The Sphere of Influence of the Bright Central Galaxies in the Diffuse Light of SDSS Clusters

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ABSTRACT

The bright central galaxies (BCGs) dominate the inner portion of the diffuse cluster light, but it is still unclear where the intracluster light (ICL) takes over. To investigate the BCG+ICL transition, we stack the images of ~3000 clusters between 0.2<z<0.3 in the SDSS gri bands, and measure their BCG+ICL stellar surface mass profile \( \Sigma_{BCG+ICL} \) down to \( 3 \times 10^4 \, M_\odot/\text{kpc}^2 \) at \( R \approx 1 \text{ Mpc} \) (~32 mag/arcsec² in the r-band). We develop a physically-motivated method to decompose \( \Sigma_{BCG+ICL} \) into three components, including an inner de Vaucouleurs’ profile, an outer ICL that follows the dark matter distribution measured from weak lensing, and an intriguing transitional component between 70 and 200 kpc. To investigate the origin of this transition, we split the clusters into two subsamples by their BCG stellar mass \( M_{BCG} \) (mass enclosed roughly within 50 kpc) while making sure they have the same distribution of satellite richness. The \( \Sigma_{BCG+ICL} \) profiles of the two subsamples differ by more than a factor of two at \( R < 50 \) kpc, consistent with their 0.34 dex difference in \( M_{BCG} \), whereas on scales beyond 400 kpc the two profiles converge to the same amplitudes, suggesting a satellite-stripping origin of the outer ICL. Remarkably, however, the discrepancy between the two \( \Sigma_{BCG+ICL} \) profiles persist at above 50% level on all scales below 200 kpc, thereby revealing the BCG sphere of influence with radius \( R_{SOI} \approx 200 \) kpc. Finally, we speculate that the surprisingly large sphere of influence of the BCG is tied to the elevated escape velocity profile within \( r_s \), the characteristic radius of the dark matter haloes.

Keywords: galaxies; evolution — galaxies; formation — galaxies; abundances — galaxies; statistics — cosmology: large-scale structure of Universe

1 INTRODUCTION

The intracluster light (ICL) is primarily produced by stray stars that have escaped individual galaxies but remain gravitationally bound to the cluster potential (Zwicky 1937; de Vaucouleurs & de Vaucouleurs 1970; Welch & Sastry 1971; Melnick, White, & Hoessel 1977; Feldmeier et al. 2004; Mihos et al. 2005; Krick & Bernstein 2007). As the by-product of galaxy interactions within clusters (for a recent review; see Contini 2021), these free-floating stars are key to unlocking the assembly history of the bright central galaxies (BCGs) with future deep imaging surveys like LSST (Rubin; Ivezić et al. 2019), Euclid (Laureijs et al. 2011), Roman (Spergel et al. 2015), and the Chinese Survey Space Telescope (CSST; Gong et al. 2019). However, it is unclear whether there exists an ICL component that is physically distinct from the diffuse stellar envelope of the BCG (Kormendy & Bahcall 1974), and if so, where the ICL begins and the sphere of influence of the BCG ends (Doherty et al. 2009). In this paper, we examine the BCG+ICL stellar surface mass profile \( \Sigma_{BCG+ICL} \) of a large sample of clusters observed by the Sloan Digital Sky Survey (SDSS; York et al. 2000), in hopes of finding a more physically-motivated method of decomposing the \( \Sigma_{BCG+ICL} \) profile and the BCG “sphere of influence” within the diffuse cluster light.

In hydrodynamical simulations, methods for kinematically decomposing BCG vs. ICL have been developed based on the apparent bimodal distribution of the intracluster stellar velocities (Dolag et al. 2010; Cui et al. 2014). However, such exquisite methods developed for simulations are not applicable in the observations of distant clusters where stellar velocities are inaccessible (but see Arnaboldi et al. 1996; Romanowsky et al. 2012; Longobardi et al. 2015; Spinelli et al. 2018; Gu et al. 2020, for kinematic studies of ICL in local clusters). As a result, traditional methods of decomposition usually assume that the diffuse light below some arbitrary surface brightness (SB) limit belongs to the ICL (Rudick et al. 2011; Burke et al. 2012; Presotto et al. 2014; Tang et al. 2018; Furnell et al. 2021), or describe the BCG+ICL SB profile \( \mu_{BCG+ICL} \) as the sum of multiple Sérac components (Gonzalez et al. 2005; Seigar et al. 2007; Donzelli et al. 2011; Cooper et al. 2015; Zhang et al. 2019; Montes et al. 2021; Kluge et al. 2021). Despite the incoming deep photometric dataset from LSST+Euclid+Roman+CSST, a well-defined physical decomposition of the BCG+ICL profile is still lacking.

Recently, several studies proposed that the ICL in the outer region

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¹ We do not conform to the more commonly-adopted nomenclature of “brightest cluster galaxies”; because the BCGs in this work are likely the central galaxies but not necessarily the brightest.
of clusters should follow the distribution of dark matter, due to the fact that the stray stars and dark matter particles are both collisionless tracers of the cluster potential (Montes & Trujillo 2019; Alonso Asensio et al. 2020; Contini & Gu 2020; Sampaio-Santos et al. 2021). By the same token, the outer ICL may also follow the distribution of satellite galaxies, whose mass loss contributes significantly to the ICL (Purcell et al. 2007; Martel et al. 2012; Contini et al. 2014; Morishita et al. 2017). In this paper, we not only measure the BCG+ICL stellar surface mass density profile $\Sigma_{B+I}$ from image stacking, but also the total surface mass density profile $\Sigma_m$ from cluster weak lensing, as well as the galaxy surface number density profile $\Sigma_g$ from cluster-galaxy cross-correlation functions. By comparing the $\Sigma_{B+I}$ profile with $\Sigma_m$ and $\Sigma_g$, we develop a physically-motivated method for the decomposition of the diffuse cluster light without resorting to arbitrary SB limits or multiple Sérsic profiles.

In theory, since the intracluster stars are unlikely born in situ (Puchwein et al. 2010; Melnick et al. 2012), the build-up of the diffuse light should be closely linked to the dynamical evolution of the BCG and satellite galaxies, including: (1) mergers of satellites with the BCG (Murante et al. 2007; Burke et al. 2015), (2) tidal disruption/striping of satellites in the central region of the cluster (Purcell et al. 2007; Wetzel & White 2010; Montes & Trujillo 2014; DeMaio et al. 2015; Contini et al. 2018), (3) tidal and ram-pressure stripping of infalling satellites (Rudick et al. 2009; Contini et al. 2014; Montes & Trujillo 2018; DeMaio et al. 2018; Contini et al. 2019; Jiménez-Teja et al. 2018), and (4) pre-processing within infalling groups (Willman et al. 2004; Sommer-Larsen 2006; Rudick et al. 2006). Among these processes, (1) and (2) can simultaneously grow the BCG and the ICL within a Hubble time, while (3) and (4) deposit stars only into the ICL without growing the BCG. In particular, the amount of ICL growth through (1) and (2) should be strongly correlated with the observed BCG stellar mass $M_{BCG}$, but the ICL growth induced by (3) and (4) would be tied instead to the number of satellite galaxies within the cluster (a.k.a., cluster richness $\lambda$).

Therefore, any physically meaningful decomposition should reveal at least two distinct components of the diffuse cluster light, one BCG-induced and the other richness-induced. Obviously, the radial extent of the BCG-induced portion can be regarded as the radius of the BCG sphere of influence $R_{SOI}$ within the diffuse cluster light. In this paper, we divide clusters into high and low-$M_{BCG}$ subsamples at fixed $\lambda$ (see also Zu et al. 2021, hereafter referred to as Z21), and infer $R_{SOI}$ by comparing the $\Sigma_{B+I}$ profiles between the two subsamples. Using weak lensing, Z21 found that the average halo concentration of the high-$M_{BCG}$ clusters is $\sim 10\%$ higher than that of the low-$M_{BCG}$ clusters, but their average halo masses are the same. Since the two populations have the same $\lambda$ (and average halo mass) but differ only in $M_{BCG}$, we expect their $\Sigma_{B+I}(R)$ profiles to have equal richness-induced contributions beyond $R_{SOI}$, but exhibit distinct levels of BCG-induced diffuse mass below $R_{SOI}$ — a potentially smoking-gun detection of $R_{SOI}$.

This paper is organised as follows. We provide an overview of the cluster catalogue and photometric images in §2, setting the stage for our BCG+ICL SB profile measurement pipeline in §3. We describe the profile and the decomposition of the BCG+ICL stellar surface density profile $\Sigma_{B+I}$ in §4, and then present the observational detection of the BCG sphere of influence in §5. We conclude by summarizing our findings and looking to the future in §6. Throughout the paper, we assume the Planck (2016) cosmology ($\Omega_m=0.31$, $\sigma_8=0.816$, $h=0.677$), and convert all distances into physical coordinates. We use $\log x = \log_{10} x$ for the base-10 logarithm and $\ln x = \log_e x$ for the natural logarithm.

2 DATA

2.1 Cluster Catalogue

Following Z21, we employ the SDSS redMaPPer cluster catalogue (Rykoff et al. 2014) derived by applying a red sequence-based cluster finding algorithm to the SDSS DR8 imaging (Aihara et al. 2011). Briefly, redMaPPer iteratively self-trains a model of red-sequence galaxies calibrated by an input spectroscopic galaxy sample, and then attempts to grow a galaxy cluster centred about each photometric galaxy. Once a galaxy cluster has been identified by the matched-filters, the algorithm iteratively solves for a photometric redshift based on the calibrated red-sequence model, and re-centres the clusters about the best BCG candidates with the highest probability of being the central galaxy $p_{cen}$ (Rykoff et al. 2014).

For each detected cluster, redMaPPer applies an aperture of $\sim 1 h^{-1}$Mpc (with a weak dependence on richness $\lambda$), and assigns each galaxy within the aperture a membership probability $p_{mem}$. The satellite richness $\lambda$ was computed by summing the $p_{mem}$ of all member galaxy candidates, which roughly corresponds to the number of red-sequence satellite galaxies brighter than 0.2 $L_\odot$. At $\lambda \geq 20$, the SDSS redMaPPer cluster catalogue is approximately volume-complete up to $z=0.33$, with cluster photometric redshift uncertainties as small as $\delta(z)=0.006/(1+z)$. We select 4593 clusters with $\lambda \geq 20$ and redshifts between 0.2 and 0.3 ($z=0.254$). The maximum redshift of 0.3 is primarily set by the requirement of sample completeness, and partly because the cosmic dimming effect renders the detection of low-SB signals within SDSS challenging at the higher redshift ($\mu \propto (1+z)^{-3}$).

We pick the galaxy with the highest $p_{cen}$ in each cluster as the BCG, and derive an $i$-band cModel magnitude-based stellar mass $M_{BCG}^*$ for each BCG. In general, the SDSS model magnitudes are preferred for measuring the color of extended objects like the BCGs (hence a better mass-to-light ratio indicator), because flux is measured consistently through the same aperture across all bands, while the cModel magnitudes provide a more robust estimate of the total flux based on independent model fits in each bandpass (but see Bernardi 2017). Therefore, we rescale the extinction-corrected $gri$ model magnitudes to the $i$-band cModel magnitudes, and fit a Stellar Population Synthesis (SPS) model to the scaled $gri$ magnitudes to infer $M_{BCG}^*$.

Following Maraston et al. (2009), we assume a simultaneous burst of two Simple Stellar Populations (SSPs) at the same epoch, one dominant stellar population (97 per cent) with solar metallicity and the other a secondary (3 per cent) metal-poor ($Z=0.008$) population. We utilize the EzGal1 software (Mancone & Gonzalez 2012) and adopt the BC03 SSP model and the Chabrier IMF for the fits. For a detailed comparison between our photometric stellar mass estimates and the spectroscopic stellar masses from Chen et al. (2012), we refer interested readers to the Figure 1 in Z21.

Due to the magnitude rescaling, our estimates of $M_{BCG}^*$ should inherit the effective aperture of the $i$-band cModel magnitudes. By examining the stacked surface stellar mass density profiles of clusters at fixed $M_{BCG}^*$ but different $\lambda$ (as will be demonstrated later in §5), we find that the effective aperture of our $M_{BCG}^*$ estimates is $R_e \sim 50$ kpc. Therefore, our fiducial $M_{BCG}^*$ roughly corresponds to $M_{*, 50kpc}$ in the language of Huang et al. (2021). To test the robustness of our $R_{SOI}$ detection, we also measure for each BCG an aperture-based stellar mass $M_{*, 20kpc}$, i.e., stellar mass enclosed within a fixed aperture of 20 kpc.
Figure 1. Example of star and galaxy masks on the standard SDSS image frame (589×811 arcsec$^2$) of a cluster with $\lambda=42.6$ at $z=0.233$. The image dimension is 2048×1489 pixels, and the white margin area between the image frame and the panel edge has a width of 100 pixels. Panel (a): SDSS $gri$-band composite image of the cluster, with its BCG indicated by the inner solid circle with a radius of 100 kpc. The outer dashed circle indicates the cluster region of 1 Mpc radius. Panel (b): The SDSS $r$-band image frame. Panel (c): Cyan circles and magenta ellipses are the star and galaxy masks, respectively, while the regions delineated by black dashed lines are the merged masks of saturated pixels surrounding bright stars. Note that we also include the masks of sources that are centred in the white margin area (i.e., outside but close to the image frame), as they could still pollute the pixels inside the image frame. Panel (d): Final masked image that only includes the light from the BCG, ICL, and unmasked sources that are below the detection threshold.

2.2 SDSS Images

For any given set of clusters, we stack their SDSS images centred on the BCGs and measure the average 1D SB profile from the stacked 2D image. In this paper, we employ the observed images derived from the SDSS DR8, the same imaging data from which the redMaPPer cluster catalogue was built. The images were processed with the latest SDSS photometric pipeline photo v5_6, which implements an updated sky subtraction method that significantly improves the flux estimates for bright objects, detection of faint objects around bright objects, and extended light measurement of large objects (Blanton et al. 2011). In particular, we make use of the “corrected frames”, i.e., the calibrated and sky-subtracted images (with bad columns and cosmic rays interpolated over) in the $g$, $r$, and $i$ bands. Each corrected frame has a dimension of 2048 pixels × 1489 pixels, which corresponds to a sky area of 13.5×9.8 arcmin$^2$ (the pixel size is 0.396 arcsec). The improved photometric reduction of the SDSS images allows a robust measurement of the large-scale, diffuse light distribution within massive clusters, which was severely underestimated in the previous SDSS photometric pipeline (Bernardi et al. 2013; Kravtsov et al. 2018).

We apply a two-step procedure to identify the defect images that could severely corrupt the low-surface brightness signal. In the first step, we perform visual inspection of each image to look for strong defects that could severely undermine the stacked signal across all scales, e.g., extremely bright stars (and their extended bright wings) and strong cosmic rays across the frame. In the second step, we develop a simple $\sigma$-clipping scheme to reject some mildly defective images that could still impair our capability of detecting the faint ICL on scales larger than a few hundred kpcs. In particular, we divide each image frame (after masking out all the galaxies, bright stars, and saturated pixels; described further below) into approximately 70 square patches with side length of 200 pixels, and measure the average pixel flux ($f_{\text{pat}}$) within each patch. In addition, we measure the mean ($f_{\text{img}}$) and scatter ($\sigma$) of the average fluxes of the 70 patches, and compute the deviation of the average flux of each patch from the mean flux of the entire image as $\Delta f = |f_{\text{pat}} - f_{\text{img}}|$. We consider any image that includes a large block of $M$ connected patches with $\Delta f > N \sigma$ to be a potential contaminant. After extensive convergence tests, we find that the combination of $M=5$ and $N=6$ provides a robust selection criteria for culling out bright extended features of...
non-cluster origin. In total, we identify 1466 strongly and 1690 mildly defective images of the 4593 clusters from all three bands and exclude them from further stacking analysis, leaving 2898 clusters within our final sample.

3 SURFACE BRIGHTNESS PROFILE

To measure the SB profiles of the BCG+ICL $\mu_{B+I}$, we mask out the stars and non-BCG galaxies (i.e., satellites and background galaxies) from each image, and then transform all the images from the cluster redshifts to the same reference redshift of $z_{\text{ref}} = 0.25$ (with the same pixel size but different image sizes).

Our method for image stacking is largely similar to that of Zibetti et al. 2005, hereafter referred to as Z05, but with three important distinctions. Firstly, we directly utilize the sky-subtracted corrected frames for our SB measurements, while Z05 performed an independent sky subtraction on images in the SDSS Early Data Release. We have tested the Z05 sky-subtraction method on the raw DR8 SDSS images and find that the Z05 method generally produces consistent results compared to the SDSS pipeline. Secondly, we estimate the background level of the SB profiles, primarily due to undetected background galaxies and foreground stars, by stacking the real SDSS images centred on the coordinates of redMaPPer random clusters, while Z05 inferred the background SB by extrapolating from the best-fitting projected Navarro-Frenk-White (NFW; Navarro, Frenk, & White 1997) profile of the SB measurement below 900 kpc. Finally, we estimate the error matrix of our SB profiles by resampling the cluster sample into 30 Jackknife samples (described further below), while Z05 divided the annulus at each radius into $N$ angular sectors and calculated the error on the mean SB as the rms of the $N$ SB values divided by $\sqrt{N-1}$. We find that the diagonal errors from our Jackknife error matrix is generally larger than the Z05 errors by a factor of two on scales above 10 kpc, likely because the SB of neighboring sectors within the same annulus are highly correlated. We describe each step of our SB measurement in turn below.

3.1 Image Masking

For any star brighter than $m_r = 20$ and has the full width at half maximum (FWHM) measured in at least one of the other two bands, we adopt the maximum FWHM of the three bands and multiply it by 30 as the diameter of its mask. We further increase the diameter of the masks to 75 FWHM for the saturated pixels. For stars detected only in $r$ band or fainter than $m_r = 20$, we leave them unmasked in the image but will remove their light statistically through background subtraction. We have extensively tested the impact of different mask sizes on the measured BCG+ICL SB profile, and verified that our choices yield the best combination of signal-to-noise ratio (S/N) and star light mitigation.

For galaxy masks, we run SExtractor (Bertin & Arnouts 1996) on the cluster images in three bands separately, using a detection threshold of $1.5\sigma$ and a minimum detection area of five pixels. Such detection criteria result in a limiting magnitude of roughly $22.08$ magnitude in the $i$ band (i.e., an absolute magnitude of $-18.49$ for a galaxy at $z = 0.25$). We multiply the semi-major and semi-minor radii of the ellipses detected by SExtractor both by a factor of eight, and adopt the augmented ellipses as the masks for galaxies. We include the BCGs in the masks for the image selection described in §2.2, but leave them unmasked in the stacked profile measurements. The factor of eight is a relatively conservative choice, which ensures that we remove almost all the light from galaxy outskirts and the scattered light from some of the very bright, nearby galaxies.

To further remove any contamination by bright stars and extended sources from outside the image boundaries, we identify all the eight images adjacent to each target image, and apply the same masking
Figure 3. Comparison of our measurements of the BCG+ICL SB (left) and colour (right) profiles with previous studies. Left: Solid, dashed, and dotted curves indicate the BCG+ICL SB profiles from our measurements for redMaPPer clusters, Z05 for maxBCG clusters, and the SDSS photometric pipeline (profMean) for the redMaPPer BCGs, respectively. Green, red, and maroon curves are the measurements for the g, r, i bands, respectively. Right: Red solid, cyan dashed, and black dot-dashed curves indicate the BCG+ICL colour profiles measured by our work from SDSS DR8, Z05 from SDSS DR1, and Zhang et al. (2019) from DES, respectively. In both panels, the dot-dashed vertical lines indicate the scale of the PSF, and the shaded bands around the solid curves represent the 1σ uncertainties estimated from Jackknife resampling.

Figure 4. Impact of the SDSS PSF on the BCG+ICL SB profiles. Top: Surface brightness profiles in the g (green), r (red), and i-band (maroon). Solid curves are the input three-Sérsic models of the SB profiles before convolving with the PSF, and the dashed curves are the results after convolving them with the PSF derived by Infante-Sainz (2020) in each band (illustrated in the inset panel, where the PSF in each band is normalized to have unit total flux). Bottom: The ratio between the SB profiles after and before PSF convolution. The bottom and top x-axes are in units of arc sec and kpc (physical), respectively.
3.2 Image Rescaling to Reference Redshift

To stack images at the same physical scale, we transform all the masked images to the reference redshift $z_{\text{ref}}=0.25$ with the same pixel size. Firstly, we rescale the pixel size of each image by the square of the angular diameter distance ratio between the observed and reference redshifts, \( (D_{\text{A}}^{\text{obs}}/D_{\text{A}})^2 \), and the flux within the pixel by the square of the ratio between the two luminosity distances, \( (D_{\text{L}}^{\text{obs}}/D_{\text{L}})^2 \). Cosmic dimming is automatically included as the pixel SB scales with \( [(1 + z_{\text{obs}})/(1 + z_{\text{ref}})]^4 \). We do not apply any $K$-correction to the cluster fluxes due to the lack of robust SED templates for the ICL. However, since the reference redshift is close to the median redshift of the sample, we anticipate that the amount of $K$-correction in the stacked images should be largely cancelled out. We explicitly test this using the colours of the BCGs to compute the distribution of $K$-correction values in each band, and find that the mean $K$-corrections are close to zero with a scatter of 0.025 magnitude in the i-band, which contributes to a 1~2% uncertainty in the stellar surface density profiles. In addition, we correct for Galactic extinction on the stacked images using the average $A_r$ of the BCG sightlines, rather than the individual BCGs. Secondly, we resample all the rescaled images to 0.396$''$ per pixel, i.e., the original pixel size of the SDSS images. We then redistribute the image fluxes into the resampled pixels, so that the flux in pixel $i$ (after resampling) is $f_i = \sum_j A_{ij}$, where $A_j$ is the SB of the $j$-th pixel in the rescaled image (i.e., before resampling) and $A_{ij}$ is the overlapped area between pixel $i$ and pixel $j$.

3.3 BCG+ICL SB Profile Measurement

With all clusters shifted to the reference redshift, we now stack their images centred on the BCGs in physical coordinates. We do not rotate the cluster images, e.g., to align the BCGs by their major axes, as we are mainly concerned with the 1D azimuthally-averaged profiles in this paper. We carefully account for the masked regions and adopt the mean flux at each pixel for the stacked image. A total SB profile $\mu^{\text{tot}}(R)$ is then computed as the azimuthally averaged SB within each annulus of radius $R$. However, this total SB profile includes not only the light from the BCG+ICL, but also contributions from the unmasked satellite galaxies, background galaxies, foreground stars, and the Galactic cirrus (which is uncorrelated with the cluster positions on the sky), hence a BCG+ICL+Background SB profile. We will estimate the unmasked satellite contribution by inspecting the satellite stellar mass functions later in §4.4, and describe the removal of the background SB induced by the other three components below.

For any given set of clusters, we select a matching sample of random clusters with the same joint distribution of redshift and richness from the SDSS redMaPPer random catalogue v6.3. Since the sensitivity of redMaPPer algorithm to the background (e.g., survey boundary, masks, and variation of photometric depth) is incorporated in the generation of random clusters (Rykoff et al. 2016), we expect the background SB of the random cluster images to be similar to that of the observed ones. To measure the background SB profile, we download the SDSS corrected frames that host the random clusters, and perform the same two-step quality inspection to remove defect images from the random sample. We then apply the same masking, rescaling, and stacking procedures to the random cluster images that pass the inspection, thereby producing a background SB profile for the clusters. We repeat such procedure ten times by reshuffling the relative positions of the random BCGs on the images after each measurement, and calculate the average of the ten measurements as our the final background SB profile $\mu^{\text{bg}}(R)$.

Finally, we derive the BCG+ICL SB profile $\mu^{\text{B+I}}(R)$ by subtracting the background SB profile from the total SB profile,

$$\mu^{\text{B+I}}(R) = \mu^{\text{tot}}(R) - \mu^{\text{bg}}(R).$$

We further normalise the $\mu^{\text{B+I}}(R)$ profile to be zero at projected distance $R=2$ Mpc, and focus on the SB signals at $R<1$ Mpc for the rest of the paper. Note that the $\mu^{\text{B+I}}(R)$ profile measured in this way includes the contribution from the faint satellite galaxies that are unmasked. We do not subtract this contribution from our measured $\mu^{\text{B+I}}(R)$ and $\Sigma_{\text{B+I}}(R)$ profiles, but will nonetheless estimate the total stellar mass of the unmasked satellites $\Sigma_{\text{M}}$ in §4.4. In order to estimate the uncertainties of $\mu^{\text{B+I}}(R)$, we employ the standard Jackknife resampling technique by dividing each cluster sample into 30 equal-size subsamples, and estimate the error matrix from the 30 “leave-one-out” (i.e., using 29 subsamples for each resampled measurement) experiments (Efron & Stein 1981).

Figure 2 shows the stacked 2D image of the BCG+ICL SB distribution (left) and the corresponding 1D SB profiles (right) for our overall cluster sample in the r band. In the left panel, the grayscale intensity represents the SB of each pixel, while the contour lines indicate seven levels of SB ranging from $\mu=26$ mag/arcsec$^2$ at $R=50$ kpc to 32 mag/arcsec$^2$ at $R=1$ Mpc (with $\Delta\mu=1$ mag/arcsec$^2$ increasing outwards), obtained using smoothing kernels of 3, 7, 11, 17, 29, and 29 pixels, respectively and colour-coded by the vertical colourbar on the right. The azimuthally averaged 1D SB profiles are shown in the right panel, where the blue dashed, grey dotted, and red solid curves indicate the total stacked SB $\mu^{\text{tot}}(R)$ (BCG+ICL+background), background SB $\mu^{\text{bg}}(R)$, and the BCG+ICL SB profiles $\mu^{\text{B+I}}(R)$, respectively. The dot-dashed vertical
Figure 6. Distribution of stars, dark matter, and galaxies around the BCG. Left: Stellar surface mass density profiles. Open circles with errorbars are the $\Sigma^\text{B+I}(R)$ profile measured by this work, while solid ($\gamma\Sigma_m$) and dashed black ($M^\text{max}_\text{ICL}$) curves are the model predictions assuming that the outer ICL follows the distributions of dark matter (middle panel) and satellite galaxies (right panel), respectively. The best-fitting scaling factors are $\gamma=1/446$ and $M^\text{max}_\text{ICL}=1.4\times10^{10}M_\odot$. Middle: Surface density contrast $\Delta\Sigma(R)$ measured by cluster weak lensing (squares with errorbars) and predicted by the best–fitting model described in Z05 (solid). Dotted curve indicates the weak lensing contribution from the stellar mass of the best-fitting de Vaucouleurs’ profile, and dashed curve is the sum of the two contributions. Right: Galaxy surface number density profile $\Sigma_g(R)$ measured from the cluster-galaxy cross-correlation function. The vertical lines in the middle and right panels mark the halo radius $R_{\text{200m}}$.

line indicates the physical scale that the PSF (point spread function) size corresponds to at $z=0.25$ (the same as the dot-dashed vertical lines in both panels of Figure 3). The shaded bands indicate the SB uncertainties estimated from Jackknife resampling. Thanks to the large sample size, we are able to robustly measure the diffuse cluster light down to roughly 32 mag/arcsec$^2$ at $R=1$ Mpc despite the relatively shallow depth of the SDSS imaging from a decade ago.

We compare our BCG+ICL SB (left) and $g-r$ colour (right) profiles with the results from previous studies in Figure 3. In the left panel, solid and dashed curves indicate the $\mu^\text{B+I}(R)$ profiles measured for the redMaPPer clusters in this work and the maxBCG (Koester et al. 2007) clusters by Z05, respectively, in the SDSS $g$ (green), $r$ (red), and $i$ (maroon) bands. The amplitudes of the maxBCG profiles are slightly higher than the redMaPPer ones on all scales, likely because the maxBCG clusters selected by Z05 are on average higher mass systems than ours. On small scales, our stacked profiles are consistent with the average BCG light profiles (dotted) derived by the SDSS photometric pipeline (photoMean), but the dotted curves are rapidly cut off on scales above 30 kpc. For the $g-r$ colour profiles shown in the right panel, our measurement (red solid) is slightly redder than the that of Z05 (black dot-dashed), consistent with the Z05 BCGs being more massive. We also show the DES $g-r$ colour profile measured by Zhang et al. (2019) for the DES clusters (cyan dashed), which exhibits a similar slope compared to Z05 and our results. The Zhang et al. profile is measured from a much smaller cluster sample than ours with $\approx 280$ DES redMaPPer clusters, so their measurements are cut off at 200 kpc despite the DES photometry is roughly two magnitudes deeper than SDSS.

Note that none of the BCG+ICL SB profile measurements shown in Figure 3 are corrected for the wide-angle effect of the PSF (Tal 2011; D’Souza 2014; Wang 2019). To test the impact of PSF on the diffuse light on large scales, Zhang et al. (2019) fit a model with three Sérsic components to the measured BCG+ICL SB profile, and convolve the best–fitting model curve with the DES PSF in each band. They found that the SB enhancement due to PSF on scales above 100 kpc is smaller than a few percent and is thus negligible in the ICL analysis. Adopting the same approach, we fit a three Sérsic model to the BCG+ICL SB profile in each band, and convolve them with the SDSS 2D PSF model inferred by Infante-Sainz (2020). Figure 4 compares the difference between the SB profiles before (solid) and after (dashed) the 2D PSF convolution in the $g$ (green), $r$ (red), and $i$ (maroon) bands, respectively. The inset panel illustrates the azimuthally-averaged SDSS 1D PSF inferred by Infante-Sainz (2020), normalized so that total flux is unity in each band, and the dashed curves in the bottom panel show the ratio profiles between the SB profiles after and before 2D PSF convolution. In the $g$- and $r$-bands, the relative difference is well below 2% and 5% on scales between 20 – 400 kpc and above 400 kpc at redshift 0.25, respectively. The difference in the $i$-band is slightly larger due to the bump feature at $\approx 20$ arcsec in the $i$-band PSF, but is still below 6% on all scales above 10 kpc and smaller than the statistical uncertainties on scales above 100 kpc. We have also examined the impact of the 2D PSF on all the other measurements in our paper, and find that our conclusions are unaffected by the wide-angle effect of the SDSS PSF.

4 STELLAR SURFACE DENSITY PROFILE

4.1 Mass-to-Light Ratio

For each cluster sample, we now convert the light profiles $\mu^\text{B+I}$ measured in three bands into a BCG+ICL stellar surface density profile $\Sigma^\text{B+I}$ using an empirically calibrated mass-to-light ratio against the $M^\text{BCG}$ measured in §2.1. In particular, we assume the $i$-band mass-to-light ratio $(M_i/L_i)$ can be described by a simple linear function of the $i$-band luminosity $L_i$, $g-r$, and $r-i$ colours,

$$\lg(M_i/L_i) = a \cdot (g-r) + b \cdot (r-i) + (c-1) \cdot \lg L_i + d.$$  

(2)

We use $M^\text{BCG}$, $i$-band eModel magnitudes, and the model colours of the BCGs to infer the values of $\{a, b, c, d\}$ via least-square fitting. Figure 5 demonstrates the efficacy of our empirical calibration of $M_i/L_i$, where we show the distribution of BCGs on the observed vs. predicted $M^\text{BCG}$ plane. Filled circles with errorbars indicate the mean observed $M^\text{BCG}$ at fixed $(M^\text{BCG})$ predicted by Equation 2 with $\{a=0.31, b=0.57, c=1.01, d=-0.55\}$, in good agreement with the one-to-one relation (solid line). The outliers in the bottom left corner mainly consist of BCGs with relatively blue colours,
which have minimal impact on the least-square fit due to their small fraction.

However, since the outer ICL has a bluer colour than the inner BCG (right panel of Figure 3), extrapolating Equation 2, which is calibrated against the inner BCG, to the outer ICL at $R>200$ kpc may incur a systematic bias in the $\Sigma^{\text{B+I}}$ measurement. Fortunately, the bias should be sufficiently small compared to our measurement uncertainties at those radii. For example, a 10% bias in the coefficient $a$ would result in a 0.03 dex bias in stellar mass for $g=r=1$, much smaller than the 20% statistical uncertainty of $\Sigma^{\text{B+I}}$ at $R\approx200$ kpc (as will be described further below). Furthermore, our detection of $R_{\text{SOI}}$ relies on the difference between the $\Sigma^{\text{B+I}}$ uncertainties at those radii. For example, a small $\Sigma$ in the measurements of cluster weak lensing component with that of the dark matter and satellite galaxies, we show that the ICL largely follows the distributions of dark matter and satellite galaxies. To compare the surface density profile of the diffuse component with that of the dark matter and satellite galaxies, we show the measurements of cluster weak lensing $\Delta \Sigma$ and galaxy number density profile $\Sigma_{\text{g}}$ for the overall sample in the middle and right panels of Figure 6, respectively (squares with errorbars).

4.2 Surface Density Profiles of Stars, Dark Matter, and Galaxies

In the left panel of Figure 6, we apply our best-fitting formula of $M_{\ast}/L_{\ast}$ (Equation 2) to the gri SB profiles in Figure 3 and derive the BCG+ICL stellar surface density profile $\Sigma^{\text{B+I}}(R)$ for the overall cluster sample, as shown by the open circles with errorbars. Clearly, the $\Sigma^{\text{B+I}}$ profile has a significant ICL component that extends to a few $\times10^4 M_{\odot}/\text{kpc}^2$ at scales $\sim500$ kpc--1 Mpc, where we expect that the ICL largely follows the distributions of dark matter and satellite galaxies. To compare the surface density profile of the diffuse component with that of the dark matter and satellite galaxies, we show the measurements of cluster weak lensing $\Delta \Sigma$ and galaxy number density profile $\Sigma_{\text{g}}$ for the overall sample in the middle and right panels of Figure 6, respectively (squares with errorbars).

We obtain the $\Delta \Sigma$ and $\Sigma_{\text{g}}$ measurements (as well as the theoretical model of $\Delta \Sigma$) by faithfully following the methods described in Z21. Briefly, the surface density contrast profile $\Delta \Sigma(R)$ is measured from weak lensing using the DECaLS DR8 imaging (Dey et al. 2019), while the galaxy surface number density profile $\Sigma_{\text{g}}(R)$ is calculated by cross-correlating clusters with the photometric galaxies within SDSS DR8. The photometric galaxies are selected with an effective absolute magnitude limit of $M_{\text{lim}}=−20.28$. We also show the best-fitting $\Delta \Sigma_{\text{m}}(R)$ profile predicted by the theoretical model of Z21 in the middle panel (solid curve), which describes the small-scale lensing using an NFW halo density profile (with the cluster miscentring effect constrained by X-ray observations), and the large-scale lensing using a biased version of the matter clustering. From the $\Delta \Sigma$ modelling, we infer the average halo mass of our cluster sample to be $M_{\text{h}}=2.57 \times 10^{14} M_{\odot}$, consistent with the results from Z21. The dotted curve indicates the $\Sigma^{\text{deV}}$ signal from the stellar mass of the best-fitting de Vaucouleurs’ profile at $R<20$ kpc, and the dashed curve shows the sum of $\Sigma^{\text{deV}}$ and $\Delta \Sigma_{\text{m}}$. The vertical lines in the two panels indicate the halo radius $R_{\text{200m}}$, inferred from the weak lensing mass. The $\Sigma_{\text{g}}(R)$ profile exhibits an inflection at $R_{\text{200m}}$, indicating the familiar transition from the 1-halo term (dominated by satellite galaxies) to the 2-halo term in the halo occupation distribution language (e.g., Zu & Mandelbaum 2015). We refer interested readers to Z21 for technical details that are beyond the scope of this paper.

Returning to the left panel of Figure 6. Solid and dashed curves show the matter surface density profile $\Sigma_{\text{m}}$ and galaxy surface number density profile $\Sigma_{\text{g}}$, multiplied by a scale factor $\gamma$ and the average mass loss per galaxy $M_{\text{loss}}$, respectively. In particular, $\Sigma_{\text{m}}$ is related to $\Delta \Sigma$ via

$$\Delta \Sigma(R) = \Sigma_{\text{m}}(<R) - \Sigma_{\text{m}}(R),$$

where $\Sigma_{\text{m}}(<R)$ is the average surface mass density within $R$. The scaling factor is defined as

$$\gamma(R) = \frac{\Sigma_{\text{ICL}}(R) + \Sigma^{\text{unmasked}}_{\text{sat}}(R)}{\Sigma_{\text{m}}(R)}$$

where $\Sigma_{\text{ICL}}$ is the ICL stellar mass profile and $\Sigma^{\text{unmasked}}_{\text{sat}}$ is the stellar mass profile of the unmasked satellite galaxies. By assuming that the ICL and unmasked satellites both follow the distribution of dark matter, the above equation can be simplified as

$$\gamma(R) \equiv \gamma = f_{\text{ICL}} + f_{\text{unmasked}}^{\text{sat}},$$

where $f_{\text{ICL}}$ and $f_{\text{unmasked}}^{\text{sat}}$ are the ICL and unmasked satellite-to-halo mass fractions, respectively. We infer the best-fitting values of $\gamma=1/446$ and $M_{\text{loss}}=1.4 \times 10^{10} M_{\odot}$ by matching the scaled profiles to the $\Sigma^{\text{B+I}}(R)$ measurements above $R=400$ kpc. We will infer the values of $f_{\text{ICL}}$ and $f_{\text{unmasked}}^{\text{sat}}$ separately in §4.4. Note that we predict the $\Sigma_{\text{m}}$ profile from the best-fitting $\Delta \Sigma$ model curve in the middle panel, and directly adopt the observed $\Sigma_{\text{g}}$ profile in the right panel. Additionally, both curves are normalized to have zero amplitudes at $R=2$ Mpc, following the same practice when measuring $\Sigma^{\text{B+I}}$.

Overall, the two scaled profiles $\gamma \Sigma_{\text{m}}$ and $M_{\text{loss}} \Sigma_{\text{g}}$ in the left panel of Figure 6 provide good descriptions to the BCG+ICL surface density profiles at $R>400$ kpc, indicating that the ICL in the outer region of clusters indeed follows the distribution of the dark matter and satellite galaxies. This is consistent with the findings from Montes & Trujillo (2019), which suggested that the ICL is an excellent tracer of dark matter, as well as satellite stripping being the dominant channel of ICL production in the outer region. In particular, we find that our observation of the diffuse light on scales above 400 kpc can be explained if $-0.1-0.2\%$ of the total mass is in the form of ICL, and if $\sim10^{10} M_{\odot}$ of stars were stripped from each satellite galaxy into the ICL.

4.3 Decomposition of the BCG+ICL Surface Stellar Mass Profile

Given that the outer region of the ICL roughly follows the distribution of dark matter, we can separate the observed BCG+ICL stellar surface mass profile $\Sigma^{\text{B+I}}$ into at least two physically distinct components, including one that follows the dark matter on large scales ($R=400$ kpc--1 Mpc) and the other BCG-dominated portion on small scales ($R<50$ kpc). By further assuming that the intrinsic BCG can be described by a de Vaucouleurs’ profile, the BCG-dominated portion may include a third component on transitional scales where the extended BCG envelope unfolds into the ICL. Following this philosophy, we can decompose the $\Sigma^{\text{B+I}}$ profile via the following three steps. Firstly, we adopt the total surface mass profile $\Sigma_{\text{m}}$ inferred from weak lensing, and multiply it by $\gamma=1/446$ to describe $\Sigma^{\text{B+I}}$ at $R>400$ kpc, as was done in the left panel of Figure 6.

$$\gamma \Sigma_{\text{m}}(R) = \Sigma_{\text{ICL}}(R) + \Sigma^{\text{unmasked}}_{\text{sat}}(R)$$

Secondly, we fit a de Vaucouleurs’ profile to the $\Sigma^{\text{B+I}}$ measurement on scales below $R=20$ kpc,

$$\Sigma^{\text{deV}}(R) = \Sigma_{\text{e}} \exp \left(-7.676 \left(\frac{R}{R_{\text{e}}}\right)^{1/4} - 1\right),$$

yielding $\Sigma_{\text{e}}=10^{10.93} M_{\odot}/\text{kpc}^2$ and $R_{\text{e}}=15.06$ kpc. Finally, we subtract $\gamma \Sigma_{\text{m}}$ and $\Sigma^{\text{deV}}$ from the measured $\Sigma^{\text{B+I}}$ profile, leaving us a “transitional component”

$$\Sigma^{\text{tran}}(R) = \Sigma_{\text{ICL}}(R) - \left[\Sigma^{\text{deV}}(R) + \gamma \Sigma_{\text{m}}(R)\right].$$
Decomposition of the Diffuse Cluster Light

\begin{equation}
\Sigma^{\text{dev}+\gamma}\Sigma_{m} \quad \ldots \quad \gamma\Sigma_{m} \quad \ldots \quad \Sigma^{\text{dev}}_{\text{m}} \quad \ldots \quad \Sigma^{\text{dev}}_{\text{tran}} \quad \ldots \quad \Sigma^{\text{dev}}_{\text{m}} \quad \ldots \quad \Sigma^{\text{dev}}_{\text{B+I}} \quad \ldots \quad \Sigma^{\text{dev}}_{\text{B+I+ICL}} \quad \ldots \quad \Sigma^{\text{dev}}_{\text{B+I+ICL}}
\end{equation}

Figure 7. Decomposition of the BCG+ICL stellar surface mass density profile \(\Sigma_{*}(R)\) (open circles with errorbars). Solid curve is the total surface mass density profile \(\Sigma_{m}\), scaled by \(\gamma=1/446\) (Equation 4), while the best-fitting de Vaucouleurs profile for the \(\Sigma_{*}^{\text{dev}}\) profile at \(R<20\) kpc is shown as the dotted curve. The sum of \(\gamma\Sigma_{m}\) and \(\Sigma_{*}^{\text{dev}}\) is indicated by the dot-dashed curve, revealing an excess mass in the observed \(\Sigma_{*}^{\text{dev}}\) profile on transitional scales of \(R=70\)–\(200\) kpc. Open squares with errorbars indicate this transitional component \(\Sigma_{*}^{\text{tran}}\). The bottom subpanel shows the ratio between \(\Sigma_{*}^{\text{tran}}(R)\) and \(\Sigma^{\text{dev}}_{\text{B+I}}(R)\), which can be described by a simple Gaussian (dashed; Equation 9).

Therefore, \(\Sigma_{*}^{\text{tran}}(R)\) represents the excess component in the diffuse light that cannot be described by the sum of a de Vaucouleurs’ profile and an ICL mass profile that follows the dark matter.

Figure 7 illustrates the physical decomposition of our observed \(\Sigma_{*}^{\text{B+I}}\) profile (open circles with errorbars) into three distinct components: a de Vaucouleurs’ profile \(\Sigma^{\text{dev}}\) (dotted curve), a scaled dark matter profile \(\gamma\Sigma_{m}\) (solid curve), and a transitional component \(\Sigma_{*}^{\text{tran}}\) (open squares with errorbars). The errorbars of \(\Sigma_{*}^{\text{tran}}\) are inherited from that of the \(\Sigma_{*}^{\text{B+I}}\) measurement, assuming zero uncertainties from the subtraction. Additionally, dot-dashed curve indicates the sum of the de Vaucouleurs’ profile and the scaled dark matter profile, which clearly under-predicts the signal on scales between 50 kpc and 300 kpc — a third component \(\Sigma_{*}^{\text{tran}}\) is required to fully describe the diffuse light. The ratio profile between \(\Sigma_{*}^{\text{tran}}(R)\) and \(\Sigma_{*}^{\text{B+I}}(R)\) is shown in the bottom panel of Figure 7. The transitional component accounts for about 17% of the total diffuse mass on scales between 50 kpc and 300 kpc, and the ratio peaks at 25% around 100 kpc.

To test the robustness of \(\Sigma_{*}^{\text{tran}}(R)\), we fit the de Vaucouleurs’ profile to a larger maximum radius of 30 kpc, finding that the centroid and amplitude of \(\Sigma_{*}^{\text{tran}}(R)\) stay almost unchanged. We also perform the decomposition using a generic Sersic profile instead of a de Vaucouleurs’ profile, which has a fixed Sersic index of four. Although the peak amplitude reduces from 25% to 15%, once we allow the Sersic index to deviate from four, the centroid stays unchanged at \(\pm 100\) kpc and the \(\Sigma_{*}^{\text{tran}}(R)\) component remains significant compared to the \(\Sigma_{*}^{\text{B+I}}\) uncertainties (\(\sim 5\%\) at \(R=100\) kpc). Therefore, we conclude that the transitional component is required to provide a complete description of the diffuse stellar mass profile on scales between 50 kpc and 300 kpc, regardless of assumptions for the stellar mass profile of the inner BCG. For the rest of the paper, we will adopt the \(\Sigma_{*}^{\text{tran}}(R)\) profile calculated from assuming a de Vaucouleurs’ profile at \(R<20\) kpc as our fiducial model of the transitional component.

Finally, the ratio profile between \(\Sigma_{*}^{\text{tran}}(R)\) and \(\Sigma_{*}^{\text{B+I}}(R)\) can be described by a Gaussian (in logspace):

\begin{equation}
\frac{\Sigma_{*}^{\text{tran}}(R)}{\Sigma_{*}^{\text{B+I}}(R)} = f_{1} \exp \left( \frac{(\log R - \log R_{c})^{2}}{2\sigma_{1}^{2}} \right),
\end{equation}

where \(f_{1}=0.26\), \(\sigma_{1}=0.23\) dex, and \(R_{c}=116.0\) kpc are the amplitude, characteristic log-width, and centroid of the transitional component, respectively. The best-fitting function is shown as the dashed curves in both panels of Figure 7.

4.4 Stellar Mass Budget of Clusters

With the physical decomposition in Figure 7, we are now ready to derive the stellar mass budget of clusters in three states: BCG (i.e., de Vaucouleurs + transitional), ICL, and satellite galaxies. In order to estimate the total amount of stellar mass inside the satellite galaxies, we make use of the conditional stellar mass function (CSMF) of clusters inferred by Yang et al. (2012). In particular, we adopt the shape of the measured CSMF for their halo mass bin of \(10^{14.2} - 10^{14.5} h^{-2} M_{\odot}\) (c.f., column 9, table 7 of Yang et al. 2012), which can be described by a Schechter function

\begin{equation}
\frac{dN(M_{*}|M_{h})}{d\log M_{*}} = \Phi^{*} \left( \frac{M_{*}}{M^{*}} \right)^{\alpha+1} \exp \left( \frac{-M_{*}}{M^{*}} \right)
\end{equation}

with \(M^{*}=8.32 \times 10^{10} M_{\odot}\) and \(\alpha=-1.093\). However, the Yang et al. CSMF was measured for a sample of galaxy groups at \(z<0.1\), which has a different value of \(\Phi^{*}\) that than of our cluster sample at \(z>0.25\). To determine \(\Phi^{*}\), we obtain the number of satellite galaxies above...
Figure 9. Stellar mass budget of our cluster sample in BCG, ICL, and satellites. Gray filled and hatched portions indicate the contributions from the transitional component and the unmasked satellite galaxies, respectively. The stellar mass fraction (left y-axis) and stellar-to-halo mass fraction (right y-axis) of each component are marked by the percentage values out and inside the parentheses, respectively. The horizontal line indicates the total stellar-to-halo mass fraction of the clusters $M_{*}/M_h$. Assuming a halo mass of $2.57\times10^{14} M_\odot$ measured from weak lensing in Z21. Assuming further that the total baryon fraction of the clusters is the cosmic value $f_b=\Omega_b/\Omega_m\approx16\%$, we can infer that $\sim88\%$ of the baryons are in the form of hot gas within clusters. For the stellar mass budget, $83.5\%$ of the stellar mass is inside the satellite galaxies and $8.4\%$ is in the BCG, leaving $8.1\%$ of the stellar mass in the diffuse form of free-floating ICL stars — hence stellar-to-halo mass ratios of $1.531\%$ (satellites), $0.155\%$ (BCG), and $0.148\%$ (ICL). Using the DES imaging, Zhang et al. (2019) estimated that the luminosity fraction of BCG+ICL is $44\% \pm 17\%$, but they did not subtract the contribution from undetected satellites. In our stellar mass budget, the sum of the stellar fraction of the BCG+ICL and undetected satellites is about $21\%$, comparable to the lower end of the Zhang et al. (2019) estimation.

5 BCG SPHERE OF INFLUENCE: DETECTING $R_{SOI}$

Although we tentatively assign the transitional component to the BCG in Figure 9, it is unclear whether this stellar mass excess is primarily tied to the BCG or the richness. Despite accounting for $\sim1\%$ of the total stellar mass, this transitional component is key to solving the sphere of influence of the BCGs $R_{SOI}$. In particular, if the excess mass is primarily richness-induced, we expect $R_{SOI}$ to stop at $R_{1}\times10^{-07} = 70$ kpc; but a BCG-induced origin would extend $R_{SOI}$ beyond the transitional component at $R_{1}\times10^{-07} = 200$ kpc. In this section, we divide our overall cluster sample into two subsamples of different average BCG stellar mass $M_{BCG}$ at fixed satellite richness $\lambda$, and aim to distinguish the two physical scenarios by comparing the two sets of diffuse light and mass profiles.

5.1 Cluster Subsamples Split by $M_{BCG}$

Following Z21, we split the clusters into two subsamples using the median $M_{BCG}$-$\lambda$ relation, illustrated by the top left panel in Figure 10. In particular, the median $M_{BCG}$-$\lambda$ relation (solid line) can be described by

$$\langle \lg M_{BCG} \rangle = 0.45 \lg \lambda + 10.86, \quad (11)$$

dividing the clusters into two halves with the same distribution of satellite richness $\lambda$, which we refer to simply as the “high-$M_{BCG}$” and “low-$M_{BCG}$” subsamples for the rest of the paper. By applying the methods described in §3 and §4, we measure the BCG+ICL surface brightness profile $\mu^{B+I}$ (top middle panel) and stellar surface mass profile $\Sigma_{B+I}$ (top right panel) for each of the two subsamples.

In the top middle panel of Figure 10, solid and dashed curves indicate the $\mu^{B+I}(R)$ profiles of the high and low-$M_{BCG}$ subsamples, respectively, in the SDSS g (green), r (red), and i (maroon) bands. By construction, the $\mu^{B+I}(R)$ profile of the high-$M_{BCG}$ subsample is $\sim0.73$ magnitudes (in the r and i bands, $\sim0.65$ magnitudes in the g band) brighter than that of the low-$M_{BCG}$ one on scales below the effective cModel aperture, i.e., $R_{e}=50$ kpc, because the average $M_{BCG}$ of the two subsamples differ by $\sim0.34$ dex. However, the small-scale discrepancy between the two subsamples persists on scales much larger than $R_{e}$, and the two sets of $\mu^{B+I}$ profiles do not converge within the uncertainties until $R\sim300$ kpc. Likewise, the two $\Sigma_{B+I}$ profiles in the top right panel exhibit a significant discrepancy on scales as large as $R\sim200$–$300$ kpc, beyond which they start to converge to the same level of stellar surface mass density.

The comparison between the two $\Sigma_{B+I}$ profiles is better illustrated in the bottom of the top right panel of Figure 10, where we show the $\Sigma_{B+I}$/4 ratios of the high (red solid) and low (blue dashed) $M_{BCG}$.
Figure 10. Distributions of clusters on the $\lambda$ vs. $M_{BCG}^*$ plane (left), surface brightness profiles (middle), and stellar surface density profiles (right) of cluster subsamples split by $M_{BCG}^*$ (top row) and $\lambda$ (bottom row). Top left: Circles show the median of $\lg M_{BCG}^*$ at fixed $\lg \lambda$, and black solid line is a linear fit to median relation, which divides the clusters into low and high-$M_{BCG}^*$ subsamples. Top middle: Surface brightness profiles $\mu_B^{B+I}$ of the low (dashed curves) and high (solid curves) $M_{BCG}^*$ subsamples. Green, red, and maroon curves indicate the measurements from $g$, $r$, and $i$-band images, respectively. Top right: Stellar surface density profiles $\Sigma_B^{B+I}$ of the low-$M_{BCG}^*$ (blue dashed), high-$M_{BCG}^*$ (red solid), and all (gray dot-dashed) clusters. The bottom subpanel shows the ratios of the $\Sigma_B^{B+I}$ profiles of the low (blue dashed) and high (red solid) $M_{BCG}^*$ subsamples over that of the overall sample. Dotted vertical line indicates $R_{SOI}=200$ kpc. The panels in the bottom row are similar to those in the top, but for subsamples split by $\lambda$ at fixed $M_{BCG}^*$.

Figure 11. Left: Stacked 2D image of the high-$M_{BCG}^*$ clusters, with the pixel SB colour-coded by the vertical colourbar on the right. Solid and dashed circles indicate the cluster characteristic radius ($r_s=227.8$ kpc) and BCG sphere of influence ($R_{SOI}=200$ kpc), respectively. Middle: Similar to the left panel, but for the low-$M_{BCG}^*$ clusters with $r_s=269.7$ kpc. Right: The difference image between the high and low-$M_{BCG}^*$ clusters. Clearly, the region outside $R_{SOI}$ (dashed circle) is largely consistent with zero. A smoothing kernel of 15 pixels is applied to the three images.
subsamples over the overall sample. The discrepancy between the two ratio profiles is more than a factor of two across all scales below $R=100$ kpc and declines slowly on larger scales, but still strongly persists at $>50\%$ level at $R\sim200–300$ kpc. Not until distances exceed $R\sim300$ kpc do the two ratio profiles begin to converge to unity (albeit with large errorbars).

Such discrepancy observed between the two subsamples provides a clear detection of the BCG sphere of influence. Since the two subsamples of clusters have the same richness and differ solely in their BCG stellar mass, the clear transition from the constant discrepancy below $R=100$ kpc to the apparent convergence above 300 kpc in the top right panel of Figure 10 demonstrates that the BCG sphere of influence extends to scales around $R_{\text{SOI}}\simeq200$ kpc. Interestingly, such transition at $R_{\text{SOI}}$ coincides with the radial extent of the transitional stellar mass component revealed by the $\Sigma^{B+I}_{2-1}$ decomposition in §4.3, i.e., $R_{\text{SOI}}\approx R_s\times10^{\gamma_1}$, suggesting a common origin of the two observed “transitions”. In particular, the excess diffuse light on scales between $R_s$ and $R_{\text{SOI}}$ could be primarily formed via processes that simultaneously enriched the BCG, likely due to the tidal disruption/stripping of satellites during periapsis and the violent relaxation after major mergers between the BCGs and satellites. Furthermore, the convergence of the two $\Sigma^{B+I}_{2-1}$ profiles on scales above 300 kpc confirms our expectation that the ICL in the outer region of clusters largely follows the distribution of satellite galaxies, hence that of the dark matter.

The bottom panels of Figure 10 shows the results of a similar experiment as in the top panels, but by dividing the 2D stacked $r$-band images between high- and low-$\lambda$ subsamples by $\lambda$ at fixed $M^{BCG}$ (bottom left panel). As expected, the two sets of $\mu^{B+I}$ and $\Sigma^{B+I}_{2-1}$ profiles are consistent on scales below $R_s\approx50$ kpc, the aperture of our $M^{BCG}$ measurements. The two subsamples start to differ on scales above $R_s$, exhibiting a 20% discrepancy on scales below 100 kpc, much weaker than the factor of two discrepancy between the two $M^{BCG}$ splits. The two $\Sigma^{B+I}_{2-1}$ profiles do not reach a discrepancy comparable to that exhibited by the $M^{BCG}$ splits until 200 kpc at 50%. This suggests that the diffuse light at 200 kpc has equal contributions from the BCG vs. satellites, further corroborating our conclusion that the BCG sphere of influence ends at $R_{\text{SOI}}\simeq200$ kpc. On scales between $R_s$ and $R_{\text{SOI}}$, the discrepancy between the low and high-$\lambda$ clusters is significantly smaller than that between the two $M^{BCG}$-split halos, indicating that the influence of satellite richness is subdominant compared to the BCG on those transitional scales — they are firmly within the sphere of influence of the BCG.

Figure 11 provides a more visually-appealing way of comparing the diffuse light distributions between the low and high-$M^{BCG}$ subsamples. In particular, we compare the 2D stacked $r$-band images of the high-$M^{BCG}$ (left) and low-$M^{BCG}$ (middle) subsamples, with the difference image between the two shown in the right panel. The SB values, in the unit of nanomaggies per arcsec$^2$, are computed with a smoothing kernel of 15 pixels, indicated by the colourbar on the right. Solid circles in the left and middle panels indicate the characteristic radii $r_s$ of the high ($r_s=227.8$ kpc) and low ($r_s=269.7$ kpc) $M^{BCG}$ clusters, respectively, inferred from weak lensing modelling by Z21. Dashed circle in each panel indicates the BCG sphere of influence with $R_{\text{SOI}}=200$ kpc. Consistent with 1D profiles in the top panels of Figure 10, the high-$M^{BCG}$ clusters exhibits a more enhanced surface brightness distribution than the low-$M^{BCG}$ systems on scales below $R_{\text{SOI}}$, but the two images are almost indistinguishable on scales above $\sim300$ kpc — the difference image is consistent with having zero SB at $R>300$ kpc.

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**Figure 12.** Similar to the top right panel of Figure 10, but with measurements for cluster subsamples split by $M_{*,20\text{kpc}}$ (stellar mass measured within a 20 kpc-aperture; dashed curves) and for clusters with the BCG centring probability $p_{\text{cen}}>0.85$ (dotted curves). Inset panel shows the $p_{\text{cen}}$ distributions of the low (blue histograms) and high (red histograms) $M^{BCG}$ subsamples, with the vertical dashed line indicating our $p_{\text{cen}}=0.85$ cut.

5.2 Systematic Tests Against Stellar Mass Aperture and BCG Centering Probability

The key conclusion of our paper, that the BCG sphere of influence extends to a characteristic radius of $R_{\text{SOI}}=200$ kpc, is based on the experiment of §5.1. However, the experiment could be affected by systematic uncertainties associated with the aperture of our stellar mass estimates or the miscentring effect in the redMaPPer cluster finding algorithm (Johnston et al. 2007; Oguri & Takada 2011; Rozo & Rykoff 2014; Hollowood et al. 2019). For example, although the effective aperture of $M^{BCG}$ is $R_s=50$ kpc, the individual apertures of some of the nearby, bright systems could be larger, thereby artificially pushing the discrepancy between the $\Sigma^{B+I}$ of high and low-$M^{BCG}$ subsample to larger radii. For miscentring, the average centring probability $p_{\text{cen}}$ of the low-$M^{BCG}$ clusters is lower (e.g., due to projection effects; see Zu et al. 2017), and is thus more likely to have satellite galaxies misidentified as centrals than their high-$M^{BCG}$ counterparts. Consequently, it is plausible that the $\Sigma^{B+I}_{2-1}$ of the low-$M^{BCG}$ subsample is heavily underestimated on small scales due to the lack of extended stellar envelope surrounding those misidentified centrals.

To investigate the impact of different stellar mass apertures, we repeat the experiment of §5.1 by adopting $M_{*,20\text{kpc}}$, the stellar mass measured within a fixed aperture of 20 kpc. By splitting the clusters into two subsamples of different $M_{*,20\text{kpc}}$ at fixed $\lambda$, we eliminate the possibility that the high-$M^{BCG}$ subsample may preferentially select the more extended BCGs. The result of this test is shown as the red (high-$M_{*,20\text{kpc}}$) and blue (low-$M_{*,20\text{kpc}}$) dashed curves in Figure 12. The $\Sigma^{B+I}_{2-1}$ of the high-$M_{*,20\text{kpc}}$ subsample is $\sim3\%$ lower than that of the high-$M^{BCG}$ clusters on scales below 200 kpc, and vice versa for the low-$M_{*,20\text{kpc}}$ subsample. Overall, the discrepancy between the $\Sigma^{B+I}_{2-1}$ profiles of the two subsamples split by $M_{*,20\text{kpc}}$...
is very similar to our fiducial measurement split by $M_B^{\text{BCG}}$ (solid curves), consistent with the BCG sphere of influence extending to $R_{\text{SOI}}=200\text{kpc}$.

To test the miscentring effect, we measure the $p_{\text{cen}}$ distributions of the BCGs of the high (red histograms) and low (blue histograms) $M_B^{\text{BCG}}$ subsamples in the inset panel of Figure 12. Both $p_{\text{cen}}$ distributions peak at $p_{\text{cen}}$ close to 100%, but the distribution of the low-$M_B^{\text{BCG}}$ clusters indeed exhibits a longer low-$p_{\text{cen}}$ tail. To eliminate the impact of low-$p_{\text{cen}}$ systems on our $R_{\text{SOI}}$ measurement, we remove clusters with the $p_{\text{cen}}$ of their BCGs lower than 85%, shown as the vertical dashed line in the inset panel, and repeat the experiment using the $M_B^{\text{BCG}}$-split subsamples. The results of the miscentring test are shown by the red and blue dotted curves for the high and low-$M_B^{\text{BCG}}$ clusters with BCG $p_{\text{cen}}>85\%$, respectively. Again, we do not find any significant deviation from our fiducial measurements due to the exclusion of the low-$p_{\text{cen}}$ systems. Therefore, based on the two systematic tests shown in Figure 12, we conclude that the detection of $R_{\text{SOI}}=200\text{kpc}$ is robust against the aperture size of the BCG stellar mass estimates and the level of miscentring in the SDSS redMaPPer catalogue.

5.3 Connection between BCG Sphere of Influence and Halo Concentration

As mentioned in the Introduction, Z21 modelled the weak lensing measurements of the two subsamples split by $M_B^{\text{BCG}}$ at fixed $\lambda$, and found that the two have the same average halo mass, but the average halo concentration of the high-$M_B^{\text{BCG}}$ clusters is ~10% higher than that of the low-$M_B^{\text{BCG}}$ systems (for a thorough explanation of such observation, see Zu et al. (2022)). Z21 speculated that the strong correlation between halo concentration and $M_B^{\text{BCG}}$ could be induced at the early phase of halo growth, when the fast accretion and frequent mergers not only built the characteristic central regions of the cluster haloes, but also fuel the in situ stellar growth of the BCGs. Interestingly, the characteristic radii $r_s$ inferred by Z21 are ~200–300 kpc, in good agreement with our constraint of $R_{\text{SOI}}$ in this paper.

Such similarity between the values of $r_s$ and $R_{\text{SOI}}$ is likely physical. In the vicinity of the BCGs, stars could be tidally disrupted/striped from satellites after periapsis passage or ejected after BCG-satellite major mergers. Most of those stray stars cannot escape to larger radii due to the relatively high escape velocities within $r_s$. Therefore, a fraction of them would fall back onto the BCGs and grow $M_B^{\text{BCG}}$, while the rest stays unbound to the BCGs and form the transitional component $\Sigma_{\text{tran}}$, which is however well confined within $r_s$, hence the BCG sphere of influence $R_{\text{SOI}}$. In this scenario, the BCG sphere of influence is primarily shaped by the growth of the BCG, but helped maintained by the concentration of the dark matter halo. Therefore, we expect that $R_{\text{SOI}}$ increases with the growth of $M_B^{\text{BCG}}$, but should always stay within the characteristic radius of the halo $r_s$.

We present a comprehensive comparison between the low (blue squares) and high (red circles) $M_B^{\text{BCG}}$ subsamples in their BCG+ICL stellar surface density profiles $\Sigma_{\text{B+I}}$ (left), weak lensing profiles $\Delta \Sigma$ (middle), and galaxy surface number density profile $\Sigma_g$ (right) in Figure 13. The left panel is similar to Figure 7, but with our decomposition method applied to the two subsamples separately. Since we adopt the same $\gamma=1/446$ as for the overall sample, the discrepancy in the total surface matter density profiles $\gamma \Sigma_m$ between the two subsamples below 200 kpc is entirely due to the different halo concentrations. After subtracting the inner de Vaucouleurs’ profile and the outer scaled matter surface density profile from each $\mu_{\text{B+I}}$ profile, the transitional component $\Sigma_{\text{tran}}(r)$ emerges as the filled symbols with errorbars that we fit using Equation 9 (dashed curves).

Focusing on the $\Sigma_{\text{tran}}(r)$ profiles in the left panel of Figure 7, we detect a shift of 26 kpc in the centroid from the low-$M_B^{\text{BCG}}$ subsample ($R_s=92\text{kpc}$) to the high-$M_B^{\text{BCG}}$ subsample ($R_s=118\text{kpc}$), while the two log-widths are comparable ($\sigma_r=0.22$ and 0.25 dex for low and high-$M_B^{\text{BCG}}$ subsamples, respectively). Assuming $R_{\text{SOI}}=R_s=10^{11}\sigma_r$, $R_{\text{SOI}}$ increases with $M_B^{\text{BCG}}$ from $R_{\text{SOI}}^{\text{low}}=153\text{kpc}$ to $R_{\text{SOI}}^{\text{high}}=210\text{kpc}$. Moreover, the integrated mass within the transitional component $\Sigma_{\text{tran}}$ of the high-$M_B^{\text{BCG}}$ subsample is $8.5\times10^{10}M_\odot$ ($f_r=0.29$), about 0.48 dex higher than that of the low-$M_B^{\text{BCG}}$ subsample with $2.8\times10^{10}M_\odot$ ($f_r=0.24$) — slightly larger than the 0.34 dex difference between average $M_B^{\text{BCG}}$.

The middle panel of Figure 13 is similar to the Figure 5 of Z21, showing the weak lensing comparison between the two subsamples. We include the weak lensing signals predicted on small scales by the de Vaucouleurs’ profiles of the BCGs (dotted curves) in the prediction of the total $\Delta \Sigma$ (dashed curves). The 10% difference in halo concentration is manifested by the discrepancy between the two $\Delta \Sigma$ profiles on scales between 100 kpc and 500 kpc, which then translates to the discrepancy in their total surface matter density profiles $\Sigma_m$ below 200 kpc in the left panel. We compare the two galaxy surface number density profiles in the right panels of Figure 13 (similar to the right panel of Figure 6 in Z21). Clearly, the galaxy distributions around the BCGs of the two subsamples are almost indistinguishable, further corroborating our conclusion that the differences in $\Sigma_{\text{B+I}}$ (left) and $\Delta \Sigma$ (middle) are tied solely to the discrepancy in $M_B^{\text{BCG}}$ and/or halo concentration.

6 CONCLUSION

In this paper, we have measured the stacked BCG+ICL surface brightness profiles $\mu_{\text{B+I}}(r)$ in the SDSS $\text{gri}$ bands for a sample of ~3000 clusters detected between $0.2<z<0.3$ from SDSS DR8 imaging. Adopting an empirically calibrated mass-to-light relation, we convert the three-band $\mu_{\text{B+I}}$ profiles to the diffuse stellar surface density profile $\Sigma_{\text{B+I}}(r)$. By comparing the $\Sigma_{\text{B+I}}$ profile with the cluster weak lensing profile, we find that the ICL on scales $r>400$ kpc can be well described by the projected dark matter density profile $\Sigma_m$ multiplied by the ICL-to-halo mass ratio of 1/675.

Further assuming that the inner BCG follows the de Vaucouleurs’ law, we develop a physically-motivated method to decompose $\Sigma_{\text{B+I}}(r)$ into three components, including an inner de Vaucouleurs’ profile, an outer ICL that follows the dark matter, and a third excess component at the transitional scales between 70 kpc and 200 kpc. We find that the ratio between this transitional component $\Sigma_{\text{tran}}$ and $\Sigma_{\text{B+I}}$ can be well described by a Gaussian function that peaks at $R_s=116$ kpc with a logarithmic dispersion of $\sigma_r=0.23$ dex. After correcting for mass incompleteness using the conditional stellar mass function of satellites measured by Yang et al. (2012), we infer the stellar mass budget of the clusters in three states as: the BCG (8.4%); de Vaucouleurs + transitional), the satellites (83.5%), and the diffuse ICL that follows the dark matter distribution (8.1%). By measuring the weak lensing halo mass as $2.57\times10^{14}M_\odot$, the stellar-halo mass fractions are 1.531% (satellites), 0.155% (BCG), and 0.148% (ICL), leading to a total stellar-to-halo fraction of 1.834%.

The transitional component $\Sigma_{\text{tran}}$ is the key to solving the radius of the BCG sphere of influence $R_{\text{SOI}}$ in the diffuse cluster light — $R_{\text{SOI}}$ could be well within $R_s=10^{10}\sigma_r~70$ kpc if $\Sigma_{\text{tran}}$ is induced by the interaction between satellite galaxies and the cluster potential, or extend to $R_s=10^{10}\sigma_r~200$ kpc if $\Sigma_{\text{tran}}$ is tied to the BCG growth.
Figure 13. Left: BCG+ICL stellar surface density profiles \( \Delta \Sigma^\text{B+I} \) of the low (blue open squares) and high (red open circles) \( M_{\text{BCG}} \) subsamples. Solid and dotted curves are the best-fitting scaled matter density and de Vaucouleurs’ profiles on relevant scales, respectively. Blue filled squares and red filled circles indicate the transitional components of the low and high-\( M_{\text{BCG}} \) clusters, respectively, while the dashed curves are predictions from the best-fitting Equation 9. Middle: Weak lensing profiles \( \Delta \Sigma \) of the low (blue open squares) and high (red open circles) \( M_{\text{BCG}} \) subsamples. Solid curves are the predictions by the best-fitting \( \Delta \Sigma \) models described in Z21. The two \( \Delta \Sigma \) models have the same halo mass, but the average halo concentration of the high-\( M_{\text{BCG}} \) subsample is \( \sim 10\% \) higher than that of the low-\( M_{\text{BCG}} \) clusters. Dotted curves indicate the predicted \( \Delta \Sigma \) signal induced by the respective de Vaucouleurs’ profiles shown in the left panel, and each dashed curve is the sum of the dotted and solid curves of the same colour. Right: The galaxy surface number density profiles \( \Sigma_g \) of the low (blue open squares) and high (red open circles) \( M_{\text{BCG}} \) subsamples. The two measured profiles are consistent with each other on all scales.

To distinguish the two physical scenarios, we divide the clusters into two subsamples by their BCG stellar mass \( M_{\text{BCG}} \) (with an effective aperture of \( \sim 50 \) kpc) at fixed satellite richness \( \lambda \), and compare their BCG+ICL surface brightness and stellar density profiles. Surprisingly, we discover that the two \( \Sigma_{B+I}^\text{B+I} \) profiles differ significantly on all scales below \( R \sim 200 \) kpc, before converging to the same amplitude on larger scales.

From the weak lensing and cluster-galaxy cross-correlations in Z21, we show that the two subsamples have the same average halo mass as well as the same satellite number density profile, but differ only in their average BCG stellar mass. Therefore, the observed discrepancy between the two \( \Sigma_{B+I}^\text{B+I} \) profiles signals a detection of the BCG sphere of influence at \( R_{\text{SIO}} \sim 200 \) kpc. We test the sensitivity of our experiment to the aperture size of stellar mass measurements as well as the miscentring effect of the optical clusters, and demonstrate that \( R_{\text{SIO}} \sim 200 \) kpc is robust against the two systematic uncertainties in the experiment.

Weak lensing measurements also suggest that the high-\( M_{\text{BCG}} \) clusters are \( \sim 10\% \) more concentrated than their low-\( M_{\text{BCG}} \) counterparts, suggesting that \( R_{\text{SIO}} \) is likely connected to the characteristic scale \( r_s \) of the NFW haloes. We speculate that the relatively high escape velocity profile within \( r_s \) may help confine the stray stars that break free of the BCGs, producing the excess mass at the transitional scales (Kelson 2002; Bender 2015; Veale 2018). Detailed kinematic analysis of the hydrodynamical simulations of cluster formation could be tremendously helpful for providing insight to the growth of the BCG sphere of influence, as well as an indirect check of the physical link between \( r_s \) and \( R_{\text{SIO}} \). Observationally, our work can be easily extended to the larger cluster catalogues (Zou et al. 2021; Wen & Han 2021; Yang et al. 2021) and deeper photometry (Huang et al. 2021; Li et al. 2021) from current stage-III imaging surveys. Future ground-based and space missions like the LSST, Euclid, Roman, and CSST with even larger cluster samples, deeper photometry, and sharper shear measurements will greatly enhance our capability of seeing cluster formation through the diffuse light.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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