($L$)- and redshift($z$)-dependent. Here we follow the KiDS450 results (Hilbrandt et al. 2017) and set it as a constant for the current stage of study.

In the first pipeline, the theoretical values are calculated with CCL (Core Cosmology Library, https://github.com/LSSTDESC/CCL, Chisari et al. (2019)), and cross-checked with results using CAMB (Code for Anisotropies in the Microwave Background, https://camb.info/, Lewis et al. (2000)). The cosmological parameters being used for the calculation are the best-fit values of KiDS450, shown in Table 1, with the redshift distribution of DIR redshift (http://kids.strw.leidenuniv.nl/sciencedata.php) in Hilbrandt et al. (2017).

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\(^1\) https://github.com/esheldon/healpix_util
Figure 3. The measurements of the observables of SC, in the four redshift bins. The shape-galaxy correlations $w^{gg}$ are shown in blue dots, and the shape-galaxy correlations with the selection $w^{gg}|S$ are shown in orange squares. The redshift bin numbers from 1 to 4 are in the labels. For most of the angular bins there is a clear separation between the two correlation functions, representing the drop of the lensing signal related with Eq. (5), due to the selection of Eq. (14).

3 RESULTS

3.1 Survey data

In this work we apply the lensing-IA separation part of the self calibration (SC, Zhang (2010b)) to Kilo Degree Survey (KiDS) data, more specifically, KiDS450 (Hildebrandt et al. 2017) and KV450 (Hildebrandt et al. 2018) data release’s shear catalogs. The information about these two surveys can also be found here (http://kids.strw.leidenuniv.nl/sciencedata.php). KiDS is one of the main stage III surveys and will give valuable cosmological information with weak lensing studies.

KiDS450 is a four-band imaging survey, covering $449.7 \, \text{deg}^2$ (with effective survey area $360.3 \, \text{deg}^2$) on the sky. The four bands are SDSS-like $u$, $g$, $r$- and $i$-bands, with corresponding limiting magnitude $[24.3, 25.1, 24.9, 23.8]$. The photo-z range for the galaxies in the shear catalog is $0.1 < z^P < 0.9$. Its effective galaxy number density is $\sim 8.53 \, \text{arcmin}^{-2}$ within this photo-z range, with overall $\sim 15$ M galaxies with shear measurements. The rms shape error is $\sim 0.290$ of all the sample galaxies in the shear catalog.

KV450 is the combination of the two sister surveys, KiDS and VIKING. It uses overall 9 photometric bands, 4 optical bands – $ugri$ from KiDS and 5 near-infrared bands – $ZJHK_s$ from VIKING. Its effective survey area reduces to $341.3 \, \text{deg}^2$ (from $360.3 \, \text{deg}^2$ of KiDS450), leading to a reduced effective galaxy number density $6.93 \, \text{arcmin}^2$ and total number of galaxies $~12 \, \text{M}$. The main improvement of the KV450 shear catalog is its photo-z quality (Wright et al. 2018): the photo-z scatter $\sigma_z$ improved from 0.082 (KiDS450) to 0.061 (KV450), which is more concentrated to the true redshift, while the photo-z outlier rate $\eta_3$ is reduced from 0.163 (KiDS450) to 0.118 (KV450), meaning the fraction of galaxies with catastrophic photo-z error outside $3\sigma$ range is reduced. KV450’s redshift range is $0.1 < z^P < 1.2$. The rms shape error is also improved a little for KV450, with the value $\sigma_e \sim 0.288$.

The KiDS450 data are processed with two pipelines to test the robustness of the method, considering their different processes for photo-z error, shape calibration, and resampling. As the results converge, we use the first pipeline to process KV450 data.

3.2 $Q_i$ measurements

We present the measurement of $Q_i$ for KiDS450 in Fig. 1 and Fig. 2. The fiducial cosmology for Eq. (5) is assumed to be either KiDS450 cosmology (here) or KV450 cosmology.
Separating Intrinsic Alignment Signal and Lensing Signal

(early in this paper) depending on which survey data we are using. The detailed values are shown in Table 1.

For proper usage of SC for KiDS450 data, one needs to use the photo-z distribution $n_s(z_P)$, in which the photo-z $z_P$ is given in the KiDS450 shear catalog as $z_B$, the peak value of the PDF (probability distribution function) from the BPZ (Bayesian Photometric redshift) code (Benitez 2000; Hildebrandt et al. 2017). Not only so, we also need the full PDF $p(z|z_B^P)$ according to Eq. (10), as well as the true-z distribution $n_t(z)$ or $n_t(x(z))$ according to Eq. (7a) and (7b). The full PDF $p(z|z_B^P)$ should also be given from the photo-z estimation and the true-z distribution $n_t(z)$ should be given from stacking the PDFs of all the galaxies.

However, we point out that for this work, this approach is not applicable. According to Hildebrandt et al. (2017), the stacked redshift distribution $n_s(z)$ requires calibration due to the limit of the photo-z techniques at the current stage. The fiducial calibration method for KiDS450 and KV450 is the DIR (direct calibration, with spectroscopic redshift) method. After the calibration, the redshift distribution $n_s(z)$ is expected to shift to a more accurate position. But due to the algorithm of SC, which requires not only the photo-z $z_B$, but also the connection between photo-z and the true redshift $p(z|z_B^P)$, which can not be calibrated with the DIR method, for each specific galaxy. Thus if we use the uncalibrated $p(z|z_B^P)$ and the calibrated $n_t(z)$ together, it will lead to some bias that is not easy to specify.

Therefore, in the calculation of Eq. (5) and (10), instead of using the PDFs given by the BPZ code for each single galaxy, we choose to use the Gaussian model (13) that we previously used, so that our SC method is self-consistent, avoiding the usage of the calibrated $n_t(z)$ and the uncalibrated $p(z|z_B^P)$ simultaneously. The photo-z bias parameter $\Delta_z$ is set to be 0, while for the photo-z scatter $\sigma_z$, instead of using the commonly assumed value 0.05, we use $\sigma_z = 0.082$ for KiDS450 and $\sigma_z = 0.061$ for KV450, borrowing the results from Wright et al. (2018). For future photo-z techniques when the estimation for the PDFs and the best-fit $(z_B^P$ from BPZ for example) are more accurate, we can directly use the PDFs instead of applying such a photo-z model.

With the above information of photo-z distribution and PDFs from data, we are able to calculate the quantity $Q_{i}$, which is shown in Fig. 1 and Fig. 2, for the lensing-IA separation later. The index $i$ is for photo-z binning, same as in KiDS450 Hildebrandt et al. (2017), namely the $0.1 < z_P^F < 0.3, 0.3 < z_P^F < 0.5, 0.5 < z_P^F < 0.7$ and $0.7 < z_P^F < 0.9$ for the four redshift bins. The shaded areas are the angular scale cut, so that we only use $50 < \ell < 3000$, which is our main interest for cosmic shear in the current stage. This range is a little larger than the range of stage III surveys as we want to have a preview of the behavior of IA. There is some angular dependency on $\ell$ for $Q_{i}$, while this dependency is more and more insignificant as we go to higher redshift, or higher bin index $i$. We also showed in Yao et al. (2019) that the minimum and maximum values for $Q_{i}$ are very close in the same redshift bin for future surveys like LSST. Therefore in this work, we use the averaged value of $Q_{i}$ for the purpose of lensing-IA separation. The average value is $Q_{\bar{i}} \approx [0.588, 0.557, 0.615, 0.650]$ for KiDS450. According to Wright et al. (2018), there is still a 10%~20% redshift outlier problem that can not be addressed by the above Gaussian PDF model. This outlier will reach to redshift range far outside the chosen bin, and is expected to lead to some bias in the $Q_{i}$ estimation by affecting $n_t(z)$ in Eq. (10), as well as the measurement of power spectra (2-points correlation function in this work, see the next section) in Eq. (7a) and (7b). We will leave details of this potential bias for future study, but we will discuss how this redshift outlier can bias the results of SC in this work. We applied a wider selection of the photo-z bins in order to alleviate the problem. For future surveys, as the error in photo-z decreases, the redshift scatter $\sigma_z$ will be smaller and the outlier rate will also decrease. So we broaden the redshift bins in KiDS450 data to simulate this improvement in the future. The redshift bins after the broadening are $0.1 < z_P^F < 0.5$ and $0.5 < z_P^F < 0.9$, with the associated values $Q_{\bar{i}} \approx [0.655, 0.674]$. We then apply the same binning to KV450 data to see the improvements with better photo-z Wright et al. (2018), with the resulting values $Q_{\bar{i}} \approx [0.638, 0.574]$. The improvements will be shown together with the measurements of the correlation functions in Section 3.4.

3.3 Correlation functions

We perform the measurements of the correlation functions as described in Eq. (18), for both the shape-galaxy correlation $w^{g\gamma}$ and the one with the selection $w^{g\gamma,S}$, where the selection function is given by Eq. (14). We included a cartoon in Appendix A to explain the physical meaning behind this selection, in support of the equations.

We use the TreeCorr code Jarvis et al. (2004) to calculate the correlations in Eq. (18), in order to get (16). To account for the shape noise and sample variances correctly, we use the jackknife resampling method for this purpose. We applied 453 jackknife regions, using each KiDS450 tile as a jackknife region (Hildebrandt et al. 2017). The estimated size of a jackknife region is at ~1 deg level. To avoid the edge effect of the jackknife regions (Mandelbaum et al. 2006), we calculate the correlation function $0.5 < \theta < 60$ arcmin, dividing into 10 logarithm bins. Each result in the Figs. 3, 4, 6 and 8 in this work has a specific covariance matrix, produced using the jackknife resampling, to calculate the errorbar on the quantity.

The second pipeline, as mentioned earlier, uses the TreeCorr code Jarvis et al. (2004) to calculate the correlations need for the estimator (19). It also makes use of jackknife resampling to account for the shape noise and sample variance. However, instead of using the KiDS450 tiles as regions, it makes use of the kmeans_radec code (https://github.com/esheldon/kmeans_radec) to instead divide the sample, i.e. each tomographic bin into chunks with roughly the same number of galaxies in each chunk.

The results of $w^{g\gamma}$ and $w^{g\gamma,S}$ measurements are shown in Fig. 3. The blue dots contain $w^{g\gamma} = w^{G\gamma} + w^{L\gamma}$, while the orange squares contain $w^{g\gamma,S} \approx Q_{\bar{i}}w^{G\gamma} + w^{L\gamma}$. The approximation is due to assuming $Q_{\bar{i}}$ is angular scale independent and using $Q_{\bar{i}}$, according to Fig. 1. The drop in the signal in $w^{g\gamma,S}$ is caused by the selection of Eq. (14) so that some lensing signal is lost.

In Fig. 3 there is a clear separation between $w^{g\gamma}$ and $w^{g\gamma,S}$, which works as a first proof that the physical differences between the lensing signal and the IA signal can be distinguished with the selection Eq. (14) in the SC method with the current stage KiDS real data. The measurements of the pure lensing signal $w^{G\gamma}$ and the pure IA signal $w^{L\gamma}$


3.4 Lensing-IA separation for KiDS450

For KiDS450 data, the measurements of the separated lensing signal and IA signal are shown in Fig. 4. The triangles are the measured values and the curves are the theoretical predictions.

The measurements from data are generally consistent with the theoretical curves, for both lensing and IA parts, showing that SC can already work with the data quality of the stage III surveys (KiDS, DES, HSC), and confirming that the tidal alignment model is good enough for the current surveys. Meanwhile, there are several important details that need to be discussed. They include: the different approaches in getting Fig. 4, the quality of photo-z, and the galaxy bias $b_g$ for the KiDS galaxy samples.

The theoretical values in Fig. 4 are calculated as described in Section 2.5, while the cosmological parameters are obtained through the cosmic shear observables (Hildebrandt et al. 2017), together with other nuisance parameters for different systematics (such as IA) with specific modeling. In contrast, our SC method uses the shape-galaxy correlation but with different selections to directly measure the lensing-galaxy correlation and IA-galaxy correlation, without any strong assumptions on the IA model. The cosmic shear measurements also use information in both auto-correlation and cross-correlation for different redshift bins. The SC method, for the purpose of signal separation on the other hand, only uses shape-galaxy correlation in the same redshift bin, as described in Eq. (6), (16) and (17). Despite these differences,
We show in this figure the agreement of the two pipelines in both the two observed 2-point correlation functions (dots for $w^{\gamma g}$ and squares for $w^{\gamma g}$ in the upper panels, and the separated pure lensing signal (up-triangles for $w^{Gg}$) and IA signal (down-triangles for $w^{IG}$) in the lower-panels. We show only the two high-z bins labeled as 3 and 4, as in the high-z bins the photo-z outlier problem is less significant as discussed in Fig. 4. “JY” denotes the default pipeline, and “EP” denotes the 2nd pipeline. In general, the two pipelines agrees very well, with some small deviations which are caused by the detailed differences described previously and in Appendix E, while the systematics such as the photo-z error and the shape calibration will also enter the two pipelines accordingly. The two curves are the theoretical predictions with KiDS450 best-fit cosmology shown in Table. 1, with the DIR redshift distribution. The results in Fig. 4 still shows good agreements between the measurements and theoretical predictions. It is not only a sanity check for us, but also a confirmation for KiDS450 cosmic shear results since our approaches are totally different.

We further discuss the systematics of the SC method, starting with the impact of photo-z quality. As discussed in previous work (Yao et al. 2017), the SC method is more sensitive to photo-z quality, compared with the conventional marginalization method with IA models. This is because SC uses extra information from photo-z when applying the selection Eq. (14). Because of this sensitivity, the error in photo-z (for example, the catastrophic photo-z error which will result in the redshift outlier problem in the PDF $p(z|z^P)$ and the redshift distribution $n_i(z)$ Zhang (2010b)) could potentially be magnified and causes some biases, which should already be included in the measurements in Fig. 4. Right now the measurements generally agree with the theoretical prediction, but for future surveys when the number of galaxies largely increases, the errorbar will shrink and such biases could appear. The bias originating from photo-z error will be addressed later in this paper when we switch to KV450 for better photo-z (Wright et al. 2018).

More specifically, the two observables $w^{\gamma g}$ and $w^{\gamma g}|_S$ has different sensitivity to photo-z due to the selection Eq. (14). Thus their measurements in Fig. 3 will be biased differently. So for better photo-z, $w^{\gamma g}$ and $w^{\gamma g}|_S$ will shift to different positions, leading to more accurate values in Fig. (4). We find that for those $w^{\gamma g}$ and $w^{\gamma g}|_S$ with a less significant separation (for example when the blue and orange errorbars overlap) in Fig. 3, the subtracted $w^{Gg}$ and $w^{IG}$ signals in Fig. 4 are generally consistent with 0.

Moreover, it is obvious that in Fig. 4, the agreement from the two high-z bins are better than that of the two low-z bins. We think this is also caused by the photo-z outlier. As discussed in Hildebrandt et al. (2017), the redshift outlier is more significant at lower redshift. This redshift outlier, due to the bad estimation of the photo-z, will lead to some bias in Fig. 3, which is then propagated to Fig. 4. The above situations will be improved in the future with better photo-z, as shown in discussions with KV450 data.

Another potential bias for SC is the galaxy bias $b_g$ in
Figure 6. The measurements of $w^\gamma$ and $w^\gamma|_S$ for both KiDS450 and KV450, with wider photo-z bins. The bin numbers in the labels 1 and 2 correspond to $0.1 < z^P < 0.5$ and $0.5 < z^P < 0.9$, respectively. In the right panel for the high-z bin, the blue $w^\gamma$ dots moved to the green dots when switching to KV450 from KiDS450, meanwhile the orange $w^\gamma|_S$ squares moved to the red squares. This is the result of using better photo-z. In the left panel for the low-z bin, similar things happened, however, the photo-z error dominates the measurement.

Figure 7. In this figure we show the $Q_i(\ell)$ quantity in solid curves for KV450 data. With the averaged $\hat{Q}_i$, shown in dotted curves, we can achieve the separation of lensing and IA signal from the measured observables in Fig. 6. All the setups are similar to Fig. 1.

Eq. (7a) and (21). The galaxy bias is the bias when using galaxy number density contrast $\delta_g$ to trace the true matter density contrast $\delta_m$, namely $\delta_g = b_g\delta_m$. In this work, we use $b_g = 1$ for the theoretical predictions, for the KiDS450 galaxies. This is a reasonable assumption as the KiDS shear galaxies are not a specific kind of galaxy. But this is a bias on the modeling side. On the observational side, the measurements do contain such a bias, however, it enters both $w^{G\gamma}$ and $w^{I\gamma}$ in the same way. So in the future, even if someone doesn’t want to address the galaxy bias, one can either tune the $b_g$ in the theoretical part so that $w^{G\gamma}$ and $w^{I\gamma}$ can fit simultaneously, or use them to give the IA-lensing ratio $w^{I\gamma}/w^{G\gamma}$ so that the $b_g$ part will cancel. Further discussion about the galaxy bias is beyond the scope of this paper, but we will get back to this in future work.

3.5 Lensing-IA separation for KV450

We then switch to KV450 data for better photo-z (Wright et al. 2018) and perform comparisons to KiDS450. With “9 KV450 bands” photo-z rather than the “4 KiDS450 bands”, the best-fit BPZ results $z_B$ is expected to be more accurate. We further use wider photo-z bins, to simulate for future photo-z quality when the redshift PDFs are more concentrated compared with the bin-width. The new redshift bins are $0.1 < z^P < 0.5$ and $0.5 < z^P < 0.9$, so that the original 2 low-z bins are combined, and the 2 high-z bins are combined. This will also increase the number of galaxies in each redshift bin, offering stronger constraining power, which is also similar to future surveys.

In Fig. 6 we present the measurements of $w^\gamma$ and $w^\gamma|_S$, which is similar to Fig. 3, but with the wider redshift bins. The measurements for both KiDS450 and KV450 are plotted, to show the improvement with KV450 photo-z. In the right panel, for the high-z bin, both $w^\gamma$ and $w^\gamma|_S$ are shifted when switching to KV450 from KiDS450. The shift is generally larger for $w^\gamma|_S$ (orange squares shift to red squares), compared with the shift of $w^\gamma$ (blue dots shift to green dots). This is due to the selection Eq. (14) using photo-z so that $w^\gamma|_S$ will be affected more when changing the quality of photo-z.

On the other hand, in the left panel, for the low-z bin, we can observe a similar shift. However, the results are strongly biased, as for KiDS450, the orange $w^\gamma|_S$ is higher than the blue $w^\gamma$, which is different from our expectation about the drop in the lensing signal. Even after using KV450 data the green dots and the red squares cannot be separated clearly. This, again we believe, is due to the redshift outlier problem, that when combining two shallow bins into a wide bin, the galaxies with photo-z outliers are cross-correlated with all
Figure 8. This figure shows the measurements of $w^{Gg}$ and $w^{Ig}$ using KV450 data and the comparison with the theoretical predictions. The orange up-triangles are the $w^{Gg}$ measurements and the down-triangles are the $w^{Ig}$ measurements. The theoretical values are plotted as the green curve and the red curve, with the KV450 best-fit cosmology shown in Table 1. The green shaded area shows the upper- and lower-limits for the lensing signal under the constraint $\sigma_8 = 0.836_{-0.218}^{+0.112}$ from KV450 cosmic shear (Hildebrandt et al. 2018). The red shaded area shows the upper- and lower-limits for the IA signal under the constraint of both $\sigma_8$ and $A_{IA} = 0.981_{-0.678}^{+0.168}$. In the right panel, for the high-z bin, we also show some extra curves for comparison. The theoretical predictions using KiDS450 cosmology and DIR redshift distribution are also plotted in the dash-dotted curves. The ones with Planck2018 cosmology (Planck Collaboration et al. 2018) plus KV450 DIR redshift distribution plus KV450 are plotted in the dashed curves. In the left panel the measurements from data are biased due to photo-z error.

The correlation functions with KiDS450 cosmology and redshift distribution, as well as the ones with Planck cosmology plus KV450 redshift distribution, are also presented for comparison. The agreement between our measured $w^{Gg}$ using SC and the theoretical values of KV450, is generally similar to the agreement between KiDS450 and KV450. We can also see that even though the best-fit cosmology of KiDS450 and KV450 are closer, the theoretical $w^{Gg}$ in Fig. 8 agrees better for KV450 and Planck, as these two cases both use the DIR redshift of KV450. This again emphasizes the importance of the quality of photo-z.

By comparing the high-z bin $(0.5 < z^P < 0.9)$ of Fig. 8 and the counterparts in Fig. 4, we can see the improvements of SC in the future as data quality improves. First of all, the error bar will be significantly reduced due to more galaxies being observed. Secondly, with better photo-z, the bias from photo-z in the measurements of $w^{Gg}$ and $w^{Ig}$ will be reduced, giving more accurate results. This improvement in the accuracy is expected to be better compared to the marginalization method as SC is more sensitive to photo-z, as shown in this work and discussed previously (Yao et al. 2017).

The orange up-triangles are the $w^{Gg}$ measurements and the down-triangles are the $w^{Ig}$ measurements. The theoretical values are plotted as the green curve and the red curve, with the KV450 best-fit cosmology shown in Table 1. The green shaded area shows the upper- and lower-limits for the lensing signal under the constraint $\sigma_8 = 0.836_{-0.218}^{+0.112}$ from KV450 cosmic shear (Hildebrandt et al. 2018). The red shaded area shows the upper- and lower-limits for the IA signal under the constraint of both $\sigma_8$ and $A_{IA} = 0.981_{-0.678}^{+0.168}$. In the right panel, for the high-z bin, we also show some extra curves for comparison. The theoretical predictions using KiDS450 cosmology and DIR redshift distribution are also plotted in the dash-dotted curves. The ones with Planck2018 cosmology (Planck Collaboration et al. 2018) plus KV450 DIR redshift distribution plus KV450 are plotted in the dashed curves. In the left panel the measurements from data are biased due to photo-z error.

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4 SUMMARY AND CONCLUSIONS

In this paper, we presented the first application of the self-calibration (SC2008, Zhang (2010b); Yao et al. (2017, 2019)) method to distinguish the galaxy lensing-galaxy density signal and the IA-galaxy density signal with the shear catalog from real data with photo-z. We developed the theoretical steps on how the SC method can be used. We apply the steps to KiDS450 data as a first approach, and later apply them to KV450 data to discuss the impact of photo-z quality. We take systematics such as the shape calibration, selection bias, survey shape, photo-z error, and galaxy bias into consideration. We use jackknife resampling to produce the covariance matrix, in order to calculate the error estimation. We perform several sanity checks such as cross-shear measurements, cosmic shear measurements, and comparing the lensing signals from SC with those from theoretical predictions extrapolated using the best-fit cosmology from cosmic shear, with the same data sets. We showed a good agreement using KiDS450 data, for both lensing and IA measurements. We further showed that for $0.5 < z_p < 0.9$ of KV450, the lensing measurements are consistent, while the results in IA suggest a stronger amplitude compared with Hildebrandt et al. (2018).

Specifically, using two pipelines, we achieved a direct split of the intrinsic shape-galaxy density ($I_g$) correlation signal and the gravitational shear-galaxy density ($G_g$) correlation signal, using the information from photometric redshift shift (photo-z).

To further extend the SC method, we discussed several systematic effects that can potentially bias the lensing-IA separation, including:

- The approximation of using the averaged $\bar{Q}_g$ instead of a scale-dependent $Q_g(t)$. This is not a severe problem, because $Q_g(t)$ will behave more like a constant with higher redshift. But it is still worth exploring for the relatively shallow surveys.
- The photo-z error (mainly the redshift outlier). This includes both the error in the photo-z PDFs $p(z_i|z')$ and the error in the best-fit photo-z ($z_B$ for BPZ code for example). As discussed in the paper, the error in $p(z_i|z')$ can potentially bias the estimation of $Q_g$, as seen in Section 2.3, while the error in best-fit $z'$ can bias the measurements of the two correlation functions $w_{Gg}$ and $w_{Gg}^{\delta_5}$, as shown in Fig. 6 for the similar galaxy samples but with different redshift measurements. The photo-z error can lead to significant bias in SC, and with the improvement of photo-z techniques, this bias is expected to drop quickly due to the sensitivity discussed in both this work and Yao et al. (2017).
- The galaxy bias $b_g$. In this work, we showed the assumption of $b_g = 1$ is good enough for the KiDS450 and KV450 shear galaxy samples. To avoid this problem we can either choose to use the IA-lensing ratio instead of the signals themselves, since $b_g$ enters these two signals in the same way, or we can use what is suggested in Zhang (2010b) to directly infer it. In the future, it is worth to explore both of these two approaches.
- We choose to ignore the impact of baryonic effects such as massive neutrinos and feedback, as they affect the modeling part, which is beyond the scope of this paper. But including them in the future analysis will also be helpful.

Based on the good agreement we achieved for KiDS450 and KV450 and the sanity checks we performed, we conclude that the above systematics are not severe for the current data quality. We then discuss the cosmological information that can be put into use in the future, based on our results.

- The subtracted IA signal $w_{Gg}^i$ (as shown in Fig. 4 and 8) contains information of the IA, without any strong assumption on the physics behind. This information can be propagated to either cosmic shear or CMB-lensing to mitigate the IA contamination, as previously discussed Zhang (2010b,a); Yao et al. (2017, 2019); Troxel & Ishak (2014); Meng et al. (2018), which was our motivation of this work at the beginning.
- The subtracted IA signal can be used to directly constrain the IA model, rather than the marginalization method that fits the cosmological parameters together with the nuisance IA parameters. We perform in Appendix B an example of using the IA signal subtracted from KV450, Fig. 8, to constrain the tidal alignment model of IA, which is used in the KV450 paper. This information can also be used to distinguish different IA models, which are widely discussed in Hikage et al. (2019); Hamana et al. (2019); Troxel et al. (2017); Blazek et al. (2017); Krause et al. (2016).
- The subtracted lensing signal $w_{Gg}^i$ can be used to constrain cosmology. This quantity uses $w_{Gg}$ and $w_{Gg}^{\delta_5}$, therefore its uncertainty is larger than both of them. However, since this measurement uses all the shear galaxies, meaning that it uses the galaxy number density $\delta_g$ as the tracer for matter, so that the overall galaxy number is much larger than the typical galaxy-galaxy lensing or galaxy auto-correlation where spectroscopic redshift is required. And this galaxy information in the shear catalog has never been used in previous cosmological studies. We showed the comparison before and after IA is subtracted for this lensing signal of Fig. 8 in Appendix C, and performed a MCMC study for $\Lambda$CDM model in Appendix D, without further addressing the systematics in the SC method. It works as a first example of the constraining power of $w_{Gg}^i$ with SC.
- The current IA models all depend on the cosmological model, meaning that our subtracted $w_{Gg}^i$ can be used together with $w_{Gg}^i$ to constrain the IA model and cosmological model simultaneously. In this way, some of the constraining power in $w_{Gg}^i$ will flow from IA parameters to cosmological parameters. If the cosmological model and the IA model are accurate enough, this method is expected to be consistent with the marginalization method.
- In this paper, we follow the process of the original SC method (Zhang 2010b), to obtain $w_{Gg}^i$ and $w_{Gg}^{\delta_5}$ and discussed the information that we can put into use in the future. On the other hand, we can directly use the SC observables $w_{Gg}$ and $w_{Gg}^{\delta_5}$ as data, and theoretically calculate the predictions from cosmological models. This can prevent the worry about the cosmology-dependency of the $Q_g(t)$ we previously discussed (Yao et al. 2017). Although this dependency is expected to be very weak, as the same cosmological model enters both the numerator and denominator of Eq. (5) and (10).

We then list the ongoing and planned future work. The extension from KiDS450 to future KiDS data release will be straightforward, and we will include more detailed discussions on the systematics of SC and their corrections (Yao+). Applying SC to a more wide range of redshift (HSC data) and testing different IA models (DES data) are also of great
importance (Pedersen+). We are also testing and quantifying the impact of the redshift outlier with different simulations (Yao+) and with machine learning photo-z (Yao+).

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Figure A1. This is a cartoon to illustrate how the selection Eq. 14 of SC works. Above the redshift arrow, the four shapes (rectangle, circle, square, ellipse) are the galaxies whose shape information we use. Below the redshift arrow, the cloud represents the galaxy whose number density information (g) we use. When calculating the shape-galaxy correlation, in the lower part when considering true-z space, the correlation contains both lensing and IA for the pairs with shape galaxies farther away than the number count galaxies (square and ellipse), while it only contains IA signal for the pairs with shape galaxies closer than the number count galaxies. In photo-z space in the upper part, however, the ordering of the shape galaxies and the number count galaxies could be different due to the photo-z error. In the figure, following the dotted line, the ellipse galaxies is mistaken to be closer to us, and the circle galaxy is mistaken to be farther. So without the selection, all the galaxies pairs (both S = 0 and S = 1) are used to get w^{\delta S}, while with the selection of SC, only the S = 1 galaxy pairs (rectangle and ellipse) are selected to calculate w^{S\delta S}. The only lensing signal contained in this kind of pairs comes from the ones with photo-z error (the ellipse). Therefore, w^{S\delta S} will have a drop in the lensing signal, and if we know the photo-z quality we can figure out how significant this drop is, quantified by the Q_j values. In this way, the true lensing signal w^{Ig} and the true IA signal w^{ig} can be solved.

APPENDIX A: ILLUSTRATING THE SC OBSERVABLES

Here we show a cartoon Fig. A1 to give a more detailed explanation of the physics behind the w^{\delta S} and w^{S\delta S} measurements. For readability reasons, we include the full discussion in the caption.

Nonetheless, we point out here there is some (weak) potential bias for this selection method using photo-z of SC. Since photo-z is obtained from different filter bands, for example agri four bands for KIDS450, the selection in photo-z could potentially lead to some selection effect on the color of the galaxies, i.e. selection effect in galaxy types. Since galaxy types are expected to be related to the IA signal, the IA signals could also be different for different selection S = 0 or S = 1. This selection effect is expected to be weak, but we still want to point it out for future studies.

APPENDIX B: CONSTRAINING THE IA MODEL

We use the subtracted IA signal in Fig. 8 of the high-z bin (0.5 < z^P < 0.9) to constrain the tidal alignment model as in Eq. 22. We use MCMC to get the constraint on the IA amplitude parameter A_{IA} = 2.31^{+0.42}_{-0.42}, which is larger than the result from KV450 cosmic shear A_{IA} = 0.981. Our likelihood is constructed as follows:

$$L \propto \exp \left[ -\frac{1}{2} \left( \mathbf{w}^{Ig}_{\text{measured}} - \mathbf{w}^{Ig}_{\text{model}} \right)^T \mathbf{Cov}^{Ig} \left( \mathbf{w}^{Ig}_{\text{measured}} - \mathbf{w}^{Ig}_{\text{model}} \right) \right].$$

(B1)

where w^{Ig}_{\text{measured}} is the IA measurements shown in Fig. 8, w^{Ig}_{\text{model}} is the theoretical prediction curve, interpolated at the same $\theta$ position as the w^{Ig}_{\text{measured}}, Cov^{Ig} is the covariance matrix that has been used to get the errorbars for the w^{Ig}_{\text{measured}} values, with jackknife resampling. The prior for A_{IA} is flat prior [-6, 6], same as in Hildebrandt et al. (2018).

Despite the potential systematics that was previously discussed in this paper, this ~3$\sigma$ tension can suggest the deviation of the true IA model from the assumed tidal alignment model. It could also be due to the selection effect on the redshift that we used (0.5 < z^P < 0.9, which is different from KV450 cosmic shear), considering the evolution of IA when redshift is changing. As a result, it will be of great importance to apply future data to both the conventional marginalization method and our SC method to see how this tension will develop. The application of other IA models will also be helpful.

We argue that an under-estimated A_{IA} will lead to an under-estimated S_9 using SC, which is also shown in some recent research Fluri et al. (2019) where deep-learning is used to subtract more cosmological information beyond the conventional two-point statistics. Thus the systematics in different approaches (e.g. SC or IA modeling) of IA mitigation will require careful discussion in the future.
Separating Intrinsic Alignment Signal and Lensing Signal

Figure C1. In this figure we show the measurements from high-z bin of KV450 data in Fig. 8 in log-log scale. The blue triangles, the green curve with the shaded errorbar, and the orange dashed curve, are our SC measurements, theoretical prediction using KV450 best-fit and varying $\sigma_8$, the theoretical prediction for KiDS450, respectively. We added the measurements of $w^\gamma_g$ when IA has not been subtracted yet, in the black dots. By cleaning IA using SC, the agreement with the green curve improves from black dots to blue triangles. The three deviated data points at large $\theta$ are for the same reason as in Fig. 8, due to the unclear separation in Fig. 6.

APPENDIX C: THE SEPARATED LENSING SIGNAL

Here we show a log-log scale Fig. C1 of the high-z wide-bin KV450 lensing results, for further comparisons with and without the IA contamination. After cleaning the IA signal in black $w^\gamma_S$ dots, we achieved the blue $w^{Gg}$ triangles, which agrees better with the KV450 theoretical values in green curves. This good agreement suggests that we can directly use this $w^{Gg}$ lensing signal to constrain cosmology. Its main advantages are: (1) it uses extra information in the shear catalog that was not being applied; (2) the lens galaxies we can use are at the same level as the source shape galaxies, which is far more (~ one order of magnitude more) than conventional galaxy-galaxy lensing where spectroscopic redshift is required for the lens galaxies.

APPENDIX D: THE CONSTRAINTING POWER FROM LENSING SIGNAL

Based on the separated signal shown in Appendix C, we can construct a likelihood for the pure lensing signal $w^{Gg}$ to constrain the cosmological parameters.

$$\mathcal{L} \propto \exp \left[ -\frac{1}{2} (w^{Gg}_{\text{measured}} - w^{Gg}_{\text{model}}) \text{Cov}^{Gg} (w^{Gg}_{\text{measured}} - w^{Gg}_{\text{model}}) \right],$$

(D1)

where $w^{Gg}_{\text{measured}}$ is the lensing measurements shown in Fig. 8; $w^{Gg}_{\text{model}}$ is the theoretical prediction curve, interpolated at the same $\theta$ position as the $w^{Gg}_{\text{measured}}$; $\text{Cov}^{Gg}$ is the covariance matrix that has been used to get the errorbars for the $w^{Gg}_{\text{measured}}$ values, with jackknife resampling. The priors for the cosmological parameters are the same as in Hildebrandt et al. (2018), to prevent the impact from different priors.

The MCMC results are shown in Fig. D1. It is obvious that the MCMC best-fit posteriors (darkest spots in the 2-D contour) generally agree with the best-fit from KV450 cosmic shear (blue dots). The $S_8 - \Omega_m$ contour is plotted together with KV450 (Hildebrandt et al. 2017) and DES Y1 (Abbott et al. 2016) results in Fig. D2. Moreover, it is worth noticing that, despite the approximations we have made in this paper, in the $S_8 - \Omega_m$ space, we have good agreements with both KV450 and DES Y1, while our degeneracy direction is different from cosmic shear. In the future when systematics are more carefully discussed, the SC-measured $w^{Gg}$ lensing signal can potentially be used to break the degeneracy.

APPENDIX E: TWO-PIPELINES

We applied two separate pipelines to process the KiDS450 data for rigorous reasons. The first pipeline is fully developed by JY, while the second pipeline was developed by EP. The main differences between the two pipelines include: different shape calibration and different version of TreeCorr code will lead to different correlation function measurements; different covariance matrices due to different Jackknife regions; different numerical approaches for photo-z and $Q_i$ values.

Despite the differences discussed above, the two pipelines still converge to very close results, demonstrating the robustness of the pipelines, as well as the stability of the IA separation method in SC (Zhang 2010b) against those changes. We present here one more result of the cross-shear null test in Fig. E1 in support of the results in Fig. 5. The formula being used is similar as in Fig. 5, while the galaxy shapes are rotated by 45 degrees so that the correlated shape is the cross shear $\gamma^x$ rather than the tangential shear $\gamma^\tau$. The results are consistent with 0 for both pipelines and for with and without the SC selection Eq. (14).
Figure D1. This figure shows the MCMC results using \( w^{Gg} \) from the high-z wide-bin of KV450 in Fig. 8, to constrain \( \Lambda \)CDM cosmology, as an example. Here \( \Omega_m \) and \( S_8 \) are derived parameters, while the rest are the standard cosmological parameters in our model. The [0.16, 0.5, 0.84] percentile lines in the 1-D posteriors are shown in the black dashed lines, while in the 2-D posteriors the 68% and 95% confidence contours are shown. The best-fit from KV450 cosmic shear are shown in blue lines in both 1-D and 2-D.
Figure D2. This figure shows the MCMC results using $w^{Gg}$ from the high-z wide-bin of KV450 in Fig. 8, to constrain $\Lambda$CDM cosmology, in particularly $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$ and $\Omega_m$. In the 2-D posteriors the 68% and 95% confidence contours are shown, with our SC results in blue, KV450 cosmic shear results in red, and DES Y1 cosmic shear results in green. We emphasize that even though our analysis used approximations for galaxy bias and $Q_1$, which could potentially lead to some small bias in the best-fit, the extra constraining power of SC-separated lensing signal and its different degeneracy direction carries valuable cosmological information.

Figure E1. We show in this figure the null test of the 45-degree cross-shear correlation and the agreement of the two pipelines in both with (dots for $w^{y_xg}$) and without (squares for $w^{y_xg}|S$) the SC selection of Eq. (14). “JY” denotes the default pipeline, and “EP” denotes the 2nd pipeline. In general the two pipelines agrees well, and are consistent with 0.