bCG subtraction

In order to facilitate the detection of those background or underlying fainter objects, the optimal strategy is to first model and subtract ICL and bCGs, and then perform source detection on ICL-and bCGs-subtracted image, i.e., the processed image. Based on visual inspection of galaxy distribution in the F160W image, it is apparent that most of luminous, extended galaxies (e.g., bCGs) tend to concentrate on the cluster central region (collectively shown as a large-scale elongated structure across the image), which results in terrible overlapping between bCG's extended envelopes and neighboring faint objects. It is just impossible to gain reliable source parameters by directly measuring this complicated area. While in the outer regions, the dominant population consists mainly of relatively fainter and smaller galaxies, which means that it still exists crowding effects but these sources are not overlapped with each other due to the absence of bCGs. Moreover, as the cluster-centric radius increases, the surface brightness of ICL declines steeply, indicating negligibly detrimental impact on source measurements on outer radial regime. Therefore, outer non-overlapping regions are much easier to deal with compared with former central case. In view of the unique galaxy spatial distribution in this cluster, we refer to the aforementioned two types of regions as *overlapping* region and *crowded* region, respectively, which will be subsequently treated in different ways. Our strategy is to transform/degrade overlapping region into crowded region by subtracting bCGs and ICL, as illustrated in Equation 1. Through this way, the original field is turned into overall crowded field that allows for more efficient detection of faint sources.

$$\text{Crowded region} = \text{Overlapping region} - \text{bCGs} - \text{ICL} \tag{1}$$

To improve the accuracy of faint source measurement, we have utilized a ring median procedure with careful mask to remove the ICL component, as well as bCG's peripheries. Without these convoluted large-scale light gradients, the faint sources behind immediately stand out on the globally flat background. However, the over-lapping issue remains in the central region (i.e, overlap-ping region). The background high-z galaxies and the cluster dwarfs in the vicinity of bCGs are obscured by the overwhelming luminosity of bCGs, impeding the detection of them. For deriving a complete catalog in this field, it is necessary to account for them as well. In an effort to reveal these overshadowed objects, we proceed to model and subtract bCGs in this section, by employing two-dimensional (2D) parametric analysis.

We use public code GALFITM to perform 2D multi-component modeling of bCGs. GALFITM is an enhanced version of GALFIT, capable of fitting galaxy profile by simultaneously using multi-band data. As we focus on one band (i.e., F160W), we actually employ GALFITM to conduct single-band fitting. We adopt Sérsic function to model bCGs. The Sérsic profile has the following form:

$$\Sigma(r) = \Sigma_{\mathrm{e}} \exp\{-b_n[(\frac{r}{r_{\mathrm{e}}})^{\frac{1}{n}} - 1]\}, \tag{2}$$

where r_{e} is the effective (or half-light) radius of the galaxy, which gives an indication of the physical size of the galaxy, Σ_{e} is the surface brightness at r_{e}, $\Sigma(r)$ is the surface brightness as a function of r, n is the Sérsic index describing the concentration of the light distribution (i.e., galaxy profile shape) and $b_n = b_n(n)$ is a normalization constant; The parameter b_n is closely connected to n by the incomplete gamma function $\Gamma(2n) = 2\gamma(2n, b_n)$, where Γ and γ represent the complete and incomplete gamma functions, respectively. Owing to the presence of complicated substructures in bCGs, single-component Sérsic profile is inadequate to model them. We thus construct multi-component Sérsic model to recover their light distribution as much detail as possible. We emphasize that the aim of this step is not to obtain physically meaningful information from the model parameters of each individual component, but only to achieve the smoothest residuals, which accentuates neighboring faint source measurement in the cluster core region.

Our bCG-subtraction procedure works mainly under the framework of GALAPAGOS2 pipeline. GALAPAGOS2 software package automates source detection, single Sérsic profile modeling and catalogue creation by integrating SExtractor and GALFIT softwares, and enable multi-wavelength simultaneous fitting in a fully automatic fashion.

In general, the main workflow of GALAPAGOS2 consists of the following tasks: (i) source detection by running SExtractor; (ii) postage stamp cutout for detected sources; (iii) local background estimation and mask image preparation; (iv) single Sérsic fitting by running GALFITM; (v) bulge-disc decomposition; (vi) catalogue compilation. To our single-band analysis in this stage, we take full advantage of the first five tasks. We now give details on these tasks and elaborate their applications in constructing best-fitting models of bCGs.

1 SExtractor cold+hot mode

Developed for deep HST surveys, SExtractor cold+hot detection mode is a two-step approach, involving two separate SExtractor runs with different configuration parameters. The cold mode run is designed to select large and bright galaxies, avoiding over-delending ('shredding') them into multiple spurious sources. The corresponding configuration requires high values for input parameters DETECT_THRESH (the detection threshold above background), DEBLEND_MINAREA (the minimum number of connected pixels above threshold), and DEBLEND_MINCONT. While the hot run puts emphasis on reaching a high detection completeness, with aggressive deblending parameters it is optimized to detect small and faint sources, but tends to break up large galaxies into spurious shreds; this is especially the case inside the highly structured spiral galaxies. By employing these two complementary detection modes, SExtractor was run twice to output the cold and hot catalogs. The two catalogs are then combined to create a final catalog containing all possible objects.

We define bCG sample to be modeled based on magnitude and size distribution of all the sources in the final combined catalog. To this aim, we run SExtractor cold+hot mode on the ICL-subtracted image obtained in the previous analysis to retrieve basic source parameters.

First, cold detection mode is run to properly extract and deblend bright extended sources at the expanse of missing a large fraction of faint sources. Then the hot run picks those faint sources up, although it prefers to break large galaxy up into several pieces that will be discarded in the subsequent combining process.

GALAPAGOS2 uses a combination routine to merge cold and hot catalogs based on analyzing their SExtractor Kron ellipses. In the following sections, we will also witness that the Kron ellipse is a key parameter on which GALAPAGOS2 pipeline critically depends. SExtractor uses the Kron ellipse to estimate the extent of an object, with semimajor axis (i.e., Kron radius) defined as R_{Kron}=A_IMAGE $\times$ KRON_RADIUS, where A_IMAGE and KRON_RADIUS are SExtractor parameters. While the ellipticity and position angle are determined by ELLIPTICITY and THETA_IMAGE, respectively. First, all sources detected in cold mode are used as reference and included in the final combined catalog. Next the position of each hot source is examined whether it locates within the Kron ellipse of any cold source. If it does, the source is treated as substructure of the cold source and excluded from the final catalog. Only the hot sources fall outside of all cold Kron ellipses enter the final catalog. In brief, the final combined catalog consists of all cold sources, supplemented by additional hot sources that are not within any cold Kron ellipse. Furthermore, the combination routine allows the users to specify a scale factor to artificially enlarge (cold) Kron ellipses. We found that it is efficient to reduce the fraction of spurious detections in the final catalog by adjusting this factor, and it can be applied to various types of galaxy fields with different crowding levels. For example, in our field using a value of 0.2 could lead to minimized spurious source detection.

We use the final merged catalog to quantitatively select and define bCGs. In the upper panel of Figure 1, we show the circularized radius of object segment as a function of magnitude for the combined catalog. The circularized radius is simply calculated by formula $r_{circ} = \sqrt{N/\pi}$, where N represents the total pixel number of source segment. We adopt this quantity because it follows a tight relation with source magnitude, which is conducive to determine the selection criteria for bCGs. In this analysis, SExtractor MAG_BEST is used for a rough estimate of the total magnitude. In view of the parameter distribution in Figure 1, we impose the magnitude of 19.56 and r_{circa}= 33 pixels cuts shown as vertical dashed and horizontal dashed lines, respectively. We therefore define those objects with magnitudes smaller than 19.55 and r_{circa} larger than 33 pixels as bCGs. In other words, any object located in the upper left quadrants of the distribution will be considered as bCGs for further analysis. A total of 26 objects were selected, accounting for less than 1th percentile of the full sample. Labelled with cyan-color Kron ellipses in the lower panel of Figure 1, we can see that they are the most extended and largest galaxies across the entire field. After running SExtractor two modes and defining bCGs, GALAPAGOS2 makes a postage stamp for each target of interest.

2 Postage stamp creation

In order to run GALFITM on each bCG, we necessitate a postage stamp image with an appropriate size to cover the full extent of an object. GALAPAGOS2 cuts out a rectangular postage stamp centered on the target from the original image. The size of the postage stamp

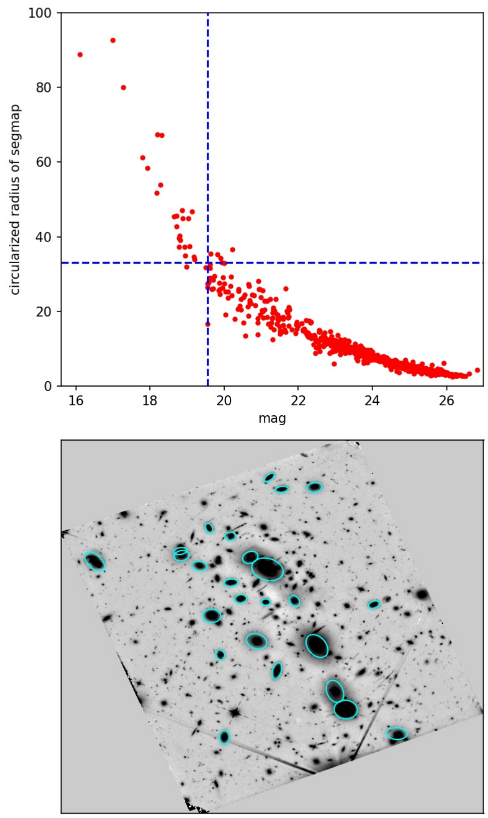

Figure 1: Upper panel: The circularized radius of object segment r_{circa} as a function of magnitude (SExtractor MAG_BEST). The reason of choosing r_{circa} is that it forms a tight relation with magnitude, which can better visualize bCG selection. The blue dashed vertical and horizontal lines are magnitude and r_{circa} cuts (19.55 mag and 33 pixels) we have applied to select bCGs, respectively. Any object that falls inside the upper-left quadrant is considered as bCGs for further analysis. There is a total of 26 galaxies satisfying our criteria, which accounts for no more than one per sent of the total sample. Lower panel: Cyan-color ellipses over-plotted onto the ICL-subtracted image mark the Kron ellipses for our selected bCGs, which are the most extended and largest objects. The positions of this selected small sample spread through the whole image field.

is dependent on the Kron radius ($R_{\rm Kron}$=A_IMAGE × KRON_RADIUS). This task allows us to enlarge the cut rectangular area by using a scale factor m, such that it will fully contain an ellipse with semi-major axis equal to m×$R_{\rm Kron}$ (while both ellipses have the same ellipticity and orientation). The X and Y dimensions of the postage stamp are determined using the following formulae:

$$X = mR_{\rm Kron}[|\sin(\theta)| + (1 - {\rm ellip})|\cos(\theta)|], \tag{3}$$

$$Y = mR_{\rm Kron}[|\cos(\theta)| + (1 - {\rm ellip})|\sin(\theta)|], \tag{4}$$

where ellip is SExtractor output parameter ELLIPTICITY, θ is the position angle THETA_IMAGE. The X and Y are in units of pixels.

The purpose of cutting postage stamps is to shorten the computational time for fitting one galaxy, by excluding objects too far from the target. Meanwhile, the size is required to be large enough to ensure that the complete light profile of the target is visually included. If it is too small, the outer light profile may fail to be fitted, and the proper value of local background can not be found. In this field, the selected bCGs are the most luminous early-type galaxies with extended wings , which require larger areas than that of pervious studies for postage stamps. Through testing, we found that a factor of m=3.5 reaches a good compromise between using a large area with enough pixels to allow a robust fit for the target, and keeping a reasonable amounts of computation time. These postage stamps of bCGs will be used by GALFIM as input images.

3 local background estimation (and mask image preparation)

The accurate determination of local sky background is critical in galaxy profile fitting. For example, overestimating the sky level can result in the underestimation of galaxy total magnitude, half-light radius, and Sérsic index. This is especially the case for galaxies with high Sérsic index, because the extended wings of galaxies contribute to the sky level. For this aim, GALFITM can internally provide a sky component to be fitted simultaneously with the science target, and SExtractor could also estimates a local sky background. When fitting the sky level as a free parameter, GALFITM desires that the postage stamp should be as large as possible to cover sufficient area for an accurate background estimation. However, in the crowded fields, too many neighboring sources would be included in the fit, and the best-fitting value might be degenerated with distant objects or outer wings of high-Sérsic-index targets. Besides, galaxies may not be perfectly represented by Sérsic profiles, producing unrealistic sky values. The sky background measurements from SExtractor is even more uncertain, since it fails to recognize where a galaxy profile ends. Instead, SExtractor determines the sky background by means of thresholding, i.e., checking where the light gradient is indistinguishable from background noise. Therefore, SExtractor will always overestimate the sky value.

Our sky estimator applies elliptical annuli centered on the galaxy of interest to calculate the azimuthally mean flux as a function of radius. For a given target, these annuli are actually the enlarged Kron ellipses with the same shape and orientation. During the process, the regions belonging to the primary and neighboring sources are ignored from calculation. The algorithm will mask out the primary galaxy using scaled Kron ellipse with semi-major axis of $a \times R_{\mathrm{Kron}} + b$ (where a and b are user-specified parameters), which means that any pixel value inside the ellipse will be treated as belonging to source flux. The neighboring sources are masked out in the same way with identical values of scale parameters a and b. This mask strategy is more conservative and flexible in comparison with using conventional SExtractor segmentation map, which sometimes does not represent the true extent of a galaxy, in particular with elliptical galaxies. The enlarged Kron ellipse of the target galaxy can be used as the starting radius for the sky background measurement in increasing annuli. The setup for sky annuli is fully user configurable. The user need to specify the annuli width, spacing between successive annuli, and distance between enlarged Kron ellipse and the inner radius of the innermost annulus.

In each annulus, we calculates an average flux value while excluding from the calculation any pixel inside the enlarged Kron ellipses (as described above) of neighboring sources (and image defects), namely the overlapped regions. We refer to Barden et al. 2012 for a detailed description with respect to pixel rejection. For the remaining pixels of annulus, the procedure uses a 3σ-clipping function to symmetrically exclude all pixel outliers. Then a Gaussian function is fitted to the residual (leftover) pixel distribution for the current annulus, aiming to derive a mean value. When each new annulus measurement is done, GALAPAGOS2 performs a linear fit to the last few annuli to determine the sky background level. As the radius increases, the flux contamination from primary galaxy decreases. The best-fitting slope would be negative as long as galaxy light profile still stands out. Once the annuli are sufficiently large compared to primary target (i.e., reaching the true background), the average slope starts to randomly change its sign. The iteration process is terminated when the calculated slope turns positive or zero for a second time, and GALAPAGOS2 use those last few annuli to obtain the final background value. For the combined source catalog detected in SExtractor stage (as described in the previous section), GALAPAGOS2 could automatically measure their sky levels.

Note that GALAPAGOS2 measures the robust sky on the whole science frame rather than the small postage stamp, which avoids the possible situation that no ample sky pixels are left on the postage stamp, thus producing biased fitting results. After getting local sky backgrounds for our bCG sample, we hold them fixed in the subsequent profile fitting stage to reduce degeneracy between sky and outer diffuse envelopes of bCGs.

4 Single Sérsic profile modeling

In this section we describe the details concerning single Sérsic modeling by running GALFITM. We therefore first fit the bCGs with a single Sérsic profile, and then we gradually increase the model complexity by adding additional Sérsic components.

Single-Sérsic fitting is the core ingredient of GALAPAGOS2 to quantitatively provide an overall description of galaxy structure and morphology. To run GALFITM on each bCGs, GALAPAGOS2 automatically prepares an input (configuration) file for galaxy fitting, which requires several considerations including: (1) initial parameters for single Sérsic profile, (2) an estimate of local sky background, (3) image postage stamp for target bCGs, (4) a mask image with with the same size as the postage stamp, and (5) a PSF image. The details of these basic setup procedures are given below.

The initial guess for fitting parameters of Sérsic component are based on SExtractor output: for total magnitude we use SExtractor parameter MAG_BEST; for half-light radius we use the formula $r_e = 0.162 \times (\text{FLUX\_RADIUS})^{1.87}$, which is empirically derived from simulations; for Sérsic index we give $n = 2.5$; the axial ratio and position angle are determined using ELLIPTICITY and THETA_IMAGE, with b/a=1-ELLIPTICITY and θ=THETA_IMAGE, respectively. By making use of SExtractor parameter, we attempt to minimize the computing time and expedite the convergence to the global minimum. The sky component, as described above, is kept fixed during the fitting. In previous section, we have created an individual postage stamp for each bCG of interest, which will be used by GALFITM as input image.

Since bCG resides in dense environments, it is quite natural that there are many close neighbors existing in its postage stamp. The fitting results of primary galaxy may be significantly affected because of the light contamination from nearby bright objects. As a result, it is best to fit these neighbors simultaneously rather than simply masking them out. To this purpose, GALAPAGOS2 utilizes an automated method to decide which neighbors are to be simultaneously fitted and which neighbors can be masked out, prior to the mask image creation. The decision is made via calculating whether the scaled Kron ellipses of target and neighboring sources overlap. We define the main target galaxy as *primary* source during the fitting process, thus it is bCG in our case. Any neighbor object whose scaled ellipse overlaps with that of the primary is fitted simultaneously. Hereafter, we will call it *secondary* source. The initial parameters for secondary models are determined in the same way as that of primaries. Objects that do not overlap with the primary are masked out and thus excluded from fitting, which are termed *tertiary* sources. For such neighboring source treatment, the semi-major axis of scaled ellipse has the form of $c \times R_{\text{Kron}} + d$, where scale parameters c and d are user-specified. In addition, some overlapping secondaries are too faint to have any significant effect on the primary fit, and therefore only those secondaries that are bright enough to significantly contaminate the primary should be simultaneously fitted. To further improve the fitting efficiency by reducing the number of faint secondaries, GALAPAGOS2 applies a magnitude cut Δm to degrade them to tertiaries, which means any secondaries that are Δm fainter than primary will be considered as tertiaries and thus masked out. We use Δm= 3 mag in modeling the bCGs.

As for producing the accurate mask image, GALAPAGOS2 provides a robust approach to conservatively mask out tertiaries. Instead of using SExtractor segmentation map, which is likely to underestimate the true extent of the galaxy, it is again based on the their scaled/expanded Kron ellipses with the same scale factor of c and d as employed in previous neighboring source treatment.

The galaxies we observed are extended surface brightness distributions convolved with the PSF. Therefore, the PSF is a key element for structural and morphological analysis of galaxies, and an accurate knowledge of the PSF is needed. During the fitting process, GALFITM requires an input PSF to convolve with the model image, in order to recover the intrinsic light profiles. We plan to generate a PSF model by median stacking the image cutouts of isolated, bright but unsaturated stars across the field of view. Unfortunately, the severe neighbor contamination makes the number of suitable/qualified stars quite limited. We only find one very bright star with strong diffraction patterns and a few much fainter ones across the entire field. Since simply stacking them will dramatically decline the signal-to-noise ratio (S/N) of outer diffraction structures for this bright star, we decide to only use this single bright star to make the PSF. The star peak position is resampled to image center within sub-pixel accuracy by using `repoject`[1] package.

Additionally, GALFITM accepts constraints to limit the parameter range during the fitting processes. To improve the fitting reliability and efficiency, we impose a set of fitting constraints to prevent the GALFITM from searching areas of parameter space which are believed to be unphysical. The constrains are placed on the object magnitude, half-light radius, and Sérsic index. For magnitude, we fix it to be within 5 mag of the SExtractor input magnitude, i.e., $-5 < m_{\mathrm{GALFITM}} - m_{\mathrm{SExtractor}} < 5$. The half-light radius is constrained within $0.3 \leq r_{\mathrm{e}} \leq 100$ pixels to avoid yielding unreasonably small or large sizes. We require Sérsic index to vary within the range $0.3 \leq n \leq 9$ in the fitting. This is a conservative range, because normal galaxies with n larger than 8 are rarely seen and are usually associated with bad fitting. We adopted exactly the same constraints for primary and secondaries.

During the fitting process, the LM algorithm from GALFITM will continuously modify all the free parameters until the χ^2 residual between the real galaxy and PSF-convolved model reaches a minimum. The calculation of χ^2 is weighted by a sigma map (noise image), which is internally generated by GALFITM using header keywords GAIN, EXPTIME, and RDNOISE in the science image.

Next, with all above setup information prepared, one Sérsic fitting is automatically ran for each selected bCG, along with associated secondaries. The top panels of Figure 2 show the fitting result for one of the bCGs, with middle and right panels being the best-fitting one Sérsic model and residual, respectively. In the residual image, it can be seen that single Sérsic profile is undesirable to adequately describe the real light distribution of bCG, delivering significantly uneven residual patterns with negative outer part (shown as white color) and central substructure (black color). The residual can be improved by introducing additional components. GALFITM uses χ^2 minimization algorithm to minimize the residual between the galaxy image and the model, and thus the reduced χ^2 value provides a simple way to quantify the quality of the fit. However, this single parameter can merely give us a general feel for how successful a fit is, given that multiple systematic uncertainties are involved in building the model. The quality of the model is guided by the smoothness of the residual.

For most of the cases in our bCG sample, we find that single Sérsic fittings converge well by inspecting their residual images. This means that during the fitting process its total flux has been fully taken into the calculation of the model, even if the resulting residual is strong, as illustrated in Figure 2. These bCGs are relatively compact/small and do not overlap considerably with neighbor fainter sources. For such kind of object, we check that our pipeline could correctly deblend its neighbors, and therefore produce a reasonable model for target itself and neighbors. However, there are few bCGs with extended envelopes, for which the total flux of the best-fitting single Sérsic model are greatly underestimated, namely representing an erroneous undersubtraction in the residual image. These special galaxies are the largest and most luminous ones in this field, and seriously overlap with neighbors. We show one of the examples in Figure 3. Their erroneous modelings are exactly due to the overlapping between its diffuse envelope and neighboring objects, which induces unreasonable deblending. In this case, we discover that the magnitudes and segmentation maps (sizes) of these overshined neighbors (secondaries) are greatly overestimated by SExtractor, under the contamination

[1]https://pypi.org/project/reproject/

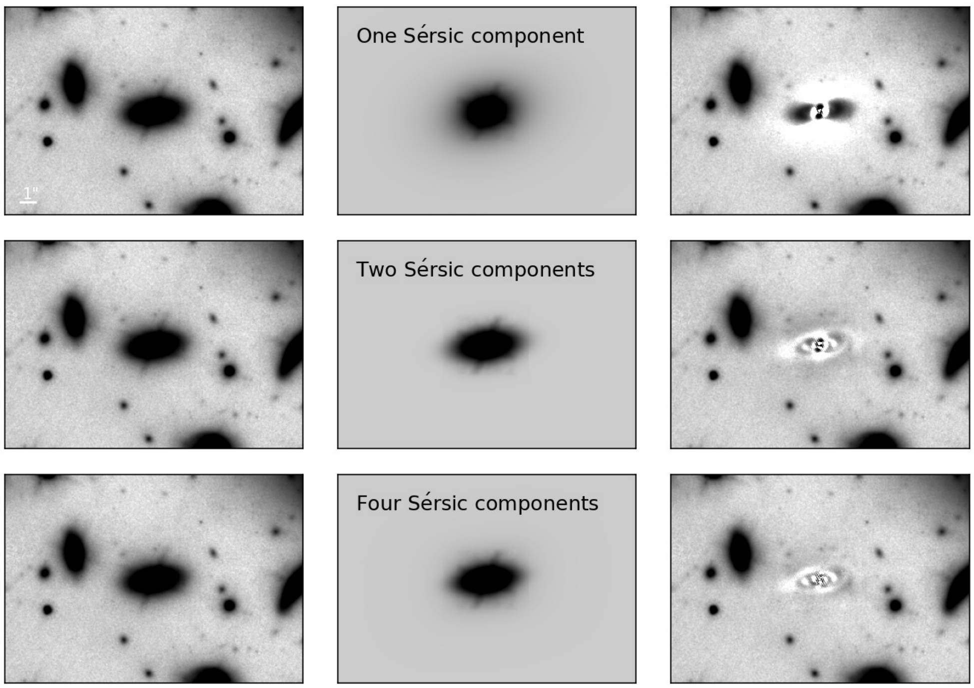

Figure 2: Fitting results for one of the relatively isolated and compact bCGs. Top panels, from left to right: the postage stamp for the target galaxy after removing ICL, one Sérsic model derived using GALFITM, and model-subtracted residual image. The middle and bottom panels follow the same manner as that of the top, but using two and four Sérsic components, respectively. This demonstrates that one Sérsic component is insufficient to model bCG, while two Sérsic component is more promising. Ultimately, we find that four Sérsic components fitting yields satisfactory result on the ICL-subtracted postage stamp.

of the diffuse light from bCG. The overestimated parameters are converted into the initial guesses of secondaries by pipeline before running GALFITM. In the following simultaneous fit stage, the resulting secondaries model will contain excessive flux that supposes to belong to the primary/bCG, which shrinks/underestimates primary model, and consequently results in an undersubtraction in the residual image. Therefore, our GALAPGOS2 pipeline is incapable of automatically dealing with such situation. We hereafter refer to these special bCGs as 'ebCGs' (i.e., extended bright cluster galaxies).

Even if the initial guesses are accurate, the resulting models for ebCGs are still highly uncertain if neighboring secondaries are fitted simultaneously. To address this issue, we add additional step to manually create accurate segmentation map for ALL neighbors, which is used as the mask in the fitting, and then solely fit the ebCG. To obtain accurate segmentation map, we apply a median filter technique to subtract the diffuse envelope from ebCG prior to running SExtractor. As shown in the first column of Figure 3, we use a typical ebCG to illustrate this procedure. The bottom row of Figure 3, from left to right, are the filtered diffuse envelope, envelope-subtracted image, and corresponding segmentation map for all neighbors (i.e., mask image), respectively. This reveals that reasonable measurements for secondaries can be achieved only if the extended diffuse envelope is sufficiently removed. The top panels in Figure 3 show the single Sérsic fitting result, after making all neighbors by providing new mask image (bottom right panel) instead of that generated by pipeline. By inspecting the residual, one can clearly see that overall light distribution has been accounted for in the fitting.

5 Multiple Sérsic profile modeling

In this section, we proceed to refine the model by gradually including more components, one at a time, and then visually examining the residual and the model parameters. By utilizing the bulge-disc decomposition task in GALAPGOS2, we first fit two Sérsic components to all of the bCGs and ebCGs, whose initial parameters are derived based on single component results (see previous section). The second rows of panels in Figure 2 and Figure 3 display two-component fitting result, showing that two Sérsic components can not give an acceptable residuals. However, previous methods only used two components, which significantly influences the further source detection.

Through trial and error, we find that four Sérsic components yield satisfactory residual, showing little of the original galaxy. The four component models and residuals of two examples are shown in the third rows of panels in Figure 2 and Figure 3. We therefore adopt four components as the optimal solution for subtracting bCGs. We caution that the number of Sérsic components required to model bCGs is lower than Bhatawdekar et al. (2019) who studies the same cluster. This is primarily because the outermost envelopes of bCGs have been removed, along with ICL, in the previous ICL-subtraction step.

After obtaining the final reasonable models for all bCGs, we subtract them from the science image (i.e., ICL-subtracted image) to acquire the ICL- and bCGs-subtracted residual image. Eventually, following the strategy in Merlin et al. (2016) and Pagul et al. (2021), we apply a median filter to refine/improve the resulting residual image. The aim of this procedure is to alleviate small-scale negative residuals (oversubtractions) around the bCGs, which

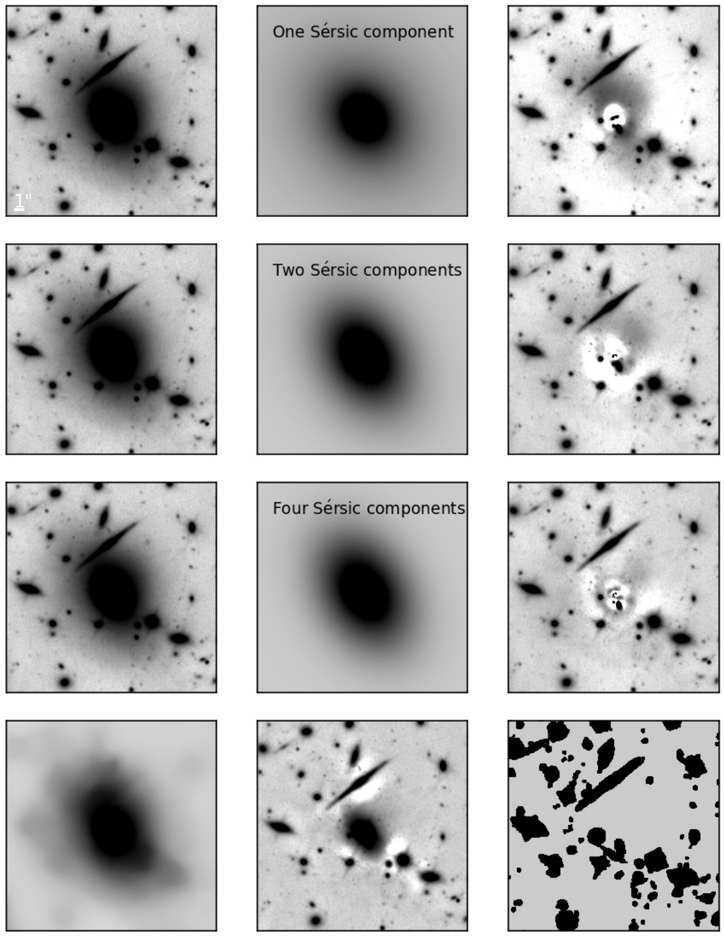

Figure 3: Fitting results for one of the special ebCGs. Top panels are image cutout of science frame with ICL subtracted (left), single Sérsic best-fitting model (middle) using updated mask image (i.e., bottom right panel of this figure, see also the text for more details), and residual image (right). The two middle rows are for two and four Sérsic components fitting, respectively, using the same mask as the top row. The left panel of bottom row shows filtered diffuse envelope of ebCG, while the middle panel is the residual image after subtracting diffuse envelope, ie., left panel of the bottom row. The bottom right panel indicates the segmentation map (updated mask image for fitting ebCG) created by running SExtractor on envelope-subtracted image.

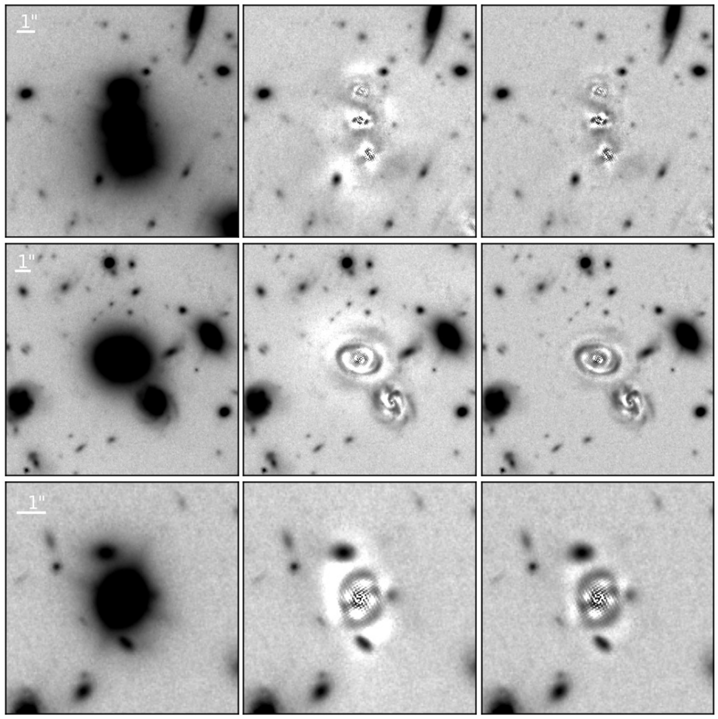

Figure 4: Illustration of the effects of median filtering procedure on improving the bCG residuals.The left column shows three examples of bCGs on the ICL-subtracted image. The middle column shows the corresponding residual images before median filtering, while the right column represents the final residual images after median filtering (i.e., by subtracting the median filtered background image). This procedure is effective at improving the bCG resiudals. See text for more details.

may have detrimental effects on neighboring source measurements. We use IRAF/median task to smooth/filter the residual image with a 1"×1" box while masking real objects using segmentation map. The refined/improved residual is then obtained by subtracting filtered image from the original one. We illustrate this improvement in the right column of Figure 4, which displays median-subtracted residuals, while middle column shows the residuals before median filtering. One can evidently see that the negative residuals (i.e., white patterns) from bCG subtraction procedure have been effectively diminished, while the outermost regions are unaltered.

In Figure 5, we overview our subtraction procedure and present the final results. The left panel of Figure 5 shows the original image of F160W band. The middle panel is the ICL and bCGs models. The right panel denotes the processed residual mosaic after subtracting ICL model, bCGs models, and median filtered background. This processed image is used as the detection image to perform source detection and photometric measurement for all sources except for modeled bCGs, which are measured in a different image. These will be described in detail in the next section.

As a sanity check for our subtraction procedure, in Figure 6 we plot the background pixel distribution of resulting processed image by masking real objects . Since segmentation map tends to underestimate the isophotal areas of sources and therefore skew the distribution

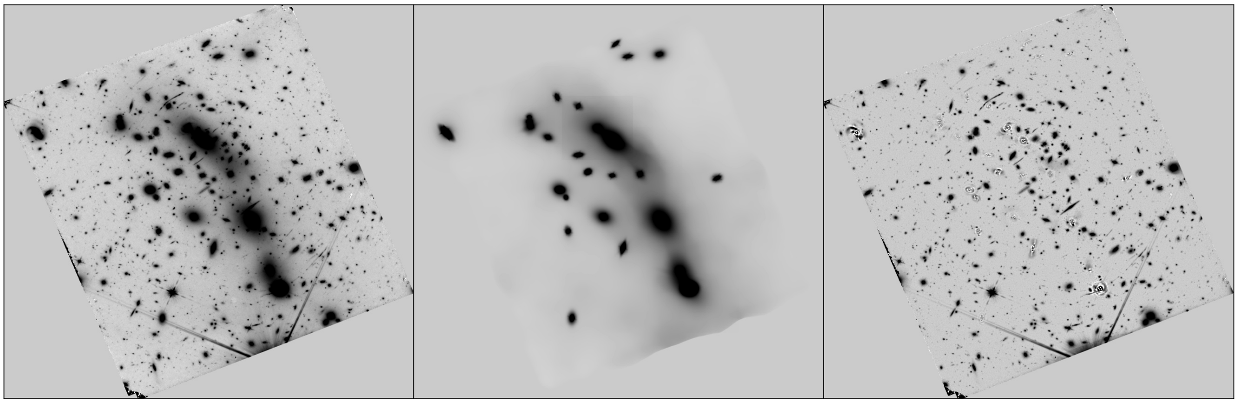

Figure 5: Summary of our subtraction procedure on the M0416 cluster. The left panel shows the original image of F160W band. The middle panel is the combined model of ICL and all defined bCGs. The right panel presents the processed image after subtracting ICL and bCGs models and median filtering. See the text for full details.

towards positive direction, we artificially expand the associated segmentation map using a gaussian kernel with a size of σ=1.5 pixels, to account for the outer wings of the sources. As shown in Figure 6, the resulting pixel distribution is both symmetric and centered on the zero value, demonstrating the robustness of our method.

References

Bhatawdekar R., Conselice C. J., Margalef-Bentabol B., Duncan K., 2019, MNRAS, 486, 3805

Merlin, E., Amorìn, R., Castellano, M., et al. 2016, A&A, 590, 30

Pagul, A et al., 2021, ApJS, 256, 27

Zibetti, S., White, S. D. M., Schneider, D. P., & Brinkmann, J. 2005, MNRAS, 358, 949

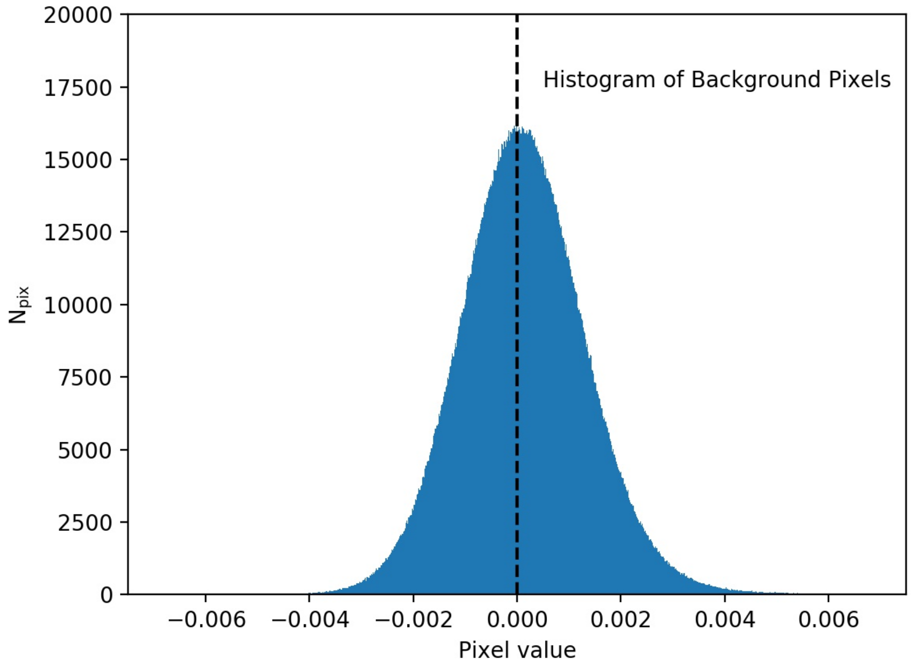

Figure 6: The background histogram after conservatively masking real sources. The mask was generated by convolving the corresponding segmentation map with a gaussian kernel of σ=1.5 pixels. The vertical black dashed line indicates the zero value. The distribution is symmetric about zero without excess of positive pixel.