An Investigation of Intracluster Light Evolution Using Cosmological Hydrodynamical Simulations

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Abstract

Intracluster light (ICL) in observations is usually identified through the surface brightness limit (SBL) method. In this paper, for the first time we produce mock images of galaxy groups and clusters, using a cosmological hydrodynamical simulation to investigate the ICL fraction and focus on its dependence on observational parameters, e.g., the SBL, the effects of cosmological redshift-dimming, point-spread function (PSF), and CCD pixel size. Detailed analyses suggest that the width of the PSF has a significant effect on the measured ICL fraction, while the relatively small pixel size shows almost no influence. It is found that the measured ICL fraction depends strongly on the SBL. At a fixed SBL and redshift, the measured ICL fraction decreases with increasing halo mass, while with a much fainter SBL, it does not depend on halo mass at low redshifts. In our work, the measured ICL fraction shows a clear dependence on the cosmological redshift-dimming effect. It is found that there is more mass locked in the ICL component than light, suggesting that the use of a constant mass-to-light ratio at high surface brightness levels will lead to an underestimate of ICL mass. Furthermore, it is found that the radial profile of ICL shows a characteristic radius that is almost independent of halo mass. The current measurement of ICL from observations has a large dispersion due to different methods, and we emphasize the importance of using the same definition when observational results are compared with theoretical predictions.

Key words: galaxies: clusters: general – galaxies: clusters: intracluster medium – galaxies: evolution – galaxies: statistics – methods: numerical – methods: observational

1. Introduction

The concept of intracluster light (ICL) or luminous intergalactic matter was first introduced by Zwicky (1951) during his studies on the Coma cluster. Most ICL is located in the cluster center and surrounds a brightness center galaxy or brightest cluster galaxy (BCG). It is thought to be the light from stars, which fills the intergalactic space in dense galaxy environments and bounds to the cluster potential but not to any individual galaxy. Observationally, ICL has been found in the local universe in locations such as Coma and the Virgo cluster (e.g., Mihos et al. 2005; Gonzalez et al. 2007; Arnaboldi & Gerhard 2010; Longobardi et al. 2013; Mihos et al. 2017), in clusters at intermediate redshift (e.g., Toledo et al. 2011; Melnick et al. 2012; Giallongo et al. 2014), and in some clusters at high redshift (e.g., Burke et al. 2012; Adam et al. 2013). Using large samples of clusters from low to intermediate redshift, such as SDSS (e.g., Zibetti et al. 2005; Budzynski et al. 2014), 2MASS (e.g., Lin & Mohr 2004), and CLASH (e.g., Burke et al. 2015), one can also obtain an ICL fraction by way of stacking the galaxies and center regions of galaxy clusters. These observations provide opportunities to explore the physical properties of ICL, such as age, metallicity, velocity, color, and spatial distribution (e.g., Arnaboldi 2004; Arnaboldi & Gerhard 2010; Montes & Trujillo 2014; Presotto et al. 2014; Mihos 2016).

The ICL is now widely regarded as an important component of galaxy clusters. Its accurate determination has important implications for the mass of bright cluster galaxies that may alter the measured shape of stellar mass functions or luminosity functions at the massive end (e.g., Li & White 2009; Bernardi et al. 2013; He et al. 2013; D’Souza et al. 2015). Therefore, it can be used as an important ingredient to constrain the theoretical model of galaxy formation (e.g., Contini et al. 2017). However, studies of how an ICL fraction evolves with halo mass and redshift are far from conclusive because of the different methods used in observations and the difficulty of obtaining data for intermediate- or high-redshift clusters.

As it is difficult to analyze the formation and evolution history of ICL directly from observational results, a more feasible approach is to investigate the problem using simulations. Inspired by the early work of Merritt (1984), who used numerical simulations to first show that ICL was formed by stars stripped from merging galaxies in clusters, numerous works using N-body and hydrodynamical simulations have been devoted to studying the formation and properties of ICL (e.g., Murante et al. 2004, 2007; Willman et al. 2004; Sommer-Larsen et al. 2005; Rudick et al. 2006, 2009, 2011; Tutukov et al. 2007; Barai et al. 2009; Dolag et al. 2010; Puchwein et al. 2010; Cui et al. 2014). These theoretical studies partly confirmed that the major of ICL is formed by dynamical stripping, and its physical properties vary for different dark matter halos. However, the ICL fraction drawn from numerical simulations is significantly higher than that from observations and depends on the dynamical models (e.g., Puchwein et al. 2010). Meanwhile, the lack of consistent methods for measuring ICL have also hampered comparisons between simulations and observations.
By using an analytical description of how stars are stripped from member galaxies falling into a cluster, the ICL can also be estimated from the semi-analytical models based on the cluster formation history (e.g., De Lucia et al. 2004; Martel et al. 2012; Contini et al. 2014). These theoretical studies generally found that the ICL fraction is closely related to the cluster formation history and it increases steadily with time, with the present fraction varying from 10% to 50% in clusters (Murante et al. 2004). Considering the multiple parameters used and the lack of cluster galaxy population, a semi-analytical model can hardly obtain accurate statistics of ICL properties. 

So far, there are still great discrepancies between results from different methods. For example, Murante et al. (2004) found that massive simulated clusters have a larger fraction of stars in diffuse light than low-mass ones, while no dependence on halo mass in reported by Puchwein et al. (2010). The difference between these two studies is whether to include AGN feedback in the simulations.

Indeed, it can be seen that the ICL is the remaining component, except for cluster member galaxies, for which the main problem and difficulty turn out to be the method of defining galaxies within a dark matter halo, especially the brightest central galaxy. For example, in some studies galaxies were defined as distinct stellar groups using the friends-of-friends (FoF) algorithm with an arbitrary linking length. Hence, the linking length largely decides galaxy size and the remaining ICL. Improvements have been made to include only gravitationally bound stellar particles to galaxies (e.g., Dolag et al. 2010; Puchwein et al. 2010). This dynamical method looks more physical, however, it is not directly applicable to compare with observational results.

Contrary to the relatively straightforward dynamical method mentioned above (see also Cui et al. 2014), the observational estimate of the ICL fraction is much more difficult and there is no consensus on how to find a robust way to identify ICL (e.g., Feldmeier et al. 2004c; Zibetti et al. 2005). In the literature, there are three primary definitions of ICL:

The ICPNs METHOD. Intracluster planetary nebulae (ICPNs), intracluster red giant branches (IC RGBs), and globular clusters (GCs) can be used as tracers of ICL in observations (e.g., Williams et al. 2007; Sand et al. 2008; Castro-Rodríguez et al. 2009; Mihos et al. 2009; Peng et al. 2011; Ventimiglia et al. 2011; Longobardi et al. 2013). This method can provide more accurate measurement of ICL. However, it requires deep observations and is often applied to close targets, such as the Virgo and Coma cluster in the local universe.

The SB PROFILE or 0.25 $R_{vir}$ METHOD. These methods distinguish ICL from cluster galaxies using the difference in their intrinsic properties, such as the kinematic properties (e.g., Rudick et al. 2011; Cui et al. 2014), the surface brightness (SB) profile (e.g., Jee 2010; Melnick et al. 2012; Giallongo et al. 2014), spatial distribution (e.g., Krick & Bernstein 2007; DeMaio et al. 2015), or mass distribution (e.g., Rudick et al. 2009) in observations and simulations. These methods are normally used for clusters at low and median redshifts in observation.

The SB LIMIT METHOD. This method directly defines the light from stars as diffuse light, which is fainter than a characteristic surface brightness limit (SBL) in the observed images (e.g., Puchwein et al. 2010; Presotto et al. 2014). This method can be applied to objects at any redshift. It is a simple and straightforward method to estimate the ICL fraction if deep optical images can be obtained from observational facilities.

These above definitions of ICL are quite different and they are often applied to targets at different redshifts with different observational depths. Therefore, it is not surprising that large discrepancies on the ICL fraction have been found and controversial conclusions have then been made. In some cases, ICL is also referred to as the diffuse (unbound) stellar component (DSC). Note that the definition of DSC is a more physical one, while the ICL is not necessarily only from unbound stars, depending strongly on the methods used to define ICL.

Combined with the fact that observational works and theoretical studies often use different definitions of ICL, the comparison between data and model predictions is complicated and not reliable. To fully understand the formation and abundance of ICL, we need consistent comparisons between observations and theoretical models, which can be achieved only through mock observation, i.e., applying observational definitions of ICL to simulated galaxy clusters. Cui et al. (2014) used simulated galaxy clusters to compare the fraction of ICL between two different definitions, one following a physical definition of ICL that separates the ICL from the BCG through fittings of double-velocity-dispersion distributions of their star particles, and the other mimicking the observational processing that defines ICL through the SB limit method. They found that the two methods produce an ICL fraction with a factor of 2–4 depending on the gas physics implemented in the simulation.

In this work we utilize a cosmological hydrodynamical simulation to identify ICL in the halos of galaxy groups and clusters. Similar to Cui et al. (2014), the SB limit method is applied to define ICL and the mock “galaxy” images are produced, where “galaxy” refers to simulated galaxy. To mimic observations more realistically, we make the improvement of additionally considering the CCD pixelation, the smoothing effect by the point-spread function (PSF), and the cosmological redshift-dimming effect. Basically, our main goal is to investigate the various selections and systematic effects used in the SB limit method when measuring ICL, rather than comparison with current observations (which will still be discussed) or other theoretical predictions. This work can serve as an understanding of the measured ICL fraction and its dependence on observational selection effects, and the predicted trends can also be tested using future observations.

This paper is organized as follows. In Section 2 we introduce the simulation data and the methods to produce mock “galaxy” images are given in Section 3. We present the main results in Section 4 and the comparison between ICL from different observations is given in Section 5. Finally, our conclusions and a discussion are given in Section 6.

2. Simulation

In this work, we utilize a cosmological simulation run with the massive parallel N-body code GADGET-2 (Springel 2005). The simulation is evolved from redshift $z = 120$ to the present epoch in a cubic box of $100 h^{-1}$ Mpc with 512$^3$ particles for both dark matter and gas particles, respectively. We use a flat $\Lambda$CDM “concordance” cosmology with $\Omega_{m} = 0.268$, $\Omega_{\Lambda} = 0.732$, $\sigma_8 = 0.85$, and $h = 0.71$. A Plummer softening length of 4.5 kpc is adopted in the simulation. In our simulation each dark matter particle has a mass of $4.62 \times 10^8 h^{-1} M_{\odot}$, and the
initial mass of gas particles is $9.20 \times 10^7 \, h^{-1} M_\odot$, which can be turned into two star particles later on. The simulation includes the processes of radiative heating and cooling, star formation, supernova feedback, outflows by galactic winds, and metal enrichment, as well as a sub-resolution multiphase model for the interstellar medium. This model is implemented using smoothed particle hydrodynamics, and enables us to achieve a wide dynamic range in simulations of structure formation. The star formation timescale in the quiescent model for star formation is directly determined form observations of galaxies, we follow a similar procedure as in Cui et al. (2011, 2014). Each star particle of the FoF group is treated as a simple stellar population such as, for example, the Sloan instrument, which is model the effect of PSF. The original image is then convolved with a 2D PSF kernel for a typical image survey instrument and without weights of both either luminosities or stellar masses. The surface brightness for each pixel is given by

$$
\mu_\lambda = -2.5 \log \frac{I_\lambda}{L_{\odot,\lambda} \cdot \text{pc}^{-2}} + 21.572 + M_{\odot,\lambda},
$$

where $I_\lambda$ is

$$
I_\lambda = \frac{L_\lambda}{\pi^2 D^2 (1+z)^{-4}}.
$$

Here, $\lambda$ indicates different filter bands at rest-frame (cf. Mo et al. 2010), and $M_{\odot,\lambda}$ is the absolute solar magnitude, which are 5.36, 4.80, 5.12, 4.64 mag arcsec$^{-2}$ (Blanton & Roweis 2007) for the B, V, SDSS g, SDSS r bands in the AB system, respectively. In the above equation, the surface brightness is dimmed by a factor of $(1+z)^{-4}$ and it is verified that such a dimming is real in an expanding universe (e.g., Sandage & Lubin 2001). In Section 4.2, we will discuss the results of the ICL fraction without this dimming effect.

To mimic the observed image of “galaxies,” we need to model the effect of PSF. The original image is then convolved with a 2D PSF kernel for a typical image survey instrument such as, for example, the Sloan instrument, which is represented by a 51 x 51 matrix. For groups with grid numbers less than 51 x 51, we provide empty grids to meet this grid number. With a given width $\omega$, the PSF kernel is given by a 2D Gaussian distribution,

$$
f(\chi, \psi) = \frac{1}{2\pi\sigma^2} e^{-\frac{1}{2} \left( \frac{(\chi-\chi_0)^2 + (\psi-\psi_0)^2}{\sigma^2} \right)},
$$

where $\sigma = \omega/\alpha$ and $\mu = 25$. For the results at different bands, both grid luminosity and mass are smoothed by applying this process.

In Figure 1, we illustrate the rest-frame surface brightness maps in each band with (right panels) and without (left panels) the PSF smoothing. This halo is the most massive one from our simulation at $z = 1.108$. An angular pixel size of $\alpha = 0\farcs396$ and a PSF width of $\omega = 1\farcs43$ are adopted as fiducial parameters for a reference. Note that there is no particular reason to choose these parameters and they are just taken from the SDSS DR7 data. Here, only pixel surface brightnesses brighter than 30 mag arcsec$^{-2}$ are shown in the figure. The two maps share the same color gradients, as indicated by the color bars. It is clear that the PSF convolution produces a much smoother map and lots of the discrete stellar light shown in the left panel disappears in the right panel (fainter than 30 mag arcsec$^{-2}$). This indicates that PSF smoothing has a significant impact on the ICL calculation when applying a realistic SBL.

After applying the above procedures, each grid of the mock image has a surface brightness. The ICL fraction is then defined as the ratio of the total luminosity of all grids with surface brightnesses fainter than a given limit at the x band, $\mu_{\lambda,\text{limit}}$, to the total luminosity in the galaxy group within the virial radius. It is also interesting to define another quantity as the intra cluster mass fraction, which is the ratio of all stellar mass in grids with surface brightnesses fainter than the limit, to the total.
stellar mass in the group. If a constant stellar mass-to-light ratio is assumed, the two definitions will be equal. However, this assumption is not often valid and it is worthwhile to check its influence on the estimation of the ICL fraction. We will later see that the ICL fraction in terms of light is lower than the stellar mass of the ICL component.

As galaxy luminosities vary with observational bands and the measured ICL fraction is usually made at a given band with a given magnitude limit, to compare the measured ICL fraction at different bands, it is important to know how to convert the SBL at different filters. As each galaxy has a different star formation history and metallicity, the color is different for different galaxies. To illustrate this effect, we use a simple SSP evolution model with metallicity $Z = 0.02 Z_e$ and a fixed stellar formation time at $z = 5$ to give the residual of SBL (relative to the $V$-band magnitude limit), as a function of the effective wavelength of 10 different bands at different redshifts. Figure 2 shows the dependence of brightness on observational bands and redshifts, where the $y$-axis represents the residual magnitude relative to the $V$-band magnitude. Different colors denote different redshifts. It is found that the residual is a function of wavelength and redshift. After applying the conversion between different bands, the ICL fractions measured at different bands are expected to converge, as we will see below for most results. However, as the stellar population in each “galaxy” is not as simple as the model used here, we will see some difference, which is expected. Note that the trend shown in Figure 2 is similar to that of Table 2 in Blanton & Roweis (2007).

4. Results

4.1. The Impacts of Pixel Size and PSF Width on ICL Fraction

The impacts of angular pixel size $\alpha$ and PSF width $\omega$ on the measured ICL fraction can be easily investigated using the mock images. In Figure 3 we show the measured ICL fraction as a function of halo mass for four different $\alpha$ (left panels) and four different $\omega$ (right panels) at a few redshifts. The results for different pixel sizes and PSF widths are shown by the curves in different colors, as indicated in the top left panels. Note that here we do not apply the cosmological redshift-dimming effect (with neglect of the $(1+z)^{-4}$ factor in Equation (5)) and only the results at the $V$ band with a fiducial SBL of $M_V = 26.5$ mag arcsec$^{-2}$ are shown. We have tested that the effects of $\alpha$ and $\omega$ have a very weak dependence on the adopted bands and the choice of SBL.

It is seen from the left panels of Figure 3 that the measured ICL fraction over all halo mass ranges and redshifts shows almost no difference from the four adopted pixel sizes $\alpha = 0''396 \sim 0''4, 1''0, 1''5, 2''0$. In the right panel, a larger PSF width $\omega$ tends to give a higher ICL fraction, and this effect...
is independent of both halo mass and redshift. It is also seen that the difference becomes smaller with larger \( \omega \).

Figure 3 shows that the influence of \( \omega \) is much more obvious than that of \( \alpha \). As surface brightness is in units of area, it is not surprising that pixel size has less influence on the ICL fraction for the highly clustered region because more particles will be assigned to the grid when the pixel size becomes larger, and eventually keep the surface brightness unchanged. On the other hand, \( \omega \) controls the width of the convolution kernel, i.e., the smoothing level of the image. Larger \( \omega \) will produce a smoother image, resulting in more pixels with lower surface brightness.\(^8\) This smoothing effect is more significant for diffuse or under-dense regions, such as low-mass halos and halos at high redshifts.

4.2. The Impact of SBLs on ICL Fraction

SBL is the simplest and most widely used method for identifying the ICL fraction. It is important to investigate its capability and limitations. Since the effects of pixel size and PSF width have been known from Figure 3, we fix \( \alpha = 0^\circ 396 \) and \( \omega = 1^\prime 43 \) in the following analysis and the cosmological redshift-dimming is also included in this section.

Appropriately, the magnitude limit and observational band are the main factors in the SBL method. In a few studies on observations and semi-analytical models, a faint SBL \( \mu_{\text{V,limit}} = 26.5 \, \text{mag arcsec}^{-2} \) is used to separate ICL from the galaxies (e.g., Vilchez-Gomez et al. 1994; Feldmeier et al. 2004c; Rudick et al. 2006, 2011; Zibetti 2008). Cui et al. (2014) used a slightly brighter magnitude limit with \( \mu_{\text{V,limit}} = 23.0, 24.7 \, \text{mag arcsec}^{-2} \) to make comparison between a dynamical method and SBL method. However, it is not clear how the results will be affected by these adopted values. In reference to these studies, in this paper we adopt three SBLs with \( \mu_{\text{V,limit}} = 23.0, 24.7, 26.5 \, \text{mag arcsec}^{-2} \) at rest-frame to distinguish the BCG and ICL components. For identifying ICL at other bands, we use the conversion factor given in Figure 2.

Again, we note that the conversion factor is from a very simple SSP model and it is not surprising that the measured ICL fractions at different bands will have slight differences.

Figure 4 shows the results of the measured ICL fraction as a function of halo mass at different redshifts. This figure contains two distinct features. First, by comparing different columns, it is not surprising to find that the ICL fraction increases with brighter SBL. This increase is weakly-dependent on both halo mass and redshift, and it is very similar at all bands. This increase of the ICL fraction is simply caused by the fact that when a brighter limit is applied, more stellar particles will be assigned to ICL. Second, groups at higher redshifts tend to have a higher ICL fraction for a given SBL. This result is mainly caused by the cosmological redshift-dimming (Equation (4)) and partly by the “galaxy” evolution itself, as a high-redshift “galaxy” is still forming with less stars (and thus fainter) compared to its counterpart at lower redshifts.

Therefore, it is not surprising to find that the measured ICL fraction reaches 100% at a high redshift with a brighter (not realistic) SBL.

With faint SBLs, e.g., \( \mu_{\text{V,limit}} = 26.5 \, \text{mag arcsec}^{-2} \), it is interesting to find that the ICL fraction does not depend on halo

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\(^8\) Note that the angular pixel size of a modern CCD is much smaller than the PSF width.
mass at low redshifts. This can be explained as follows. The stellar distribution of all halos at low redshift is similar and most of the stellar particles in very faint (outer) regions of halos have been counted as ICL components (see Figure 7). More importantly, the observational influence, i.e., the cosmological redshift-dimming and PSF effect, can be ignored because of the high stellar density within halos at low redshift, as can be demonstrated later in Figure 6. These facts cause the similar ICL fraction seen for all halos at low redshifts with faint SBL.

Figure 4 shows a major limitation of the SBL method for identifying ICL for which a very faint magnitude limit is needed; otherwise, all stars could be identified as ICL. It is also seen from the figure that a magnitude limit at the V band fainter than 26.5 is needed to identify the ICL for the group at \( z = 1 \).

By using the simple SBL conversion in Figure 2, we expect to obtain an approximately similar ICL fraction at other bands. However, the results for the \( r \) band seem to have a higher fraction than those of others. This indicates that the \( r \) band magnitude limit is brighter than that obtained from the conversion. One possible reason is that the simulated galaxies have a more extended star formation history and lower metallicity, thus the \( V - r \) color is bluer than that obtained from a simple SSP model with a star formation epoch at \( z = 5 \) with a metallicity of \( Z = 0.02 Z_\odot \).

In Figure 5, we show the ratio between the mass fraction locked in the ICL component to the light fraction in the ICL component. It is found that ICL fraction estimated from luminosity is systematically lower than that estimated from the
stellar mass. The difference is slightly bigger for fainter SBL and shows an obvious dependence on the redshift and halo mass. These differences indicate that there is more stellar mass locked in the ICL component due to the higher mass-to-light ratio of ICL than that of the main “galaxy” within the halo. The higher mass-to-light ratio of ICL indicates that the color of stars in the ICL component is redder than the main “galaxy.” We have checked the luminosity-weighted metallicities and ages of star particles assigned to the “galaxies” and ICL component, and found that the ICL stars have higher metallicity and older age than “galaxies.” In this paper we do not investigate in detail which factor contributes the most to the higher mass-to-light ratio of the ICL component, but such an analysis would be useful in future work for comparison with observations.

In order to separate the intrinsic “galaxy” evolution from the observational cosmological redshift-dimming effects on the ICL fraction, we further compare the measured ICL fraction evolution as a function of redshift in Figure 6. In the left panel, we only use the “galaxies” from the $z \sim 0$ snapshot and shift them to different redshifts to produce mock images. In the middle panel, we use “galaxies” produced in the simulation at different redshifts. In these two panels we do not apply the cosmological redshift-dimming effect (omitting the $(1+z)^{-4}$ term in Equation (4)). The right panel shows the results using the “galaxies” produced in the simulation at different redshifts and with cosmological redshift-dimming included. Different rows show the results in different halo mass bins, and the lines in different colors indicate different SBLs at the V band. Here, results for more redshift outputs are plotted than seen in Figures 3 and 4 in order to obtain smoother curves.

This figure shows some interesting results. First, the left panel represents the pure effects of PSF and cosmological geometry on ICL fraction. It is seen that the ICL fraction is almost flat across all redshifts, except for the results with the
highest SBL. By simply putting $z = 0$ “galaxies” at high redshifts, regardless of cosmological redshift-dimming, only the pixel size and the PSF can have effects on the ICL fraction. Since the pixel size has no significant effect (see Section 4.1 for details), the redshift evolution of the ICL fraction shown in the left panel of Figure 6 should only lie in the PSF effect, which is much more significant for fainter regions. Therefore, we are expecting a slightly larger increase of the ICL fraction for the halos with smaller mass, and a more obvious evolution of the ICL fraction with brighter SBL.

Furthermore, given a faint SBL, i.e., $\mu_{V,\text{lim}} = 26.5$ mag arcsec$^{-2}$, there is a flat redshift evolution, as can be seen from both the left and the middle panels. The redshift evolution is also flat for all halos over the redshift range of 0 and 0.2, even taking into account the cosmological redshift-dimming effect, as shown in the right panel.

In the left panel of Figure 6, the curves slightly bend down at high redshift. This is from the cosmological geometry effect. It has been given that $D = \alpha * \frac{\mu V}{1 + z} = \frac{\alpha}{H_0(1 + z)} \int_0^z \left(\Omega_m(1 + z)^3 + \Omega_K(1 + z)^2\right)^{1/2} dz$. At a fixed CCD pixel size, $D$ increases with redshift until $z \sim 1.6$, and then decreases. The PSF can make the target smoother and fainter when $D$ is larger. Therefore, if cosmological redshift-dimming is not taken into account, the target moving to high redshift beyond $z \sim 1.6$ will become fainter and then brighter, because its image will become smoother and then turn sharper. In such a case, from the peak redshift to high redshift, the ICL fraction will decrease. The curves also have a dependence on the SBLs and halo mass, as their peaks become more prominent with a higher SBL or for less massive halos. One can speculate that the PSF has different effects at inner and outer regions of BCG, in good agreement with the PSF influence, which has a more significant effect on fainter components.

![Figure 6](image-url)
Second, as shown in the middle panel, the measured ICL fraction is higher for less massive halos and demonstrates a strong redshift evolution. Compared to the left panel, the ICL fraction shows a deeper drop at higher redshifts, especially for massive halos. This could reflect the facts that “galaxies” at higher redshift are less massive and more compact than those directly shifted from a $z \sim 0$ snapshot, while the diffuse stellar components are consecutively produced. Those curves show a peak at $z \sim 1$, which is later than those in the left panel. These two facts regulate the redshift evolution of ICL fraction.

Finally, with the cosmological redshift-dimming, for all halos within mass bins, there is a significant redshift evolution of ICL fraction that increases sharply with redshift. With the brightest SBL adopted here, the measured ICL fraction will quickly reach 100% at redshifts beyond $z > 0.6$ and $z > 1$ for less massive halos and massive halos, respectively, as can be seen from the right panels.

4.3. The Evolution of the ICL Profile

Another interesting problem is the radial distribution of the ICL component around BCG. If the ICL is the byproduct of galaxy formation, its spatial distribution will be expected to give information on the cluster formation at the current stage. We calculate the abundance of the ICL fraction at each radius bin normalized by the halo virial radius $R_{\text{vir}}$. Figure 7 shows the radial profile of the ICL fraction at a few redshifts. The profiles seem to be independent of halo mass, but slightly extend with increasing redshift. It is interesting to see that almost all the star particles distributed outside of a certain distance are counted as ICL components. As most of the ICL stars are assumed to be formed through galaxy mergers or stripping, this characteristic radius can indicate an important range of galaxy merger events.

This normalized characteristic radius, where the measured ICL fraction reaches 100%, slightly increases from $\sim 0.04 R_{\text{vir}}$ at low redshift to $\sim 0.1 R_{\text{vir}}$ at high redshift. This change could be caused by the increase of the halo virial radius toward $z \sim 0$ but with a fixed physical radius where ICL fraction $\sim 1$, or the physical characteristic radius decreases with redshift. Using several randomly selected halos to check both the evolution of halo virial radius and the physical characteristic radius of ICL, we find that the main evolution is the decrease of the physical radius of ICL.

5. Observational and Theoretical Constraints on the ICL Fraction

In Table 1, we compile data from both observations and theoretical predictions. The observational data can be roughly separated into four categories using the methods described in Section 1. The individual clusters are categorized as single cluster in our comparison. Table 1 provides only the mean parameters for the CLASH and Nearby Cluster populations, while the accurate ICL fraction of each cluster is plotted in Figure 8. For various theoretical results, the physical models applied and the methods to identify ICL are quite diverse. Therefore, as we have mentioned, it is not possible to make a fair comparison if the definition of ICL is obviously not similar to that of the observations. This is the reason why we compile only the observational results and why our predictions in Figure 8 illustrate the ICL fraction as a function of halo virial mass and its redshift evolution.

In Figure 8, the single clusters are represented by solid stars, which can be separated into three sets according to their ICL identifications. The first set includes three data points (red solid stars; Feldmeier et al. 2004a, 2004b; Longobardi et al. 2015) defined by the ICPNs (or GCs) method because they are very low-redshift local targets. The second set includes the results for five other clusters (green solid stars; e.g., Montes & Trujillo 2014; Presotto et al. 2014) obtained using the SBL method. Note that their SBLs are different from each other, and the higher ICL fraction is caused by the brighter SBL, except A2390 has a brighter SBL in the $B$ band (Vilchez-Gomez et al. 1994), but shows a lower ICL fraction. The discrepancy is caused by the brighter optical detection depth in Vilchez-Gomez et al. (1994). Generally, the surface brightness of the ICL component is so faint that a optical depth should be reached to detect such components. And the last set includes the remaining single clusters (blue solid stars; e.g., Uson et al. 1991; Scheick & Kuhn 1994) obtained by the SB profile method. After checking their SB profiles, it is found that the brightness profiles being in excess of the $i^{1/4}$ law causes the high observed ICL fractions. In Gonzalez et al. (2000) the ICL fraction of A1651 is found to be $\sim 2\%$. With more accurate calculation, its ICL fraction becomes $\sim 13\%$ (see Table 4 in Gonzalez et al. 2005 and Table 1 in Gonzalez et al. 2007).

The SDSS clusters can be separated into two types by their ICL definitions. ICL for a fraction of clusters (blue square) is defined by a modified SB profile method, and the mean fraction is 0.31. The others (green square) are obtained by the SBL method with a value of 25.0 mag arcsec$^{-2}$ in the $r$ band, and the
mean fraction is $\sim15\%$. Note that the pixel size $0'' 396$ and PSF value $1'' 43$ applied in our calculation are adopted from SDSS.

Burke et al. (2015) used the SBL method to define ICL for all the CLASH clusters (green solid circles) with $\mu_{\text{limit}} = 25$ mag arcsec$^{-2}$ in the rest-frame $B$ band, where the image pixel size and PSF width are $0'' 05$ and $0'' 07 \sim 0'' 15$ (e.g., Zitrin et al. 2011; Postman et al. 2012; Merten et al. 2015), respectively, much smaller than those of SDSS. As discussed in Section 4.1 for the PSF smoothing effect, the smaller PSF width for CLASH data may partly account for the lower ICL fraction than seen in SDSS results, apart from the dependence on halo mass. In addition, the SBLs vary for different clusters, and thus the calculated ICL fraction shows a big scatter over a narrow halo mass range.

For the nearby clusters, two methods are used to define ICL. For the first one, ICL (blue triangle) is estimated through a modified SB profile method (Gonzalez et al. 2005, 2007), with $\alpha = 0.7$, $\omega = 1.4$, over a redshift range of $0.03 < z < 0.13$. For the other one, ICL (yellow triangle) is defined as the flux at the region outside of $0.25 R_{\text{vir}}$ (Krick & Bernstein 2007), with $\alpha = 0.345$, $\omega \sim 1.0$, over a redshift range of $0.05 < z < 0.3$. It is seen that the former obtained a much higher ICL fraction and a larger scatter. We have checked their surface brightness profiles, and found that Gonzalez et al. (2005, 2007) split the BCG from ICL at a smaller radius than Krick & Bernstein (2007), so the SBL in Gonzalez et al. (2005, 2007) is actually higher than the latter, leading to a higher ICL fraction.

### Table 1: The Observation and Analytic Data

| Cluster/Analytic | $M(10^{14}M_\odot)$ | $z$ | Band | Method | $\mu_{\text{limit}}$ | $f_{\text{ICL}}$ | References |
|------------------|----------------------|----|------|--------|-------------------|----------------|-------------|
| **Observational results:** |
| Abell 2744       | 17.6$^a$             | 0.308 | F106W | SB profile | Non | 0.08$^d$ | Morishita et al. (2016) |
| MACS 0416        | 21.8$^a$             | 0.396 | F106W | J SB limit | 25 | 0.051$^d$ | Montes & Trujillo (2014) |
| MACS 0717        | 65.0$^d$             | 0.548 | F106W | SB profile | Non | 0.22$^d$ | Morishita et al. (2016) |
| MACS 1149        | 57.3$^a$             | 0.544 | F106W | SB profile | Non | 0.13$^d$ | Morishita et al. (2016) |
| C1 0024+17       | 1.5$^b$              | 0.395 | F625W | SB profile | Non | 0.08$^d$ | Morishita et al. (2016) |
| Nearby cluster I | 0.6 $\sim$ 10.0$^c$ | 0.03 $\sim$ 0.13 | SDSS-i | SB profile | Non | 0.3 $\sim$ 0.5$^d$ | Gonzalez et al. (2007) |
| A2029            | 11.2$^b$             | 0.0767 | R SB limit | Non | 0.34$^d$ | Uson et al. (1991) |
| A1656            | 9.7$^a$              | 0.0232 | R SB profile | Non | 0.5$^d$ | Bernstein et al. (1995) |
| A1689            | 9.6$^a$              | 0.18 | V SB profile | Non | 0.3$^d$ | Tyson & Fischer (1995) |
| A1651            | 6.2$^b$              | 0.084 | I SB profile | Non | 0.13$^d$ | Gonzalez et al. (2005) |
| C1 0024+1652     | 3.2$^b$              | 0.39 | V SB profile | Non | 0.15$^d$ | Tyson et al. (1998) |
| A2670            | 2.7$^b$              | 0.0745 | R SB profile | Non | 0.3$^d$ | Scheic & Kuhn (1994) |
| CLASH            | $\sim$10.0$^c$       | 0.1 $\sim$ 0.4 | B SB limit | 25 | $\sim$0.23$^d$ | Burke et al. (2015) |
| MACS 1026        | 14.1$^b$             | 0.44 | V SB limit | 26.5 | 0.125$^d$ | Presotto et al. (2014) |
| SDSS             | $\sim$1.0/$h^b$      | 0.2 $\sim$ 0.3 | r SB profile | 27.5 | $\sim$0.109$^d$ | Zbetti (2008) |
| $\sim$5.7$^b$   | 0.15 $\sim$ 0.4 | X-ray SB profile | Non | 0.2 $\sim$ 0.4$^d$ | Budzynski et al. (2014) |
| A2390            | 14.9$^b$             | 0.232 | B SB limit | 24.75 | 0.16$^d$ | Vilchez-Gomez et al. (1994) |
| A1914            | 9.4$^a$              | 0.1712 | V SB limit | 26.5 | 0.15$^d$ | Feldmeier et al. (2004b) |
| A1413            | 6.4$^a$              | 0.1427 | V SB profile | Non | 0.13$^d$ | Feldmeier et al. (2002) |
| Nearby cluster II | 2 $\sim$ 40/$h^b$ | 0.05 $\sim$ 0.3 | B $R_{\text{vir}}$ | Non | 0.04 $\sim$ 0.2$^d$ | Krick & Bernstein (2007) |
| M87              | 0.024$^d$            | 0.00436 | Non | ICPNs | Non | 0.12$^d$ | Longobardi et al. (2015) |
| M81 Group        | 0.012$^d$            | $-$0.000113 | Non | ICRGB | Non | 0.013$^d$ | Feldmeier et al. (2004a) |
| Virgo            | 1.5$^b$              | 0.004 | Non | ICPNs | Non | 0.16$^d$ | Feldmeier et al. (2004a) |

| **Theoretical results:** |
| N-body           | 0.01 $\sim$ 1/$h^b$ | 0 | Non | FoF method | Non | $\sim$0.25$^d$ | Contini et al. (2014) |
| GADGET-3         | 0.01 $\sim$ 10/$h^b$ | 0 | Non | dynamical method | Non | 0.6 $\sim$ 0.8$^d$ | Cui et al. (2014) |
| GADGET/-2        | 1 $\sim$ 10/$h^b$   | 0 | Non | Binding Energy | Non | 0.15 $\sim$ 0.30$^d$ | Rudick et al. (2011) |
| N-body           | 1 $\sim$ 10/$h^b$   | 0 | Non | Instantaneous Density | Non | 0.10 $\sim$ 0.15$^d$ | Rudick et al. (2006) |
| hyd-simulation   | 0.01 $\sim$ 1/$h^b$ | 0 | Non | SB limit | Non | 0.45$^d$ | Puchwein et al. (2010) |
| hyd-simulation   | 1/$h^b$              | 0 | Non | SKID | Non | 0.2 $\sim$ 0.5$^d$ | Murante et al. (2004) |

**Notes.** The fractions of M87, M81, and Virgo actually are the ratios of ICL/(BCG+ICL) luminosity based upon their data.

$^a$ $M_{500}$

$^b$ $M_{200}$

$^c$ ICL mass fraction

$^d$ ICL light fraction

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In Longobardi et al. (2015), their ICL is defined by the ICPNs method (red symbol), and according to their definition, the ICL fraction is obtained as intraccluster PNs (ICPNs) divided by the total PNs (ICPNs + BCG PNs), namely the ratio of ICL/(BCG+ICL) in luminosity. Therefore, their derived ICL fraction is different from others, as they did not consider the contribution from “galaxies” other than the central BCG. Thus, the ICL fraction serves as only an upper limit. Note that the significant scatter in Longobardi et al. (2015) is caused by the small number statistics of ICPNs data.

It is also found that the observed ICL fraction obtained by the SB profile method (blue symbol) varies within a large range. The SB profile method normally implies a bright SBL for halos with low- and intermediate-mass, and thus causes a larger ICL fraction. Actually, the ICL fraction calculated by this method is more close to ICL/(ICL+BCG). The observational data defined by the SB method (green symbol) are located in a smaller region than the SB profile data.

For the data defined by the 0.25 Rvir method (yellow symbol), according to what we have discussed in Section 4.3, the characteristic radius evolves with redshift. Thus, the constant radii for halos at different redshifts should no longer be valid to accurately define ICL, so as to cause an increasing observed ICL fraction with mass. The ICL fraction of all the data in the left of Figure 8 apparently show an obvious dependence on the halo mass, which differs from our results.

In the right panel of Figure 8 we show the redshift evolution of the ICL fraction for a few observational results and our simulation predictions (shown in the gray shaded region). Note that both observational and theoretical results have included SBLs that evolve with redshift as 2.5 log(1 + z)^4 for our simulated data to make a fair comparison with the data of Burke et al. (2015) in the right panel. The width of the PSF and pixel size are those used in CLASH data, 0.75 and 0.05, respectively.

**Figure 8.** Comparison between the observed ICL fractions as a function of halo mass (left panel) and redshift (right panel). The symbols have the following meanings.

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6. Discussion and Summary

In this paper, we make mock observational images of galaxy groups and clusters from a cosmological hydrodynamical
simulation and investigate the measured ICL fraction identified by the SBL method. These mock images are smoothed by a Gaussian kernel with a PSF width $\omega$ over all image pixels with size $\alpha$. Results at four different filter bands $B$, $V$, SDSS $g$, and SDSS $r$ are presented in this paper. The main results can be summarized as follows:

1. PSF width $\omega$ has a clear effect on the measured ICL fraction, while pixel size $\alpha$ has little effect. Larger $\omega$ leads to a strong smoothing that leads to a higher ICL fraction. The cosmological redshift-dimming and observational detection depth (or SBL) have significant impacts on the measurement of the ICL component.

2. As shown in Figure 4, the measured ICL fraction strongly changes with the surface magnitude limit so that ICL fraction decreases with fainter SBL, ranging between 0.2 and 0.4 for massive halos at low redshift. The measured ICL fraction also depends mildly on halo mass. With a certain SBL and a fixed redshift, the measured ICL fraction decreases with increasing halo mass and becomes almost independent of halo mass beyond $M_{200} > 10^{13} h^{-1} M_{\odot}$, especially at low redshift. In particular, with a faint SBL, i.e., $\mu_{V,\lim} = 26.5$ mag arcsec$^{-2}$, the measured ICL fraction does not depend on halo mass at low redshifts. There is almost no difference among $B$, $V$, SDSS $g$ band, while the results for SDSS $r$ may be largely affected by the conversion factor derived from a simple SSP model.

3. Using this SBL method, the measured ICL fraction clearly shows apparent redshift evolution. It dramatically increases with redshift, due to the efficient cosmological redshift-dimming effect, as can be seen from Figure 4 and the right panel of Figure 6. Removing the effect of cosmological redshift-dimming, as shown in the middle panel of Figure 6, the measured ICL fraction increases with redshift, reaches a peak around $z \sim 1$, and then decreases.

4. Figure 5 shows that the mass and luminosity fraction of the intracluster stellar component are different and there is more mass locked in the ICL component than the light. This is due to the larger mass-to-light ratio in the ICL component than the main “galaxy.” Our results indicate that the use of a constant mass-to-light ratio at high surface brightness levels will lead to an underestimate of the mass in ICL.

5. Figure 8 shows that current measurement of ICL from observations has a large dispersion due to different ICL definitions and observational environments. The general trend of ICL redshift evolution in observational results of Burke et al. (2015) agrees with our theoretical predictions, using the same ICL definition and similar SBL, PSF, and pixel size. Given the above, we emphasize the importance of using the same method and observational parameters (e.g., surface magnitude limit, PSF, and pixel size) when observational results are compared with theoretical predictions.

Although the hydrodynamical simulation used in this work is not perfect, and may have an influence on the results, we claim that our qualitative conclusions are solid, especially the effects of SBL, PSF, and cosmological redshift-dimming. The results for low-mass halos and halos at high redshift are not reliable due to the lower-mass resolution of the simulation. In order to fully understand the physics of the ICL component, more high-resolution simulations with proper baryonic physics included are required. For example, including AGN feedback in simulations will have a large impact on the ICL fraction (Cui et al. 2014).

The SBL method may also help to improve studies of galaxies. In some simulations, the predicted stellar mass functions of galaxies are roughly consistent with observational data in the range of intermediate stellar mass, while the low-mass end is overpredicted and the high-mass end is underpredicted (e.g., Liu et al. 2010). Liu et al. (2010) also checked the mass function for different types of galaxies, and found that the identification of substructures (SUBFIND) in theories assigns too many stars, which causes the results to not be consistent with observations. The overassigned stars must come from the regions around galaxies. If these stars are re-assigned to the ICL component, the stellar mass function may decrease to match with data. Furthermore, in observations, very faint galaxies might be omitted, or confused with ICL due to their faint surface brightness. In addition, if a large fraction of the ICL component has been omitted from observations of galaxy groups, the so-called missing baryon problem may be alleviated.

We believe, using the SBL method to define galaxies or the ICL component in the more realistic cosmological hydrodynamical simulations, e.g., the ILLUSTRIS or EAGLE simulations, the predictions of the ICL fraction and the galaxy luminosity function should more likely match with observational results. This will be the focus of our future work.

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References
Adami, C., Durret, F., Guennou, L., & Da Rocha, C. 2013, A&A, 551, A20
Arnaboldi, M. 2004, in Baryons in Dark Matter Halos, ed. D. Ralf-Jürgen, K. Uli, & S. Paolo (Trieste: SISSA), 026
Arnaboldi, M., & Gerhard, O. 2010, HiA, 15, 97
