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GALAXIES AS A PROBE OF GRAVITATIONAL WAVES AND DARK MATTER: RESULTS FROM THE DARK ENERGY SURVEY

Thesis submitted for the Degree of Doctor of Philosophy of the University of London

by

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To my mum, dad and brother, who have always inspired me, supported me and loved me.

I, Antonella Palmese, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis. In particular I note these contributions:

- The work presented in Chapter 2 has been published with the DES Science Verification data release at `https://des.ncsa.illinois.edu/releases/sva1`, ANNz2 has been written by Iftach Sadeh, Ofer Lahav and Filipe Abdalla, the BMA code has been written by James Annis and myself.

- The work presented in Chapter 3 has been published in Palmese et al. (2017). GalFit runs have been performed by Federica Tarsitano and William Hartley, pixel color magnitude diagrams have been produced by Chris Conselice. The DES gravitational wave follow up program involves the effort of a whole team composed by roughly ten people. The host matching work has been performed with the help of DES Supernovae experts. The whole pipeline has been used in the analysis of GW170814, which will shortly be published in Zoheyr et al. 2018. My contribution to the DECam GW follow up work partially described in this chapter has granted me co-authorship in LIGO Scientific Collaboration et al. (2017), Soares-Santos et al. (2017), Scolnic et al. (2017) and Cowperthwaite et al. (2017).

- The work presented in Chapter 4 has been published in Palmese et al. (2016).

- The work presented in Chapter 5 will shortly be published in Palmese et al. 2018 and Welch et al. 2018. Palmese et al. 2018 is currently undergoing the DES review process required for submission. The membership probability assignment work has been lead by Brian Welch, with major contribution by James Annis, Huan Lin, Marcelle Soares-Santos and myself. The weak lensing mass-calibration of the mass proxy presented in Palmese et al., 2018 has been published in Pereira et al. (2018), who lead the work with contributions by our same team.

- The work presented in Chapter 6 will also shortly be published in Palmese et al. 2018. In the last sections I present work on Intra–cluster light, which has been lead by Yuanyuan Zhang and to which I gave major contributions. This work is undergoing the DES review process and will shortly be published in Zhang, Yanny, Palmese et al. 2018. The work on the effect of the Intra–cluster light on photo-z has been lead by Daniel Gruen in particular for what concerns the weak lensing formalism, and will shortly be published in Gruen, Zhang, Palmese et al. 2018.

Abstract

FIRST PARAGRAPH MUST BE IN HERE.

OTHER PARAGRAPHS FOLLOW.

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"So remember, look at the stars and not at your feet."

Stephen Hawking

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Chapter 1

Introduction

"The mind loves the unknown. It loves images whose meaning is unknown, since the meaning of the mind itself is unknown."

René Magritte

In this introductory chapter, I present the main topics necessary to understand the contents of this thesis. I start from an introduction to cosmology, to then focus on the main areas treated in my work: galaxy evolution, galaxy clusters and gravitational waves. In particular, I stress the importance of galaxy evolution studies for clusters cosmology and gravitational wave optical follow ups.

2 pages introduction, then 2 pages for each topic.

1.1 Cosmology

Cosmological probes

1.2 Galaxy clusters

1.3 Galaxy evolution

Halo model

LF/SMF

Figure 1.1: Total stellar content locked up in galaxies as a function of halo mass compared to the cosmic baryon fraction measured by the Wilkinson Microwave Probe (WMAP5; Dunkley et al. 2009). Left panel: Our prediction from the z1 bin m ($z < 0.37$). Right panel: Our three redshift bins. z1 is shown by the solid dark blue line, z2 is shown by the blue line, and z3 is shown by the turquoise line. Dotted lines show the contribution to Mtot from the central galaxy and dashed lines show the contribution from satellite galaxies. Shaded regions represent the errors on M tot /M . M tot is dominated by the central galaxy at $M < 2 \times 10^{13} M_\odot$ and by satellites at $M_h > 2 \times 10^{13} M_\odot$.

From Leauthaud et al. (2012a): The transition between the two regimes is driven by the steep decline in Mcen/M at $M > 10^{12} M_\odot$. This decline occurs as the contribution from satellites begins to rise. One might then naturally ask if central galaxies in group-scale halos experience stunted growth simply because stellar mass is accumulating within the halo in the form of satellite galaxies, instead of merging onto the central galaxy. Figure 16 reveals that this is not the case. Indeed, the solid line in this Figure demonstrates that the total stellar mass fraction of halos declines at $M > 10^{12} M_\odot$.

1.4 Gravitational waves

Einstein 1915, LIGO, VIRGO

1.4.1 LIGO events

4 BBH events, BNS

1.4.2 The electromagnetic counterpart

H0 estimation

1.5 The Dark Energy Survey and DECam

The DES[1] is an optical-near-infrared survey that is imaging 5000 deg^2 of the South Galactic Cap in the $grizY$ bands over 525 nights spanning almost six years. The survey is being carried out using a ~ 3 deg^2 CCD camera (the DECam, see Flaugher et al. 2015) mounted on the Blanco 4-m telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. DES started in 2012 with a testing period (November 2012 – February 2013) called DES Science Verification (SV)[2]. The data used in this work come from the first three years of observations (September 2013 – February 2016) and cover $1,839$ deg^2 with up to 4 passes per filter. It also includes Target of opportunity time from the fouth year of observations At the time of writing, five observing seasons have been completed.

The survey strategy is designed to optimize the photometric calibration by tiling each region of the survey with several overlapping pointings in each band. This provides uniformity of coverage and control of systematic photometric errors. This strategy allows DES to determine photometric redshifts of $\sim 300,000$ galaxies to an accuracy of $\sigma(z) \simeq 0.07$ out to $z \gtrsim 1$, with some dependence on redshift and galaxy type, and cluster photometric redshifts to $\sigma(z) \sim 0.02$ or better out to $z \simeq 1.3$ (The Dark Energy Survey Collaboration 2005). It will find ~ 100 million clusters and also provide shapes for approximately 200 million galaxies for weak lensing studies. For further information, see The Dark Energy Survey Collaboration (2005).

The DES Data Management (DESDM) pipeline was used for data reduction, as described in detail in Sevilla et al. (2011), Desai et al. (2012) and Mohr et al. (2012). The process includes calibration of the single-epoch images, which are co–added after background subtraction and then cut into tiles. The source catalogue was created using Source Extractor (SExtractor, Bertin & Arnouts 1996*a*) to detect objects on the

[1] `www.darkenergysurvey.org`
[2] For public data release see: `http://des.ncsa.illinois.edu/releases/sva1`

riz co-added images.

The data used in this thesis also includes target of opportunity time from the DECam Gravitational wave follow up program, and Anglo-Australian Telescope (AAT) target of opportunity time data. Other pubicly available datasets have been used (VHS, HST, 2dF, 6dF, 2MASS).

1.6 Thesis Outline

Throughout this work we assume a ΛCDM flat cosmology with $h = 0.7$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ unless otherwise stated. The notation adopted for the cluster mass and radius follows the one often used in literature. The radii of spheres around the cluster centre are written as $r_{\Delta m}$ and $r_{\Delta c}$ where Δ is the overdensity of the sphere with respect to the mean matter density (subscript m) or the critical density (subscript c) at the cluster redshift. Masses inside those spheres are therefore $M_{\Delta m} = \Delta \frac{4\pi}{3} r_{\Delta m}^3 \rho_m$ and similarly for $M_{\Delta c}$. In the following, we quote $\Delta = 200$, which roughly corresponds to the density contrast at virialisation for a dark matter halo at $z = 0$. In order to convert between the different mass definitions we use the Python Colossus tools (Diemer 2017). Logarithms indicated as Log have base 10.

Chapter 2

Galaxy Spectral Energy Distribution methods and applications

"Everything we see hides another thing, we always want to see what is hidden by what we see. "

René Magritte

The work presented in this Chapter is part of **Palmese et al., 2018***, currently in the DES review process, and of my contribution to* **Bonnett et al., 2016, PRD 94, 4** *with photometric redshift estimation with ANNz2.*

2.1 Introduction

In this Chapter we describe the methods used in this thesis to evaluate galaxy properties, from photometric redshifts to stellar masses and star formation rates.

2.2 Redshift

2.3 Methods

2.3.1 Bayesian Model Averaging algorithm

A major cause of uncertainty in stellar mass estimation from broadband photometry is in the model assumptions (see e.g. Mitchell et al. 2013) that are needed in model fitting techniques. These assumptions mainly involve redshift, star formation history (SFH), the initial mass function (IMF), the dust content and the knowledge of stellar evolution at all stages. We therefore choose not to ignore the uncertainty on model selection and use a set of robust, up-to-date stellar population synthesis (SPS) models and average over all of them, marginalizing over the model uncertainty. The method used here is called Bayesian Model Averaging (BMA, see e.g. Hoeting et al. 1999). BMA has already been successfully applied to galaxy SED fitting parameter estimation in Taylor et al. (2011).

Our code can be used to estimate physical parameters of galaxies (stellar masses, specific star formation rates, ages, metallicities) as well as cluster stellar masses and total SFR (when provided with cluster membership probabilities), and it is publicly available at `https://github.com/apalmese/BMAStellarMasses`.

The BMA starting point is Bayes' theorem, through which we can write the posterior probability distribution $p(\bar{\theta}_k|D, M)$ of the set of parameters $\bar{\theta}_k$ given the data D and the model M_k:

$$p(\bar{\theta}_k|D, M_k) = \frac{p(D|M_k, \bar{\theta}_k)p(\bar{\theta}_k|M_k)}{p(D|M_k)}\,, \tag{2.1}$$

where $p(D|M_k, \bar{\theta}_k)$ is the likelihood, $p(\bar{\theta}_k|M_k)$ is the prior probability of the parameters given the model M_k, and $p(D|M_k)$ is the evidence.

The model averaged posterior distribution of the parameters θ_k is given by the sum of the single model M_k posteriors, weighted by the model prior:

$$p(\bar{\theta}_k|D) = \frac{\sum_k p(\bar{\theta}_k|D, M_k)p(M_k)}{\sum_k p(M_k|D)}\,. \tag{2.2}$$

From BMA it also follows that the posterior distribution of a quantity Δ is the average of

the single model posteriors for that quantity, weighted by their posterior model probability:

$$p(\Delta|D) = \sum_k p(\Delta|D, M_k)p(M_k|D)\,. \tag{2.3}$$

The posterior model probabilities can be computed by:

$$p(M_k|D) = \frac{p(D|M_k)p(M_k)}{\sum_k p(D|M_k)p(M_k)}\,, \tag{2.4}$$

where

$$p(D|M_k) = \int p(D|M_k, \bar{\theta}_k)p(\bar{\theta}_k|M_k)\mathrm{d}\bar{\theta}_k\,. \tag{2.5}$$

In our case $p(\bar{\theta}_k|M_k)$ is simply a delta function, as the parameters $\bar{\theta}_k$ (i.e. the SFH parameters, metallicities, etc.) fully define our models M_k.

From eq. 2.5 one can write:

$$\langle\Delta\rangle = \sum_k \bar{\Delta}_k p(M_k)\mathcal{L}_k\,, \tag{2.6}$$

where Δ_k is the mean Δ value from the model M_k. $\mathcal{L}_k$ is the likelihood $p(D|M_k)$ that we will reconstruct from the χ^2 distribution.

In our code, the mass-to-light ratio $M_\star/L$ is the quantity Δ. Its posterior mean over all the models considered is then used to estimate the stellar mass $M_\star$ of each single galaxy through:

$$\mathrm{Log}(M_\star/M_\odot) = \langle M_\star/L\rangle - 0.4(i - DM + \langle kii\rangle - 4.58)\,, \tag{2.7}$$

where $\langle M_\star/L\rangle$ is the weighted mean stellar–mass–to–light–ratio in solar mass units, i is the observed i band magnitude, DM is the distance modulus, $\langle kii\rangle$ is the weighted mean of the K-correction $i_{\mathrm{restframe}} - i$ and 4.58 is the $i-$band absolute magnitude of the Sun. Weighted means are considered over all models.

In this work we use the flexible stellar population synthesis (FSPS) code by Conroy & Gunn (2010) to generate simple stellar population spectra. Those are computed assuming Padova (Girardi et al. 2000, Marigo & Girardi 2007, Marigo et al. 2008) isochrones and Miles (Sánchez-Blázquez et al. 2006) stellar libraries with four different metallicities ($Z =$

Figure 2.1: Comparison of galaxy stellar masses from Laigle et al. (2016) using COSMOS data with those computed with the BMA algorithm using DES data in different redshift bins. The lines represent the mean value of the distributions.

$0.03, 0.019, 0.0096$ and 0.0031). We choose the four-parameter SFH described in Simha et al. (2014):

$$SFR = \begin{cases} A(t-t_i)\mathrm{e}^{(t-t_i)/\tau} & \text{if } t < t_i \\ SFR(t_t) + \Gamma(t-t_t) & \text{otherwise} \end{cases}$$

where t_i is the time at which star formation commences ($\sim$ 1 Gyr), t_t is the time when the SFR transitions from exponential to a linear fall off ($\sim$ 9 Gyr), τ is the exponential time scale, and Γ is the slope of the linearly decreasing SFR as a function of time t after t_t. Defining θ as $\Gamma \equiv \tan\theta$, we make the four parameters vary on a grid of values within the following ranges: $\tau \in [0.3, 13]$ Gyr, $t_i \in [0.7, 2]$ Gyr, $t_t \in [7, 13]$ and $\theta \in [-10, -80]$ deg.

For each observed galaxy we construct the likelihood $\mathcal{L}_k$ in Eq. (2.6) as $\mathcal{L}_k = e^{-\chi_k^2}$, with $\chi_k^2 = \sum_i \frac{(C_i - C_{k,i})^2}{\sigma_{C_i}^2}$ summed over the colors $g-r$, $r-i$, and $i-z$. C_i are the observed colors, while $C_{k,i}$ are the colors predicted by the model M_k. σ_{C_i} are the observed errors added in quadrature with a lower limit of 0.02.

Validation of the BMA method

In order to test our method for stellar mass estimation, we use as reference a catalog that overlaps with DES observations and has been proven to provide robust stellar mass estimates. Laigle et al. (2016) used LePhare to compute stellar masses with multiband data in 16 filters from UV to infrared over the 2 deg^2 COSMOS field. From this sample, matched to DES data, we cut all objects at $z = 0$ to eliminate stars, and at $z > 1.5$, as we do not expect DES to be able to estimate stellar masses beyond that value. Galaxies with i-band magnitude above 23.0 are also cut out. The remaining sample comprises galaxies with $SNR > 10$ in DES, for which we compute stellar masses using the BMA code and DES data. The bias distribution given by the difference in log galaxy stellar mass between the two samples $\mathrm{Log}(M_\star^{\mathrm{COSMOS}}) - \mathrm{Log}(M_\star^{\mathrm{BMA}})$ is shown in Figure 2.1. Mean bias and scatter (that we quantify as the standard deviation of the distribution) are below the typical error on galaxy stellar masses from SED fitting (~ 0.2 dex) in the redshift range $0.2 < z < 0.6$, where we expect good performance for optical surveys such as DES. At higher redshift, it is harder to constrain the optical to near-infrared (NIR) SED with the DES bands and therefore the scatter increases. Also at low redshifts ($z < 0.2$), the 4000Å break is harder to constrain, as it is blue-ward of the g-band effective wavelength. The scatter will also be partially due to the fact that the COSMOS stellar masses are not "true" stellar masses, and will depend on the assumptions and methodology in Laigle et al. (2016). The slight bias that seems to exist in our DES stellar masses, particularly towards higher redshift, is probably due to the degeneracies between stellar mass and dust extinction. Laigle et al. (2016) are able to constrain dust extinction better than in this work because of the information brought by the infrared data available to them.

2.3.2 LePhare

2.3.3 ANNz2

ANNz2 (Sadeh et al. 2016) [1] is an updated version of the neural network code ANNz (Collister & Lahav 2004). ANNz2 differs from its previous version by incorporating several additional machine learning methods beyond Artificial Neural Networks (ANNs), such as Boosted Decision Trees (BDTs) and k-Nearest Neighbours (KNN) algorithms. These are

[1] `https://github.com/IftachSadeh/ANNZ`

Figure 2.2: ANNz2 performance on SVA1 data and BCC-UFig simulations, showing how the re- weighting affects the $n(z)$ of the validation sample.

implemented in the TMVA package (Hoecker et al. 2007)[2].

For the 100 ANNs run on the spectroscopic training set, we randomly varied: the number of nodes in each layer, the number of training cycles, the usage of the so-called *Bayesian regulator*, that reduces the risk of over-training, the type of activation function, the type of variable transformation performed before training (such as normalisation and PCA transformation), the number of subsequent convergence tests which have to fail to consider the training complete, and the initial random seed. After training is complete, the performance of each method is quantified through an optimisation process, which leads to a single nominal photo-z estimator for ANNz2. The entire collection of solutions is used in order to derive a $p(z)$, constructed in two steps. First, each solution is folded with an error distribution, which is derived using the KNN error estimation method of Oyaizu et al. 2008. The ensemble of solutions is then combined using an optimised weighting scheme. This methodology allows us to take into account both the intrinsic errors on the input parameters for a given method, and the uncertainty on the method itself. The methodology described above is what is called "randomised regression". Another important feature implemented in ANNz2 is the weighting method (Lima et al. 2008). It is therefore possible to give in input a reference sample and re-weight the training set to make its relevant variables distributions more representative of the former, this was technique was applied in this work. Examples of re-weighting are shown in Figure 2.2.

[2]TMVA is a part of the ROOT C++ software framework (**?**)

2.4 Applications for cosmology and galaxy evolution

2.4.1 Stellar masses with machine learning

2.4.2 DES Science Verification and Year 1 photo-z's catalogs

2.5 Conclusions

Chapter 3

Galaxy hosts for gravitational wave follow up

"Open your eyes, look up to the sky, and see"

Queen

The work presented in this Chapter is an extended version of **Palmese et al. 2017, ApJ 849L, 34P**, *with some information from the GW170817 DECam discovery paper* **Soares–Santos et al. 2017, 848, L16** *and work done as part of the DECam–GW follow up program yet to be published. The DECam–GW pipeline is shortly described in Herner et al. 2017 and has been used in the GW170814 analysis by Doctor et al., in preparation.*

The first identification of the optical counterpart (LIGO Scientific Collaboration et al. 2017) of a gravitational wave (GW) signal (Abbott et al. 2017) marks the beginning of a new era for multi-messenger astronomy. The coalescence of neutron stars is expected to have strong optical and near-infrared signatures in the form of a kilonova, the ejecta from which are heated by the decay of heavy nuclei produced via r-process. The optical counterpart to the BNS coalescence signal GW170817 was discovered independently by several collaborations using optical telescopes, including the Dark Energy Camera (DECam; Flaugher et al. 2015) GW team (Soares-Santos et al. 2017).

In this Chapter we exploit galaxy catalogs for follow ups of gravitational wave events, focusing on the follow up of the DECam golden event GW170817. We show how deriving

properties of galaxies, including redshifts, stellar masses and star formation rates, from photometric and spectroscopic surveys can boost our GW EM follow up strategy and understanding of GW sources. We start by presenting the DECam–GW follow up program in Section 3.1, focusing on the galaxy host matching of candidates which has been my main task within the follow up effort. In Section 3.2 we describe a study of NGC 4993, the host galaxy of the GW170817 GW event, the GRB170817A short gamma–ray burst (sGRB) and the AT2017gfo kilonova. We use Dark Energy Camera imaging, AAT spectra and publicly available data, relating our findings to binary neutron star (BNS) formation scenarios and merger delay timescales. NGC4993 is a nearby (40 Mpc) early–type galaxy, with i-band Sérsic index $n = 4.0$ and low asymmetry ($A = 0.04 \pm 0.01$). These properties are unusual for sGRB hosts. However, NGC4993 presents shell–like structures and dust lanes indicative of a recent galaxy merger, with the optical transient located close to a shell. We constrain the star formation history (SFH) of the galaxy assuming that the galaxy merger produced a star formation burst, but find little to no on–going star formation in either spatially–resolved broadband SED or spectral fitting. We use the best–fit SFH to estimate the BNS merger rate in this type of galaxy, as $R^{gal}_{NSM} = 5.7^{+0.57}_{-3.3} \times 10^{-6}\mathrm{yr}^{-1}$. If star formation is the only considered BNS formation scenario, the expected number of BNS mergers from early–type galaxies detectable with LIGO during its first two observing seasons is $0.038^{+0.004}_{-0.022}$, as opposed to ~ 0.5 from all galaxy types. Hypothesizing that the binary system formed due to dynamical interactions during the galaxy merger, the subsequent time elapsed can constrain the delay time of the BNS coalescence. By using velocity dispersion estimates and the position of the shells, we find that the galaxy merger occurred $t_{\mathrm{mer}} \lesssim 200$ Myr prior to the BNS coalescence. Note that in this work we may use the word "merging" for both the galaxy merging and the binary coalescence.

3.1 Gravitational wave follow up with DECam

A subset of GW events are expected to produce an electromagnetic (EM) emission that once detected, can provide information complementary to the waveform. Observing the EM counterparts offer a number of exciting scientific opportunities for cosmology, astrophysics and physics of the space–time, as we have described in Chapter 1. It is worth to stress that follow ups of BBH events are interesting even though most accepted BBH merger models do not predict an EM counterpart. In fact, there exist theoretical models

that could produce an EM signal (e.g. Loeb 2016, de Mink & King 2017): these are highly speculative, and assume the presence matter around the binaries in the form of circum–binary disks, or mergers happening within another star. There are three (not mutually exclusive) reasons for non-detections: (1) the probable sky regions of previous BBH detections were not searched comprehensively, (2) the BBH emission could not be distinguished from background transients, and/or (3) emission from BBH mergers is below the detectable threshold of current instruments. The possibility of (1) and (2) implies that detectable BBH emission cannot yet be ruled out, an placing upper limits on the emission places interesting constraints on theoretical models of BBH mergers.

With these benefits in mind, the LVC established partnerships with several collaborations around the globe, including DECam. Shortly after their first analysis of the GW signal, LVC shares with the partner collaborations a number of useful information, including the estimated distance to the source, the type of event (BBH, BNS, BH+NS mergers) and a map of the probability for the source of the event to be located in different positions of the sky. The LVC trigger information are communicated through a private network to the EM follow up partners, similarly to what is used in the gamma–ray community. The partner collaborations then decide whether to follow up the candidate, depending on factors such as the observability of high probability regions of the skymap from their telescope. Our EM follow up group consists mainly of DES members, and some external collaborators from the astronomical community, so that the program was named DECam–GW program. At present, DES is one of the primary users of DECam, and the DECam–GW team obtained ~ 4 nights of telescope time per year over the past two observing seasons, to be added to the DES allocation of ~ 105 nights per year. When a LVC trigger is received, the team uses dedicated observing strategy codes to decide whether to observe the event. If the decision is positive, DES observations are interrupted to start the follow up. The LVC might update their analysis of the event later on, resulting in a new skymap. If this happens while the follow up observations are still on, we modify our observing strategy accordingly.

3.1.1 Observing strategy

The observing strategy is mostly optimised to catch the EM emission expected from BNS merger models. These predict that the EM counterpart will fade in a matter of days to a week time from the GW trigger. It is therefore crucial to quickly identify, analyse

and eventually report candidates for further photometric and/or spectroscopic follow up. Clearly, DECam represents a premier instrument in the Southern emisphere to achieve these goals, given its wide and unique field of view. A general rule is to observe candidates three times: once as soon as possible after the trigger, 2 or 3 days later and about two weeks later, in order to observe the decline in flux of potential kilonova events. The first steps in planning the observations once the trigger is received consist in (i) produce 10σ limiting magnitude maps for the following 24 hours for 90 seconds exposures, (ii) calculate source detection probabilities for those maps and (iii) select pointings to be observed based on these probabilities. This is done for time slots of $\sim 1/2$ hour. The source detection probabilities are computed given the limiting magnitudes from (i) and a source model. At present, we do not have a realistic model for BBH EM and we just assume that the source has an apparent magnitude of $i = 20$. The kilonova model used for BNS and BH+NS events is a modified version of the model by Barnes & Kasen (2013). The detection probability maps are divided into DECam pointings, and time slots of roughly half an hour containing an integer number of pointings are created. The exposures are taken in $i-$band for BBH follow up and in an izz sequence for NS mergers, given that we expect kilonovae to emit in the optical–near infrared. This is done for all available time slots, and it is repeated for the following available nights.

3.1.2 Image processing

Once the images have been taken, they are processed through the difference imaging pipeline, initially developed for supernovae searches with DES by Herner et al. (2017). Supernova light curves are typically very similar to what we expect a kilonova to look like from our DES photometry, just bluer and brighter. It is thus natural to borrow some methods from SN searches. The difference imaging consists in subtracting from the new follow up images the "templates", which are DECam images of the same area of the sky taken previously to the event. We search for new objects in the residual images obtained, which constitute our potential candidate transients. This pipeline is able to use as templates partially overlapping exposures, and also publicly available images taken with DECam outside of the DES allocated time. In particular, part of us in the DES-GW team are also involved in the BLanco Imaging of the Southern Sky (BLISS), a dedicated program aimed at providing templates in the whole observable southern sky (along with other science cases). BLISS has already observed 1000 deg^2 of the DECam observable sky

Figure 3.1: Illustration of the host matching classification for the transients to different galaxies. In this case, the tranients lies closer to the centre of the smaller galaxy, but the DLR (shown by the arrows) of the bigger galaxy is larger and its d_{DLR} will be smaller.

in *griz* which had not previously been covered.

3.1.3 Post–processing

After the images have been processed, we assess the outputs and create a candidate list to analyse. An important step consists in rejecting non–astrophysical artifacts that may arise from the difference imaging, for example close to CCD edges. This is achieved by classifying the candidate transients through a machine learning method that assigns a score between 0 (high probability of being an artifact) and 1 (high probability of being a real object). So far in the analyses we have assumed a cut in the score at ≥ 0.7, where the efficiency of this cut was measured from point sources injected into our images to be $\gtrsim 90\%$ in both i and z up to $z = 22$. Depending on the type of event, one may want to apply other cuts to the list of transients. The next step consists into rejecting the most likely contaminants to kilonova events: Supernovae (SN).

SN rejection and host matching

The light curve (i.e. the flux as a function of time) of a SN may look similar to a closer kilonova, given that the latter is meant to be redder and dimmer than the former. One plausible way of rejecting supernovae in a kilonova search consists in requiring that the observed flux of candidates has significantly declined within the first weeks from the trigger (e.g. Soares-Santos et al. 2016 require $S/N < 3$ at 24 days), given their longer lightcurve

lifetime. This cut will not exclude all the SN, especially those that exploded prior to the trigger. Assuming that those SN happen in galaxies, we identify those contaminant transients by matching them to galaxies, and associating the host galaxy redshift to the SN. If the SN results to be too far to be detected by the GW experiment, we identify it as a SN reject it as a contaminant. This is achieved by constructing a dedicated galaxy catalog with redshifts and morphological information over the whole DECam observable sky (i.e. the whole southern sky up to a declination of 30 deg) and defining a host matching method. In our catalog we include galaxies out to redshift $z < 0.4$, as that is the furthest distance we would be able to see a SN given the DES-GW strategy for 90 second exposures and a typical $i-$band absolute magnitude at the peak of the SN lightcurve of -19. Host galaxies are searched for in a catalog containing Y3Q2 DES data with LePhare photo$z$-s that I have computed using `MAG_AUTO` magnitudes and errors. These galaxies are complemented with 2MASS and SDSS galaxies available in the southern sky. Our host matching script queries the relevant DES Easyaccess database table to obtain transient coordinates which are then matched to potential host galaxies. The search is done for each candidate in the HEALPix[1] pixel at its position and all the 8 adjacent pixels. Our matching script searches within a 15 arcsec radius from the transient position and ranks all sources according to their dimensionless separation from the transient d_{DLR}, which is in units of directional light radius (DLR):

$$d_{\mathrm{DLR}} = \frac{\text{galaxy} - \text{transient angular separation (arcsec)}}{\text{DLR (arcsec)}}\,, \tag{3.1}$$

where the DLR is the elliptical radius of a galaxy in the direction of the SN in units of arcseconds. The DLR is computed from some basic morphological quantities from SExtractor: `A_IMAGE`, `B_IMAGE` and `THETA_IMAGE` . These are respectively, the profile RMS along the major and minor axis, and the position angle of the major axis.

This method has already been used for SN searches in by Gupta et al. (2016). In Figure 3.1, the DLR for each galaxy is represented by the blue arrows. The maximum value allowed for the d_{DLR} is 4, if no galaxy meets these requirements the candidate is flagged as hostless. If one or more galaxies satisfy this condition, they are assigned a `DLR_RANK` depending on their d_{DLR}: the lowest d_{DLR} gets a rank of one, and so on up to rank 3, galaxies that are further than the third are excluded. The results are output to a

[1] `http://healpix.sourceforge.net`

Figure 3.2: Probability sky map from LIGO containing 90 and 50% of the probability for the EM counterpart location (solid lines for the updates version, dashed for the first skymap) for GW150914 (left), GW151226 (middle) and GW170817 (right). Red hexagons are the DECam pointings taken as part of the follow–up program. The yellow point in the right hand side panel indicates the position of the kilonova. From Soares-Santos et al. (2016), Cowperthwaite et al. (2016) and Soares-Santos et al. (2017) respectively.

text file and written to the DES database SNGALS table.

At present we have not put any cut at low redshift for the SN host matching catalog, and therefore matches output from the same code can be used to match potential GW counterparts to host galaxies by separating the matches depending on their redshift, and on the maximum redshift at which the counterpart can be as provided by LIGO.

3.1.4 Results from past observing seasons

During the first LIGO observing season we followed up the two BBH events GW150914 (Soares-Santos et al. 2016; Annis et al. 2016) and GW151226 (Cowperthwaite et al. 2016). Neither of the searches found a credible EM counterpart, as all candidates were rejected as background. This result is not surprising, given that (1) we do not expect an EM counterpart to BBH mergers and (2) the observed area was relatively small (11% and 3% of the LIGO BAYESTAR updated probability map). The large 90% probability region is clear in Figure 3.2. During the second observing run, joint detections from LIGO and Virgo were able to reduce these regions by roughly one order of magnitude, from thousands/hundreds of sq. deg. to hundreds or tens. O2 was a lot more fortunate for the DECam-GW program: we were able to follow up two golden events triggered within 3 days, GW170814 and GW170817, both having 90% probability regions fully within the DECam observable sky. GW170817 was followed up extensively, and we imaged 70deg^2 in i and z band, corresponding to 80.7% of the final probability map. A bright optical transient

Figure 3.3: Possible formation channels for binary neutron stars. *Left:* pure or secular star formation scenario. The binary is formed as a system during some star formation event, and follows the usual steps of stellar evolution: the most massive of the two stars undergoes a supernova event and becomes a neutron star.

was detected in our images at 11.4 hours after the GW trigger, and we found it located at $10.6''$ from the centre of NGC 4993 at redshift $z = 0.0098$. This redshift is consistent with the distance of 40 ± 8 Mpc reported by LIGO, provided that $H_0 = 70\text{kms}^{-1}\text{Mpc}^{-1}$. The apparent magnitudes of the transient at its first detection were $i \simeq 17.30$ and $z \simeq 17.45$, corresponding to an $i-$band absolute magnitude of $M_i = -15.7$, consistent with what expected from kilonova models. After performing the difference imaging, we found $1,500$ potential transient candidates, all but one rejected as background sources after some simple selection cuts, which include rejecting SN events. Thus the candidate found in NGC 4993 is the only plausible GW counterpart, and we reject chance of coincidence at the 99.5% confidence level. Our analysis of the GW170814 follow up images is on–going and still blinded. However, we find that our method for SN rejection through galaxy matching allows us to exclude $\sim 50\%$ of candidates with a machine learning score of ≥ 0.7. This method has been tested on SN events simulated with SNANA (Kessler et al. 2009).

3.2 GW170817 Host galaxy follow up with DECam

While the models predicting optical and NIR emission from the coalescence of binary neutron stars are widely accepted in the astronomical community, the formation of the binary and the physics involved in merging are still a matter of debate (Lipunov et al. 1997; Faber & Rasio 2012). In this work we use this DECam data and supplement it with

Hubble Space Telescope, AAT spectroscopic data and with publicly available datasets to understand the source of GW170817 in the context of its host galaxy and the local environment. In particular, we relate the BNS formation to the dynamics and stellar evolution of the host over time, asking whether the binary system was born as such, or whether dynamical interactions caused its formation. Usually it is assumed that BNSs form through the scenario that we call "pure star formation". In this case, the binary of two massive stars is formed as a system during some star formation event, and follows the usual steps of stellar evolution: the most massive of the two stars undergoes a supernova event and becomes a neutron star, and before the second star also undergoes a SN explosion, there is a "common envelope phase" in which the NS is orbiting in the outer layers of the other star. Once the second star also becomes a NS, if the binary is still bound after the two explosions, and it is close enough to merge within a Hubble time, then this system will be a source of GW emission at merging that we can observe.

Dynamically–driven binary formation has been proposed for BBH (e.g. Rodriguez et al. 2016). By dynamically–driven, we mean any dynamical interaction that may facilitate the formation of a BNS that can merge in less than a Hubble time. In the simplest case, two single NS may form a binary system due to a close encounter. Given the typical dimensions of NS, their cross sections are not large and this is only a possibility in very dense stellar environments. Other dynamical processes may intervene: a widely separated binary system may be brought to a orbit on a shorter distance due to interactions with a third body, or an existing binary system including one NS may capture another NS. See Figure 3.3 for a schematic representation of the two different scenarios presented.

Previous studies (Carter et al. 1988) classified this galaxy as an atypical elliptical galaxy with faint concentric shells and spectral features suggesting that the galaxy has undergone a merging event. Several analytical and numerical studies support the galaxy merger scenario for the formation of shells in galaxies (e.g. Quinn 1984; Pop et al. 2017), and show that the distribution of shells can constrain the time of the merger event. We study the evolution of this galaxy to discern between different BNS formation scenarios and estimate the rate of BNS formation in early-type galaxies, using Dark Energy Survey (DES) data to place NGC4993 in the context of the galaxy population.

3.2.1 Data

Photometric data: DECam, VHS and HST

The DECam images used in this work were taken as part of the DECam-GW follow up program between the nights of 2017 August 17 and September 1, using $ugrizY$ filters. We also use public $ugrizY$ DECam data from June 2015 to avoid contamination in the transient region. In addition, we extract YJK data from the VISTA Hemisphere Survey (VHS; McMahon et al. 2013), covering the host galaxy. The images are coadded and registered to a common pixel scale ($0.2636''$) using `SWARP` (Bertin et al. 2002) with 3.5 sigma clipping to remove cosmic ray artifacts. An RGB coadded image of the galaxy is presented in Figure 3.4. We build a χ^2 detection image from the r, i and z-band data and run SExtractor (Bertin & Arnouts 1996a) in dual mode on the coadded images.

The photometry is corrected for galactic extinction. In order to compare the galaxy properties to a broader sample, we also use DES data from the first year of observations (Y1; Drlica-Wagner et al. 2017a). We use `MAG_AUTO` magnitudes unless otherwise stated.

NGC4993 was also observed during HST Cycle 24 (PropID 14840, PI: Bellini) using ACS in F606W. The data were publicly released in April 2017 and were accessed via the Hubble Source Catalog (HSC; Whitmore et al. 2016).

Spectroscopic data: 6dF and AAT

The 6dF Galaxy Survey (Jones et al. 2004) final release (Jones et al. 2009) includes an optical spectrum of the center of NGC4993 with an estimated redshift ($z = 0.009680 \pm 0.000150$).

Spectra of 14 galaxies with $v_{helio} \sim 3000$ km s^{-1} and within one degree radius of NGC4993 were obtained in one target of opportunity exposure of the AAOmega spectrograph at the Anglo–Australian Telescope (AAT) on 2017 August 27. Of those, 10 spectral fits passed quality cuts. All the spectra used here are centered on their galaxy nucleus with a $2''$ aperture.

3.2.2 Host morphology

CAS and Galfit

We begin our study of NGC4993 with an analysis of its morphological properties, employing the CAS non-parameteric light quantification (Conselice 2003) and parametric

Figure 3.4: *Left panel:* DECam coadded image of NCG4993 in *gri*. Shell structures indicative of a recent galaxy merger are clearly visible. *Middle panel:* *r*-band residuals from GALFIT after subtraction of the best-fit single Sérsic light profile. *Right panel:* F606W-band HST ACS image with a 3 component galaxy model subtracted. Dust lanes crossing the centre of the galaxy are evident. The green lines show the position of the transient. The BNS counterpart is only present in the middle panel.

Sérsic light profile fitting with GalFit (Peng et al. 2010). Both methods utilise a mask to exclude other sources in the image and the location of the kilonova event. The CAS system is able to pick out the salient features of galaxy morphology, allowing galaxy types to be assigned and identifying objects that are likely to have undergone a recent major merger. Meanwhile, fitting the light profile additionally provides us with an alternative estimate of the total magnitude and can reveal more subtle aspects of galaxy morphology within the residuals of the model-subtracted image.

The CAS system estimates three morphological parameters, concentration C, asymmetry A, and clumpiness S to classify objects. The concentration is defined as the logarithm of the ratio of the 80% to 20% curve of growth radii r_{80}, r_{20}:

$$C = 5 \times \log_{10}(r_{80}/r_{20}) \,, \tag{3.2}$$

where the curve of growth is the integrated flux inside an aperture of radius r as a function of r. In general, elliptical galaxies tend to be more concentrated than disk galaxies and dwarf galaxies. In order to compute the asymmetry A we rotate the galaxy image I by 180° (R) and subtract it from its original image. The absolute value of these residuals is divided by the original image flux I, so that: $A = |I - R|/I$. The asymmetry is particularly related to the merger history. The clumpiness S is given by subtracting the original image of the galaxy by a smoothed image, so that the residual map only contains the high-frequency components of the light distribution:

$$S = 10 \times \Sigma_{x,y=1,1}^{N,N} \frac{(I_{x,y} - I_{x,y^\sigma}) - B_{x,y}}{I_{x,y}} \,, \tag{3.3}$$

where $I_{x,y}$ is the sky–subtracted galaxy flux in the pixel at (x, y), $I^{\sigma}_{x,y}$ is the map smoothed with a filter of width σ and $B_{x,y}$ is the background flux value in an area which is equivalent to that of the galaxy. Elliptical galaxies are usually very smooth and therefore present a low clumpiness value, while star forming galaxies can be very patchy and present a high S value. The CAS quantities are all defined within 1.5 times the Petrosian inverted radius at $r(\eta = 0.2)$, where η is a dimensionless quantity defined in terms of the surface brightness at radius r: $\eta \equiv I(r)/\langle I(r)\rangle$[2]. This radius was chosen because more than 99% of the light is included within $r(\eta = 0.2)$. For a detailed definition and analysis of these parameters see Bershady et al. (2000).

[2]This is the inverse of the definition that was introduced by Petrosian (1976)

GalFit is run on the DES and VHS images to fit the galaxy with a Single Sersic profile, performing the deconvolution with a PSF model extracted with PSFEx (Bertin 2011) and using input guesses from SExtractor . As reported in (Peng et al. 2010), the adopted Sérsic function has the following form:

$$\Sigma(r) = \Sigma_e \exp\left[-k\left(\frac{r}{r_e}\right)^{\frac{1}{n}} - 1\right], \tag{3.4}$$

where Σ_e is the pixel magnitude at the effective radius r_e. The Sérsic index n quantifies the profile concentration: if n is large, we have steep inner profile with a highly extended outer wing; inversely, when n is small, the inner profile is shallow and presents a steep truncation at large radii. In the case of $n = 1$ we have an exponential light profile. Galfit provides measurements for the free parameters of the Sérsic function: central position, integrated magnitude $m_{\rm tot}$, effective radius r_e measured along the major axis, Sérsic index n, axis ratio q and position angle θ. The integrated magnitude is determined through its definition as a function of the flux integrated out of $r = \infty$ for the Sérsic profile. The fit is done in two ways: band-by-band and simultaneously across all bands using a modified version, GalFit-m (Vika et al. 2013). In the second case the Sérsic fitting parameters are allowed to vary with wavelength as a second-order polynomial. All parameters are left free without constraints, except for the central position in the single-band fits. This is allowed to vary by only ± 1 pixel as it is well-constrained by SExtractor already.

In order to assess the stability of GalFit and obtain an estimate of the uncertainties on the measurements, each single–band run is performed 10,560 times, varying the inputs around their nominal values. We take the median as our final measurement and the standard deviation as the uncertainty.

Results

Following the definitions given in Conselice (2003), we find: concentration $C = 3.348 \pm 0.035$, asymmetry $A = 0.04 \pm 0.01$, and clumpiness $S = 0.05 \pm 0.05$. These values are typical for an early-type galaxy. In Figure 3.5 we compare these values to field galaxies of similar masses (within 0.2 dex of NGC4993) and redshifts ($z < 0.2$) from the GAMA survey, and to a sample of sGRB hosts (Conselice et al. in prep.) taken in F814W imaging from HST. NGC4993 stands out as peculiar with respect to other GRB hosts: such objects tend to lie on the more highly asymmetric side of late-type galaxies.

Figure 3.5: Concentration versus asymmetry for NGC4993 (in blue), compared to a sGRB hosts sample (Conseliece et al., in prep.) in red, and field galaxies (black dots) with stellar mass within ±0.2 dex of NGC4993 value and redshift $z < 0.2$. The lines separate different Hubble types as shown in Conselice (2003).

Filter	MAG_AUTO	Mag	r_e	n	ϵ	θ
u	14.24	14.15	61.8	3.2	0.15	-13.9
g	12.95	12.80	62.5	3.4	0.15	-12.8
r	12.08	11.90	63.5	3.7	0.16	-11.2
i	11.65	11.45	64.4	4.0	0.16	-9.9
z	11.34	11.13	65.3	4.3	0.16	-8.4
Y	11.13	10.96	65.7	4.4	0.16	-7.7
$Y_{\rm VHS}$	11.27	11.00	65.9	4.5	0.16	-7.5
J	11.00	10.77	67.3	5.0	0.17	-5.2
K_s	11.08	10.68	72.9	6.7	0.19	+3.5
		$\pm 5 \times 10^{-4}$	± 0.07	$\pm 3 \times 10^{-3}$	$\pm 4 \times 10^{-5}$	$\pm 5 \times 10^{-3}$

Table 3.1: Outputs from GALFIT parametric Sérsic fits performed on the $ugrizY$ DECam coadd images and $YJKs$ VHS data. The fit was joint across bands, allowing the effective radius, r_e (in pixels), Sérsic index, n, ellipticity, $\epsilon = 1 - b/a$, and position angle, θ, to vary with wavelength. One pixel corresponds to $0.2636''$. The final row lists indicative errors based on the single band analysis.

The results from the single Sérsic fit across all bands are summarized in Table 3.1 (the band-by-band fits give broadly consistent results). We find an increase in Sérsic index towards redder bands and a rotation in the position angle. This rotation of bluer versus redder bands suggests there could be two superimposed stellar populations with differing orientations. This may have arisen during the course of the galaxy's secular evolution but could also be caused by a minor galaxy merger, as indicated by the presence of shells.

The middle panel of Figure 3.4 shows DECam r-band residuals from GalFit and the position of the transient. At least four shell structures are clearly visible. Closer inspection with HST data (right panel in Figure 3.4) reveals a possible further broad inner shell, on which the transient seems to lie, and obvious dust lanes (visible also as a negative residual in the DECam version). The r-band absolute magnitude from a 4 sq.arcsec region around the transient location in the galaxy-subtracted template image is -10.65. This luminosity implies a rather high stellar density in the locale of the BNS coalescence. In summary, we find compelling evidence for a recent minor galaxy merger in NCG4993, and the location of the kilonova event with respect to the shells leads us naturally to ask whether there is a causal connection between the two.

From Figure 3.5 we see that clear major galaxy mergers are unusual amongst sGRB hosts. Furthermore, the other sGRBs are at cosmological distances and thus are mostly undergoing extensive galaxy formation through star formation or merging. If the hosts have to be related by some common features, this is an indication that NGC4993 has undergone some merging activity, but a minor merger such that the bulk morphology is still elliptical. We thus explore the possibility that the kilonova was a result of a recent galaxy merger in NGC4993.

3.2.3 Photometric and spectroscopic SED

SED fitting methods

We use `pPXF` (Cappellari & Emsellem 2004; Cappellari 2017), for the spectral fitting. It enables extraction of the stellar kinematics and stellar population from absorption line spectra of galaxies, using a maximum penalized likelihood approach. We use the Miles stellar libraries, and fit over the wavelengths $4000-7409$ Å, excluding the range $5500-5600$ Å of the 6dF spectrum, where a strong sky line contaminates the flux.

We use LePhare (Arnouts et al. 1999, Ilbert et al. 2006) for the broadband Spectral

Figure 3.6: Spectroscopic fit of the 6dF optical spectrum. The black line is the observed spectrum,the red line is the pPXF fit for the stellar component, and the orange line is the best–fit including ionized gas emission lines. The zoomed panels show H_β, OIII, NII and H_α lines. The green points at the bottom are the fit residuals, while the purple line is the gas-only best–fit model spectrum.

Figure 3.7: BPT diagram for NGC4993 (red star) and the other galaxies (black points) in the galaxy group with AAT spectra available. The dashed lines represent the Kewley et al. (2006) classification method for AGN, star–forming (HII) and composite (Comp) galaxies. Many of the group galaxies have very weak AGN or LINER-like emission. Error bars represent 1σ error from the propagation of fit errors on line strengths.

Figure 3.8: sSFR (left) and stellar mass (right) maps resulting from the pixel SED fitting of DES+VHS bands. Other objects have been masked out. x and y axes correspond to the map pixels. One pixel corresponds to a physical size of 0.526 kpc at the galaxy redshift.

Energy Distribution (SED) fitting. We add a 0.05 systematic uncertainty in quadrature to the magnitudes. The simple stellar population (SSP) templates used are Bruzual & Charlot (2003), with two metallicities ($Z_\odot$ and $2.5Z_\odot$), a Chabrier (2003) Initial Mass Function (IMF) and a Milky Way (Allen 1976) extinction law. The SFH chosen is lognormal:

$$\Psi(t, t_0, \tau) = \frac{1}{t\sqrt{2\pi\tau^2}} e^{-\frac{(\ln t - \ln t_0)^2}{2\tau^2}} , \tag{3.5}$$

as it is the most representative family of models with only two parameters (Gladders et al. 2013). Here t_0 and τ are the half–mass–time and width.

Motivated by our morphological analysis, we allow for an additional burst of recent SF. This is modeled as a Gaussian centered at t_{burst} with width of 10 Myr and peaking at a fraction $0.4 - 0.1$ of the peak of the log-normal SFH (as no evidence for strong late SF is found).

The same templates are used to perform spatially–resolved SED fitting across DES+VHS coadded images within 10×10 pixels, including the galaxy dust extinction. The other sources in the field are masked out using the segmentation map output by SEXTRACTOR.

SED fitting results

Figure 3.6 shows the best fit model of the 6dF spectrum, which results in a reduced χ^2 of 1.22. An analysis of the mass fraction in age shows that part of the core galaxy stellar population has a supersolar metallicity, but the weighted mean value $\langle [M/H] \rangle = -0.012 \pm$

Figure 3.9: Pixel color-magnitude diagram for the pixels covering NGC4993 from DECam g and r single epoch exposures taken previously to the BNS event. The core of the galaxy is shown in red, while the cyan points represent the 1.5″ around the location of the BNS event (10.6″ from the center).

0.010 is marginally consistent with solar metallicity. The mean age is 11.298 ± 0.054 Gyr, and the mass-to-light ratio is 5.23 ± 0.15 in r-band.

The stellar model fit reveals the existence of weak ionized gas emission lines. However, the line ratios from the fit suggests they are produced by a harder ionizing source than star-formation, formally lying in the AGN region of the Baldwin, Phillips & Telervich (BPT; Baldwin et al. 1981) diagram. Blanchard et al. (2017) argue that there is a weak AGN present in the core of the galaxy on the basis of radio and X-ray emission, and so we conclude there to be no evidence of recent star-formation from the 6dF spectrum, irrespective of the highly uncertain O III/H_β ratio. A comparison of galaxies in the group using AAT spectra and classification by Kewley et al. (2006) is shown in Figure 3.7.

Given the evidence of dust presence in the HST study, we estimate the dust content using the Balmer decrement (Berman 1936) observed from the spectrum. The reddening is $E(B-V) = 0.12 \pm 0.50$ in the case of $I(H_\alpha)/I(H_\beta) = 3.1$, which is expected in the case of AGN activity. We therefore restrict our dust models to have reddening values $0.1, 0.2, 0.3, 0.4, 0.5$ in the photometric fits.

The photometric best–fitting template has a solar metallicity, a quickly declining log-normal SFH with $t_0 = 3\,\mathrm{Gyr}$ and $\tau = 0.1$. A low reddening $E(B-V) = 0.1$ is preferred, and the stellar mass is $(2.95 \pm 0.65) \times 10^{10} M_\odot$. The inclusion of a late SFH burst is

disfavored by the fitting apart from intermediate apertures.

Previous work found that the presence of dust lanes may bias the galaxy stellar mass from unresolved galaxy SED fits to lower values (Sorba & Sawicki 2015). The total stellar mass from fitting over the SExtractor segmentation map of NGC4993 is $(3.8 \pm 0.20) \times 10^{10} M_{\odot}$, more than 1σ higher than the unresolved SED fitting. The specific SFR (sSFR) and stellar mass maps from our pixel SED fits are shown in Figure 3.8, where the shell structure is clearly visible, suggesting that the sSFR is slightly more accentuated in the stellar halo compared to the inner parts. Younger ages (by ~ 2 Gyr) are also preferred in the outer regions, though we still do not find evidence for a star formation burst at late times, and explain our results by the stripping of stellar populations from the lower-mass galaxy in a minor dry merger. A dust model with $E(B-V) = 0.1$ is preferred in the inner few kpc, while $E(B-V) = 0$ is found outside. Despite the presence of dust lanes, an analysis of the HST photometry and a comparison with extinction models suggests that the effect of dust is not extreme, with reddening values that are consistent with 0.1 in the core. We therefore believe that the dust obscuration does not play a significant role in our SFR estimates.

Pixel Color Diagrams

In Figure 3.9 we show a color-magnitude diagram for all the pixels within the field of view of the DECam data near the galaxy. The image has been cleaned of stars and other contamination, thus all points come from the galaxy itself. The position of the GW source, $10.6''$ offset from the center, is the cyan colored pixels, while the center of the galaxy is shown in the red points. This galaxy is well represented by a pixel "main sequence" that is bluer at fainter levels, which is typical of early–type galaxy color gradients (e.g., Lanyon-Foster et al. 2007). We conclude that there is no significant difference between the transient position and other outer light, although it is bluer than the core region. This further supports the scenario in which the BNS formation is not related to some particular recent star formation event in this region.

3.2.4 Implications for the binary neutron star fomation and coalescence

BNS formation and delay time under the hypothesis of galaxy merger

In the most accepted shell formation scenarios the shells are stellar debris coming from the less massive, stripped galaxy, and the arcs form at the apocenter of the orbits of the infalling material (Quinn 1984).

Based on our results, we believe that NGC4993 experienced a dry minor galaxy merger with still visible signs. The shells are expected to be washed out within a time that depends on the velocity dispersion at their position. We estimate the shell survival time in two ways, based on the velocity dispersion of the galaxy as well as the velocity dispersion of the shell itself. From the 6dF spectrum the line–of–sight central velocity dispersion is $\sigma_v = (160.0 \pm 9.1)$ km s^{-1}. We estimate its value at the position of the transient. The velocity dispersion of early type galaxies drops from its central peak value at larger radii, and observations show that the maximum drop to the outer parts of ellipticals near the effective radius is $\sim 40\%$ of the central value (Emsellem et al. 2004). Based on the distance of the shell from the center, $R \approx 4$ kpc, we estimate that the dynamical time at this radius is $t_{\rm dyn} \equiv R/\sigma_v \approx 60$ Myr (the line-of-sight velocity is relevant here, given the shell's geometry, but e.g. if we assume a 3D isotropic velocity dispersion it would reduce the dynamical time by $\sqrt{3}$).

So far we have no measurement of the shell's velocity dispersion, but estimates from the literature suggest for similar shells in other galaxies $\sigma_v \approx 20$ km s^{-1} (Quinn 1984). This would give a dynamical time scale of $t_{\rm dyn} \approx 192$ Myr. Detailed simulations of shells in other galaxies suggest that survival time could be even larger that 1 Gyr, depending on the assumed scenario (Pop et al. 2017).

The survival time of the shell could be used as an upper limit for the time the minor merger took place, i.e $t_{\rm dyn} \geq t_{\rm merg}$, so we estimate $t_{\rm merg} \lesssim 200$ Myr.

If the BNS was formed as such in a shell, then we would have expected to see evidence for recent star formation, but we find no indication of this. In the absence of star formation it is plausible that the BNS coalescence was triggered by a dynamical process, e.g. NS-NS capture or the destabilization of a pre-existing wide-separation binary. These processes will be quite sensitive to the stellar density which, given the Sérsic index and the luminosity from the residual image found in section 3.2.2, is high in the center of NGC4993 and around the transient position. If this dynamical hypothesis is true, then the delay time

Figure 3.10: A schematic timeline of events for NGC 4993.

Δt_{NSM} between the BNS formation and coalescence is $\lesssim$ 200 Myr. Figure 3.10 shows a schematic timeline of the events described for NGC 4993.

Galaxy environment

If the binary formation is related to dynamical processes in galaxy merging as we are investigating here, then this is most likely to happen in galaxy groups and low mass clusters. According to the 2MASS catalog (Tully 2015), NGC4993 resides in a group, of which we analyze the remaining 7 galaxies. A spectral analysis shows that NGC4993 is not the only galaxy showing AGN activity (see Figure 3.7), but it is peculiar in terms of age, metallicity and mass-to-light ratio. It shows an older stellar population (the mean age of the other 13 galaxies is $\mathrm{Log}(Age) = 9.56 \pm 0.17$), lower metallicity (mean: $M/H = -0.31 \pm 0.11$), and higher M/L_r (mean: 2.41 ± 0.45) than the average. The group has a projected virial radius of $R_{vir} = 0.36$ Mpc and a line-of-sight velocity dispersion $\sigma_v = 143\mathrm{km\,s^{-1}}$ (Tully 2015). The crossing time is therefore $t_{\mathrm{cr}} \sim R_v/(\sqrt{2.5}\sigma_v) \sim 1.6$ Gyr.

If galaxy mergers are correlated to BNS coalescence, future GW studies could possibly concentrate on galaxy groups (but note that these are crowded regions and therefore matching candidates to a host could be difficult). In order to have precise measurements

of H_0, one needs to identify the host galaxy redshift clearly. When the match is clear, the properties of the type of host galaxy found could help future studies to select the right host galaxy or create galaxy catalogs of likely hosts for GW EM follow-up and untriggered kilonova searches (Doctor et al. 2017). In fact, large photometric surveys such as DES, LSST or WFIRST are expected to observe kilonova events at redshifts beyond the sensitivity of GW experiments, where the angular separation between galaxies decreases (Scolnic et al. 2017).

BNS merging constraints

We derive a constraint on neutron stars merging rate at time t by using:

$$R_{NSM}(t) = \alpha R_{NS}(t')\,, \tag{3.6}$$

where α is the fraction of neutron stars which are in binaries, $t' = t - \Delta t_{NSM}$ and the fraction of mass of formed stars that are NS is:

$$R_{NS}(t') = \int dM_\star \Phi(M_\star)\Psi(t_\star)\Theta_{NS}(M_\star)\,, \tag{3.7}$$

with $\Phi(M_\star)$ being the IMF, $\Psi(t_\star)$ is our best fit SFH, $\Theta_{NS}(M_\star)$ is 1 for star mass ranges of $8\,M_\odot < M < 20\,M_\odot$, zero otherwise. We drop the metallicity dependence in Θ_{NS} because we only consider a solar metallicity for the galaxy, as a result of our spectroscopic fit. $t_\star$ is the time when the progenitor of the NS was formed, therefore satisfying $t' = t_\star + t_{\rm life}$, with $t_{\rm life}$ being the lifetime of the progenitor before becoming a NS. We assume a $t_{\rm life} = 0.02$ Gyr, but our calculation is insensitive to this choice as the typical lifetime of these massive stars ($\sim 0.01 - 0.03$ Gyr) is much shorter than the timescale over which the SFH found for NGC4993 is changing at late times. We assume a Chabrier IMF, but this choice is not relevant as we are only exploring the high mass end of the IMF. Assuming $\alpha = 0.002$ and the distribution of Δt_{NSM} from Vangioni et al. (2016) (their Figure 3 for solar metallicity), and our best fit SFH from Eq. 3.5 with $t_0 = 3$Gyr and $\tau = 0.3$, we get a NS formation rate of $R_{NS}^{\rm gal} = 3.6^{+28}_{-3.6} \times 10^{-5}$ yr^{-1} and a BNS merger rate of $R_{NSM}^{\rm gal} = 5.7^{+0.57}_{-3.3} \times 10^{-6}$ yr^{-1} for the whole galaxy. Errors reflect the uncertainty on the SFH, which dominates our errors: they represent the two central quartiles of the rates distribution computed with the SFHs of the pixel SED fitting over the galaxy.

Given the sensitivity of the BNS merger event rate to the recent SFR of a galaxy, it is

Figure 3.11: Sample of galaxies from DES Year 1 data with available GalFit parameters, having size, surface brightness and Sérsic index within 10% of the best fit values for NGC4993. Roughly 15% of them present shell structures, while in the remaining galaxies we find also some spirals and barred spirals. In the top panels we show also the corresponding residual images for three galaxies from this sample. The first two clearly show shell structures, while the third also shows dust lanes.

somewhat surprising that GW170817 occurred in an old, early type galaxy. We therefore ask what is the probability of observing such an event in any early–type galaxy within the LIGO–detectable volume. To make this estimate we integrate the stellar mass function of early–type galaxies from Weigel et al. (2016) and scale the per–solar–mass rate from Eq. 3.6 to the mass contained within the LIGO detectable volume (radius 80 Mpc). We find $R_{NSM}^{\rm early} = 23^{+2}_{-14}$ yr^{-1}Gpc^{-3} resulting in $0.038^{+0.004}_{-0.022}$ expected events. This calculation assumes that the SFH of NGC4993 is representative of local early–type galaxies. In fact much of the mass will be contained in more massive, and on average older and less star–forming, galaxies. We contrast this with a similar calculation for all galaxy types, using the cosmic SFR density from Gladders et al. (2013), finding $R_{NSM}^{\rm all} \approx 270$ yr^{-1}Gpc^{-3} and ~ 0.5 expected events.

This result shows that it is unlikely that we observed one such BNS merger with LIGO over the combined nine months of operations in an early–type galaxy. The assumptions in the calculation include the fraction of NS that form in binaries ($\alpha = 0.002$) and the delay time distribution, both coming from binary star models (where the progenitors of the BNS were already a bound system) and satisfying Milky Way constraints. If the BNS formation mechanism is via dynamical interaction, our result could point to a higher value

of α or a shorter Δt_{NSM} for systems that recently underwent a galaxy merger, more so for those that have high stellar density (such as early–type galaxies). It is therefore of interest to know the fraction of galaxies similar to NGC4993 that show similar signs of a galaxy merger in the form of visible shells. We select galaxies from the first year of DES data with size, surface brightness and Sérsic index within 10% of the best fit values for NGC4993. We find 1100 such galaxies, and visually inspect them to identify shell galaxies. A subsample of those is shown in Figure 3.11. Only 15% of these objects display shells, and so NGC4993 is unusual amongst early-type galaxies.

On the other hand, Blanchard et al. (2017) find a median delay time of $11^{+0.7}_{-1.4}$Gyr under the assumption that the binary was formed through secular SF, and that no interactions disturbed the binary since it was formed $\sim$ 11Gyr. This is derived from the measured SFH, which is similar to what we find, and from which they find that 50% of the stellar mass of NGC4993 was formed $11^{+0.7}_{-1.4}$Gyr ago. This scenario is possible and cannot be excluded, although our study shows that it is unlikely.

Or results are far from conclusive evidence for a merger origin of BNS events. However, the coincidence of evidence for a recent merger in a galaxy for which a BNS event was otherwise improbable is compelling.

3.3 Conclusions

In this Chapter we have shown how galaxy properties are important not only for GW electromagnetic follow up strategies, but also to study the formation and evolution of the GW sources. In particular, we can use the SED fitting results that we get from the methods described in the previous Chapter to:

- Match the transients found from GW follow up searches to galaxies. The goal of this search is twofold. First, by identifying a GW source host with a photo-z or spectroscopic redshift, we can relate it to the distance provided by LIGO and use the GW event as a standard siren and measure cosmological parameters. Secondly, we can identify and reject Supernovae that contaminate our candidate list and restrict our analysis to a smaller sample.

- Study binary systems formation and evolution. In the case of GW170817, the star formation and the properties of the host galaxy showed that the fact that this event happened in NGC4993 was unlikely based on the current BNS models based on

pure star formation, and that these should be revisited in the future. Other works followed our line of thought and reached similar conclusions (Belczynski et al. 2017; Ebrová & Bílek 2018).

- Constrain the delay time of the GW sources, either through estimating a time for dynamical interactions in the case of dynamically–driven formation of the system (as in Palmese et al. 2017), or through a study of the star formation history (as in Blanchard et al. 2017).

Furthermore, galaxy catalogs such as the one described in this Chapter, can be used to point small FoV telescopes after a GW trigger towards galaxies with the properties that are most likely to be those of the host of the event. For example, one could assume that these events are most likely to happen where most of the stellar mass is, or in the most luminous or star–forming galaxies. However, only further follow ups will provide some statistics and will allow us to identify the galaxy properties of the most likely hosts.

Chapter 4

Stellar mass versus dark matter in galaxy clusters: RXJ2248

"I have forced myself to contradict myself in order to avoid conforming to my own taste."

Marcel Duchamp

The work described in this chapter is part of **Palmese et al., 2016, MNRAS, 463, 1486**.

4.1 Introduction

In the last decade, large photometric galaxy surveys, such as SDSS, have provided us with a massive amount of data that have proven to be extremely useful for studies of cosmology. On the other hand, smaller area but deeper surveys like the Hubble Space Telescope (HST) based Cluster Lensing And Supernova Survey (CLASH) (Postman et al. 2012), allowed us to characterise single objects with unprecedented precision. The importance of finding synergies between these surveys relates to several aspects of observation (e.g. target selection, photometric calibration) and data analysis (photometric redshifts, physical properties of galaxies). This is particularly relevant for overlapping ground–based and space–based surveys: the higher quality that can be obtained from space can enable calibration and tests for the data collected by ground–based telescopes.

α_{J2000}	δ_{J2000}	Redshift	Luminosity (erg s^{-1})
22:48:44.29	-44:31:48.4	0.348	3.08×10^{45}

Table 4.1: Main properties of the cluster RXC J2248-4431. The quoted luminosity is in the rest frame 0.1-2.4 keV band.

In this Chapter, we study the cluster of galaxies RXC J2248.7–4431 (RXJ2248 hereinafter). We make use of the synergies between DES and CLASH, and test in this way the performance of the early DES data at a catalog level (*i.e.* without making use of the images for the results). Photometric redshift (photo-z) and stellar mass results from CLASH are also used as a validation set for DES stellar mass estimates.

The aim of this work is twofold: the first goal is to compare between DES's wide area breadth and CLASH's small area precision for the cluster RXJ2248. In fact, checks using HST data had not been done before to test the DES data, although the similar optical filters and the additional UV and IR HST bands make CLASH an optimal candidate for validation and quantifying uncertainties of photometry, photo-z's and stellar masses. The second is to illustrate how an analysis of the stellar mass distribution of this massive cluster over the wider Dark Energy Camera (DECam) field of view can be done.

In Section 4.2, we start by describing the two surveys considered. The cluster is described in Section 4.3. The comparison of DES and CLASH, in terms of photometric redshifts and star/galaxy separation, is presented in Section 4.4. Section 4.5 contains the second part of this work, where we present the stellar mass results obtained from CLASH and DES, and compare the DES stellar masses to the total mass from the DES weak lensing analysis by Melchior et al. (2016). In the following, we assume a concordance ΛCDM cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$. In this cosmology, $1'$ corresponds to a physical transverse length of 295 kpc at the cluster redshift $z = 0.3475$.

4.2 Data

The data used for the analyses developed for this work come from DES and CLASH.

The fact that DECam has a ~ 3 deg^2 field of view gives us the opportunity of studying the large scale structure of galaxy clusters with only one pointing.

The cluster RXJ2248 was observed during the SV season, with typical exposure times of 90 seconds for the *griz* bands and 45 seconds for the Y band. It was re-observed later in 2013 to benefit from improvements to telescope performance and general image

Figure 4.1: A portion of $1' \times 1'$ image centered in RA 22:48:48.003 and DEC -44:31:38.52 in the CLASH F625W band (top) and the DES r band (bottom).

Survey/ Instrument	Authors	FoV	Filters	Mag limits	Spectra	Objects
NTT+ GMOS	Gómez et al. (2012)	$5' \times 5'$	V, R	–	116	711
CLASH	Postman et al. (2012) Monna et al. (2014)	$3.4' \times 3.4'$ (ACS), $2' \times 2'$ (WFC3)	16 in 2000– 17000 Å	$\sim$ 25-27 (10σ)	–	3471
WFI	Gruen et al. (2013)	$33' \times 33'$	$UBVRIZ$	26.4, 26.7, 24.4 (VRI 5σ)	–	–
DES SV	Melchior et al. (2016)	$2.2\,\mathrm{deg}^2$	$grizY$	24.45, 24.30, 23.50,22.90, 21.70 (10σ)	–	374 294

Table 4.2: Some experimental specifications of the surveys that have observed RXJ2248, with the corresponding paper in which those data have been used. The work presented in those papers is shortly summarised in Section 4.3. The magnitude limits reported for DES are the mean 10σ galaxy magnitudes.

quality. The data reduction was done using the SVA1 DES Data Management (DESDM) pipeline, described in detail in Sevilla et al. (2011), Desai et al. (2012) and Mohr et al. (2012). The process includes calibration of the single-epoch images, that are then co–added after a background subtraction and cut into tiles. The SVA1 catalogue was created using Source Extractor (SExtractor, Bertin & Arnouts 1996*b*, Bertin & Arnouts 1996*a*) to detect objects on the riz coadded images. The median 10σ depths of SV data are $g \sim 24.45, r \sim 24.30, i \sim 23.50, z \sim 22.90, Y \sim 21.70$, which reach close to the expected DES full depths. Limiting magnitudes were estimated for the 200 deg^2 SPT-E part of the wide–field SV area using Balrog (Suchyta et al. 2016) and PSF magnitude errors for

true point sources.

We use AB magnitudes throughout this work, and `MAG_AUTO` measurements given by SExtractor, as these proved to be robust and were thus used in several DES SV papers (e.g. Bonnett et al. 2016,Crocce et al. 2015). The objects selected for the analysis have a signal to noise $S/N > 10$ in the i band.

The other survey considered here is CLASH (Postman et al. 2012), a 524-orbit HST multi-cycle treasury program that has observed 25 massive clusters, having a range of virial masses between $5 \times 10^{14} M_{\odot}$ to $30 \times 10^{14} M_{\odot}$ and an average redshift of $\bar{z} = 0.4$. The wavelength range covers the UV, the visible and the IR ($2000 - 17000$ Å) through 17 bands using the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC 3).

The CLASH mosaics were produced using the "MosaicDrizzle" pipeline (see Koekemoer et al. 2002, Koekemoer et al. 2011). The CLASH catalogue creation pipeline makes use of SExtractor: the software is run in dual image mode, where a detection image is created from a weighted sum of the ACS/WFC and WFC3/IR images. The WFC3/UVIS images are not used in the construction of the detection image but the UVIS data are still used to compute source photometry. The photometry given in the public catalogue (`http://www.stsci.edu/~postman/CLASH`), which is also the one used in this work, was measured in isophotal apertures, as they have been shown to produce reliable colours (Benítez et al. 2004). ACS/WFC3 reach a depth of 26.8, 26.4, 26.2, 26.0 and 26.6 (10σ galaxy AB magnitudes for circular apertures of 0.4 arcsec in diameter, Postman et al. 2012) in the F475W, F625W, F775W, F850LP and F105W filters, respectively.

Below, we compare the information obtained with 5 DES filters and with 17 HST filters.

4.3 The Cluster RXC J2248.7–4431

In this section we present what is known about this cluster from previous works. The cluster of galaxies RXC J2248.7–4431, where RXC stands for ROSAT X-ray Cluster, is also known as Abell S1063 or MACS 2248–4431. It is a very luminous cluster, having an X–ray bolometric luminosity of $(6.95 \pm 0.1) \times 10^{45}$ erg s^{-1} in the energy range $0.1 - 100$ keV (Maughan et al. 2008). Its properties are listed in Table 4.1. It was first catalogued by Abell et al. (1989), who counted 74 galaxies. Thanks to the ROSAT-ESO Flux Limited

Figure 4.2: Throughput of the DES filters (solid lines) and HST similar filters (dashed lines).

X-ray (REFLEX) Galaxy Cluster survey, Böhringer et al. (2004) measured a spectroscopic redshift $z = 0.3475$, which has been adopted in the recent literature and has also been confirmed in Gómez et al. (2012), who quoted a mean redshift of $z = 0.3461^{+0.0010}_{-0.0011}$ for 81 members.

Gómez et al. (2012) were the first to study in detail RXJ2248, even though it is the second most luminous cluster in the REFLEX survey (having a reported luminosity of $\sim 3.08 \times 10^{45}$ erg s^{-1} in the rest frame $0.1 - 2.4$ keV band).

In Gómez et al. (2012), the cluster is presented as one of the hottest X-ray clusters known at that time. The high X-ray temperature, together with the high velocity dispersion, suggest a very massive cluster ($M_{200\mathrm{c}} > 2.5 \times 10^{15} M_{\odot}$) and/or a merger system. The merger model is supported by a small offset between the galaxy distribution and the peak of X-ray isophotes, and a non-Gaussian galaxy velocity distribution. Gómez et al. (2012) also reported that the velocity distribution is better represented by the velocity dispersion produced during a merger than by the velocity distribution of a relaxed cluster.

Gruen et al. (2013) used Wide-Field Imager (WFI) data to perform a weak lensing analysis of the cluster. They parametrised the cluster density with a NFW profile (Navarro et al. 1996) and obtained a mass $M_{200m} = 33.1^{+9.6}_{-6.8} \times 10^{14} M_{\odot}$ (or $M_{200c} = 22.8^{+6.6}_{-4.7} \times 10^{14} M_{\odot}$). They also identified a second galaxy cluster in the field of view at redshift ~ 0.6, with an estimated mass of $M_{200m} = 4.0^{+3.7}_{-2.6} \times 10^{14} M_{\odot}$.

Melchior et al. (2016) studied the weak lensing masses and galaxy distributions of four massive clusters observed during the DES SV period, including RXJ2248. They found $M_{200\mathrm{c}} = 17.5^{+4.3}_{-3.7} \times 10^{14} M_{\odot}$, which is in agreement with previous mass estimates.

For RXJ2248, they also identified filamentary structures of the luminous red-sequence galaxies found with the REDMAPPER (Rykoff et al. 2014*a*) algorithm.

Umetsu et al. (2016) combined HST and wide field imaging (from the Subaru telescope or the ESO/WFI) observations to reconstruct the surface mass density profiles of 20 CLASH clusters. Their analysis jointly uses strong lensing as well as weak lensing with shear and magnification, and for RXJ2248 they found $M_{200c} = 18.78 \pm 6.72 \times 10^{14} M_{\odot}$.

4.4 Comparison of DES and CLASH

In this section, we assess detectability, photometry, and stellar masses of DES galaxies, treating matched CLASH galaxies as truth table.[1] In order to make the comparison, we seek to identify similar filters in both data sets. Figure 4.2 shows that the closest HST analogs to DES *griz* are F475W, F625W, F775W and F850lp. We will refer to the corresponding HST and DES bands as g, r, i and z for simplicity of notation. In the following, we will also use the DES Y band, that does not have a similar HST filter. When we refer to 5 CLASH filters, it means we are including the F105W filter, that is broader than the DES Y.

In the DES catalogue of the RXJ2248 area, there are 374 294 sources in a roughly circular area of approximately 3 deg^2. The deeper, higher resolution CLASH catalogue includes 3 471 sources in a much smaller area ($\sim 5' \times 4'$).

We perform a spatial matching (using a matching radius of $1.5''$) between the DES and CLASH catalogues and we find 609 matched sources. Thus the DES recovered only 18% of the sources in the CLASH catalogue. The high percentage of sources missed in DES is due to various problems, one of them being that the *griz* 10σ depths differ by $\gtrsim 2$ magnitudes between the two datasets. This accounts for most of the undetected sources in DES: when we simulate fake faint galaxies with BALROG[2] (Suchyta et al. 2016) on the DES image of RXJ2248, we find that the completeness in *riz* bands (which are those used to run the detection) drops below 20% between magnitude 24 and 25, justifying

[1] A comparison of weak lensing measurements between DES and CLASH was not performed because they predominantly reveal differences in the shear calibration. The majority of galaxies with shape measurement in both catalogs are very faint for DES, resulting in large and noisy calibration factors (see Section 4.2.1 in Melchior et al. 2016). In addition, the high density of galaxies in the central region of this cluster creates many more close galaxy pairs or even blends in ground–based DES images than when viewed with HST, rendering shape measurement even more challenging. A detailed analysis of those relevant effects is beyond the scope of this work.

[2] A software pipeline for embedding simulations into astronomical images. See: `https://github.com/emhuff/Balrog`.

the incompleteness found when comparing to the even deeper CLASH survey. We also expected one of the problems to be blending, especially close to the bright cluster core. We run some completeness tests using a DES enhanced deblending catalogue (Zhang et al. 2016*a*) that would increase the percentage of recovered sources to 20%, but found that blending is not a major reason of incompleteness. Also, CLASH object detection is run on ACS+IR images, while DES detection only involves optical bands and it may miss redder sources. A visual comparison of DES and CLASH images is shown in Figure 4.1.

A comparison of measured isophotal magnitudes at the catalogue level between the matched galaxies in the two datasets here considered shows a mean shift $|\Delta m| \leq 0.13$ in all bands, where the offsets due to the different filters compared have been taken into account. This is true when a signal to noise cut $S/N > 10$ is performed on the matched galaxies, and objects with saturated pixels and corrupted DES data are removed.

4.4.1 Magnitude comparison

Considering only those matched sources with a signal to noise ratio $S/N > 10$ in the DES i-band, excluding stars and objects with SExtractor `FLAGS` > 3 (in order to exclude objects with saturated pixels or corrupted data, but include objects that were initially blended) we are left with 327 sources observed in the g and r bands, and 331 in the i and z bands. The differences $\Delta_{\rm m} = m_{\rm DES} - m_{\rm CLASH}$ are plotted in Figure 4.3, as well as the DES magnitudes as a function of the CLASH ones for the matched sources. The magnitudes plotted are SExtractor isophotal magnitudes `MAG_ISO` for both DES and CLASH. $\Delta_{\rm m}$ in the $griz$ bands has been corrected for the magnitude shifts due to the differences between these DES and HST filters. The offsets have been computed using two "extreme case" SED templates (one elliptical, one irregular) at the cluster redshift. We have not taken into consideration the Y band offset as the HST and DES filters are too different, but we still report the comparison for completeness.

Figure 4.3 shows an offset in the DES magnitudes, especially in the gri bands, which may be due to different choices of threshold or background when running SExtractor. Nevertheless the linear trend is clear, bringing to Pearson coefficients between 0.91 and 0.98 in all bands. The higher scatter that we could expect in the Y band (as the corresponding CLASH filter is the F105W, which is much more spread towards the infrared than the DES Y filter) is actually compensated for by higher DES photometric errors. The mean difference in magnitude $\Delta_{\rm m}$ between the two datasets is 0.13, 0.04, -0.07, -0.07 and 0.08

Figure 4.3: DES magnitues compared to CLASH magnitudes, with bottom plots of $\Delta_{\rm m} = m_{\rm CLASH} - m_{\rm DES}$ in the g,r,i and z bands for the matched sources that satisfy $S/N > 10$ and filtering the sources with `FLAGS`> 3. CLASH errorbars are not plotted for visualisation purposes, while those on the DES magnitudes represent the 1σ error. The dashed black lines represent the ideal case $m_{\rm CLASH} = m_{\rm DES}$.

CLASS_STAR	g	r	i	z
G(DES)	551	538	535	522
G(CLASH)	553	553	553	553
S(DES)	58	71	74	87
S(CLASH)	56	56	56	56

SPREAD_MODEL	g	r	i	z
G(DES)	388	463	428	405
G(CLASH)	553	553	553	553
S(DES)	221	146	181	204
S(CLASH)	56	56	56	56

Table 4.3: Number of galaxies G and stars S found in DES and CLASH, when considering CLASS_STAR < 0.8 (top table) and SPREAD_MODEL > 0.003 (bottom table) for galaxies in DES.

in the $grizY$ bands respectively.

4.4.2 Star/galaxy separation

For the purpose of studying the star/galaxy separation, we adopt the same notation used in Soumagnac et al. (2015). We study the galaxy completeness c_g, defined as the ratio of the number of true galaxies classified as galaxies to the total number of true galaxies (including then also the number of true galaxies classified as stars M_G):

$$c_g = \frac{N_G}{N_G + M_G} \,, \tag{4.1}$$

where here N_G is given by the galaxies in the DES catalogue, and the number of true galaxies is given by the object classified as such in CLASH.
Moreover the galaxy purity p_g is defined as

$$p_g = \frac{N_G}{N_G + M_S} \,, \tag{4.2}$$

where M_S is the number of stars classified as galaxies.

We consider as true galaxies the sources that have a SExtractor stellarity index CLASS_STAR< 0.08 in the CLASH catalogue, otherwise they are stars. This cut has been proven to perform well in other CLASH works (e.g. Jouvel et al. 2014). We try to understand if the star/galaxy performance is compatible between the two datasets.

We first consider the CLASS_STAR parameter given in the DES catalogue. We find that a cut between 0.7 and 0.9 for the CLASS_STAR_I gives purity and completeness above the 90%. The number of galaxies and stars in the two catalogues can be found in Table 4.3.

We also test the performance of star/galaxy separation with the SPREAD_MODEL parameter (defined in Desai et al. 2012 and tested in Bouy et al. 2013). SPREAD_MODEL is

Figure 4.4: Comparison of the DES versus CLASH photo-z's for the sources matched between the two catalogues. photo-z's were obtained using LePhare. *Top:* only the 5 HST filters similar to the $grizY$ filters in DES have been used to compute CLASH photo-z's. *Middle:* 3 of the HST UV filters have been added to the 5 HST optical filters for the CLASH photo-z estimation. *Bottom:* all the 17 available CLASH filters have been used to estimate the photo-z's. The red dashed line represents $z_{DES} = z_{CLASH}$, and the grey area the expected DES accuracy of $|z_{DES} - z_{CLASH}| < \sigma(1 + z_{CLASH})$, where $\sigma = 0.12$.

a morphological star/galaxy separation parameter given by SExtractor which acts as a linear discriminant between the best fitting local PSF model and a slightly "fuzzier" version made from the same PSF model, convolved with a circular exponential model. A threshold is set to 0.003 by the DESDM pipeline to separate stars (PSF like, having absolute values below 0.003) from galaxies (non-PSF like, with values higher than 0.003). As a result, 77.4% of the galaxies are catalogued in DES as such, and the purity is 97.3%. A plot for the purity and the completeness for varying `SPREAD_MODEL_I` cuts is shown in Figure 4.9. We list the number of galaxies and stars in the two catalogues in Table 4.3. It can be seen from Figure 4.9 that cut at lower values ($\sim 0.001 - 0.002$) would give a higher completeness without affecting the purity significantly. Moreover, in this case may be better using the `SPREAD_MODEL` in the r band, which is deeper than the i one, and this can also be seen in Figure 4.9, where it is clear that, for the same cut, the completeness is higher. We also find that using the `CLASS_STAR` parameters with the mentioned cut is more efficient than adopting the `SPREAD_MODEL_I` with the cut at 0.003.

4.4.3 Photo-z

Considering only those matched sources with a signal to noise ratio $S/N > 10$ in the DES i-band, excluding stars (in this case we exclude all objects with `CLASS_STAR_I`> 0.8) and objects with `FLAGS` $\neq 0$ (in order to exclude objects with saturated pixels or corrupted data, and originally blended sources) we are left with 155 sources. This is the subset of

galaxies that we will use for the photo-z and stellar mass comparison.

In order to estimate the photo-z's, we used the publicly available software LePhare (Arnouts et al. 1999, Ilbert et al. 2006)[3], as it also produces the stellar masses that we want to study in this work. Previous works on DES photo-z's have tested the performance of this code in comparison with other softwares and spectroscopic redshifts. In particular, Sánchez et al. (2014) found that LePhare fulfils the DES requirements on scatter and 2σ outlier fraction when it is run on SV data, and the metrics obtained are compatible with those from other template-based methods within 10%. Training-based methods showed a lower bias compared to template-fitting codes, and this can be improved in the latter using adaptive recalibration methods, which are available in LePhare. However, stellar masses tests have not been performed with DES data so far.

We therefore need to further check the DES photo-z and stellar mass estimation with LePhare first. This is where the HST data are particularly useful in this work, as we need to check DES against a more precise photometric survey covering the wavelengths from optical to IR.

Furthermore, LePhare is a reliable code, as seen in e.g. Ilbert et al. (2009).

LePhare photo-z technique

The main purpose of LePhare is to compute photometric redshifts by comparing template Spectral Energy Distributions (SEDs) to the observed broadband photometry, but it can also be used to calculate physical parameters such as stellar masses and rest-frame luminosities. Several SEDs sets are available within the code, and these are redshifted and integrated through the instrumental transmission curves. Additional contribution of emission lines in the different filters can be included and extinction by dust can be taken into account. The synthetic colours obtained from the SEDs for each redshift are then compared to the data. The best fitting template and redshift for each object is then found by χ^2 minimisation. In addition, prior information can be supplied, including a photo-z distribution prior by galaxy type computed from the VVDS survey in the i band (see Ilbert et al. 2006).

[3] `http://www.cfht.hawaii.edu/~arnouts/LEPHARE/lephare.html`

Results

We run LePhare on both CLASH (with 5, 8 and all 17 filters) and DES (5 filters) catalogues, fitting the 31 synthetic SEDs templates given by the COSMOS (see Ilbert et al. 2009) libraries. We use four galaxy extinction values ranging from 0.05 to 0.3 using a Calzetti et al. (2000) extinction law for DES. For CLASH, two more extinction values are added (0.4 and 0.5), in order to take into account the wider wavelength range covered when we use all its filters.

The results are plotted in the upper panel of Figure 4.4 for the 155 matched sources when 5 filters are considered for CLASH. Of all the sources considered, 85% have a photo-z which is compatible with the CLASH photo-z within the DES requirement[4] $|z_p - z_s| < \sigma(1 + z_s)$, where $\sigma = 0.12$. We notice an offset in the CLASH redshift when 17 filters are used (see lower panel of Figure 4.4), while 77% of the sources still satisfies the DES requirement. This most likely stems from the inclusion of near-UV filters to get an accurate redshift from the Balmer break for galaxies below a redshift of 0.4 (see e.g. Eisenstein et al. 2001). In fact, this offset starts to be seen also when adding only three UV bands (namely F336W, F390W and F435W) to the $grizY$ filters (see middle panel in Figure 4.4). A problem around redshift 0.4 for DES galaxies had already been seen in Sánchez et al. (2014) (see their Figure 5) and Bonnett et al. (2016). In particular, Bonnett et al. (2016) also pointed out a lack of matching SEDs for galaxies around redshift 0.4 with template fitting methods (see their Figure 8).

Zero points[5] have not been adopted in the DES photo-z estimation, as we saw that their introduction causes systematic effects. Zero points are calculated using field galaxies, so we believe we would need spectroscopy in the cluster field to be helpful at photo-z calibrations for this study.

4.4.4 Stellar Masses

Stellar masses are key observables in the study of galaxy evolutionary models. Unfortunately, they cannot be directly measured, but require multicolour photometry to be fitted with stellar population models, therefore making a series of assumptions. One of these is

[4]Where z_p and z_s are the photometric and spectroscopic redshifts, so here we consider the CLASH photo-z as the "spectroscopic" one.

[5]Zero–points define the shift in the observed magnitudes due to various systematics.

the galaxy redshift if spectroscopy is not available: in the view of our goal of computing the stellar mass profile of the RXJ2248 cluster, we have to bear in mind that galaxy redshift accuracy is essential not only to ensure the correct template match in the template fitting method here used and the distance to the galaxy, but also to determine the cluster membership. We will therefore see how the redshift assumptions affect the stellar mass estimation and elaborate a reasonable technique to correctly estimate the stellar mass profile.

Method

We use the same sample of matched galaxies with $S/N > 10$ used in Section 4.4.3 and their redshift estimations in order to compute the stellar masses for both DES and CLASH using LePhare. In the first place, the redshifts of the galaxies are fixed to those photo-z's previously computed (*i.e.* to DES photo-z's for DES stellar masses, and to CLASH photo-z's for CLASH stellar masses). In the second case, we fix the galaxy redshifts at the cluster redshift for both DES and CLASH, and the LePhare DES photo-z's are only used to select a subsample of cluster members satisfying $|z_{phot} - z_{cl}| \leq 0.12$. For this subsample both DES and CLASH stellar masses are estimated.

We chose to use LePhare, together with the Bruzual & Charlot (2003) templates, as this combination has been shown to be robust in the estimation of physical parameters of galaxies (Ilbert et al. 2010).

We derive our stellar mass estimates by fitting synthetic SEDs templates while keeping the redshift fixed as described previously in the two cases. The SED templates are based on the stellar population synthesis (SPS) package developed by Bruzual & Charlot 2003 (BC03) assuming a Chabrier (2003) initial mass function (IMF). Our initial set of templates includes 9 models using one metallicity ($Z = 1Z_{\odot}$) and nine exponentially decreasing star formation rates $\propto exp(-t/\tau)$ where t is the time and τ takes the values $\tau = 0.1, 0.3, 1, 2, 3, 5, 10, 15, 30$ Gyr. The final template set is then generated over 57 starburst ages ranging from 0.01 to 13.5 Gyr, and four extinction values ranging from 0.05 to 0.3 using a Calzetti et al. (2000) extinction law. For CLASH, two more extinction values are added (0.4 and 0.5).

The uncertainties on our stellar masses estimates (`MASS_BEST` from LePhare) are given by the 68% confidence limits on the SED fit.

Figure 4.5: DES stellar masses versus CLASH stellar masses computed using LePhare. In the stellar mass estimation, each source is assumed to be at the redshift given as output by LePhare, as described in Section 4.4.3. The dashed line line represents $M_\star^{DES} = M_\star^{CLASH}$. In the bottom panel $\Delta Log(M_\star) = Log(M_\star^{DES}) - Log(M_\star^{CLASH})$ is presented. All available filters (*i.e.* 5 for DES and 17 for CLASH) have been used in the estimation process. Uncertainties represent the 68% Confidence Level.

Photo-z consistency test

In this Section we test whether the fact that we assumed a photo-z that was computed with a certain set of templates to then compute the stellar mass with a larger set of templates is consistent. With photometric surveys data, it is a common method to perform estimation of the photometric redshift and SED fitting in two steps, which involve fixing the redshift of a galaxy at the best fit value obtained in the first step. Although this may not be the most elegant way of solving the problem of the lack of spectroscopic information, it has been proven to lead to only a small bias in the SED fitting parameters, when compared to results given by the simultaneous estimation of redshift and stellar mass (see Acquaviva et al. 2015). Moreover, here we can take advantage of the prior information that this is a cluster.

In order to do test the consistency of the photo-z choice, we want to show that the resulting photo-z is not drastically dependent on the choice of templates. Therefore, we compare the photo-z's given by Le Phare when using the COSMOS templates and the BC03 ones. A comparison is shown in Figure 4.8 for all the galaxies in the DES field of view. We retrieve that 71% of the galaxies have $|\Delta z| = |z_{BC03} - z_{COSMOS}| < 0.12$.

Figure 4.6: DES stellar masses versus CLASH stellar masses computed using LePhare. Here only sources around the cluster redshift are considered (*i.e.* sources with a DES photo-z that satisfies $|z - z_{cl}| \leq 0.12$, where $z_{cl} = 0.3475$ is the cluster redshift). In the DES and CLASH stellar mass estimation, these galaxies are all assumed to be at z_{cl}. The dashed line line represents $M_\star^{DES} = M_\star^{CLASH}$. In the bottom panel $\Delta Log(M_\star) = Log(M_\star^{DES}) - Log(M_\star^{CLASH})$ is presented. The offset seen in Figure 4.5 seems to disappear in this plot, showing that this effect was due to the photo-z offset. All available filters (*i.e.* 5 for DES and 17 for CLASH) have been used in the estimation process. Uncertainties represent the 68% Confidence Level.

Results

In Figure 4.5, we show the comparison between DES and CLASH stellar mass estimates for the first case, where the redshifts are fixed to the LePhare estimates. The linear correlation between the two estimates is clear, but there is an offset of mean value ~ 0.16 dex. This should be considered in light of two aspects:

1. the offset in the photo-z's that we addressed in Section 4.4.3;

2. the uncertainties in the DES stellar masses may be underestimated as those are the 68% confidence limits on the SED fit and do not take into account systematic error contribution.

In Figure 4.6 we show the results for the second case, where we select the galaxies with a DES photo-z close to the spectroscopic cluster redshift z_{cl}, satisfying $z_{cl} - 0.12 < z_{phot} < z_{cl} + 0.12$. The redshift of these sources is fixed at z_{cl} in the stellar mass estimation, and the reason for this choice is twofold:

Figure 4.7: DES and CLASH total stellar mass maps computed using LePhare for the galaxies matched between the two catalogues. The stellar masses plotted are the same as those shown in the bottom panel of Figure 4.6 (*i.e.* all the galaxies with a DES photo-z that satisfies $|z - z_{cl}| \leq 0.12$, where z_{cl} is the cluster redshift, have a redshift fixed to z_{cl} in the SED fitting). The map is centred on the BCG, but its stellar mass is not visible as it was originally blended and therefore did not pass the quality flag cut applied in Section 4.4.4. The resolution is $0.12'$/pixel and the map is smoothed with a Gaussian of $\sigma = 0.144$ arcmin. At the cluster redshift, $1'$ corresponds to 294 kpc in the assumed cosmology.

Figure 4.8: *Left panel*: Comparison of the photo-z's computed using the Bruzual and Charlot 2003 templates and those using the COSMOS templates. *Right panel:* Residuals of the photo-z's computed using the two differnt set of templates.

Figure 4.9: Galaxy purity (blue dashed line) and completeness (black solid line) for the star/galaxy separation problem using the `SPREAD_MODEL` parameter in the DES catalogue for the r (top) and i (bottom) bands. The red vertical line represents a typical cut used for `SPREAD_MODEL`, which is 0.003.

1. to minimise circularity associated with using Le Phare to both measure redshifts and stellar masses;

2. to take into account the shift in the redshift estimates pointed out in Section 4.4.3 (and therefore put at the correct cluster redshift the cluster members which photo-z appeared to be at $z_{phot} \sim 0.4$).

Of course this choice results in considering some sources as being at z_{cl} even though they are not, and we shall take this into account in the following. A consistency test for the choice of redshifts done is presented in Appendix 4.4.4.

The correlation between the estimated stellar masses significantly increases if also the CLASH sources are set to be at the cluster redshift, as seen in a comparison of Figure 4.5 with Figure 4.6, where we find that stellar masses from DES can be estimated within 25% of CLASH values. This shows that the offset seen in the former is due to the offset in the redshifts given in input, rather than other systematics. Therefore, the wavelengths covered by the DES broadband filters are capable of providing a good estimation of stellar mass if the photometric redshift is sufficiently precise.

In Figure 4.7 we show the spatial distribution of the total stellar mass spatial distributions for both DES and CLASH in the CLASH field ($\sim 4.8' \times 4.2'$), represented with a resolution of $0.12'$/pixel and smoothed with a Gaussian of $\sigma = 0.144$ arcmin. The stellar masses of galaxies are summed over in each pixel. Obviously the two samples show very good agreement in terms of the spatial distribution of stellar mass. The Pearson coefficient for the pixel by pixel stellar mass values of the two non-smoothed maps is 0.93. The

difference map without any smoothing has a mean of 0.02 and $\sigma = 0.12$.

4.5 Dark Matter and Stellar Masses

In this section we study the stellar mass radial profile of the cluster and relate it to that of dark matter that has been obtained though DES weak lensing studies in Melchior et al. (2016). As shown in Section 4.4.4, stellar mass estimation can be biased if the redshift assumed is biased too: this is a problem if one wants to compute stellar masses with photometric surveys data. In the lack of spectroscopy, it is a common method to perform estimation of the photometric redshift and SED fitting in two steps, which involve fixing the redshift of a galaxy at the best fit value obtained in the first step. Although this may not be the most elegant way of solving the problem, it has been proven to lead to only a small bias in the SED fitting parameters, when compared to results given by the simultaneous estimation of redshift and stellar mass (see Acquaviva et al. 2015). Nevertheless, here we want to adopt a more consistent methodology for the stellar mass estimation, taking advantage of the fact that we are looking at a cluster with a known redshift. This technique is outlined in the first part of this section, followed by a study of the different mass radial profiles obtained. To allow a straightforward comparison with the weak lensing reconstructed mass, we compute total stellar mass and surface density on a projected 2-dimensional plane, *i.e.*:

$$M_\star(R) = \sum_i m_\star^i \qquad \Sigma_\star(R) = \frac{\sum_i m_\star^i}{A_{\rm annulus}}\,, \tag{4.3}$$

where the sums are intended over the galaxies within annuli of projected radius R. Similar definitions apply for the cumulative distributions $M_\star(< R)$ and $\Sigma_\star(< R)$, computed within circles of radius R. The centre of the image is taken to be that of the BCG. At last, we present a comparison between the stellar and total DES mass maps.

4.5.1 Galaxy samples and stellar mass estimates

Our goal is to compare the reconstructed mass from weak lensing to the total stellar mass of the cluster members. In order to do so, we split the galaxies into two populations. The following steps are performed:

- We select the red members using the RedMaPPer SV catalogue (Rykoff et al.

2016*b*), which identifies cluster members with high precision (Rozo et al. 2014). Their stellar masses are computed using the same parameters presented in Section 4.4.4 (but fixing the redshift at z_{cl}).

- The RedMaPPer galaxies profile has been corrected by a factor representing the contribution coming from faint sources at luminosities smaller than the limit of the sample ($0.2L^*$). This is done by integrating the luminosity with a Schechter function, *i.e.* we computed the fraction:

$$F_L = \frac{\int_0^{0.2L^*} L\phi(L)dL}{\int_0^{\infty} L\phi(L)dL}\,, \tag{4.4}$$

  where $\phi(L) = \phi_*(\frac{L}{L^*})^{\alpha}e^{-L/L^*}$ with $\alpha = -1$ (as done in Rykoff et al. 2014*a* for the SDSS sample, that has properties similar to DES). We find that the galaxies below the luminosity limit contribute to a fraction $F_L = 0.18$ of the total luminosity, and therefore, assuming a constant $M_\star/L$ ratio for the red galaxy population, they contribute to the same percentage of stellar mass.

- The contribution to the total stellar mass of each red member is weighted by its membership probability (reported in the RedMaPPer catalogue).

- In order to study the mass profile at radii higher than r_{200c}, we decide not to neglect the contribution coming from the bluer population. First, we exclude all objects with saturated pixels or corrupted data, but include galaxies that were initially blended (such as the BCG). Then we select the rest of the galaxies in the field of view that have magnitudes m_i in the i band satisfying $m_i^{\rm BCG} < m_i < m_i^{\rm lim}$. In this way we exclude any source which is brighter than the BCG and cut at $m_i^{\rm lim} = 21$ mag in order to ensure the completeness of the sample. After having performed a SED fitting as in the previous step, we filter out all galaxies that do not give a good fit (cutting on reduced $\chi^2 < 2$) when the redshift is fixed at the cluster value.

4.5.2 Masking and background correction

We estimate the survey area lost due to masked regions and blending of faint galaxies with large cluster members near the core. We calculate corrections for both effects as follows.

- Healpix (Górski et al. 2005) maps of depth and masking fractions are produced for DES with Mangle (Swanson et al. 2008). From these, we calculate mean depth and

fractions of masked area in our set of annuli. The depth is approximately constant out to ≈ 50 arcmin from the BCG, which defines the outer limit of the area used for our background estimation scheme. Masking fractions are below 5 per cent for all annuli and applied to the binned stellar mass estimates from both galaxy samples.

- For the blue galaxy sample, some objects are lost due to blending with cluster member galaxies. Without correction, this would bias our stellar mass estimates of blue galaxies near the cluster centre low. We estimate the area lost in each annulus as the isophotal area above the SExtractor detection threshold, `ISOAREA_I`. This yields a ≈ 7 per cent correction in the innermost arcminute, which drops quickly towards larger radii. For the blue galaxy sample, this correction and the masking fraction are applied in an additive fashion.

The contribution coming from galaxies that do not actually sit at the cluster redshift is removed from the blue galaxies sample by performing a background subtraction: we estimate the projected surface density of the stellar mass $\Sigma_\star(R)$ at large radii ($30 - 50$ arcmin, which means outside $\approx 4r_{200c}$ [6]), where the stellar mass profile tends to become flat. The value found is $\Sigma_\star = 1.36 \times 10^{10} M_\odot/\mathrm{arcmin}^2$ and this is subtracted on the smaller scales, with an uncertainty given by a Poissonian error. The remaining stellar mass contribution is then added to that of the red galaxies.

4.5.3 Stellar mass profile

We look at the radial distribution of stellar mass, taking into account both the red cluster members present in the RedMaPPer catalogue, and the blue members, as explained in the previous section. The splitting into red and blue galaxies is justified by the possibility of improving the SED fitting by using different priors for the two populations, and considering the systematics differently. In fact, it is well known that stellar masses estimated for quiescent galaxies are more reliable than for star-forming ones, partially because the colour–$M_\star/L$ (from which $M_\star$ is derived) relation are more uncertain for very blue colours (see e.g. Conroy 2013 and Banerji et al. 2013).

The total stellar mass cumulative profiles $M_\star(< R)$ for the red and blue galaxies are shown in Figure 4.10. Within the innermost 5 arcmin, the contribution of the red

[6] $r_{200c} = 2200$ kpc from the NFW fit of Melchior et al. (2016), which means $r_{200c} \simeq 7.46'$ at the cluster redshift

Figure 4.10: Cumulative radial distributions of total stellar mass for the DES red (red points), blue (blue points) and all galaxies (purple points) in the cluster, together with the total, non-parametric mass profile reconstructed from DES weak lensing (Melchior et al. 2016, green points). The purple solid line is our NFW fit to the DES stellar mass profile, while the blue solid line is the NFW best fit from DES weak lensing. The black points represent the CLASH total stellar mass profile computed in this work, with our NFW fit (black solid line). The red solid line is the Umetsu et al. (2016) NFW best-fit for CLASH from a strong lensing, weak lensing and magnification joint analysis. This profile is restricted to the NFW fitting range $R < 2$Mpc h^{-1} chosen in Umetsu et al. (2016), which is larger than the HST field of view as other datasets were used in a joint analysis. The radius R is projected, and $r_{200c} = 2.2$ Mpc. Errorbars show the 68% confidence level.

cluster members to the total stellar mass is dominant ($\gtrsim 80\%$) with respect to the bluer galaxies, while at larger radii, namely outside r_{200c}, the second population considered gives a $20 \ldots 50\%$ contribution to the total stellar mass. In Figure 4.10 we also plot the stellar mass profile from CLASH, where the galaxy cluster members were selected cutting on the CLASH photometric redshift with $|z_{phot} - z_{cl}| < 0.12$.

4.5.4 Comparison to total mass from Weak Lensing

The weak lensing mass profile is computed through the aperture mass densitometry (see Clowe et al. 1998) using $M_{tot}(< R) = \pi R^2 \zeta(< R) \Sigma_{cr}(z_l, z_s)$, where $\zeta(< R) = \bar{\kappa}(< R) - \bar{\kappa}(r_1 < r < r_2)$ is the difference between the mean convergence within a circular aperture of radius R and the mean convergence between r_1 and r_2 (annulus radii that are fixed for all the apertures in the measurement), z_l and z_s are the redshift of lens and sources. The convergence κ is defined as the projected surface mass density Σ, in units of the critical surface mass density Σ_c:

$$\kappa = \frac{\Sigma}{\Sigma_c}, \qquad \Sigma_c = \frac{c^2}{4\pi G} \frac{D_s}{D_d D_{ds}} \tag{4.5}$$

where D stands for angular diameter distance and the subscripts s, d, ds indicate the distance from the observer to the source, from the observer to the lens, and from the lens to the source respectively. In particular, Melchior et al. (2016) used $r_1 = 30$ arcmin and $r_2 = 45$ arcmin. This explains our choice of estimating the stellar mass surface density background in the range 30 to 50 arcmin, where its profile is also essentially flat. In Figure 4.10 we also present the NFW mass profile derived by using the best fit parameters as found in Melchior et al. (2016) for this cluster. Given the similarity between the WL and stellar mass profiles, we try to fit the stellar mass one with a NFW projected mass profile, as the one derived in e.g. Oaxaca Wright & Brainerd (1999):

$$M(< x) = \begin{cases} \frac{3\delta_c M_{200c}}{200 c_{200}^3} \left[\frac{2}{\sqrt{1-x^2}} \text{arctanh} \sqrt{\frac{1-x}{1+x}} + \ln(\frac{x}{2}) \right] & (\text{if } x < 1) \\ \frac{3\delta_c M_{200c}}{200 c_{200}^3} \left[1 + \ln(\frac{1}{2}) \right] & (\text{if } x = 1) \\ \frac{3\delta_c M_{200c}}{200 c_{200}^3} \left[\frac{2}{\sqrt{x^2-1}} \text{arctan} \sqrt{\frac{x-1}{1+x}} + \ln(\frac{x}{2}) \right] & (\text{if } x > 1) \end{cases} \tag{4.6}$$

Figure 4.11: Cumulative radial distribution of the fraction of stellar mass of the galaxies in the cluster as computed in this work over the total mass from lensing studies. For the DES $f_\star$, the total mass comes from the non-parametric reconstruction of the weak lensing shear profile done in Melchior et al. 2016 (purple points), or from their NFW best fit (green squares). For CLASH, M_{tot} is a result of the Umetsu et al. (2016) NFW best-fit for CLASH from a strong lensing, weak lensing and magnification joint analysis (red triangles). The mean DES stellar mass fraction from non-parametric weak lensing mass profile is $f_\star = (7.3 \pm 1.7) \times 10^{-3}$, and is represented by the dashed line. The radius R is projected, and rescaled with $r_{200c} = 2.2$ Mpc. Errorbars show the 68% confidence level.

where $x = R/r_s$, $c_{200} = r_{200c}/r_s$ is the concentration parameter and

$$\delta_c = \frac{200}{3} \frac{c_{200}^3}{\ln(1 + c_{200}) - c_{200}/(1 + c_{200})} \,. \tag{4.7}$$

Our non-linear least squares fit uses the Levenberg-Marquardt algorithm and gives the following parameters for DES stellar mass profile: $M^\star_{200c} = (5.38 \pm 0.11) \times 10^{12} M_\odot$, $c^\star_{200} = 2.4 \pm 0.13$ with a reduced $\chi^2 = 0.6$.

From the DES stellar mass profile and the aperture mass densitometry total matter profile, we derive the stellar mass fraction $f_\star(< R) = M_\star(< R)/M_{tot}(< R)$, which is represented by the purple points in Figure 4.11. Within r_{200c} radius, we find $f_\star^{DES}(< r_{200c}) = (6.8 \pm 1.7) \times 10^{-3}$, compatible within 1σ in the outer regions with the result from Bahcall & Kulier (2014): $f_\star \simeq (1.0 \pm 0.4) \times 10^{-2}$ above $\sim 300h^{-1}$ kpc. In their paper, Bahcall & Kulier (2014) examine the stellar fraction profile by stacking $> 10^5$ SDSS groups and clusters, divided into 3 richness subsamples.[7] Inside r_{200c} we recover a lower stellar

[7]They define the richness N_{200} as the number of galaxies in the red sequence with rest-frame i-band

mass fraction compared to their work. The discrepancy can be explained in light of the different analyses carried out in Bahcall & Kulier (2014):

- Bahcall & Kulier (2014) stack clusters with different properties and at different redshifts.
- They included the contribution of the diffuse intracluster light (ICL), which increases $f_\star$ by a factor 1.15 within r_{200c}.
- The luminosity profiles and weak lensing mass profiles have been de-projected to obtain 3D profiles in their work. On the other hand, considering the projected $f_\star$ means that we are including the contribution of the cluster outskirts along the line of sight when we look at cluster core. In these regions, the stellar mass fraction is lower, and this tends to reduce 2D $f_\star$ at small radii with respect the 3D behaviour.

On the other hand, the average stellar mass of the Universe, estimated to be $f_{\star,cosmic} = (9 \pm 1) \times 10^{-3}$ (as derived in Bahcall & Kulier 2014) is recovered outside r_{200c}, as we would expect even for a projected profile.

Overall, no particular radial trend is found, in agreement with Bahcall & Kulier (2014) and also with Andreon (2015), who studied the stellar-to-total mass ratio of three CLASH clusters at $z \sim 0.45$. Nevertheless, a radially varying profile might be hidden by the large errors. In order to reduce the latter, dominated by the weak lensing reconstructed mass, and have a precise estimation of the stellar mass fraction, we will need to apply the same reasoning to a large sample of DES clusters.

If we take the NFW mass profile with the lensing best-fit parameters as total mass in $f_\star$, we get the green points in Figure 4.11 for DES, and the red ones for CLASH. Towards the centre of the cluster these profiles are higher than the one previously discussed. This is due to the fact that in this case M_{tot}, as can be seen in eq. (4.6), goes to zero for $R \to 0$, while the BCG stellar mass contributes to $M_\star$ up to very small radii. Moreover, the halo/cusp problem (see e.g. de Blok 2010) is a known problem of the NFW profile, that will therefore produce different results from a non-parametric mass profile from weak lensing. Use of the same dark matter halo parameterisation brings the two datasets into agreement at the 1σ level.

luminosity $L_i > 0.4L^*$ located within a radius r_{200}^{gals} from the BCG (i.e. within the radius where the local galaxy overdensity is 200).

Figure 4.12: DES total stellar mass distribution (coloured density plot) compared to the mass map (*i.e.* map of M_{ap}/σ_{ap}, in contours) from the weak lensing analysis by Melchior et al. (2016). Both maps have a resolution of $0.4997'$/pixel and have been smoothed with a Gaussian of $\sigma = 1'$.

4.5.5 DES Stellar Masses and Weak Lensing Mass Maps

In this section, we explore the correlation between the stellar mass maps and the DES weak lensing mass map by Melchior et al. (2016). Melchior et al. (2016) adopted the aperture-mass technique from Schneider (1996) and computed the map of M_{ap}/σ_{ap} for this cluster, where M_{ap} is the aperture mass and it is defined as the sum of all ellipticity measurements $\epsilon_t(\vartheta_j)$ inside a circular aperture:

$$M_{ap}(\vartheta) = \sum_j Q(|\vartheta - \vartheta_j|)\epsilon_t(\vartheta_j) \ . \tag{4.8}$$

In eq. (4.8) Q is a weight function, and the ellipticities are computed with respect to the centre ϑ of the circular aperture. The variance of the aperture mass is given by:

$$\sigma^2_{M_{ap}} = \frac{\sigma^2_\epsilon}{2} \sum_j Q^2(|\vartheta - \vartheta_j|) \ . \tag{4.9}$$

In Figure 4.12 we show the DES aperture mass map (black contours) and our stellar mass map (coloured density map) in $30' \times 30'$ around the BCG position. Both maps, have a resolution of $0.4997'$/pixel and have been smoothed with a Gaussian of $\sigma = 1'$.

An elongated structure spanning for ~ 4 Mpc around the BCG is clearly present in both maps, as well as a few clumps lying inside and outside the r_{200c} radius. Note that the mass structures that can be seen in the total mass map may lie outside the cluster but still cause the lensing, as they are along the line of sight, while the DES galaxies considered here, are only those at the cluster redshift. This fact partially explains why the peaks and minima in the stellar mass and aperture mass maps may be not always coincident. Also, the peak of the stellar mass distribution coincides with the BCG position, while the weak lensing map shows a small offset of the peak from the BCG: Gruen et al. (2013) already addressed this effect to the expected shape noise studied by Dietrich et al. (2012).

The correlation that can be seen by eye between M_{ap}/σ_{ap} and $\log M_\star$, is quantified by a Pearson coefficient of $r = 0.30$ when cross-correlating the maps pixel by pixel. Again, the correlation expected between stellar mass and total matter (quantified in this case by the aperture mass and convergence) in a cluster is diminished by the fact that the gravitational lensing gives an integrated information about the mass along the line of sight.

4.6 Conclusions

We compared the catalogues derived from DES and CLASH observations of the galaxy cluster RXC J2248.7–4431, treating CLASH as a validation set for DES. Photometric redshifts and stellar masses for both datasets were computed using LePhare, and we found that stellar masses can be estimated with good precision with DES, despite the lower number of bands available. Gravitational lensing results from both DES and CLASH were used to compare stellar and total mass maps, as well as the mass profiles and stellar mass fraction.

We conclude that:

1. HST data can be used as a validation set for DES data and results. We expect 3 more CLASH clusters (Abell 383, MACS0416.1–2403 and MACS0429.6–0253) to be included in the whole DES footprint. We found that in this case, using the `CLASS_STAR` parameters with the mentioned cut is more efficient than adopting the `SPREAD_MODEL_I` with the cut at 0.003.

2. DES photo-z's are compatible with the 17 HST filters photo-z's within the DES requirements. The $z \sim 0.1$ offset observed in the DES photo-z's, is due to a colour-redshift degeneracy that cannot be broken without UV bands at redshifts below 0.4.

We found that such offset would percolate into the stellar mass estimates and bias the results by ~ 0.16 dex. In order to perform stellar mass studies, we therefore overcame the problem of the redshift estimation for single cluster members by devising a technique as follows. This method treats separately the red galaxies, as found by RedMaPPer, and the blue galaxies. The redshift information can either be the spectroscopic redshift of the cluster, if available, or the RedMaPPer cluster photometric redshift (as RedMaPPer photo-z's are estimated with high precision). In order to estimate the blue galaxies contribution to the stellar mass, we perform a background subtraction which is only possible thanks to the DECam wide field of view.

3. We then estimated total stellar mass and stellar mass fraction profiles for both DES and CLASH, reaching large radii with DES. Within the projected r_{200c} radius, we find a fraction of stellar mass over total mass (derived from weak lensing) $f_\star(< r_{200c}) = (6.8 \pm 1.7) \times 10^{-3}$ with DES, which is compatible with other recent measurements from an independent dataset (Bahcall & Kulier 2014).

4. On cosmological scales the ratio of baryon to total matter densities is $\Omega_b/\Omega_m \approx 16\%$ (e.g. Planck Collaboration et al. 2015). In the cluster core we find that the ratio of stellar mass to total matter is $\sim 0.7\%$. This means that if the cluster distribution is representative, then only 4% of the baryons are locked into stars (compatible within 2σ with Fukugita & Peebles 2004).

5. The stellar mass fraction profiles we derive from DES and CLASH are compatible within 1σ, provided that the same parametrisation is used for the total matter halo profile.

6. HST clusters can be used to test and calibrate stellar mass estimates. In future works we plan to test the stellar mass to light ratio derived from DES to that from HST, as this should be nominally invariant under changes in galaxy apertures (that are different between the two datasets used in this work), and therefore better matched than $M_\star$ between the surveys. In addition, an extensive spectroscopic campaign carried out with the Very Large Telescope (VLT) (CLASH–VLT, Rosati et al. 2014) is currently providing thousands of spectra for 14 CLASH clusters. In the future, we plan to use this survey to further test our technique: this dataset will include spectra

up to very large cluster radii, making CLASH–VLT ideal to test stellar masses on the large scales explored by DES. CLASH–VLT analysis of stellar masses for the cluster RXJ2248 are in course of preparation (Annunziatella et al., in prep.), and stellar mass density profiles have been studied recently for other clusters (Annunziatella et al. 2014, Annunziatella et al. 2015).

7. In the future, we plan to apply the same techniques to a sample of 100 000 stacked DES clusters and deduce important information about galaxy evolution by looking at the relation between stellar and total mass, as a function of radii and redshift, at the Stellar Mass Function and at the stellar mass environment dependence. The stacking of the whole DES sample would allow us to estimate $f_\star$ with an error significantly smaller than what is given here.

At the time of writing, DES observations have not been completed yet, but clusters catalog have been finalised for Year 1 data. We therefore show results on the relation between stellar mass and halo mass in clusters using those data.

Chapter 5

Stellar mass as a cluster mass proxy

"It is the unknown we fear when we look upon death and darkness, nothing more."

J. K. Rowling – Harry Potter and the Half-Blood Prince

The work described in this chapter is part of **Palmese et al., 2018** *"Stellar mass as a galaxy cluster mass proxy and stellar–to–halo connection in the Dark Energy Survey redMaPPer clusters", currently in the DES collaboration review process, and the companion papers* **Welch, Annis, Lin, Palmese, Soares–Santos et al., in prep.,** *and* **Pereira, Soares-Santos, Makler, Annis, Lin, Palmese et al., 2018, MNRAS 474, 1361P**.

5.1 Introduction

Galaxy clusters are fundamental cosmological probes for large galaxy surveys such as the Dark Energy Survey. The estimation of cosmological parameters from clusters abundance is allowed by the dependence of the halo mass function on cosmology (Press & Schechter 1974; Sheth & Tormen 2002; Tinker et al. 2008), but this requires estimates of cluster total masses from the observables of our galaxy survey. In practice, we seek cluster mass

observables (or mass proxies) that tightly correlate with halo mass. In other words they exhibit a low scatter in halo mass at fixed mass proxy (and vice versa).

Several cluster finders are based on the cluster red-sequence (e.g. Koester et al. 2007*a*; Hao et al. 2010; Oguri 2014; Rykoff et al. 2014*a*). Amongst those, redMaPPer (Rykoff et al. 2014*a*) has been extensively studied and its mass proxy, the richness λ, calibrated for large photometric surveys such as the Sloan Digital Sky Survey (SDSS) and the DES over the past decade (Rozo et al. 2009*a*; Rozo et al. 2009*b*; Rozo et al. 2011; Rykoff et al. 2016*a*). On the other hand, there exists broad evidence that the content of clusters includes a non-negligible fraction of bluer, star–forming galaxies that do not follow the red sequence colour-magnitude relation, in particular towards increasing redshift (Oemler 1974; Butcher & Oemler 1978; Butcher & Oemler 1984; Donahue et al. 2002). This effect is known as the Butcher–Oemler effect. Whether the inclusion of the blue cloud can improve cluster mass estimates for cosmology is a matter of debate (e.g. Rozo et al. 2011) and depends on the survey characteristics. At higher redshifts, the blue fraction becomes significant (it can reach $\sim 30\%$ below redshift ~ 0.3; Zu & Mandelbaum 2016*a*) and the red sequence is not as distinguishable in colour-magnitude space as at lower redshift. In these regimes, the inclusion of the bluer members may play a significant role in cluster abundance studies of DES and other on-going and future photometric surveys (the Large Synoptic Sky Survey, Euclid) that push towards higher redshifts, $z = 1$ and beyond. One clear advantage of including blue galaxies in cluster catalogs is in studying cluster properties and their evolution with redshift, in particular the Butcher-Oemler effect and quenching mechanisms. Moreover, cluster finders able to identify also cluster members that do not belong to the red sequence (Miller et al. 2005; Soares-Santos et al. 2011) already exist. For these reasons, we develop a low–scatter mass proxy for cluster finders that are not red-sequence based.

Previous works (for example Andreon 2012) have exploited stellar masses as a possible cluster mass proxy. We here extend this study by using a larger sample of X-ray clusters for calibration and by complementing the stellar mass estimates with a membership probability scheme. We call this mass proxy "$\mu_\star$". A feasibility study for stellar mass computation with DES data has been presented in Chapter 4, where we found that stellar masses of clusters members can be recovered within 25% of HST-CLASH values. We therefore apply our method to a well-established cluster catalog, the DES Year 1 (Y1) redMaPPer catalog. Nevertheless, this mass proxy can easily be used with other, non-red-sequence based,

Figure 5.1: Distribution in richness λ and redshift for the volume–limited sample of DES Year 1 redMaPPer clusters used in this work.

cluster finders.

In Section 5.2 we describe the DES Y1 galaxy catalog, the Y1 redMaPPer catalog and the X-ray clusters catalog used. In Section 5.3 we describe the method used to compute cluster stellar masses, the completeness of the sample, and the membership probability assignment scheme. Finally in Sections 5.4 and 5.5 we calibrate our mass proxy against X–ray and weak lensing measurements.

5.2 Data

5.2.1 DES Year 1 data

The data used in this Chapter come from the first year of observations (September 2013 – February 2014, Diehl et al. 2014) and cover $1,839$ deg^2 with up to 4 passes per filter. At the time of writing, five observing seasons have been completed.

The median 10σ limiting magnitudes of Y1 data for galaxies are $g = 23.4$, $r = 23.2$, $i = 22.5$, $z = 21.8$, and $Y = 20.1$. Drlica-Wagner et al. (2017*a*) made further selections to produce a high-quality object catalog called the Y1A1 "gold" catalog.

The cluster catalog used here is the cosmology Y1 redMaPPer catalog v6.4.14 with richness $\lambda > 5$, which consists of 87,297 clusters. The cosmology catalog is built such that it

is volume limited and therefore simplifies our analysis with respect to selection effects. The 2D distribution of richness and redshift of this sample is shown in Figure 5.1. The centre position (given by the galaxy with the highest central probability p_{cen}) and the cluster redshift are the only outputs used from this catalog. The galaxies associated with each cluster are taken from the Y1A1 gold catalog. We select objects with `MODEST_CLASS`=1 in order to exclude sources that are likely not to be galaxies.

While the cluster catalog is based on Y1 data, the photometry comes from the deeper Year 3 data (median 10σ coadded catalogue depths for a $1.95''$ diameter aperture: $g = 24.33$, $r = 24.08$, $i = 23.44$, $z = 22.69$, and $Y = 21.44$ mag; Abbott et al. 2018). The photometry is the result of the Multi-Object Fitting (MOF) pipeline that uses the `ngmix` code.[1]

In order to compute the membership probabilities (as described in Section 5.3.1), we use photo-zs from the template-based Bayesian Photometric Redshifts (BPZ) algorithm (Benítez 2000). The catalog used in this work uses the same procedure as outlined in Hoyle et al. (2017). Briefly, six basic templates taken from Coleman et al. (1980) and Kinney et al. (1996) were corrected for redshift evolution and any residual calibration errors. Corrections were performed via finding the best-fit template for a subset of the PRIMUS spectroscopic data set (Cool et al. 2013) and computing median offsets between the observed photometry and template predictions within each template type, in a sliding redshift interval, $\Delta z = 0.06$. The magnitude and galaxy type redshift prior was then calibrated using the COSMOS+UltraVISTA photometric redshift catalogue of Laigle et al. (2016). Our BPZ run produces redshift probability distributions for $0 < z < 3.5$ in steps of $dz = 0.01$. We use the mean of the probability distribution function (PDF) and an estimate of the width of the PDF: Welch et al. (2018) show that this is a good enough approximation to estimate membership probabilities with our method. The member galaxy properties are instead computed assuming the much more precise cluster redshift.

5.2.2 X-ray catalogs

The $\mu_\star$-X-ray mass observable relations are computed using *XMM* and *Chandra* data. The DES Y1 redMaPPer cluster catalog is used to find galaxy clusters on the X-ray databases at the same positions. Consequently, the samples are not X-ray selected, but at the same time X-ray temperature and luminosity measurements are not available for all

[1] `https://github.com/esheldon/ngmix`

of the redMaPPer clusters.

The X-ray Multi–Mirror Mission (*XMM*; Jansen & Laine 1997) is a European Space Agency space mission launched in 1999. The *XMM* Cluster Survey (*XCS*) consists in a search for galaxy clusters in archival *XMM-Newton* observations. In order to derive the cluster X-ray temperature and luminosity, we use the *XCS* Post Processing Pipeline (`XCS3P`) as described in Manolopoulou et al. (in prep), and briefly describe the methodology here. Cluster spectra are extracted and fit using the XSPEC (Arnaud 1996) package, performed in the 0.3-7.9 keV band with an absorbed MeKaL model. The cluster spectra are extracted within r_{500c}, which is estimated through an iterative procedure. An initial temperature is estimated using the XAPA source detection region (Lloyd-Davies et al. 2011), and r_{500c} estimated from the r_{500c}-kT relation of Arnaud et al. (2005). This process is then iterated until r_{500c} converged to within 10%. Furthermore, during each iteration, a calculation of coefficient of variation (Koopmans et al. 1964) of T_X is performed, defined as the ratio of the standard deviation (σ) to the mean (μ), given by $C_v = \sigma(T_X)/\mu(T_X)$. In this work, we adopt a value of $C_v < 0.25$ as an indicator of a reliable measurement of the iterative temperature. For our final temperature–mass proxy relation analysis we select a high signal–to–noise subsample by excluding clusters with $\sigma_T > 30\%$ and redMaPPer richness error $\sigma_\lambda > 15\%$. The final sample is composed of 74 clusters in the DES Y1 wide field.

The *Chandra X-ray Observatory* is a NASA telescope launched in 1999. In order to obtain X-ray temperatures and luminosities for archival *Chandra* data, we use the Mass Analysis Tool for *Chandra* (`MATCha`) pipeline, described in Hollowood et al. (in prep). This pipeline finds, downloads, and cleans archival *Chandra* data for each of its input cluster candidates. It then iteratively finds a galaxy cluster center (until converged within 15 kpc), and iteratively fits X-ray temperatures and luminosities within 500 kiloparsec, r_{2500c}, and r_{500c} apertures (until converged within 1σ). As with `XCS3P`, `MATCha` performs its fitting using XSPEC, with an absorbed MeKaL model. Unlike `XCS3P`, `MATCha` performs its fits within the 0.5–2.0 keV band. For consistency with the *XCS* selection, we apply the same signal-to-noise–ratio (SNR) cut to this sample. We choose to use temperatures within r_{2500c} for this sample because they are more accurate for nearby clusters, where the the r_{500c} apertures becomes too big compared to the *Chandra* chip. Our final *Chandra* sample is composed of 69 clusters in the DES Y1 wide field.

Figure 5.2: Comparison of BMA clusters stellar mass to Millennium simulation true values at different redshift values. The dashed lines indicates the one–to–one relation.

5.3 Method

The BMA method in clusters

Rykoff et al. (2016*a*) showed that the redMaPPer photometric redshifts for DES are excellent, with errors of the order $\sigma_z/(1+z) \sim 0.01$ up to $z \sim 0.9$. This allows us to safely assume the cluster redshift for the cluster members and to avoid exploring the photo-z dependence of stellar masses, as was done in another DES study by Capozzi et al. (2017). Despite the fact that in the present work we can safely assume that the cluster redshift is a good estimate of the real galaxy redshift, all the other assumptions remain unconstrained. We therefore choose not to ignore the uncertainty on model selection and use the BMA code presented in Chapter 2 to estimate stellar masses and other properties of the single galaxies, from which we derive the total cluster stellar masses. We test our results against the Millennium simulation semi-analytic model from De Lucia & Blaizot (2007)[2], and show the results for the sum of stellar mass in clusters, in Figure 5.2. We run the BMA algorithm using the simulated magnitudes for the *griz* SDSS filters, which are very similar to the DES ones. In this case the scatter of the bias distribution is even lower ($\lesssim 0.1$ dex) than what found in the comparison with the COSMOS results, showing that our method works well against other SED fitting methods and simulations.

[2] `http://gavo.mpa-garching.mpg.de/Millennium/Help?page=databases/millimil/delucia2006a`

Figure 5.3: Analysis of the completeness of the galaxy sample. *Top panel:* observed r-band magnitudes that the galaxies in our sample would have if they had the absolute magnitude used as our limit ($M_r^{\rm lim} = -19$). The 95th percentile of the magnitude distribution lies below the median DES Y1 10σ limit in r-band (dashed line). *Bottom panel:* limiting mass $M_\star^{lim}$ that each galaxy would have, at its redshift, if its absolute magnitude were equal to $M_r^{lim} = -19$. The limiting mass is below $10^{10} M_\odot$ at all redshifts; we therefor cut our sample at this stellar mass.

Completeness of the stellar mass sample

The galaxy sample described in Section 5.2 is cut at $M_r < -19$, where M_r is the r-band absolute magnitude. Absolute magnitudes were estimated using K-corrections computed from galaxy templates generated by kcorrect v4.2 (Blanton & Roweis 2007). We took each galaxy's redshift to be the same as its photo-z, found the closest kcorrect template on a grid of redshift and colors ($g-r$, $r-i$, and $i-z$), and used that template's K-correction from observed i-band to rest-frame r-band to calculate M_r. An absolute magnitude cut M_r brighter than -19 was then applied to the galaxy catalog before computing membership probabilities. This cut ensures that our galaxy sample is volume limited across the redshift range considered. In Figure 5.3 we show the observed r-band magnitudes that the galaxies in our sample would have if they had an absolute magnitude $M_r = -19$ as a function of redshift. These are computed using the k-corrections and distance modulus output by our BMA code for the galaxies with a membership probability $> 8\%$, in order to be representative of a realistic cluster galaxy population. We show that the 95th percentile of the distribution in redshift bins is below the 10σ limit of the Y1 DES catalog over the redshift range covered by the redMaPPer cosmology catalog. We compare to the Y1 magnitude limit as our galaxy catalog contains objects detected in Y1, even if they are matched to the deeper Y3 photometry. We can conclude that with the chosen cut we are always $\gtrsim 95\%$ complete.

In order to estimate the completeness in stellar mass, we look at the mass $M_\star^{lim}$ each galaxy would have, at its redshift, if its absolute magnitude were equal to $M_r^{lim} = -19$. This can be achieved by converting the mass-to-light ratio fitted by BMA through $\log(M_\star^{lim}) = \log(M_\star) + 0.4(M_r - M_r^{lim})$, where M_r and $M_\star$ are the galaxy estimated absolute magnitude and stellar mass. From Figure 5.3 it is clear that, if all the galaxies were at M_r^{lim} or fainter, $\gtrsim 95\%$ of them would have a stellar mass $\lesssim 10^{10} M_\odot$. We therefore are $\gtrsim 95\%$ complete above $M_\star = 10^{10} M_\odot$ over the whole redshift range. The scatter in mass at each redshift is given by the scatter in M/L of the different models. We therefore cut our stellar mass sample at $M_\star > 10^{10} M_\odot$.

5.3.1 From galaxy stellar masses to $\mu_\star$

The cluster mass proxy $\mu_\star$ is computed by weighing the stellar mass of each galaxy in the cluster by its membership probability $p_{\mathrm{mem},i}$:

$$\mu_\star = 10^{-10} \sum_i p_{\mathrm{mem},i} M_{\star,i} \,, \tag{5.1}$$

where the factor 10^{-10} simply gives to the mass proxy an order of magnitude similar to that of the number of observed cluster galaxies. The sum is over all the galaxies from the DES Y1A1 gold catalog having $M_r < -19$ and within 3 Mpc from the centre of the cluster as given by the redMaPPer Y1 catalog. The errors on $\mu_\star$ were computed using jackknife resampling. Intuitively, this method allows us to estimate the variance on our estimator by considering a galaxy cut from the cluster at each time.

Membership probability assignment

The membership probability for a galaxy in a cluster is given by

$$p_{\mathrm{mem}} = p_R \, p_z \,, \tag{5.2}$$

where the components represent the probability of the galaxy being a member given its redshift (p_z) and its distance from the cluster center (p_R). The radial probability p_R is assigned by assuming a projected Navarro–Frenk–White (NFW; Navarro et al. 1996) profile, with R_{200c} computed by counting galaxies within 3 Mpc and finding the halo profile by assuming an Halo Occupation Distribution model. Useful information is also contained in the color probability. In order to assign these probabilities to each galaxy in a cluster, we therefore need to complete the following steps:

1. **Assign redshift probabilities.** By assuming that each galaxy redshift follows a Gaussian probability density function (PDF) with the mean being the observed photometric redshift z and the standard deviation being the uncertainty in the photometric redshift δz, we define the probability as the integral of the redshift PDF over a window around the redshift of the cluster z_0:

$$p_z = \int_{z_{min}}^{z_{max}} \frac{1}{\sqrt{2\pi}(\delta z')} e^{-\frac{(z'-z_0)^2}{2(\delta z')^2}} dz' \,. \tag{5.3}$$

In order to account for changing photometric redshift uncertainties at different redshifts, we evolve the size of the window with redshift based on the median photometric redshift uncertainty $\langle \delta z \rangle$ of galaxies in our sample at a given redshift. The bounds of our integral z_{min} and z_{max} are defined to evolve as

$$\begin{aligned} z_{min} &= z_0 - \langle \delta z \rangle \\ z_{max} &= z_0 + \langle \delta z \rangle \end{aligned} \tag{5.4}$$

This redshift probability gives galaxies of approximately the same redshift as the cluster center a greater weight than galaxies at vastly different redshifts.

2. **Count galaxies**. We count all galaxies along the line of sight within circular apertures with radii $0.1 \leq r \leq 3.0$ Mpc, weighted by p_z. This effectively selects galaxies near the cluster redshift while avoiding a sharp, arbitrary cutoff in redshift. The redshift weighted galaxy number counts as a function of radius are divided by the surface area at each radius. This converts our number counts into a surface density, which is background–subtracted.

3. **Background subtraction.** Background or foreground galaxies are likely to enter into our number counts. To remove this contribution, we measure a local background galaxy density in the environment around each cluster. Similarly to the previous step, this contribution is estimated by summing the photo-z probability weighted galaxy counts in an annulus around the cluster. We choose the internal radius of this annulus to be 4 Mpc in order to be far enough away from the cluster virial radius. The outer radius was chosen to be 6 Mpc to provide a sizable area to smooth out small fluctuations in density. The derived profile is transformed into a surface density and subtracted from the cluster surface density.

4. **Convert from a number density of galaxies to a mass density**. This step is performed by assuming the HOD model of Tinker et al. (2011). We interpolate the background subtracted cluster mass density within our apertures to find where the density equals 200 times the critical density, thus giving our value of R_{200c}.

5. **Assign radial probabilities.** Our radial probability assume a projected NFW mass profile, of the form (Wright & Brainerd 2000):

Figure 5.4: Colour distribution in $g - r$ of an example cluster at $z = 0.59$ from the Y1 redMaPPer sample. The histogram is made by counting all galaxies within 3 Mpc of the cluster center, weighted by their membership probability. The red and blue Gaussians represent the best fit of the red sequence and blue cloud from the Gaussian Mixture Model after background subtraction.

$$\Sigma(R) = \begin{cases} \frac{2\rho_s R_s}{r^2-1}\left[1 - \frac{2}{\sqrt{r^2-1}}\arctan\sqrt{\frac{r-1}{r+1}}\right] & r > 1 \\ \frac{2\rho_s R_s}{3} & r = 1 \\ \frac{2\rho_s R_s}{r^2-1}\left[1 - \frac{2}{\sqrt{1-r^2}}\operatorname{arctanh}\sqrt{\frac{1-r}{r+1}}\right] & r < 1 \end{cases} \tag{5.5}$$

where $r = R/R_s$, and $R_s = R_{200c}/c$ is the scale radius, with c being the concentration parameter set to $c = 3$.

The radial probability is computed from Eq. (5.5) as:

$$p_R = \frac{k\Sigma(R)}{k\Sigma(R) + \Sigma_{\rm bg}}\,, \tag{5.6}$$

where k is a constant given by the background subtracted surface number density $n_{\rm tot} - n_{\rm bg}$ and $\Sigma_{\rm bg}$ is the background surface density.

6. **Assign colour probability.** Colour probabilities $p_{\rm c}$ are estimated through a Gaussian Mixture Model (GMM), similarly to Hao et al. (2009). The fit is performed using a modified version of `scikit-learn` Python package (Pedregosa et al. 2011).

This method fits two Gaussians to the colour distribution of the galaxies in each cluster, weighted by their radial and redshift probabilities. The Gaussians fit the color distribution of the red sequence and blue cloud of cluster galaxies well. Figure 5.4 shows the two Gaussians for a randomly selected cluster from the Year 1 redMaPPer sample. A Gaussian PDF for the probability that a galaxy would have color x given it is in a color distribution of mean colour μ and variance σ^2 can be written as:

$$p(x|\mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} . \tag{5.7}$$

We define a colour probability density that a galaxy with color x is a member of a cluster with red and blue Gaussian color distribution given by μ_r, σ_r and μ_b, σ_b from the GMM fit as:

$$\Pi(x) = w_r p(x|\mu_r, \sigma_r^2) + w_b p(x|\mu_b, \sigma_b^2) , \tag{5.8}$$

where w_r and w_b are the area of the Gaussians and satisfy $w_r + w_b = 1$. Finally, we compute the probability that the galaxy is in the cluster given its colour:

$$p_{\rm c} = \frac{\kappa\Pi(x)}{\kappa\Pi(x) + N_{\rm bg}(x)} , \tag{5.9}$$

where κ is the background–subtracted number of galaxies. We can also define the probability of being in the red sequence:

$$P(\mathrm{RS}|x) = \frac{\kappa\Pi_{\rm RS}(x)}{\kappa\Pi_{\rm RS}(x) + N_{bg}(x)} , \tag{5.10}$$

where

$$\Pi_{\rm RS}(x) = w_r p(x|\mu_r, \sigma_r^2) . \tag{5.11}$$

These probabilities are computed for the available colors $g - r$, $r - i$, and $i - z$.

5.4 Calibrating $\mu_\star$ against X-ray mass observables

5.4.1 The $T_X - \mu_\star$ relation

Following previous works (e.g. Rozo et al. 2009*a*; Rozo et al. 2011; Mulroy et al. 2014), we perform a Bayesian linear regression of the scaling relation between the logarithm of the X-ray mass proxy (in this case the temperature T_X) and the logarithm of our photometric mass proxy, including an intrinsic scatter $\sigma_{\mathrm{Log}T_X|\mu_\star}$ of the temperature at fixed $\mu_\star$. Namely, we fit:

$$\langle \mathrm{Log}\ T_X|\mu_\star\rangle = \alpha + \beta\ \mathrm{Log}\Big(\frac{\mu_\star}{\tilde{\mu_\star}}\Big)\,, \tag{5.12}$$

where $\tilde{\mu_\star} = 1000$ is roughly the mean $\mu_\star$ of the sample. We use the publicly available Python version of Kelly 2007 and separately fit the X-ray temperatures presented in Section 5.2.2 for the *XMM* and *Chandra* samples. We perform separate fits for the two samples as combining different temperature measurements is not straightforward and we are not interested in fitting a generic $T_X - \mu_\star$ relation but rather to test our methodology against other well established mass proxies. The results of the regression are reported in Table 5.1 and shown in Figure 5.5. The slope found for the *Chandra* temperatures is shallower ($\beta = 0.295^{+0.070}_{-0.071}$) because the dynamical range explored by T_X is not as wide as in the *XMM* sample and some cluster temperatures have a very low signal-to-noise in the low T_X and low $\mu_\star$ end regimes (thus they are cut by our SNR selection). Farahi et al. (2018) also find a shallower slope in the $T_X - \lambda$ relation for the *Chandra* sample matched to Y1 redMapper clusters. The mass proxy seems to correlate better with the *XMM* temperatures, resulting in a slope of $\beta = 0.483 \pm 0.053$.

The weak lensing mass–$\mu_\star$ relation studied in Pereira et al. (2018) shows a steeper slope (1.74 ± 0.62 at $0.1 < z < 0.33$ for SDSS redMaPPer clusters) than the analysis presented here. We believe that the correlation of stellar mass with total cluster mass is higher than with the X-ray temperatures because the X-ray measurement only probes the inner part of the cluster gravitational potential (within R_{500c} and R_{2500c} for the *XMM* and *Chandra* data respectively), while the weak lensing probes larger radii.

We perform the same linear regression of Eq. (5.12) with the X-ray luminosities in units of 10^{44}erg/s in place of the temperatures. Results are reported in Table 5.1. We find a larger scatter for this relation, which is expected as the temperature directly probes the

Sample–observable	α	β	$\sigma_{\mathrm{Log}T/L_X\|\mu_\star}$
XCS–T_X	$0.580^{+0.021}_{-0.021}$	$0.483^{+0.053}_{-0.053}$	$0.152^{+0.017}_{-0.015}$
XCS–L_X	$0.392^{+0.064}_{-0.065}$	$1.54^{+0.18}_{-0.17}$	$0.514^{+0.051}_{-0.047}$
Chandra–T_X	$0.784^{+0.022}_{-0.022}$	$0.295^{+0.070}_{-0.071}$	$0.139^{+0.015}_{-0.014}$
Chandra–L_X	$0.644^{+0.062}_{-0.062}$	$0.84^{+0.20}_{-0.20}$	$0.436^{+0.040}_{-0.037}$

Table 5.1: Fits of the scaling relation following Eq.(5.12) for X-ray temperatures and luminosities. Values represent the median of the parameters posterior distribution, and the errors are the 16th and 84th percentiles. Temperatures are in units of keV and luminosities in 10^{44}ergs^{-1}

potential well of the halo, while the luminosity depends primarily on the density of the Intra–cluster Medium (ICM). This causes baryon effects to be included to a higher order and the scatter with halo mass to increase.

5.4.2 Intrinsic scatter

We find an intrinsic scatter of $\sigma_{\mathrm{Log}T_X|\mu_\star} = 0.152^{+0.017}_{-0.015}$ for the *XMM* sample, which is only $\sim 2\sigma$ above the value that we get if we reproduce the same analysis with the redMaPPer richness: $\sigma_{\mathrm{Log}T_X|\lambda} = 0.121^{+0.014}_{-0.013}$. This is a promising result in light of the fact that the redMapper mass proxy has been refined and optimised over several works (Rozo et al. 2009*b*, Rozo et al. 2009*a*) and that the sample was selected using richness cuts ($\sigma_\lambda < 15\%$, $\lambda > 5$). No cuts have been performed based on $\mu_\star$. The scatter on T_X from the *Chandra* sample is similar ($\sigma_{\mathrm{Log}T_X|\lambda} = 0.139^{+0.015}_{-0.014}$) and it is also less than 2σ above the redMaPPer richness estimate ($0.118^{+0.014}_{-0.014}$).

The value found for the *XMM* scatter corresponds to a 41% scatter (from $10^\sigma - 1$): even though it is not straightforward to compare results computed with different methods and using different samples, several works find that the intrinsic scatter is $\sigma_{\log M_h|X} = 10 - 70\%$ for a mass proxy X (see Table 3 of Mulroy et al. 2014 for a comparison). This result shows that our mass proxy is competitive with other methods of cluster mass estimation. Note that the scatter computed here is different from what we would find for the total cluster mass at fixed $\mu_\star$. In fact, as suggested in the previous subsection, not only do current X-ray temperature measurements probe a restricted cluster scale, but they are also influenced by gas and baryon physics. In other words, there is a non-negligible intrinsic scatter between total cluster mass and X-ray mass observables ($\sigma_{\mathrm{Log}L_X|M_h} \sim 0.17$ in Vikhlinin et al. 2009).

We perform a number of tests to understand if the membership probabilities are taken into account in an optimal way. We find that including the blue cloud galaxies does not

Figure 5.5: Bayesian linear regression of X-ray temperature and $\mu_\star$ for the XCS high signal-to-noise sample (top panel) and the Chandra sample (bottom panel). The grey points are our sample data points, the blue points are the mean temperature and mass proxy values in $\mu_\star$ bins. The red lines are a random sample from the posterior distribution of slope and intercept, and the blue band represents 1σ around the mean value of the intercept plus the intrinsic scatter.

Figure 5.6: Bayesian linear regression of X-ray luminosity and $\mu_\star$ for the XCS high signal-to-noise sample (top panel) and the Chandra sample (bottom panel). The grey points are our sample data points. The red lines are a random sample from the posterior distribution of slope and intercept, and the blue band represents 1σ around the mean value of the intercept plus the intrinsic scatter.

bring a significant increase in the scatter: the inclusion of the second term in the right-hand side of Eq. (5.8), compared to having the red sequence term only or redMaPPer members only, brings an additional scatter which is an order of magnitude lower than the error. This is consistent with what we would expect for this sample, as it has been matched to a red-sequence cluster finder. Rozo et al. (2011) found that the blue galaxies significantly increase the scatter of their sample, but the fact that this is not true in our case allows us to keep this contribution which may become relevant at low richness and high redshift regimes, which should be tested using a non-red sequence based cluster finder and matched against other mass observables. It is beyond the scope of this work to test this hypothesis. Rozo et al. (2011) also show that differences between the true and predicted scatter of the mass proxy–mass relation are irrelevant for a DES–like survey as long as these differences are about 5% or less (i.e., $\Delta\sigma < 0.05$), which further supports our choice.

We find that the inclusion of the radial probability works well in terms of the choice of an arbitrary radial cut between 0.7 and $3h^{-1}$ Mpc: in fact, the intrinsic scatter of the temperature-mass relation is independent of this choice. On the other hand, we tested the use of the red galaxies only without including the radial probability contribution. In this case, we find similar trends to previous work (e.g. Andreon 2015): optimal choices for the aperture *do* exist when no membership probability is considered. We find that the scatter can increase by up to $\sim 15\%$ within the inner 1.5 Mpc, and outside that range mostly noise is added.

We tested the inclusion of color probabilities p_c in the full membership probabilities by modifying Eq. (5.2) into $p_{\rm mem} = p_R p_z p_c$. We also tried to combine the color membership probabilities from different colors in different redshift ranges. This is justified by the fact that most of the colour information in a galaxy SED is contained in the 4000 Å break, that shifts between the bands with redshift. We therefore use $g-r$ for the range $z < 0.35$, $r-i$ in $0.35 < z < 0.75$ and $i-z$ at $z > 0.75$. We find that these tests did not have a significant impact on the mean scaling relation fit and intrinsic scatter, so it is reasonable to include the simpler version of the full probabilities as given in Eq. (5.2).

The fact that our scaling relation scatter and slope are insensitive to the choices made in these tests shows that the membership probabilities are robust and that cluster size and colors (that enter in $p_{\rm mem}$ though the redshift probability estimation) are taken into account well.

Figure 5.7: Weak lensing mass calibration of $\mu_\star$ from Pereira et al. (2018). The shaded regions represent 2σ confidence intervals. Miscentering corrections have been applied to the mass estimates. In the mass–$\mu_\star$ relation we adopt the median of $\mu_\star$ as the mass proxy pivot, which is, in order for the three panels: $\mu_\star^0 = 5.16 \times 10^{12} M_\odot$ (redMaPPer low redshift sample), $\mu_\star^0 = 7.30 \times 10^{12} M_\odot$ (VT low redshift sample), $\mu_\star^0 = 6.30 \times 10^{12} M_\odot$(VT high redshift sample).

5.5 Weak lensing calibration

In Pereira et al. (2018) we use two cluster samples from the SDSS Stripe 82 data to calibrate $\mu_\star$ and λ against weak lensing measurements: 230 redMaPPer clusters at redshift $0.1 \leq z < 0.33$ and 136 VT clusters at $0.1 \leq z < 0.6$. The source galaxy catalog used comes from the CS82 survey (Erben et al. 2017), with shape measurements and photometric redshifts from matched SDSS co-add (Annis et al. 2014) and UKIDSS YJHK (Lawrence et al. 2007) photometry. Clusters are stacked in $\mu_\star$ bins to measure a mass-observable power law relation of the form:

$$\langle M_{200c} | \mu_\star \rangle = M_0 \left(\frac{\mu_\star}{\mu_\star^0} \right)^\alpha . \tag{5.13}$$

For redMaPPer clusters we obtain $M_0 = (1.77 \pm 0.36) \times 10^{14} h^{-1} M_\odot$, $\alpha = 1.74 \pm 0.62$, while for VT clusters: $M_0 = (4.31 \pm 0.89) \times 10^{14} h^{-1} M_\odot$, $\alpha = 0.59 \pm 0.54$ and $M_0 = (3.67 \pm 0.56) \times 10^{14} h^{-1} M_\odot$, $\alpha = 0.68 \pm 0.49$ for the low and high redshift bins, respectively. This fits are shown in Figure 5.7. The results found for the redMaPPer richness with this method are consistent with the literature, showing that this method can be applied to any cluster-finding algorithm, including VT. The on–going work consists in replicating this analysis using DES Year 3 data, which comprises of a larger and deeper sample than SDSS.

5.6 Conclusions

In this Chapter we presented a stellar mass based mass proxy that can be applied to photometric surveys. Our main results can be summarised as follows:

- The outputs of our BMA code presented in Chapter 2 are used to estimate our mass proxy $\mu_\star$ for DES Year 1 data. We study the scatter of this mass proxy compared to X-ray mass observables: we find $\sigma_{\mathrm{Log}T_X|\mu_\star} = 0.152^{+0.017}_{-0.015}$ and $0.138^{+0.015}_{-0.014}$ for the *XMM* and *Chandra* temperatures respectively. These values are less than 2σ above the scatter we measure with the widely used redMaPPer richness λ. This measurement shows that $\mu_\star$ is a promising low–scatter mass proxy.

- This mass proxy has been calibrated with weak lensing measurements using SDSS data; the same analysis is currently being done for DES Year 3 data.

- Future work will include the development of a new version of the VT cluster finder, that integrates this mass proxy into the pipeline (Bugard et al., in prep.), and a production of a cluster catalog for DES data.

Chapter 6

Cluster evolution results from DES Year 1 redMaPPer clusters

It is our choices, Harry, that show what we truly are, far more than our abilities.

J. K. Rowling

The work described in this chapter is part of **Palmese et al., 2018** *"Stellar mass as a galaxy cluster mass proxy and stellar–to–halo connection in the Dark Energy Survey redMaPPer clusters", currently in the DES collaboration review process, and the companion paper* **Welch, Annis, Lin, Palmese, Soares–Santos et al., 2018**. *The Intra–cluster light section features work from* **Zhang, Yanny, Palmese et al., 2018** *and* **Gruen, Zhang, Palmese et al., 2018**, *both in the DES review process.*

6.1 Introduction

The method presented in the previous Chapter enables studies of the whole galaxy content of redMaPPer clusters. The cluster red sequence is the main feature used to identify galaxy clusters in optical data and produce samples that are used to measure cosmological parameters (Gladders & Yee 2005; Gladders et al. 2007; Koester et al. 2007*a*; Rozo et al. 2010; Rykoff et al. 2014*a*, 2016*a*), but our understanding of the underlying physical

precesses leading to the formation and evolution of this feature is limited. For example, simulations of the stellar content of galaxy cluster members hardly reproduce the color evolution of red sequence members (see Roediger et al. (2017) and references therein). Red sequence cluster finders therefore use the red sequence as an empirically developed method. However, in order to make the most precise cosmological measurements using red sequence-selected clusters, we must investigate and quantify the impact of the red sequence assumptions in the systematic uncertainties. The membership assignment scheme that we have presented allows us to study the photometric properties of cluster members, in particular measure the red sequence slope and width.

Using the quantities derived in the previous Chapter, we can also measure the stellar–to–halo mass relation (SHMR). Measuring such a relation is key to understanding the efficiency of assembling baryons into stars, which does not appear to be an efficient process: less than 10% of baryons are converted into stars (e.g. Gallazzi et al. 2008). Theoretical semi-analytical models and simulations (see Somerville & Davé 2015 for a review), make use of feedback processes from AGN and supernovae to switch star formation off and reproduce the observations, in particular at clusters scales. Therefore the efficiency with which halos convert the matter they contain into stars is a crucial ingredient in our understanding of galaxy formation and evolution, particularly the discrepancies currently existing between simulations and observations and also between different observational analyses. Several methods have been used to observationally study the link between stellar mass and halo mass. Amongst these, Halo Occupation Distribution (HOD; Seljak 2000; Peacock & Smith 2000) models allow us to connect the observed galaxies to the underlying dark matter. The basic assumption of the HOD model is that the probability that a halo hosts a galaxy with certain properties only depends on the halo mass. Several studies using the HOD (Zu & Mandelbaum 2015, Zu & Mandelbaum 2016*a*, Zu & Mandelbaum 2017) have extended the model to study effects such as quenching and environmental dependence with SDSS data. An alternative method uses abundance matching: it assumes that stellar masses or luminosities of galaxies are tightly correlated to the masses of dark matter halos (e.g. Moster et al. 2010), and measures the SHMR from stellar mass functions (SMF) or luminosity functions (LF). The majority of previous measurements on the SHMR were mainly limited to direct measurements of stellar mass and total mass (from lensing or X-ray mass scaling relation) on a small sample of clusters and groups (in the order of $\sim 1-100$, e.g. Kravtsov et al. 2014), or to the use of HOD or abundance matching

methods on large but low redshift ($z \lesssim 0.3$) samples (such as Zu & Mandelbaum 2015), or within small fields (e.g. Coupon et al. 2015, Shan et al. 2017).

The galaxy content of clusters can also be examined through the galaxy stellar mass function, and is used to connect galaxies with the underlying dark matter as mentioned above. Its shape and evolution provide insights into galaxy formation and evolution processes, and their connection with the galaxy environment. Extensive work has been done to constrain the SMF for galaxies with different colour, morphology and environment (Bundy et al. 2006; Baldry et al. 2008; Pozzetti et al. 2010; Vulcani et al. 2012; Mortlock et al. 2015; Weigel et al. 2016; Etherington et al. 2017; Capozzi et al. 2017). Usually the SMF and LF are well fitted by a single or double Schechter function (Schechter 1976*a*). It is of particular interest to focus on clusters, where other than the star formation history, a number of external stresses (e.g. galaxy harassment, strangulation, merging, tidal forces) impact on the stellar mass function of the cluster members over cosmic time. Most works find that the luminosity or stellar mass function of these galaxies is consistent with a passive evolution since $z \sim 1$ (e.g. Kodama & Bower 2003; Andreon 2006), suggesting that star formation and mass assembly are accelerated in such dense environments and have been completed by $z \sim 1$. Zhang et al. (2017) find a hint for evolution of the faint end LF between $z \sim 1$ and $z \sim 0.1$, such that the low mass red sequence galaxies are more abundant than brighter ones at lower redshift, indicating different formation times. Other works find similar results (e.g. De Lucia et al. 2007; Lin et al. 2017). However, there is no consensus yet on the LF evolution, especially given the different methods and samples used, and the difficulties in detecting and measuring photometry of faint galaxies in crowded environments. Additional measurements of SMF over wide redshift ranges may help in further understanding the discrepancies.

An important ingredient of stellar mass measurements in clusters is also the so–called Intra–cluster light (ICL). The central galaxy of clusters tends to be surrounded by an extended light envelope (Zwicky 1951, 1952; Matthews et al. 1964; Morgan & Lesh 1965). Studies indicate that this light envelope extends to hundreds of kpcs and sometimes encloses several galaxies, especially if the cluster is experiencing a merging process (see reviews in Mihos 2004; Lauer et al. 2014). Given its diffuse nature and the fact that it may enclose multiple galaxies, it seems more reasonable to consider this envelope as a component of galaxy clusters rather than as a part of single galaxies. This diffuse light envelope is thus frequently referred to as ICL. Despite the conceptual difference of central

galaxy and ICL, they are almost impossible to observationally distinguish because the outskirts of centrals naturally blend into ICL. Outside the outskirts of centrals, the ICL is extremely faint, which poses significant challenges for separating it from centrals, and for further characterizing its distribution and properties. Studying the statistical distribution of ICL in an ensemble of clusters is one approach toward easing systematic effects from ground based observations. An approach towards this direction, called "stacking", consists in combining the images of several galaxy clusters by aligning the centers of the clusters and measuring ICL in the combined image. This method is used in Zhang et al. (2018) to detect ICL in DES clusters and its results are used to study the properties of ICL and its plausible formation scenarios. It is likely that ICL forms through multiple channels, but the relative contributions are still being explored. Depending on the formation mechanism, simulated ICL exhibits different color and spatial distributions, and the total amount of ICL stellar mass varies, which provides clues for testing ICL formation hypotheses with observations.

In this Chapter we present measurements of the red sequence, SHMR and stellar mass functions in clusters out to $z \sim 0.7$ from $\sim 1,839\,\mathrm{deg}^2$ of the sky taken during the first year of DES observations, and study some ICL properties. This Chapter is divided into eight sections. In Section 6.2 we present cluster properties that naturally come out of our membership probability scheme, in particular for the red sequence galaxies. Section 6.3 contains measurements of the SHMR for centrals, satellites and total galaxy population. In Section 6.4 we present measurements of the stellar mass function for centrals and for all galaxies in clusters, while in Section 6.5 we study the mass growth of the centrals over redshift and discuss the identification of those and Brightest Cluster Galaxies (BCGs) from our sample. Section 6.6 is dedicated to the effect of the galaxy Initial Mass Function (IMF) on the SHMR and SMF. In Section 6.7 we study measurements of the intra–cluster light in terms of its color and stellar mass. We also present results on the impact of ICL on photometric redshifts. Section 6.8 contains discussion and conclusions.

6.2 Photometric properties of clusters

In the previous Chapter, we have introduced the membership probabilities method used. In particular, the colour probabilities allow measurements of the red sequence properties. A quantity of interest is the red sequence slope in colour–magnitude space, which we

Figure 6.1: Colour–magnitude diagram for the same cluster. The red points are weighted by $P_{\rm mem} \times P_{\rm red}$, and the blue points by $P_{\rm mem} \times P_{\rm blue}$. The red line is the best fit from the GMM method.

measure by performing a weighted linear fit of observed r versus $g - r$, i versus $r - i$ and z versus $i - z$. The weights in the three cases are given by the membership probability multiplied by the red sequence probability defined in Eq. (5.10), as computed from the colours $g - r$, $r - i$ and $i - z$ respectively. An example of this fit is shown in Figure 6.1 for the $g - r$ colour.

Other quantities of interest in cluster studies are the mean colour and the scatter around it of the red sequence galaxies. These are measured by our GMM fit as the mean and the width of the Gaussian distribution associated with the red sequence. The observed scatter $\sigma_{\rm obs}$ will be given by the contribution of the intrinsic scatter in colour of the galaxies in the cluster and of the photometric error in the colour $\sigma_{\rm phot}$. Assuming these two errors are independent, they can be summed in quadrature, and the intrinsic scatter we are interested in is given by:

$$\sigma_{\rm int} = \sqrt{\sigma_{\rm obs}^2 - \sigma_{\rm phot}^2}\,. \tag{6.1}$$

The typical photometric error for each cluster can be measured as the mean measured colour error from its members. We consider only members with $p_{\rm mem} > 20\%$ to avoid including a high number of interlopers. In Figure 6.2 we show red sequence mean color $\mu_{\rm red}$, intrinsic scatter $\sigma_{\rm red}$ and slope $m_{\rm red}$ from the three considered colours as a function

Figure 6.2: Red sequence mean color $\mu_{\rm red}$, intrinsic scatter $\sigma_{\rm red}$ and slope $m_{\rm red}$ as a function of redshift for $\sim 80,000$ clusters from the DES Y1 redMaPPer cosmology sample (purple density plot). The magenta lines are the estimates from redMaPPer using SDSS data (from Rykoff et al. 2014*a*).

of redshift. These results can be compared to the results from Rykoff et al. (2014*a*) in $g-r$ for SDSS clusters. The mean colours tend to become redder at higher redshifts, as expected, while the intrinsic scatter increases, while also becoming a noisier measurements due to the fact that the photometric errors become more substantial, in particular in $g-r$, as most of these red sequence galaxies are very faint in g–band. The slope is negative and quite shallow, as seen in previous studies (e.g. Mei et al. 2009, Rykoff et al. 2014*a*). On–going work is focused on measuring the mentioned quantities, along with the blue fraction, from rest–frame galaxy colours. These measurements will allow physical interpretations of the evolution of the studied properties, which is not possible with the observed colours only. The results shown in Figure for the observed colours still provide a solid consistency check for our membership probability assignment scheme.

6.3 Stellar-to-halo mass

While the weak lensing calibration of the mass scaling relation for $\mu_\star$ is carried out in a companion paper for SDSS clusters (Pereira et al. 2018), here we use an independent mass estimate through the richness-mass relation which has been extensively studied for redMaPPer clusters in Melchior et al. (2016). This allows us to transform the redMaPPer richness λ into a halo mass M_{200m} for all the Y1 redMaPPer clusters and estimate the stellar–to–halo–mass relation for DES clusters.

For the full Y1 redMaPPer sample we focus on a statistical measurement of the stellar to halo mass relation. This means that while binning our sample in halo mass and redshift, we assume that the intrinsic scatter of stellar mass around a certain halo mass would reduce to a stochastic scatter around the mean SHMR value. The validity of this assumption has already been pointed in other works (Zu & Mandelbaum 2015; Guo et al. 2014). We therefore choose a method that allows us to fit an intrinsic scatter and to take into account errors on stellar mass, halo mass and redshifts.

We fit the SHMR with a linear model in $\mathrm{Log}(M_\star),\ \mathrm{Log}(M_{200c}),\ \mathrm{Log}(1+z)$ in the form:

$$\mathrm{Log}\Big(\frac{M_\star}{\tilde{M}_\star}\Big) = \alpha \mathrm{Log}\Big(\frac{M_{200c}}{\tilde{M}_{200c}}\Big) + \beta \mathrm{Log}\Big(\frac{1+z}{1+\tilde{z}}\Big) + \gamma \ , \tag{6.2}$$

where $\tilde{M}_\star$, $\mathrm{Log}(\tilde{M}_{200c}) = 13.79$ and $\tilde{z} = 0.46$ are the median values of the full sample. $\tilde{M}_\star$ is changed from case to case. This relation is a fair assumption at cluster scales, and it is often used in the literature (Brough et al. 2008; Moster et al. 2010; Pillepich et al. 2017). We add a Gaussian scatter σ_0 on $\mathrm{Log}(M_\star/\tilde{M}_\star)$ independent of halo mass, which enters in our analysis as an additional term to the covariance matrices of the data. We further assume that the measurements of the data D_i for each cluster i, namely $M_{\star,i}$, $M_{200c,i}$ and z_i, are independent, and that the errors on the data are Gaussian. Given these assumptions and Bayes' theorem, the posterior distribution of the parameters $\alpha,\ \beta,\ \gamma,\ \sigma_0$ in Eq. (6.2) given the data D becomes proportional to the product of 1D Gaussians $\mathcal{N}^{1\mathrm{D}}(\mu;\sigma^2)$ of mean μ and variance σ^2 for each cluster i as:

$$\begin{aligned} p(\alpha,\beta,\gamma,\sigma_0|D) &= \prod_i p(\alpha,\beta,\gamma,\sigma_0|D_i) \\ &\propto \prod_i \mathcal{N}^{1\mathrm{D}}(\bar{x}_i - \alpha\bar{y}_i - \beta\bar{z}'_i - \gamma;\, \sigma_0^2 + \Lambda_x + \alpha^2\Lambda_y + \beta^2\Lambda_{z'})\,, \end{aligned} \tag{6.3}$$

where $x_i \equiv \mathrm{Log}\left(\frac{M_{\star,i}}{\tilde{M}_\star}\right)$, $y_i \equiv \mathrm{Log}\left(\frac{M_{200c,i}}{\tilde{M}_{200c}}\right)$, $z_i' \equiv \mathrm{Log}\left(\frac{1+z_i}{1+\tilde{z}}\right)$, and Λ is the covariance matrix of the $i-$th cluster, which is diagonal under our assumptions. We assume uniform truncated priors for all of the four fitting parameters.

6.3.1 Central stellar mass to halo mass

We select as the central the galaxy with highest $P_{\rm cen}$ centering probability from the redMaPPer catalog, and consider as satellites all of the remaining galaxies. We fit the stellar mass of centrals, $M_\star^{\rm cen}$, as a function of M_{200c} and estimate the parameters in Eq. (6.2) and (6.3). The results are presented in Table 6.1 and Figure 6.3. The scatter at fixed halo mass is substantial (~ 0.3 in logarithmic scale) but a trend with halo mass is clearly found, with a slope of $\alpha = 0.4052 \pm 0.0048$. In Figure 6.3 we show the results for redMaPPer clusters in the red density plot, while the black solid lines are 100 random samples from the α and β posterior distributions obtained with the Bayesian linear regression on that data. For visualisation purposes, we plot mean stellar mass values in halo mass bins in three redshift bins ($z < 0.25$, $0.25 < z < 0.4$, $0.4 < z < 0.7$). These results are compare to others from the literature that use a range of different methods. For a more consistent comparison, we show results that assume a Chabrier IMF. Kravtsov et al. (2014) use SDSS photometry and X-ray data for single clusters at $z < 0.1$ and compare with abundance matching predictions, while Zu & Mandelbaum (2015) and Coupon et al. (2015) implement HOD methods on SDSS and CFHTLS data respectively. Zhang et al. (2016*a*) present a study of BCGs from DES Science Verification data for X-ray selected clusters, and we show their results for 32 kpc apertures around the BCG at the mean redshift of our sample $z = 0.45$. Pillepich et al. (2017) use the latest Illustris simulations to measure the stellar mass content of groups and clusters.

Kravtsov et al. (2014) perform a detailed analysis to derive extended luminosity profiles around BCGs, and fit those with multiple Sérsic profiles. The model profile is then extrapolated to infinity to derive total magnitudes. They find that `CMODEL` magnitudes computed with the standard SDSS pipeline underestimate the total BCG luminosity by a factor $\sim 2-4$. The MOF magnitudes used in this work are computed similarly to the SDSS `CMODEL` magnitudes: a composite model made of a bulge plus a disk component is fit to the profile and extrapolated to infinity. In order to compare our results to Kravtsov et al. (2014) we downweight their best fit by 0.45 dex in stellar mass. This is their SHMR estimate presented in Figure 6.3, which is consistent with our result at all halo masses, but

Figure 6.3: *Top:* Stellar–to–halo mass relation for central galaxies (left panel), and posterior distributions of the parameters in Eq. (6.2) (right panel). *Bottom:* Total stellar–to–halo mass relation (left panel), and posterior distributions of the parameters in Eq. (6.2) (right panel). The data points represent the mean stellar mass values and the standard error of the mean of the distribution in halo mass bins. The black lines are 100 random samples from our α and β posterior distributions, and the light shaded broad region represents our scatter. The lines from the literature represent their best fit. The shaded region around the Kravtsov et al. (2014) best fit is their 1σ uncertainty on slope and intercept. The shaded region around the IllustrisTNG best fit is the Pillepich et al. (2017) scatter estimate for 32 kpc apertures around galaxies. All the data and fits presented assume a Chabrier IMF.

with a slightly shallower slope. They find a slope of 0.39 ± 0.17 and 0.33 ± 0.11 when they include the clusters from Gonzalez et al. (2013) (and this is the result we show), which is within 1σ from our best–fit. The de–corrected normalisation is consistent with ours, although they focus on clusters at $z < 0.1$ and our data points from the lowest redshift bin are ~ 0.1 dex below the rest of the cluster sample. This discrepancy is comparable to the uncertainty on stellar masses and could be due to the difference in the photometry and the qualitative correction we have applied.

The analysis from Zu & Mandelbaum (2015) is also valid at low redshifts ($z < 0.3$) and it looks qualitatively in agreement with our lowest redshift bins measurements. The slope from Zhang (2018) of 0.37 ± 0.10 is within 1σ of what we find, while the normalisation depends on the aperture chosen and a comparison is not straightforward: we use magnitudes from MOF, that are not computed within a fixed aperture but vary from object to object.

The Coupon et al. (2015) estimate has the shallowest slope of all the results discussed here, which makes their results deviate from ours towards halo masses. Their redshift range is overlapping with ours from $z > 0.5$, but going up to $z \sim 1$ with a mean around 0.8. It is possible that galaxy evolution affects the stellar mass of galaxies at redshifts that we are considering in this work, but the weak redshift evolution that we observe seems to go towards higher values of stellar mass at higher z. We argue that the difference in normalization may be due to the different framework used to estimate the stellar masses. In particular, they utilize a wider range of galaxy dust models, which they may constrain better thanks to the K_s band information. Also, they do not consider models with super-solar metallicity, which may be relevant when fitting BCGs and luminous red galaxies in clusters.

Results from the latest IllustrisTNG simulations (Pillepich et al. 2017) deviate from our result and other observational data at high halo mass. In Figure 6.3 we plot their best fit SHMR for centrals when the stellar mass is computed within a 30 kpc aperture. They de-correct Kravtsov et al. (2014) result to match that aperture and find their best fit to be higher than Kravtsov et al. (2014). They find that the SHMR is very sensitive to the change of aperture considered, which could also explain our disagreement. In particular, for brighter (and thus greater stellar mass) objects we may be systematically underestimating the total luminosity of the central galaxy (as also pointed in Kravtsov et al. 2014), as we are only considering a model that fits well to the inner luminosity profile,

Figure 6.4: Stellar mass of the central over the total stellar mass for the Y1 redMaPPer clusters (red density plot). The data points represent the median stellar mass fraction values at different halo masses and the errorbars indicate the standard error of the mean of the fraction distribution in each halo mass bin. The central contributes roughly 40-20% of the total stellar mass. The line is from Pillepich et al. (2017) results at $z = 0$ and with 30 kpc apertures.

and not the extended stellar halo. Also, in brighter environments, there is a chance that the subtracted background is overestimated. This would explain our shallower slope in the SHMR. On the other hand, we find a high scatter (~ 0.3 dex) in stellar mass that still makes our results consistent at the high mass end.

Our scatter is larger than typically found in other works (0.22 dex in Zu & Mandelbaum 2015 and Coupon et al. 2015, 0.17 dex in Kravtsov et al. 2014). Given that these values may include a contribution from measurement uncertainty, and given the differences between the eemethods and samples adopted, we believe that we should not expect these values to match. Furthermore, our sample spans a wider combination of area and redshift range than other works, making contributions to the intrinsic scatter from sample variance and galaxy or cluster evolution more substantial. Amongst the works discussed in this section, the analysis from Kravtsov et al. (2014) is the closest to ours. They consider a much smaller ($\sim$ tens of clusters) sample of clusters over a redshift range $z < 0.1$, thus it is not surprising that our scatter is ~ 0.12 dex larger than theirs.

The redshift dependence of the SHMR seen in the β parameter is positive, and this can be understood in light of the results presented in Section 6.5.1.

IMF		α	β	γ	σ_0	$\mathrm{Log}(\tilde{M}_\star)$
Chabrier	Central	$0.4052^{+0.0048}_{-0.0048}$	$0.531^{+0.030}_{-0.030}$	$-0.0520^{+0.0013}_{-0.0014}$	$0.3048^{+0.0009}_{-0.0010}$	11.52
	Satellites	$1.1351^{+0.0063}_{-0.0066}$	$-0.332^{+0.037}_{-0.037}$	$-0.1285^{+0.0016}_{-0.0016}$	$0.2512^{+0.0013}_{-0.0013}$	12.01
	Total	$0.8918^{+0.0048}_{-0.0048}$	$-0.194^{+0.028}_{-0.028}$	$-0.0536^{+0.0012}_{-0.0013}$	$0.2492^{+0.0010}_{-0.0010}$	12.12
Salpeter	Central	$0.4042^{+0.0050}_{-0.0054}$	$0.642^{+0.032}_{-0.042}$	$-0.0549^{+0.0012}_{-0.0013}$	$0.30216^{+0.00099}_{-0.00094}$	11.56
	Satellites	$1.1181^{+0.0065}_{-0.0067}$	$-0.2863^{+0.037}_{-0.035}$	$-0.1010^{+0.0016}_{-0.0016}$	$0.2368^{+0.0014}_{-0.0014}$	12.22
	Total	$0.8653^{+0.0053}_{-0.0050}$	$-0.116^{+0.028}_{-0.032}$	$-0.0401^{+0.0012}_{-0.0012}$	$0.2320^{+0.0010}_{-0.0010}$	12.28

Table 6.1: Fits of the SHMR from Eq. (6.2) for centrals and all galaxies. Values represent the median of the parameters posterior distribution, and the errors are the 16th and 84th percentiles. Redshift and halo mass pivot values are respectively $\tilde{z} = 0.46$ and $\mathrm{Log}(\tilde{M}_{200c}) = 13.79$.

Figure 6.5: Stellar mass fraction (total stellar mass of each cluster over its halo mass) as a function of halo mass. The data points represent the mean stellar mass fraction values at different halo masses and the error bars indicate the standard error of the mean. The dashed line is the prediction of Kravtsov et al. (2014) using abundance matching with scatter in the SHMR and a Chabrier IMF. The stellar masses have been corrected to galaxies within R_{200c} only for the comparison.

6.3.2 Total stellar to halo mass

Satellite galaxies become a significant contribution to the stellar content of the halo at higher halo masses. In fact, the total mass of clusters can be accounted for by the contribution of the satellite sub-halos, while the central halo contribution decreases. This can be seen in terms of stellar mass in Figure 6.4. The central contributes roughly 40-20% of the total stellar mass at all halo masses, decreasing with halo mass. We do not find any significant redshift dependence of this behavior.

Fit results for the total SHMR with the power law presented in Eq. (6.2) are listed in Table 6.1 and shown in Figure 6.3. Our errors on the power law parameters are very small, in the order of $\sim 0.5 - 7\%$, because of the large number statistics used. We find that the total SHMR follows a steeper and less scattered power law than centrals only, as also found in previous works (e.g. Pillepich et al. 2017). The slope is significantly steeper than what is found in other observational works, such as Andreon (2012) 0.37 ± 0.07, and Kravtsov et al. (2014) 0.59 ± 0.08, while the central SHMR slope is still consistent with Kravtsov et al. (2014) within 1σ. One reason for the discrepancy is that they consider a fixed $M_\star/L$ ratio to compute the stellar masses of all galaxies. Secondly, we have a deeper dataset

and MOF photometry that performs well in crowded environments such as clusters, and membership probabilities that take into account the galaxy properties. These factors will change the contribution that the satellite galaxies give to the total stellar mass of clusters. Our result is closer to what is found in the latest IllustrisTNG simulations: 0.84 when including centrals, intra–cluster light (ICL) and satellites, reaching 1.14 for satellites only. This value is also less than 1σ away from our result. The inclusion of centrals is what lowers the slope, an effect which is mitigated in our case by the inclusion of membership probabilities, given that we do not have a truth table of members. In fact, centrals will also have $p_{\rm mem} < 1$ by construction.

Our analysis shows that the total SHMR has a weaker dependence on redshift than for centrals, with the value of β being closer to 0. However the inversion in sign of β is due to the probabilities that are used to weight the stellar masses, and this is an unavoidable effect due to our survey specifics. In fact, the stellar mass of the redshift bin containing galaxies around $z \sim 0.4$ is larger than the others. The number density of DES galaxies shows in fact a peak around that redshift: more galaxies are assigned to a similar photo-z there compared to other redshifts, and therefore they will have a larger contribution from the p_z component in the membership probabilities. At the same time more constraining power will come from the higher redshifts with lower stellar masses, because there are more clusters there in our volume limited sample. We therefore believe that the observed redshift dependence of the total SHMR is mostly due to the photometric redshifts rather than to any physical evolution.

The amount of scatter in stellar mass at fixed halo mass is also an important ingredient for halo or sub-halo abundance matching (AM) methods, and Kravtsov et al. (2014) showed how the scatter can impact the SHMR measurements. Our 1-σ scatter in the logarithmic stellar mass at fixed halo mass is 0.2492 ± 0.0010. For AM a scatter of $\sim 0.1 - 0.3$ is usually assumed. The intrinsic scatter found in the other works discussed here (e.g. Pillepich et al. 2017 and Kravtsov et al. 2014) is usually $0.1 - 0.2$ dex. As discussed for the centrals, we believe that this larger scatter is due to the different samples and methods used. We refer to future work to introduce a redshift and halo mass dependent intrinsic scatter.

We find a scatter in halo mass at fixed stellar mass of $\sigma_{{\rm Log}(M_{200c})|M_\star} \sim 0.17$. Our result is similar to what Andreon (2012) finds for the scatter at fixed stellar mass (0.21-0.32 dex). This value can also be compared to what we find in the X-ray temperature–$\mu_\star$ calibration at fixed $\mu_\star$: it is $\sim 1\sigma$ above the latter. Chiu et al. 2017 find a higher scatter in the

SHMR compared to the ICM-to-halo relation, with the ICM being estimated from X-ray *Chandra* data. This is a motivation to think that the higher scatter we find in T_X is at least partially intrinsically due to the physical interplay between the X-ray emitting matter and the total cluster mass, and between the stellar mass and the total mass. On the other hand, to truly compare the scatter on a physical level, one would need to understand the selection effects introduced by the X-ray selection. Even though the X-ray measurements are done at the redMaPPer cluster positions, a cut in the temperature SNR is essential to avoid taking into account spurious detections. This selection introduces a redshift and mass dependent cut on the sample (a Malmquist bias).

We find that the total stellar mass fraction $f_\star = M_\star^{tot}/M_{200c}$ is ~ 0.025, and it is flat over the range of halo masses studied. The results are shown in Figure 6.5, where we normalize by the baryon-to-matter mass ratio from cosmological constraints $\Omega_b/\Omega_m \simeq 0.16$ (Planck Collaboration et al. 2016) for a better understanding of the fraction of baryons locked into stars: roughly 15% of cluster baryons are transformed into stars. The stellar masses have been corrected to galaxies within R_{200c} for the comparison, as our analysis brings the total stellar mass of clusters out to 3 Mpc (although contributions outside ~ 1.5 Mpc are negligible because of the radial membership probabilities), which is roughly 30% higher than the mass within 1 Mpc. The radial probability gives most of the weight to the galaxies within R_{200c}, and extensive studies have been performed on mock data so that $\Sigma p_{mem} \sim N_{\rm members}$. We therefore believe that our total stellar mass is a good estimator of the whole cluster stellar mass besides the ICL.

Despite some possible difference in the stellar mass measurements that could be due to the mass-to-light ratio assumed, of the different cluster selection, our results confirm what is found in Kravtsov et al. (2014): the suppression of star formation efficiency at larger halo masses is not as strong as previously expected (e.g. Behroozi et al. 2013*a*), and that is due to the contribution of satellites that makes this efficiency a milder function of halo mass compared to centrals alone. Also Pillepich et al. (2017) find that the $f_\star$ dependence on halo mass is shallower at the high mass end, dropping only by a factor of ~ 2 with respect to Milky Way halo masses. Coupon et al. (2015) find that the total stellar mass fraction is close to flat at cluster scales, slightly increasing at the high mass end. A roughly flat stellar mass fraction at cluster masses is also explained in Leauthaud et al. (2012*b*) through galaxy merging in the absence of significant star formation. Above the peak in $f_\star$ at Milky Way halo masses, halos can only grow because of merging with halos of lower

stellar mass fraction, therefore lowering the total $f_\star$. Towards higher halo masses, this means that the stellar mass fraction will be enhanced by the mergers, inverting the trend again. This behaviour will repeat towards increasing halo masses, causing the flattering.

As for the total SHMR, we do not find evidence of redshift evolution in the stellar mass fraction. Chiu et al. (2016) and Chiu et al. (2017) also find that the stellar mass fraction in X-ray and SZ selected clusters depends only weakly on redshift, implying that the stellar content at a given halo mass changes very little since $z \sim 0.7$. Similar results are found in simulations, as in Pillepich et al. (2017): the overall cluster stellar mass build-up happens at a similar pace as the dark matter halo assembly, resulting in very little change from redshift 1. Chiu et al. (2017) also point out that in the hierarchical formation scenario, this means that at these redshifts the halos mainly accrete from structures outside the virialised halo that have a stellar mass fraction close to the cosmic mean.

Previous works found no or little dependence (Vulcani et al. 2013; Etherington et al. 2017) of the faint end galaxy stellar mass function on environment. We choose to employ the SMF from Capozzi et al. (2017), that was estimated for the whole DES SV COMMODORE galaxy catalog. They use a double Schechter function (Schechter 1976*a*) the lowest redshift bin ($z < 0.2$), and a single Schechter function in the higher bins. By integrating the GSMF best fits, we find that our total stellar mass would be $23 - 24\%$ higher if we were to include all galaxies below the $10^{10} M_\odot$ limit chosen, although this would have to be weighted by the membership probabilities for consistency.

In Zhang et al. (2018) we find that the central plus ICL contribution in low redshift ($0.2 < z < 0.3$) Y1 redMaPPer clusters is $\sim 40\%$ of the total stellar mass computed as in this paper, meaning that the ICL contribution to the total stellar mass can be up to $\sim 30\%$, bringing the stellar mass fraction up by a factor up to 1.3. Note that this factor would include also the contribution coming from undetected members, so it would at least partially take into account the low mass end of the SMF mentioned in the previous paragraph.

6.4 Stellar mass functions

6.4.1 Central stellar mass function

Several works (e.g. Lauer et al. 2014) find that the luminosity function of BCGs follows a log-normal distribution. Given that we expect a similar $M_\star/L$ for these galaxies, it is

CENTRALS

IMF		$A\,[\mathrm{Mpc}^{-3}]$	$\mathrm{Log}M_{\star,c}$	σ_c
Chabrier	$\langle z\rangle \sim 0.2$	$(5.791 \pm 0.098) \times 10^{-4}$	11.4131 ± 0.0044	0.2487 ± 0.0032
	$\langle z\rangle \sim 0.4$	$(4.876 \pm 0.083) \times 10^{-4}$	11.481 ± 0.0043	0.2425 ± 0.0027
	$\langle z\rangle \sim 0.6$	$(3.042 \pm 0.038) \times 10^{-4}$	11.462 ± 0.0031	0.2417 ± 0.0022
	Whole	$(4.828 \pm 0.037) \times 10^{-4}$	11.461 ± 0.0019	$0.2455 \pm 0.0014^{\mathrm{stat}}$ $\pm 0.05^{\mathrm{syst}}$
Salpeter	$\langle z\rangle \sim 0.2$	$(8.67 \pm 0.016) \times 10^{-4}$	11.6687 ± 0.0049	0.2515 ± 0.0036
	$\langle z\rangle \sim 0.4$	$(7.33 \pm 0.10) \times 10^{-4}$	11.744 ± 0.0036	0.2485 ± 0.0027
	$\langle z\rangle \sim 0.6$	$(4.54 \pm 0.69) \times 10^{-4}$	11.728 ± 0.0039	0.2421 ± 0.0028
	Whole	$(7.249 \pm 0.074) \times 10^{-4}$	11.7251 ± 0.0026	0.2478 ± 0.0020

TOTAL

IMF		$\phi^*\,[\mathrm{Mpc}^{-3}]$	$\mathrm{Log}M^*$	α
Chabrier	$\langle z\rangle \sim 0.2$	$(1.68 \pm 0.16) \times 10^{-4}$	11.510 ± 0.026	-1.267 ± 0.0038
	$\langle z\rangle \sim 0.4$	$(1.841 \pm 0.088) \times 10^{-4}$	11.460 ± 0.013	-1.185 ± 0.022
	$\langle z\rangle \sim 0.6$	$(1.228 \pm 0.083) \times 10^{-4}$	11.395 ± 0.019	-1.108 ± 0.034
	Whole	$(2.02 \pm 0.11) \times 10^{-4}$	11.401 ± 0.019	-1.119 ± 0.025
Salpeter	$\langle z\rangle \sim 0.2$	$(2.009 \pm 0.036) \times 10^{-4}$	11.713 ± 0.057	-1.1845 ± 0.0066
	$\langle z\rangle \sim 0.4$	$(2.28 \pm 0.15) \times 10^{-4}$	11.659 ± 0.022	-1.074 ± 0.028
	$\langle z\rangle \sim 0.6$	$(1.57 \pm 0.16) \times 10^{-4}$	11.574 ± 0.035	-0.955 ± 0.051
	Whole	$(2.47 \pm 0.20) \times 10^{-4}$	11.593 ± 0.032	-1.010 ± 0.035

Table 6.2: Best–fit results of the SMF for centrals and all galaxies in the clusters in redshift bins and for the whole redMaPPer catalog. The redshifts reported are the mean values. The parameters are presented in Eq. (6.4) and Eq.(6.5). Fits are performed over the stellar mass range ($\mathrm{Log}(M_{\mathrm{cen}}/M_{\odot})$) between 10.5 (10.3) and 12.5 for the centrals (total) SMF. These values are 0.2 dex higher for the Salpeter IMF case.

reasonable to expect that also the SMF of centrals follows a similar behaviour, as also found in Yang et al. (2009) for SDSS galaxy groups. In order to compute the SMF, we divide the stellar mass distribution by the comoving volume over the Year 1 footprint and by the bin width in stellar mass (0.15 dex). We estimate errors by making 200 bootstrap resamplings. Given the huge size of the cluster sample used, these errors are 2-3 orders of magnitude smaller than the SMF values. In Figure 6.6 we show our results from a least–χ^2 fit in redshift bins for a log–normal function in the form:

$$\phi_{\mathrm{cen}}(M_\star) = \frac{A}{\sqrt{2\pi}\sigma_c} \exp\Big[-\frac{(\mathrm{Log}M_\star - \mathrm{Log}M_{\star,c})^2}{2\sigma_c^2}\Big], \tag{6.4}$$

where $\mathrm{Log}M_{\star,c}$ is by definition the expectation value for the logarithm of the stellar mass of centrals and $\sigma_c = \sigma(\mathrm{Log}M_\star)$. The SMF for the whole redshift range has been computed by dividing by the "effective" comoving volume of the redMaPPer catalog: it takes into

account the masking and depth variations over the footprint. The best–fit parameters for the two redshift bins and the whole sample are presented in Table 6.2. We also find that the mass function has a similar behavior when binning in halo mass [i.e. the conditional luminosity function $\phi_{\rm cen}(M_\star|M_{200c})$].

In order to estimate the systematic contribution to the SMF from the photometry and stellar model selection, we assume the errors on the stellar masses to be Gaussian and randomly draw 200 "noisy" stellar mass values $M_\star^{\rm noise}$ for each galaxy. The Gaussian width is given by the error estimate from the BMA code, as this will reflect the stellar population model uncertainty, as well as the photometry errors. The 16th and 84th percentiles of the SMF from such resampling are shown in the grey region in Figure 6.6. As we could have expected, this resampling has the effect of broadening the distribution (shown by the black points) because the uncertainty on the stellar masses has the effect of scattering the galaxies within different bins. This effect is known as the Eddington bias. Given that we assume the resampled stellar mass distribution to be a Gaussian in the logarithm of the stellar mass (as done also in Caputi et al. 2011) convolved with the SMF which is also Gaussian, the result is that the measured SMF has the Gaussian widths added in quadrature. The width of the $\mathrm{Log}(M_\star^i) - \mathrm{Log}(M_\star^{i,\rm noise})$ distribution is 0.05 and we consider this effect as a systematic error from the photometry on the width σ_c.

The systematic error on is driven by the IMF choice (see Section 6.6). The results are reported in Table 6.2. The reduced χ^2 are high because of the contribution coming from the low mass end ($\mathrm{Log}M_\star \lesssim 10.8$): the SMF is not log–normal there. Assuming the abundance matching theory, where the central stellar mass function at fixed halo mass has a log–normal scatter in $M_\star$, then the convolution of those distributions would be Gaussian in $\mathrm{Log}M_\star$ over the clusters halo mass range. We tested this using the Buzzard simulations (DeRose et al. 2018; Wechsler et al. 2018) made for DES Year 1 data: when the true centrals for halo masses $M_{200c} > 10^{13} M_\odot h^{-1}$ are selected, no deviation from Gaussianity is seen in the luminosity function (LF) in absolute magnitude space (see Figure 6.8). On the contrary, when redMaPPer centrals are selected from the same simulation, the luminosity function deviates from a Gaussian at the faint end. Assuming that the mass–to–light ratio does not vary significantly for these galaxies, we believe that both the SMF and the LF faint ends are affected by the redMaPPer centering. In fact, the distribution of centering probability $P_{\rm cen}$ shifts towards lower values at those lower luminosities.

Yang et al. (2009) explored the conditional stellar mass function $\phi_{\rm cen}(M_\star|M_{200c})$ in bins

Figure 6.6: Stellar mass function of central galaxies in redshift bins. Errorbars come from 200 bootstrap samples of stellar mass values for each galaxy. The dashed lines represent the best fits of these data and errors with a log–normal function. The grey region represents the 16th and 84th percentiles of the SMF from the resampling of the stellar masses to include SSP and photometric uncertainties. The red shaded region shows the part excluded in the fit.

of halo masses for SDSS groups and clusters. They find that the width of the log–normal distribution is $\sigma_c \sim 0.17$ in all mass bins, while the mean increases by ~ 0.25 dex between halo masses of $10^{13.5} M_\odot$ and $10^{15} M_\odot$, which is similar to what we find in the SHMR for centrals in Section 6.3. Our width is larger than theirs as one could expect, given that we consider all halo masses in that range. Their mean values ($\mathrm{Log} M_{\star,c} \sim 11.1 - 11.4$) are systematically lower than what we find, even in the lowest redshift bin that should contain a similar cluster population. We believe this may be due to SDSS luminosities being often underestimated for bright galaxies. Furthermore, there are differences in the stellar mass computation which may introduce systematic biases, such as the IMF assumption (they use a Kroupa IMF) and the fact that a single the mass-to-light ratio is used for all galaxies. However, the ~ 0.2 dex difference observed between the results is compatible with a conservative error on stellar mass estimation.

6.4.2 Total stellar mass function

The stellar mass function for all galaxies in the clusters is computed from the stellar mass distribution of the galaxies in our members catalog, with their entries being weighed

Figure 6.7: Stellar mass function of all cluster galaxies in redshift bins. Errorbars represent the Poisson noise and the systematic error from a resampling of the stellar masses added in quadrature. The dashed lines represent the best fits of these data and errors with a single Schechter function. The red shaded region shows the part excluded in the fit. The best fit from Vulcani et al. (2013) shown are from a sample of ESO Distant Cluster Survey clusters at $0.4 < z < 0.8$ for all galaxy morphological types. The dotted line is the best fit from Weigel et al. (2016) for SDSS clusters with halo masses $13.5 < \mathrm{Log}M_h < 15$. Both distributions have been arbitrarily renormalized to match our results at $\mathrm{Log}M_\star = 11$ at the relevant redshifts for a visual comparison of the shape of the functions.

Figure 6.8: Luminosity function of central galaxies from Buzzard simulations. The light blue data points come from the catalog of true centrals, while the orange data points represent the centrals from the redMaPPer algorithm run on the simulated data. The deviation from Gaussianity for the redMaPPer distribution is seen at the faint end. The normalisation is arbitrary.

by their membership probability. The comoving volume is computed as in the previous section for different redshift bins, and we divide the distribution by the stellar mass bin width. A Schechter function of the form:

$$\phi(M) = \phi^* e^{-M/M^*} \left(\frac{M}{M^*}\right)^{\alpha}, \tag{6.5}$$

is fit to the data, with M being the stellar masses for clarity of notation, α the parameter that controls the low-mass end slope of the SMF, ϕ^* a normalisation factor and M^* the characteristic stellar mass at which the slope of the SMF changes significantly. Errors on ϕ come from adding in quadrature the statistical error from Poisson noise and a systematic error from a resampling of the galaxy stellar mass as for the centrals. Best–fit values are listed in Table 6.2. We exclude from the fit the bins below $\mathrm{Log}M_\star < 10.3$ to be further from the completeness limit. It is not straightforward to compare stellar mass function measurements from different galaxy and cluster samples that used different methods and observations. In particular, the amplitude of SMF will strongly depend on the selection function of the galaxy survey considered. In this work we therefore focus on a comparing the shape of the SMF with previous literature results, where the normalization is completely arbitrary.

In Figure 6.7 we show our data points and best fit in different redshift bins and for the whole redshift range, along with the results from Vulcani et al. (2013) for all galaxy morphological types in clusters from the ESO Distant Cluster Survey clusters at $0.4 < z < 0.8$. We normalize their results so that they match ours at $\mathrm{Log}M_\star = 11$ in the lowest redshift bin. They find that the SMF is roughly flat at those redshifts, with a low–mass slope just above -1 (-0.915 ± 0.026), and less steep than the low–redshift sample (where $\alpha = -0.987 \pm 0.009$ at $0.04 < z < 0.07$). We also find that the slope is less steep in the highest redshift bin at $0.5 < z < 0.7$ ($z_{mean} \sim 0.6$), but still below -1 (-1.108 ± 0.034). However, if we were to push out fit limit to lower masses, our α would also raise above -1. This is in fact seen when we assume a Salpeter IMF and fit over the same mass range, as this has the effect of shifting the whole distribution towards higher masses. We conclude that the discrepancy is due to different ways of dealing with the sample incompleteness. At the high mass end Vulcani et al. (2013) have low–number statistics due to the few clusters analysed, so the SMF is not well constrained there.

We also plot the best fit from Weigel et al. (2016), who used the SDSS clusters catalogue

from Yang et al. (2007) in the halo mass range $13.5 < \mathrm{Log}M_h < 15$. This sample partially overlaps with our lowest redshift bin ($0.1 < z < 0.3$), given that their cluster catalog goes out to redshift 0.2. We normalize their results so that they match ours at $\mathrm{Log}M_\star = 11$ in the highest redshift bin. Their low mass end slope is also below -1 (-1.07 ± 0.02), but slightly less steep than our lowest redshift bin. In Yang et al. (2009) they take carefully into account the cluster completeness for the same sample of Weigel et al. (2016), which may impact on the normalization but also the shape of the SMF (e.g. if we consider a higher fraction of high mass clusters than another analysis, we may measure a higher $M_\star$). They find that the satellites low-mass–end slope is steeper ($\alpha \sim -1.2$ to -1.6) than what found in Weigel et al. (2016) at our halo masses, and satellites are the dominant contribution at the low–mass end. Our best–fit M^* is ~ 0.5 dex above the result from Weigel et al. (2016), causing the discrepancy seen at the high mass end. We cannot compare to the results from Yang et al. (2009) this value as they separate satellites from central galaxies in the conditional luminosity function, however we believe that the discrepancy is due to the cluster selection function: a qualitative analysis of the two samples shows that our volume–limited redMaPPer catalog has a fraction of clusters out to $\mathrm{Log}M_{200c} \lesssim 14$ which is $5 - 10\%$ less than what is found in Yang et al. (2007) catalog. This might cause the difference in the characteristic mass of the SMF.

The main conclusion of our SMF analysis is that we find evidence for an evolution of the low–mass end slope over the redshift range $0.1 < z < 0.7$, and no or little evolution at the high–mass end. This implies that the population of low mass galaxies evolved significantly since redshift 0.7, while the mass build-up of the more massive galaxies has mostly been completed by then. Given the absence of evidence for redshift evolution seen in the previous subsection, the behaviour observed at the massive end includes the centrals.

6.5 Mass growth and definition of centrals

6.5.1 Central stellar mass growth

While semi-analytic models (De Lucia & Blaizot 2007) predict BCG stellar mass growth of the order of 4 between redshift 1 and 0, observations seem to be in contrast. Lidman et al. (2012) found an increase of ~ 1.8 between $z = 0.9$ and $z = 0.2$. We follow a similar method and correct the stellar mass of the central in order to take into account for the

Figure 6.9: Central mass growth with redshift. The stellar masses are divided by the corresponding cluster halo mass at $z = 0$ for a comparison of different clusters. The data points represent the mean stellar mass fractions in redshift bins.

Figure 6.10: Distribution of the offsets from the redMaPPer central for the most massive cluster galaxy (black points) and the brightest cluster galaxy (red triangles) when they do not coincide. Errorbars are given by the Poisson error.

correlation with the mass of the halo it belongs to. When we correct the BCG mass using the M_{200c} estimate from the weak lensing calibration we find no evidence of stellar mass growth between redshift 0.7 and 0.1. It follows that the mild redshift evolution found in Section 6.3 for the SHMR of centrals is due to a different cluster selection function at different redshifts. Correcting by the halo mass that the cluster would have today brings to a different result. We use the mean accretion rate from Fakhouri et al. (2010) to extrapolate the mass of the clusters from the redshift at which they were observed to the current time. The results are shown in Figure 6.9. Between redshift 0.7 and 0.1 we find a growth of a factor ~ 1.6: as expected due to the significant mass accretion of halos from redshift 1, the central mass growth is higher when correcting for the halo mass as it would be today. On the other hand, the scatter in the mass fraction is considerably high, $\sim 30 - 50\%$ in each redshift bin. This result corresponds to a ~ 0.2 dex growth, which is consistent with 0.29 ± 0.11 dex between $z = 1$ and $z = 0$ found by Zhang et al. (2016*a*) for the cluster sample with $\mathrm{Log}(M_{200c}) > 13.85$ (the lowest mass systems are excluded due to uncertainties in the X-ray temperature–mass relation).

6.5.2 Definition of central, BCG and most massive galaxy

So far we have considered redMaPPer centrals in comparison with results from some studies of BCGs, as if they were the same objects. Identifying and in case discerning between these two components is not always trivial because galaxies in the core of the cluster are moving at speeds of ~ 200 km/s and also will undergo merging and stripping events.

We identify the BCG as the brightest galaxy in i-band absolute magnitude and the most massive cluster galaxy (MMCG) as the galaxy with the highest stellar mass. The latter should also roughly correspond to the BCG if we consider that most of the giant red galaxies close to the cluster core have similar mass-to-light ratios. In order to select the possible candidates, we use $N = \Sigma_i p_{\mathrm{mem}}$ to estimate the number of galaxies N in each cluster, where the sum goes over all the galaxies associated with the cluster. Only galaxies in the highest 40th percentile of the p_{mem} distribution are considered, in order to avoid considering galaxies that are not associated with the cluster. We find that $\sim 24\%$ of clusters have a MMCG that is not the redMaPPer central, and $\sim 30\%$ have a BCG which is not the central. If the redMaPPer centre is given as a truth table, then the most massive galaxy traces better the central than the brightest. We can interpret this result in terms of abundance matching. If there were no scatter in the halo-galaxy abundance

Figure 6.11: Most commonly used Initial Mass Functions. Note that the Salpeter IMF diverges at the low-mass end.

matching, then this statement would always be true: the galaxy with most stellar mass would also be the central as its sub-halo would be the most massive among all sub-halos. In reality, the existing scatter between stellar mass and sub-halo mass impacts on the one-to one relation between those two quantities and the MMCG will not always be the central. Similarly, Hoshino et al. (2015) found that $20-30\%$ of SDSS redMaPPer centrals are not the brightest Luminous Red Galaxies (LRGs) in the cluster. The offset distribution of the MMCGs and BCGs compared to the redMaPPer centers are shown in Figure 6.10 for those clusters in which MMCG (or BCGs) and centers do not correspond.

6.6 Impact of the Initial Mass Function

The choice of the IMF is regarded as one of the main cause of systematics in stellar mass estimation (Coupon et al. 2015). The IMF describes the distribution in mass of the stars when they enter the main sequence for the SSP used in the galaxies. It is given as the number of stars that have been born with initial stellar masses between $M_\star$ and $M_\star + \mathrm{d}M_\star$: $\xi(M_\star)\mathrm{d}M_\star$. Some of the most used IMFs are shown in Figure 6.11 and are defined as:

- Salpeter (1955): $\xi(M_\star) = kM_\star^{-2.35}$, where k is a normalization factor.

- Kroupa (2001): $\xi(M_\star) = kM_\star^{-\alpha}$, where

$$\alpha = \begin{cases} 0.3 & \text{if } M_\star < 0.08 \\ 1.3 & \text{if } 0.08 < M_\star < 0.5 \\ 2.3 & \text{if } M_\star > 0.5 \end{cases} \tag{6.6}$$

- Chabrier (2003):

$$\xi(M_\star) = \begin{cases} \frac{0.158}{\ln(10)M_\star} \mathrm{e}^{-\frac{(\mathrm{Log}(M_\star)-\mathrm{Log}(0.08))^2}{2\times 0.69^2}} & M_\star < 1 \\ kM_\star^{-2.3} & M_\star > 1 \end{cases} \tag{6.7}$$

  where k is a normalization factor.

Most works report their results assuming a Chabrier IMF, but several studies (e.g. Barnabè et al. 2013, Martin-Navarro et al. 2015, Smith et al. 2015) have shown that the IMF of massive elliptical galaxies is better described by a more bottom-heavy function. If that is the case, SHMR may be biased (Kravtsov et al. 2014) at all halo masses, as a result of the stellar mass estimates being biased for most of the red sequence galaxies. So far we have assumed a Chabrier IMF for a more straightforward comparison with other literature results. Here we reproduce the same analyses assuming a Salpeter IMF in the SSP models used to fit the stellar mass. This represents the extreme case of an IMF diverging at the low mass end: the difference between the SHMR obtained by assuming a Chabrier and a Salpeter IMF will give us an estimate of the systematic uncertainty due to the uncertainty on the IMF. In Table 6.1 we report the results for the SHMR when assuming a Salpeter IMF, and in Table 6.2 for the SMFs. This different IMF has the effect of biasing the galaxy and the cluster stellar masses, resulting in a change in the intercept of the linear relation between halo mass and stellar mass, and in the mean of the centrals SMF log–normal fit. Table 6.1 shows that the pivot $\mathrm{Log}(\tilde{M}_\star)$ is 0.23–0.27 dex higher in the case of a Salpeter IMF. Kravtsov et al. (2014) find that the effect of a more bottom-heavy IMF steepens the SHMR, as they study this effect by introducing a mass-to-light ratio which depends on the velocity dispersion in galaxies (and therefore on their total mass). In our work we are assuming the same IMF for all galaxies, as our SED fitting of photometric optical data would not be able to distinguish between different IMFs, and most of the cluster stellar mass is contributed by the old elliptical galaxies. This measurement gives us the most conservative upper limit to the SHMR and SMF.

Figure 6.12: This figure shows the derived ICL profiles (upper panel) and the uncertainties of the measurements (lower panel). Cluster galaxy residue (red point) is subtracted from the raw ICL measurements (blue line) to derive pure ICL profile (red line). Uncertainties of the ICL profiles are displayed as the shaded regions (upper panel) and also shown in the lower panel against radii. The ICL profiles are measured with high S/N to 1 Mpc, despite the subtraction of cluster galaxy residue introduces significant noise into the profile. Plot by Yuanyuan Zhang.

6.7 Intra-cluster light

6.7.1 Colour and stellar mass

In Section 6.3.2 we mentioned that the ICL can contribute up to $\sim$ 40% of the total cluster stellar mass. This statement is based on ICL measurements from the DES data. Through averaging $\sim$ 300 galaxy clusters from the DES Y1 redMaPPer catalog, in Zhang et al. (2018) we report the detection of diffuse intra-cluster light at a surface brightness limit of 30 mag/arcsecond^2 to 1 Mpc in DES $r-$band. The analysis is further verified by averaging the images of random points and point-like sources. After estimating the light from cluster galaxies, we infer that the diffused intra-cluster light associated with the cluster central galaxies extend to 200 kpc and beyond. This diffuse light constitutes a significant component of the central galaxy light: light contained beyond 32 kpc makes up $\sim$ 42% of the total light within 200 kpc. In Figure 6.12 we show the derived ICL profiles (upper panel) and the uncertainties of the measurements (lower panel). Cluster galaxy residue (red point), excluding the central galaxy, is subtracted from the raw ICL measurements (blue line) to derive a "pure" ICL profile (red line). The pure ICL profile therefore contains the contribution of the central galaxy and the diffuse stellar matter, given that there is no clear separation between the two components. Uncertainties of the

Figure 6.13: Color Profile of pure ICL. Errors are computed with the Jackknife method. The horizontal lines are the mean redmaPPer colors (K-corrected to $z = 0.25$) from the redMaPPer cluster members at $0.2 < z < 0.3$ and their central galaxies. The shaded region around the members' color mean represents 1 standard deviation of the sample.

ICL profiles are displayed as the shaded regions (upper panel) and also shown in the lower panel against radii, where the errors are computed through a jackknife resampling of 40 regions. The ICL profiles are measured with high S/N to 1 Mpc, despite the subtraction of cluster galaxy residue introduces significant noise into the profile.

We further derive the ICL colour profile of $g - r$, utilizing our measurements of ICL profiles in the $g-$band. The result is shown in Fig. 6.13. We find that the mean color of pure ICL becomes bluer at larger radii. A χ^2 minimization gives a gradient $\nabla(g - r) \equiv \frac{\mathrm{d}(g-r)}{\mathrm{d}\,\mathrm{Log}(r)} = -0.203 \pm 0.011$ within the inner 90 kpc, showing a negative color gradient at a 18σ level. If we only consider the range $10 < r < 90$ kpc, therefore excluding the central part of the CG we find $\nabla(g - r) = -0.152 \pm 0.027$. The result is consistent with previous works (e.g. DeMaio et al. 2018) on ICL color gradient in individual clusters, although there exist clusters that does not display this trend.

In Figure 6.13, we also show the colors of cluster central and satellite galaxies for comparison to ICL. Those are the mean colors from `MODEL_MAG` magnitudes, K-corrected to $z = 0.25$ as done for the ICL. While in the inner $\lesssim 10$ kpc the ICL is as red as most central galaxies, outside this range it appears to be consistent with the cluster satellite galaxies. This result, together with ICL getting bluer at larger radii, indicate that in the inner tens of kpc the central galaxy blends in the ICL profile, and in the outer regions

Figure 6.14: Left: Cumulative stellar mass profile contribution of different cluster components for DES clusters at $0.2 < z < 0.3$. Right: Fraction of stellar mass that resides in the central plus the pure ICL as a function of radius. These measurements are too sensitive to the noise in the galaxies profile subtracted from the raw ICL profile beyond 100 kpc, we thus can only base our analysis below that value.

the ICL build–up channel is likely dwarf disruption and tidal stripping. In fact, the former mechanism is expected to create a color gradient as the disrupted dwarfs lived at different radii depending on their mass (and therefore on their color). On the other hand, tidal stripping will be stronger closer to the cluster center and will be able to strip the redder, inner parts of the cluster galaxies. Major mergers are not likely to be the main ICL formation mechanism, as this would give rise to more uniform color profiles (e.g. Eigenthaler & Zeilinger 2013).

From the g and r profiles we can also derive stellar mass profiles. We use the relation between colour and mass-to-light ratio in $r-$band derived in Bell et al. (2003): $\mathrm{Log}(M_\star/L_r) = 1.097(g-r) - 0.306$. This equation has been derived for g and r SDSS filters, but the difference in the magnitudes brought by the use of DES filters is negligible compared to the typical errors in the stellar mass. These values have been corrected by 0.1 dex to provide estimates consistent with a Chabrier IMF, while Bell et al. (2003) used a corrected Salpeter IMF. The M/L–colour relation is used at all considered radii to derive a stellar mass surface brightness profile $\Sigma_\star = M/L_r \times \Sigma L_r(R)$. Luminosities are estimated from the absolute magnitudes M_r derived from the apparent magnitude r as $M_r = r - k_{rr} - EC(z) - DM$ where k_{rr}, $EC(z)$ and DM are the K-correction, the evolutionary correction and the distance modulus respectively. Similarly it is done for g band. The evolutionary correction used is from Bell et al. (2003): $EC(g,r) \sim (-1.6, -1.3)z$, and the conversion from magnitudes to luminosities in $L_\odot$ units is performed using the abso-

lute magnitudes of the Sun $M_{g,\odot} = 5.15$ and $M_{r,\odot} = 4.67$. Here we show results for the $r-$band as it is less noisy than the g band. In Figure 6.14 we show the cumulative stellar mass profiles obtained in this way, and compare to the stellar mass results computed as described in Chapter 2 and Chapter 5 with the BMA method. From the Y1 redMaPPer sample, we only select the same clusters used for the ICL detection for this comparison. The profile of the central galaxy plus the pure ICL is shown in red, with the shaded region being the error. Jackknife errors on the measured fluxes have been propagated to the stellar mass with the error propagation chain. This measurement is too sensitive to the noise in the galaxies profile subtracted from the raw ICL profile beyond 100 kpc, and we therefore restrict the analysis to this radius. This profile is comparable to the mean stellar mass value of centrals (dashed line) in the range 8 kpc $\lesssim r \lesssim$ 30 kpc, showing that our stellar mass estimates from the MOF photometry are able to recover the diffuse ICL component within this range on average. The brown line represents the profile from member galaxies in our cluster catalog with masses computed through the BMA method. Clearly in this case the mass of the central is considered at 0 kpc from the centre instead of being an extended component, explaining the discrepancy at low radii. We also show the mean value of the total (i.e. from all members) mass within 200 kpc. It is interesting to understand what fraction of the total stellar mass is in the ICL component. This is shown in the right–hand panel of Figure 6.14, where the total stellar mass comes from the ICL measurement plus the members from our cluster catalog (excluding the central, already included in the ICL measurement), and is shown in blue in the left–hand panel. While the size of a typical galaxy, taken as the radius within which most of the light ($\sim$ 90%) is emitted, is roughly 32 kpc, the extended halo around the cluster centrals constitutes a significant contribution ($\sim$ 40%) to the total stellar mass of clusters out to 100 kpc and possibly beyond. Note that the ICL stellar mass fraction only drops by 10% between 30 and 100 kpc, showing the importance of the aperture considered when computing SHMR and SMF for centrals.

6.7.2 The impact of ICL on photo-z's and weak lensing measurements

Weak lensing mass calibration of clusters is a key ingredient for both for our mass proxy analysis and the SHMR measurements. It is therefore important for our analysis to check how the diffuse ICL affects the photo-z's estimates of background galaxies, that could in turn bias the weak lensing measurements of galaxy cluster mass. In fact, the diffuse light

biases the flux and color measurements of field galaxies, and causes a systematic change in photometric estimates of their redshift distributions. Among other effects, the spectral energy distribution of passive stellar populations at the cluster redshift introduces a mild cluster rest-frame D4000 break to the observed SED of the background galaxy. These changes in flux and color affect the redshift assigned, especially for star-forming galaxies with weaker break features. In Gruen et al. (2018) we evaluate the magnitude of this bias and identify the regimes in which it can be ignored.

Our goal is to derive a model F for the bias due to leakage of ICL into lensing source galaxy photometry used for photo-z. We define this bias as

$$\left(\hat{\beta}/\beta\right) - 1 \approx F(f_{\rm ICL}, z_d, \text{source depth}) \ , \tag{6.8}$$

where $\hat{\beta}$ is the photo-z based estimate of the amplitude of the shear signal of a given lens at redshift z_d and $f_{\rm ICL}$ is the surface brightness of intra-cluster light. The larger the statistical power of a lensing survey, the smaller a bias can be tolerated before it significantly affects the analysis. Current (and future) surveys aim for multiplicative biases to be below the few (to one) per cent level.

The image of a background source (or ensemble of sources) located on some annulus around a gravitational lens at redshift z_d is subject to tangential gravitational shear (e.g. **?** for a review)

$$\gamma_t = \Sigma_{\rm crit}^{-1} \times \Delta\Sigma = \frac{4\pi G D_d}{c^2}\frac{D_{ds}}{D_s} \times \Delta\Sigma \equiv \frac{4\pi G D_d}{c^2} \times \beta \times \Delta\Sigma \ , \tag{6.9}$$

where D_d, D_s, D_{ds} are the angular diameter distances to the lens, source, and between lens and source, respectively. The excess surface density $\Delta\Sigma$ at radius r is defined as the difference of the mean mass per area *inside* and *on the edge* of a circle of radius r,

$$\Delta\Sigma(r) = \langle \Sigma(< r) \rangle - \Sigma(r) \ . \tag{6.10}$$

β, in practice, is estimated as $\hat{\beta}$, e.g. from the photo-z redshift probability density $\hat{p}(z)$,

$$\hat{\beta} = \int \hat{p}(z) \frac{D_{ds}(z_d, z)}{D_s(z)} \, \mathrm{d}z \ . \tag{6.11}$$

For the mean shear signal of an ensemble of source galaxies i, each with weight w_i, this

can be written as

$$\hat{\beta} = \frac{\sum_i w_i \times \hat{\beta}_i}{\sum_i w_i} \,, \tag{6.12}$$

where w_i is a source weight and $\hat{\beta}_i$ the estimated β of source i from Eq. (6.11)ref. For the optimal (minimum variance) estimator of mean shear or surface mass overdensity, $w_i \propto \beta_i/\sigma^2_{e,i}$, or, in practice, $\propto \hat{\beta}_i/\sigma^2_{e,i}$ where σ^2_e is the shape noise variance including intrinsic and measurement noise.

In the case of an unbiased estimate $\hat{\beta}$, this connects mean tangential shear $\langle\gamma_t\rangle$ and excess surface mass density $\Delta\Sigma$ as

$$\langle\gamma_t\rangle = \frac{\sum_i w_i \times \gamma_{t,i}}{\sum_i w_i} = \frac{4\pi G D_d}{c^2} \times \hat{\beta} \times \Delta\Sigma \tag{6.13}$$

Thus, for example, if $\hat{\beta}$ is biased low, e.g. due to a bias in photo-z, the estimated $\Delta\Sigma$ is biased high, and vice versa.

Our framework for estimating the effect of ICL on photo-z is a simple empirical method from Gruen & Brimioulle (2016) that gives an unbiased estimate of $p(z|\mathbf{m})$, where $\mathbf{m}$ is a vector of colors and magnitude. Given this, and a model for the color of and total flux from diffuse light that enters each source, we can estimate how much the $\hat{\beta}$ of 6.12 will be biased. We therefore need to develop a model of ICL that enters in the right hand side of 6.8. We model it as a function of cluster mass $M_{200\mathrm{m}}$, cluster redshift z_d, and projected physical distance r from the cluster center.

There are three components empirically seen as diffuse light in clusters: pure ICL due to stars not bound to any galaxy, the light of faint, undetected cluster members, and scattered light of the cluster galaxies in the outskirts of the point-spread function (PSF).

We will call the first component, dominant in most regimes, *pure* ICL. This is what is measured in Zhang (2018). The PSF effect exists with every ground-based telescope at similar levels (see studies in Moffat 1969; King 1971; Racine 1996; Bernstein 2007; Sandin 2014 and also discussions in Zhang 2018). It is a contaminant to the measurement in Zhang (2018), yet greatly subdominant in the case of the DECam PSF, given that 97 per cent of light is contained within 5" radius of the PSF (Zhang 2018 their section 4), and intrinsic ICL is a much larger fraction of total cluster light.

Our second term, the amount of light in *undetected* galaxies, depends on the depth to

which cluster members are detected and can be successfully deblended. We approximate this as a fixed limiting magnitude $m^{\rm lim}$.

The full function we are trying to model is thus

$$\begin{aligned} f_{\rm ICL}(M_{200m}, z_d, r, m^{\rm lim}) &= f_{\rm pure\ ICL}(M_{200m}, z_d, r) \\ &+ f_{\rm undetected}(M_{200m}, z_d, r, m^{\rm lim}) \ . \end{aligned} \tag{6.14}$$

Model for pure ICL

Zhang (2018) have measured the pure ICL profile around a richness-redshift selected sample of redMaPPer clusters in DES Y1 data. In this subsection, we convert their measurement of true ICL at these fixed parameters into a prediction for $f_{\rm true\ ICL}(M_{200m}, z_d, r)$ based on the assumptions that

- at a fixed cluster mass, ICL is due to a passively evolving stellar population. As a function of redshift, it follows the color of the red sequence, with a fixed stellar mass density profile in physical coordinates. We note that there is an ongoing debate in the literature about the growth of ICL over cosmic time, which is discussed below.
- The stellar mass density profile is self-similar, i.e. indistinguishable between different clusters when expressed as a function of r/r_{200m}. This is qualitatively consistent with the results of a richness-binned analysis in Zhang (2018).

With these assumptions, we can write

$$\begin{aligned} & f^{i'}_{\rm pureICL}(M_{200m}, z_d, r) = \\ & f^{\rm Z}_{\rm ICL}\left(r \times \left(\frac{M_{200m}}{M^{\rm Z}_{200m}}\right)^{-1/3}\right) \times 10^{-0.4(m_{i',z_d} - m_{\rm Z})} \times \left(\frac{D_A(z_d)}{D_A(z_{\rm Z})}\right)^2 \ , \end{aligned} \tag{6.15}$$

where $f^{\rm Z}_{\rm ICL}(r)$, $M^{\rm Z}_{200m}$, $z_{\rm Z}$ are the ICL surface brightness, typical mass and typical redshift of clusters in Zhang (2018). $m_{i',z_d} - m_{\rm Z}$ is the apparent magnitude difference of a passively evolving galaxy seen at redshift z_d in CFHT i' band and at redshift $z_{\rm Z} = 0.25$ in DES r' band. For the purpose of this paper, we use a Bruzual & Charlot (2003) model with solar metallicity ($Z = 0.02$), no dust, and an exponentially declining star formation history with half-time $\tau = 0.1$ and an age of 10 Gyr at $z = 0$. The ratio of angular diameters D_A corrects for the change of angular scale of the ICL profile with redshift.

a [nJy arcsec^{-2}]	b_r	b_λ	b_z
9.95 ± 0.12	1.205 ± 0.010	-0.831 ± 0.037	8.96 ± 0.10

Table 6.3: Best–fit values for eq. (6.20) for the DES r' band flux from redMaPPer members. The reduced χ^2 is 1.5.

Note that we assume ICL to not accrete or eject stars over time. It is often argued that ICL forms relatively late, assembling most of its total stellar mass during galaxy interactions after redshift 1.0 (Monaco et al. 2006; Conroy et al. 2007; Burke et al. 2012; Behroozi et al. 2013*b*; Contini et al. 2014; Zhang et al. 2016*b*). Since our model is based on ICL measurements at $z \sim 0.25$, the luminosity of ICL at higher redshift ($z > 0.25$) is likely to be lower than, or at most equal to, the amount predicted from our passive evolution model. Hence, the photometric bias due to ICL at higher redshift ($z > 0.25$) is likely to be less severe than that predicted in the paper. Passive evolution is a conservative assumption for the purpose of estimating photo-z bias.

ICL from undetected cluster members

To model the contribution of undetected cluster members to diffuse light in the cluster, we use measurements of the average surface brightness due to brighter members, extrapolated with the luminosity function. The same approach is used in Zhang (2018) to remove contributions from cluster members below their threshold from the signal and arrive at a measurement of pure ICL.

We will model the light of undetected members at a given cluster-centric radius as homogeneously distributed, rather than concentrated at the positions of the actual galaxies. If the surface brightness at the positions of actual undetected galaxies is small enough so that the linearity of photo-z bias found in **??** holds, the predicted mean bias does not depend on this assumption of homogeneity. For member galaxies with larger surface brightness that are close to the detection limit, non-linear blending effects will likely play a role - we consider these to be an issue separate to the ICL studied in this paper.

Formally, we write

$$\begin{aligned} f_{\rm undetected}(M_{200m}, z_d, r, m^{\rm lim}) &= f_{\rm members}(M_{200m}, z_d, r) \\ &\times S(z_d, m^{\rm lim}, \infty) \,, \end{aligned} \tag{6.16}$$

where $S(z_d, m^{\rm lim}, \infty)$ is the fraction of the integral over the cluster member luminosity

function contributed by the faint end from $m^{\rm lim}$ to ∞. Note that more than 99% of the total flux as extrapolated to arbitrarily faint galaxies is contained in members brighter than $m^\star + 5$.

For a Schechter (1976*b*) luminosity function with faint-end slope α,

$$\frac{\mathrm{d}N_{\rm gal}}{\mathrm{d}L} \propto \phi(L) \propto \left(\frac{L}{L^\star}\right)^\alpha \exp[L/L^\star] \,, \tag{6.17}$$

the integrated luminosity is given by

$$I(L_1, L_2) = \int_{L_1}^{L_2} L\,\phi(L)\,\mathrm{d}L \propto \left[\Gamma\left(\alpha+2, \frac{L_2}{L^\star}\right) - \Gamma\left(\alpha+2, \frac{L_1}{L^\star}\right)\right] \,, \tag{6.18}$$

with the incomplete gamma function Γ. In this work, we assume $\alpha = -1$, thus

$$S(z_d, m_1, m_2) = \Gamma\left(1, 10^{0.4(m^\star - m_1)}\right) - \Gamma\left(1, 10^{0.4(m^\star - m_2)}\right) \tag{6.19}$$

The characteristic magnitude $m^\star$ (Koester et al. 2007*b*; Rykoff et al. 2014*b*) is a function of cluster redshift z_d, which we calculate from the Bruzual & Charlot (2003) model, normalized to match the SDSS DR8 (Aihara et al. 2011) redMaPPer catalog (Rykoff et al. 2014*b*) at $z = 0.2$.

We approximate $f_{\rm members}$ from the light of redMaPPer cluster members $f_{\rm redMaPPer}$, i.e. passive galaxies down to $0.2L_\star$. They are detected by DES over the full redshift range of the redMaPPer catalog, allowing us to empirically constrain the evolution of $f_{\rm members}$ with redshift. For $f_{\rm members}$ in 6.16, we use the luminosity function to re-scale $f_{\rm redMaPPer}$ by a factor 1.22 for the missing members at $L < 0.2L_\star$. In the relevant radial range, these passive galaxies dominate the cluster member population (Zu & Mandelbaum 2016*b* e.g.).

We find that the DES r' band flux $f_{\rm members}$ of redMaPPer cluster members follows a power law in projected radial distance, cluster richness and redshift as:

$$f_{\rm members}(\lambda, z_d, r) = a\left(\frac{r}{\tilde{r}}\right)^{-b_r}\left(\frac{\lambda}{\tilde{\lambda}}\right)^{-b_\lambda}\left(\frac{1+z_d}{1+\tilde{z}_d}\right)^{-b_z} \,, \tag{6.20}$$

where $\tilde{r} = 240$ kpc, $\tilde{\lambda} = 40$ and $\tilde{z}_d = 0.5$ are the pivot values. Eq. (6.20) is fit between 20 and 1000 kpc, and the best fit results from a χ^2 minimization are given in Table 6.3 and r is the comoving projected distance from the cluster center in kpc. The flux used is the SExtractor `FLUX_AUTO_R` and this is weighted for each galaxy from the redMaPPer catalog

by the corresponding membership probability. The masked regions are taken into account when computing the flux per area, and the errors on the flux profiles are computed through a jackknife resampling. The bins in richness ($20 < \lambda < 140$) and redshift ($0.1 < z < 0.8$) are chosen to have a similar number of clusters in most bins. The correction for undetected cluster members discussed above adds a fraction 0.22 of the measured flux in this case.

To convert $f_{\rm members}(\lambda, z_d, r)$ to $f_{\rm members}(M_{200m}, z_d, r)$ we apply the $\langle \ln \lambda | M_{500c} \rangle$ relation of Saro et al. (2015). We convert between M_{200m} and their M_{500c} using the mass-concentration relation of Duffy et al. (2008). We note that $\langle \lambda | M \rangle \neq e^{\langle \ln \lambda | M \rangle}$ due to intrinsic scatter in λ at fixed M. For the purpose of this paper and consistency with our scaling of the Zhang (2018) model for pure ICL, we set the amplitude of the scaling relation such that $\langle \lambda | M_{200m} = 3 \times 10^{14} M_\odot, z = 0.25 \rangle$=30.

The $m_{\rm lim}$ to use with 6.16 is dependent on survey and detection strategy. For the DES Y1 Gold catalog Drlica-Wagner et al. (2017*b* their Figure 8), a conservative $m_{\rm lim}$ for the purpose of estimating the contribution of cluster members to diffuse light is a DES i' band magnitude of 22.5.

We note that the contribution of undetected cluster members becomes important at large cluster mass, high redshift, and for a shallow survey. For our DES parameters, it contributes the majority of ICL for a cluster of $M_{200m}/M_\odot = 10^{15}$ at $z_d > 0.6$. For lower mass or redshift in DES, it is a subdominant component – contributing, in the relevant regimes, between 10 and 40 per cent of ICL. For LSST it is negligible due to the completeness down to fainter magnitudes.

Our model for diffuse light in clusters is simplistic yet conservative for the purpose of this exercise: a pure component of ICL due to un-bound stars in the cluster potential, measured at low redshift (Zhang 2018) and re-scaled in mass and redshift by assuming self-similarity and passive evolution; and a component due to stars in undetected, faint cluster members, extrapolated from detected galaxies by means of the luminosity function. The effect of this surface brightness on photo-z is estimated from an idealized empirical photo-z estimation scheme (Gruen & Brimioulle 2016).

We find that for a DES-like cluster lensing experiment, i.e. with cluster masses up to $M_{200m} = 10^{15} M_\odot$, detection and deblending of cluster members brighter than $i' = 22.5$, and a source sample no fainter than $i' = 23.5$, ICL-related photo-z bias does not significantly affect weak lensing mass reconstruction. Outside a cluster-centric radius of 200kpc, which is commonly excluded in lensing studies for other reasons, biases are below

1 per cent, even under the conservative assumptions we make.

Deeper source catalogs will be somewhat more susceptible to ICL-related photo-z biases because the flux and color of faint source galaxies can be changed more strongly by ICL contamination.

6.8 Conclusions

In this Chapter we provided clusters measurements for the DES Y1 redMaPPer clusters using DES Y3 photometry which are interesting in terms of cluster evolution. Our main results can be summarised as follows:

- A power law fits well the stellar-to-halo mass relation over the halo mass range studied ($10^{13.5} \lesssim M_{200c} \lesssim 10^{14.6}$) for centrals and the whole galaxy population in a volume–limited sample of DES Year 1 redMaPPer clusters. A Bayesian linear regression method allows to take into account errors on stellar mass, halo mass and redshift, while introducing an intrinsic scatter to the relation. We find that the total stellar mass scales almost linearly with halo mass in logarithmic scale: $M_\star^{tot} \propto M_{200c}^{0.89}$ with an intrinsic scatter at fixed halo mass of 0.2492 ± 0.0010. The slope found is significantly steeper than previous works, showing that the star formation efficiency is not as suppressed as previously thought at higher halo masses. We find that $\sim 15\%$ of cluster baryons are transformed into stars. On the other hand, definitions and measurement methods of stellar masses may cause the discrepancies seen between this work and others, and these have to be taken into account when drawing conclusions for simulations inputs.

- Our results on the SHMR are mostly in agreement with previous results but our cluster sample is 1-3 orders of magnitude larger than other measurements.

- We provide measurements of the SMF for centrals, which is found to be log–normal at masses $\mathrm{Log}M_\star \gtrsim 10/8$. In particular, the value of the width σ_c is $0.246 \pm 0.002^{\mathrm{stat}} \pm 0.05^{\mathrm{syst}}$ and can be used to constrain abundance matching models.

- The SMF of the whole galaxy population in clusters is fit to a single Schechter function, with a low-mass end slope of $\alpha = -1.119 \pm 0.025$ for a Chabrier IMF. We find evidence this slope is evolving over the redshift range $0.1 < z < 0.7$, while there

is no or little evolution at the high–mass end. This implies that the population of low mass galaxies evolved significantly since redshift 0.7, while the mass build-up of the more massive galaxies has mostly been completed by then.

- We find evidence for a weak stellar mass growth (factor of ~ 1.6) of the centrals over the considered redshift range ($0.1 < z < 0.7$).

- The most massive galaxy in terms of stellar mass gives a better proxy of the cluster centering than the brightest galaxy. This result will be used in future implementation of our mass proxy to cluster finders.

- The impact of the IMF on our results is substantial. Stellar mass functions and SHMR can be shifted by up to 0.27 dex towards higher stellar mass values if the chosen IMF is Salpeter instead of Chabrier. We do not find a dependence on halo mass, but an increase in the SHMR overall intrinsic scatter.

- The membership probability assignment code naturally provides measurements of the photometric properties of clusters, in particular the red sequence and blue cloud colour and their width. An interesting property to study is the fraction of galaxies in the blue cloud as a function of redshift. In the future, we plan on using the colour probabilities to analyze the SHMR and SMF contribution from the red and blue cloud from DES Year 3 data.

- A measurement of the diffuse intracluster light has been possible for ~ 300 DES clusters at redshift $0.2 < z < 0.3$ using g and r fluxes. We find that the mean color of pure ICL becomes bluer at larger radii. A χ^2 minimization gives a gradient $\nabla(g-r) \equiv \frac{\mathrm{d}(g-r)}{\mathrm{d}\,\mathrm{Log}(r)} = -0.203 \pm 0.011$ within the inner 90 kpc, showing a negative color gradient at a 18σ level. While in the inner $\lesssim 10$ kpc the ICL is as red as most central galaxies, outside this range it appears to be consistent with the cluster satellite galaxies. This result, together with ICL getting bluer at larger radii, indicate that in the inner tens of kpc the CG blends in the ICL profile, and in the outer regions the ICL build–up channel is likely dwarf disruption and tidal stripping. We also find that the central plus ICL components contribute to $\sim 40\%$ of the total stellar mass of clusters within 100 kpc at $0.2 < z < 0.3$.

- We studied the effect of ICL on photo-z's estimates, resulting on a bias in the weak gravitational lensing measurements of clusters. In particular we produce a simplified

model for the ICL, and find that this bias is negligible for photometric surveys like DES, while for deeper ongoing and future surveys such as LSST more conservative cuts on scales and source magnitudes may be necessary.

Chapter 7

Conclusions and future work

"My real love has always been the sleep that rescued me by allowing me to dream."

Luigi Pirandello

In this thesis I have exploited properties of galaxies that can be analysed through the Dark Energy Survey to study gravitational wave sources and dark matter in galaxy clusters.

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"Of course it is happening inside your head, Harry, but why on earth should that mean it is not real?"

J. K. Rowling, The Deathly Hallows