THE WEAK LENSING SIGNAL AND THE CLUSTERING OF BOSS GALAXIES. I. MEASUREMENTS

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Received 2014 July 12; accepted 2015 March 17; published 2015 June 3

ABSTRACT

A joint analysis of the clustering of galaxies and their weak gravitational lensing signal is well-suited to simultaneously constrain the galaxy–halo connection as well as the cosmological parameters by breaking the degeneracy between galaxy bias and the amplitude of clustering signal. In a series of two papers, we perform such an analysis at the highest redshift ($z \sim 0.53$) in the literature using CMASS galaxies in the Sloan Digital Sky Survey-III Baryon Oscillation Spectroscopic Survey Eleventh Data Release (BOSS DR11) catalog spanning 8300 deg$^2$. In this paper, we present details of the clustering and weak lensing measurements of these galaxies. We define a subsample of 400,916 CMASS galaxies based on their redshifts and stellar-mass estimates so that the galaxies constitute an approximately volume-limited and similar population over the redshift range $0.47 \leq z \leq 0.59$. We obtain a signal-to-noise ratio (S/N) $\approx 56$ for the galaxy clustering measurement. We also explore the redshift and stellar-mass dependence of the clustering signal. For the weak lensing measurement, we use existing deeper imaging data from the Canada–France–Hawaii Telescope Legacy Survey with publicly available shape and photometric redshift catalogs from CFHTLenS, but only in a 105 deg$^2$ area that overlaps with BOSS. This restricts the lensing measurement to only 5084 CMASS galaxies. After careful systematic tests, we find a highly significant detection of the CMASS weak lensing signal, with total S/N $\approx 26$. These measurements form the basis of the halo occupation distribution and cosmology analysis presented in More et al. (Paper II).

Key words: cosmology: observations – galaxies: halos – gravitational lensing: weak – large-scale structure of universe

1. INTRODUCTION

In the current concordance cosmological model ($\Lambda$CDM), dark matter and dark energy constitute a large fraction ($\approx 95.5\%$) of the energy density of the universe; this conclusion is supported by a growing body of diverse observational astrophysical evidence (see e.g., Beutler et al. 2011; Blake et al. 2011; Sullivan et al. 2011; Anderson et al. 2012; Reid et al. 2012; Suzuki et al. 2012; Hinshaw et al. 2013; Aubourg et al. 2014; Planck Collaboration et al. 2014; Rest et al. 2014). Yet, we have little theoretical understanding of the fundamental physics that governs the physics of dark matter or dark energy. For this reason a large number of wide-area galaxy surveys are ongoing or planned for the near future and are aimed at characterizing the dark matter distribution and understanding the nature of dark energy. These include both the imaging and spectroscopic surveys: the Kilo-Degrees Survey\textsuperscript{10}, the Subaru Hyper Suprime-Cam Survey\textsuperscript{11} (see also Miyazaki et al. 2012), the Dark Energy Survey\textsuperscript{12}, Extended Baryon Oscillation Spectroscopic Survey\textsuperscript{13}, Subaru Prime Focus Spectrograph Survey\textsuperscript{14} (see also Takada et al. 2014), Dark Energy Spectroscopic Instrument\textsuperscript{15}, and ultimately the Large Synoptic Survey Telescope (LSST\textsuperscript{16}); see also LSST Science Collaboration et al. 2009; the Euclid project\textsuperscript{17}; and the Wide-Field Infrared Survey Telescope project\textsuperscript{18}; see also Spergel et al. 2013).

The measurement of galaxy clustering statistics is one of the most powerful probes in observational cosmology (Tegmark et al. 2004; Cole et al. 2005; Percival et al. 2010; Saito et al. 2011; Zehavi et al. 2011; Reid et al. 2012, 2014; Samushia et al. 2014). However, our lack of a detailed understanding of the relationship between the distribution of galaxies and that of dark matter limits the full use of the measured amplitude of the clustering signal for constraining cosmological parameters. Seljak et al. (2005) first proposed and demonstrated that it is possible to break this degeneracy between the unknown bias between galaxies and matter and the cosmological parameters by utilizing the theoretical dependence of galaxy bias on halo mass (Mo & White 1996; Sheth & Tormen 1999). By probing the halo masses of galaxies via the weak gravitational lensing around galaxies, commonly referred to as galaxy–galaxy lensing, on small scales (see also Yoo et al. 2006; Cacciato et al. 2009; Li et al. 2009; Leauthaud et al. 2012; Tinker et al. 2013).
or selection inhomogeneities at the low stellar-mass end on our cosmological constraints. This paper, the first in a series of two, will present the details of the subsamples and the clustering and lensing measurements. In Paper II we will present the constraints on the halo occupation distribution of galaxies and cosmological parameters derived from the measurements.

The structure of this paper is as follows. In Section 2, we describe the BOSS data used in this paper, the definition of our subsamples constructed from the parent CMASS catalog, and the details of the clustering signal measurements. In Section 3, we describe the CFHTLenS data used in our lensing measurement, the details of our weak lensing analysis methodology, and the systematic tests of the CFHTLenS catalog using random catalogs. Section 4 is devoted to discussion and conclusions. Unless stated otherwise, we will adopt a flat \( \Lambda \)CDM cosmology with \( \Omega_m = 0.27, \Omega_b = 0.73 \), and the Hubble parameter \( h = H_0/(100 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}) = 0.703 \).

2. SDSS-III BOSS DATA AND CLUSTERING MEASUREMENTS

2.1. SDSS-III BOSS Galaxies

For the clustering measurements, we use the sample of galaxies compiled in Data Release 11 (DR11) of the SDSS-III project. The SDSS-III is a spectroscopic investigation of galaxies and quasars selected from the imaging data obtained by the SDSS (York et al. 2000) II covering about 11,000 deg\(^2\) (Abazajian et al. 2009) using the dedicated 2.5 m SDSS Telescope (Gunn et al. 2006). The imaging employed a drift-scan mosaic CCD camera (Gunn et al. 1998) with five photometric bands (\( u, g, r, i \) and \( z \); Fukugita et al. 1996; Smith et al. 2002; Doi et al. 2010). The SDSS-III (Eisenstein et al. 2011) BOSS project (Ahn et al. 2012; Dawson et al. 2013) obtained additional imaging data of about 3000 deg\(^2\) (Ahara et al. 2011). The imaging data was processed by a series of pipelines (Lupton et al. 2001; Pier et al. 2003; Padmanabhan et al. 2008) and corrected for Galactic extinction (Schlegel et al. 1998) to obtain a reliable photometric catalog. This catalog was used as an input to select targets for spectroscopy (Dawson et al. 2013) for conducting the BOSS survey (Ahn et al. 2012) with the SDSS spectrographs (Smee et al. 2013). Targets are assigned to tiles of diameter 3\(^0\) using an adaptive tiling algorithm designed to maximize the number of targets that can be successfully observed (Blanton et al. 2003). The resulting data were processed by an automated pipeline which performs spectral classification, redshift determination, and various parameter measurements, e.g., the stellar-mass measurements from a number of different stellar population synthesis codes which utilize the photometry and redshifts of the individual galaxies (Bolton et al. 2012). In addition to the galaxies targeted by the BOSS project, we also use galaxies that pass the target selection but have already been observed as part of the SDSS-I/II project (legacy galaxies). These legacy galaxies are subsampled in each sector so that they obey the same completeness as that of the CMASS sample (Anderson et al. 2014).

To perform measurements of the clustering and lensing signals, we create various subsamples of the parent large-scale
structure catalog provided with DR11. To define the subsamples we use for the analysis, we make use of the stellar-masses processed through the Portsmouth stellar population synthesis code (Maraston et al. 2013) with the assumptions of a passively evolving stellar population synthesis model and a Kroupa (2001) initial mass function. The upper panel of Figure 1 shows the distribution of a random subsample of all galaxies in the large-scale structure catalog in the stellar-mass–redshift plane. The number density of this sample varies as a function of redshift and peaks at \( z \approx 0.5 \), as shown in the bottom panel. The fiducial subsample we use in this paper, denoted as subsample A, consists of all galaxies between \( z \in [0.47, 0.59] \) and with \( \log M_* h^{-2}_\odot \in [11.1, 12.0] \). This selection results in a sample with an approximately uniform number density with redshift compared to the parent sample, as shown by the black dashed line in the lower panel of Figure 1. The number density of this fiducial subsample is \( \approx 3 \times 10^{-4} \, h^3 \text{Mpc}^{-3} \). The total number of galaxies in this subsample is 378,807 (400,916) and constitutes about half of the parent sample used for the measurements of the baryon acoustic oscillations. In order to test the effects of incompleteness at the low stellar-mass end in our fiducial subsample, we additionally consider two different subsamples of galaxies which lie in the same redshift range, but where the stellar-mass selection is \( \log M_* h^{-2}_\odot \in [11.30, 12.0] \) and \( \log M_* h^{-2}_\odot \in [11.40, 12.0] \), respectively. These subsamples will be denoted as B and C, respectively. The numbers of galaxies in these subsamples are 196,578 and 116,682 (these numbers include fiber-collided and redshift failure galaxies), while the number densities of the galaxies are \( 1.5 \times 10^{-4} \) and \( 0.8 \times 10^{-4} \, h^3 \text{Mpc}^{-3} \), respectively. The number density of galaxies is approximately constant in the redshift range we use. In addition to these subsamples, we will also consider subsamples in different redshift bins to test the redshift and stellar-mass dependence of the clustering signals.

We must account for a number of subtle selection effects in order to obtain a precise measurement of clustering (Ross et al. 2012). The spectroscopic target sample is obtained from the SDSS imaging observations after the application of a variety of color and photometric selection cuts (Dawson et al. 2013). However, due to the limited number of fibers available, not all galaxies from this target sample can be allocated a fiber while performing spectroscopic observations to determine their redshifts. This could also happen if two targets are within 62″ of each other and hence they cannot be fiber-collided and redshift "ber, but its redshift could not be determined. If such fiber-collided galaxies lie in a region of the sky that is visited multiple times (due to overlaps in the target tiling) then they may have redshift measurements. There are also instances where a galaxy is assigned to a fiber, but its redshift could not be obtained. Finally, there are also instances where it is difficult to perform star-galaxy separation, especially in fields with a high number density of stars. These effects have been quantified in the parent DR11 catalog of CMASS galaxies by assigning a weight to each galaxy such that

\[
w_f = w_\# \left( w_{\text{noz}} + w_{\text{cp}} - 1 \right),
\]

where \( w_{\text{noz}} \) is the weight assigned to a galaxy if it is the nearest neighbor (in the plane of the sky) of a redshift failure galaxy,
$w_{\text{cp}}$ is similarly assigned to account for the nearest neighbors of fiber-collided galaxies\(^{20}\), and $w_{\text{c}}$ accounts for the systematic relationship between the density of stars and the density of BOSS target galaxies (for details, see Anderson et al. 2014). The BOSS parent catalog contains an additional weight, $w_{\text{FKP}}$, for each galaxy which depends upon the number density of galaxies in the sample at its redshift (Feldman et al. 1994). This weight is important for the parent galaxy catalog, which has a much larger variation in the number density of galaxies than the variation in $n(z)$ for the subsamples of galaxies we use. Therefore, in our analysis, we do not include this weight.

The weights $w_{\text{cmax}}$ and $w_{\text{cp}}$ can only be used if the entire sample of galaxies within a given redshift range is used to measure the clustering signal. In particular, for the subsamples of galaxies selected by stellar mass (or luminosity), it is unclear whether the fiber-collided or redshift-failure galaxy will be part of our subsample if it is assigned the same redshift as its nearest neighbor, as it may or may not satisfy the stellar-mass cut we have imposed. If we were to use the weights $w_{\text{cmax}}$ and $w_{\text{cp}}$ as provided, then we would spuriously include the weights of some galaxies which should not be in the subsample. We will also miss some fiber-collided or redshift-failure galaxies which should have been part of our subsample because their nearest neighbors failed to make it to our subsample due to stellar-mass cuts. In addition there is a possibility that the small-scale clustering will be affected by using the weights, as all pairs of galaxies involving a fiber-collided or redshift-failure galaxy are assigned line-of-sight (LOS) separations equal to zero.

Given these issues, we refrain from using the weights $w_{\text{cmax}}$ and $w_{\text{cp}}$ in our analysis. Instead, we have obtained the stellar masses using the measured photometry of the fiber-collided and the redshift-failure galaxies with the redshift of its nearest neighbor. Each of these galaxies is assigned the same $w_{\text{c}}$ as its nearest neighbor. We have verified that the stellar-mass–redshift distribution of such galaxies are similar to that of the sample of galaxies which have well-measured redshifts (catastrophic failures in the nearest neighbor redshift assumption will result in both a an incorrect redshift and stellar mass). We then decide whether to include these galaxies in our subsample based on whether these galaxies pass the stellar mass cuts we impose. Given our treatment of fiber-collided galaxies, the only weight we have to use in our analysis is

$$w_I = w_{\text{c}}.$$  \hspace{1cm} (2)

### 2.2. CMASS Galaxy Clustering Measurements

The clustering of galaxies can be quantified using the two-point correlation function. The two-point correlation function, $\xi(r)$, depends only upon the true three-dimensional distance between galaxies, $r$, if the universe is isotropic. However, the assumption of isotropy is broken due to the modulation of the distances of galaxies along the LOS ($\pi$), caused by peculiar motions of galaxies. In contrast, the distances along the plane of the sky ($r_p$) do not suffer from this modulation. The resultant correlation function displays a characteristic anisotropic pattern which elongates (flattens) the iso-correlation contours in the ($r_p$, $\pi$) plane on small (large) projected scales. The impact of such effects can be minimized by focusing on the projected two-point correlation function obtained by integrating the correlation function $\xi(r_p, \pi)$ along the LOS,

$$w_p(r_p) = 2 \int_0^{\pi_{\text{max}}} \xi(r_p, \pi) \, d\pi. \hspace{1cm} (3)$$

Unless stated otherwise, we will use $\pi_{\text{max}} = 100 \, h^{-1} \, \text{Mpc}$, and employ the same finite LOS integration limit while analytically modeling the observations in Paper II. When calculating the integral, we adopted the binning of $\Delta \pi = 1 \, h^{-1} \, \text{Mpc}$.

We use the estimator proposed by Landy & Szalay (1993),

$$\xi(r_p, \pi) = \frac{DD - 2DR + RR}{RR} \hspace{1cm} (4)$$

to obtain the two-point correlation function $\xi(r_p, \pi)$. Here, DD, RR, and DR represent the number of appropriately weighted pairs of galaxies with a given separation ($r_p, \pi$), where both galaxies lie either in the galaxy catalog or the random catalog or one in each of the catalogs, respectively.

We use random catalog with the same angular and redshift selection as our galaxy subsample. These random catalogs consist of about 50 times more points than the number of galaxies in each of our subsamples. We assign each random point a weight of $N_{\text{gal}}/N_{\text{ran}}$ to account for this difference. In practice, we use the random catalogs provided with SDSS DR11 (Anderson et al. 2014). We subsample these random catalogs in order to tailor them to the CMASS subsamples we use. For this purpose, we first divide the entire CMASS catalog into narrow redshift bins ($\Delta z = 0.05$). For each bin we calculate the fraction of galaxies in our subsample after the stellar-mass and redshift cuts are applied to the total sample, and interpolate this fraction as a function of redshift. This fraction is used at each redshift as the probability to accept points from the random catalog. This procedure also automatically accounts for the redshift cuts as the fraction outside the redshift range we have chosen is identically equal to zero.

In Figure 2, we explore the stellar-mass and redshift dependence of the clustering signal. For this purpose, we use the galaxy subsamples enclosed in the six color boxes in Figure 1. Each panel shows the dependence of the clustering signal on stellar-mass selection at fixed redshift.\(^{21}\) This figure demonstrates that the clustering signal varies with stellar mass at fixed redshift. Given that the stellar-mass threshold of the full sample of CMASS galaxies varies with redshift, the stellar mass dependence of the clustering signal implies the necessity of a proper redshift dependent modeling of the clustering if the entire galaxy sample is used. In Figure 3, we show that the clustering signals of the stellar-mass limited subsamples do not vary substantially with redshift. Although not a formal justification, this result supports our assumption of a single effective redshift for modeling our measurements. For our main analysis, we will therefore focus on subsamples A, B, and C that are defined by constant stellar-mass thresholds in the redshift range $z \in [0.47, 0.59]$.

We show the projected clustering signals for subsamples A, B, and C of the CMASS galaxies in Figure 4. The error bars are

\(^{21}\) We use a line-of-sight integration length $\pi_{\text{max}} = 60 \, h^{-1} \, \text{Mpc}$ for projecting the redshift space correlation function for these tests only given the limited redshift range of the data. Everywhere else in the paper we use $\pi_{\text{max}} = 100 \, h^{-1} \, \text{Mpc}$.

\(^{20}\) Nearest neighbor corrections have been shown to accurately correct for fiber collisions above the fiber collision scale ($\sim 0.4 \, h^{-1} \, \text{Mpc}$) by Guo et al. (2012). Both $w_{\text{cmax}}$ and $w_{\text{cp}}$ are equal to unity by default for all galaxies. Their values are incremented for the nearest neighbors of every redshift failure or fiber-collided galaxy.
obtained using the jackknife technique, where we utilized 192 jackknife regions on the sky covering the entire survey footprint. The cross-correlation matrices of the projected clustering measurement in each of our subsamples (normalized to have a value of unity on the diagonals) are shown in each of the panels of Figure 5. The correlation coefficients are defined as

$$C_{ij} = \frac{\text{Cov}(i, j)}{\sqrt{\text{Cov}(i, i)\text{Cov}(j, j)}}$$

where the subscripts $i$ and $j$ denote the radial bin index.

We observe that there is a significant covariance between the error bars of the measurements on large-scales, and we include this covariance while modeling the signal. The total signal-to-noise ratio (S/N) of the clustering in our fiducial subsample is 55.6, properly accounting for the covariance. It decreases to $\sim 100$ deg$^2$. The number of CMASS galaxies that lie within the CFHTLS footprint is 5084 for our fiducial subsample A, 2549 from subsample B, and 1577 for subsample C, compared to $\sim 0.4$ million CMASS galaxies in the entire BOSS footprint. In Figure 6, we show the different CFHTLS fields. The positions of CMASS galaxies in subsample A within these fields are indicated by black dots.

The quantities needed for a shape estimate of each galaxy image, its ellipticity, calibration factors, and weight are provided in the CFHTLenS catalog (Heymans et al. 2012; Erben et al. 2013; Miller et al. 2013). The two ellipticity components in the celestial coordinate system, $(\epsilon_1, \epsilon_2)$, were estimated from the $i'$-band data of each galaxy image using the lensfit software, which is based on a Bayesian model-fitting method (Miller et al. 2007) for a model with two components. The ellipticity is defined as $e = (a - b)/(a + b)$, where $a$ and $b$ are the major and minor axes of the ellipse, respectively. Using a shear recovery test based on galaxy image simulations, the CFHTLenS team also provided calibration factors that are a function of galaxy size and detection of S/N, so that the input shear for simulated galaxy images is recovered to the desired accuracy after application of these factors. The calibration factors consist of the shear multiplicative bias factor $m$, which is commonly applied to both $\epsilon_1$ and $\epsilon_2$, and the additive term $c_2$, which is applied to $\epsilon_2$ alone. The shear correction is greater for a galaxy with small S/N and small scale-radius (size). We will describe the details of the shear calibration scheme in Section 3.2. The inverse-variance weight for each galaxy is defined by the variance that is estimated from the intrinsic galaxy ellipticity and the measurement error due to photon noise (for details, see Miller et al. 2013).

Unfortunately, the overlap between the CFHTLS and the DR11 BOSS fields is limited to an area of only $\sim 100$ deg$^2$. The number of CMASS galaxies that lie within the CFHTLS footprint is 5084 for our fiducial subsample A, 2549 from subsample B, and 1577 for subsample C, compared to $\sim 0.4$ million CMASS galaxies in the entire BOSS footprint. In Figure 6, we show the different CFHTLS fields. The positions of CMASS galaxies in subsample A within these fields are indicated by black dots.

The quantities needed for a shape estimate of each galaxy image, its ellipticity, calibration factors, and weight are provided in the CFHTLenS catalog (Heymans et al. 2012; Erben et al. 2013; Miller et al. 2013). The two ellipticity components in the celestial coordinate system, $(\epsilon_1, \epsilon_2)$, were estimated from the $i'$-band data of each galaxy image using the lensfit software, which is based on a Bayesian model-fitting method (Miller et al. 2007) for a model with two components. The ellipticity is defined as $e = (a - b)/(a + b)$, where $a$ and $b$ are the major and minor axes of the ellipse, respectively. Using a shear recovery test based on galaxy image simulations, the CFHTLenS team also provided calibration factors that are a function of galaxy size and detection of S/N, so that the input shear for simulated galaxy images is recovered to the desired accuracy after application of these factors. The calibration factors consist of the shear multiplicative bias factor $m$, which is commonly applied to both $\epsilon_1$ and $\epsilon_2$, and the additive term $c_2$, which is applied to $\epsilon_2$ alone. The shear correction is greater for a galaxy with small S/N and small scale-radius (size). We will describe the details of the shear calibration scheme in Section 3.2. The inverse-variance weight for each galaxy is defined by the variance that is estimated from the intrinsic galaxy ellipticity and the measurement error due to photon noise (for details, see Miller et al. 2013).

Figure 2. Stellar mass dependence of the projected clustering signal at fixed redshift is displayed in each of the panels for three different redshift bins. Data points with error bars show the clustering measurements of the different subsamples shown in Figure 1. Squares with error bars correspond to the stellar-mass bin $\log M_* / h^{30} M_\odot \in [11.10, 11.40]$ while circles with error bars correspond to the stellar-mass bin $\log M_* / h^{30} M_\odot \in [11.40, 12.00]$. The line-of-sight integration length used to project the redshift space correlation function is $60 h^{-1}$ Mpc. At fixed redshift, the clustering amplitude increases strongly with the stellar mass of galaxies.

3. CFHTLENS DATA AND LENSING MEASUREMENT

3.1. CFHTLenS Catalog

For the measurements of the galaxy–galaxy lensing signal around the subsamples of CMASS galaxies, we must measure the tangential distortion of background galaxies. For this purpose, we rely on the deeper and better quality imaging data from the Canada–France–Hawaii Telescope Legacy Survey (CFHTLS). This information allows us to measure the tangential distortion of background galaxies around the different subsamples of CMASS galaxies. In particular we make use of the photometric reduction and image shape determinations in the publicly available CFHTLenS catalog.\footnote{http://www.cfhtlens.org/astronomers/data-store}

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details, see Hildebrandt et al. 2012). The BPZ code provides a probability distribution function (PDF) of the photo-z estimate for each galaxy (hereafter $P(z)$). We make use of the full information of $P(z)$ when computing lensing signal.

To make a reliable lensing measurement, we use the following catalog of source galaxies. First, we discard galaxies that have the flag $\text{MASK} > 1$ indicating masked objects. We use the galaxies that have the ellipticity weight $\text{weight} > 0$, and the ellipticity fitting flag $\text{fitclass} = 0$, which indicates that the shape is reliably estimated. We do not apply any cut to magnitude or S/N, i.e., we use all the faint galaxies as long as the above conditions are satisfied. Although the faint galaxies are highly downweighted and largely corrected for the calibration factors, they contribute to the lensing signal and slightly increase the S/N.

3.2. Galaxy–Galaxy Lensing Measurements

Galaxy–galaxy weak lensing measures a coherent distortion of source galaxy shapes due to all matter around lens galaxies, including dark matter (see Mandelbaum et al. 2013, and references therein). The lensing signal is only statistically measurable and can be estimated by stacking tangential components of source galaxy ellipticities with respect to the position of the lens galaxy, for all the pairs of lens and source galaxies in each circular annulus. The lensing distortion probed in this way is expressed in terms of the projected surface-mass density profile of the average mass distribution around the lens galaxies:

$$\gamma(t)(R) = \frac{\Delta \Sigma(R)}{\Sigma_{cr}} = \frac{\bar{\Sigma}(<R) - \Sigma(R)}{\Sigma_{cr}}.$$  (6)
Figure 4. Clustering (left) and lensing (right) signal measurements for subsamples in the redshift range $z \in [0.47, 0.59]$, but with stellar-mass threshold cuts log $M_*$ > 11.10, 11.30, and 11.40 shown using blue circles with errors, red triangles with errors, and green squares with errors, respectively. The line-of-sight integration length used to project the redshift-space correlation function is 100 $h^{-1}\text{Mpc}$ for all the three subsamples. These measurements will be used to constrain the halo occupation distribution parameters of galaxies as well as the cosmological parameters in Paper II.

where $R$ is the projected separation between the source and lens galaxies at the redshift of each lens galaxy, $\Sigma(R)$ is the projected mass density profile at radius $R$, $\Sigma_c(<R)$ is the average mass density within a circle of radius $R$, and $\Sigma_{cr}$ is the critical surface-mass density. A spectroscopic redshift for each CMASS galaxy, $z_l$, enables an estimation of the projected radius from the observed angle separation $\Delta \theta$ via $R = d_A(z_l) \Delta \theta$, where $d_A(z_l)$ is the comoving angular diameter distance to the lens galaxy. The critical density $\Sigma_{cr}$ for lens and source galaxies at redshifts $z_l$ and $z_s$, respectively, is defined as

$$\Sigma_{cr}^{-1}(z_l, z_s) = \frac{4\pi G}{c^2} \frac{d_A(z_l) d_A(z_s)}{d_A(z_s)} (1 + z_l)^2 (1 + z_s)^2.$$ (7)

Here $d_A(z_s)$, $d_A(z_l)$, and $d_A(z_s, z_l)$ are the angular diameter distances for the source–lens system. The factor of $(1 + z_l)^2$ arises from our choice of comoving coordinates. Another component of shear, $\gamma_{\phi}$, which is a 45° rotated component from the tangential shear, should be statistically consistent with zero for weak gravitational lensing (but potentially nonzero for shape distortions due to systematic errors). Hence we can use the measured $\gamma_{\phi}$ as a monitor of a possible residual systematics in the lensing measurement.

For each pair of lens and source galaxies, we compute the tangential ellipticity component using

$$e_t = -e_1 \cos 2\phi - e_2 \sin 2\phi,$$ (8)

where $\phi$ is defined as the angle measured from right ascension direction to a line connecting the lens and source galaxies at source galaxy position. Using spherical trigonometry, the angle $\phi$ is given in terms of the galaxy positions $(\alpha, \delta)$ as

$$\cos \phi = \frac{\cos \delta_1 \sin(\alpha_2 - \alpha_1)}{\sin \theta},$$
$$\sin \phi = -\sin \delta_1 \cos \delta_2 + \cos \delta_1 \cos(\alpha_2 - \alpha_1) \sin \delta_2,$$ (9)

where the angles with subscripts “1” or “2” denote the coordinate components for the lens or source galaxies, respectively, and $\theta$ is the separation angle between the galaxies on the sphere:

$$\cos \theta = \sin \delta_1 \sin \delta_2 + \cos \delta_1 \cos \delta_2 \cos(\alpha_1 - \alpha_2).$$ (10)

The 45° rotated component, $e_{\delta}$, is also similarly computed.

While the lens equation (Equation (6)) is for a single source redshift $z_l$, we take into account the uncertainty in the posterior distribution of the source galaxy photometric redshift. This uncertainty dominates the small uncertainty in the spectroscopic redshift estimate of lens CMASS galaxies.

We follow the method of Mandelbaum et al. (2013), and estimate the average projected mass density profile, $\Delta \Sigma(R)$ in Equation (6), as

$$\Delta \Sigma(R) = \frac{\sum_l w_i e_i^{(l)} \left\{ \Sigma_{cr}^{-1} \right\}^{-1}}{(1 + K(R)) \sum_l w_i},$$ (11)

where the summation runs over all the pairs of source–lens galaxies separated by the projected radius $R$ to within a given bin width, the superscripts “l” or “s” stand for lens or source galaxies, respectively, and $\left\{ \Sigma_{cr}^{-1} \right\}$ is the critical density averaged with the photo-z PDF for each source–lens pair.
**Figure 5.** Correlation matrix of the clustering measurements for the subsamples, estimated by using 192 jack-knife samples. The covariance will be used while calculating the likelihood of the clustering measurements given the parameters.

**Figure 6.** Distribution of our fiducial CMASS galaxy subsample (subsample A) in each of the four CFHTLenS fields as labeled at the top of each panel. The number of CMASS galaxies in each CFHTLenS field is given in the upper right of each panel. The hatched regions denote CFHTLenS fields. The CMASS galaxy subsample in this paper is selected based on their redshift and stellar-mass estimates so that the subsample constitutes approximately volume-limited sample and physically similar population of galaxies (see Section 2.1 and Figure 1 for details).
defined as
\[
\left\langle m^{(\ell)} \right\rangle = \frac{\int_0^\infty \int_0^\infty dz z P(z) \, dz}{\int_0^\infty P(z) \, dz}.
\] (12)

Here the integration is performed from \( z = 0.025 \) to \( z = 3.475 \) with the interval of \( \Delta z = 0.05 \), following the full \( P(z) \) information from the CFHTLenS catalog. We set \( \Sigma^{-1} - \Sigma^{-1}(z_l, z_s) P(z_s) \, dz_s \)

\[
\int_{z_s}^{\infty} P(z_s) \, dz_s.
\]

The above equation automatically corrects for a possible dilution of the lensing signal caused by non-vanishing probability that a source galaxy is at \( z_s < z_l \). The weight \( w_{ls} \) is defined as
\[
w_{ls} = w_l w_f \left( \frac{\Sigma^{-1} - \Sigma^{-1}(z_l, z_s)}{\Sigma^{-1}} \right)^2,
\] (13)

where \( w_f \) is defined by Equation (2), \( w_l \) is the weight given by the CFHTLenS catalog described in Section 3.1, and the factor \( \left( \frac{\Sigma^{-1} - \Sigma^{-1}(z_l, z_s)}{\Sigma^{-1}} \right)^2 \) downweights pairs that are close in redshift and therefore are inefficient in weak lensing and vice versa. The overall factor \( (1 + K(R)) \) is introduced in Equation (11) as recommended in Miller et al. (2013). This factor corrects for a multiplicative shear bias, and is implemented after the stacking average, rather than on a per-galaxy basis. The calibration factor is calculated as
\[
1 + K(R) = \frac{\sum_l w_{ls} \left( 1 + m^{(\ell)} \right)}{\sum_l w_{ls}},
\] (14)

where \( m^{(\ell)} \) is the multiplicative bias factor defined in Miller et al. (2013).

For a radial binning for the lensing profile, we set the innermost bin to \( R_{\text{min}} = 0.0245 \, h^{-1} \, \text{Mpc} \) and employ logarithmically spacing binning given by \( \Delta R/R = 0.4 \) (about six bins in one decade of radial bin spacing).

### 3.3. Correcting Lensing Systematic Errors with Random Catalogs

The shear profile measured according to the method given in the preceding section might still be contaminated by residual systematic effects inherent in the data. One possible systematic error is a dilution of the lensing signal caused when including “source” galaxies, which are actually physically associated with the lens galaxy (or its halo), into the stacking analysis. Another one is a possible residual systematic in the shape measurement, e.g., caused by an imperfect correction of optical distortion across the field of a camera. In this section, following the method in Mandelbaum et al. (2005), we use random catalogs provided by the SDSS-III/BOSS collaboration (Anderson et al. 2014), which is appropriately downsampled to match our subsamples as described in Section 2.2, to test and correct for these systematic effects. We use random catalogs which consist of 100 times more points than the number of CMASS galaxies, and divide them into 100 realizations to estimate the systematic uncertainties in the following measurements.

#### 3.3.1. Boost Factor

If some of the galaxies in the source sample are physically associated with a lens galaxy, they will dilute the lensing signal (because they are not lensed). For instance, this is the case if source galaxies are in the same halo of a lens galaxy. This contamination can be estimated by searching for an excess in the number counts of source galaxies in the region of lens galaxies compared to the random distribution. To study the possible excess, we can use the random catalogs that are randomly distributed on the sky, but are generated mimicking the redshift distribution of CMASS lens galaxies. Thus, taking into account the weights, we estimate the boost factor defined as
\[
B(R) = \frac{\sum_l w_{ls} W_l \left( \frac{\Sigma^{-1} - \Sigma^{-1}(z_l, z_s)}{\Sigma^{-1}} \right)^2}{\sum_l W_l},
\] (15)

where the superscript “r” stands for random catalogs, and \( w_l \) is the weight for random-lens, at each projected radius \( R \). For an ideal source catalog, \( B(R) = 1 \), while \( B(R) > 1 \) if there is a contamination by physically associated source galaxies.

The left panel of Figure 7 shows the boost factor we measured for our subsample A, where the error bars are estimated from the scatters of random realizations. The small scales at \( R \lesssim 100 \, h^{-1} \, \text{kpc} \) display \( B(R) < 1 \), implying that the number of source galaxies behind the CMASS lens galaxies is smaller than the random distribution, which is not expected from physically associated source galaxies. A possible origin of \( B(R) < 1 \) is that a contamination from light of foreground CMASS galaxies reduces the efficiency of detecting source galaxies. The CMASS galaxies are indeed the brightest galaxies in the redshift range in the SDSS catalog, and can be too bright (perhaps causing saturated images) for a much deeper survey such as CFHTLenS. Given that these details rely on the detection of objects in the CFHTLenS lensfit processing, we are not in a position to investigate this issue further. Another possibility is sky subtraction. The size of the sky mesh is 128 pixels\(^2\), which corresponds to \( \approx 100 \, h^{-1} \, \text{kpc} \) at the redshift of CMASS galaxies. Therefore an over-subtraction of the sky might be a possible origin of \( B(R) < 1 \) at the small radii. Magnification can also affect the observed counts of galaxies near bright objects. Duncan et al. (2014) showed a deficit is expected for the similar magnitude depth.\(^{24}\) Because of the difficulty in identifying the origin of possible systematic errors on small scales, in the following analysis we do not use data at scales smaller than \( 100 \, h^{-1} \, \text{kpc} \) (we use different cuts for other subsamples, which are described later). On the other hand, as shown on the plot, the boost factor is consistent with unity at scales larger than \( 100 \, h^{-1} \, \text{kpc} \), meaning that a contamination of physically associated galaxies with CMASS galaxies is negligible. Thus we need not adopt the boost factor correction for the CMASS lensing at \( R > 100 \, h^{-1} \, \text{kpc} \). For comparison, in Figure 7 we also plot the boost factor measured for brighter CFHT galaxies with \( m_{\text{mag} < 21.5} \). In this case, \( B(R) > 1 \) at \( R \lesssim 1 \, h^{-1} \, \text{Mpc} \), comparable with a virial radius of massive halos. This result implies that some of the bright\(^{23}\) T. Erben (2015, private communication).

\(^{24}\) On the other hand, they showed an excess as expected for a bright sample \( m_{\text{mag} < 21.5} \).
3.3.2. Testing Lens Signal of Random Catalogs

We can also use the random catalogs of CMASS galaxies for testing possible residual systematic errors in the shape measurement of CFHTLenS source galaxies. Since the random points are randomly distributed on the sky, we should not detect any coherent tangential distortion of CFHTLenS galaxy shapes around the random points, if the shape measurement is not contaminated by systematic errors. This test can be done by using the random points instead of CMASS galaxy positions in Equation (11).

The right panel of Figure 7 shows the tangential and 45° rotated distortion profile measured from the random catalogs for our subsample A. While the distortion is consistent with zero within the error bars at $R \lesssim 3 \ h^{-1} \text{Mpc}$, the larger radii show an increasing deviation from zero. Thus the larger radius scales indicate residual systematic errors in the shape measurement. The projected radius $R = 10 \ h^{-1} \text{Mpc}$ for the CMASS mean redshift $z \approx 0.53$ corresponds to about 1°, comparable with the field of view (FOV) of CFHT/MegaCam. Thus the systematic errors are likely due to an imperfect PSF correction in the galaxy shape measurement, or more precisely, an imperfect correction of the optical distortion of the camera, which tends to cause a tangential or radial pattern of the PSF ellipticities in the edge of the FOV (Hamana et al. 2013). Since the source and random-point pairs of larger radii are preferentially sensitive to a coherent PSF anisotropy in the edge of FOV, the result indicates such a residual systematic error. In the following analysis, we correct for the lensing signals of CMASS galaxies by subtracting the random signal in Figure 7 from the measured signal. As described in Mandelbaum et al. (2005; see also Mandelbaum et al. 2013), this correction rests on the assumption that the distribution of lens galaxies is uncorrelated with residual systematics in the shape measurements. This assumption holds in our analysis because the lens catalog and the shape measurements are taken from completely different datasets, the SDSS and CFHTLenS data. The size of correction is consistent with zero at small radii, and increases to 10%–15% of the measured signals at large radii at $R \approx 10 \ h^{-1} \text{Mpc}$.

3.4. CMASS Galaxy–Galaxy Lensing Signal

In Figure 8, we present the CMASS galaxy–galaxy lensing signals for our subsample A, after correcting for the systematic errors as we described above. As can be found in the lower panel, the signal in the 45° rotated component is consistent with zero over all the radii we consider. The upper panel shows the tangential distortion, which shows the expected trends of decreasing signal as the projected radius increases. The cumulative S/N is about 26. For comparison, we show the lensing signal of the SDSS luminous red galaxy (LRG) catalog using the CFHTLenS source catalog and the same lensing measurement procedures (for details of the LRG lensing measurement, see the Appendix). The CMASS galaxy lensing signal is about 40% smaller than the LRG lensing signal, suggesting that the CMASS galaxies preferentially reside in less massive halos. As a verification of our lensing measurement, we also show the LRG signal measured from the independent data, the SDSS source catalog, in RM13. The CFHTLenS and SDSS LRG lensing signals are in excellent agreement with each other. To be more quantitative, the inverse-variance weighted ratio of the two LRG signals from these different surveys with completely independent shape measurements and photo-$z$, averaged over all the radial bins, is $1.006 \pm 0.046$. We note that the LRG lensing measurement is performed under the cosmological model of $\Omega_m = 0.25$ and $\Omega_{\Lambda} = 0.75$ to make it consistent with the measurement in RM13.
We comment on a possible systematic bias in the CMASS lensing signal that may be caused by a residual bias in the photo-z estimates of source galaxies, to the level of $\Delta z \sim 0.02$, due to photo-z outliers as claimed in Erben et al. (2013). We checked that even shifting the photo-z PDF, $P(z)$, for all the source galaxies by $\Delta z = \pm 0.02$ in the analysis causes only a few percent shift in the lensing signal. Hence we ignore the possible photo-z bias in the following results.

Another systematic uncertainty might come from the difference between the CMASS galaxy subsample in the entire BOSS region and that in the CFHTLS region. We compare the probability distribution of the stellar mass, $P(\log M_*)$, and that of the redshifts, $P(z)$, for our subsamples in these regions in the panels of Figure 9. Although the stellar mass distributions in the CFHT region are not particularly special, the redshift distributions show some noticeable differences, presumably due to the structures in the CFHT field. We assessed the systematics of the differences in the redshift distribution by including a weight $w_{\text{sys}}(z) = P^{\text{CMASS}}(z)/P^{\text{CFHT}}(z)$, where $P^{\text{CMASS}}(z)$ and $P^{\text{CFHT}}(z)$ is the spectroscopic distribution in the entire CMASS region and that in the CFHTLS region, respectively, when calculating the weak lensing signal. The differences in the lensing signal when including this weight are of the order 2%, much smaller than our error bars on the lensing signal. We therefore conclude that this weight is not needed for the analysis, and that the subsample of CMASS galaxies in the CFHT fields is sufficiently close to a fair sample for our purposes.

To construct a model interpretation of the CMASS lensing signal, we need to compute the error covariance matrix of the lensing profile. There are two sources of the statistical errors. First, since the number of source galaxies used is finite, the intrinsic shape noise contributes to the errors. In fact this is a dominant source of the errors over the range of radial scales we consider. The shape noise is naively expected to scale as $\sigma_e / \sqrt{N_{\text{pair}}}$, where $\sigma_e$ is the rms intrinsic ellipticity combined with the rms ellipticity measurement error, per component, and $N_{\text{pair}}$ is the number of source–lens pairs used in the lensing measurement of a given radius. However, the scaling does not hold for large radii, because the same source galaxies are used multiple times as the stacking annuli of such large radii overlap for different lens CMASS galaxies. The other noise source arises from a projection effect: large-scale structure along the same LOS to the CMASS lens galaxy, at different redshifts, causes statistical scatters in the distortion of CFHTLenS galaxies. We estimate these contributions by computing the covariance matrix of lensing signals from the 100 random catalog realizations. The random catalog enables us to estimate both the covariance contributions of the shape noise and the projection effect. We note that we cannot use the jackknife method for the covariance estimation of the lensing measurements. Unlike for the BOSS clustering measurements, the area of the CFHTLS region that overlaps with BOSS is too small to have a sufficiently large enough resampling of the CFHTLenS regions for the jackknife method (especially for the large separation radii). The left panel of Figure 10 shows the correlation coefficients of the covariance matrix for subsample A. The large separation radii display a strong correlation between neighboring bins. Figure 11 shows the ratio of the diagonal covariance elements to the naively expected shape noise error, where the shape noise expectation is computed taking into account the weights. At larger scales, the ratio is significantly greater than unity, meaning that the projection effect and the correlated shape noise become significant at these radii.

The lensing signals for the three subsamples A, B, and C of CMASS galaxies are shown in the right panel of Figure 4. We perform the same analysis for subsamples B and C, such as the systematic tests by boost factor and correction for imperfect PSF modeling by random signals. For subsamples B and C we find that the boost factor is significantly smaller than one at scales below 150 $h^{-1}$ kpc, and thus discard the lensing signal at these scales. As the stellar-mass threshold increases, the amplitude of lensing signal becomes larger. Correlation coefficients of subsamples B and C are shown in the middle and right panels of Figure 10, respectively.

We also explore the redshift dependence of the lensing signal. In Figure 12, we show lensing signals for the three redshift subsamples with the lowest stellar-mass threshold. The lensing signals do not vary substantially with redshift, similar to the behavior of the clustering signal.

4. DISCUSSION AND CONCLUSIONS

In this paper, we have shown the clustering and lensing measurements of the SDSS-III/CMASS galaxies at $z \approx 0.53$. In our analysis, we constructed a subsample of galaxies so that it constitutes an approximately stellar-mass limited sample ($\log M_*/h^{-2}_{100} \in [11.10, 12.00]$) over the redshift range $z \in [0.47, 0.59]$, with an approximately constant number density (subsample A). This subsample of galaxies was used to measure the projected clustering signal with a total S/N of 56 for scales $0.85 \ h^{-1} \ \text{Mpc} \lesssim r_p \lesssim 80 \ h^{-1} \ \text{Mpc}$ (see
Figure 9. Comparison of the redshift distributions of galaxies in the CFHTLS fields (blue solid line) and those in the CMASS fields (red solid line) for the three stellar-mass subsamples we use for our analysis shown in the top left, top right, and bottom left panels. The bottom right panel shows a similar comparison but for the stellar-mass distribution of galaxies. The stellar-mass distribution of the CFHT subsample appears fairly representative of that of the entire CMASS population. The redshift distribution shows noisy deviations due to structures in the CFHT regions.

Figure 10. Correlation coefficients of the error covariance matrix for the CMASS galaxy weak lensing signal for our subsamples, where the covariance matrix is computed from the 100 random catalogs.
Figure 11. Square root of the diagonal covariance elements relative to the naively expected shape noise, where the latter is estimated by scaling the shape noise by \( \sqrt{N_{\text{pair}}} \) (the total number of source-lens galaxy pairs at each radial bin). To estimate the shape noise expectation, we properly take into account the errors, while the projection effect and the correlated shape noise become significant at larger radii.

Figure 12. Lensing signals of redshift subsamples at fixed stellar-mass threshold \( \log M_\ast/h_{70}^{-2} M_\odot \in [11.30, 12.00] \) and \( \log M_\ast/h_{70}^{-2} M_\odot \in [11.40, 12.00] \) (subsamples B and C respectively). The subsamples of higher stellar mass thresholds progressively display the higher amplitudes in the clustering and weak lensing signals (Figures 2 and 4). These results suggest that the CMASS galaxies of higher stellar-mass tend to reside in more massive halos. On the other hand, we found the weak redshift dependence of the signals for each subsample (Figures 3 and 4). This result allows us to employ an effective signal redshift bin over the redshift range when making the model interpretation.

In Paper II, we will use the clustering and lensing measurements of the CMASS galaxies to explore the dark matter-galaxy connection in the framework of the halo model. By fitting the halo occupation parameters and cosmological parameters to both of these observables simultaneously, we will explore the physical nature of CAMSS galaxies and their host dark matter halos as well as constrain cosmological parameters.

We greatly thank Hong Guo, Anatoly Klypin, Francisco Prada, Ramin Skibba, and Simon White for useful comments during the SDSS internal review. H.M. and R.M. greatly thank Alexie Leauthaud, Melanie Simet, Lance Miller, Catherine Heymans, Ludovic Van Waerbeke, and Hendrik Hildebrandt for useful discussion about the CFHTLenS catalog.

H.M. is supported by the Japan Society for the Promotion of Science (JSPS) Postdoctoral Fellowships for Research Abroad and JSPS Research Fellowships for Young Scientists. S.M. and M.T. are supported by World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan, by the FIRST program “Subaru Measurements of Images and Redshifts (SuMIRe),” CSTP, Japan, and by the JSPS Program for Advancing Strategic International Networks to Accelerate the Circulation of Talented Researchers. R.M. is supported in part by the Department of Energy Early Career Award program. M. T. is supported in part by the JSPS KAKENHI (grants No. 23340061 and 26610058). D.N.S. is supported in part by the National Science Foundation (NSF) under grant No. AST-1311756. This work is supported in part by the NSF grant No. PHYS-1066293 and the hospitality of the Aspen Center for Physics.

HM is supported by Japan Society for the Promotion of Science (JSPS) Postdoctoral Fellowships for Research Abroad and JSPS Research Fellowships for Young Scientists. MT is supported in part by JSPS KAKENHI (Grant Number: 23340061), by World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan, and by the FIRST program “Subaru Measurements of Images and Redshifts (SuMIRe),” CSTP, Japan. RM is supported in part by the Department of Energy Early Career Award program. This work was supported in part by the National Science Foundation under Grant No. PHYS-1066293 and the hospitality of the Aspen Center for Physics.

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III web site is http://www.sdss3.org/.

SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, University of Cambridge, Carnegie Mellon University,
Figure 13. Left panel: boost factor of LRGs. Although the boost factor is slightly smaller than unity at intermediate scales, this does not affect the consistency between our CFHTLenS LRG signal and the SDSS LRG lensing signal described in Section 3.4 (see the text for discussion). Right: random signal of LRGs. As seen in the CMASS galaxy measurement, the random signal is not consistent with zero, which implies a coherent PSF anisotropy at the edge of the field of view is not fully corrected. We corrected for this effect by subtracting the random signal from a measured lensing signal.

University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofisica de Canarias, the Michigan State/Notre Dame/JINNA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

This work is based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/IRFU, at the Canada–France–Hawaii Telescope (CFHT), which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This research used the facilities of the Canadian Astronomy Data Centre operated by the National Research Council of Canada with the support of the Canadian Space Agency. CFHTLenS data processing was made possible thanks to significant computing support from the NSERC Research Tools and Instruments grant program.

APPENDIX

CALCULATION OF LRG LENSING SIGNAL

In this section we describe details of our measurement of the SDSS LRG lensing signal shown in Figure 8. We select LRGs (Eisenstein et al. 2001) in the regions overlapping with CFHTLenS fields from the SDSS DR7 catalog (Abazajian et al. 2009). Out of 62,081 LRGs of the entire SDSS fields, 534 LRGs are selected. The number of LRGs in each CFHTLenS field is 149 in W1, 0 in W2, 338 in W3, and 47 in W4, respectively. We use the same weighting scheme as that in RM13, which is given as

$$w_i = \frac{w_{\text{rad}} w_{\text{fc}}}{C}, \quad (A1)$$

where $w_{\text{rad}}$ is the weight to account for the radial selection function, $w_{\text{fc}}$ is the fiber collision weight, and $C$ is the “sector completeness” that accounts for the redshift success rate. These weights are available in the publicly available LRG catalog (see the appendix in Kazin et al. 2010 for the details).

We perform systematic tests of the LRG lensing signal using random catalogs as described in Section 3.3. We generate 100 realizations of the random catalogs for the overlapping regions of the SDSS and CFHTLenS fields. The left panel of Figure 13 shows the boost factor for the LRG sample. As we found from the boost factor for our subsample of the CMASS galaxies in Figure 7, the small scales display $B(R) < 1$. Thus we do not use the lensing measurements at $R < 150 h^{-1} \text{kpc}$ (up to the 4th bin). While the boost factor is consistent with unity at the larger radii, it is slightly smaller than unity by a few percent at the intermediate radii. Since our lensing signal remains consistent with RM13 (Figure 8) within this offset, we do not adopt the boost factor correction for the LRG lensing signals. The right panel shows the lensing measurements for the random catalogs of LRGs. As seen for the measurements of the CMASS random catalogs in Figure 7, the large radii show non-zero signals, indicating residual systematics in the shape measurements (see Section 3.3.2 for the discussion). We correct for the LRG lensing signal by subtracting the random signal from the measured signal. Figure 8 shows the measurement of LRG lensing signal, compared to the measurement in RM13 that was done using the independent data, the SDSS imaging galaxies, for the galaxy shape measurements. The CFHTLenS and SDSS measurements for LRG lensing show an excellent agreement with each other.

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