ICL subtraction

However, given the intrinsically crowded environment with such exceptionally deep observations, HFF are particularly challenging to reliably measure constitute galaxies. Generally speaking, in such dense fields there are a few major complications preventing us from obtaining accurate physical parameters of galaxies. Among these are the bright and extended elliptical galaxies that tend to populated the geometric cluster core region where the blending effects are most notorious, and contribute significant fraction of total cluster light. These luminous galaxies are surrounded by extensive, diffuse stellar envelopes that were accreted during mass assembly. Due to the crowding effect, their diffuse envelopes are inevitably overlapped with neighboring faint objects, which make it impossible to accurately measure the physical properties of those faint sources. Furthermore, as cluster central region hosts the strongest gravitationally amplifying power, the locations where luminous elliptical galaxies reside are crucial for finding high-z lensed galaxies. Hereafter we use the term 'bCGs' to collectively refer to those bright, extended galaxies that were selected based on our selection criteria and subsequently subtracted. The lower case 'b' is intended to distinguish from conventional brightest cluster galaxies (BCG) located in the cluster center, which are the largest and most optically luminous galaxies in the Universe, even if our bCG sample includes BCG.

In addition to severe crowding and overlapping, the presence of intra-cluster light (ICL) further complicate this field. ICL is the diffuse, low-surface brightness starlight occupying the intergalactic space in the clusters and groups. It is comprised of stars which are not belong to any particular cluster galaxy. The stars constituting ICL are commonly believed to originate from the ongoing tidal interaction between galaxy members, making the ICL a fossil record of cluster assembly history. As an important component of massive clusters, ICL is primarily concentrated around the central galaxies of the cluster, with its outer radial surface brightness pro- file extending to a few hundred kpc away from the cluster center, and contributes a substantial fraction (~10-50%) of the overall optical luminosity of the cluster. Additionally, due to the low surface brightness properties, the ICL is entangled with the extended envelopes of bright cluster galaxies, which is quite challenging to unambiguously dissociate them, making the measurement of galaxy parameters highly uncertain. Since from 2D observational image of HFF, both cluster galaxies and background galaxies are embedded within this diffuse emission, the ICL can be considered as large-scale background gradient.

In order to facilitate the detection of those background or underlying fainter objects, we first need to model and subtract ICL. In this section, we embark on reconstruction of the ICL distribution, and then subtract it from original image to yield a globally flat image. We developed a new non-parametric method that demands no presumptions about ICL profile shape. Our method is mainly based on a ring median filter technique implemented in

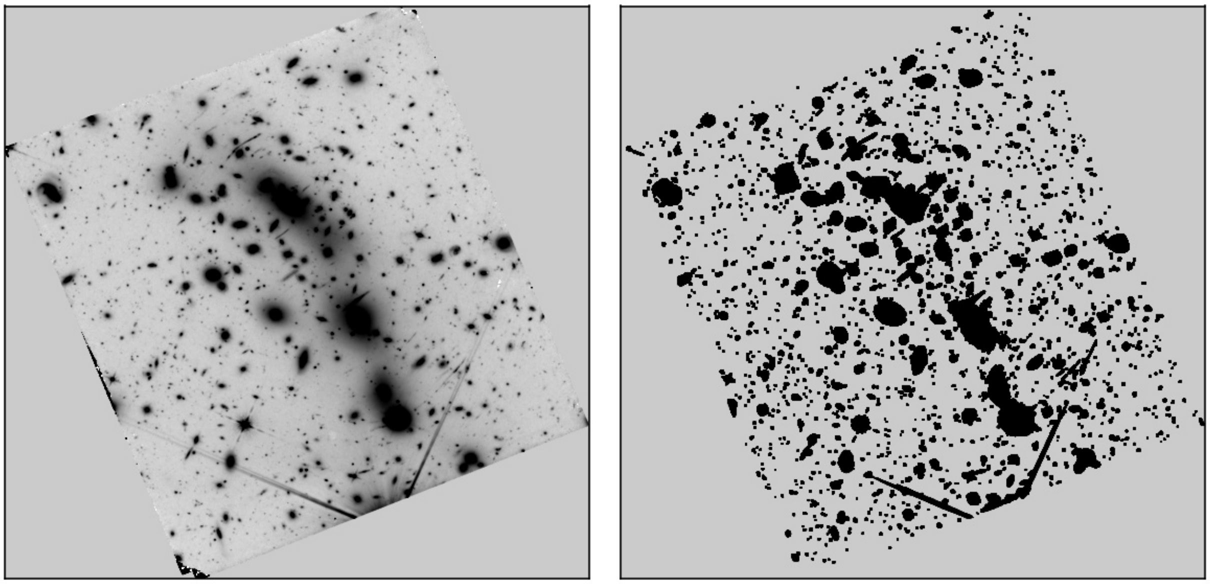

Figure 1: Left: Original F160W images of HFF M0416 cluster. Right: Segmentation map obtained from SExtractor cold+hot mode. All images are displayed in an inverted color and locked to the same asinh scale.

IRAF/RMEDIAN[1] task. By definition, ring median filter assigns weight only to those pixels in an an- nulus, i.e., local background pixels. In order to perform this task, the user should specify the inner and outer radii, r_{in} and r_{in}, for the operating annulus. Any object in the image with a scale size smaller than the r_{in} is filtered and replaced by the median of local background (i.e., the annulus). Consequently, the selection of the r_{in} is crucial. In an attempt to leave the real galaxies unaffected, the choice of r_{in} must be large enough to exceed the apparent radius of largest galaxies in the image.

Moreover, we also use segmentation map to mask any real object that presents in the image during the filter- ing process, to further prevent the flux of galaxies being over-subtracted. The Segmentation map was created by running SExtractor cold+hot mode. However, in view of ICL-bCGs blending, the outskirts of bCGs and ICL can not be clearly separated, which means that in any case the segmentation map can not accurately describe the bCG's area. By adjusting the detection parameters, we generated a special segmentation map with less aggressive coverages for our selected bCGs. We have checked that for relatively fainter objects the image segments can properly capture all the flux, but for bCGs only central areas are enclosed. The left panel shows the original F160W image, and the right panel is the segmentation map.

The aim of this less-aggressive-mask strategy is to ensure not only the ICL, but also the outskirts of bCGs to participate the median filtering process. With real galaxies completely smoothed away, the resultant filtered (smoothed) image exhibits uneven large-scale light distribution, primarily consisting of ICL and outer, diffuse part of bCGs. We consider this

[1]The Image Redcution and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the US National Science Foundation.

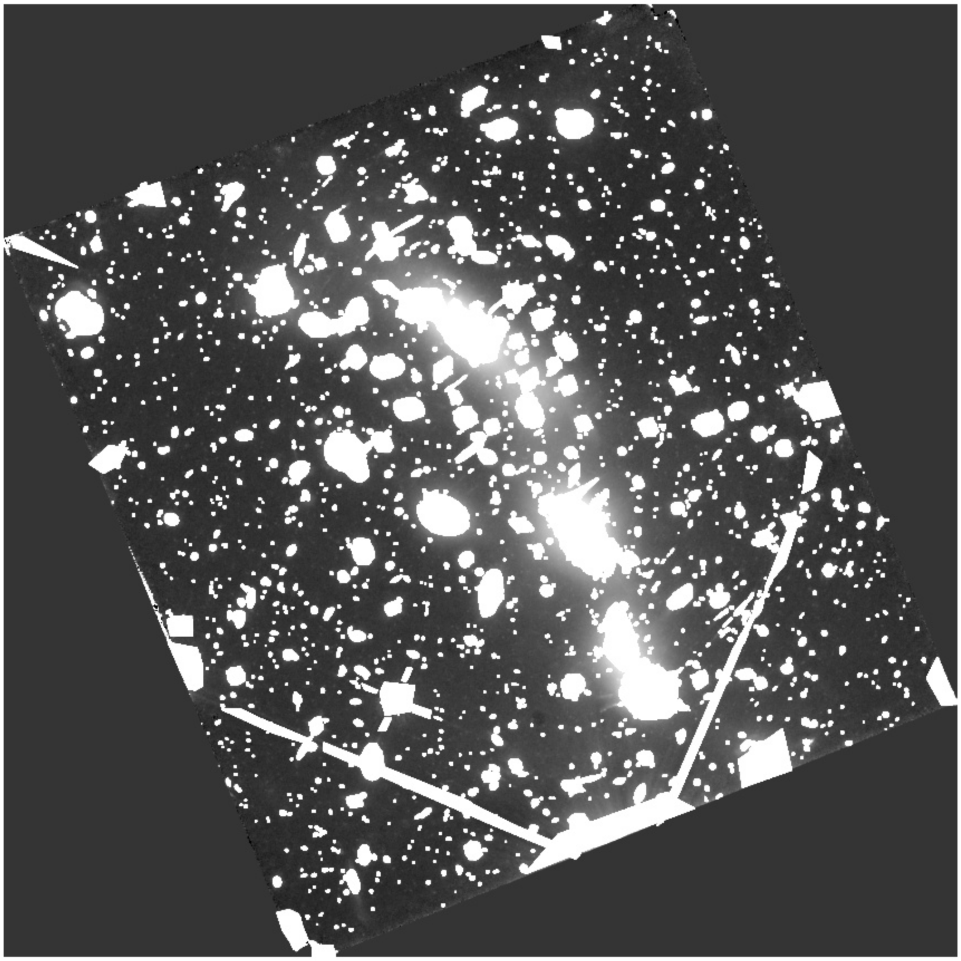

Figure 2: . The ‘Masked’ science image that is obtained by converting pixels in the segmentation map to the value of 10^6. The image is displayed in a gray-scale color and locked to the same asinh scale.

smoothed image as a rough approximation of real ICL light distribution, which is then subtracted from original, leaving behind real sources (they are mostly small, discrete galaxies) on a globally flat image background. The advantage of this strategy is to subtract the outer envelopes of bCGs in advance, together with ICL, before the following galaxy parametric modeling (see next subsection), since it is highly uncertain to parametrically model such diffuse substructure due to its low-surface brightness properties. Nonetheless, IRAF/RMEDIAN routine will perform the masking directly upon the original image by rejecting pixels above specified threshold, instead of accepting separate mask image. Using previous segmentation map as the reference, we converted the corresponding pixels in the original image into the values exceeding predefined threshold, namely 10^6 electrons. We then use this ‘masked’ science image (shown in Figure 2) as the only input for the ring median filtering.

As regards to the selection of median filtering annulus, we repeatedly run the procedure with different annuli (rings) spanning a wide range of sizes. We discovered that using ring (i.e., annulus) median filtering would introduce discernible noise pattern in the filtered back-

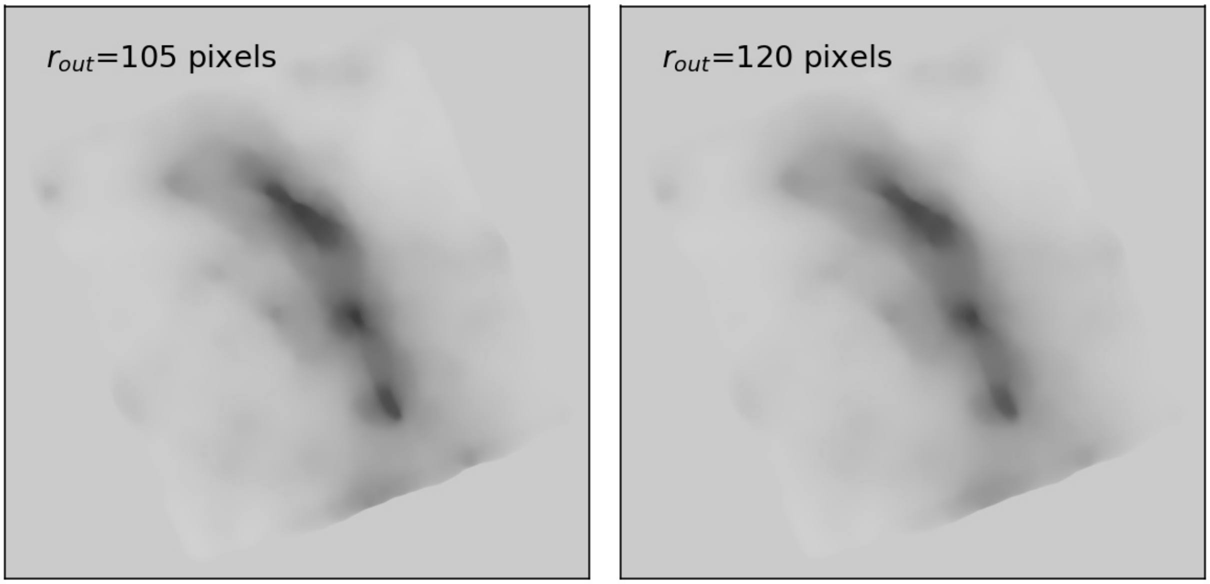

Figure 3: . Left: ICL map derived using r_{out}=105 pixels; Right: ICL map derived using r_{out}=120 pixels.

ground image, leading to large-scale negative regions in the background-subtracted image. We consequently use circle median filter that is equivalent to ring median filter with $r_{in} = 0$ to carry out the analysis, even though it is more computationally expensive. To determine the optimal r_{out}, we experiment the procedure by varying r_{out} from 105 to 180 pixels, in steps of 5 pixels. The lower limit r_{min}=105 pixels is the Kron radius of largest image segment, corresponding roughly to a physical radius 33.6 kpc, sufficient to include even the largest bCGs. This ensures that any real object with $r \leq r_{min}$ is enclosed and centered within this filter, such that the calculated median value corresponds to the genuine background level. On the other hand, the experiments for $r_{out} \geq r_{max}$=180 pixels are redundant and meaningless, except that the computational time is dramatically increased. Based on the visual inspection of filtered background images, we found their appearances (i.e., large-scale diffuse structures) are quite resemble over our defined radius range.

To access whether varying r_{out} value would affect the subsequent measurement from a quantitative point of view, we compared two catalog that are derived from background-subtracted images by using r_{out}=105 and 120 pixels, respectively. The left panel of Figure 3 show the ICL model derived using r_{out}=105 pixels, while the right one is derived with r_{out}=120 pixels.

To achieve this, we run SExtractor cold+hot mode separately on the background-subtracted images of both cases, with same configuration parameters. We cross-matched the two catalog and then compared their SExtractor parameters FLUX_RADIUS and MAG_BEST, respectively. Looking at the two panels of Figure 4, we can see that the measurements on both images are consistent with each other, without any evident systematic trend. This demonstrates that our following source detection and measurement are not r_{out}-dependent. We eventually adopt $r_{out} = r_{min}$=105 pixels as the optimal solution in our circle median filtering, for the sake of high-resolution filtering and saving computation time.

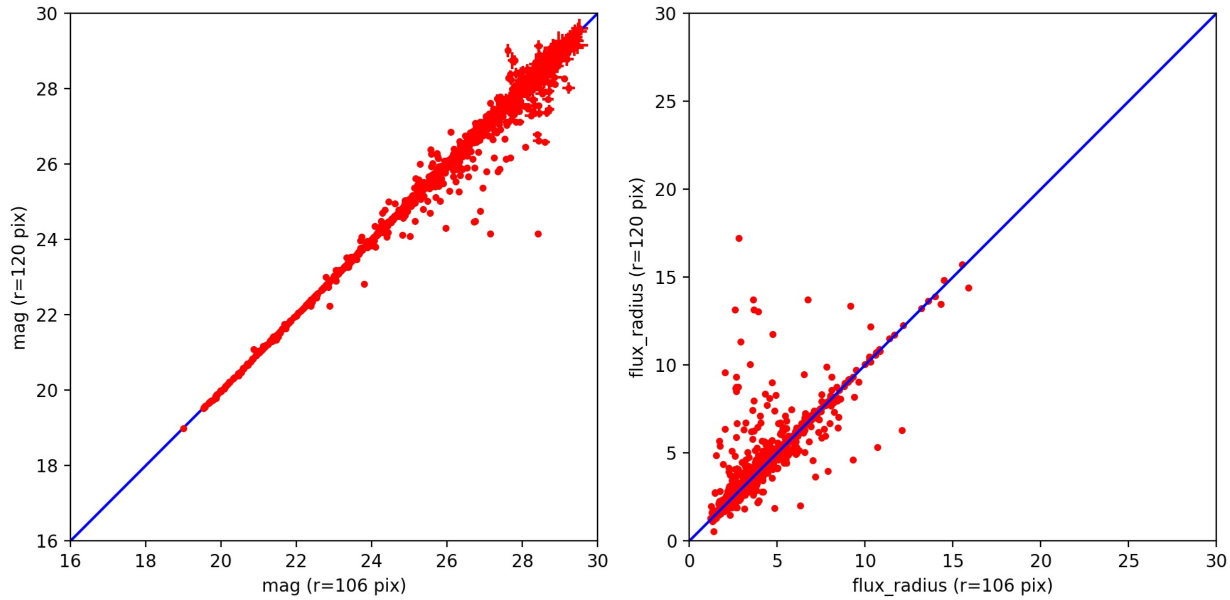

Figure 4: . Comparison of two matched catalog which are derived from background-subtracted images using r_{out}=105 and 120 pixels, respectively. Note that the bCGs are subtracted as well before source extraction. Left panel: Comparison of SExtractor parameter MAG_BESTs from two catalog. Right panel: Comparison of FLUX_RADIUS. The blue solid lines indicate 1:1 relationships. The red filled circles with errorbars represent the matched sample.

The whole filtering procedures are summarized in Figure 5. In the second panel of Figure 5, this segmentation map is overlaid onto the science image with cyan color, for illustration purpose. The third panel of Figure 5 shows the resulting filtered background, which consists of ICL and peripheries of bCGs. The fourth panel gives the background-subtracted image. We can see that the diffuse component has been efficiently removed, with cluster background being globally flat and the visibility of faint sources being enhanced. Otherwise, image segments will be erroneous, particularly for sources in the central region.

We stress that the goal of this step is only to obtain and subtract an approximated ICL model, so as to derive a residual image on which photometry of the faint sources can be carried out reliably. Although in this step the low surface brightness peripheries of extended bCGs have been also subtracted, the population of fainter galaxies is unaffected. However, this is not worthy to be a concern because these bCGs will be the targets to be subtracted temporarily as well in the next step, in order to simplify faint source detection and measurement. In addition, median filtering is a more efficient way to remove the faint, diffuse peripheries of bCGs than the parametric modeling. Removing them in this step is therefore a better choice.

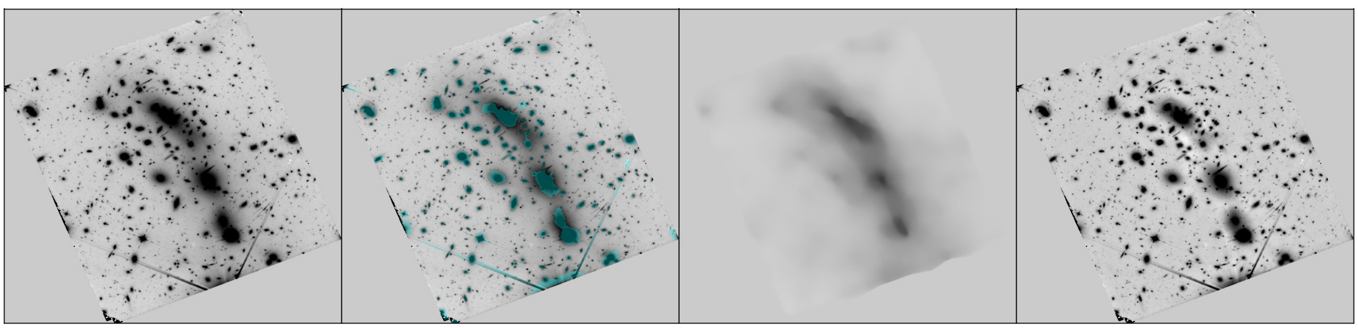

Figure 5: .Illustration of our ICL subtraction method. From left to right: original image, original image with segmentation map overlaid (cyan color), filtered background image using r_{out}=105 pixels as described in the text, background-subtracted image. All images are displayed in an inverted color and locked to the same asinh scale.