Cosmic shear as a tool for precision cosmology: minimising intrinsic galaxy alignment-lensing interference

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Abstract. Cosmic shear leads to a correlation of the observed ellipticities of galaxies, an effect which is used to place constraints on cosmological parameters, and to explore the evolution of dark matter and dark energy in the universe. However, a possible systematic contaminant of the lensing signal is intrinsic galaxy alignment, with a correlation length of a few Mpc. Hirata & Seljak (2004) have recently demonstrated that for some models of intrinsic distortions, there may also be a cross-correlation between the intrinsic and lensing signals, which may dominate the intrinsic signal, and suppress the lensing power spectrum by several tens of percent. Unlike the pure intrinsic signal, this new term cannot be accounted for by neglecting or down-weighting pairs of galaxies which are physically close. Extending the correlation function tomography method of King & Schneider (2003) we illustrate how the impact of both intrinsic and cross-correlations can be significantly reduced, in the context of surveys with photometric redshift information. For a ground-based cosmic shear survey of ∼ 100 sq. degrees with photometric redshifts, even in the presence of systematic contaminants at the level considered here, cosmological models degenerate in the Ω_m – σ_8 plane can be distinguished well in excess of the 3-σ level.

1. Introduction

The tidal gravitational field of mass inhomogeneities distorts the images of distant galaxies, resulting in correlations in their observed ellipticities. This cosmic shear signal depends upon cosmological parameters and the matter power spectrum (Blandford et al. 1991; Miralda-Escudé 1991; Kaiser 1992). In 2000, four teams announced the first detections of cosmic shear (Bacon et al. 2000; Kaiser et al. 2000; van Waerbeke et al. 2000; Wittman et al. 2000; Maoli et al. 2001). The current and next generation of multi-colour surveys will cover hundreds or thousands of square degrees, and have the potential to measure the dark matter power spectrum at small scales (inaccessible to CMB measurements) with unprecedented precision, and furthermore to probe its evolution. These surveys will tighten errors on cosmological parameters, particularly when combined with results from the CMB, SNIa and galaxy surveys (e.g. van Waerbeke et al. 2002). For example, Tereno et al. (2005) forecast the errors on parameters from CFHTLS (Canada-France-Hawaii Telescope Legacy Survey) coupled with CMB, primarily from WMAP (Wilkinson Microwave Anisotropy Probe), noting that many combinations benefit greatly from the joint constraint.

A possible systematic contaminant of the lensing correlation function (ξ_{LL}) is intrinsic alignment, which may arise during the galaxy formation process. This has been subject to numerical, analytic and observational studies [e.g. Croft & Metzler 2000; Heavens et al. 2000 (HRH); Crittenden et al. 2001; Catelan et al. 2001; Mackey et al. 2002; Brown et al. 2002; Jing 2002; Hui & Zhang 2002]. However, a great deal of uncertainty remains, with amplitude estimates spanning more than an order of magnitude.

Recently, Hirata & Seljak (2004; hereafter HS04) demonstrated that there may be a finite intrinsic alignment-lensing cross-term (ξ_{LI}), depending on the mechanism giving rise to intrinsic alignments. One such mechanism is tidal stretching: the shape of a galaxy is determined by the shape of a halo in which it forms - which is in turn related to the tidal field where the halo resides. If this tidal field also lenses a background galaxy, then one might expect a correlation between the ellipticities of the foreground and background galaxies. HS04 estimated that the cross-term can potentially suppress the lensing power spectrum by several tens of percent, adopting an intrinsic alignment model where the mean ellipticities of galaxies are linear functions of the tidal field in which they form. However, they note that this cross-term is strongly model dependent - for instance it vanishes for a quadratic rather than a linear dependence on the tidal field.

It has been shown that photometric redshift information could be used to suppress ξ_{LI}, by downweighting or ignoring galaxy pairs at approximately the same redshift
The comoving distance at a time of the first kind, and a matter density parameter at the present epoch, and $\Omega_m$ today. If $\bar{z}_i$, $\bar{z}_j$, and $\bar{z}_i - \bar{z}_j$ are those values $\hat{z}_i$ and $\hat{z}_j$ given photometric estimates $\hat{z}_i$ and $\hat{z}_j$. This is given by

$$p(z_i, z_j|\bar{z}_i, \bar{z}_j, \theta) = \frac{p(z_i|\bar{z}_i) p(z_j|\bar{z}_j) [1 + \xi_{\text{gg}}(r)]}{\int dz_i \int dz_j p(z_i|\bar{z}_i) p(z_j|\bar{z}_j) [1 + \xi_{\text{gg}}(r)]},$$

where $\xi_{\text{gg}}$ is the galaxy spatial correlation function, which may also include redshift dependent evolution, and $r$ is the comoving separation of galaxies in a pair.

One can determine $\xi(\theta, \bar{z}_i, \bar{z}_j)$ on a 3-dimensional grid of $N_K$ angular separation bins of width $\Delta \theta$ centred on $\theta_K$ (index $K$), and $N_Z$ photometric redshift bins of width $\Delta z$ centred on each of $\bar{z}_i$ (index $I$) and $\bar{z}_j$ (index $J$). We will refer to an observed signal using the notation $\tilde{\xi}_{IJK}^{\text{obs}}$, and to a theoretical prediction for a particular cosmology, intrinsic alignment mechanism, and cross-term using $\langle \tilde{\xi}_{IJK} \rangle$. The lensing, intrinsic and cross-term correlations can be expressed in terms of sets of template functions $A_n$, $B_n$ and $C_n$

$$\xi^I(\theta, \bar{z}_i, \bar{z}_j) = \sum_{n=1}^{N_I} a_n A_n(\theta, \bar{z}_i, \bar{z}_j),$$

$$\xi^L(\theta, \bar{z}_i, \bar{z}_j) = \sum_{n=1}^{N_L} b_n B_n(\theta, \bar{z}_i, \bar{z}_j),$$

$$\xi^{IJK}(\theta, \bar{z}_i, \bar{z}_j) = \sum_{n=1}^{N_{IJ}} c_n C_n(\theta, \bar{z}_i, \bar{z}_j),$$

where $a_n$, $b_n$ and $c_n$ are the amplitudes of the $n$-th lensing, intrinsic and cross-term template functions respectively. As noted in KS03, extra functions can be added as required, to span the range of plausible models. We describe our choice of models in Sect. 2.3 below. A single index $m$ identifies correlations between two bins with redshift indices $I$ and $J$, and with angular separation index $K$. There are $N_M = N_Z (N_Z + 1) N_K / 2$ such independent measurements. The total of $N = N_L + N_I + N_{IJ}$ gridded template models for the correlation functions can be written as an $N_M \times N$ design matrix $M$, and their amplitudes as an $N$-dimensional column vector $\mathcal{G}$ so that

$$\langle \tilde{\xi}_m^{\text{obs}} \rangle = M_{mn} \mathcal{G}_n.$$

We recover $\tilde{\xi}_{IJK}^{\text{obs}}$ in terms of the template functions: using the method of least squares, the best-fit estimates of the amplitudes $\mathcal{G}_n$ are those values $\hat{\mathcal{G}}_n$ which minimise

$$S = (\tilde{\xi}_{IJK}^{\text{obs}} - M \mathcal{G}) C^{-1}(\tilde{\xi}_{IJK}^{\text{obs}} - M \mathcal{G}),$$

where

$$C = (MM^T)^{-1},$$

and

$$M = \frac{2\pi}{\Omega_m H_0^2} \int d\ell \int d\ell' \int \frac{d\ell}{2\pi} P_\delta \left( \frac{\ell}{f(w)}, w \right) J_0(\ell\theta) R(w, w') / f(w')$$

is the angular diameter distance of a source at comoving distance $w'$ seen from a distance $w$, to that seen from $w = 0$.

When we account for the availability of photometric redshift estimates rather than spectroscopic ones, the galaxy ellipticity correlation function becomes

$$\xi(\theta, \bar{z}_i, \bar{z}_j) = \int dz_i \int dz_j p(z_i, z_j|\bar{z}_i, \bar{z}_j, \theta) \xi(\theta, z_i, z_j),$$

where $p(z_i, z_j|\bar{z}_i, \bar{z}_j, \theta)$ is the probability to have true redshifts $z_i$ and $z_j$ given photometric estimates $\bar{z}_i$ and $\bar{z}_j$.
where $\mathcal{C}$ is the covariance matrix. Since $\langle \tilde{\xi}^{\text{mod}} \rangle_m$ is a linear combination of template functions, the linear least squares estimators are

$$\hat{G} = (\mathcal{M}^T \mathcal{C}^{-1} \mathcal{M})^{-1} \mathcal{M}^T \mathcal{C}^{-1} \tilde{\xi}^{\text{obs}} \ .$$

(9)

With an observed correlation function $\tilde{\xi}^{\text{obs}}$, a design matrix $\mathcal{M}$ containing our choice of template functions, and $\mathcal{C}$, we can obtain $\hat{G}$ i.e. the projection of $\tilde{\xi}^{\text{obs}}$ into the template functions. This means that separate fits for the lensing, intrinsic and cross contributions can be obtained. Most importantly, for the purpose of using the lensing signal in a subsequent analysis, is that we reduce the impact of any contamination from the intrinsic alignment-lensing cross-term as well as from the intrinsic alignment.

2.2. Covariance matrix

To evaluate (9), the covariance matrix $C_{mm'}$ is required. Following KS03 a simplified model which neglects the cosmic variance contribution will be used; thus the elements of $\mathcal{C}$ come from the intrinsic ellipticity dispersion of the source galaxies. This is the dominant contribution to the covariance at small angular scales; at larger angular scales, the cosmic variance terms start to dominate, with the transition angular scale depending on the survey geometry (Kaiser 1998; Schneider et al. 2002).

The elements of the covariance matrix are

$$C_{mm'} = \frac{2 (\sigma_z^2/2)^2}{N_p(m)} \left[ \left( 1 + \delta_L, \delta_L, \delta_{1,1} \right) \right] \ ,$$

(10)

where there is an extra contribution from auto-variance terms. Since $\mathcal{C}$ is diagonal, the elements of its inverse are simply $(C^{-1})_{mm'} = \delta_{mm'}/C_{mm}$. The galaxy ellipticity dispersion is denoted by $\sigma_z$. In bin $m$, the number of pairs is given by

$$N_p(m) = N_F \left[ \frac{\langle n_0 p(z) \rangle_\Delta z}{\langle n_0 p(z) \rangle_\Delta z} \right] L^4 \delta_L \frac{\theta}{L} \ ,$$

(11)

where $n_0$ is the galaxy number density, $p(z)$ is the redshift probability density for redshift bin $i$, and $L$ is the extent of the field, assumed to be square. $\tau(\theta/L)$ is a function that takes into account the fact that fields have finite extent, and is evaluated numerically as in KS03.

2.3. Basis models

The simple, restricted, set of template functions used here is described below.

2.3.1. Lensing basis models

The lensing template functions $A_n$ are the gridded $\xi_L(\theta, \bar{z}_i, \bar{z}_j)$ for 3 models of the underlying cosmology: i) ΛCDM ($\Omega_m = 0.3$, cosmological constant density parameter $\Omega_\Lambda = 0.7$), ii) OCDM ($\Omega_m = 0.3$, $\Omega_\Lambda = 0$) and iii) σCDM ($\Omega_m = 1$, $\Omega_\Lambda = 0$); for simplicity, the power spectrum normalisation $\sigma_8 = 0.9$, and shape parameter $\Gamma = 0.21$ for each model. We could choose templates close to ΛCDM, as described in Section 4.

Starting with a 3-dimensional primordial power spectrum $P(k) \propto k$, the Bardeen et al. (1986) transfer function is used to describe its evolution, along with the prescription of Peacock & Dodds (1996) for evolution in the non-linear regime. The lensing correlation functions are calculated using the relationship between the power spectrum and $\xi_L$ given in (2), and then integrated over the photometric redshift uncertainties as in (3). Here it is assumed that $p(z|\bar{z})$ is a Gaussian with dispersion $\sigma_{\text{phot}}$, centred on $\bar{z}$.

2.3.2. Intrinsic alignment basis models

Nine template models $B_n$ for the intrinsic alignments are considered, the true spatial intrinsic correlation function being parameterised in terms of a correlation length $R_{\text{corr}}$, and an exponent $\alpha$:

$$\eta(r, z) = (1 + z_{\text{av}})^\alpha \left[ \exp \left( -r/R_{\text{corr}} \right) \right] \ ,$$

(12)

where $z_{\text{av}}$ is the mean redshift of galaxies in a pair and $r$ is their comoving separation. We use the approximation $r^2 = (w_i - w_j)^2 + \theta^2 P \left[(w_i + w_j)/2\right]$. $R_{\text{corr}}$ is taken to be $[1, 3, 10] h^{-1}$ Mpc and $\alpha$ to be $[-1, 0, 1]$. The availability of photometric redshift estimates is accounted for by integrating $\eta(r, z)$ as in (4), and finally we obtain each of the model correlation functions on a grid. Note that the intrinsic models are calculated using the relationships for the distances $f(w)$ pertaining to the ΛCDM cosmology described above, and that we use $\xi_{\text{corr}}(r) = (r/5 h^{-1}$ Mpc$)^{-1.8}$.

2.3.3. Cross-term basis models

A simple toy-model prescription for the cross-term is adopted, parameterising $\xi_{\text{LI}}$ directly, and evaluated for the ΛCDM cosmology. The main feature of the model is the dependence on angular diameter distance as in HS04; for fixed $z_i < z_j$, the cross-term at a certain angular scale increases with $z_j$. To describe the angular dependence, an exponential term is used so that the observed signal is

$$\xi_{\text{LI}}(\theta, \bar{z}_i, \bar{z}_j) = T \exp \left( -\theta/\theta_{\text{x}} \right) \int f_k(w_i, w_j) p(z)dz \ ,$$

(13)

where $T$ is a normalisation and $\theta_{\text{x}}$ is a scale angle. The normalisation of the templates is fixed so that the magnitude of the cross-term is 12% of the ΛCDM lensing signal in the lowest angular separation bin, with respect to redshift slices at $z = 0.62$ and $z = 1.13$, and is negative as in HS04. Since the intrinsic alignment and cross-term models are currently poorly constrained, and this normalisation is model dependent, it has been chosen to result in a cross-term that is sub-dominant to the intrinsic signal for sources with small physical separations, and to dominate the intrinsic signal and have a measurable effect on the two point correlation function for sources with larger physical separations - in other words a cross-term
that would have to be accounted for in the analysis of cosmic shear survey data. Note that for the templates, this normalisation is however arbitrary, since the signal is projected into the template functions, determining best-fit estimates of their amplitudes. Two sets of templates are used for the cross-term: a set of three templates with $\theta_X$ set to [1, 5, 10] /3000 radians, and a set of nine templates with $\theta_X$ values [0.05, 0.1, 0.3, 0.1, 1.0, 2.0, 4.0, 6.0, 8.0] /3000 radians (where 1/3000 radian $\approx 1.15'$ $\approx 0.55$ Mpc at $z = 1$). Again, since predictions for the cross-term encompass a wide range of amplitudes, the template set would be expanded on as necessary.

3. Results

The results are presented in the context of possible future multi-colour cosmic shear surveys, with field size $L = 14'$, hence the largest scale on which the ellipticity correlation function is available is $\sqrt{2} \times 14'$. A galaxy number density of 30 arcmin$^{-2}$ and ellipticity dispersion of $\sigma_\eta = 0.3$ (typical of ground-based observations) are used throughout. We consider surveys of various areas, the fiducial survey having $N_F = 300$ independent pointings. The value of $\sigma_{\text{phot}} = 0.1$ is chosen since this is characteristic of that obtained with current SED fitting procedures such as hyperz using a wide range of optical and near-infrared filters (Bolzonella et al. 2000). There are $N_z = 65$ redshift slices between $\bar{z} = 0.2$ and 2.12, and $N_K = 25$ angular separation bins between $0.3'$ and 15'.

The galaxy redshift distribution follows the parameterisation from Smail et al. (1995), i.e. $p(\bar{z}) = \beta/[z_0 \Gamma_3(3/\beta)](\bar{z}/z_0)^2 \exp \left(-\left(\bar{z}/z_0\right)^\beta\right)$, where $\Gamma_3$ denotes the gamma function. We take $\beta = 3/2$ and $z_0 = 2/3$ yielding $\langle \bar{z}\rangle \approx 1$.

3.1. Minimising the contamination from the intrinsic and cross correlation signals

We start with a survey of $N_F = 300$ fields. Our “observed” correlation functions $\xi_{\text{obs}}$ comprise a lensing, an intrinsic and a cross contribution. The intrinsic alignment model for spirals from HRH, $\eta(r, z) = 0.012 \exp(-r/1.5\ h^{-1}\text{Mpc})$ was used to obtain $\xi^{\Lambda\text{CDM}}$, the lensing signal $\xi^{\text{L}}$ was calculated for a $\Lambda\text{CDM}$ cosmology and $\xi^{\Lambda\text{CDM}}$ for an exponential model with a scale angle of 4.8/3000 radians (which will be our fiducial cross-term model). In this subsection, the larger set of nine cross-term templates was used.

Random gaussian distributed errors with dispersion $\sigma = 0.05\sigma_{\text{nom}}$ were added to these correlation functions giving noise realisations, and best-fit parameters $\xi_n$ were recovered. Fig.1 and Fig.2 show the (noise-free) input and recovered correlation functions between two combinations of redshift slices: Fig. 1 shows correlations for slices at $\bar{z} \sim 0.6$ and $\bar{z} \sim 1$ and Fig. 2 shows the correlations between two neighbouring slices at $\bar{z} \sim 1$. In both figures we show the total signal, and Fig.1 (we also plot the lensing correlation function expected for an OCDM cosmology.

For bins with a large separation in redshift, the intrinsic signal is negligible, as expected. Similarly, for bins with a small separation in redshift, the cross-term is negligible. The reduced $\chi^2$ values of the recovered fits to the noise realisations are $\approx 1$. Note that if we were simply to down-weight physically close pairs to minimise any intrinsic alignment signal, that neglecting the cross-term may cause e.g. an underestimation of $\sigma_8$.

This procedure was repeated, this time with the angular dependence of the cross-term taken to be a power-law $\propto \theta^{-1.5}$. Note that this functional form is not contained in the template set, providing a check of the robustness of the method. We also show in Fig. 3 shows the (noise-free) input and recovered correlation functions between two redshift slices at $\bar{z} \sim 0.6$ and $\bar{z} \sim 1$, along with the total signal, and the OCDM lensing correlation function. We also show in Fig. 4 the corresponding results for $N_F = 3000$ (i.e. a survey of $\approx 160$ sq. degrees, similar to the ongoing CFHTLS). Note than in practice, the template sets for both the IA and cross-term would encompass a wide range of models; this is particularly important for the cross-term as discussed below.

3.2. Lifting the $\Omega_m - \sigma_8$ degeneracy

A well-known degeneracy in cosmic shear constraints is between $\Omega_m$ and $\sigma_8$. How accurately can a survey with $N_F = 3000$, 1000 or 300 distinguish between a $\Lambda\text{CDM}$ model and a near-degenerate model ($\Omega_m = 0.4, \sigma_8 = 0.78$) for the lensing model, in the presence of both an intrinsic alignment and a cross signal?

The gridded correlation functions for lensing in the $\Lambda\text{CDM}$ and degenerate cosmologies were taken and added to the gridded HRH intrinsic correlation function, along with the fiducial cross-term model. The simulations involved generating 10000 (1000) noise realisations for the 3000 and 1000 (300) field surveys, to obtain the “observed” gridded correlation functions $\xi^{\Lambda\text{CDM}}$ and $\xi^{\text{deg}}$. The best-fit amplitudes $\hat{G}_n$ for the template functions were recovered. A set of thirteen template functions was used containing a) the nine models for intrinsic alignments, b) the set of three models for the cross-term, along with c) either the $\Lambda\text{CDM}$ lensing template or the degenerate model template in turn. We end up with four sets of best-fit amplitudes for each size of survey, and corresponding values of $\chi^2$ for how well the signal is modeled by projection into the templates: two sets generated using the $\Lambda\text{CDM}$ (degenerate) lensing template, one of which is projected into a template set containing the $\Lambda\text{CDM}$ lensing template, and the other projected into a template set containing the degenerate lensing template. Values were determined for $\Delta \chi^2(\Lambda\text{CDM} - \text{degen})$ and (ii) $\Delta \chi^2(\text{degen} - \Lambda\text{CDM})$, corresponding to the difference in goodness-of-fit for the noise realisations when $\hat{\xi}^{\Lambda\text{CDM}}$ and $\hat{\xi}^{\text{deg}}$ are used in the template set. When the fiducial $\Lambda\text{CDM}$ model (degenerate model) is the best-fit and is contained in the template set, values of $\Delta \chi^2$ should be negative. This gives a mea-
sure of our ability to differentiate between models using correlation functions between redshift slices.

For $N_f = 3000$, when the model for the cosmology is contained in the template set, in all cases the noisy correlation functions for that cosmology are better fit. When $N_f = 1000(300)$, and $\bar{\xi}_{\Lambda CD M}$ is contained in the template set, in 99.77 (93.9) % of cases the noisy $\Lambda$CDM correlation functions are better fit. Also, when $\bar{\xi}_{\text{degen}}$ is in the template set, 99.88 (94.4) % of the noisy degenerate correlation functions have better fits. Hence, within the assumptions made, and in the presence of intrinsic and cross-term signals, these two cosmological models could be distinguished well in excess of the 3-\(\sigma\) level when $N_f = 1000$, and just in excess of 2-\(\sigma\) when $N_f = 300$.

For comparison, simulations were undertaken without any intrinsic and cross-term signal, so the only signal was from cosmic shear in a $\Lambda$CDM cosmology for a survey with $N_f = 300$. When $\bar{\xi}_{\Lambda CD M}$ is the lensing template for recovery, in just over 99% of cases the noisy correlation functions are better fit, compared with when $\bar{\xi}_{\text{degen}}$ is the lensing template. The same holds for simulations where the cosmic shear signal is from the degenerate cosmology, and $\bar{\xi}_{\text{degen}}$ is the lensing template.

Although in the foregoing example, the form of the cross-term is quite close to the templates, this is achievable in practice since the template set used would be large. Nevertheless, for the observed signal, let us next replace the cross-term model with exponential dependence on angular separation, with the power-law model (scale dependence $\propto \theta^{-1.5}$), and use the expanded set of nine exponential cross-term templates. The $\Lambda$CDM model for lensing, HRH intrinsic alignment model, and power-law model for the cross-term were used to generate 10000 noise realisations of a $N_f = 1000$ survey. Best-fit amplitudes for the template functions were determined in the same manner as above, first when the template set only contains a $\Lambda$CDM template, and second when it only contains the degenerate template. Again, the two cosmological models can be distinguished in excess of the 3-\(\sigma\) level.

4. Discussion and conclusions

Recently, it was suggested by HS04 that the lensing correlation function may be contaminated, not only by intrinsic galaxy alignments, but also by a cross-term which results in a correlation between the ellipticity of a background lensed galaxy and a foreground galaxy. The current and next generation of cosmic shear surveys have the potential to probe the evolution of the matter power spectrum, and to test other families of cosmological models (e.g. quintessence models) with similar physical manifestations as the concordance model (e.g. Benabed & Bernardeau 2001; TERENO et al. 2005). In this era of precision cosmology, it is therefore essential to have the ability to quantify and isolate the contribution from both intrinsic galaxy alignments and the intrinsic-lensing cross-term in order to remove these systematics. Although the intrinsic and intrinsic-lensing terms are important in their own right, providing constraints on physical processes at the epoch of galaxy formation, here we have concentrated on their role as contaminants of the pure lensing signal.

That the lensing, intrinsic and cross-term have different dependency on redshift enables the components to be isolated when photometric redshifts are available. In particular, the impact of the potential cross-term suggested by HS04, which is impossible to remove by simply neglect-
the Ω - perhaps finely sampling models which are degenerate in close to our best estimate for the cosmological parameters relation functions corresponding to cosmological models strategy for the lensing templates could be to have cor-
of functional forms for the intrinsic and cross-terms. One
of template functions as possible, particularly a wide range
coupled with a large survey area, is beneficial in obtaining
a wide range of template functions for each of the terms,
more akin to the cross-term than to the intrinsic signal,
Since the dependence on redshift of the lensing signal is
be minimised using this type of tomographic procedure.
Applying or down-weighting physically close galaxy pairs, can
be minimised using this type of tomographic procedure.
Since the dependence on redshift of the lensing signal is
more akin to the cross-term than to the intrinsic signal,
a wide range of template functions for each of the terms,
coupled with a large survey area, is beneficial in obtaining
an estimate of the cross-term magnitude.
Application to a real survey will warrant as large a set of
functionals as possible, particularly a wide range of functional forms for the intrinsic and cross-terms. One
strategy for the lensing templates could be to have correla-
tion functions corresponding to cosmological models
close to our best estimate for the cosmological parameters - perhaps finely sampling models which are degenerate in the Ω_m − σ_8 plane. If the reduced χ² of the best fit is
significantly larger than 1, this indicates that additional
template functions do need to be included. Additional con-
straints on intrinsic alignment templates could come from
direct measurements of the pure intrinsic alignment signal
in low redshift surveys where it could dominate lensing
(e.g. Brown et al. 2002), or in surveys where spectroscopic
redshifts are available. For the cross-term, HS04 note that
an estimate of the density-intrinsic shear correlation has
already been made on small scales in the context of as-
sessing the contamination of galaxy-galaxy lensing in the
SDSS (Hirata et al. 2004b). Such measurements on larger scales would help to define the template set, albeit at a
low redshift so that the possibility of evolution would have to be accounted for.

The main goal of the method developed here and in
KS03 is to harness redshift information in order to min-
imise the contamination of the lensing signal by any in-
trinsic alignment or lensing-intrinsic signal. Although a
comparison between how well discrete cosmological mod-
els fit the data can be made (such as in the discussion
above of models degenerate in the Ω_m − σ_8 plane), the
intention is not to determine best-fit cosmological param-
eters. In the absence of an intrinsic alignment or cross-
term, Simon, King & Schneider (2004) have demonstrated
how even crude redshift binning can greatly decrease er-
rors on cosmological parameters determined by measuring
shear correlation functions. Almost an order of magnitude
improvement is obtained when a few redshift bins are em-
ployed, and progressively little is gained as the number of
bins is increased. For cosmological parameter constraint,
a standard technique with much cruder redshift binning,
and a much finer sampling of cosmological parameters
could be applied to the cleaned lensing signal obtained
from the method presented here. Such techniques are typ-
ically analogous to the use of eq. (8), but in the form

\[ S = \left( \xi_{\text{obs}} - \xi(\pi) \right) C^{-1} \left( \xi_{\text{obs}} - \xi(\pi) \right), \]

where \( \xi(\pi) \) is the theoretical shear correlation function
for a set of cosmological parameters \( \pi \).

The simulations in this paper have been carried out
for a field of 14′ on one side; this is similar to the imager
on VLT-VIMOS. Having a larger field would increase the
number of pairs of galaxies in a particular bin from which
the correlation function is measured, so decreasing the
shot noise. The accuracy with which photometric redshifts
can be determined for the galaxies in a survey also im-
acts on the results: upcoming multi-colour surveys such
as the DES (Dark Energy Survey) will have redshift ac-
curacies of Δz = 0.03 − 0.07 for galaxies out to z ~ 1.1,
depending on redshift and galaxy type (white paper at
http://decam.fnal.gov). Cosmic shear surveys are carried
out at optical frequencies, but when wide-field infrared
observations of the same fields are carried out (with tele-
scopes such as VISTA), this will greatly assist photometric
redshift estimation.

With our restricted set of exponential templates for the
cross-term, and an exponential form for its true amplitude,
a survey of ~ 60 sq. degrees, with photometric redshifts for
the galaxies used in the analysis, would enable us to dis-
tinguish between models degenerate in Ω_m − σ_8 in excess of

Fig. 3. As for Fig. 1 but for a cross-term with a power-law
dependence on angular separation.

Fig. 4. As for Fig. 1 but for a cross-term with a power-law
dependence on angular separation, and for a survey with
3000 fields.
the 3-σ level. When the angular dependence of the cross-term is a power-law form, the same degree of distinction between models requires an expanded set of (exponential) template functions. Keeping in mind our simplified ansatz for the covariance matrix, this would crudely correspond to ~ 100 sq. degrees in practice - although given such a large number of fields we beat down cosmic variance. Accurate representations of the covariance matrix will be calculated using ray-tracing through large N-body simulations.

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