Describing galaxy weak lensing measurements from tenths to tens of Mpc and up to \( z \sim 0.6 \) with a single model

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Accepted 2013 October 3. Received 2013 September 12; in original form 2013 March 21

ABSTRACT
The clustering of galaxies and the matter distribution around them can be described using the halo model complemented with a realistic description of the way galaxies populate dark matter haloes. This has been used successfully to describe statistical properties of samples of galaxies at \( z < 0.2 \). Without adjusting any model parameters, we compare the predicted weak lensing signal induced by Luminous Red Galaxies to measurements from SDSS DR7 on much larger scales (up to \( \sim 90 \, h_{70}^{-1} \) Mpc) and at higher redshift (\( z \sim 0.4 \)). We find excellent agreement, suggesting that the model captures the main properties of the galaxy–dark matter connection. To extend the comparison to lenses at even higher redshifts we complement the Sloan Digital Sky Survey (SDSS) data with shape measurements from the deeper RCS2, resulting in precise lensing measurements for lenses up to \( z \sim 0.6 \). These measurements are also well described using the same model. Considering solely these weak lensing measurements, we robustly assess that, up to \( z \sim 0.6 \), the number of central galaxies as a function of halo mass is well described by a log-normal distribution with scatter \( \sigma_{\log L_\mathrm{c}} = 0.146 \pm 0.011 \), in agreement with previous independent studies at lower redshift. Our results demonstrate the value of complementing the information about the properties of the (lens) galaxies provided by SDSS with deeper, high-quality imaging data.

Key words: gravitational lensing; weak – methods: statistical – galaxies: haloes – dark matter – large-scale structure of Universe.

1 INTRODUCTION
Since the advent of large and homogeneous galaxy surveys, it has become possible to constrain the relation between the observed properties of galaxies and their host dark matter haloes with ever increasing precision, albeit in a statistical sense. In particular, studies of the observed abundances and clustering properties of galaxies (e.g. Guzzo et al. 2000; Norberg et al. 2001, 2002; Vale & Ostriker 2004, 2006; Zehavi et al. 2003; Conroy, Wechsler & Kravtsov 2006; Shankar et al. 2006; Wang et al. 2007; Yang, Mo & van den Bosch 2008; Moster et al. 2010; Guo et al. 2010; Behroozi, Conroy & Wechsler 2010; Moster, Naab & White 2012) have played a crucial role in establishing this relation with increasing detail.

Complementing these methods, the weak gravitational lensing signal around galaxies of different observed properties (galaxy–galaxy lensing) has emerged as another powerful technique to constrain this relation. Since the first detections (e.g. Brainerd, Blandford & Smail 1996; Griffiths et al. 1996; Hudson et al. 1998), the galaxy–galaxy lensing signal is now detected routinely as a function of the properties of the lens galaxies, thanks to multi-wavelength data becoming readily available (e.g. Fischer et al. 2000; McKay et al. 2001; Hoekstra et al. 2003, 2005; Sheldon et al. 2004; Mandelbaum et al. 2006; Heymans et al. 2006; Parker et al. 2007; Mandelbaum, Seljak & Hirata 2008; van Uitert et al. 2011; Choi et al. 2012; Velander et al. 2013). The systematics involved in these measurements have also been studied in great detail (see e.g. Mandelbaum et al. 2005, 2006, 2008). The main application remains the study of the galaxy–dark matter connection, such as measurements of scaling relations between halo mass and baryonic properties (e.g. Hoekstra et al. 2005; Mandelbaum et al. 2006; Cacciato et al. 2009; Leauthaud et al. 2010; van Uitert et al. 2011; Choi et al. 2012), constraints on the halo properties (e.g. Hoekstra, Yee & Gladders 2004; Mandelbaum et al. 2006; Limousin et al. 2007; Mandelbaum et al. 2008; van Uitert et al. 2012), and measurements of bias parameters (e.g. Hoekstra, Yee & Gladders 2001; Hoekstra et al. 2002; Sheldon et al. 2004). More recently galaxy–galaxy lensing has also been used as a cosmological probe in combination with galaxy abundance and/or clustering measurements (Rozo et al. 2010; Zu et al. 2012; Mandelbaum et al. 2012; More et al. 2013; Cacciato et al. 2013, hereafter C13).

There is growing scientific interest in probing the cosmic evolution of structure formation in the Universe, which is now becoming possible thanks to new and forthcoming galaxy surveys.

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Refereed by guest on 28 July 2018
For instance, one will be able to perform statistically representative analyses up to \(z \sim 1\) in the near future (e.g. KiDS, de Jong et al. 2012; VIPERS, Marchetti et al. 2012; Pan-STARRS, Kaiser et al. 2002; DES, HSC\(^\dagger\)), and possibly up to \(z \sim 2\) in a decade, e.g. with missions such as LSST,\(^\ddagger\) and Euclid\(^\ddagger\) (Laureijs et al. 2011).

Alongside the progress in observational capabilities, theoretical modelling has also improved substantially. Numerical simulations have proven important to investigate the link between galaxy–galaxy lensing and the galaxy–dark matter connection (e.g. Tatsitsiomi et al. 2004; Limousin, Kneib & Natarajan 2005; Natarajan, De Lucia & Springel 2007; Hayashi & White 2008). Furthermore, the observed abundance, clustering and lensing signal have been successfully explained using a statistical description of the dark matter distribution in the Universe as provided by the halo model (see e.g. Cooray & Sheth 2002; van den Bosch et al. 2013) coupled to a realistic model that describes the way galaxies of different observable properties populate host haloes (see e.g. Yang, Mo & van den Bosch 2003; Cooray & Milosavljević 2005; Cooray 2006; Yang et al. 2008).

In this study, we examine the modelling of the galaxy–galaxy lensing signal up to \(z \sim 0.6\). To this end, we first compare a model that describes the statistical properties of galaxies at low redshift (van den Bosch et al. 2013; Cacciato et al. 2013) to existing galaxy–galaxy lensing data measured around Luminous Red Galaxies (LRGs) at higher redshift (Mandelbaum et al. 2012). To extend the redshift range even further, and to obtain higher precision measurements, we follow van Uitert et al. (2011) and complement the ninth data release (hereafter DR9) of the Sloan Digital Sky Survey (hereafter SDSS) with \(\sim 450\) deg\(^2\) of high-quality imaging data from the second generation Red-sequence Cluster Survey (RCS2; Gilbank et al. 2011).

This paper is organized as follows. We describe the analytical model in Section 2, and its application to LRGs in Section 3. We then describe the surveys and the strategy to extract the new lensing measurements in Section 4. Results are presented in Section 5. Conclusions are drawn and discussed in Section 6.

Throughout this paper, we adopt the most basic (‘vanilla’) \(Λ\) cold dark matter (\(Λ\)CDM) cosmological model. Such \(Λ\)CDM cosmologies are described by five parameters: the energy densities (in terms of the critical density) of baryons, \(\Omega_\text{b}\), and cold dark matter, \(\Omega_\text{dm}\); the spectral index, \(n_\text{s}\), and normalization, \(\sigma_8\), of the initial power spectrum; and the Hubble parameter, \(h_\text{0}\), \(\equiv H_\text{0}/(70\text{ km s}^{-1}\text{ Mpc}^{-1})\). The flat geometry implies that \(\Omega_\Lambda = 1 - \Omega_\text{b} - \Omega_\text{dm}\). Throughout the paper, the results of Cacciato et al. (2013), we assume \((\Omega_\text{dm}, \Omega_\Lambda, \sigma_8, h_\text{0}, n_\text{s}, \Omega_\Lambda h^2) = (0.278, 0.722, 0.763, 1.056, 0.978, 0.0228)\). Radii and densities are in comoving units.\(^5\) When physical units are used they are explicitly indicated with ‘\(p\)’. Furthermore, log is used to refer to the 10-based logarithm.

## 2 MODELLING GALAXY–GALAXY LENSING

In this section we briefly describe how model predictions for the galaxy–galaxy (hereafter gg) lensing signal can be provided once one has a statistical description of dark matter properties (i.e. their average density profile, their abundance and their large-scale bias) complemented with a statistical description of the way galaxies of a given luminosity populate dark matter haloes of different masses (also known as halo occupation statistics). The model is identical to the one presented in van den Bosch et al. (2013) and successfully applied to SDSS in C13. Readers familiar with this model may skip this section and continue from Section 3 where we describe its application to Red Luminous Galaxies.

Weak gravitational lensing is sensitive to the mass distribution projected along the line of sight. Specifically, the quantity of interest is the excess surface density (ESD) profile, \(\Delta \Sigma(R)\), given by

\[
\Delta \Sigma(R, z_{\text{le}}) = \frac{2}{R^2} \int_0^R \left( \Sigma(R', z_{\text{le}}) - \Sigma(R, z_{\text{le}}) \right) dR' - \Sigma(R, z_{\text{le}}).
\]

(1)

Here \(z_{\text{le}}\) represents the average redshift of the lens galaxies, \(R\) is the projected radius around the lenses and \(\Sigma(R, z_{\text{le}})\) is the projected surface mass density, which is related to the galaxy–dark matter cross-correlation, \(\xi_{\text{gm}}(r, z_{\text{le}})\), according to

\[
\Sigma(R, z_{\text{le}}) = \bar{\rho}_\text{m} \int_0^{\omega_\text{so}} \left[ 1 + \xi_{\text{gm}}(r, z_{\text{le}}) \right] d\omega,
\]

(2)

where the integral is along the line of sight, \(\omega\) is the comoving distance from the observer and the subscript ‘so’ stands for ‘source’.

The three-dimensional comoving distance \(r\) is related to \(\omega\) through \(r^2 = \omega^2 - 2\omega_\text{c} \omega \cos \theta\). Here, \(\omega_\text{c}\) is the comoving distance to the lens, and \(\theta\) is the angular separation between lens and source (see fig. 1 in Cacciato et al. 2009). Note that the galaxy–dark matter cross-correlation is evaluated at the average redshift of the lens galaxies.

Observationally, the ESD profile is inferred by measuring the average tangential distortion of background galaxies (sources) around foreground galaxies (lenses):

\[
\langle \gamma(t) \rangle(R) = \frac{\Delta \Sigma(R)}{\Sigma_\text{crit}},
\]

(3)

where \(\langle \ldots \rangle\) indicates the azimuthal average inside an annulus at distance \(R\) from the centre of the lens and of width \(dR\). In equation (3), \(\Sigma_\text{crit}\) is a geometrical factor determined by the distances of (lens and source) galaxies:

\[
\Sigma_\text{crit} = \frac{c^2}{4\pi G D_\text{ls} D_{\text{ls-so}}(1+z_{\text{le}})^2},
\]

(4)

with \(D_\text{ls}\), \(D_{\text{ls-so}}\) and \(D_{\text{ls-so}}\) the angular diameter distance to the lens, the source and between the lens and the source, respectively, and the factor \((1+z_{\text{le}})^2\) accounts for our use of comoving units.

Under the assumption that each galaxy resides in a dark matter halo, \(\Delta \Sigma(R, z)\) can be computed using a statistical description of how galaxies are distributed over dark matter haloes of different mass (see e.g. van den Bosch et al. 2013). Specifically, it is fairly straightforward to obtain the two-point correlation function, \(\xi_{\text{gm}}(r, z)\), by Fourier transforming the galaxy–dark matter power-spectrum, \(P_{\text{gm}}(k, z)\), i.e.

\[
\xi_{\text{gm}}(r, z) = \frac{1}{2\pi^2} \int_0^\infty P_{\text{gm}}(k, z) \frac{\sin kr}{kr} k^2 dk,
\]

(5)

with \(k\) the wavenumber. \(P_{\text{gm}}(k, z)\) can be expressed as a sum of a term that describes the small scales (one-halo, 1h), and one that describes the large scales (two-halo, 2h), each of which can be further subdivided based upon the type of galaxies (central or satellite) that contribute to the power spectrum, i.e.

\[
P_{\text{gm}}(k) = P_{\text{cm}}^{1h}(k) + P_{\text{sm}}^{1h}(k) + P_{\text{cm}}^{2h}(k) + P_{\text{so}}^{2h}(k).
\]

(6)
As shown in van den Bosch et al. (2013), these terms can be written in compact form as

$$ P_{xy}^{1h}(k, z) = \int \mathcal{H}_s(k, M, z) \mathcal{H}_i(k, M, z) n_i(M, z) \, dM, $$
(7)

$$ P_{xy}^{2h}(k, z) = \int dM_1 \mathcal{H}_s(k, M_1, z) n_i(M_1, z) $$
$$ \times \int dM_2 \mathcal{H}_s(k, M_2, z) n_i(M_2, z) Q(k|M_1, M_2, z), $$
(8)

where ‘x’ and ‘y’ are either ‘c’ (for central), ‘s’ (for satellite), or ‘m’ (for matter), $Q(k|M_1, M_2, z)$ describes the power spectrum of haloes of mass $M_1$ and $M_2$, and it contains the large-scale bias of haloes as well as a treatment of halo exclusion. Furthermore, $n_i(M, z)$ is the halo mass function of Tinker et al. (2010) (see van den Bosch et al. 2013, for further detail C13; ). Here, we have defined

$$ \mathcal{H}_m(k, M, z) = \frac{M}{\rho_m} \tilde{u}_i(k|M, z), $$
(9)

$$ \mathcal{H}_c(k, M, z) = \mathcal{H}_s(M, z) = \frac{\langle N_i|M \rangle}{\bar{n}_i(z)}, $$
(10)

and

$$ \mathcal{H}_s(k, M, z) = \frac{\langle N_i|M \rangle}{\bar{n}_i(z)} \tilde{u}_i(k|M, z). $$
(11)

Here $\langle N_i|M \rangle$ and $\langle N_i|M \rangle$ are the average number of central and satellite galaxies in a halo of mass $M \equiv 4\pi(200)\rho_{200}/3$, whereas $\bar{n}_i(z)$ is the number density of galaxies at redshift $z$. We compute these quantities using the following expressions:

$$ \langle N_i|M \rangle = \int_{L_\ast}^{L_\ast} \Phi_s(L|M) \, dL, $$
(12)

where $\Phi_s(L|M)$ is the conditional luminosity function (CLF; see below and Appendix A), $L_\ast$ and $L_\ast$ refer to the lower and upper limit of a luminosity bin, respectively. Again, the subscript ‘x’ stands for either ‘c’ (centrals) or ‘s’ (satellites), and

$$ \bar{n}_i(z) = \int \langle N_i|M \rangle n_i(M, z) \, dM. $$
(13)

Furthermore, $\tilde{u}_i(k|M)$ is the Fourier transform of the normalized number density distribution of satellite galaxies that reside in a halo of mass $M$, and $\tilde{u}_i(k|M)$ is the Fourier transform of the normalized density distribution of dark matter within a halo of mass $M$. In this paper, supported by the results of C13, we assume for both these profiles the functional form suggested in Navarro, Frenk & White (1997). The CLF $[\Phi_s(L|M)]$ describes the average number of galaxies with luminosities in the range $L \pm dL/2$ that reside in a halo of mass $M$. Following C13, we parametrize the CLF with nine parameters (see Appendix A for a thorough description). We note here that the CLF methodology describes the halo occupation statistics of both central and satellite galaxies and it is not limited to the choice of specific luminosity bins, rather it applies to galaxies as a function of their luminosity. This will be of crucial importance when we will interpret the data presented in Section 4.

### 2.1 Additional lensing terms

In the analytical model used by C13, which was summarized above, the lensing signal is modelled as the sum of four terms: two describing the small (sub-Mpc) scale signal mostly due to the dark matter density profile of haloes hosting central and satellite galaxies; and the other two describing the large (several Mpc) scale signal due to the clustering of dark matter haloes around central and satellite galaxies, respectively. This reads:

$$ \Delta \Sigma(R, z) = \Delta \Sigma_{1h}^{1h}(R, z) + \Delta \Sigma_{1m}^{1h}(R, z) + \Delta \Sigma_{2h}^{1h}(R, z) $$
$$ + \Delta \Sigma_{2m}^{2h}(R, z). $$
(14)

In the halo model the small-scale signal (the one-halo term) has two more contributors corresponding to: (i) the baryonic mass of the galaxies themselves; and (ii) the dark matter density profile of the sub-haloes which host satellite galaxies.

The smallest scales probed by the data in this study are about 50 kpc, which are much larger than the typical extent of the baryonic content of a galaxy. Therefore, it is adequate to model the lensing signal due to the baryonic content of the galaxy as the lensing due to a point source of mass $M_{gl} \approx M_{star}$ (see e.g. Leauthaud et al. 2010). This reads

$$ \Delta \Sigma_{1h}^{1h}(R, z) \approx \frac{(M_{star}(z))^{1/2}}{\pi R^2}. $$
(15)

When accounting for the baryonic mass, this term adds to the other four indicated in equation (14). Throughout the paper, we model the lensing signal as in Section 2. However, when describing Fig. 5, we comment on how model predictions are modified once the baryonic mass is taken into account in the simplified way described above. To that aim, we use the value of the average stellar masses, $M_{star}$, for the galaxies in the luminosity bins under investigation here (see Section 5). For completeness, we list these values in Table 1.

The modelling of the dark matter density profile of the sub-haloes which host satellite galaxies is conceptually simple (see e.g. Mendelbaum et al. 2005; Li et al. 2009, 2012; Giocoli et al. 2010; Rodriguez-Puebla, Avila-Reese & Drory 2013) However, a proper implementation of this term is hampered by the poor knowledge of the subhalo mass function (see e.g. Giocoli, Tormen & van den Bosch 2008) and of the stripping mechanism (see e.g. Gao et al. 2004) which occurs once a dark matter halo enters a larger halo, i.e. when an initially central galaxy becomes a satellite. Many of the results about such subhalo properties are obtained from pure N-body simulations for which the limited mass resolution may still be an important limiting factor. Furthermore, it is unclear how these results are affected by various baryonic processes in place during galaxy evolution (e.g. van Daalen et al. 2011). Given these uncertainties and since subhaloes only contribute a small fraction to the total lensing signal on small scales (see e.g. Li et al. 2009), in this paper we make the simplifying assumption that these terms add to the other four indicated in equation (14). Throughout the paper, we model the lensing signal as in Section 2. However, when describing Fig. 5, we comment on how model predictions are modified once the baryonic mass is taken into account in the simplified way described above. To that aim, we use the value of the average stellar masses, $M_{star}$, for the galaxies in the luminosity bins under investigation here (see Section 5). For completeness, we list these values in Table 1.

#### Table 1. Properties of the ESD data.

| Label | $M_t$ (1) | $l_{g}M_{*}$ (2) | $z_{bd}$ (3) | $N_{le}$ (4) |
|-------|----------|-----------------|-----------|----------|
| L1    | (-18.0, -17.0) | 9.21 | 0.07 | 1,418 |
| L2    | (-19.0, -18.0) | 9.72 | 0.09 | 3,650 |
| L3    | (-20.0, -19.0) | 10.23 | 0.12 | 8,918 |
| L4    | (-21.0, -20.0) | 10.75 | 0.19 | 15,254 |
| L5    | (-21.5, -21.0) | 11.09 | 0.36 | 14,013 |
| L6    | (-22.0, -21.5) | 11.32 | 0.44 | 13,555 |
| L7    | (-22.5, -22.0) | 11.57 | 0.51 | 5,730 |
| L8    | (-23.0, -22.5) | 11.82 | 0.59 | 1517 |

The galaxy samples used to measure the ESD profiles, $\Delta \Sigma(R)$. For each of these samples Column 1 lists the magnitude label, Column 2 lists the magnitude range, where $M_t \equiv 0.1 M_e$, Column 3 lists the log of the average stellar mass ($l_{g}M_{*} \equiv \log [(M_{star}/h_{70} M_{\odot})]$), Column 4 lists the mean redshift, and Column 5 lists the number of lens galaxies.
paper, we refrain from modelling the lensing term due to the subhaloes which host satellite galaxies. We comment on the impact of this simplification when comparing model predictions with actual measurements.

3 SDSS LENSING SIGNAL AROUND LRGs

The model summarized in Section 2 was used by C13 to fit the galaxy–galaxy lensing signal measurements performed via SDSS in the spatial range \(0.05 \lesssim R \lesssim 2\) Mpc and at redshift \(z \lesssim 0.2\). The same model can be used to make predictions about the scale and redshift dependence of the lensing signal. To test the robustness of the model, it is therefore interesting to examine how it performs, without any adjustments of the parameters (including the best-fitting cosmology from C13), when compared to different data.

We first consider the gg lensing signal for a sample of LRGs (Eisenstein et al. 2001). Mandelbaum et al. (2012) have measured the lensing signal around two LRG samples based on the SDSS DR7 catalogue. The selection of LRGs allows the study of the dark matter distribution via weak gravitational lensing at higher redshift compared to the main sample. The effective redshifts of the two samples are \(z_{\text{le}} \approx 0.26\) and \(z_{\text{le}} \approx 0.40\). Here, the effective redshift is a weighted mean over the lens redshift distribution, with the weights set by the lensing efficiency of the lens–source pairs (Mandelbaum et al. 2012). Both samples have absolute magnitude limits \(-23.2 < M_g < -21.1\). Note that k-corrections and evolution corrections to convert r-band magnitude to \(M_g\) are taken from Eisenstein et al. (2001). More details about the procedure to select LRGs can be found in Kazin et al. (2010) and in Mandelbaum et al. (2012).

Fig. 1 shows the data (filled circles with error bars). The model predictions (solid lines) are obtained by using the same cuts as Mandelbaum et al. (2012) and the same model parameters found in C13. The model, although constrained using the main sample, describes the observed LRG signals very well. The value of the reduced \(\chi^2\) computed in the range\(^6\) \(0.2 \lesssim R \lesssim 90\) h\(^{-1}\) Mpc is 1.0 for the main LRGs and 0.8 for the high-z LRGs. The lensing signal around LRGs is reproduced over a large range of scales (0.2 \(\lesssim R \lesssim 90\) h\(^{-1}\) Mpc) and at high redshifts \(z \sim 0.26\) and 0.4.

It is worth emphasizing that the lensing signal on small and large scales carries different information. To first order, smaller scales probe the mass distribution within haloes, whereas larger scales probe the cosmological framework (mostly through a combination of the parameters \(\Omega_m, \sigma_8\)). We recall here that C13 embedded their analysis in a fully Bayesian framework in which they also constrained the cosmological parameters which define a ‘vanilla’ ΛCDM cosmology. They found that the parameters \((\Omega_m, \Omega_\Lambda, \sigma_8, h, n, \Omega_b, h^2) = (0.278, 0.722, 0.763, 1.056, 0.978, 0.0228)\) best fit their model. Hence the agreement with the measurements is an important validation of the model determined by C13. It not only implies that the parameters that describe the halo occupation distribution are also valid at higher redshifts, but also implies that the cosmological parameters are consistent.

Before comparing the model to gg lensing measurements based on a different data set in Section 4, we exploit the quality of the agreement between LRGs lensing data and model predictions to compute the average host halo mass of LRGs for both the main and the high-z sample. The estimation of the average halo mass follows

\[
\langle M_{200} \rangle \equiv \frac{1}{\bar{n}_c(z_{\text{le}})} \int \langle N_c | M \rangle n_h(M, z_{\text{le}}) M \, dM ,
\]

where \(n_h(M, z_{\text{le}})\) is the halo mass function (Tinker et al. 2010) at the lens redshift, and \(\langle N_c | M \rangle\) is computed via equation (12). We find that both the main and the high-z LRGs reside in haloes with \(\log[M_{200}/(h_70^3 M_{\odot})] \approx 13.6\), in general agreement with independent previous studies (see e.g. Mandelbaum et al. 2006; Zheng et al. 2009).

4 RCS2 GALAXY–GALAXY LENSING SIGNAL

The weak lensing signal decreases as the lens galaxy approaches the source. This limits the gg lensing analysis of the SDSS main spectroscopic sample (DR7) to lenses with \(z \sim 0.2\) when SDSS shape measurements are used. Reliable measurements at higher redshift are only possible by targeting very luminous lens galaxies; see the case of LRGs in the previous section. A unique aspect of the SDSS is the wealth of spectroscopic information, which extends to higher redshifts as is shown in Fig. 2. To improve the signal-to-noise ratio for higher redshift lenses, van Uitert et al. (2011)

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\(^6\) Note that the LRG lensing measurements used here are uncertain at scales smaller than about 0.14 h\(^{-1}\) Mpc (R. Mandelbaum, private communication)
measured the shapes of source galaxies using imaging data of a deeper survey that overlap with the SDSS. Specifically, van Uitert et al. (2011) studied the lenses in the region of SDSS DR7 that overlaps with the RCS2 (Gilbank et al. 2011). RCS2 is a 900 deg$^2$ imaging survey in three bands ($g'$, $r'$ and $i'$) carried out with the Canada–France–Hawaii Telescope (CFHT) using the 1 deg$^2$ camera MegaCam. The RCS2 data are $\sim2$ mag deeper than the SDSS in the $r'$ band and the median seeing of 0.7 arcsec is roughly half of that of the SDSS. Consequently the survey is well suited to improve the lensing constraints for lenses with $z \geq 0.3$, where the source distribution of the main sample in SDSS decreases significantly. In particular, it allows us to improve the lensing constraints for the most massive/luminous galaxies, which are preferentially selected at higher redshifts.

As shown in Fig. 2, a major change between the spectroscopic samples of SDSS DR7 and DR9 is that high-redshift ($z > 0.3$) LRGs were targeted as part of the Baryon Oscillation Spectroscopic Survey (BOSS; Anderson et al. 2012). As we show in this section, the lensing signal around these lenses can be determined with high precision using RCS2 shape measurements.

The SDSS DR9 (Ahn et al. 2012) overlaps with 471 RCS2 pointings. This amounts to roughly 450 deg$^2$ (about 150 deg$^2$ more overlap than between the RCS2 and the DR9 used in Van Uitert et al. 2011). The lens sample in the study presented here consists of all objects from the DR9 in the overlapping area that have a reliable spectroscopic redshift (according to the SciencePrimary flag) and that are spectroscopically classified as galaxies. In contrast to van Uitert et al. (2011), we do not require the DR9 objects to have a match with an object from the RCS2 catalogues, but only that they reside within the field of view of a RCS2 pointing. This leads to a lens sample of $\sim70,000$ objects, four times more than the lens sample used in van Uitert et al. (2011). In the remainder of the paper, we shall refer to this sample as $\text{DR9}$. The redshift distribution of the lenses is shown in the left panel of Fig. 2. For comparison, we also show the lens sample used in van Uitert et al. (2011), labelled as $\text{DR7}$. The majority of lenses with $z > 0.3$ are LRGs, whereas at lower redshifts, our lens sample consists of a mix of early-type and late-type galaxies. We do not consider these samples separately in this paper, as the halo model in use does not account for this split. The right-hand panel of Fig. 2 shows the distribution of absolute magnitudes for the whole sample, and for different redshift slices. The luminosities of the lenses are computed using the $r$-band Petrosian magnitudes from the SDSS photometric catalogues, corrected for extinction using the dust maps of Schlegel, Finkbeiner & Davis (1998). $K$-corrections were calculated to $z = 0.1$ using the \textsc{Kcorrect} v4.2 code (Blanton et al. 2003; Blanton & Roweis 2007). Finally, a passive luminosity evolution correction, $E$, was computed following Mandelbaum et al. (2012). Passive evolution is a term that refers to the fact that galaxies, without active star formation, become steadily fainter (and redder) as more massive (and brighter/bluer) stars exit the main sequence. In summary, the absolute magnitudes were computed as $M_r = m - DM - K(z = 0.1) + E$, where $m$ is the apparent magnitude of a galaxy, $DM$ is the distance modulus, $K$ is the correction mentioned above and $E$ is the passive evolution correction taken from Mandelbaum et al. (2012), i.e. $E = 2(z - 0.1)[1 - (z - 0.1)]$. We will comment on the impact of this assumption in Section 5.2.1.

The creation of the shape measurement catalogues for the RCS2 is detailed in van Uitert et al. (2011) and we refer the reader to it for a detailed description. Since we lack redshifts for the background galaxies, we select galaxies with $22 < m_r < 24$ that have a reliable shape estimate as sources. The resulting average source density is 6.3 arcmin$^{-2}$. The approximate source redshift distribution for the sources (left-hand panel of Fig. 2) is obtained by applying identical magnitude cuts to the photometric redshift catalogues of the COSMOS field (Ilbert et al. 2009). This procedure is detailed in Appendix C.

In contrast to van Uitert et al. (2011), we do not limit our lensing measurements to individual pointings, but we include the sources from neighbouring patches when measuring the azimuthally averaged tangential shear. This has the advantage that the lensing signal-to-noise ratio at large radii improves, due to the larger

\[ M_r = m - DM - K(z = 0.1) + E, \]

\[ E = 2(z - 0.1)[1 - (z - 0.1)]. \]
Figure 3. Upper panel: the ESD signal measured in Van Uitert et al. (2011). Note the limited spatial scale ($0.05 \lesssim R \lesssim 2 \, p$-Mpc) and that the error budget is, on average, between 10 and 20 per cent. Lower panel: the ESD measurements presented in this study. Note that the probed spatial range now extends up to $R \sim 10 \, p$-Mpc and that the error budget is below 10 per cent for most of the probed scales.

number of sources at these separations. Another advantage of including neighbouring patches is that it reduces the impact of systematic contributions to the lensing signal, as is explained in Appendix B. There we also present a detailed description of the error estimate.

To compare the statistical power between the current work and the analysis in van Uitert et al. (2011), we show the lensing signal of the respective lens samples in Fig. 3. We find that the signal-to-noise ratio of the lensing measurements improves by about 50 per cent on average. Importantly, the lensing signal is robustly measured out to larger separations (see Appendix B). We also split the lens sample in three redshift bins, and show the lensing signals for each bin in Fig. 4. This illustrates that even at $z > 0.5$ (with $z_{ls} \sim 0.59$), we are able to obtain significant lensing measurements. Furthermore, the higher normalization of the lensing signal measured at higher redshift is indicative of the fact that, not surprisingly, more massive lenses are selected at higher redshift.

5 RESULTS

The C13 model was constrained combining SDSS galaxy abundance and clustering measurements to gg lensing data at low redshift, $z \lesssim 0.2$, and relatively small scales, $R \lesssim 2 \, p$-Mpc. The comparison with the LRG sample in Section 3 provides an important test of the model, but the lensing measurements are derived from the same pipeline as the data used by C13. It is therefore interesting to study how well the predictions compare to the results of the independent analysis that uses RCS2 shape measurements. Such a comparison tests both the fidelity of the shape measurements and the model at even higher redshifts. To do so, we split the lens sample in eight luminosity bins and compare the gg lensing signal to model predictions (see Section 5.1). Following this comparison we proceed to use the lensing measurements to investigate the possibility to constrain the galaxy–dark matter connection at those higher redshift (see Section 5.2).

5.1 Comparison of the RCS2 lensing signal to model predictions

To study the model predictions as a function of luminosity we divide the DR9 lens sample in eight luminosity bins. The main properties of each bin are listed in Table 1. The black triangles with error bars in Fig. 5 indicate the resulting ESD measurements based on the RCS2 lensing catalogue as a function of projected lens–source separation. Over the large range in luminosity and scale.
Figure 5. The ESD around lenses in DR9 that overlap with RCS2. The black triangles indicate the lensing signal measured using the RCS2 imaging data. Magenta solid and red dashed lines refer to the model predictions from C13; see Sections 2 and 3, respectively. The shaded cyan region refers to the MCMC results where we consider $L_0$, $M_1$, $\gamma_2$ and $\sigma_{\log L_c}$ as free parameters.

On small scales, e.g. $R < 0.2$ Mpc, model predictions based on C13 can be easily modified to account for the contribution to the lensing signal due to the galaxy baryonic mass (red dashed lines in Fig. 5). Using the simplest assumption for how the stellar content of the galaxy may contribute to the lensing signal (see Section 3), we note that fainter/less massive galaxies are virtually unaffected by such a correction, whereas brighter/more massive galaxies exhibit a boost of the lensing signal but only on scales $R \lesssim 0.2$ h$_{70}^{-1}$ Mpc, reaching up to a factor of about 1.5 on scales $R \sim 0.05$ h$_{70}^{-1}$ Mpc, and leaving the signal at larger scales unaltered. We note here that in the current analysis the average stellar mass per luminosity bin is estimated by matching our lens sample to the MPA-JHU DR7 value added catalogue which provides stellar mass estimates. Specifically, we use the matching objects to fit a linear relation between absolute magnitude and stellar mass. We then use this relation to assign a stellar mass to all our lenses, and finally determine the average for each luminosity bin (reported in Table 1). A technical caveat must be mentioned here: the MPA-JHU catalogue only contains galaxies from the DR7, and not the more recently observed ones from BOSS. Therefore, when we use the average stellar mass to compute the baryonic term in the halo model, we implicitly assume that the relation between luminosity and stellar mass is similar for the DR7 galaxies as for those that were
observed as part of BOSS. This assumption may not be accurate, but the use of the stellar mass in this paper serves only to roughly quantify on which scales and by what amount the gg lensing signal might be affected by the baryonic mass of the galaxy. As the quality of the lensing signal improves, it will become mandatory to add this extra term especially if one aims to retrieve the amount of stellar mass by fitting the small-scale \( R \lesssim 0.2 \, h^{-1}_70 \, Mpc \) lensing signal. As an extra cautionary note, we comment here on the fact that the model presented in this paper does not account for the mass distribution in the subhaloes which host satellite galaxies.

We quantify the quality of the agreement between the data and the C13 model predictions in the spatial range 0.1–10 \( h^{-1}_70 \, Mpc \). Over this range, the model is less sensitive to the inclusion of the stellar mass and the data are less affected by systematics (see Appendix B). For the highest four luminosity bins, the C13 model predictions seem to systematically overestimate the gg lensing signal at about 1.5\( \sigma \) level. The reduced chi-squared, \( \chi^2_{\text{red}} \), of each bin (ordered by increasing luminosity) is \( \chi^2_{\text{red}} = 1.5, 1.4, 2.1, 2.3, 2.5, 2.4, 2.6, 2.0 \). Here, \( \chi^2_{\text{red}} \) is computed as \( \chi^2_{\text{red}} = \chi^2 / N_{\text{data in bin}} \), where \( N_{\text{data in bin}} \) represents the number of data points per bin. Although chi-squared values are above unity, we can conclude that there is an overall agreement between model predictions and data. This is especially true given that the C13 model predictions have not been tuned to fit this set of data. In Section 5.2, we will specifically investigate how well the model can fit this set of data, once model parameters are allowed to vary from the values retrieved in C13.

5.2 Constraining the galaxy–dark matter connection with weak lensing only

More luminous galaxies reside on average in more massive haloes. Using equation (16) we find that this is indeed the case, and that the luminosity bins listed in Table 1 correspond to halo masses that range from \( \log M_{200}/(h^{-1}_70 \, M_\odot) \sim 11.4 \) to \( \log M_{200}/(h^{-1}_70 \, M_\odot) \sim 14.2 \). The signal-to-noise ratio of the measurements presented in Fig. 5 is highest for lens galaxies with \( -23 \lesssim \log M_{200}/(h^{-1}_70 \, M_\odot) \lesssim -21 \), which correspond to relatively massive haloes \( [12.5 \lesssim \log M_{200}/(h^{-1}_70 \, M_\odot)] \lesssim 14.2 \). We explore here whether, thanks to the improved precision at the highest masses, we can constrain the model parameters which govern this regime using solely gg lensing measurements. To this aim, we employ the same model used so far, but we now leave the parameters that govern the mass relation free to vary. Guided by the results of Yang et al. (2008), we assume that the relation between the luminosity of a central galaxy and its host halo mass follows:

\[
L_c(M) = L_0 \left( \frac{M}{M_1} \right)^{\gamma_c} \left[ 1 + (M/M_1)^{\alpha_c} \right]^{\gamma_2} \sim L_0 \left( \frac{M}{M_1} \right)^{\gamma_c} \text{ for } M \gg M_1. \tag{17}
\]

Furthermore, the average number of central galaxies of a given luminosity is related to the halo mass via a log-normal distribution:

\[
\Phi_c(L|M) \, dL = \frac{\log e}{\sqrt{2\pi} \sigma_{\log L_c}} \exp \left[ -\frac{(\log L - \log L_c)^2}{2 \sigma_{\log L_c}^2} \right] \frac{dL}{L}, \tag{18}
\]

where \( \sigma_{\log L_c} \) indicates the scatter in luminosity at fixed halo mass and \( \log L_c \) is computed from equation (17) and is, by definition, the expectation value for the logarithm of the luminosity of the central galaxy:

\[
\log L_c = \int \Phi_c(L|M) \, \log L \, dL, \tag{19}
\]

(see Appendix A for more detail). Here, we consider \( L_0, M_1, \gamma_c \) and \( \sigma_{\log L_c} \) as four free parameters, while keeping \( \gamma_2 \) fixed to 3.18, the value retrieved in C13. The first free parameter has the units of a luminosity \( (h^{-2}_70 \, L_\odot) \), the second has the units of a mass \( (h^{-1}_70 \, M_\odot) \), whereas the remaining two are dimensionless.

To determine the probability distribution of the model parameters discussed above we run a Markov Chain Monte Carlo\(^9\) (hereafter MCMC) using the standard Metropolis–Hasting algorithm (Metropolis et al. 1953). In this chain, the parameters \( L_0, M_1, \gamma_2 \) and \( \sigma_{\log L_c} \) are free to vary and no prior information is used, whereas the remaining parameters are fixed at the same value as the one in the C13 model (see also Appendix A). As the satellite fraction is supposed to be very low for bright galaxies (e.g. C13; Mandelbaum et al. 2006; Cacciato et al. 2009; van Uitert et al. 2011), and the faintest galaxies in this study have relatively large uncertainties, we do not expect significant biases from selecting a subsample of the model parameters that govern the galaxy–dark matter connection of central galaxies only.

The 95 per cent confidence levels of the gg lensing models explored with the MCMC are indicated by the cyan shaded regions in Fig. 5. As expected, the subset of parameters that we have varied has almost no impact on the predictions for the lensing signal around the faintest galaxies. For brighter galaxies, the MCMC brings the model in better agreement with the observables than the initial C13 model predictions. Specifically, the value of \( \chi^2_{\text{red}} = \chi^2 / N_{\text{data in bin}} = 1.5 \), with similar contributions from each panel. Here \( N_{\text{data in bin}} = N_{\text{data}} - N_{\text{parameters}} = (15 \times 8) - 4 = 116 \). The agreement between model predictions and data has improved by assigning smaller halo masses to galaxies of the same luminosity. From our analytical model (see especially equations 17 and 18), one can see that lower halo masses at the same luminosity can be obtained by altering the \( L_c(M) \) relation at the massive end or by increasing the scatter, \( \sigma_{\log L_c} \). As outcome of the MCMC we find that the \( L_c(M) \) relation has substantially changed from the one retrieved in C13. However, as discussed in the following subsection, the inference of the parameters which govern the \( L_c(M) \) relation is very sensitive to the assumed correction for luminosity evolution, which is uncertain. Interestingly, the inference of the parameter \( \sigma_{\log L_c} \) is more robust against those uncertainties. Therefore, we report here only the corresponding result. The blue shaded histogram in Fig. 6 shows the posterior distribution of the scatter in the number of galaxies of a given luminosity at any halo mass, \( \sigma_{\log L_c} \) (see Appendix A for more details on this parameter). We find that \( \sigma_{\log L_c} = 0.146 \pm 0.011 \) (median ± one standard deviation), in excellent agreement with independent studies based on abundance, clustering and/or satellite kinematics at lower redshift. Specifically, using a large SDSS galaxy group catalogue, Yang et al. (2008) obtained \( \sigma_{\log L_c} = 0.13 \pm 0.03 \) (black star) and they did not find evidence for a halo mass dependence. Cooray (2006) explicitly assumed no mass dependence in \( \sigma_{\log L_c} \) when studying the luminosity function and clustering properties of SDSS galaxies, and found

\(^9\) The chain consists of four different chains which start from different initial guesses in the parameter space. In total, we perform about three million model evaluations. With an average acceptance rate of \(~30\) per cent, the complete chain used in the analysis is a well-converged chain of one million model evaluations.
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Figure 6. Posterior distribution of the parameter $\sigma_{\log L_c}$. Blue shaded histogram refers to the analysis in Sections 5.1 and 5.2, whereas the grey shaded histogram refers to the result of the test performed in Section 5.2.1 to assess the sensitivity of the analysis to passive evolution correction. The value of the scatter $\sigma_{\log L_c}$ is robust against the uncertainties deriving from passive evolution correction.

$\sigma_{\log L_c} = 0.17_{-0.01}^{+0.02}$ (grey triangle). More et al. (2009) studied the properties of satellite galaxy kinematics around massive/luminous central galaxies and found $\sigma_{\log L_c} = 0.16 \pm 0.04$ (magenta circle). Finally, C13 combining abundance, clustering and lensing of galaxies in SDSS found $\sigma_{\log L_c} = 0.157 \pm 0.007$ (red square).

5.2.1 Sensitivity to passive evolution correction

Ideally, one would like to compare the results on the $L_c(M)$ relation obtained here with those obtained at lower redshift to infer an evolutionary scenario. However, the physical interpretation of the results of the MCMC is hampered by the fact that the sample of galaxies used in this analysis is not uniform. In fact, the mix of early- and late-type galaxies changes with redshift due to the luminosity-based selection of the lenses. This leads to an uncertain correction for luminosity evolution which enters in the definition of the reference absolute magnitude of a galaxy, $M_r$, as indicated by the grey shaded histogram in Fig. 6. However, we refrain from drawing any conclusion about the cosmic evolution in narrow luminosity bins and up to $z \sim 0.6$. A different selection of lens galaxies directly translates into a different lensing signal. Specifically, we find that using the passive evolution correction of Blanton et al. (2003) leaves the lensing signal of faintest galaxies virtually unaltered, while leading to a higher normalization (at about 1σ level) of the lensing signal of the four brightest bins. Repeating the MCMC analysis as in Section 5.2 but on this new selection of lenses, we recover similar values of the scatter, $\sigma_{\log L_c}$, as indicated by the grey shaded histogram in Fig. 6. However, we retrieve values for $M_1$, $L_0$ and $\gamma_2$ that differ by about 3σ from our initial analysis. The changes in the retrieved model parameters are to be attributed to the expected degeneracies due to the assumed parametrization (see equation 17). We conclude that the retrieved values of the model parameters $M_1$, $L_0$ and $\gamma_2$ are sensitive to the details of luminosity evolution correction. Therefore, in this paper we refrain from drawing any conclusion about the cosmic evolution of the $L_c(M)$ relation, deferring it to the analysis of a homogeneous sample of early-type galaxies (van Uitert et al., in preparation) for which passive luminosity correction can be modelled with higher confidence than in the current study where we consider a mix of early- and late-type lens galaxies.

6 CONCLUSIONS

We investigated how measurements of the galaxy–galaxy lensing signal around lenses at increasingly higher redshifts and at larger projected distances can be used to study the galaxy–dark matter connection. We showed that the analytical model presented in van den Bosch et al. (2013) and constrained by (SDSS) abundance,
clustering and lensing data at $z < 0.2$ (see C13), reproduces, without further adjustments, the galaxy–galaxy lensing signal measured around LRGs (Mandelbaum et al. 2012) at $z \sim 0.26$ and $z \sim 0.4$ and throughout the probed spatial range, $0.02 \lesssim R \lesssim 90 \ h^{-1}_{70} \ \text{Mpc}$ (see Fig. 1). This agreement is an important validation of the model determined by C13. It not only implies that the parameters that describe the halo occupation distribution are also valid at higher redshifts, but also implies consistency with the cosmological parameters found by C13.

Following van Uitert et al. (2011), we measure the lensing signal around lenses from the SDSS (Data Release 9) using shape measurements from the 450 deg$^2$ that overlap with the RCS2 (Gilbank et al. 2011). The higher source density and redshift result in a significant improvement, compared to SDSS data alone, for lenses with $z \gtrsim 0.3$. We split the lenses into eight luminosity bins and measure robust tangential shear signals as a function of the transverse separation, $R$, in the range $0.05 \lesssim R \lesssim 10 \ h^{-1}_{70} \ \text{Mpc}$ (see Fig. 5).

Compared to the earlier study by van Uitert et al. (2011) which used the overlap with DR7, the use of the overlap with DR9 increases the number of lenses, resulting in an improvement of about 50 per cent in the precision of the lensing shear over the entire range probed here ($0.05 \lesssim R \lesssim 10 \ \text{Mpc}$). In addition, we now include the sources from neighbouring RCS2 pointings (previously the analysis was done on a pointing-by-pointing basis). This increases the lensing signal-to-noise ratio at large projected lens–source separations (see Fig. 3), and reduces systematic contributions to the lensing signal (see Fig. B1). Finally, compared to the DR7 catalogue, the redshift distribution of lens galaxies in DR9 has a large number of galaxies at $z > 0.4$ (see Fig. 2), enabling us to probe the matter distribution at those high redshifts (see Fig. 4).

We split the lens galaxies in eight luminosity bins, ranging from $-18 < M_r < 0.1M_r < -17$ to $-23 < 0.1M_r < -22.5$. Brighter galaxies are distributed at increasingly higher redshift such that the data span a wide range in redshift from $z = 0.07$ to $z = 0.59$. Moreover, since brighter galaxies live on average in more massive haloes, the range in luminosity probed here spans a correspondingly wide range in host halo mass. As a result, the measurements presented here simultaneously probe the matter distribution in different regimes from small groups to massive clusters, and from low to high redshift (see Fig. 5).

Without any adjustment, the C13 model also describes the lensing signal obtained with RCS2 data very well. This corroborates the results based on the SDSS analysis of LRGs, but also implies consistency of the measurement of the lensing signal. We note that the smallest scales probed here ($0.05 \lesssim R \lesssim 0.2 \ h^{-1}_{70} \ \text{Mpc}$) are affected by the inclusion of the contribution from the stellar mass of the galaxies: a simple point-mass model for the stellar component of the galaxies is sufficient to boost model predictions at those small scales. It thus become apparent that, as the quality of the lensing measurements improves, it will become mandatory to add this extra term in the modelling of the ESD.

Finally, exploiting the high signal-to-noise ratio of the lensing signal around bright galaxies, we attempt to constrain aspects of the galaxy–dark matter connection across cosmic time. While the inference of an evolutionary scenario for the galaxy luminosity–halo mass relation is hampered by current uncertainties in the evolution of galaxy luminosity, we robustly assess that, up to $z \sim 0.6$, the number of central galaxies as a function of halo mass is well described by a log-normal distribution with scatter, $\sigma_{\log L} = 0.146 \pm 0.011$, in agreement with previous independent studies at lower redshift.

Our results demonstrate the value of complementing the excellent information about the properties of the lenses provided by the SDSS with deeper, high-quality imaging data. This allows us to probe the link between galaxies and matter around them in increasing level of detail and at increasingly higher redshift. In this paper we tested the model of C13 and found that it overall performs very well. In future publications we will use our data to examine the evolution of early-type galaxies only, and we will carry out a comprehensive study of the possible evolution with cosmic time of the galaxy luminosity–halo mass relation for early-type galaxies.

ACKNOWLEDGEMENTS

We are grateful to Rachel Mandelbaum for providing us the ESD measurements of LRGs (Fig. 1) in electronic format. HH and MC acknowledge support from NWO VIDI grant number 639.042.814. HH also acknowledges ERC FP7 grant 279396.

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Yang et al. (2008) and More et al. (2009, 2011), we assume that $\Gamma$ and $\phi_1$ are in principle all functions of $L$, $M$, $s$, $\sigma$, which expresses the scatter in log $M$ for $M \sim M_1$. Here $M_1$ is a characteristic mass scale, and $L_0 = 2^{0.75} L_\ast(M_1)$ is a normalization. For the satellite galaxies we adopt $\phi_1(L|\Delta L) = 0.562 L_\ast(M_1)$, $\alpha_s(M) = 0.3$, $\alpha_c(M) = 0.3$, [i.e. the faint-end slope of $\Phi_i(L|M)$ is independent of mass and redshift], and $\log(\phi_i(M)) = b_0 + b_1(\log M_1) + b_2(\log M_2)^2$.  

**APPENDIX A: THE CONDITIONAL LUMINOSITY FUNCTION**

Throughout the paper, the average number of galaxies with luminosities in the range $L \pm dL/2$ that reside in a halo of mass $M$ is described by the CLF, $\Phi(L|M)$, introduced by Yang et al. (2003):

$$\langle N_c(L|M) \rangle = \int_{L-c}^{L+c} \Phi_c(L|M) dL.$$  

(A1)

Following Cooray & Milosavljević (2005) and Cooray (2006), we split the CLF in two components, $\Phi(L|M) = \Phi_c(L|M) + \Phi_s(L|M)$, where $\Phi_c(L|M)$ describes the contribution due to central galaxies (defined as those galaxies that reside at the centre of their host halo), while $\Phi_s(L|M)$ characterizes satellite galaxies (those that orbit around a central).

Our parametrization of the CLF model is motivated by the results obtained by Yang et al. (2008) from a large galaxy group catalogue (Yang et al. 2007) extracted from the SDSS Data Release 4, and by Tal et al. (2012) from a study of the luminosity function of satellite galaxies of LRGs. In particular, the CLF of central galaxies is modelled as a log-normal function:

$$\Phi_c(L|M) dL = \frac{\log e}{\sqrt{2\pi}\sigma_{\log L_c}} \exp \left[ -\frac{(\log L - \log L_c)^2}{2\sigma_{\log L_c}^2} \right] dL,$$  

(A3)

and the satellite term as a modified Schechter function:

$$\Phi_s(L|M) dL = \phi_s \left( \frac{L}{L_\ast} \right)^{\alpha_s + 1} \exp \left[ -\left( \frac{L}{L_\ast} \right)^{\gamma} \right] dL,$$  

(A4)

which decreases faster than a Schechter function at the bright end. Note that $L_c$, $\sigma_c$, $\phi_s$, $\alpha_s$ and $L_\ast$ are in principle all functions of the halo mass $M$.

Following Cacciato et al. (2009), and motivated by the results of Yang et al. (2008) and More et al. (2009, 2011), we assume that $\sigma_{\log L_{\Delta}}$, which expresses the scatter in $\log L$ of central galaxies at fixed halo mass, is a constant (i.e. is independent of halo mass and redshift). Note though that this does not imply that the scatter in halo mass at a fixed luminosity, $\sigma_{\log M}$, is constant: as discussed in Cacciato et al. (2009) and More et al. (2009), $\sigma_{\log M}$ increases because the slope of the $L_c(M)$ relation becomes shallower with increasing $M$. In addition, for $L_c$, we adopt the following parametrization:

$$L_c(M) = L_0 \left( \frac{M/M_1}{1 + (M/M_1)^{1/2}} \right).$$  

(A5)

Hence, $L_c \propto M^{\gamma}$ for $M \ll M_1$ and $L_c \propto M^{\gamma}$ for $M \gg M_1$. Here $M_1$ is a characteristic mass scale, and $L_0 = 2^{0.75} L_c(M_1)$ is a normalization. For the satellite galaxies we adopt $L_\ast(M) = 0.562 L_c(M)$.

$$\alpha_s(M) = \alpha_c,$$  

(A7)

[i.e. the faint-end slope of $\Phi_i(L|M)$ is independent of mass and redshift], and $\log(\phi_i(M)) = b_0 + b_1(\log M_1) + b_2(\log M_2)^2$,  

(A8)
with $M_{12} = M/(10^{12} h_{70}^{-1} M_{\odot})$. Note that neither of these functional forms has a physical motivation; they merely were found to adequately describe the results obtained by Yang et al. (2008) from the SDSS galaxy group catalogue.

To summarize, our parametrization of the CLF thus has a total of nine free parameters. Based on the results of Cacciato et al. (2013), unless otherwise specified, we adopt the values $(\log[M_*/(h_{70}^{-1} M_{\odot})], \log[L_*/(h_{70}^{-2} L_{\odot})], \gamma_1, \gamma_2, \sigma_{\log L_*, \alpha, b_0, b_1, b_2} = (11.39, 10.25, 3.18, 0.245, 0.157, -1.18, -1.17, 1.53, -0.217)$.

**APPENDIX B: SHEAR SYSTEMATICS AND COVARIANCE MATRIX**

For this paper the inaccuracies in the correction for PSF anisotropy is a main source of bias. On small scales we average over many lens–source pairs which have a random orientation with respect to the direction of PSF anisotropy, and as a result the lensing signal is robust. At large radii the lensing signal is small and residual systematics may become more dominant because the angles between the PSF anisotropy and the lens–source pairs may no longer be isotropic because of masks or the survey geometry. In this section we therefore examine the reliability of the lensing signal on scales $\gtrsim 1 h_{70}^{-1} \text{p-Mpc}$.

To account for residual systematics in our shape measurement catalogues, and for the impact of image masks on the lensing signal, we compute the lensing signal around a large number of random points, $\Delta \Sigma_{\text{rndm}}(R)$, and subtract that from the measured galaxy–galaxy lensing signal:

$$\Delta \Sigma(R) = \Delta \Sigma_{\text{measured}}(R) - \Delta \Sigma_{\text{rndm}}(R). \quad \text{(B1)}$$

In the absence of systematics or an isotropic orientation of lens–source pairs, this signal should vanish. The red line in Fig. B1 compares the random signal contribution [$i.e. -\Delta \Sigma_{\text{rndm}}(R)$] to the observed lensing signal (triangles with error bars) for the various luminosity bins. We find that the correction is generally very small: it is negligible for the L1 to L5 bins, and for the other bins it is significantly smaller than the lensing signal over the range $0.05 < r < 10 h_{70}^{-1} \text{p-Mpc}$ which we use in our analysis. Therefore, any small error in the calculation of the random shear signal will have a minor effect at most on our results.

The random shear signal is small because we include neighbouring pointings in our lensing analysis. Consequently, at large projected separations, the lensing signal is averaged over many more lens–source orientations, which averages out any residual systematics in our shape measurement catalogues at those scales. The dashed orange curves show the random signal contribution for the case where we perform the lensing measurements on single exposures only. In this case, the random signal strongly varies with increasing lens–source separation, and its amplitude becomes comparable or even larger than the size of the lensing signal itself. The behaviour of the random shear can be explained by the impact of the survey mask on the azimuthal averages, and by an imperfect PSF correction scheme. For instance, for $\sim 150$ RCS2 exposures, the PSF has a clear pattern such that the PSF ellipticity becomes large and radially oriented in the corners of the images. A small PSF residual in the galaxy shape could produce the observed signal. Even a relatively small error in the computation of the random lensing signal could seriously affect the results, which is clearly undesirable. Therefore, it is important to conduct the analysis on patches rather than individual exposures.

Another commonly used test is the measurement of the cross-shear, which is the projection of the source ellipticities to a unit vector that is rotated by 45° from the vector that connects that lens and the source. Galaxy–galaxy lensing only produces tangential shear and not cross-shear, as the average gravitational potential of a large number of lenses with random orientations is circularly symmetric. Therefore, if we measure a cross-shear that is not consistent with zero this indicates the presence of systematics in our shape measurement catalogues. For all luminosity bins we find that the cross-shear is consistent with zero on all scales used in our analysis.

In order to quantify the level of correlation between the lensing signals of different radial bins, we compute the correlation matrix from the data using the ‘delete one jackknife’ method (Shao & Wu

![Figure B1](https://academic.oup.com/mnras/article-abstract/437/1/377/999265/388-M.-Cacciato-E.-van-Uitert-and-H.-Hoekstra)

**Figure B1.** Assessment of systematics in the ESD measurements. Each panel refers to a luminosity bin as indicated by the labels. Black triangles with error bars refer to the ESD signal. The orange dashed lines denote the random shear contribution obtained if one were to use only one single exposure, whereas the red solid line refers to the random shear contribution obtained including neighbouring patches as in our analysis.
1989). We treat each pointing of the total $N$ pointings as a sub-volume that is subsequently left out to create a new realization of the data. The covariance matrix is then determined as

$$C_{ij}(\gamma_i, \gamma_j) = \frac{N - 1}{N} \sum_{k=1}^{N} \left( \gamma_i^k - \bar{\gamma}_i \right) \left( \gamma_j^k - \bar{\gamma}_j \right),$$

(B2)

with $\gamma_i$ the shear of the $i$th radial bin, $\gamma_i^k$ the shear at that location from one of the jackknife realizations and $\bar{\gamma}_i$ the mean shear of that bin determined by averaging over all the jackknife realizations. The correlation matrix follows from $\text{Corr}_{ij} = C_{ij} / \sqrt{C_{ii} C_{jj}}$.

We find that the correlation matrix is practically diagonal for almost all of our luminosity bins. Only for L2, L3 and L4 we find some low-level off-diagonal terms only around scales of $\sim 1 h_{70}^{-1} \text{p} \text{Mpc}$. Since our analysis is mostly sensitive to the highest luminosity bins, we assume that the correlation matrices are diagonal when we fit the models to the data.

Note that the correlation matrix that results from the jackknife method depends on the size of the sub-volume that is subsequently left out. This is demonstrated in Norberg, Frenk & Cole (2008), who compared several ways to determine the variance and covariance of two-point clustering measurements. For our purposes, the covariance matrix we determine is expected to be sufficiently accurate. However, for using measurements like these to constrain cosmological parameters, this is an issue that needs to be addressed, separately from the fact that the inverse of a noisy but unbiased correlation matrix is not unbiased (Hartlap, Simon & Schneider 2007).

### APPENDIX C: SOURCE REDSHIFT DISTRIBUTION

Using lens galaxies at higher redshifts, the mean lensing efficiency $(D_h/D_s)$ becomes more sensitive to the adopted redshift distribution of the sources, $P(z_{\text{gal}})$. Therefore, we have updated the method for determining $P(z_{\text{gal}})$, van Uitert et al. (2011) used the photometric redshift catalogues of the CFHTLS ‘Deep Survey’ fields (Ilbert et al. 2006) and selected all objects in the range $22 < r' < 24$ that satisfied the selection cuts as described in the release notes that accompanied the catalogues, i.e. only objects with reliable photometry in all the bands, that were observed in unmasked regions and with a best-fitting template number $<54$. Since the main interest there was to determine the redshift distribution rather than to select galaxies with reliable photometric redshifts, galaxies in the redshift range $0.05 < z_{\text{phot}} < 2.0$ were selected instead of $0.2 < z_{\text{phot}} < 1.5$ where the redshifts were deemed reliable. van Uitert et al. (2011) did not account for the scatter of the photometric redshifts, nor for the fraction of outliers. Also, they did not account for the fact that bright sources have a larger weight in the lensing measurements than faint ones.

To increase the precision of the lensing efficiencies for higher lens redshifts, in this paper, we use the photometric redshift catalogue from the 2 deg$^2$ COSMOS field (Ilbert et al. 2009) instead. The photometry in 30 bands results in photometric redshifts that are reliable up to higher redshifts. Using the overlap with the CFHTLS-D2 catalogue, kindly provided by H. Hildebrandt, we determined the conversion between the $r'$ band from the COSMOS catalogues, and the $r'$ band from the CFHTLS. Using this conversion we selected source galaxies in COSMOS based on their $r'$ magnitude corresponding to a selection of $22 < r' < 24$.

When integrating $D_h/D_s$ over the $P(z_{\text{gal}})$, we have to account for the fact that bright galaxies have a larger weight in our lensing measurements than faint ones. For this purpose, we determined the average lensing weight of the source galaxies in the RCS2 in narrow $r'$-band magnitude bins, finding that on average the sources with $r' < 22$ have a weight that is twice that of $r' > 22$ source galaxies. We used the conversion between the $r'$ and $r'$ band to compute the corresponding weight of each galaxy in the COSMOS catalogue, and used that weight to determine the weighted mean lensing efficiency.

To account for the outliers, we assigned a new redshift to a random fraction of the galaxies equal to the outlier fraction. The new redshift was drawn from the photometric redshift distribution of the sources, and replaced the catalogue value when it fulfilled the outlier criterion $(1 + z_{\text{phot}})/(1 + z_{\text{phot}}^\text{random}) > 0.15$. The outlier fraction depends on the brightness; we adopted a value of 0.7 per cent for galaxies with $i^+ < 23$, and 15.3 per cent for galaxies with $i^+ > 23$, as quoted in Ilbert et al. (2009). We created 16 realizations of the photometric redshift catalogues, each with a different randomly assigned set of outliers, and adopted the mean as our new lensing efficiencies. The scatter between the different realizations is small, and can safely be ignored compared to the statistical errors of the lensing analysis. We show the mean lensing efficiency at 10 lens redshifts in the second column of Table C1.

We ignored the impact of scatter of the photometric redshifts with respect to the spectroscopic redshifts. The effect of scatter is that it moves galaxies in redshift from where their abundance is large to where it is small. To estimate the impact that might have on $(D_h/D_s)$, we additionally scattered each photometric redshift by randomly drawing a value from a Gaussian, whose width depends on the galaxies’ $i'$-band magnitude, as quoted in Ilbert et al. (2009). We multiplied that random value with $1 + z_{\text{phot}}$ and added it to $z_{\text{phot}}$. We created 16 new realizations, and determined the mean

11 Formally, Ilbert et al. (2009) quote the scatter on $(1 + z_{\text{spec}})$ with $\Delta z = z_{\text{phot}} - z_{\text{spec}}$, so we should have multiplied the random value with $1 + z_{\text{spec}}$ rather than $1 + z_{\text{phot}}$. However, we expect the difference to be minor.

| $z_{\text{spec}}$ | $(D_h/D_s)$ | $(D_h/D_s)$ (CFHT) | $(D_h/D_s)$ ($z_{\text{phot}} < 2$) |
|-----------------|-------------|--------------------|----------------------------------|
| 0.1             | 0.774       | 0.777 (1.00)       | 0.768                            |
| 0.2             | 0.602       | 0.586 (1.03)       | 0.588                            |
| 0.3             | 0.461       | 0.440 (1.05)       | 0.443                            |
| 0.4             | 0.350       | 0.328 (1.07)       | 0.329                            |
| 0.5             | 0.264       | 0.240 (1.10)       | 0.241                            |
| 0.6             | 0.194       | 0.172 (1.13)       | 0.172                            |
| 0.7             | 0.141       | 0.118 (1.19)       | 0.118                            |
| 0.8             | 0.103       | 0.079 (1.30)       | 0.081                            |
| 0.9             | 0.076       | 0.053 (1.43)       | 0.055                            |
| 1.0             | 0.057       | 0.036 (1.58)       | 0.037                            |

(1) Lens redshift; (2) lensing efficiency determined using the photometric redshift catalogues of COSMOS (Ilbert et al. 2009); (3) lensing efficiency determined using the photometric redshift catalogues of the CFHTLS ‘Deep Survey’ fields (Ilbert et al. 2006), restricted to source galaxies in the range $z_{\text{phot}} < 2$. The bracketed values show the ratio between Columns 2 and 3; (4) lensing efficiency determined using the photometric redshift catalogues of COSMOS, restricting the source galaxies in the range $z_{\text{phot}} < 2$. 

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lensing efficiency. We found that the impact is less than a per cent at all lens redshifts, and can therefore be safely ignored.

To see how the lensing efficiencies compare to those computed using the CFHTLS ‘Deep’ catalogues, we applied the same procedure to compute the average lensing efficiencies. We accounted for outliers by adopting the outlier fractions as a function of $i$-band magnitude from Ilbert et al. (2006), and applied the same weight as a function of $r'$-band magnitude. However, we only selected galaxies with $z_{\text{phot}} < 2$. Again, we created 16 realizations, and determined the mean. We show the resulting values of $\langle D_{ls}/D_s \rangle$ in the third column of Table C1. At low redshifts, the resulting lensing efficiencies only differ by a few per cent compared to the ones based on the COSMOS catalogue. However, we find that if the lens redshift increases, the $\langle D_{ls}/D_s \rangle$ from COSMOS becomes increasingly larger. To demonstrate that this difference is due to source galaxies at $z_{\text{phot}} > 2$, we repeated the calculation using the COSMOS photometric redshift catalogue, but now restricting the analysis to $z_{\text{phot}} < 2$. We show the resulting lensing efficiencies in the fourth column of Table C1. We find that the lensing efficiencies agree very well with those based on the CFHTLS ‘Deep’ catalogues. The difference is at most 4 per cent over the entire redshift range that we probed.

In previous work where we used the photometric redshift catalogues from Ilbert et al. (2006) to compute the lensing efficiencies, we focused at galaxies at low redshifts. Hence the lensing efficiencies that we used there were of sufficient accuracy. However, for galaxies at redshifts $z > 0.5$, our results show that it is important to include source galaxies at $z_{\text{phot}} > 2$ in the computation of $\langle D_{ls}/D_s \rangle$.

Note that we have ignored cosmic variance. However, we find very similar lensing efficiencies using the COSMOS and CFHTLS ‘Deep’ photometric redshift catalogues when we restrict the galaxies to $z_{\text{phot}} < 2$. This suggests that cosmic variance does not have a large impact on the lensing efficiencies that we use.