Environment-based selection effects of Planck clusters

R. Kosyra^{1,2}, D. Gruen^{1,2}, S. Seitz^{1,2}, A. Mana^{1,2}, E. Rozo^{3,4}, E. Rykoff³, A. Sanchez² and R. Bender^{1,2} \star

¹Universitäts-Sternwarte München, Ludwig-Maximilians-Universität München, Scheinerstraße 1, D-81679 München, Germany

²Max Planck Institut für Extraterrestrische Physik, Giessenbachstr., D-85748 Garching, Germany

³SLAC National Accelerator Laboratory, Menlo Park, CA 94025, U.S.A.

⁴University of Arizona, Department of Physics, 1118 E. Fourth St., Tucson, AZ 85721, U.S.A.

14 January 2015

ABSTRACT

We investigate whether the large scale structure environment of galaxy clusters imprints a selection bias on Sunyaev Zel'dovich (SZ) catalogs. Such a selection effect might be caused by line of sight (LoS) structures that add to the SZ signal or contain point sources that disturb the signal extraction in the SZ survey. We use the Planck PSZ1 union catalog (Planck Collaboration et al. 2013a) in the SDSS region as our sample of SZ selected clusters. We calculate the angular two-point correlation function (2pcf) for physically correlated, foreground and background structure in the *RedMaPPer* SDSS DR8 catalog with respect to each cluster. We compare our results with an optically selected comparison cluster sample and with theoretical predictions. In contrast to the hypothesis of no environment-based selection, we find a mean 2pcf for background structures of -0.049 on scales of $\leq 40^{\circ}$, significantly non-zero at $\sim 4\sigma$, which means that *Planck* clusters are more likely to be detected in regions of low background density. We hypothesize this effect arises either from background estimation in the SZ survey or from radio sources in the background. We estimate the defect in SZ signal caused by this effect to be negligibly small, of the order of $\sim 10^{-4}$ of the signal of a typical *Planck* detection. Analogously, there are no implications on X-ray mass measurements. However, the environmental dependence has important consequences for weak lensing follow up of *Planck* galaxy clusters: we predict that projection effects account for half of the mass contained within a 15' radius of *Planck* galaxy clusters. We did not detect a background underdensity of CMASS LRGs, which also leaves a spatially varying redshift dependence of the *Planck* SZ selection function as a possible cause for our findings.

Key words: galaxies: clusters: general - cosmology: observations.

arXiv:1501.02840v1 [astro-ph.CO] 12 Jan 2015

1 INTRODUCTION

Clusters of galaxies play a major role in astrophysics and cosmology, as they can be used to put constraints on the dark matter content of the universe. Furthermore galaxy clusters are particularly sensitive to the interplay of dark matter and dark energy. They are cosmological probes that could potentially help to distinguish between dark energy and modified gravity explanations for the accelerating expansion of the universe (for a review, see Allen et al. 2011; Borgani & Kravtsov 2011; Weinberg et al. 2013).

A variety of different methods for cluster detection and mass measurement exists. Gravitational lensing probes the dark and luminous matter distribution of a cluster by measuring the distortion of background galaxies (weak lensing, for example in Hoekstra et al. 2001; Gruen et al. 2013, 2014), or by detecting multiple images of single background galaxies close to the LoS of the cluster core (strong lensing, for example in Zitrin et al. 2012; Eichner et al. 2013; Monna et al. 2014). The most widespread method for optical cluster detection, the so-called *red sequence method* (Gladders & Yee 2005; Koester et al. 2007; Rykoff et al. 2014) is based on spatial overdensities of red galaxies. Further methods include the observation of the X-ray Bremsstrahlung emission by the hot gas in the intra-cluster medium (ICM, Piffaretti et al. 2011; Vikhlinin et al. 2009; Mantz et al. 2010) and the observation of inverse Compton scattering of the cosmic microwave background (CMB) photons by the ICM, which is known as the SZ effect (Sunyaev & Zeldovich 1972). The latter describes the distortion of the CMB spectrum along the LoS through clusters and groups. The amplitude of the SZ effect is proportional to the dimensionless Compton parameter y, defined as the integral over the thermal electron pressure along the LoS:

$$y = \frac{\sigma_T}{m_e c^2} \int P dl, \qquad (1)$$

while the integral over a solid angle yields the SZ observable *Y*:

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-76SF00515.

^{*} E-mail: kosyra@usm.uni-muenchen.de

2 R. Kosyra et al.

$$D_A^2 Y = D_A^2 \int y d\Omega = \frac{\sigma_T}{m_e c^2} \int P dV, \qquad (2)$$

where σ_T is the Thomson cross section, $m_e c^2$ the rest energy of the electrons and D_A the angular diameter distance.

All of these methods may have selection effects induced by structures along the LoS. Lensing, for example can yield biased mass estimates when there are groups along the LoS which contribute to the shear signal (e.g. Spinelli et al. 2012). The X-ray signal of LoS structures can stack, resulting in a biased mass estimate. The same is true for the SZ effect, however more severely as the SZ signal is proportional to the gas density ρ , while the X-ray flux is proportional to ρ^2 , making the effect of LoS structure on SZ signals much larger at larger angular separation. Due to this reason we will investigate whether SZ selected clusters are possibly biased by structures along the LoS, either by physically uncorrelated foreground or background structures, or by correlated structures at the same redshift as the cluster itself.

Several effects could potentially contribute to a selection bias. The blending of the SZ signal of the detected cluster with groups along the LoS could bias the SZ estimate high and cause clusters along overdense lines of sight to be more likely detected. If, on the contrary, unresolved groups in the vicinity of clusters increase the background level, this could lead to a lower detection probability as the signal from the cluster is partly suppressed by the wrong background estimate. Furthermore, if the background of a cluster is contaminated with radio-loud galaxies, this could raise the noise such that clusters with a weak SZ signal are not detected.

In this paper we address this question by analyzing the projected group environment of SZ-selected clusters from the Planck PSZ1 union catalog (Planck Collaboration et al. 2013a) and test for group overdensities or underdensities along the LoS in the foreground, background and at the redshift of the clusters. The group sample is taken from the RedMaPPer red-sequence catalog based on SDSS DR8 photometry (Rykoff et al. 2014; Rozo & Rykoff 2014; Rozo et al. 2014). We compute the angular two-point correlation function (2pcf) of galaxy clusters and groups for different subsamples of our catalogs (correlated, foreground and background structures) to quantify correlated and physically uncorrelated group overdensities and underdensities. We compare these results to the 2pcf obtained for an independent cluster sample with similar redshift and richness distribution, drawn as a subsample of the RedMaPPer SDSS DR8 catalog, and to theoretically predicted values.

1.1 Motivation

We briefly discuss several possible effects that could cause a selection bias. The filter function that is used for the *Planck* cluster detection might estimate a too large background value if there are groups surrounding the cluster that contribute to the signal, which could lead to a decreased detection probability in crowded fields as the subtracted background estimate is too large. On the other hand, the clusters are detected by combining six frequency bands with different filter sizes, so it is rather unlikely that this still causes problems when detecting clusters based on the differential signal.

Another possible origin of a selection effect might be radioloud galaxies in the background. Donoso et al. (2010) state that radio-loud active galactic nuclei (RLAGNs) are predominantly found in dense environments compared to radio quiet galaxies and regular red luminous galaxies (LRGs) at redshifts 0.4 < z <0.8. They conclude that this clustering effect is stronger for more massive RLAGNs. In Yates et al. (1989) the clustering effect of RLAGNs at $z \approx 0.2$ is compared to the one at $z \approx 0.5$, with the result that the latter objects are found in environments three times denser on average. They also state that more powerful RLAGNs are found in denser environments than less powerful ones. Based on these findings we hypothesize that a high background group density entails a higher probability of containing radio sources and thus increases the noise along the line of sight, potentially leading to a lower SZ detection probability for clusters in dense background environments.

This paper is structured as follows. In section 2, we describe the *Planck* PSZ1 union catalog and the *RedMaPPer* SDDS DR8 group catalog, as well as our matching of these two. In section 3, we briefly discuss two-point correlation functions. Furthermore we describe our method of generating random points for the *Planck* catalog and the procedure of defining the cluster comparison sample out of the *RedMaPPer* catalog. We also include the description of our theoretical prediction of the 2pcf. In section 4, we present our results, give a detailed description of our error estimation and generalized χ^2 analysis and we estimate the implications of the measured effect on SZ and lensing analyses of *Planck* clusters. We conclude in section 5.

2 DATA

2.1 The Planck PSZ1 catalog

The Planck PSZ1 union catalog is a cluster catalog, covering the whole sky based on SZ detections using the first 15.5 months of Planck survey observations. It contains a total of 1227 clusters, 861 of which are confirmed while the remaining 366 are cluster candidates (Planck Collaboration et al. 2013a). The Planck satellite features a low frequency and a high frequency instrument, the former covers the bands at 30, 44 and 70 GHz (Planck Collaboration et al. 2013e) while the latter operates at frequencies of 100, 143, 217, 353, 545 and 857 GHz (Planck Collaboration et al. 2013b) with angular resolutions between 9.53' and 4.42' FWHM, for a total of nine detection bands. The channel maps of the six highest frequency bands (100 to 857 GHz) were used to build the SZ-detection catalog, in order to avoid problems caused by strong radio point sources in cluster centers, which typically have steep spectra and thus do not appear in the high frequency bands (Planck Collaboration et al. 2013a).

The generalized NFW (Navarro et al. 1997) profile from Arnaud et al. (2010) was adopted for the cluster detection.

Three detection algorithms were used to create the cluster catalog, two realizations of the *Matched Multi-filter (MMF)* method (Herranz et al. 2002; Melin et al. 2006) and (*Powell Snakes (PwS)*, Carvalho et al. 2009, 2012).

The *MMF* method detects clusters by using a linear combination of maps and a spatial filtering to suppress foregrounds and noise. The two implementations (*MMF1* and *MMF3*) split the whole sky in 640 patches of size 14.66×14.66 square degrees covering 3.33 times the area of the sky (*MMF1*), and in 504 patches of size 10×10 square degrees covering 1.22 times the area of the sky (*MMF3*). The *MMF3* algorithm is run in two iterations: the second is centered on the positions of the candidates from the first one, rejecting all candidates that fall below the signal-to-noise (S/N) threshold. The matched multi-frequency filter optimally combines the six frequencies of each patch and the resulting sub-catalogs for all patches are finally merged together to a single SZ-catalog per

method, selecting the candidate with the highest S/N ratio. For estimating the candidate size, the patches are filtered over the range of potential scales, selecting the scale with the highest S/N of the current candidate. Finally, the SZ-signal is estimated by running *MMF* with fixed cluster size and position.

Powell Snakes is a Bayesian multi-frequency detection algorithm, optimized to find compact objects in a diffuse background. After cluster detection, *PwS* merges all intermediate sub-catalogs. The cross-channel covariance matrix is calculated directly from the pixel data, which is done in an iterative way to minimize the contamination of the background by the SZ signal itself. In each iteration step, all detections in the same patch with higher S/N than the current target are subtracted from the data before re-estimating the covariance matrix. This so-called "native" mode of background subtraction produces S/N values 20% higher than those of the *MMF* method. In order to emulate the estimation of the background noise cross-power spectrum of the *MMF* method, *PwS* is run in "compatibility" mode, skipping the re-estimation step.

Each of the three detection algorithms creates a catalog of SZ sources with an S/N ratio ≥ 4.5 . Obvious false detections are removed from each of the three individual catalogs (Planck Collaboration et al. 2013a).

The union catalog contains all sources that have been detected by at least two algorithms with S/N \ge 4.5 within a distance of 5', fixing the position of the *MMF3* detection or, in case of no *MMF3* detection, keeping the position of the *PwS* detection.

2.2 The RedMaPPer SDSS DR8 catalog

The Red Sequence Matched-filter Probabilistic Percolation (RedMaPPer) algorithm (Rykoff et al. 2014) is a red-sequence cluster finder based on the optimized richness estimator λ (Rykoff et al. 2012). It has excellent photo-z performance and λ has been designed to be a low-scatter mass proxy (Rozo & Rykoff 2014; Rozo et al. 2014). The algorithm is divided into two stages. The first is a calibration stage where the red sequence model is derived directly from the data by relying on spectroscopic galaxies in galaxy clusters: given an initial model of the red-sequence, RedMaPPer selects cluster member galaxies, uses these to derive a new red-sequence model, and then iterates the whole procedure until convergence is achieved, as which point the red-sequence model is adequately calibrated. The second is the cluster-finding stage, where RedMaPPer utilizes the red-sequence model to search for clusters around every galaxy in the SDSS. This work uses the updated version (v5.10) of the original RedMaPPer catalog of Rykoff et al. (2014) presented in Rozo et al. (2014).

2.3 Matching of the Planck and RedMaPPer catalogs

In order to match the *Planck* PSZ1 union catalog to the *RedMaPPer* SDSS DR8 cluster catalog we used an algorithm similar to the one described in Rozo et al. (2014). We find all matches in the *RedMaP-Per* catalog in a radius of 10' around each *Planck* cluster. In the case of multiple matches we define the best match as the *RedMaP-Per* system with the highest richness. We flag all matches with a redshift difference between the *Planck* and *RedMaPPer* redshift of more than 3σ , where σ corresponds to the redshift error given in the *RedMaPPer* catalog. This gives us a total of 290 matched clusters.



Figure 2. Log-log histogram of the detection probability.

Outlier rejection

We reject all matches that are obvious SZ-projections (5 cases), as identified by Rozo et al. (2014). All clusters that have been flagged as 3σ redshift outliers are cross-matched with the Rozo et al. (2014) table of redshift outliers, and in the case of an incorrect *Planck* redshift and a correct *RedMaPPer* redshift, we accept the cluster using the *RedMaPPer* redshift and vice versa. Furthermore we reject clusters with bad z-matching when a visual inspection identified them clearly as a mismatch (one case only), and we reject clusters that are outliers in the mass- Y_{SZ} -plane (according to Rozo et al. 2014) due to a low *RedMaPPer* richness (one case only). After rejecting all outliers the final matched catalog includes 265 clusters.

3 METHODS

3.1 Two-point correlation function

We measure the crowding of clusters and groups with the angular two-point correlation function, which traces the amplitude of cluster/group clustering as a function of their separation. The angular correlation function $w(\theta)$ is defined as the excess probability over a random, uncorrelated distribution of finding two objects separated by an angle θ . The probability of finding two objects in two infinitesimal solid angle elements $\delta\Omega_1$ and $\delta\Omega_2$ separated by angle θ then reads:

$$\delta P = n_1 n_2 \left(1 + w(\theta) \right) \delta \Omega_1 \delta \Omega_2,\tag{3}$$

with n_1 and n_2 being the mean cluster/group densities in both samples.

A multitude of different estimators exist for calculating the twopoint correlation function from data catalogs. Kerscher et al. (2000), who compared the nine most important of these estimators in terms of the cumulative probability of returning a value within a certain tolerance of the real correlation, show that the Landy-Szalay estimator (hereafter LS, Landy & Szalay 1993) performs best according to their criteria. Hence we adopt this estimator, which reads:

$$\hat{w}_{LS}(\theta) = \frac{DD - 2DR + RR}{RR},\tag{4}$$



Figure 1. Redshift (left) and richness distribution (right) of the Planck sample (black) and the comparison sample (red). Planck error bars are Poissonian. Comparison sample error bars are not shown but are of comparable size.

or, in case of a cross-correlation between two different samples:

$$\hat{w}_{LS}(\theta) = \frac{D_1 D_2 - D_1 R_2 - D_2 R_1 + R_1 R_2}{R_1 R_2},$$
(5)

where *DD*, *DR* and *RR* stand for the data-data, data-random and random-random pair counts, respectively. All pair counts in eq. 5 are normalized to the total number of data pairs in the respective samples. Random points account for geometrical effects like survey boundaries and masks in the survey area. We do not want the random points to correct for environment-based detection effects, since this is the effect we want to measure, so we are using random points where the true detections have been erased. The pair counts have been computed using the 2d-tree code *Athena* (Kilbinger et al. 2014).

3.2 Generation of random points for the Planck catalog

The LS estimator (eq. 5) needs a random catalog for each data catalog, in order to correct for geometrical effects that could mimic a signal.

There are two effects that might imprint a spatial variation on the *Planck* detection function: the variation in the noise level and the distance from the galactic disk. In this section we describe our approach to generate random points for the *Planck* catalog taking into account the varying noise level. The variation of the detection probability as a function of distance from the galactic disk is investigated in appendix A.

Since the noise level of the *Planck* observations varies over the SDSS region, we need to test whether the density of SZ detections has a significant correlation with the noise level that has to be accounted for when generating a random catalog. We use the *Planck SMICA* map (which comes in HEALPIX (Górski et al. 2005) coordinates with $N_{\text{side}} = 2048$, which is 50331648 pixels, resolution ~ 1.7'), which uses an optimal combination of the nine frequency bands (Planck Collaboration et al. 2013c) to generate a map displaying the weighted average noise of all channels, averaged to 3072 pixels, to find the noise at the position of each cluster.

We test for correlation of the density of *Planck* detections with the noise quantitatively. In this case we assume the number of Planck detections per unit area f_i to be a power law of the noise N per redshift bin i with redshift dependent exponent α_i :

$$f_i(N) = f_i(1) \cdot N^{\alpha_i}.$$
(6)

We perform a likelihood analysis over the parameters $f_i(1)$ and α_i , by calculating the expected number of clusters in each sky cell via eq. 6 and computing the Poisson probability with the actual number of detections in that sky cell. The power α_i scatters around and is consistent with zero for redshifts $z \le 0.5$. Above this redshift, we find $\alpha_i \approx 0.8$. In conclusion, the noise level has no impact on detections for z < 0.5. We decide to remove all clusters with z > 0.5 from our catalog, bringing our sample size down to 250 clusters. Based on these findings, we decide to use uniformly distributed random points for the *Planck* catalog.

We use the Planck survey mask (HEALPIX $N_{side} = 2048$) to define the region where to generate the points and cut them afterwards to the SDSS footprint. The random points are generated in HEALPIX coordinates to ensure a uniform distribution over the sky.

3.3 Generation of random points for the RedMaPPer catalog

To generate a random point catalog for *RedMaPPer*, we first draw a random position in the sky, and then randomly draw a *RedMaP-Per* cluster. Given the assigned cluster redshift and richness, we use our cluster model to randomly draw cluster galaxies to create a synthetic cluster. We then run *RedMaPPer* at this location, and determine whether the synthetic cluster is detected of not. The procedure is repeated 100 times, and we calculate the fraction of times w that the cluster was detected at that location. The quantity w is the weight assigned to this random point.



Figure 3. Sketch of the selection method for the group catalogs. The green, blue and red volumes show the selection for the correlated, foreground and background samples respectively. The total z-depth of the green volume is 0.1, with the cluster in the center. The angular radius for all volumes is 1° (see cyan circles).

There is one subtlety associated with the above procedure: by random luck, some fraction of our synthetic clusters will overlap with real *RedMaPPer* clusters in both location in the sky and redshift. If one did not remove the galaxies associated with the original *RedMaPPer* cluster before placing the synthetic cluster at that location, upon running *RedMaPPer* one will always find a cluster there (i.e. the original cluster), and one would erroneously conclude w = 1 irrespective of the details of the synthetic cluster. Thus, it is critically important to remove the original *RedMaPPer* galaxy clusters from the galaxy catalog prior to drawing our random points. We erase clusters probabilistically: given a cluster of richness lambda at redshift z, we collect all of its member galaxies, and remove each galaxy according to the assigned membership probability, so that a galaxy that is 90% likely to be a cluster member is removed from the galaxy catalog with 90% probability.

3.4 Definition of a comparison sample

We want to test whether SZ selected clusters are generally found in a different environment than similar (in terms of redshift and richness) clusters that are selected for their optical properties. Thus we need to compare the cluster-group two-point correlation functions that we obtain for groups in the vicinity of *Planck* selected clusters to an independent sample of optically selected clusters that resembles the selection function of our main sample in terms of their redshift and richness distribution. To this end, we need to model the *Planck* detection probability. We assume that the probability that a *RedMaPPer* cluster is detected by *Planck* takes the form:

$$P_{\rm det} = \frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{\Lambda - \Lambda_{\rm det}}{\sqrt{2}\sigma}\right) \right],\tag{7}$$

where erf is the error function, Λ_{det} is the richness at which the detection probability is 50% and σ the scatter in richness at fixed SZ signal. P_{det} states the probability that a cluster of given richness Λ is detected by the *Planck* survey, if it was inside the survey area. We use the *RedMaPPer* SDDS DR8 catalog, calculate P_{det} for each cluster and assign it as a weight to the cluster itself.

We parameterize the redshift evolution of $\Lambda_{\rm det}$ and σ as:

$$\Lambda_{\rm det} = \alpha_{\Lambda} (1+z)^{\beta_{\Lambda}} \tag{8}$$

and

$$\sigma = \alpha_{\sigma} (1+z)^{\beta_{\sigma}}.$$
(9)

To find the optimum values for α_{Λ} , β_{Λ} , α_{σ} and β_{σ} , we perform a likelihood analysis in these four parameters:

$$\ln(\mathbf{L}) = \sum_{i \operatorname{Plck}} \ln\left[\mathbf{P}_{\operatorname{det}}(i)\right] + \sum_{i \operatorname{non}\operatorname{Plck}} \ln\left[1 - \mathbf{P}_{\operatorname{det}}(i)\right].$$
(10)

Here the first sum is over all *RedMaPPer* clusters that have been detected by Planck and the second sum is over all *RedMaP-Per* clusters that have not been detected by Planck. Figure 1 shows the photo-z distribution of the Planck sample (black) compared to the subsample (red) defined by the selection algorithm based on detection probability. The data agree in most bins within 1σ (of the Poissonian errors) and in all bins within 2σ . To validate the quality of the comparison sample we drew 1000 random subsamples of 250 clusters according to their P_{det} and determined the likelihood of each subsample. Comparing to the likelihood of the original *Planck* sample, we obtain a p-value of 0.27, so we consider our comparison sample as reasonable (i.e., 27% of subsamples have lower likelihood than the actual *Planck* sample).

We generate a random catalog for the comparison sample by using the derived values for the four parameters α_{Λ} , β_{Λ} , α_{σ} and β_{σ} and calculate the detection probability for each entry in the *RedMaPPer* random catalog.

3.5 Theoretical two-point correlation function

Our purpose is to compute the cross-correlation between a reference cluster at given redshift and correlated structures within a certain redshift range. Note that this differs from computing the usual angular correlation function between two samples. In our case, in fact, we restrict our calculation of the cluster-group two-point correlation function to redshift bins centered around the reference cluster. The correlated group redshift distribution is thus dependent on the reference cluster redshift. We then obtain the total correlation function by summing up all the redshift-binned contributions according to the cluster redshift distribution.

The numerical tool we use for calculating the theoretical correlation function is CAMB SOURCES ¹(Lewis & Challinor 2007), which

¹ http://camb.info/sources/

computes the angular power spectrum C_l s of the matter density perturbations, for given input redshift distributions and for different cosmological models. We restrict our calculation to standard flat Λ CDM cosmology ($\Omega_m = 0.25$, h = 0.7) and the linear regime only. The relation between the cross-spectra and the projected twopoint correlation function is given by

$$w(\theta) = \sum_{l \ge 0} \left(\frac{2l+1}{4\pi}\right) P_l(\cos\theta) C_l , \qquad (11)$$

where P_l are the Legendre polynomials of degree *l*. We use a maximum l = 3000 and $\theta \in [0.01, 300]$ arcmin. We calculate the expected two-point correlation (eq. 11) for 20 reference cluster redshifts $z_{cl} \in [0.05; 0.5]$. For the reference cluster redshift distribution, we assume a Gaussian distribution centered at the cluster redshift z_{cl} , with standard deviation equal to the mean photometric redshift error associated to the cluster redshift in the Planck catalog, i.e. $\mathcal{N}(z_{cl}, 0.02)$. For the correlated groups redshift distribution, we use the observed redshift distribution of the RedMaPPer groups with richness $\lambda > 5$, limited to a range of ± 0.06 , centered around $z_{\rm cl}$. This interval is greater than the bin width in the analysis of the observational data of ± 0.05 (see section 4), in order to account for the errors in photometric redshift (~ 0.02). The observed correlation is the average of the $w_i(\theta)$ calculated in each redshift bin *i*, weighted by the cluster and group distributions and respective average biases, normalized by the total number of objects:

$$w(\theta)_{\text{theory}} = \frac{\sum_{i=1}^{20} dN_i^c dN_i^g \bar{b}_i^c \bar{b}_i^g w_i(\theta)}{\sum_{i=1}^{20} dN_i^c dN_i^g} .$$
(12)

Here dN_i^c and dN_i^g are the counts per redshift bin of clusters and groups respectively. Furthermore, \bar{b}_i^c and \bar{b}_i^g are the average biases for clusters and groups within the bin *i*. We estimate the bias for each cluster in the matched *Planck* catalog and each group in the *RedMaPPer* catalog by using the analytic formula of Tinker et al. (2010). This assumes a fixed mass-richness scaling relation, for which we employ the result of Rykoff et al. (2012). An analog estimate for the foreground/background structures at $|z_{cl} - z_{gr}| > 0.05$ yields a 2pcf consistent with zero within the statistical errors of our analysis.

4 ANALYSIS AND RESULTS

The relevant quantities we are interested in are the 2pcfs of clusters and groups for correlated structure (groups with similar redshifts as the cluster), foreground structure (groups with lower redshift than the cluster) and background structure (groups with higher redshift than the cluster). We compute the angular correlation function, where cluster pairs are subjected to one of three constraints:

(i) the *RedMaPPer-Planck* cluster pair is separated by less than $|\Delta z| < 0.05$.

(ii) the *RedMaPPer-Planck* cluster pair is such that $z_{\rm rm} < z_{\rm pl} - 0.05$.

(iii) the *RedMaPPer-Planck* cluster pair is such that $z_{\rm rm} > z_{\rm pl} + 0.05$.

The first set of pairs allows us to test for the environmental impact of physically correlated structures, the second for the impact of foreground structures and the third for the impact of background structures. This selection method is displayed graphically in figure 3, with the green volume being the correlated structure, in blue the foreground and in red the background. We draw 100 sets of 250 *Planck* random points, assigning them the same redshift distribution as the cluster sample. We perform the procedure described above on each set, averaging the results. We proceed analogously for the comparison sample, by drawing 100 samples of unweighted clusters by selecting randomly among all clusters of the comparison sample according to their detection probability. The sample size is on average 247, the same as the sum over all detection probabilities. The same procedure is performed on the random catalog of the comparison sample (see section 3.4).

4.1 Error estimation

For estimating errors and covariance matrices, we use three different methods: for the errors of the *Planck* sample with respect to theory, we use a "replace-one" implementation of the Jackknife resampling method, for the errors of the comparison sample with respect to theory (zero) we use Bootstrap resampling and for the errors of the *Planck* sample with respect to the comparison sample we use a "delete-one" Jackknife resampling by drawing 100 different (unweighted) representations out of the complete comparison sample randomly according to the detection probabilities. The former two will be explained in more detail in the following subsection.

4.1.1 Errors of the Planck sample with respect to theory

We use a modification of the Jackknife resampling method. In the standard "delete-one" Jackknife technique, the survey area is subdivided into a number of subsamples and the analysis is done a number of times equal to the number of subsamples, considering each time all samples except one. The Jackknife covariance reads:

$$C_{ij} = \frac{m-1}{m} \sum_{k=1}^{m} (x_{i,k} - \bar{x}_i) \left(x_{j,k} - \bar{x}_j \right), \tag{13}$$

where *m* is the number of Jackknife samples, $x_{i,k}$ is the data value in bin *i* of sample *k* and \bar{x}_i is the mean value in bin *i*. Since galaxy groups are clustered intrinsically, the errors in neighboring bins may be correlated, so we need to take into account the full covariance matrix in our analysis.

We define our Jackknife samples to be equal to the datacylinders in our sub-catalogs. We are using 250 samples containing exactly one cluster each and all groups in its vicinity.

Since our theoretical prediction is made for the exact redshift distribution of *Planck*, we need to find the errors with respect to this distribution. A delete-one Jackknife would introduce a systematic error here, as the redshift distribution of the sample changes when deleting one cluster. To overcome this problem, we use a modified Jackknife method: in each Jackknife sample we leave out one subsample (cluster) and assign a weight of two to another cluster. This cluster is chosen to be the closest in redshift to the left-out cluster, in order to minimize the effect on the redshift distribution of the sample. We have to modify equation 13 to account for the changed sample size:

$$C_{ij} = \frac{1}{2} \sum_{k=1}^{m} (x_{i,k} - \bar{x}_i) \left(x_{j,k} - \bar{x}_j \right).$$
(14)

The validity of the formula has been verified in a Monte-Carlo-simulation.



Figure 4. Two-point correlation function for groups in the vicinity of *Planck* clusters (blue) and groups in the vicinity of clusters in our comparison sample (red). In this plot we show the 2pcf for groups with redshift equal to the cluster redshift ± 0.05 (correlated structure). The cyan line represents the theoretical prediction. Top: complete sample, bottom left: only clusters with S/N >median, bottom right only clusters with S/N <median. In the low S/N case there is a slight underdensity in the *Planck* sample in the region between 10' and 20'. For interpretations see sections 4.2, 4.3 and 5.

4.1.2 Errors of the comparison sample with respect to theory

In order to perform an error estimation on the comparison sample with a resampling method, we need a multitude of comparison samples. We perform a Bootstrap resampling on the *RedMaPPer* catalog by drawing 1000 random catalogs with the same number of clusters as in the original catalog. We then count the number of pairs in angular bins around each cluster weighted with the detection probability and compute the covariance in each angular bin from these 1000 samples. It turns out that the errors estimated by this method tend to be higher than the errors of the *Planck* sample, since we did not account for the modified redshift distribution due to the bootstrap here. To overcome this problem we slightly change the procedure by bootstrapping sets of 5 groups instead of single groups. The sets are created by dividing the catalog into 5 subsamples split by redshift, and selecting one group from each of these subsamples. We sort the subsamples by weight, so we ensure that each package contains 5 groups with similar weights and different (equally distributed) redshifts. In this way the systematic error due to the modified redshift distribution is minimized.



Figure 5. Same as figure 4, but for groups with redshift $z_{gr} < z_{cl} - 0.05$ (foreground structure). The two data sets agree well in the complete sample and the high S/N case, while for low S/N a slight overdensity can be observed in the *Planck* sample nearly over the complete angular region tested, albeit most data points still agree within the error margins.

4.2 Results

In this subsection we present the results of the angular two-point correlation function of galaxy clusters and groups obtained as described earlier in this section. We analyze $w(\theta)$ in 15 equidistant angular bins with a width of 4'. We compare the results obtained for the *Planck* sample (blue points in figures 4, 5 and 6) with those for our comparison sample (red points) and with our predictions (cyan line). A likelihood analysis is presented in subsection 4.3.

We expect that a possible effect is stronger for clusters that are just above the detection threshold S/N of 4.5. Due to this reason we also split the clusters into a high and low S/N sample. The most useful approach here would be to split the sample at S/N 7, which is the threshold above which the clusters are included in the *Planck cosmological sample* (Planck Collaboration et al. 2013d). Unfortunately, in this case the high S/N sample would contain too few clusters causing the error limits to become too large, so we decided to split the sample at the median S/N 5.4, generating two equally large subsamples with 125 clusters each.

The top of figure 4 shows $w(\theta)$ for groups at the same redshift as the cluster redshift ± 0.05 (correlated structure). In the two innermost angular bins both samples are affected by blending effects and halo exclusion. The latter is the effect of two nearby structures



Figure 6. Same as figure 4, but for groups with redshift $z_{gr} > z_{cl} + 0.05$ (background structure). We observe a slight underdensity in the *Planck* sample with respect to the comparison sample, which is more severe in the low S/N subsample.

merging into one halo, which has not been included in the theoretical prediction. In most bins up to approximately 40' the *Planck* sample shows a slight underdensity with respect to the comparison sample, albeit the individual data points still agree within the error margins (likelihood analysis shows the underdensity is not significant, see table 1). The excess in the third bin with respect to the predicted curve is potentially due to non-linear structure growth. In case of the split sample we see a better agreement between the two samples for the high S/N subsample (bottom left plot), while the agreement is worse in the low S/N case (bottom right) where *Planck* clusters are found in even more underdense background environments. Figure 5 shows the 2pcf for groups with redshift $z_{gr} < z_{cl} - 0.05$ (foreground structure). The fact that we also observe blending here (in the innermost bins), shows that the detection probability of *RedMaPPer* groups also suffers from blending effects, i.e. *RedMaPPer* is less likely to detect groups in the vicinity of a rich foreground or background cluster. Besides this effect, one can see a slight overdensity in the *Planck* sample at angular scales >10', but the errorbars suggest that this difference is not significant. The effect is again weaker in the high S/N and stronger in the low S/N subsample.

Figure 6 shows the 2pcf for groups with redshift $z_{gr} > z_{cl}+0.05$ (background structure). Here the 2pcf suffers from blending on

small angular scales, too. A slight underdensity can be seen in the *Planck* sample with respect to the comparison sample in nearly all angular bins. The individual data points are, however, in agreement within the error margins. Also here the observed underdensity appears less severe in the high S/N and more severe in the low S/N case.

4.3 Likelihood analysis

In this subsection we investigate the significance by which the 2pcf in the *Planck* sample differ from the comparison sample and from the theoretical prediction. We perform a generalized χ^2 analysis that takes into account the full covariance matrix, since as mentioned before we expect the errors in neighboring bins to be correlated positively due to the clustering of groups. The generalized χ^2 reads:

$$\chi_{\rm gen}^2 = \boldsymbol{\delta}^T \cdot \boldsymbol{C}_{ij}^{-1} \cdot \boldsymbol{\delta},\tag{15}$$

where C_{ij}^{-1} is the inverse covariance matrix and δ is the residual vector, containing the difference between measured and expected values (where measured values correspond to the *Planck* 2pcf and expected values correspond to either the comparison sample or predicted values) in angular bins. For the foreground and background sample we compare the results with zero, since the theoretical predictions in these cases are several orders of magnitude lower than our measurement uncertainty.

Table 1 gives the p-values for all our three different data samples for *Planck* with respect to the comparison sample, *Planck* compared to theory and the comparison sample with respect to the theoretical prediction. The four innermost angular bins have been ignored in the χ^2 calculation, since the data in these bins apparently suffer from halo exclusion and blending effects, which have not been considered in our theoretical prediction. Thus, the number of degrees of freedom is 11.

The p-values with respect to the comparison sample are typically quite high (the lowest one being 0.28 for the foreground sample), so the null-hypothesis, which states that the two samples are similar, cannot be rejected. The p-values are generally slightly lower in the low S/N case which supports our assumption that selection effects are predominately observed in the low S/N regime. Nevertheless, we cannot confirm a selection bias based on our data sample, since the values of the *Planck* sample and the comparison sample are in agreement everywhere.

When comparing the *Planck* data with the theoretical prediction, we find high p-values in the correlated and foreground samples, while we find very low values in the background sample, which suggests a selection effect related to lower background density. To support this assumption, we look at the p-value of the comparison sample vs zero (for the background sample) which suggests much better agreement than the value of the *Planck* sample. When looking at the splitted sample with respect to S/N, the pvalues for the *Planck* sample are higher than for the complete sample in both cases, which comes from the larger uncertainties in the splitted sample. The p-values for *Planck* relative to the comparison sample in the high S/N case are in good agreement, yet both only marginally agree with zero, which we assume comes from cosmic variance. In the low S/N sample however, the agreement of Planck with zero is significantly worse than for the comparison sample. We conclude that the background underdensity for *Planck* clusters is a function of S/N and the effect becomes stronger for low S/N detections.

We also split the group sample in two subsamples at richness 12 (high λ and low λ in table 1), but we found no significant differences in these two subsamples.

Table 2 gives the best-fitting constant values for the 2pcf and the corresponding 1σ errors. The first four angular bins which suffer from blending have been ignored in this fit. We see that the background correlation is not consistent with zero for Planck with more than 4σ , while the comparison sample is consistent with zero within 1.25σ , which can still be due to statistical fluctuations. Since we detect a background underdensity of -0.049 with a significance of ~ 4σ with respect to zero but the comparison sample also differs from zero with a value of -0.02 at ~ 1.25σ , we conclude that statistical fluctuations in the particular regions used (cosmic variance), likely also contribute to the observed defect of Planck background groups, but are no sufficient explanation of the full observed effect. On the other hand, one could imagine that RedMaPPer detections are biased in the vicinity of massive clusters due to the correlated structure that surrounds them out to large radii, which might affect the detection of groups due to the blending effect, as discussed in section 4.2.

When looking at the foreground sample, the slight overdensity one might expect from figure 5 is not significant, with a p-value of 0.72.

4.4 2pcf for *Planck* and LRGs

We want to verify our results by comparing them to an independent sample of background sources. We replace the *RedMaPPer* group catalog with the *CMASS* catalog of luminous red galaxies (LRG) with spectroscopic redshifts (Eisenstein et al. 2011; Dawson et al. 2013; Anderson et al. 2014). As clusters and groups tend to feature mostly red galaxies, we expect the LRGs to show a similar clustering behavior. Furthermore, if the origin of the underdensity we observed is truly the presence of radio sources, which tend to cluster at high redshifts, we expect to see the same effect in *CMASS* galaxies.

When looking at figure 7, we cannot confirm the underdensity that we found for background *RedMaPPer* groups. If the physical effect has a z-dependence, the fact that the redshift distributions of the *RedMaPPer* groups and the *CMASS LRGs* differ largely might be responsible for the observed effect. As we are using uniformly distributed random points for the *Planck* clusters, we do not account for a potential position dependence of the selection function. In particular, a spatial variation of the redshift dependence of the *Planck* detection probability could possibly mimic such a selection effect. We investigated the most likely version of this possibility in Appendix A, although more complex dependencies might exist.

4.5 Implications for SZ and lensing masses

The potential underdensity in the background of *Planck* detected clusters is nearly constant in all angular bins except the ones that are affected by blending. Hence it is straightforward to model the effect as the best fitting constant 2pcf in these bins. We use this value of -0.049 for further approximations. We estimate the defect SZ signal caused by this effect in the average beam size of the *Planck* channels that are involved in the cluster detection. We use the median redshift of the 250 *Planck* clusters in our sample (0.23) and calculate the mean SZ signal of all *RedMaPPer* groups with redshift higher than that value +0.05 (as our background selection), using the scaling relation from Planck Collaboration et al. (2013d).

Table 1. P-values for the different samples for *Planck* with respect to the comparison sample and to the theoretical prediction and for the comparison with respect to the theoretical prediction.

Sample		All	High S/N	Low S/N	High λ	Low λ
Correlated	Plck-Comp Plck-Theo	0.805 0.901	0.555	0.433		
Foreground	Plck-Comp Plck-Zero Comp-Zero	0.28 0.72 0.34	0.98 0.64 0.18	0.39 0.34 1.0		
Background	Plck-Comp Plck-Zero Comp-Zero	0.48 0.0060 0.16	0.70 0.051 0.023	0.37 0.097 0.64	0.89 0.18	0.73 0.010

Table 2. Best fit values and 1- σ intervals for the foreground and background samples, for *Planck* and comparison sample. For the background sample, *Planck* is not consistent with zero within 4σ while the comparison sample is consistent with zero within 1.3σ .

Sample		All	High S/N	Low S/N	High λ	Low λ
Foreground	Plck-Zero Comp-Zero	0.040 ± 0.027 -0.00039 ± 0.021	-0.014 ± 0.041 0.0052 ± 0.033	0.071 ± 0.036 0.016 ± 0.027		
Background	Plck-Zero Comp-Zero	-0.049 ± 0.012 -0.02 ± 0.016	-0.047 ± 0.015 -0.037 ± 0.023	-0.046 ± 0.016 -0.017 ± 0.022	-0.044 ± 0.016	-0.058 ± 0.016



Figure 7. Same as figure 6, but for CMASS LRGs with redshift $z_{LRG} > z_{cl} + 0.05$ (background structure). We do not observe the underdensity that we observed for the *RedMaPPer* group background in figure 4. The small errorbars come from the much larger number of objects due to the non-overlapping redshift distributions of *Planck* and CMASS (all LRGs are background to all clusters with respect to redshift alone).

Analogously we compute the mean SZ signal of the *Planck* clusters themselves. With the number of background groups with respect to the previously mentioned *Planck* median redshift inside the average beam size of the involved channels and the average background underdensity we can calculate the Y_{SZ} -defect caused by a background underdensity of -0.049. We find a number of of 1.7×10^{-4} relative to the mean signal of the cluster. This is due to the self-similar slope of the Y_{SZ} -MOR. Based on this low number, we conclude that there will be no implications on cluster masses derived from their SZ-signal. For the same reason we conclude the effect of the background underdensity on X-ray measurements to be negligible as well.

We estimate the effect of the potential background underdensity on the convergence κ , which is the quantity that determines the magnification in gravitational lensing. As an example, we are using a cluster with a mass of $M = 3 \times 10^{14} M_{\odot}$, at the *Planck* median redshift 0.23 and sources at redshift of 1.0, assuming that 5% of the matter between the cluster redshift and the source redshift is missing. In a radius of 15' around such a cluster, the relative κ deficit would then be ~ 80% of the mean κ of the cluster. Due to the mass-sheet degeneracy (Schneider & Seitz 1995; Seitz & Schneider 1995, 1997), this large κ defect might have a much smaller effect on shear measurements. It will, however, have a non-negligible effect on magnification measurements. Magnification increases the surface area of observed objects with constant surface brightness, leading to higher total brightness (lower magnitude). On the one hand, the consequence is a higher (observed) galaxy density, as faint background galaxies (just below the detection limit) might by detected as their brightness increases. On the other hand, the increased surface area also increases the separation between the magnified objects, leading to a lower (observed) galaxy density, counteracting the first effect. For steep luminosity functions the first effect is stronger (which is generally the case for blue galaxies), while for flat luminosity functions the second effect dominates (red galaxies). As a consequence, we expect a negative 2pcf of red background galaxies around clusters caused by this effect. A potential background underdensity would counteract this effect, causing a slightly less negative 2pcf at small angular scales and a slightly positive 2pcf at intermediate angular scales. We estimate the amplitude of this effect for a typical *Planck* cluster using equation 10 from Umetsu et al. (2011). We get a result in the order of $w(\theta) \leq 10^{-2}$ for $\theta = 10'$ for the effect caused by the magnification of the cluster itself, while the counteracting effect caused by the underdensity is in the order of $w(\theta) \approx 10^{-3}$, both of which is too small to be detected in our measurement.

5 CONCLUSIONS

Our main scientific goal was to investigate possible selection effects on SZ selected clusters based on their group environment and estimate implications of such an effect on SZ, X-ray and lensing mass estimates.

We summarize our results as follows:

(i) We do not find an overall selection effect due to correlated or foreground structure.

(ii) We find a potential underdensity of galaxy groups in the background of *Planck* clusters which manifests in an average 2pcf in an angular range <40' of -0.049 with a significance of ~ 4σ . However, we cannot confirm this effect when replacing *RedMaP-Per* groups with CMASS LRGs in our analysis.

(iii) This effect grows stronger for low S/N detections and vanishes for high S/N detections. We find no dependence of the effect on the richness of the groups.

(iv) We consider three possible explanations for this effect:

• An erroneous background estimation in overdense environments might lead to a lower detection probability of low signal clusters in these regions. The details and relative importance of these effects is likely dependent on the instrumental and survey design and the object detection algorithm. On the other hand, the fact that *Planck* detections combine six bands makes this explanation rather unlikely.

• RLAGNs, which tend to cluster at high redshifts (Donoso et al. 2010; Yates et al. 1989), contribute to the radio signal in regions where the background density is high and could suppress low S/N detections.

• The *Planck* selection function is responsible for this effect. A spatial variation of the *Planck* selection function that correlates with the spatial variation of the *RedMaPPer* selection function could mimic the observed background group underdensity. Due to lack of access to the *Planck* selection function we we are not able to test this at this point. On the other hand, we do get the same results if we split our sample by distance to the galactic disk, as shown in Appendix A.

(v) This potential selection effect has a vanishing impact on SZ and X-ray mass estimates. The implications on lensing mass estimates are however much larger with an estimated relative κ deficit of order unity.

In the latter context, it is interesting to note that Gruen et al. (2014) found a discrepancy from the self-similar slope ($\beta = 5/3$) in the Y_{SZ}-mass scaling relation for low S/N Planck clusters, with a slope of 0.76 ± 0.20 . Sereno et al. (2014) found a slope of the Y_{SZ} -mass scaling relation of 1.22 ± 0.24 using all *Planck* clusters detected by the MMF3 algorithm, and a slope of 1.40 ± 0.31 when using only the cosmological subsample (S/N > 7). They made an additional analysis forcing the intrinsic scatter to zero, obtaining even lower results for the slopes, 0.95 ± 0.10 for the full and 1.09 ± 0.17 for the cosmological samples. The background underdensity in *Planck* clusters that we find in this work potentially explains their findings, since that could cause a low-biased lensing mass, depending on the S/N ratio of the SZ signal, resulting in a shallower slope of the scaling relation. The fact that Sereno et al. (2014) find a slightly steeper slope in the cosmological sample, supports the assumption of the S/N dependence of this effect. Von der Linden et al. (2014), who compared cluster masses from the Planck catalog with weak lensing masses from the Weighing the Giants project, found evidence for a mass dependence in the calibration ratio between the Planck mass M_{Planck} and the weak lensing mass $M_{\rm wl}$ which takes the form $M_{Planck} \propto M_{\rm wl}^{0.68^{+0.15}_{-0.11}}$. A possible explanation for their findings might be low-biased weak-lensing masses for low-mass clusters, caused by a background underdensity that dominates at low S/N, as we hypothesize it in this work.

ACKNOWLEDGEMENTS

The authors thank Martin Kilbinger for discussions concerning the *Athena* tree code. We also acknowledge Ben Hoyle for giving useful instructions on using the *Healpix* software. Furthermore we thank Francesco Montesano for helpful discussions about methods

of error estimation. We thank Tommaso Giannantonio for giving invaluable advice for the generation of *Planck* random points. We acknowledge the advice given by Jim Bartlett and Jean-Baptiste Melin concerning the *Planck* selection function.

REFERENCES

- Allen S. W., Evrard A. E., Mantz A. B., 2011, ARA&A, 49, 409
- Anderson L. et al., 2014, Mon. Not. Roy. Astron. Soc., 441, 24
- Arnaud M., Pratt G. W., Piffaretti R., Böhringer H., Croston J. H., Pointecouteau E., 2010, A&A, 517, A92
- Borgani S., Kravtsov A., 2011, Advanced Science Letters, 4, 204 Carvalho P., Rocha G., Hobson M. P., 2009, Mon. Not. Roy. As-
- tron. Soc., 393, 681
- Carvalho P., Rocha G., Hobson M. P., Lasenby A., 2012, Mon. Not. Roy. Astron. Soc., 427, 1384
- Dawson K. S. et al., 2013, AJ, 145, 10
- Donoso E., Li C., Kauffmann G., Best P. N., Heckman T. M., 2010, Mon. Not. Roy. Astron. Soc., 407, 1078
- Eichner T. et al., 2013, ApJ, 774, 124
- Eisenstein D. J. et al., 2011, AJ, 142, 72
- Gladders M. D., Yee H. K. C., 2005, ApJS, 157, 1
- Górski K. M., Hivon E., Banday A. J., Wandelt B. D., Hansen F. K., Reinecke M., Bartelmann M., 2005, ApJ, 622, 759
- Gruen D. et al., 2013, Mon. Not. Roy. Astron. Soc., 432, 1455
- Gruen D. et al., 2014, Mon. Not. Roy. Astron. Soc., 442, 1507
- Herranz D., Sanz J. L., Hobson M. P., Barreiro R. B., Diego J. M., Martínez-González E., Lasenby A. N., 2002, Mon. Not. Roy. Astron. Soc., 336, 1057
- Hoekstra H. et al., 2001, ApJ, 548, L5
- Kerscher M., Szapudi I., Szalay A. S., 2000, ApJ, 535, L13
- Kilbinger M., Bonnett C., Coupon J., 2014, athena: Tree code for second-order correlation functions. Astrophysics Source Code Library
- Koester B. P. et al., 2007, ApJ, 660, 239
- Landy S. D., Szalay A. S., 1993, ApJ, 412, 64
- Lewis A., Challinor A., 2007, Phys. Rev. D, 76, 083005
- Mantz A., Allen S. W., Rapetti D., Ebeling H., 2010, Mon. Not. Roy. Astron. Soc., 406, 1759
- Melin J.-B., Bartlett J. G., Delabrouille J., 2006, A&A, 459, 341
- Monna A. et al., 2014, Mon. Not. Roy. Astron. Soc., 438, 1417
- Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
- von der Linden A. et al., 2014, Mon. Not. Roy. Astron. Soc., 443, 1973
- Piffaretti R., Arnaud M., Pratt G. W., Pointecouteau E., Melin J.-B., 2011, A&A, 534, A109
- Planck Collaboration et al., 2013a, ArXiv e-prints, 1303.5089
- Planck Collaboration et al., 2013b, ArXiv e-prints, 1303.5067
- Planck Collaboration et al., 2013c, ArXiv e-prints, 1303.5072
- Planck Collaboration et al., 2013d, ArXiv e-prints, 1303.5080
- Planck Collaboration et al., 2013e, ArXiv e-prints, 1303.5063
- Rozo E., Rykoff E. S., 2014, ApJ, 783, 80
- Rozo E., Rykoff E. S., Bartlett J. G., Melin J. B., 2014, ArXiv e-prints, 1401.7716
- Rykoff E. S. et al., 2012, ApJ, 746, 178
- Rykoff E. S. et al., 2014, ApJ, 785, 104
- Schneider P., Seitz C., 1995, A&A, 294, 411
- Seitz C., Schneider P., 1995, A&A, 297, 287
- Seitz C., Schneider P., 1997, A&A, 318, 687

- Sereno M., Ettori S., Moscardini L., 2014, ArXiv e-prints, 1407.7869
- Spinelli P. F., Seitz S., Lerchster M., Brimioulle F., Finoguenov A., 2012, Mon. Not. Roy. Astron. Soc., 420, 1384
- Sunyaev R. A., Zeldovich Y. B., 1972, Comments on Astrophysics and Space Physics, 4, 173
- Tinker J. L., Robertson B. E., Kravtsov A. V., Klypin A., Warren M. S., Yepes G., Gottlöber S., 2010, ApJ, 724, 878
- Umetsu K., Broadhurst T., Zitrin A., Medezinski E., Hsu L.-Y., 2011, ApJ, 729, 127
- Vikhlinin A. et al., 2009, ApJ, 692, 1060
- Weinberg D., Bard D., Dawson K., Dore O., Frieman J., Gebhardt K., Levi M., Rhodes J., 2013, ArXiv e-prints, 1309.5380
- Yates M. G., Miller L., Peacock J. A., 1989, Mon. Not. Roy. Astron. Soc., 240, 129

Zitrin A. et al., 2012, ApJ, 749, 97

APPENDIX A: SPLITTED SAMPLE WITH RESPECT TO GALACTIC DISTANCE

As mentioned in section 4.4, we found a discrepancy in our results as we observe an underdensity in the background of *Planck* selections for *RedMaPPer* groups but not for CMASS LRGs. In order to investigate the cause of this difference we splitted the sample at the median absolute galactic latitude to find out whether the *Planck* selection function depends on the distance to the galactic disk, as it could be caused for example by galactic foreground emission. Our uniformly distributed set of *Planck* random points would not account for such an effect.

The results of the absolute latitude split are shown in figure A1, the according p-values are found in table A1 and the best fitting values and $1-\sigma$ intervals in table A2. The split results in a nearly unchanged result for 2pcf at angular distances up to ~ 30'. Above that value however, the underdensity vanishes in the low latitude sample while it persists in the high latitude sample.

APPENDIX B: SPLITTED SAMPLE WITH RESPECT TO GROUP REDSHIFT

As the redshift distributions of *RedMaPPer* and CMASS are largely different, we investigated the possibility of a redshift dependence of this effect by splitting the *RedMaPPer* group sample at z=0.45. This value has been chosen to ensure the sample sizes to be approximately equal for the high z and low z sample *after* selecting the background groups.

The results of the redshift split are shown in figure B1, while the p-values are shown in table A1 and the best fitting values and $1-\sigma$ intervals in table A2. The split reveals a slightly more distinct underdensity of the *Planck* sample with respect to zero for low redshift background groups, as it might be expected from the null results with the (high redshift) CMASS sample. On the other hand, a similar degree of difference between high z and low z background can be observed in the Comparison sample, making the relative difference non-significant.

14 R. Kosyra et al.

Table A1. Same as table 1, this time for the splitted samples with respect to distance to the galactic disk and redshift.

Sample	High abs(lat)	Low abs(lat)	High z	Low z
Plck-Zero	0.012	0.25	0.52	0.018
Comp-Zero	0.17	0.32	0.86	0.0057

Table A2. Same as table 2, this time for the splitted samples with respect to distance to the galactic disk and redshift.

Sample	High abs(lat)	Low abs(lat)	High z	Low z
Plck-zero	-0.029 ± 0.023	-0.023 ± 0.016	-0.037 ± 0.017	-0.059 ± 0.017
Comp-zero	-0.039 ± 0.017	-0.0023 ± 0.015	-0.0079 ± 0.0075	-0.032 ± 0.0099



Figure A1. 2pcf for background groups with far from the galactic disk (left) and close to the disk (right). The sample has been splitted at the median absolute galactic latitude.



Figure B1. 2pcf for background groups with redshift >0.45 (left) and with redshift ≤ 0.45 (right).