Survey geometry and the internal consistency of recent cosmic shear measurements


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1 INTRODUCTION

Cosmic shear, the weak lensing of background galaxies by large-scale structure in the Universe, has been viewed for many years as a promising cosmological probe (Albrecht et al. 2006; Peacock & Schneider 2006; Weinberg et al. 2013). With the current generation of surveys, among them the Kilo-Degree Survey (KiDS, Kuijken et al. 2015) and the Dark Energy Survey (DES), we are beginning to see this promise fulfilled. Alongside the improved statistical power of these latest data sets, weak lensing methodology has developed rapidly over the last several years (Fenech Conti et al. 2017; Huff & Mandelbaum 2017; Sheldon & Huff 2017; Zuntz et al. 2017; Mandelbaum et al. 2017, 2018). With DES and KiDS, we have two independent weak lensing data sets of comparable constraining power — capable of constraining the amplitude of the two-point correlation function at better than the 3% level in the case of DES. If the reduction of systematic uncertainties can keep pace, these constraints will

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Survey geometry and cosmic shear measurements

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rapidly improve over the coming years as the area of sky analysed and the integrated exposure time of each survey increases by factors of several. A third, similarly powerful constraint from the Hyper-Suprime Cam (HSC) survey is also expected on a similar timescale. The Canada-France-Hawaii Telescope Lens Survey (Joudaki et al. 2017) and the Deep Lens Survey (Jee et al. 2016) have also published cosmic shear constraints of similar precision to those of KiDS-450.

Cosmic shear is one of several low-redshift probes that tightly constrain the amplitude of structure in the standard cosmological model ($\Lambda$CDM). By comparing these constraints to high-redshift measurements like the cosmic microwave background (CMB), we are able to fundamentally test the ability of $\Lambda$CDM to predict observations of the structure in and geometry of the Universe across its entire history. One important question is whether the amplitude of structure measured by lensing surveys is compatible with predictions based on CMB observations, extrapolated to late times assuming $\Lambda$CDM. In order to interpret these results as strong, reliable tests of $\Lambda$CDM, we must first subject them to stringent tests of internal and mutual consistency.

Internal consistency tests the agreement of different subsets of the weak lensing data vector with predictions based on the same $\Lambda$CDM parameters. The most simple such test is whether the best-fitting $\Lambda$CDM model describes these measurements (i.e., the correlation function) at an acceptable goodness-of-fit ($\chi^2$). Both the latest DES (Troxel et al., T17) and KiDS (Hildebrandt et al., H17) cosmic shear analyses reported a large $\chi^2$ per degree of freedom (dof) in their initially released results.

Tests of mutual consistency, e.g. between the fully independent cosmic shear real-space two-point correlation function from KiDS-450 (H17) and DES Y1 (T17) are a unique opportunity to validate the entire analysis process. We note that mutual consistency between the DES and KiDS cosmic shear results is not a new result in this work – good agreement between the two data sets has already been demonstrated in T17.

In this paper we make substantial progress on these critical consistency tests by implementing three improvements:

(i) to the shape noise component of analytic cosmic shear covariance matrix estimates relative to the initial implementation in both analyses. This correction was first implemented during the refereee process for the DES Y1 analyses (Krause et al., K17; DES Collaboration et al., D17; T17). We find that it non-trivially impacts current generation weak lensing surveys, especially in the regime of small fields or non-compact footprints, including the KiDS-450 covariance matrix (H17) described below;

(ii) to the treatment of uncertainty in the multiplicative shear bias calibration in the H17 covariance matrix; and

(iii) to the angular separation estimate used for evaluating the predicted shear signal for the bins in H17 (see footnote 1 of Joudaki et al., 2018).

The first update has a significant impact on the interpretation of internal consistency in both H17 and T17, particularly the best-fit $\chi^2$. The shape noise component of the covariance in such surveys should thus be treated with care beyond the simple geometric approximations commonly used in earlier work. Each of the latter two updates shift the H17 contours only by a fraction of the 68% CL, but jointly are relevant for evaluating mutual consistency and consistency with CMB observations.

This paper is organised as follows: In Sec. 2, we describe the cosmic shear data used and our analysis framework relative to H17 and T17. We describe methods to appropriately describe the shape noise term in non-compact or disjoint survey geometries and discuss how this impacts the H17 results in Sec. 3, including also update (ii) mentioned above. We then discuss the resulting interpretation of the cosmic shear results from H17 and T17 in Sec. 4. We conclude and discuss the outlook for future such studies in Sec. 5.
Survey geometry and cosmic shear measurements

3 MODELLING THE COVARIANCE

The fiducial analyses of H17 and T17 both use covariances obtained from analytic models (see H17, K17 for model details and validation). These analytic covariances consist of a Gaussian part, which combines cosmic variance and shape noise, and a non-Gaussian part, which includes contributions from the connected matter trispectrum as well as super-sample covariance (Takada & Hu 2013).

The pure shape noise contribution to the covariance CovSN is given by (Schneider et al. 2002; Joachimi et al. 2008)

\[
\text{Cov}^{\text{SN}}(\xi_a^{ij}(\theta_1), \xi_a^{kl}(\theta_2)) = \frac{(\sigma_g^I)^2}{\Delta p^{ij}(\theta_1, \Delta \theta_1)} \theta_{ij} \delta_{ijl} \delta_{jkl} + d_i d_{jk}.
\]

where \(i, j, k, l\) are tomographic bin indices, \(\sigma_g\) is the ellipticity dispersion, \(\Delta p(\theta, \Delta \theta)\) is the number of galaxy pairs in angular bin \(\Delta \theta\), and \(d\) is the Kronecker delta function. While Schneider et al. (2002) provide an exact expression for \(\Delta p\) as the weighted sum over all galaxy pairs, this is commonly approximated with \(\Delta p(\theta, \Delta \theta) = 2 \pi \theta \pi \delta(\theta)\), where \(\Lambda\) is the survey area, \(\lambda_{\text{eff}}\) the mean effective projected galaxy density, and \(2 \pi \theta \pi \delta\) the approximate area of the annular bin. We will refer to this approximation as the geometric shape noise estimate. In all cases, we use \(\lambda_{\text{eff}}\) and \(\sigma_g\) as defined in (Heymans et al. 2013), where the total \(\sigma_g\) is used.

We revisit this common geometric estimate and instead calculate \(\Delta p\) directly for an infinitesimal annular bin element, taking into account both the survey geometry, as well as the clustered distribution of source galaxies. This calculation starts from the continuous limit of the discrete pair count expression of Schneider et al. (2002).

\[
\Delta p^{ij}(\theta, d\theta) = \int d^2 \theta' \int_{\theta' - d\theta}^{\theta'} d^2 \theta'' W(\theta') n^i(\theta') W(\theta'' - \theta') n^j(\theta'' - \theta') = 2 \pi \theta \pi \delta(\theta) n^i(\theta') W(\theta' - \theta') n^j(\theta' - \theta') d\theta' = 2 \pi \theta \pi \delta(\theta) \int W(\theta) \left(1 + \frac{d^i}{d j}\right) d\theta.
\]

Here \(W(\theta)\) is the angular survey mask, normalised such that \(\int d^2 \theta W(\theta) = 1\), \(\delta(\theta)\) is the projected galaxy density field, and \(d^i(\theta, \theta')\) is the projected source galaxy density contrast. \(W\) and \(\delta\) have angular correlation functions \(w_W\) and \(w_\delta\).

The latter is often considered source clustering, and we define \(w_W\) to be normalised such that \(w_W(0) = 1\). We compute \(w_W\) from the galaxy power spectrum of the mask, which is evaluated using the HEALPix\(^9\) sphere pixelization software package (Görski et al. 2005).

In addition to the analytic calculation of \(\Delta p\), we can also measure components of the shape noise in Eq. 5 directly from the data. One way to do this is by counting the effective number of pairs of galaxies in the survey footprint, \(\Delta p(\theta, \Delta \theta)\), to use in Eq. 5. This approach still makes use of the measured \(\sigma_g\). The total shape noise contribution CovSN can also be measured from the variance of \(\xi_a\) across many random realisations of the shape catalogue (e.g., Gruen et al. 2017; Sánchez et al. 2017; Murata et al. 2018), where \(\xi_a\) is measured in each realisation after randomly rotating the measured galaxy shapes.

We note that survey geometry also affects the other terms in the analytic covariance; the impact of the KiDS footprint on super-sample variance is included in the analytic covariance from H17, and the impact of survey geometries on the cosmic variance and mixed covariance terms is explored in Kilbinger & Schneider (2004); Joachimi et al. (2008). Singh et al. (2017) also considers the effect of masking on the covariance of several large-scale structure probes. However, in this analysis we focus on the shape noise, which is the leading contribution to the total variance on most angular scales included in the cosmology analysis.

3.1 Impact of survey geometry on shape noise

We demonstrate that the three approaches to measuring CovSN give consistent results for KiDS-450 in Fig. 1, while they disagree substantially with the geometric estimate. We find that in surveys that are non-compact or composed of multiple small fields, like KiDS-450, measurements of the shape noise that account for survey geometry can be significantly boosted relative to the standard geometrical

\footnote{For example, we reproduce the peak 1-D value of \(S_8\) in the original H17 chain to 0.03\%, while finding a 0.14\% weaker constraint.}

\footnote{https://bitbucket.org/joezuntz/cosmosis/wiki/Home}

\footnote{http://healpix.sf.net}
The impact of updates to the KiDS-450 covariance diagonal. Upper panel: The ratio of the true shape noise term to the geometric approximation in the (1,1) tomographic bin pair, which has a nominal range of $\sigma = 0.1$ to $0.3$, from (a) the variance of $\xi_+$ (Var$(\xi_+)$) is also consistent) measured from 1000 random rotations of the KiDS-450 shape catalogue (blue circles), (b) replacing $\sigma_{\text{eff}}$ with the measured $N_\ell(\theta)$ in Eq. 5 (red squares), and (c) an analytic prediction for $N_\ell(\theta)$ from the survey mask in Eq. 5 with (solid) and without (dotted) source clustering (green line). We compare the impact for a DES Y1-like survey footprint. For KiDS-450, the correction increases the shape noise by up to a factor of 3.5 on the largest measured scales, which corresponds to a maximum factor of 1.4 for DES Y1. On the smallest scales, the shape noise is slightly decreased due to source clustering. Lower panel: The ratio of the final corrected covariance to the original covariance for $\xi_+$ (black stars) and $\xi_-$ (blue triangles). Only angular scales used in the H17 analysis are shown. We include the (4,4) tomographic bin pair with nominal range $\sigma = 0.7$ to 0.9 for comparison (open symbols).

ric shape noise estimate. This update slightly reduces the impact of shape noise on scales $< 2$ arcmin due to source clustering, while significantly boosting the measured shape noise on large scales, up to a factor of 3.5 relative to the geometric estimate at 300 arcmin. We also show the impact of the shape noise update to the total covariance in KiDS-450 in the lower panel of Fig. 1.

This is less of an issue for survey geometries that are more contiguous and compact, such as DES Y1, but there is still a non-negligible difference in the shape noise term compared to the geometric estimate. This is shown in the top panel of Fig. 1, which compares the effect on the KiDS-450 and DES Y1 analyses. This difference will diminish as survey footprints become larger and for those that are designed to be contiguous and compact.

### 3.2 Treatment of multiplicative shear bias uncertainty

In addition to the shape noise update described in Sec. 3.1, we also modify how the multiplicative shear bias uncertainty $\sigma_m$ is added to the covariance, which is given in Eq. 12 of H17:

$$\text{Cov}^{ij} = 4\sigma_m^2 \xi_+^i \xi_+^j + \text{Cov}^{ij}.$$  \hfill (7)

This approach of analytic marginalisation should be equivalent for a single $m$ value to what was done in T17 (e.g., Bridle et al. 2002) when the predicted (theory) template $(\xi_+^m)$ is used.

In the original H17 covariance, the measured $\xi_{+, \text{meas}}$ was used as a fixed template to evaluate this term, which can lead to a bias in the inferred amplitude of the signal $(\sigma_m)$ due in part to there being a larger relative addition to the covariance for the data points which scatter high due to noise than for those that scatter low. The use of the data vector as a template in Eq. 7 was identified by accident while separating terms in the H17 covariance to update the shape noise component described in the previous section. We agreed that this should be changed if it non-negligibly biased the resulting cosmological inference prior to knowing its precise impact on the inferred parameter values.

After we decided to change the template used in Eq. 7, we further explored the impact of using various fixed templates for the analytic marginalisation of $m$ relative to the formally correct, cosmology-dependent template in Eq. 7. This included 1) using a fixed predicted $\xi_+^m$ as the template at the cosmology used to evaluate the other covariance terms, 2) using fixed predicted templates at two cosmologies with amplitudes of $\pm 10\%$, 3) marginalising over $m$ by including it as an additional model parameter in the inference, and 4) using the data vector as a fixed template. The first three approaches were found to give consistent results to the cosmology-dependent approach, while using the data as a fixed template biases the inferred $\sigma_m$ low, as shown in Fig. 2. For consistency, we implement Eq. 7 using a fixed template at the same cosmology used to evaluate the rest of the covariance in the results described below.

### 4 INTERPRETATION OF COSMIC SHEAR RESULTS

The accuracy of the cosmic shear covariance can significantly impact the interpretation of measurements. We have found in the recent DES Y1 analyses that underestimating the shape noise by 10-30% on most scales due to the effects described in Sec. 3 can significantly worsen the best-fit reduced $\chi^2$ for a cosmological model, even if it does not (as found in T17) significantly modify the resulting cosmological constraints. The effect is larger for the KiDS-450 geometry, due to the presence of multiple disjoint fields, leading to changes in both the $\chi^2$ and, to a small degree, the inferred model parameters. In the original parameter space of H17, we find significant improvements to the $\Lambda$CDM best-fit $\chi^2$ of the KiDS-450 cosmic shear data due to the shape noise update. The best-fit $\chi^2$ is reduced from 161 to 121 for 118 dof, corresponding to an increase in the $p$-value from $5 \times 10^{-3}$ to 0.4. Similarly, in the parameter space of T17, the best-fit $\chi^2$ is reduced from 122 to 78 for 67 dof. The interpretation of the DES cosmic shear best-fit $\chi^2$ in this parameter space is similar, with a $\chi^2$ that was reduced from 268 to 227 for 211 dof, with $p = 0.21$.

The update to the way $\sigma_m$ is included in the covariance in Eq. 7 more strongly impacts the inferred cosmology, while not significantly modifying the $\chi^2$. This is shown in the left panels of Fig. 2 combined with the shape noise update (solid contour), along with the impact of updating the reported $\theta$ value in the data vector.
Figure 2. Left panels: The impact of data vector and covariance corrections on the KiDS-450 cosmic shear results in the H17 analysis configuration. ‘θ corr.’ refers to the update of the θ values for the data vector that appropriately averages the mean pair separation noted in Footnote 1 of Joudaki et al. (2018). ‘θ+Covcorr.’ refers to additionally including the covariance corrections discussed in Sec. 3 – updating the CovSN and σm components. The CovSN update alone has relatively little impact on the cosmological constraints compared to the σm change. Right panels: A comparison of the final cosmic shear results from the KiDS-450 and the DES Y1 data in the T17 analysis configuration. In both panels, we include constraints from the CMB (Planck) for comparison, analysed separately in the two analysis configurations, and show the marginalised $S_8$ constraints on each side. Note that, among other differences described in the text, the neutrino mass density is fixed in the left panels (H17) and marginalized over in the right panels (T17), which causes the Planck contours in particular to differ. The cosmic shear results of the DES and KiDS analyses are strongly consistent, though the complete overlap found here is likely coincidental and not necessarily expected statistically. The 2-D 68% CL of both overlap with those of the CMB in the right panels (and nearly so in the left panels).

(dotted), both relative to the analysis of the original data vector and covariance (dashed). Both of these updates increase the inferred $S_8$. We find a similar shift in $S_8$ in the T17 parameter space. This shift improves agreement in the $S_8$–Ωm plane compared to both DES Y1 (T17) and Planck (Ade et al. 2016, TT-lowP) results. However, the complete overlap of the KiDS and DES constraints found here is likely coincidental and not necessarily expected statistically.

We compare the final parameter constraints from KiDS-450 and DES Y1 in the right panels of Fig 2, finding complete overlap of the KiDS-450 and DES Y1 cosmic shear contours in $S_8$ and Ωm, with constraints of $S_8 = 0.782^{+0.027}_{-0.022}$ for DES Y1 and $S_8 = 0.772^{+0.037}_{-0.031}$ for KiDS-450 in the T17 analysis configuration. Beyond the primary cosmological parameters, it is also important to recognise (as recently highlighted in Efstathiou & Lemos 2018) the impact that the major astrophysical systematic in cosmic shear, the intrinsic alignment of galaxies (IA) (see Joachimi et al. 2015; Troxel & Ishak 2015, and references therein), can have on the interpretation of cosmological results. One diagnostic of potential residual systematics is an inconsistent model fit for the IA signal, up to a potential difference in the effective amplitude due to the use of different shape measurement methods. We also find excellent agreement here, with an amplitude for the intrinsic alignment model of $A_{IA} = 1.0^{+0.4}_{-0.3}$ (DES Y1) and $A_{IA} = 0.9^{+0.9}_{-0.6}$ (KiDS-450) in the T17 analysis configuration, marginalising over a free redshift power-law evolution which is also strongly consistent. This is a powerful demonstration of consistency between the cosmic shear analyses of these two surveys, which lends credence to the robustness of constraints shown here from cosmic shear.

5 CONCLUSIONS & OUTLOOK

We have demonstrated that using an exact measurement (e.g., the actual $N_p(θ)$) of the shape noise component of analytic cosmic shear covariance matrix estimates is critical for ongoing and future analyses where the survey footprint is non-compact or disjoint. In the case of KiDS-450, we have demonstrated that this correction increases the shape noise term in the covariance by up to a factor of 3.5 on the largest scales. This shape noise correction is sufficient to completely resolve the large best-fit reduced χ^2 for ΛCDM from the original analysis of H17, and the first pre-print version of T17. With these updates, there is no longer any evidence for a lack of internal model consistency in this basic test for these cosmic shear analyses. We find that these changes can also relieve previously discussed tensions in other internal consistency tests, such as those performed in Efstathiou & Lemos (2018). For the six subsets of the data considered in that work, we find that all subsets are now consistent using the statistical methods described therein.

We find that two additional updates in (1) the addition of σm to the covariance matrix described in Sec. 3.2 and (2) the determination of the effective angular values for the data vector both shift the inferred $S_8$ from KiDS-450 to slightly larger values. This improves the mutual consistency in cosmological constraints between the KiDS-450 and DES Y1 cosmic shear data sets found in T17, while also bringing the KiDS-450 and Planck results into better agreement in the $S_8$–Ωm plane. These results are an important step forward in the mutual validation of cosmic shear results. A more complete comparison of the DES and KiDS weak lensing results and a full investigation of the impact of survey geometry on the mixed and cosmic variance covariance terms is warranted and is left to future work. An extended study of the internal and mutual...
consistency between several existing weak lensing surveys, including KiDS-450, will be presented in Chang et al. in prep.

Our results weaken evidence that $\Lambda$CDM can not consistently describe both low-redshift cosmic shear and the CMB, given the agreement shown here between DES Y1, KiDS-450, and Planck. With the next releases of DES, HSC, and KiDS weak lensing results and CMB results from Planck, $\Lambda$CDM will face a much stronger test. These upcoming results will determine whether the current agreement converges further, or whether we begin to see evidence of new fundamental physics needed to describe the evolution of the Universe from the surface of last scattering to the low redshifts probed by weak lensing.

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