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THE SPLASHBACK RADIUS OF PLANCK-SZ CLUSTERS

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ABSTRACT

We present evidence for the existence of the splashback radius in galaxy clusters selected using the Sunyaev-Zeldovich effect. We show that the deprojected cross-correlation of galaxy clusters found in the Planck survey with galaxies detected photometrically in the Pan-STARRS survey, shows a sharp steepening feature (a logarithmic slope steeper than -3), which we associate with the splashback radius. We infer the three-dimensional splashback radius for the SZ cluster sample to be $r_{\rm sp} = 1.85^{+0.26}_{-0.30}\ h^{-1}$Mpc, where the cluster sample has an average halo mass $M_{500c} = 3.0 \times 10^{14} h^{-1} {\rm M}_\odot$ at an average redshift of $z = 0.18$. The inferred value of the splashback radius appears consistent with the expected location for dark matter halos in the standard cold dark matter paradigm. However, given the limited precision of our measurements, we cannot conclusively rule out the smaller splashback radius measured so far in the literature for optically selected galaxy clusters. We show that the splashback radius does not depend upon the galaxy magnitude for galaxies fainter than $M_i - 5\log h = -19.44$, and is present at a consistent location in galaxy populations divided by color. The presence of the splashback radius in the star-forming galaxy population could potentially be used to put lower limits on the quenching timescales for galaxies. However, these results need further verification with deeper datasets, as photometric errors could cause contamination of the star-forming galaxy sample by quenched galaxies.

1. INTRODUCTION

The density distribution of matter within dark matter halos shapes the potential well in which galaxies form and grow. Therefore, the structure of these dark matter halos has been extensively studied both theoretically as well as in numerical simulations (see e.g., Gunn & Gott III 1972; Fillmore & Goldreich 1984; Bertschinger 1985; Navarro et al. 1997; Moore et al. 1999). Studies with numerical simulations show that the density profiles of dark matter halos within their virial radii are roughly self-similar and follow the Navarro-Frenk-White (NFW) profile (Navarro et al. 1997), which asymptotes to a slope of -1 in the inner regions and -3 at large radii. There has been intense debate in the literature about the exact form of the density profile (e.g., Navarro et al. 2004), the value of the asymptotic inner slope, as well as the outskirts and boundaries of dark matter halos (Cuesta et al. 2008; More et al. 2011; Diemer et al. 2013).

The recent study of Diemer & Kravtsov (2014) has sparked a renewed interest in understanding the structure of dark matter halos on scales beyond the typical virial radii. Diemer & Kravtsov (2014) investigated the outskirts of dark matter halos in numerical simulations and found the existence of a physical feature, namely a sharp steepening in the density distributions of dark matter halos, which is not captured by commonly used functional forms such as the NFW profile. They showed that even for halos of the same mass, the position of the feature changes depending upon the mass accretion rate of the halos. A simple theoretical toy model to explain this feature was presented by Adhikari et al. (2014). They showed that the feature observed by Diemer & Kravtsov (2014) results from the piling up of recently accreted dark matter particles at the apocenters of their orbits, and its location corresponds to the last density caustic in the self-similar models of secondary infall (Fillmore & Goldreich 1984; Bertschinger 1985; Lithwick & Dalal 2011). They coined the term "splashback radius" for this feature. Their toy model also naturally explains the accretion rate dependence – faster accreting halos have smaller splashback radii. Subsequently, More et al. (2015) suggested the use of the splashback radius as a natural boundary for dark matter halos and explored its consequences for the inferred boundaries and growth rates of the halos. Depending on the accretion rate of the halo, the splashback radius can lie well beyond the commonly used virial radius (Diemer & Kravtsov 2014; More et al. 2015).

The interpretation of the accretion rate dependence is straightforward. Due to the continuous change of the gravitational potential of the halo, depending on its accretion rate, the kinetic energy of a recently accreted dark matter particle, gained during its infall onto the cluster, does not suffice to climb the deepened potential well completely again, but instead it "splashes back" at a distance that depends on the recent deepening of the potential well.

Given the mass of the halo, the location of the splashback radius constitutes a direct probe of the halo accretion rate. Motivated by these studies, More et al. (2016) attempted to detect this feature in observations. Using the optically selected Sloan Digital Sky Survey RedMaPPer galaxy cluster catalog (Rykoff et al. 2014), and by cross-correlating it with the SDSS photometric galaxy sample, More et al. (2016) found evidence for the steepening of the dark matter density profile, and therefore the splashback radius of this sample of galaxy clusters (further corroborated by including further models for mis-centering by Baxter et al. (2017) and in the Dark Energy Survey data by Chang et al. (2017)). Somewhat surprisingly, More et al. (2016) found that the location of the splashback radius was inconsistent with that expected from numerical simulations of dark matter by about $20 \pm 5\%$. Although they investigated potential systematic issues, they did not have access to mock cluster catalogs which could mimic the selection effects of optically-identified clusters. Busch & White (2017) used a simplified optical cluster selection al-

gorithm on the Millennium simulation, and pointed out that optical clusters can be heavily affected by projection issues, and could potentially introduce systematics in the inference of the splashback radius, as well as halo assembly bias. The existence of projection effects in the optical cluster catalog in the context of halo assembly bias was also demonstrated by Zu et al. (2016).

Umetsu & Diemer (2017) as well as Contigiani et al. (2018) recently used Xray selected clusters to look for the splashback radius using the weak lensing signal, however stacking issues and the low signal-to-noise ratio remains a significant hurdle for both of them. Chang et al. (2017) found evidence for the splashback radius in the weak lensing signal, but their analysis was again done using optically selected clusters in the Dark energy survey (Collaboration 2005). Regardless of the projection issues present in the optical cluster catalog, there is some inherent circularity present in the logic of using photometric galaxies to select clusters as over-densities in a given aperture, and then using the same photometric sample of galaxies to look for the splashback radius. There is a possibility that the aperture used to select the cluster catalogs could be imprinted in a non-trivial way on the measured number density profiles of clusters.

In this work, we move away from the optical cluster selection and explore the use of SZ selected cluster catalogs. While the SZ selected clusters can also be susceptible to systematic selection effects, the scales on which the SZ signal is measured and the cluster selection is performed is much smaller than the expected location of the splashback radius (typically R_{500c}). We use this sample to explore the evidence for the splashback radius in observations. Due to the low signal-to-noise ratio of the weak lensing signal, we perform our analysis using cross-correlation of galaxies with clusters. The SDSS sample used by More et al. (2016) was deep enough such that biases in the location of the splashback radius due to dynamical friction effects were expected to be small. Nevertheless, we use galaxy samples, which are even fainter by $0.5-1$ magnitudes compared to those used by More et al. (2016).

Given that the splashback radius represents a true halo boundary, the observations of the splashback radius can be used to study a variety of galaxy formation questions. Questions regarding the timescales and the spatial scales within which star forming galaxies quench after they fall into the cluster potential are of particular interest to understand the fate of star formation in satellite galaxies. In particular, if star forming galaxies quench before they reach the apocenters of their orbit after infall, then they are not expected to show a splashback feature in their density distribution. In pursuit of this question, we also explore the dependence of the cluster-galaxy cross-correlations separately for star forming and quenched galaxy populations separated by color.

This paper is organized as follows. We introduce the observational data sets we use in Section 2, namely the cluster and the galaxy catalogs. We describe the methods and analysis procedures we use in Section 3. We present and discuss our results in Section 4. Finally, we summarize our findings in Section 5 and discuss possible future directions. Throughout the paper, we use a flat ΛCDM cosmology with $\Omega_m = 0.27$ to convert redshifts and angles into cosmological distances. Also, we denote three-dimensional distances by r and projected distances by R.

2. DATA

Table 1

Comparison of the PSZ2 cluster catalog against the RedMaPPer cluster catalog used by More et al. (2016). The values of the mass estimates M_{500c}, M_{200m}, redshifts z and expected splashback radii $r_{sp}^{3D,theo}$ represent the catalog averages. The redshifts for both catalogs are given from the survey. For the RedMaPPer catalog the M_{200m} mass estimates were obtained from gravitational lensing and for the PSZ2 catalog the M_{500c} estimates were calculated from the survey parameters using the scaling relation between the integrated Compton Y-parameter Y_{500c} and M_{500c} as found by Ade et al. (2014). The missing mass estimates as well as the expected values of the splashback radii were calculated using the Python package COLOSSUS (Diemer 2017). The predictions for the splashback radii $r_{sp}^{3D,theo}$ are given in comoving units.

	RedMaPPer	PSZ2
z	0.24	0.177
# objects	8643	596
M_{500c} $[h^{-1}10^{14}M_\odot]$	0.9	3.0
M_{200m} $[h^{-1}10^{14}M_\odot]$	1.8	6.2
$r_{sp}^{3D,theo}$ $[h^{-1}$ Mpc]	1.37	1.89

2.1. *Cluster catalog*

The baryonic component of a galaxy cluster is dominated by the hot, ionized intra-cluster medium (ICM), which is gravitationally bound within the cluster. The cosmic microwave background (CMB) photons that pass through the cluster inverse Compton scatter off the hot electrons and gain energy. This effect is known as the thermal Sunyaev-Zeldovich (SZ) effect (Sunyaev & Zeldovich 1970, 1980). The effect has a characteristic frequency dependence and results in an intensity decrease below 220 GHz and an associated increase at higher frequencies. The multiple frequency channels on the Planck satellite allow a detection of galaxy clusters using the SZ effect (Ade et al. 2016a). As part of the 2015 Data Release of the Planck mission, the second Planck Catalogue of Sunyaev-Zeldovich Sources (PSZ2) was made available to the community. The PSZ2 catalog contains detections based on three different techniques (Ade et al. 2016b), and the union of these catalogs has in total 1653 galaxy clusters, of which 1203 clusters have been confirmed by cross-matching to other galaxy clusters from external data sets.

The 1-σ errors on the cluster positions are $\sim 1.6'$ and the estimated purity of the catalog has a lower limit of 83% (**?**). The integrated Compton Y-parameter Y_{500c} of each of the clusters are also provided. The mass estimates M_{500c} provided by the Planck collaboration are based on the scaling relation between Y_{500c} and M_{500c} (Ade et al. 2014; Adam et al. 2016; Ade et al. 2016a). The PSZ2 union cluster catalog is publicly available from the *Planck Legacy Archive*[1].

We restrict ourselves to the redshift range $0.03 \leq z \leq 0.33$ in order to have a similar redshift range used in More et al. (2016). Due to the larger beam size of the Planck satellite, the cluster positions as reported in the catalog may be miscentered from the true centers of the galaxy clusters. We perform a visual inspection of Pan-STARRS images taken around the detected galaxy clusters in order to locate the nearest, brightest cluster galaxy (BCG). We regard the position of the BCG as the true cluster location, under the assumption that the BCG is located at the true, gravitational center. Due to this crude assumption, we additionally study the effects of a possible, remaining mis-centering of the cluster positions in our model for the two-dimensional correlation function (see Appendix B).

[1] https://pla.esac.esa.int/pla/#home

Table 2
Summary and comparison of the properties of the galaxy catalogs used in this work as well as the SDSS catalog used in More et al. (2016).

	SDSS	PS 21	PS 21.5	PS 22
depth [mag]	21.00	21.00	21.50	22.00
eff. area [deg^2]	$\approx$ 10'000	21'148	20'586	15'689
# objects	57'181'113	93'772'329	123'188'529	105'809'113
objects/deg^2	5718	4434	5984	6744

Table 3
Summary of the priors used in the MCMC sampling procedure. The MCMC chains are constrained using flat priors or normal priors on some of the fitting parameters. This table lists the ranges of the flat priors and the central positions as well as the scales of the normal priors (format: center | scale), respectively.

	$\log_{10}(\rho_s)$	$\log_{10}(\alpha)$	$\log_{10}(r_s)$	ρ_0	s_e	$\log_{10}(r_t)$	$\log_{10}(\beta)$	$\log_{10}(\gamma)$
Prior Type	None	Normal	Flat	None	None	Flat	Normal	Normal
Prior Range	-	$\log_{10}(0.2)\|1.2$	[0.1,5.0]	-	-	[0.1,5.0]	$\log_{10}(6.0)\|0.4$	$\log_{10}(4.0)\|0.4$

The final sample that we use consists of 596 galaxy clusters and is about an order of magnitude smaller compared to the sample used in More et al. (2016). The sample we use in this paper has an average redshift of 0.177, and an average cluster mass M_{500c} of about $3.0 \cdot 10^{14} h^{-1} \mathrm{M}_\odot$. In Table 1 we compare the main properties of the cluster catalog used in this work to that used by More et al. (2016). A map of the sky positions of the clusters can be found in Figure 7 in Appendix A.

Kosyra et al. (2015) found no evidence for a significant correlation between the density of Planck detections and the weighted average noise of all Planck channels at $z < 0.5$. Since we restrict ourselves to $z < 0.33$, we utilize the selection mask of the PSZ2 union catalog in order to construct a random galaxy cluster catalog, which is roughly one order of magnitude larger than the original catalog. The redshifts of these random objects are drawn from the parent cluster catalog in order to match the redshift distribution of the original cluster catalog.

2.2. *Galaxy catalog*

The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) is a wide-field astronomical imaging and data processing facility operated by the University of Hawaii's Institute for Astronomy (Kaiser et al. 2002, 2010). We use data from the 3π Steradian Survey carried out with this facility, which was released as part of Data Release 1 (DR1). The survey covers the entire sky north of $\delta = -31°$ (in ICRS coordinates) in five broadband filters ($g_{\mathrm{P1}}, r_{\mathrm{P1}}, i_{\mathrm{P1}}, z_{\mathrm{P1}}, y_{\mathrm{P1}}$) with multiple pointings. The mean 5σ point source limiting sensitivities amount to (23.3, 23.2, 23.1, 22.3, 21.4) magnitudes for the individual bands, respectively.

For the visual inspection and centering of the clusters, we use the Pan-STARRS *gri stack* images around each cluster position. The galaxy catalog is obtained from the *StackObjectThin* table, which is publicly available on the *Barbara A. Mikulski Archive for Space Telescopes* (MAST)[2]. To select only objects detected with acceptable precision we restrict our search to those objects which have been flagged as *BestDetection*s. We further restrict the catalog to objects flagged as *PrimaryDetection*s in order to select unique objects. This is necessary since the survey is divided into overlapping *projectioncells* and *skycells*, which causes some objects to be listed multiple times.

The magnitudes of the selected objects are then corrected for the extinction caused by dust present in the Milky Way. This is done using the mwdust[3] Python module provided by Bovy et al. (2016). The extinction correction is performed using a dust map combining the measurements of Marshall et al. (2006), Green et al. (2015) and Drimmel et al. (2003). Only objects with an extinction corrected i_{P1} band Kron magnitude brighter than 22.0 are selected from the catalog. Starting from this catalog we construct three different sub-catalogs corresponding to survey depths of 21.0, 21.5 and 22.0 magnitudes, and we name these catalogs PS 21, PS 21.5 and PS 22, respectively.

As mentioned in the description of the Pan-STARRS survey by Chambers et al. (2016) there is a significant variation in the depth of the 3π Steradian survey even on small scales. In order to avoid choosing objects in shallow regions of the survey the maximum observed Kron magnitude in the i_{P1} band in each *skycell* is recorded and only objects in skycells with a maximum observed Kron magnitude of 21.0, 21.5 and 22.0 or brighter are selected depending on the corresponding catalog. Since most of the shallow regions lie in the galactic plane, we mask out the region at low galactic latitudes $|b| < 20°$. The resultant HEALPix maps showing the excluded areas on the sky can be found in Figure 8. We further disregard objects in bad pixel regions as indicated by the i_{P1} band *stack.mask* images.

At this point of the analysis, our object catalogs contain both galaxies and stars. The 3π Steradian Survey provides both the Kron and PSF model based magnitudes for each object. These magnitudes are expected to be similar for stars while the Kron magnitudes are brighter for galaxies. Therefore, we flag all objects with a value of $i_{\mathrm{P1,PSF}} - i_{\mathrm{P1,Kron}} < 0.05$ as stars (Farrow et al. 2013). Despite this cut, bright, close-by stars at magnitudes brighter than 13.5 tend to be classified as extended objects (Chambers et al. 2016). To avoid contamination of the galaxy catalog due to such bright stars, we further remove all objects with $i_{\mathrm{P1,PSF}} < 15.0$. Since there are very few galaxies at such low magnitudes this does not introduce a selection bias. We list the main characteristics of the galaxy catalogs we have used in Table 2.

3. METHODS

The methodology we adopt for locating the splashback radius closely follows that of More et al. (2016). We perform a cross-correlation between SZ selected galaxy clusters with photometric galaxies in order to assess the existence and location of the splashback radius. We use the Davis-Peebles estimator (Davis & Peebles 1983) to compute the

[2] http://archive.stsci.edu/

[3] https://github.com/jobovy/mwdust

cross-correlation between our galaxy clusters and galaxies. This estimator can be written as

$$\xi_{2D}(R) = \frac{D_1D_2 - R_1D_2}{R_1D_2} \quad (1)$$

where D_1D_2 and R_1D_2 are the normalized numbers of cluster-galaxy pairs and cluster randoms-galaxy pairs at a given co-moving projected separation R. The subtraction of the signal around random cluster positions gets rid of the uncorrelated pairs and allows us to estimate the projected cross-correlation. The uncertainty in the galaxy distribution masks prevents us from using the Landy-Szalay estimator (Landy & Szalay 1993).

Given the flux limited galaxy catalog that we use, we expect to observe more correlated galaxies in galaxy clusters that lie closer to us, but with much fainter absolute magnitudes. To avoid such biases with redshift of the clusters we restrict ourselves to galaxies with absolute magnitudes brighter than a certain magnitude limit, which depends on the depth of the used galaxy catalog. We make the assumption that the galaxies reside at the redshift of the cluster in question. The used magnitude limits are (-19.44, -18.94 and -18.44) for the catalogs PS 21, PS 21.5 and PS 22, respectively.

We use the functional form of Diemer & Kravtsov (2014) in order to model our two-dimensional correlation function measurements. This functional form consists of an inner Einasto profile and an outer power law profile connected by a smooth transition

$$\xi_{3D}(r) = \rho_{in}(r) f_{trans}(r) + \rho_{out}(r)\,, \quad (2)$$

$$\rho_{in}(r) = \rho_s \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right), \quad (3)$$

$$\rho_{out}(r) = \rho_0 \left(\frac{r}{r_{out}}\right)^{-s_e}, \quad (4)$$

$$f_{trans}(r) = \left(1 + \left(\frac{r}{r_t}\right)^{\beta}\right)^{-\gamma/\beta}, \quad (5)$$

where r indicates the three-dimensional radial distance from the halo center (Diemer & Kravtsov 2014). We model the two-dimensional correlation function, ξ_{2D} as an integral over the three-dimensional correlation function

$$\xi_{2D}(R) = \frac{1}{R_{max}} \int_0^{R_{max}} \xi_{3D}(\sqrt{R^2 + x^2})dx \quad (6)$$

where we adopt $R_{max} = 40\ h^{-1}$Mpc for the maximum projection length. Variations of this length do not change the location of the splashback radius appreciably as tested in More et al. (2016). The functional form adopted in Equation 6 has nine model parameters, $\rho_s, \alpha, r_s, r_{out}, \rho_0, s_e, r_t, \beta$ and γ. Given the perfect degeneracy between the parameters r_{out} and ρ_o, we fix $r_{out} = 1.5\ h^{-1}$Mpc.

Therefore the model is described by eight model parameters. We infer the posterior distributions of those parameters by fitting the model for the two-dimensional correlation function to the measured two-dimensional correlation signal. We use the affine invariant Markov Chain Monte Carlo sampler of Goodman et al. (2010) as implemented in the parallel python package *emcee* by Foreman-Mackey et al. (2013). We adopt priors similar to More et al. (2016) on some of our parameters based on the expectations of their values from numerical simulations, but double the scales of the normal priors compared to their work (see Table 3). The central value for the prior on α is deduced from mass estimates (Gao et al. 2008), whereas the central values on the priors of β and γ were recommended by Diemer & Kravtsov (2014).

The splashback radius for halos on galaxy cluster scales is consistent with the location of the steepest logarithmic slope of the density profile. We estimate the steepest slope of both the two-dimensional and the three-dimensional cross-correlation function. The locations of the steepest slope in the two-dimensional and the three-dimensional case are expected to be different by about 20% for typical cluster halo parameters (Diemer & Kravtsov 2014; More et al. 2016).

Mis-centering of the central cluster positions can affect the small-scale correlation function on scales smaller than the typical mis-centering distance. Although, the splashback radius is located at much larger scales, the change of the inner part of the correlation function can alter the model fit significantly. Mis-centering effects are not expected to change the location of the splashback feature but they can in principle decrease the significance of the evidence for the splashback feature (Baxter et al. 2017). We discuss the modelling of mis-centering and its effects on the inferred splashback radii in Appendix B.

3.1. *Separation of red and blue galaxies*

We are also interested in measuring the cluster-galaxy cross-correlations for the blue and the red galaxy samples separately. We use a $g_{P1} - r_{P1}$ color cut which varies with the redshift of the clusters in order to account for the k-corrections, which cannot be computed individually for each galaxy.

In order to compute the color cut to be used, we first match spectroscopic galaxies in the Sloan digital Sky Survey (DR 13) to their Pan-STARRS photometry. We bin these galaxies in narrow redshift bins and produce a histogram of the $g_{P1} - r_{P1}$ colors of the galaxies in each bin. Due to the presence of the 4000Å-break present in the quenched galaxy population, the two galaxy populations separate in such histograms into two populations and we fit a double Gaussian distribution to it. Based on the fitted distribution we use a cut in color to exclude a contamination to the star-forming galaxy population with a confidence of 3σ. We repeat this procedure for each redshift bin, to obtain a redshift dependent color cut that separates the red from the blue population minimizing the contamination of the blue population by red galaxies. Although being much simpler and faster than calculating the individual k-corrections for each galaxy, this procedure has its own shortcomings as discussed in Appendix D, in particular due to the photometric errors of red galaxies. We would therefore exercise appropriate caution while interpreting the results obtained by dividing galaxies in to color bins.

In our analysis, the same galaxy may be considered red or blue depending upon the cluster redshift under consideration. Our method avoids the use of uncertain photometric redshifts to derive k-corrections (cf. Baxter et al. 2017). We will study the cross-correlations to derive the splashback radii for these galaxy populations separately, as well as the fractional contributions of the red and the blue galaxies to the total density profile as a function of radius. The caveats in the interpretation of these results are mentioned in the Appendix D.

4. RESULTS

4.1. *Cluster-galaxy cross-correlations*

Figure 1. The estimates of the two-dimensional cross-correlation signals (black dots) are shown in the left column. The colored curves show the two-dimensional model fits of the functional form in Equation 6. The magnitude limit applied to the galaxy catalog is indicated in each row along with the signal-to-noise ratio (SNR). The vertical, shaded regions indicate the estimates of the locations of steepest slope of the profiles as estimated from the corresponding minima of the derivative profiles, which are shown in the right column. For comparison, the location of the r_{200m} radius as calculated from the average cluster sample properties is indicated by the black, dotted lines.

Table 4

We list the signal to noise ratios (SNRs) of our different estimates of the two-dimensional cross-correlation obtained by using the different galaxy samples. For comparison: The SNR achieved by More et al. (2016) is 263. It is much higher due to size of the cluster sample used in their study.

gal cat	PS 21	PS 21.5	PS 22
SNR	42.4	43.3	30.9

The measurements of the two-dimensional cluster-galaxy cross-correlations are shown as black points with error bars in the left column of Figure 1. The different rows correspond to the three different absolute magnitude limits that we have used to select all the galaxies when calculating the cross-correlations. The cross-correlation signal is clearly detected in all three measurements and the corresponding signal-to-noise ratios of the measurements are listed in Table 4.

We fit these measurements with our parametric model in Equation 6 and compute the posterior distribution of the model parameters as described in Section 3. The median of the MCMC fit is indicated by the central solid line, while the shaded area marks the 68% credible interval for the fit. The median values of the posterior distributions of the parameters along with their 68% confidence intervals are listed in Table 5 along with the corresponding reduced χ^2 values for the best fit. The two-dimensional posterior distributions for each pair of parameters are shown in Figures 9, 10 and 11 for the three absolute magnitude limits, respectively.

The right panels in Figure 1 show the corresponding analytical derivatives of the two-dimensional cross-correlations and the 68% confidence interval based on our model fits. The logarithmic derivatives show a distinct steepening feature at around 1.3 h^{-1}Mpc. The figure shows that the location of the steepest slope does not change appreciably when the magnitude limit is changed, even though we use a sample which is one magnitude brighter than $M_i - 5\log h = -19.44$. The 68% confidence interval of the location of the steepest slope is indicated by the vertical, shaded region. We also show the location of the virial radius r_{200m} based on the Planck SZ mass estimate as a black, dotted line in each panel.

We use the posterior distributions of our model parameters to infer the three-dimensional cross-correlation and its first and second order logarithmic derivatives. These inferences along with the corresponding 68% confidence intervals are presented in Figure 2, maintaining the same color scheme as in Figure 1 for ease of comparison. The three-dimensional cross-correlations also show significant steepening in each of the cases that we have explored, reaching logarithmic derivatives steeper than −3. The inferred 68% confidence regions of the locations of the steepest slope of the three-dimensional cross-correlations are shown with vertical, shaded regions in each panel. The posterior distributions of the locations of the steepest slope in the two-dimensional and three-dimensional cross-correlations can be found in the left hand and the right hand panels of Figure 4, respectively. The estimates of the splashback radii for each of the samples are listed in Table 5 and our results show that the location of the splashback radius does not depend upon the sample once we use galaxies fainter than $M_i - 5\log h = -19.44$. Our measurements have an accuracy of ∼15%.

Following Baxter et al. (2017), we also present the values of the logarithmic derivatives at the location of the steepest slope for the total three-dimensional cross-correlations, as well as those for the inner halo term in the left and right hand panels of Figure 3, respectively. The logarithmic slope of the cross-correlation is significantly steeper than −3 at the location of the splashback radius, making it difficult to be reproduced by classical fitting functions like the NFW profile, which reach such slopes only asymptotically and even that only without the presence of the outer 2-halo term. This provides evidence for the existence of the splashback feature. From the second derivative profiles we also note that the drop in the cross-correlation signal is very sharp and happens within a factor 2 in radius.

We perform a preliminary comparison of the measurements with expectations from cold dark matter models. The average halo mass of the PSZ2 clusters as estimated from the Sunyaev-Zeldovich signal is $M_{500c} = 3.0 \times 10^{14}\ h^{-1}\mathrm{M}_\odot$. We convert this mass estimate to $M_{200m} = 6.2 \times 10^{14}\ h^{-1}\mathrm{M}_\odot$ using the average concentration mass relation of halos following Hu & Kravtsov (2003). Given the average mass and redshift of our cluster sample, we calculate the expected splashback radius to be 1.89 h^{-1}Mpc. We base this estimate on the fitting functions presented in More et al. (2015). The splashback radius we find for the three samples is consistent with this expectation, although we can not rule out ∼ 15% deviations in either directions, given our large error bars.

Next we present our measurements of the projected and three-dimensional cross-correlations of the red and blue galaxy populations satisfying $M_i - 5\log h < -18.94$ with our SZ-selected cluster sample. The projected cross-correlations are presented in Figure 5, whereas the three-dimensional counterparts are shown in Figure 6. The shaded regions show the 68% confidence intervals from our fits. The vertical, shaded bands with different colors indicate the 68% confidence regions of the locations of the steepest slope of the

Figure 2. The estimates of the three-dimensional cross-correlation signals are shown in the leftmost column. The colored curves show the model fits of the functional form in Equation 2. The magnitude limit applied on the galaxy catalog is indicated in each row along with the signal-to-noise ratio (SNR). The vertical, shaded regions indicate the estimates of the splashback radii as estimated from the corresponding minima of the derivative profiles, which are shown in the column in the middle. The rightmost column shows the second derivative profiles in matching color. The grey curves show the corresponding, estimated first and second derivatives of the one-halo term (namely $\rho_{in}(r) f_{trans}(r)$ in Equation 5). For comparison, the location of the r_{200m} radius as calculated from the average cluster sample properties is indicated by the black, dotted lines.

Table 5

We list our findings for the fitting parameters obtained from cross-correlating the galaxy cluster sample with the different galaxy catalogs. For each parameter estimate the median as well as the 16% and 84% quantiles of the posterior distribution are given. We also list the estimated locations of the steepening feature in the two-dimensional cross-correlation signal (R_{sp}^{2D}) as well as the three-dimensional splashback radius (r_{sp}^{3D}). In the last column the minimal, reduced χ^2 value of the model fit is indicated. The two-dimensional posterior distributions of the fitting parameters are displayed in Figure 9 up to Figure 13.

gal cat	$\log_{10}(\rho_s)$	$\log_{10}(\alpha)$	$\log_{10}(r_s)$	ρ_0	s_e	$\log_{10}(r_t)$	$\log_{10}(\beta)$	$\log_{10}(\gamma)$	R_{sp}^{2D}	r_{sp}^{3D}	χ^2/ν
PS 21	$-2.93^{+0.44}_{-0.50}$	$-1.06^{+0.14}_{-0.18}$	$0.35^{+0.27}_{-0.24}$	$0.000179^{+0.000075}_{-0.000086}$	$0.78^{+0.24}_{-0.19}$	$0.123^{+0.051}_{-0.122}$	$0.74^{+0.21}_{-0.31}$	$0.35^{+0.13}_{-0.21}$	$1.384^{+0.088}_{-0.096}$	$1.86^{+0.25}_{-0.26}$	1.524
PS 21.5	$-2.93^{+0.45}_{-0.45}$	$-0.95^{+0.13}_{-0.16}$	$0.32^{+0.25}_{-0.25}$	$0.000103^{+0.000047}_{-0.000065}$	$0.56^{+0.25}_{-0.22}$	$0.095^{+0.045}_{-0.115}$	$0.74^{+0.24}_{-0.32}$	$0.27^{+0.12}_{-0.19}$	$1.323^{+0.080}_{-0.086}$	$1.85^{+0.26}_{-0.30}$	0.285
PS 22	$-2.95^{+0.49}_{-0.44}$	$-0.91^{+0.14}_{-0.17}$	$0.28^{+0.25}_{-0.27}$	$0.000062^{+0.000028}_{-0.000051}$	$0.41^{+0.25}_{-0.28}$	$0.094^{+0.060}_{-0.190}$	$0.76^{+0.29}_{-0.36}$	$0.24^{+0.14}_{-0.27}$	$1.31^{+0.11}_{-0.14}$	$1.90^{+0.32}_{-0.40}$	0.211
PS 21.5 (R)	$-0.69^{+0.55}_{-0.54}$	$-0.99^{+0.17}_{-0.20}$	$0.24^{+0.30}_{-0.31}$	$0.0092^{+0.0046}_{-0.0065}$	$0.63^{+0.30}_{-0.27}$	$0.157^{+0.091}_{-0.171}$	$0.54^{+0.16}_{-0.20}$	$0.36^{+0.17}_{-0.26}$	$1.437^{+0.099}_{-0.089}$	$2.13^{+0.22}_{-0.21}$	0.502
PS 21.5 (B)	$-1.00^{+0.47}_{-0.24}$	$-0.31^{+0.21}_{-0.15}$	$0.22^{+0.19}_{-0.31}$	$0.0078^{+0.0036}_{-0.0047}$	$0.52^{+0.24}_{-0.21}$	$0.31^{+0.29}_{-0.27}$	$0.61^{+0.31}_{-0.44}$	$0.30^{+0.29}_{-0.39}$	$1.43^{+0.12}_{-0.13}$	$2.34^{+0.33}_{-0.34}$	1.355

two- and the three-dimensional cross-correlations. The black dashed lines show these ranges for the entire galaxy sample without regard to color. The best fit parameters as well as the inferred splashback radii are listed in Table 5. We see that the red galaxies have a steeper cross-correlation profile than the blue galaxies. Although there seems to be a tendency for the red galaxies to have a smaller splashback radius, the differences we see are not statistically significant given the current errors. The slopes of the three-dimensional cross-correlations reach values steeper than -2.5 at the splashback radius, which is difficult to model with traditional NFW profiles. We take the detection of those steepening features as evidence for the existence of the splashback feature in both galaxy populations. Taken at face value, our finding of the splashback feature in the blue population would imply that there needs to be a reasonable fraction of blue galaxies that fall into the cluster and continue to stay blue even after reaching their apocenters.

We caution however that the cut we use to define our samples was defined based on spectroscopic galaxies, which tend to be brighter than the typical galaxies we use for the cross-correlation. As we use galaxies at fainter magnitudes for the cross-correlation, the photometric errors increase dramatically and can scatter many more of the red galaxy population into the blue galaxy sample. We report on our investigations in Appendix D as a cautionary tale, and to guide future efforts to establish the splashback radius in the blue galaxy population. We show that given the current state of the data we cannot exclude a contamination of the correlation function of

Figure 3. We show the distributions of the logarithmic derivatives of the three-dimensional cross-correlation signals at the location of the splashback radius. In the left panel the distributions of the derivatives of the full profiles are shown, whereas only the inner halo term (namely $\rho_{in} f_{trans}$) is considered in the right panel.

Figure 4. Shown are the posterior distributions of the inferred locations of steepest slope of the two- and three dimensional cross-correlation signals. On the left side the distributions of the locations of the two-dimensional steepening feature (R_{sp}^{2D}) are shown, whereas the distributions of the three-dimensional counterparts (r_{sp}^{3D}) are shown on the right. The magnitude limit applied to the galaxy catalogs is indicated for each distribution. Note that the colors of the distributions match with the colors used in Figure 1 and Figure 2. For comparison, the location of the virial radius r_{200m} as calculated from the average cluster sample properties is indicated by the black, dotted lines.

Figure 5. The two-dimensional cross-correlations of the red and blue galaxy populations as inferred by cross-correlating the cluster sample with the color-separated subsamples that were extracted from the PS 21.5 galaxy catalog are shown in the left panel, whereas the associated derivative profiles are shown on the right. The vertical, shaded bands indicate the locations of steepest slope of the cross-correlation signal as inferred from the two subsamples, whereas the black, dashed lines indicate the upper and lower bounds of the same feature but as estimated from the full PS 21.5 galaxy catalog.

blue galaxies from the red galaxy population and appropriate caution be warranted in the interpretation or use of the results derived using the color separated galaxy populations.

5. CONCLUSIONS AND FUTURE DIRECTIONS

The splashback radius of dark matter halos is a unique observational probe of the mass accretion rate of dark matter halos. Although the splashback radius has been well-characterized in simulations, the observational evidence for the splashback radius presented using optical cluster catalogs has come under intense scrutiny. In this work, we tackle this issue by searching for evidence of the splashback radius in galaxy clusters found by the Planck surveyor using the thermal Sunyaev-Zeldovich effect. The use of this sample avoids the circularity of using photometric galaxy catalogs to identify clusters as well as to detect the splashback radius.

We cross-correlate these clusters with photometric galaxies from the Pan-STARRS survey to obtain the two-dimensional cross-correlation function and search for evidence for the splashback feature. Additionally, we divided our galaxy catalog into two subsamples of red and blue galaxies and investigated the cross-correlations of the two subsamples with the clusters, separately.

Our main findings can be summarized as follows:

Figure 6. We show the three-dimensional cross-correlations as inferred by cross-correlating the cluster sample with the color-separated galaxy subsamples, as well as the corresponding splashback radii (indicated by the colored, vertical bands) and their first and second order derivative profiles. The light-colored curves show the corresponding first and second derivatives of the one-halo term (namely $\rho_{\rm in}(r) f_{\rm trans}(r)$ in Equation 5) Here, the black, dashed lines indicate upper and lower bounds of the three-dimensional splashback radius corresponding to the full PS 21.5 galaxy sample.

- We detect a clear signature of a steepening feature in the cross-correlation of Planck SZ clusters with Pan-STARRS galaxies. The steepest logarithmic slopes that we find in our cross-correlation signals are steeper than -3, and would hence be poorly fit by the NFW profile. We associate this steepening with the splashback feature.

- The location of the inferred splashback radius is $r_{\rm sp} = 1.85^{+0.26}_{-0.30}\, h^{-1}$Mpc, which is consistent with expectations from numerical simulations for halos of an average mass $M_{\rm 500c} = 3.0 \times 10^{14} h^{-1} {\rm M}_\odot$ at an average redshift of $z = 0.18$ in a collision-less dark matter Universe. However, given the errors we cannot currently rule out $\sim 15\%$ deviations from these expectations.

- We find that the location of the steepest slope does not strongly depend on the magnitude of the galaxy samples we use, once we go fainter than $M_i - 5 \log h = -19.44$.

- By separately studying the cross-correlation of red and blue galaxies with the clusters, we present evidence for the presence of the splashback feature in both populations. The existence of the splashback radius for the star forming galaxy population could be of significance for the models of satellite quenching in galaxy clusters. However, photometric errors hinder a clean interpretation of the signal.

The signal-to-noise ratio of the current measurement is a result of the limited depth of the Pan-STARRS catalog, as well as the limited number of galaxy clusters detected using the SZ effect. As we consider fainter galaxy catalogs, the sky fraction in which the Pan-STARRS galaxy catalogs are complete reduces. Furthermore, the contamination from background galaxies is expected to increase at deeper magnitudes as well. A more precise estimation of the uncorrelated component would be possible by using a random galaxy catalog in addition to the random cluster sample. The masking information in Pan-STARRS is not currently easily accessible, which prevents the use of the more sophisticated Landy & Szalay estimator. Increasing the redshift range of clusters could potentially yield a bigger cluster sample, but would require us to use a sample of galaxies with a brighter absolute magnitude limit for galaxies, which reduces the number of galaxies that can be used to infer the cross-correlation signal. We are exploring the use of alternative cluster catalogs such as those detected from Xray surveys.

The separation of the blue and red galaxy populations as described in Section 3.1 is prone to photometric errors as explored in the Appendix. A deeper galaxy catalog would be required in order to confirm or rule out the existence of the splashback feature in the blue galaxy population. The ongoing deep galaxy surveys such as the Hyper Suprime-Cam (HSC) and the Dark Energy Survey (DES) would be able to provide such data sets, albeit in a limited area. The Large Synoptic Survey telescope (LSST) would eventually provide deep as well as wide galaxy catalogs to eventually establish the locations of the splashback radius at high significance.

Lastly, but most importantly, the investigation of any systematics which might originate from the SZ selection of the Planck clusters is beyond the scope of the current work. We caution that there may be residual systematics in the selection which could affect the interpretation of our measurements. We plan to investigate such selection systematics with the help of hydrodynamical simulations.

Our curated galaxy catalogs from the Pan-STARRS survey for different depths and the corresponding masks are available upon request.

While this work was in preparation, we became aware of a related study by Shin et al. (2018). Our results are complementary to theirs given the different data samples and cluster catalogs.

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APPENDIX

A. SKY MAPS

We present the sky locations of the SZ selected clusters from the PSZ2 catalog that we used in our study. The purple areas mark the masked out regions as defined by the union selection function of the PSZ2 catalog. The sky maps in Figure 8 show the survey masks of our three galaxy catalogs. All sky maps presented in this section use the ICRS coordinate system.

B. MODELLING CLUSTER MIS-CENTERING

As can be seen for the analysis and results in Baxter et al. (2017), the mis-centering of the central cluster positions in optical clusters were not large enough to change the location of the steepest slope in the cluster-galaxy cross-correlations. They do however decrease the significance of the finding. Therefore, we explore the effects of mis-centering on the correlation function and its influence on the results.

The mass dependence of the exact mis-centering fractions (for the brightest galaxy to be the central) are not well understood and mis-centering effects are therefore difficult to model (Skibba et al. 2011; Hoshino et al. 2015). We follow the approach outlined in Baxter et al. (2017) to take the effects of a possible mis-centering of a fraction of the cluster positions into account by modelling the influence on the two-dimensional correlation function.

Figure 7. Sky map showing the sky positions of the used clusters as selected from the PSZ2 catalog. In total 596 clusters have been selected. The purple areas mark the regions that are excluded by the union survey selection function. Note that all clusters with $\delta < -31^\circ$ have been removed since this region is not covered by the Pan-STARRS 3π Steradian survey. The ICRS coordinate system is used.

Figure 8. Sky maps displaying the masked out regions of the used galaxy catalogs extracted from the Pan-STARRS 3π Steradian survey in purple. The ICRS coordinate system is used.

If a fraction $f_{\rm mis}$ of the galaxy clusters in our sample are mis-centered, then the measured correlation function $\xi'_{\rm 2D}(R)$ is given by

$$\xi'_{\rm 2D}(R) = (1 - f_{\rm mis})\xi_{\rm 2D}(R) + f_{\rm mis}\xi_{\rm (2D,mis)}(R), \tag{B1}$$

where $\xi_{\rm (2D,mis)}$ denotes the contribution of the mis-centered clusters to the correlation function, and $\xi_{\rm 2D}(R)$ corresponds to the contribution of the correctly centered clusters. We model the mis-centered component $\xi_{\rm (2D,mis)}$ as

$$\xi_{\rm (2D,mis)}(R) = \int_0^\infty {\rm d}R_{\rm mis} P(R_{\rm mis})\xi_{\rm (2D,mis)}(R|R_{\rm mis})\,, \tag{B2}$$

where $P(R_{\rm mis})$ denotes the probability that a cluster is centered at a comoving distance $R_{\rm mis}$ from the brightest galaxy. The contribution $\xi_{\rm (2D,mis)}(R|R_{\rm mis})$ is related to the correlation function of the correctly centered clusters $\xi_{\rm 2D}$ as

$$\xi_{\rm (2D,mis)}(R|R_{\rm mis}) = \int_0^{2\pi} \frac{{\rm d}\theta}{2\pi}\xi_{\rm 2D}\left(\sqrt{R^2 + R_{\rm mis}^2 + 2RR_{\rm mis}\cos\theta}\right), \tag{B3}$$

according to Yang et al. (2006) and Johnston et al. (2007). We model the mis-centering probability $P(R_{\rm mis})$ as a Rayleigh distribution,

$$P(R_{\rm mis}) = \frac{R_{\rm mis}}{\sigma^2}\exp\left(-\frac{R_{\rm mis}^2}{2\sigma^2}\right), \tag{B4}$$

Thus, the mis-centered contribution is fully characterized by the two parameters $f_{\rm mis}$ and the witdh of the mis-centering probability distribution σ.

To find the priors for the two mis-centering paramters $f_{\rm mis}$ and σ we cross-match our SZ selected cluster sample with the X-Ray selected ACCEPT cluster sample (Cavagnolo et al. 2009). Assuming the ACCEPT clusters to lie at the minimum of the gravitational potential, we infer Gaussian priors for the two mis-centering model parameters $f_{\rm mis} = 0.15\pm0.21$ and $\sigma = 0.41\pm0.30$.

To study the influence of mis-centering on our findings we repeat the MCMC model fitting using our new model including mis-centering given in Equation B1, which now includes two more model parameters.

We find that the use of a projected mis-centering model increases the errorbars on the predicted confidence intervals for the projected cross-correlation signal by $\sim 25\%$. However, the effect is barely noticeable in the three-dimensional profiles. The inclusion of mis-centering is reflected as a small increase in the inferred errors of the projected and three-dimensional splashback radii as seen in Table 6. Although we notice shifts in the inferred central values of the splashback radii, none of these shifts appear systematic or significant given the errors.

Table 6
Listing of the splashback radii inferred by including the effects of mis-centering of the central cluster positions.

gal cat	$R_{\rm sp}^{\rm 2D}$	$r_{\rm sp}^{\rm 3D}$
PS 21	$1.35^{+0.13}_{-0.12}$	$1.76^{+0.29}_{-0.33}$
PS 21.5	$1.30^{+0.10}_{-0.10}$	$1.81^{+0.28}_{-0.33}$
PS 22	$1.33^{+0.13}_{-0.17}$	$1.96^{+0.37}_{-0.45}$
PS 21.5 (R)	$1.45^{+0.12}_{-0.11}$	$2.23^{+0.27}_{-0.26}$
PS 21.5 (B)	$1.42^{+0.20}_{-0.25}$	$2.39^{+0.39}_{-0.39}$

C. CORNERPLOTS

In Figures 9 to 13 we present the two-dimensional posterior distributions for each pair of the fitting parameters corresponding to the functional form in Equation B1. We obtained the distributions by using the affine invariant Markov Chain Monte Carlo sampler of Goodman et al. (2010) as implemented in the parallel python package *emcee* by Foreman-Mackey et al. (2013).

D. ESTIMATING THE CONTAMINATION OF THE BLUE GALAXY POPULATION

Add figures to this appendix.

To infer the color cut to separate star forming galaxies from the quenched galaxy population, we cross-matched the SDSS spectroscopic sample to its Pan-STARRS photometry. In Figure **??**, we show the plot of the Pan-STARRS $(g - r)$ color as a function of redshift, and the color cut we use in our analysis. The SDSS spectroscopic sample is however quite shallow, and thus consists of galaxies that are brighter than the Pan-STARRS galaxies that we wish to cross-correlate. At fainter magnitudes, we can expect photometric errors to scatter red galaxies into the blue population, potentially contaminating the correlation function measurement. This could erroneously cause for the splashback feature observed in the blue population. Therefore, we need to assess the possiblity of such a contamination.

In Figure **??**, we show the photometric errors of the Pan-STARRS galaxies as a function of magnitude in each of the bands we use. The galaxies that we use in our cross-correlation for the red/blue analysis have an absolute magnitude of $M_i - 5\log h = -18.94$. This corresponds to a different apparent magnitude limit at each redshift. For each spectroscopically matched galaxy, we figure out how faint the apparent magnitude limit in the i band is compared to the actual apparent magnitude of the galaxy. We assume that the populations of galaxies that we use to cross-correlate with clusters have the same intrinsic colors, but are just fainter. This gives us the true intrinsic magnitude of the galaxies that we cross-correlate in the g and the r band. We perturb these magnitudes by the expected errors at that magnitude as seen in Figure **??**.

Next, we compute the fraction of galaxies which were intrinsically red that now enter the blue population as defined using the same color cut, but based on the perturbed magnitudes as a result of photometric errors. We find such contamination of intrinsically red galaxies to the blue population to be about 5 percent. This value would apply in the field. Given that the red fraction is higher in clusters ($\sim$ 60 percent in the whole cluster) than in the field ($\sim$ 40 percent), we expect there to be a larger proportion of red galaxies which could potentially contaminate the blue galaxies due to photometric errors. This would roughly double the contamination to be about 10 percent.

This is a conservative estimate of the contamination, because the spectroscopic galaxy sample we use has a large incompleteness at the blue end at redshifts beyond 0.2, where SDSS targetted the luminous red galaxy population. Thus we are missing a lot of the blue galaxy population in the highest redshift bins in our spectroscopic sample. Nevertheless we estimate what a roughly 10 percent contamination would mean for the cross-correlation signal found for the blue galaxies.

The null hypothesis that we would like to establish or rule out is that the blue galaxies just consist of the infall population and show no splashback feature. We assume a simple $r^{-1.5}$ power law for the cross-correlation of the blue population with clusters consistent with an infalling population, and the inferred 3d cross-correlation function of the red galaxy population from our analysis. Given these cross-correlation functions we can estimate the cross-correlation of the blue population when contaminated with a given amount of red galaxies. We find that in order to reproduce the observed cross-correlation function of blue galaxies, we need a contamination of about 20%. While our conservatively estimated contamination is smaller than this value, a proper modeling of this contamination is warranted before definitive conclusions can be drawn. Larger galaxy surveys with better photometry such as the HSC or LSST would be of significant help in alleviating these issues.

Figure 9. The two-dimensional posterior distributions of each pair of the fitting parameters corresponding to the functional form in Equation B1 for the PS 21 sample.

Figure 10. The two-dimensional posterior distributions of each pair of the fitting parameters corresponding to the functional form in Equation B1 for the PS 21.5 sample.

Figure 11. The two-dimensional posterior distributions of each pair of the fitting parameters corresponding to the functional form in Equation B1 for the PS 22 sample.

Figure 12. The two-dimensional posterior distributions of each pair of the fitting parameters corresponding to the functional form in Equation B1 for the PS 21 sample, where we restricted our cross-correlatoin analysis to the red galaxy population.

Figure 13. The two-dimensional posterior distributions of each pair of the fitting parameters corresponding to the functional form in Equation B1 for the PS 21 sample, where we restricted our cross-correlatoin analysis to the blue galaxy population.