

New Constraints on the Halo Mass of Ultra-Diffuse Galaxies with UNIONS using Weak Gravitational Lensing

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

I hereby declare that I am the sole author of this thesis, which was written under the co-supervision of Michael Balogh and Mike Hudson.

I would like to acknowledge and thank Cristóbal Sifón for providing the catalogue of Ultra-Diffuse Galaxies (UDGs) described in [Sifón et al. \(2018b\)](#). The data analyzed for this thesis includes data products from the Ultraviolet Near Infrared Optical Northern Survey (UNIONS) collaboration. The following figures were taken from the literature: Figure 1.1.a from [Bullock & Boylan-Kolchin \(2017\)](#), Figure 1.1.b from [Behroozi et al. \(2013\)](#), Figure 1.2.a from [McGaugh \(2021\)](#), Figure 1.2.b from [Kelvin et al. \(2014\)](#) (modified), and Figure 5.2 from [Wang et al. \(2015\)](#) (modified). All other work presented in this thesis is my own.

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Abstract

While a lot of progress has been made in detecting and measuring various properties of Ultra-diffuse Galaxies (UDGs) over the last decade, the dark matter halo mass of these extremely faint and large objects remains a mystery. A better constraint on the total halo mass of UDGs would disentangle the wide variety of proposed formation mechanisms.

We detect a contaminated sample of 545 potential UDGs, of which we estimate 290 to be true UDGs, in the ongoing Ultraviolet Near Infrared Optical Northern Sky Survey (UNIONS) using the Canada-France Imaging Survey (CFIS) r -band imaging, limiting our search to within 66 galaxy clusters up to redshift $z \leq 0.1$.

From weak gravitational lensing measurement around our UDG sample corrected for interloper contamination, we find an excess surface density consistent with zero (no detection) and a 2σ upper limit on the average halo mass of $m_{200} \leq 10^{12.51} M_\odot$. By combining our measurement with that of Sifón et al. (2018), the only other weak gravitational lensing measurement of UDGs, we are able to constrain the halo mass further with a 2σ upper limit of $m_{200} \leq 10^{12.05} M_\odot$ when accounting for the potential low-biasing effect of interlopers in this combined sample. Our results do not disentangle whether UDGs tend to be, on average, more dark matter-dominated or dark matter-deficient galaxies and therefore does not allow us to put new constraints on their formation mechanism. This work on UDG detection in a wide field survey optimized for weak lensing helps pave the way for future direct halo mass measurements of UDGs in upcoming surveys such as the Euclid Wide Survey.

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I would like to thank both of my co-supervisors, Dr. Michael Balogh and Dr. Mike Hudson, for the enormous amount of support they provided throughout the work presented in this thesis. The guidance they gave me over the last two years allowed me to grow as a researcher, for which I am grateful. I would also like to thank the members of my thesis committee, Dr. Avery Broderick and Dr. James Taylor, for useful discussions and advice.

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List of Abbreviations

Λ CDM Λ -Cold Dark Matter [1](#), [21](#), [83](#)

2MASS Two Micron All Sky Survey [55](#)

AGN Active Galactic Nuclei [7–9](#)

CFHT Canada-France-Hawaii Telescope [xi](#), [19](#), [22](#), [33](#), [35](#), [37](#), [55](#), [70](#)

CFIS Canada France Imaging Survey [xi](#), [xii](#), [xv](#), [24](#), [28](#), [36](#), [54](#)

CMB Cosmic Microwave Background [3](#)

CNN Convolutional Neural Network [89](#)

DES Dark Energy Survey [13](#), [89](#)

ELVIS Exploring the Local Volume in Simulations [73](#)

EWS Euclid Wide Survey [86–89](#)

FWHM Full Width at Half Maximum [13](#), [86](#), [87](#)

GAMA Galaxy And Mass Assembly [x](#), [10](#), [12](#)

GNHR Globular cluster Number - Halo mass Relation [16](#), [82](#), [85](#)

HEALPix Hierarchical Equal Area isoLatitude Pixelation [24](#), [27](#)

HMF Halo Mass Function [x](#), [3](#), [4](#), [6](#), [7](#)

HST Hubble Space Telescope [2](#), [82](#)

ICM Intracluster Medium [9](#)

LSB Low Surface Brightness [xi](#), [xii](#), [xv](#), [3](#), [10](#), [11](#), [19](#), [23](#), [24](#), [27](#), [28](#), [33](#), [36](#), [37](#), [43](#), [52](#), [53](#), [55](#), [89](#), [90](#)

MCXC Meta-Catalogue of X-ray detected Clusters of galaxies [xi](#), [xv](#), [25–32](#), [64](#), [90](#)

MENeaCS Multi-Epoch Nearby Cluster Survey [13](#), [70](#), [71](#)

NFW Navarro–Frenk–White [29](#), [72–74](#), [79](#), [91](#)

NIHAO Numerical Investigation of a Hundred Astrophysical Objects [xiv](#), [83](#), [84](#)

Pan-STARRS Panoramic Survey Telescope and Rapid Response System [19](#)

PSF Point Spread Function [xii](#), [19](#), [20](#), [26](#), [33](#), [34](#), [42–44](#), [86](#), [87](#), [90](#)

PSFEx PSF Extractor [xii](#), [34](#), [42](#), [43](#)

RASS ROSAT All-Sky Survey [25](#)

redMaPPer red-sequence Matched-filter Probabilistic Percolation [xi](#), [xv](#), [25–28](#), [30–32](#), [87](#), [90](#)

SDSS Sloan Digital Sky Survey [2](#), [25](#), [55](#), [87](#)

SExtractor Source Extractor [xi](#), [xii](#), [xv](#), [34–44](#), [49–51](#), [53](#), [55](#), [59](#), [90](#)

SMBH Suppermassive Black Hole [7](#), [8](#)

SMF Stellar Mass Function [x](#), [4](#), [6](#), [7](#), [10](#), [12](#)

SMHR Stellar Mass to Halo mass Relation [xiv](#), [82–84](#)

SMUDGes Systematically Measuring Ultra-diffuse Galaxies [13](#)

SNR Signal-to-Noise Ratio [36](#), [41](#)

UDG Ultra-diffuse Galaxy [x](#), [xii–xv](#), [10–17](#), [19–24](#), [26](#), [27](#), [33–36](#), [40](#), [41](#), [45–92](#)

UNIONS Ultraviolet Near Infrared Optical Northern Survey [xi](#), [xii](#), [xv](#), [19](#), [20](#), [22–28](#),
[31–33](#), [36](#), [37](#), [49](#), [52](#), [54–56](#), [58](#), [59](#), [62](#), [70](#), [85–88](#), [90–92](#)

WISE Wide-field Infrared Survey Explorer [xi](#), [27](#), [28](#), [59](#)

Chapter 1

Introduction

1.1 Galaxy Evolution

1.1.1 Cosmology

The currently accepted cosmological model to describe our expanding universe is the [\$\Lambda\$ -Cold Dark Matter \(\$\Lambda\$ CDM\)](#) model. It allows us to describe the evolution of the different components of the universe, namely the matter component composed of dark matter and baryons, the radiation component, and the dark energy component. As the universe expanded and therefore cooled, the radiation energy density quickly decreased. About 380,000 years after the Big Bang, the photons which make up a large portion of the radiation component decoupled from the baryons. The baryonic matter, which includes protons, neutrons and electrons, can interact with itself and emit light through various processes and therefore be directly observed. It includes all the gas and stars which make up galaxies.

The idea of a dark and invisible matter to explain astronomical observations was proposed in 1933 to explain large velocity dispersion in the Coma galaxy cluster ([Zwicky, 1933](#)). One of the strongest arguments which led dark matter to be widely accepted was its indirect measurement via the rotation curves of spiral galaxies in the 1970s ([Roberts & Rots, 1973](#); [Rubin et al., 1978, 1980](#)). As of today, this dark matter is understood as a cold form of matter which only interacts gravitationally with baryons and itself. The dark energy component was first proposed by [Einstein \(1917\)](#) as a placeholder to ensure the idea of a static universe, but since then has been a key component to explain the accelerated expansion of the universe in the Λ CDM model of cosmology ([Riess et al., 1998](#); [Perlmutter](#)

et al., 1999). At present day, the dark energy component makes up 70% of the universe, while the matter component the other 30%, of which 84% is composed of dark matter and 16% baryonic matter (Planck Collaboration et al., 2020).

1.1.2 Galaxy Observations

Galaxies are composed of both dark matter and baryons which include gas, dust, and stars. Galaxies found to date exist in a wide variety of shapes and sizes, and cover a wide range of luminosity, stellar mass, and dark matter content. Historically, galaxies were first broken down based on their appearance into different morphological types following the “tuning fork” classification from Hubble (1926), with two main types of galaxies observed in the local universe being elliptical and spiral galaxies. This galaxy classification grouped galaxies together ranging from completely elliptical to spiral. The elliptical or “early type” galaxies are massive, featureless and spheroidal while the spiral or “late type” galaxies are rotating disks with spiral arms. A subset of spiral galaxies is known to have a bar shaped central bulge and therefor classified as barred spiral galaxies. Galaxies which did not fit into any of these categories were classified as irregulars. With the advancements of telescopes, more advanced classification of galaxies continued to emerge based on their detailed features, such as that from de Vaucouleurs (1959).

Holmberg (1958) showed that these morphological types traced different physical properties such as star formation rate. Further technological advances have allowed for very large statistical studies of galaxies with surveys such as Sloan Digital Sky Survey (SDSS) (York et al., 2000), as well as much deeper and higher resolution imaging with space-based telescopes such as the Hubble Space Telescope (HST). A bimodal color distribution of galaxies, which traces star formation, was found by Strateva et al. (2001) using SDSS. It showed that the bluer galaxies are generally spirals (late type) with higher star formation rates than the redder galaxies, which are generally “quiescent” ellipticals (early type) with low star formation rates.

The abundance of different morphological types of galaxies was also shown to depend strongly on both environment and redshift (Dressler, 1984; Butcher & Oemler, 1978). More specifically, the typical spiral and elliptical galaxies seen in the local universe were simply not as common at redshift $z > 1$ (van den Bergh et al., 1996), with a larger population of peculiar and merging objects seen. By studying the number density of different galaxy

types over cosmic time it was shown that the more massive early type ellipticals are mostly formed by redshift $z = 1$ (Bundy et al., 2005), while the number of lower-mass galaxies continues to increase at lower redshifts. The size of galaxies is also now known to depend on redshift, with galaxies being more compact at earlier times (Daddi et al., 2005; Trujillo et al., 2007).

Historically, the most well studied galaxy populations have been the brighter elliptical and spiral galaxies due to technological limitations, however a large number of Low Surface Brightness (LSB) and low stellar mass, dwarf galaxies have been discovered (Sandage & Binggeli, 1984; Bothun et al., 1991) adding even more diversity to galaxies.

1.1.3 Galaxy Formation Models

To develop comprehensive models of galaxy formation and evolution which are able to fully capture the wide variety of observed galaxies, it is important to understand the evolution of both dark matter and baryons throughout cosmic time. Small initial quantum fluctuations in the density field of both baryons and dark matter were scaled up by inflation (Guth, 1981) then grew and clumped together. The discovery of the Cosmic Microwave Background (CMB) (Penzias & Wilson, 1965), made up of the photons which decoupled from baryons, allowed us to directly measure these initial fluctuations in the early universe to high accuracy.

Since dark matter only interacts gravitationally, it can evolve freely as the universe expands. The densest initial fluctuations eventually grew into gravitationally bound and virialized halos via spherical collapse (Gunn & Gott, 1972). These halos are considered virialized if the kinetic energy of its components is large enough to offset it from collapsing under its own gravity. Through hierarchical growth (Peebles, 1965), these halos have combined and evolved into larger structures non-linearly with complex matter distribution which form the cosmic web (Bond et al., 1996). The most massive virialized halos which have had time to grow in the universe are galaxy clusters, with halo masses up to $\sim 10^{15} M_{\odot}$, which themselves are composed of many virialized subhalos containing galaxies.

Starting from the initial fluctuations, Press & Schechter (1974) developed a model for the number density of halos at a given mass, the Halo Mass Function (HMF). The HMF has since been refined using N-body simulations (Tinker et al., 2008) and more realistic

analytical models. For instance, [Sheth et al. \(2001\)](#) calculated the [HMF](#) accounting for ellipsoidal collapse rather than spherical which matched better the results from simulations. The [HMF](#) at present day from [Sheth et al. \(2001\)](#) is shown in Figure 1.1.a ([Bullock & Boylan-Kolchin, 2017](#)) (black solid line). It follows a power-law for most halo masses up to an exponential cutoff at $M \approx 10^{14} M_\odot$ where it drops sharply for more massive halos.

After the baryons decoupled from the photons in the early universe, they became free to evolve gravitationally with the dark matter. Driven by the same gravitational forces but less abundant than dark matter by a factor of five, the baryons concentrated in the various structures of dark matter where they settled in the deeper gravitational potential wells. We show in Figure 1.1.a the cosmic baryon fraction $f_b = 0.16$ multiplied by the [HMF](#) which would correspond to the mass function of baryons in the universe if they evolved the same way as the dark matter does (black dashed line). However, the evolution of baryons is much more complex due to interactions with other baryons, therefore their distribution in the universe is not the same as that of dark matter.

The baryons present in halos in the form of cold gas clouds fragment and collapse, forming the stars we can observe in galaxies ([Rees & Ostriker, 1977](#)). This process depends strongly on the timescale at which the gas can radiate and cool compare the timescale of this collapse. The [Stellar Mass Function \(SMF\)](#), which similarly to the [HMF](#) is the number density of galaxies as a function of the amount of stellar mass they contain, is shown in Figure 1.1.a. This measured [SMF](#) from [Bernardi et al. \(2013\)](#) (magenta stars) and [Wright et al. \(2017\)](#) (cyan squares) is very different than the [HMF](#) shown. If all baryons were converted into stars and traced the dark matter, then we would expect the [SMF](#) to match the cosmic baryon fraction in each dark matter halos shown (black dashed line). Instead, we see a power-law slope for the [SMF](#) smaller than the slope of the [HMF](#) for stellar masses below $M \approx 10^{11} M_\odot$ and an exponential cutoff at stellar masses larger than $M \approx 10^{11} M_\odot$. The fact that baryons do not properly trace dark matter can also be clearly seen in the stellar mass to halo mass relation shown in Figure 1.1.b ([Behroozi et al., 2013](#)). The fraction of stellar mass to dark matter as a function of dark matter halo mass peaks at $M_h \approx 10^{12} M_\odot$, indicating a maximum efficiency in converting gas to stars at this halo mass.

Modeling the radiative cooling and shock heating of gas ([Silk, 1977](#); [Rees & Ostriker, 1977](#); [Binney, 1977](#)) gave rise to the two-stage formation mechanisms of galaxies, where the dark matter halos first formed then the gas within halos collapsed to form stars ([White & Rees, 1978](#)). However, these models had the tendency to convert gas to stars more efficiently than was observed in galaxies. To model for the lack of star formation efficiency

observed in galaxies, both internal processes as well as external processes needed to be considered. Internal processes are the feedback mechanisms which originate from within the halo of galaxies, while external processes are all the mechanisms which affect a galaxy caused by the dark matter and baryons in the environment outside the galaxy as well as interactions with other galaxies and dark matter halos. A brief overview of the main internal and external processes which could either hinder or boost star formation is given below.

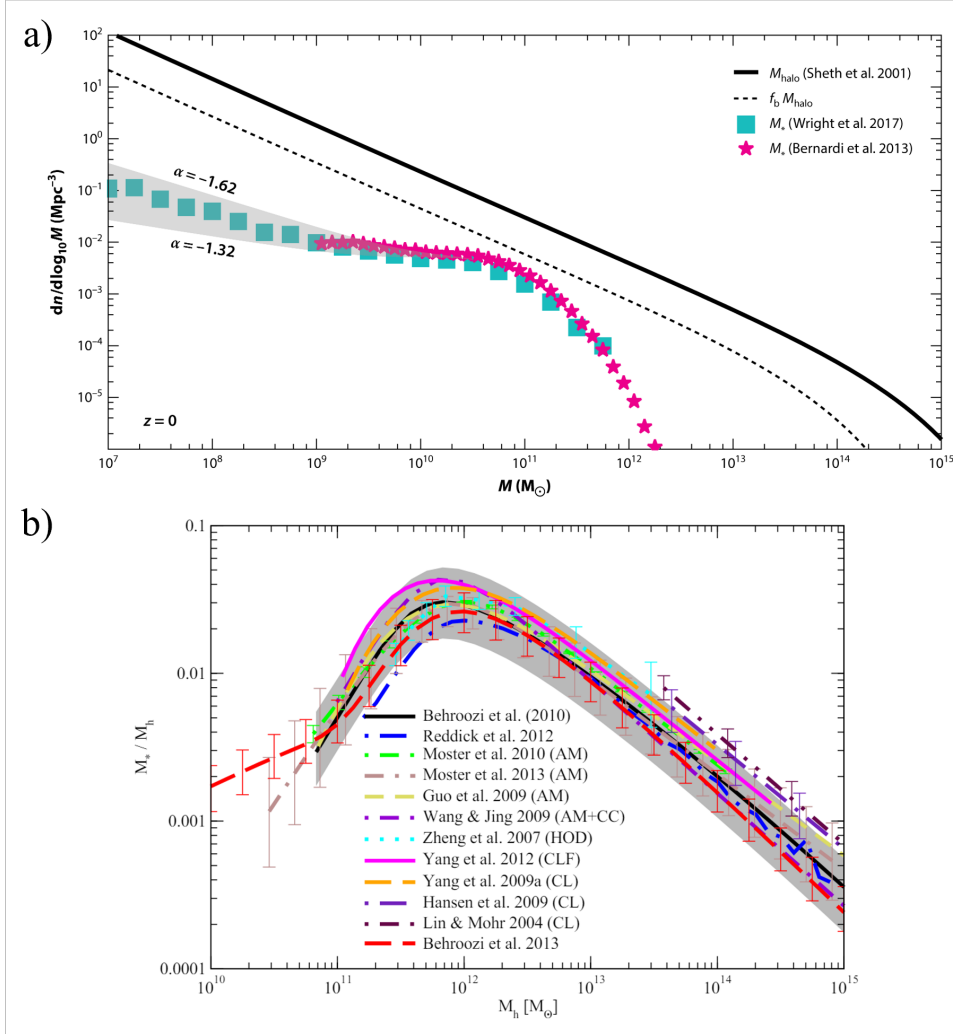


Figure 1.1: a) Figure 5 from [Bullock & Boylan-Kolchin \(2017\)](#) which shows the HMF at $z = 0$ ([Sheth et al., 2001](#)) (black solid line) and cosmic baryon fraction f_b (black dashed line) compared to the observed SMF from [Bernardi et al. \(2013\)](#) (magenta stars) and [Wright et al. \(2017\)](#) (cyan squares). b) Figure 14 from [Behroozi et al. \(2013\)](#) which shows best-fit models for the ratio of stellar mass M_* to halo mass M_h as a function of halo mass at $z = 0.1$. A comparison is shown of works which use different methods such as abundance matching (AM), Halo Occupation Distribution (HOD) and Conditional Luminosity Function (CLF) modeling, and cluster catalogue (CC) measurements. Grey shaded region corresponds to the 68% confidence contour from [Behroozi et al. \(2010\)](#). We note that all these measurements are in good agreement with a peak M_*/M_h at $M_h \approx 10^{12} M_{\odot}$.

Internal Processes

As was shown in Figure 1.1.a, the SMF has a very different shape than the HMF. The SMF has a shallower slope towards low masses compared to the HMF and a sharp exponential cutoff towards high masses happening at a mass of $\sim 10^{11} M_{\odot}$ compared the exponential cutoff of the HMF at a mass of $\sim 10^{14} M_{\odot}$. Figure 1.1.b shows the ratio of the stellar mass to dark matter halo mass M_*/M_h which is not constant as a function of dark matter halo mass M_h but rather peaks at $M_h \approx 10^{12} M_{\odot}$. Even at its peak, the ratio of stellar mass to dark matter halo mass is at most $M_*/M_h \approx 0.04$, which is significantly smaller than the cosmic baryon fraction $f_b = 0.16$. This indicates that the star formation efficiency is relatively low at all scales, meaning that not all gas present in halos is converted into stars. For halo masses below and above $M_h \approx 10^{12} M_{\odot}$, this star formation is seen to decrease dramatically towards both the low mass end and high mass end. The physical processes which reduce star formation efficiency at the low mass end are likely different than the ones affecting the high mass end.

One of the mechanisms which limits the ability of gas to convert into stars is supernovae feedback. Some stars end in violent explosions as a result of depleting their fuel, which imparts both energy and momentum to the surrounding medium. The resulting heating of the surrounding gas was included in models such as that of White & Frenk (1991), Somerville & Primack (1999) which regulated the cooling of gas and therefore star formation. This feedback mechanism can lead to powerful stellar winds, which can be driven by stars as well (Parker, 1958), and eject the gas out of less massive galaxies (Dekel & Silk, 1986). While this feedback mechanism is more effective in shallower gravitational potentials and was able to explain the lower fraction of stellar mass to halo mass seen for less massive galaxy halos shown in Figure 1.1.b, it did not explain the suppression of star formation for higher mass galaxies (Benson et al., 2003).

Understanding of Active Galactic Nuclei (AGN) and their role in galaxy evolution was necessary to develop a full picture of galaxy formation. AGN are extremely powerful sources of energy fuelled by accretion of material onto a central Supermassive Black Hole (SMBH) and are found in most massive galaxies. While the exact processes which form SMBH is still debated, they have been shown to scale in mass with their host galaxy's bulge velocity dispersion (Gebhardt et al., 2000; Ferrarese & Merritt, 2000) and likely grow through galaxy mergers (Volonteri & Natarajan, 2009). The effect of their AGN in ionizing and heating the surrounding medium as well as expelling material away from the host galaxies has been shown in models to dramatically reduce star formation (Silk & Rees,

1998; Di Matteo et al., 2005; Springel et al., 2005). This reduced star formation efficiency will be more significant in the more massive galaxies hosting the most massive SMBHs. This AGN feedback therefore helps explain the trend seen in stellar mass to halo mass ratio in Figure 1.1.b where the star formation efficiency decreases dramatically towards high halo mass.

External Processes

Galaxies within their dark matter halos are known to interact with one another as well as with the larger distribution of both baryons and dark matter of the environments they live in. These interactions have very significant effects on the evolution of galaxies. In this section we review the main external processes affecting galaxy evolution. As halos build up through hierarchical clustering, both the dark matter halos and the baryons present within those halos can interact and change significantly the physical properties of the resulting galaxies. Some galaxies in denser regions will fall into galaxy groups and galaxy clusters where, due to more frequent interactions with and within these clusters, they will evolve and change much more than their counterpart in the lower density “field” (Moore et al., 1996).

Galaxies can merge together and significantly disturb both the baryons and dark matter distribution of one another. These galaxy-galaxy mergers play an important role in some of the striking features seen in galaxies. First shown in early simulations such as that of Holmberg (1941) with an analog computer and that of Toomre & Toomre (1972) with one of the first modern N-body simulation, merging spiral galaxies can lead to very large tidal features and significantly disrupt one another. Furthermore, galaxy-galaxy mergers have been observed to be able to stimulate or suppress star formation (Ellison et al., 2008; Knapen et al., 2015; Ellison et al., 2022). The rate of these mergers for high mass galaxies is low compared to that of lower mass galaxies (Lacey & Cole, 1993). While they play an important role in explaining some of the features seen in galaxies today, these direct galaxy collisions are not the dominant factor which shape galaxies embedded within the larger dark matter halos of galaxy clusters.

As subhalos orbit their host halos, they will slowly fall deeper in the potential well. Dynamical friction is the process through which a massive body will slow down as it travels through collisionless material which was first derived by Chandrasekhar (1943). This friction results in a loss of angular momentum for the orbiting subhalo which leads to orbital decay. These halo mergers can be seen across a wide range of masses, such as a galaxy (i.e.

subhalo) falling into a cluster (i.e. host halo) or a dwarf galaxy (i.e. subhalo) falling into more massive galaxy (i.e. host halo). Within the denser environments of galaxy clusters, mergers between galaxy halos as well as galaxy-galaxy mergers are inhibited compared to mergers in the field (Gottlöber et al., 2001) due to the high relative velocity between member galaxies within clusters. However, high speed galaxy interactions still play an important role within clusters.

Within cluster or galaxy halos, galaxy subhalos will experience many “fly-bys” interaction where energy is transferred from the orbit of galaxies to internal motions within galaxies. This process, first referred to as “harassment” by Moore et al. (1996) was shown in simulations to destroy features within galaxies which explained the observed decrease in abundance of spiral galaxies within clusters over redshift by creating more elliptical galaxies (Moore et al., 1996, 1998; Gnedin, 2003). Another phenomenon, tidal stripping, strips away gravitationally bound material from a galaxy due to tidal interactions with another nearby halo. First described with respect to stars within globular clusters by von Hoerner (1957), this process which has been well characterised using both semi-analytical models and N-body simulations, was shown to be essential in shaping galaxies at many scales from dwarf galaxies orbiting our Milky Way (Mayer et al., 2001) to satellites galaxies in clusters (Taffoni et al., 2003; Read et al., 2006).

While the above processes are caused by gravitational interactions alone, the baryonic gas present in halos and subhalos will also interact. As galaxies orbit a cluster, it will move at high speeds through the hot *Intracluster Medium* (ICM). The gas within the galaxy will feel a pressure force from the gas within the cluster which, if strong enough to overcome the gravitational potential of the galaxy, can strip the gas away. This process, referred to as ram-pressure stripping, was first described by Gunn & Gott (1972) and since then has been refined using hydrodynamic simulations (Abadi et al., 1999; McCarthy et al., 2008). The efficiency of ram-pressure stripping at removing gas from a galaxy depends strongly on many factors which are still not completely understood. Various studies have focused on the dependence of ram-pressure stripping on different properties such as the gravitational potential of galaxies, the gas distributions and density, the inclination of the galaxy with respect to its trajectory, the angular momentum of the galaxy halo, and the presence of AGNs in the galaxy (Marcolini et al., 2003; Roediger & Hensler, 2005; Steihauser et al., 2016; Peluso et al., 2022). In more extreme cases, ram-pressure stripping can leave a tail of materials extending away from the galaxy such as that seen in jellyfish galaxies (Bekki, 2009; Poggianti et al., 2017).

Despite the advances and successes of galaxy formation and evolution models to explain the various population of galaxies observed by including all mechanisms described above (Boselli & Gavazzi, 2006; Somerville & Davé, 2015), some class of galaxies require further attention to fully understand how they could form. The focus of this thesis is on the relatively new and mysterious class of LSB galaxies with dwarf-like stellar masses but Milky Way-like sizes: Ultra-diffuse Galaxy (UDG)s.

1.2 Ultra-diffuse Galaxies

The galaxies identified to date cover many orders of magnitudes in range of sizes, stellar mass, halo mass, absolute magnitude and surface brightness. We show in Figure 1.2.a (McGaugh, 2021) the half light radius and stellar mass of various morphological types of galaxies including late type (Lelli et al., 2016), early type (Dabringhausen & Fellhauer, 2016), and dwarf spheroidal galaxies (Lelli et al., 2017). UDGs from the Coma and Virgo clusters are shown for comparison (van Dokkum et al., 2015a; Mihos et al., 2015). The galaxies span over two orders of magnitudes in half light radius and seven order of magnitudes stellar masses which highlights the wide diversity of galaxies that exists. This figure shows that early type galaxies are generally larger and have more stellar mass than the late type galaxies while dwarf spheroidal galaxies have generally smaller sizes and lower stellar masses. This figure highlights that UDGs, while having similar stellar masses as dwarf galaxies, are significantly larger.

The number density, and therefore SMF, of galaxies can vary significantly for different morphological types. Figure 1.2.b (Kelvin et al., 2014) shows the SMF of early type (red) and late type (blue) galaxies in the Galaxy And Mass Assembly (GAMA) survey. These morphological types are known to trace physical properties such as galaxy colors, with early type galaxies redder and late type galaxies bluer. The SMF from red and blue galaxies from Baldry et al. (2012) (dashed line) and Peng et al. (2012) (dotted line) are shown for comparison and are in relatively good agreement with the results of Kelvin et al. (2014) separated based on morphological types.

With the advancement of instrumentation and telescope, deeper surveys have allowed to probe the fainter end of this parameter space composed of galaxies with relatively low stellar masses which is still not well constrained by current models. A specific type of ultra-faint and very large galaxies, UDG, has gained a lot of attention in the last decade since the term was first coined in 2015 (van Dokkum et al., 2015a). These UDGs are comparable

in size to the Milky Way galaxy, but are far fainter, as shown in Figure 1.2 when comparing UDGs to various morphological types of galaxies. LSB galaxies have been studied for decades, with some LSB studies including examples of such extremely large galaxies being detected well before the term UDG was first used (Sandage & Binggeli, 1984; Impey et al., 1988; Davies et al., 1988). However, the discovery of a significant population of UDGs in the Coma cluster (van Dokkum et al., 2015a) and in other galaxy clusters in subsequent studies (van der Burg et al., 2016; Mancera Piña et al., 2019) revealed hundreds of these galaxies amounting to $\sim 0.2\%$ of the total stellar mass of galaxy clusters (van der Burg et al., 2016). Despite the large number of UDGs found today, the formation mechanism of these extreme galaxies remains unknown.

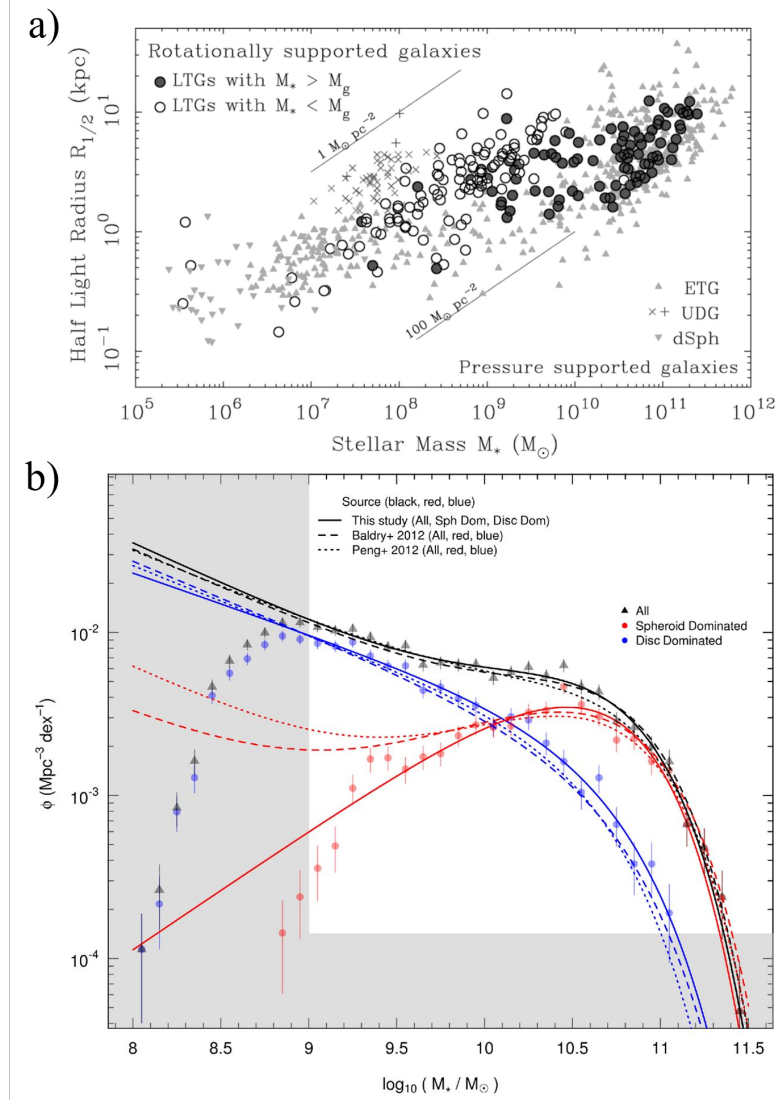


Figure 1.2: a) Figure 2 from [McGaugh \(2021\)](#) showing the size - stellar mass distribution of observed galaxies. Galaxy types shown include early type galaxies (ETG) from [Dabringhausen & Fellhauer \(2016\)](#), late type galaxies (LTG) from [Lelli et al. \(2016\)](#), dwarf spheroidal (dSph) from [Lelli et al. \(2017\)](#), and UDGs from [van Dokkum et al. \(2015a\)](#); [Mihos et al. \(2015\)](#). b) Figure 4 from [Kelvin et al. \(2014\)](#) showing the SMF for “spheroid dominated” or early type galaxies (blue) and “disk dominated” or late type galaxies (red) in the [GAMA](#) survey ([Driver et al., 2009](#)). Fits to the red and blue populations from [Baldry et al. \(2012\)](#) (dashed line) and [Peng et al. \(2012\)](#) (dotted line) are shown.

1.2.1 Definition and Properties

All [UDGs](#) are defined based on a minimum size threshold and a maximum surface brightness threshold. In practice, these thresholds can vary and have been motivated by observational constraints rather than the physical properties of [UDGs](#). This has caused the definition of [UDGs](#) to be somewhat arbitrary and therefore vary significantly throughout the literature. The literature definitions vary in terms of minimum size, minimum surface brightness, definition of the surface brightness, and filter on which the surface brightness is defined, typically r-band or g-band.

In [van Dokkum et al. \(2015a\)](#), [UDGs](#) were found to have half-light radius in the range $1.5 \text{ kpc} < r_{\text{eff}} < 4.5 \text{ kpc}$ and a central surface brightness in the g-band in the range of $24 \text{ mag/arcsec}^2 < \mu_{0,g} < 26 \text{ mag/arcsec}^2$ when assuming that these galaxies were at the Coma cluster distance. Using the r-band imaging of the Coma cluster from the Subaru data archive ([Okabe et al., 2014](#)), [Koda et al. \(2015\)](#) and [Yagi et al. \(2016\)](#) reported 854 [UDGs](#) found, defined based on the [Full Width at Half Maximum \(FWHM\)](#) such that $\text{FWHM} > 1.9 \text{ kpc}$ at the Coma cluster distance and the mean surface brightness within the half light radius $\langle \mu \rangle > 24 \text{ mag/arcsec}^2$. Motivated by these findings, [van der Burg et al. \(2016\)](#) found an estimated 1,446 [UDGs](#) in a set of 8 galaxy clusters observed with the [Multi-Epoch Nearby Cluster Survey \(MENeCS\)](#) ([Sand et al., 2012](#)). The [UDGs](#) in [van der Burg et al. \(2016\)](#) were defined based on $r_{\text{eff}} > 1.5 \text{ kpc}$ and $\langle \mu \rangle > 24 \text{ mag/arcsec}^2$ in the r-band. It has been shown that both the way that [UDG](#) sizes are defined ([Chamba et al., 2020](#)) as well as the exact definition used ([Van Nest et al., 2022](#)) can significantly change the final selected sample and therefore care must be taken in comparing studies.

Despite these differences, all [UDG](#) definitions require some form of distance information in order to convert their projected angular size to a physical size and to correct their surface brightness for cosmological dimming ([Tolman, 1930, 1934](#)). The previously mentioned [UDG](#) studies assumed that these galaxies were located at the host cluster’s redshift, motivated in part by the overabundance of these sources in the clusters compared to the field. A similar method of associating [UDGs](#) to overabundances based on catalogues of galaxies with redshift information was used to estimate distances in the [Systematically Measuring Ultra-diffuse Galaxies \(SMUDGes\)](#) survey ([Zaritsky et al., 2019, 2022](#)) and [Dark Energy Survey \(DES\)](#) ([Sevilla-Noarbe et al., 2021; Tanoglidis et al., 2021](#)). One of the initially discovered 47 [van Dokkum et al. \(2015a\)](#) [UDGs](#), DF44, was soon after followed up spectroscopically which confirmed it to be at the distance of the Coma cluster ([van Dokkum et al., 2015b](#)). Such spectroscopic data on these extremely faint sources requires a lot of

observing time, therefore only a relatively small subset of UDGs discovered to date have been spectroscopically confirmed (Kadowaki et al., 2021; Gannon et al., 2024).

As of today, UDGs have been found across all environments ranging from the field (Leisman et al., 2017; Prole et al., 2019), to groups (Román & Trujillo, 2017; Müller et al., 2017; Somalwar et al., 2020) and galaxy clusters (van Dokkum et al., 2015a; Koda et al., 2015; Mihos et al., 2015; van der Burg et al., 2016; Sifón et al., 2018b; Mancera Piña et al., 2019; Lim et al., 2020). A tight correlation between host halo mass and number of UDGs has been shown (Karunakaran & Zaritsky, 2023). Karunakaran & Zaritsky (2023) suggests that the slope of the power law measured hints that formation of these galaxies is independent on its environment. On the other hand, some evidence of radial alignment of UDGs with their host cluster center has been found which could indicate a link between UDG formation and their cluster environment (Yagi et al., 2016; Rong et al., 2020a), however this alignment is not present in all studied clusters (Mancera Piña et al., 2019). Most UDGs are generally smooth with a light profile well described by a Sérsic profile (Sersic, 1968), while other have been found to have a central nucleus (Yagi et al., 2016; Forbes et al., 2020b). Field UDGs have been shown to be generally bluer than redder UDGs in galaxy clusters, which indicates that these galaxies are more efficiently quenched in dense environments (Prole et al., 2019). The 3D shape of UDGs can be estimated from the distribution of their projected 2D axis ratio to differentiate between prolate, elongated bar-like or “football-like” structures, and oblate shape, thick disk or “pancake-like” structures. Using the Koda et al. (2015) UDGs, Burkert (2017) showed that UDGs are prolate. However, allowing for any triaxial 3D shapes rather than either oblate or prolate when modeling this axis ratio distribution, Rong et al. (2020b) showed that, using UDGs from Koda et al. (2015), Mancera Piña et al. (2019), van der Burg et al. (2016) and Lee et al. (2017), UDGs are more oblate. Some studies of the globular cluster systems of UDGs seem to reveal two distinct types of UDGs across environments, globular cluster rich and globular cluster poor UDGs (Forbes et al., 2020a; Buzzo et al., 2022), however this trend is not seen in every study (Marleau et al., 2021).

1.2.2 Formation Models

Any model of UDGs must be able to explain the observed abundance across environments, potential alignment with host halos, nucleated fraction, color difference between field and cluster UDGs, 3D shape and globular cluster population. While most observational studies

of UDGs have focused on the baryonic content of these galaxies, we must study observationally their dark matter content in order to fully understand UDGs. Fuelled by simulations, many models have been proposed for the formation mechanisms of UDGs. The key to differentiating between these formation mechanisms is to measure the dark matter halo of these galaxies.

It was initially suggested that UDGs were “failed” Milky Way-like galaxies which lost their gas through some external mechanism such as ram pressure stripping and therefore were unable to form as many stars as expected (van Dokkum et al., 2015a). This idea was motivated by both the extended size and large amount of UDGs found in massive galaxy clusters, which due to tidal disruptions would have been unable to survive the cluster environment unless they lived within a deep gravitational potential. Such formation mechanism predicts red, quenched and gas poor UDGs that live in massive Milky Way like dark matter halos and are therefore dark matter-dominated.

With the stellar mass of UDGs being similar to that of dwarf galaxies, a lot of formation mechanisms have proposed that UDGs are some form of typical dwarf galaxy which were “puffed up” through internal or external mechanisms, predicting UDGs to reside in dwarf-like dark matter halos. For instance, internal mechanisms such as high spin dark matter halo (Amorisco & Loeb, 2016; Rong et al., 2017) or star formation feedback (Di Cintio et al., 2017) have been shown in simulations to cause dwarf galaxies to expand and create the observed UDGs both in the fields and in denser environments. Early infall of dwarf galaxies onto a host halo has been suggested to quench and create the red UDGs we see today in clusters (Yozin & Bekki, 2015; Tremmel et al., 2020).

Other mechanisms proposed could even create UDGs with no dark matter. For instance, van Dokkum et al. (2022) suggests that UDGs DF2 and DF4 are the result of a high velocity head-on collision between dwarf galaxies, which has been shown to be able to create redder and dark matter-free galaxies in simulations (Silk, 2019; Shin et al., 2020). The clumping of ram-pressure stripped gas from jellyfish galaxies (Poggianti et al., 2019; Iodice et al., 2021) as well as the debris of tidal interactions similar to tidal dwarf galaxies (Lelli et al., 2015; Ploekinger et al., 2018; Gray et al., 2023) have also been suggested as a possible mechanism for dark matter-free UDGs. While no consensus has been reached in the literature, it is generally accepted that not all UDGs are formed via the same formation mechanisms, and therefore more than one of the models mentioned above can create UDGs.

1.2.3 Dark Matter Halo Measurements

Many different approaches have been used to infer the mass of the dark matter halo that UDGs reside in. One common approach is to estimate their dynamical mass based on the stellar velocity dispersion (van Dokkum et al., 2016; Trujillo et al., 2017; Toloba et al., 2018) which require spectroscopic data. A few UDGs have been studied in-depth using spectroscopic data which revealed a wide range of halo masses from dark matter-dominated, such as DF44 with halo mass of $10^{11.2} M_{\odot}$ (van Dokkum et al., 2019b) to dark matter-free, such as DF2 with halo mass of $10^{8.2} M_{\odot}$ (van Dokkum et al., 2018), reinforcing the idea that multiple formation mechanisms exist for UDGs.

The dark matter content of UDGs has also been estimated using the Globular cluster Number - Halo mass Relation (GNHR) (Spitler & Forbes, 2009; Harris et al., 2013; Hudson et al., 2014) in many UDG studies such as that of Zaritsky et al. (2023) and Forbes & Gannon (2024). Unfortunately, this GNHR has not yet been very well constrained in this regime of low globular cluster counts and low mass, with significant scatter seen when applied to UDGs (Forbes et al., 2018). The halo mass of UDGs has also been estimated using scaling relations between galaxy sizes, brightness and velocity dispersion for low mass galaxies (Zaritsky & Behroozi, 2023), which was shown based on six UDGs to be in good agreement with the GNHR method (Zaritsky et al., 2023). However, this method also relies on empirical relations which must be tested for UDGs. Other arguments have been made based on the observed lack of UDGs in the central and densest regions of galaxy clusters (van Dokkum et al., 2015a). Assuming that UDGs would be destroyed by tidal interactions in the cluster environment if not within a massive enough gravitational potential, van der Burg et al. (2016) estimated a lower limit on the halo masses of UDGs in the Coma cluster of $\sim 10^{9.3} M_{\odot}$.

A more direct and reliable approach is to measure the halo mass of UDGs using gravitational lensing, the measure of the average distortion of background sources around a lens. Sifón et al. (2018b) found 784 UDGs in a set of 18 galaxy clusters and stacked the weak lensing signal to estimate the average halo mass of their sample. Their result gave no detection but allowed for an estimated upper limit on the total halo mass of UDGs of $10^{11.8} M_{\odot}$. While this upper limit suggests non-Milky Way mass halos for UDGs, this average measurement does not rule out the possibility of some UDGs residing in massive halos and being dark matter-dominated such as DF44. This approach has the enormous advantage of not requiring deep spectroscopic data and not relying on scaling relations which must be properly calibrated in the UDG regime. In order to better understand and

disentangle the formation mechanisms of UDGs, we describe in this thesis our approach which uses weak gravitational lensing to improve on the measurements of the average halo mass of UDGs of Sifón et al. (2018b).

1.3 Gravitational Lensing

As light emitted from a distant object, the “source”, travels passed a strong gravitational field referred to as the “lens”, the light path is deflected. This effect can lead to unique observables which are dependent on the properties of the source and the lens. The first instance of light deflection by a gravitational field was measured during the 1919 solar eclipse with the light from a background star being redirected by the Sun’s gravitational field (i.e. the lens) which led to a measurable shift in the star’s apparent location on the sky (Dyson et al., 1920). In 1979, a much more distant point-source, the twin quasars 0957+561 A/B at a redshift $z = 1.41$, was measured to be gravitationally lensed by an elliptical galaxy at redshift $z = 0.39$, which led to a duplicate version of the same quasar being spatially resolved on the sky and is considered the first gravitational lensing system discovered (Walsh et al., 1979). Such extreme examples of gravitational lensing are generally referred to as “strong” gravitational lensing. In 1989, the first strongly lensed extended source, an elliptical galaxy at $z = 0.73$, was measured to be strongly distorted into a long arc by the galaxy cluster Abell 370 at redshift $z = 0.37$ (Lynds & Petrosian, 1986; Soucail et al., 1987).

While many more extreme image distortions caused by strong gravitational lensing have been found since then, such scenarios are extremely rare since they require a strong gravitational field from the lens, a very bright much more distant source, and an almost perfect lens-source alignment. However, the more subtle effect of gravitational lensing for lens-source pairs which are not aligned is also observable and referred to as “weak” gravitational lensing. Our focus is on this weak gravitational lensing between a source galaxy and lens galaxy, also referred to as “galaxy-galaxy” lensing.

The subtle effect of weak gravitational lensing is to change slightly the observed ellipticity of background sources tangentially with respect to a foreground lens. Due to the homogeneous and isotropic nature of the universe, the orientation of galaxies is expected to be random, therefore this excess tangential alignment can be measured and used to directly infer the total matter distribution, which includes the dark matter. The first weak gravitational lensing measurement was made in 1990 on the lens clusters Abell 1689 and

CL 1409+52, which allowed for a direct measurement of the cluster matter distribution (Tyson et al., 1990). However, galaxy clusters are some of the most massive structures in the universe and therefore have the strongest lensing effect. To measure the halo mass of galaxies, it is possible to stack together this measurement for many galaxy lenses (Tyson et al., 1984), which can reveal the average dark matter distribution for any sample of galaxies (Brainerd et al., 1996; Fischer et al., 2000).

In this section, we introduce the mathematical framework of weak gravitational lensing for the purpose of this thesis but refer the reader to reviews such as Dodelson (2017) for a comprehensive summary of the topic and complete mathematical description. Effectively, the gravitational field from the lens will induce a shear onto the observed background source. This shear can be described based on the orientation of a background source with respect to the foreground lens such that

$$\begin{pmatrix} \gamma_t \\ \gamma_\times \end{pmatrix} = \begin{pmatrix} -\cos 2\phi & -\sin 2\phi \\ \sin 2\phi & \cos 2\phi \end{pmatrix} \begin{pmatrix} \gamma_1 \\ \gamma_2 \end{pmatrix} \quad (1.1)$$

where γ_1 and γ_2 are the components of the shear in a cartesian frame, γ_t and $\gamma_\times$ are the tangential and the cross shear, and ϕ the azimuthal angle of the source with respect to the lens-source vector. The excess surface density $\Delta\Sigma$, defined as

$$\Delta\Sigma = \bar{\Sigma}(r_p) - \Sigma(r_p) \quad (1.2)$$

is the difference between the average projected mass density $\bar{\Sigma}(r_p)$ within a given projected radial distance between the lens and the sources, r_p and the mass density $\Sigma(r_p)$ at a given r_p . The tangential shear is directly proportional to the excess surface density such that

$$\Delta\Sigma = \gamma_t \Sigma_{crit} \quad (1.3)$$

where Σ_{crit} is the result of the effect of mass on the space-time metric as described by general relativity. Σ_{crit} depends on the source redshift z_s and lens redshift z_l such that

$$\Sigma_{crit} = \frac{c^2}{4\pi G} \frac{D_A(z_s)}{D_A(z_l)D_A(z_l, z_s)} \quad (1.4)$$

where c is the speed of light in vacuum, G the gravitational constant, $D_A(z_s)$ and $D_A(z_l)$ the angular diameter distance to the source and lens respectively, and $D_A(z_l, z_s)$ the angular diameter distance from the lens to the source.

The tangential shear described above assumes a perfectly circular background source. All galaxies have some intrinsic ellipticity e which complicates this measurement. However, due to the homogeneous and isotropic nature of the universe, we can average the measurement from many lens-source pairs such that the average tangential component of the ellipticity is equal to the tangential shear $\langle e_t \rangle = \gamma_t$. The resulting excess surface measurement can then be described as

$$\Delta\Sigma = \frac{\sum_{ls} w_s \Sigma_{crit}^{-1}(z_l, z_s) e_t}{\sum_{ls} w_s \Sigma_{crit}^{-2}(z_l, z_s)} \quad (1.5)$$

where w_s is the weight assigned to the source galaxy based on the uncertainty in the shape measurement, e_t is the tangential ellipticity component of the lens-source pair and $\sum_{ls}$ is the sum over all possible lens-source pairs. The excess surface measurement is made by separating sources into radial bins at different r_p from the lens. While the measurement process has been described for a single lens with many pair, the signal from around many lenses can be stacked together with the same formalism shown in equation 1.5.

Precise measurements of the average mass profile of a galaxy sample through galaxy-galaxy lensing require large number of lenses to stack as well as many background source galaxies on which to make the shear measurements. This usually requires large area surveys which contain many lenses with enough depth and good image quality to see distant and therefore smaller and fainter source galaxies. Since the weak lensing measurement relies on the shape of background sources, a very well characterized [Point Spread Function \(PSF\)](#) is required to ensure there is no bias on the measured shapes of galaxies.

[Ultraviolet Near Infrared Optical Northern Survey \(UNIONS\)](#) is an ongoing multi-band wide field survey optimized for weak gravitational lensing and is ideal for the galaxy-galaxy lensing measurements we are interested in. It will cover $\sim 4,800 \text{ deg}^2$ of extragalactic sky in the northern hemisphere in the u, g, r, i and z band, with the u and r band measured from the [Canada-France-Hawaii Telescope \(CFHT\)](#), the g and z band from the Subaru telescope, and the i band from [Panoramic Survey Telescope and Rapid Response System \(Pan-STARRS\)](#). The limiting magnitude for a 5σ detection of a point source within a $2''$ aperture is 24.3, 25.2, 24.9, 24.3 and 24.1 in the u, g, r, i and z band, respectively ([Li et al., 2024](#)). Data products of [UNIONS](#) of interest for our purposes include preprocessed r-band imaging optimized for [LSB](#) sources as well as shape catalogues and associated calibration catalogues. This preprocessed r-band data has an average seeing of $\sim 0.65''$ ([Guinot et al., 2022](#)) and a detection performance down to $28.4 \text{ mag/arcsec}^2$ for extended sources ([Li et al., 2024](#)) which makes it ideal for [UDG](#) detection.

1.4 Outline of Thesis

The objective of this work is to constrain the formation mechanisms of [UDGs](#). By stacking the weak gravitational lensing signal of many [UDGs](#), it is possible to measure their total mass and constrain their dark matter content. Such measurement was first made by [Sifón et al. \(2018b\)](#) (which we will refer to as S18) in 2018 focusing on 784 potential [UDGs](#) in a set of 18 galaxy clusters, which they showed to provide an upper limit on the total halo mass of [UDGs](#) of $10^{11.8} M_{\odot}$. In this work, we set to improve on this constraint and its interpretation to help solve the mystery of how [UDGs](#) formed. Since [UDGs](#) are defined based on physical parameters such as size and surface brightness which require distance information, we limit of search to within galaxy clusters where we can correctly assume that a subset of our sample is at the cluster’s redshift. We use the [UNIONS](#) r-band imaging to find and measure properties of [UDGs](#) and the [UNIONS](#) source shape catalogues to perform our weak lensing measurement on the sample of [UDGs](#) found.

In chapter 2, we describe the selection of the sample of galaxy clusters in [UNIONS](#) within which we will search for [UDGs](#). We describe the [UNIONS](#) survey and data used in this thesis. We then describe the galaxy cluster catalogues used. We describe our selection criteria based on redshift, dust emission maps, and available [UNIONS](#) masks. Lastly, we estimate each cluster’s halo mass M_{200} and associated size R_{200} using the information available in the cluster catalogues combined with known cluster halo mass, richness and concentration relations.

In chapter 3, we describe the search for [UDGs](#) within our sample of galaxy clusters using the r-band imaging from [UNIONS](#). We describe our pipeline for finding [UDGs](#). This involves measuring the [PSF](#), detecting faint extended [UDG](#)-like sources, fitting light profiles to extract relevant physical parameters, selecting for [UDGs](#) based on these parameters and a visual classification to improve the purity of the sample. Lastly, we describe how we generate a sample of field interlopers, which is a representative sample of the contamination within our [UDG](#) sample of sources which are in the line of sight of the galaxy clusters we use but are not associated with the clusters.

In chapter 4, we describe the measurement of the gravitational lensing signal around [UDGs](#) and the model used to estimate the average dark matter halo mass of these galaxies. We first describe the [UNIONS](#) source and calibration catalogues used. We proceed to describe the excess surface density profile measurements made on our sample of contaminated [UDGs](#) and sample of field interlopers. We also describe measurements made on sets

of randoms, as well as boost factor corrections applied. Since a similar weak gravitational lensing measurement was made on a separate sample of UDGs by S18, we describe how we combine our measurements with the S18 measurements. Lastly, we describe the projected dark matter halo profile used to model these excess surface density profile measurements and our various fitting results. Since none of our measurements lead to a signal detection, we focus on the 2σ upper limit on the average halo mass of UDGs which we constrain.

In chapter 5, we model for how interlopers affect both our and S18 measurements of the upper limit on the halo mass of UDGs and estimate a more realistic upper limit by limiting assumptions made on the effect of interlopers in the sample. We interpret these results in the broader context of UDG formation mechanisms. We then discuss potential improvements to the work described in this thesis as well as future works and datasets which will allow for improved constraints on the halo mass of UDGs. Lastly, we provide a summary of the work and results presented in this thesis.

Throughout this thesis, we assume a flat Λ CDM cosmology with $\Omega_{m,0} = 0.30$ and $H_0 = 70$ km/s/Mpc (Planck Collaboration et al., 2020).

Chapter 2

Galaxy Cluster Selection

In this chapter, we describe the selection of galaxy clusters in which we will search for [UDGs](#). Since [UDGs](#) are defined based on physical parameters such as size and surface brightness, we need reliable distance estimates. By focusing on galaxy clusters, we measure an overabundance of sources in the line of sight compared to the field and can reliably assume that these sources are at the same distance as the galaxy cluster. We first introduce the details of [UNIONS](#) imaging for our purposes since we will make use of [UNIONS](#) data to search for [UDGs](#) as well as to perform our weak lensing analysis. We then describe the cluster catalogues used and a selection based on [UNIONS](#) mask maps. We describe the selection process of galaxy clusters based on redshift and dust maps. Lastly, we estimate the cluster size R_{200} and mass M_{200} using known scaling relations and the information available in each cluster catalogue as well as remove duplicate clusters from our final sample.

2.1 UNIONS Photometric Data and Catalogues

Throughout this work, we use various data products of [UNIONS](#), which is an ongoing multi-band survey which will cover an area of $\sim 4,800 \text{ deg}^2$. We will use the preprocessed [UNIONS](#) r-band imaging to search for [UDGs](#), described in details in chapter [3](#), as well as the shape and calibration catalogues to perform our weak lensing analysis described in chapter [4](#).

The [UNIONS](#) r-band imaging is taken from the [CFHT](#) using the MegaCAM wide-field camera ([Boulade et al., 1998](#)). The median seeing of the r-band data is $0.65''$ ([Guinot](#)

et al., 2022) and median limiting magnitude for a 5σ detection of a point source within a $2''$ aperture is 24.9 (Li et al., 2024). The raw images are preprocessed, calibrated and combined into $0.5^\circ \times 0.5^\circ$ “tiles” using the MegaPipe processing pipeline (Gwyn, 2008). These tiles combine many overlapping images taken at different times and therefore have varying exposures and seeing over the tile. Each tile has an associated weight map which weighs more heavily pixels which contain longer exposures. The pixel resolution of these tiles is $0.1857''/\text{pix}$ which is similar to the resolution of the MegaCAM instrument. Multiple preprocessing pipelines exist for the UNIONS r-band imaging. We choose to use the LSB tiles which improves the visibility of extended, low surface brightness sources (Lim et al., 2023) with a detection performance down to $28.4 \text{ mag/arcsec}^2$ for extended sources. One key aspect of the LSB preprocessing is that a flat background is subtracted from each exposures before combining them as opposed to a background allowed to vary over the entire image, which ensures that large, extended LSB features are recovered in the tiles. The effects and corrections of this preprocessing onto our UDG detection pipeline are discussed in sections 3.5.3, 3.5.4, and 3.6.5.

Each tile is placed exactly 0.5° apart in declination, DEC and $0.5^\circ/\cos(DEC)$ in right ascension, RA. The tiles have an additional $28.5''$ on all sides to help correct for any edge effect. This results in a small overlap of 6.4% in area between all tiles, which is depicted in Figure 2.1. This overlap can lead to duplicate sources being detected when processing the tiles. This effect on our UDG detection pipeline is corrected for and described in section 3.6.3.

For the purposes of our weak gravitational lensing analysis described in chapter 4, we use UNIONS shape catalogues to measure the shear of background sources. These shape catalogues are measured using the UNIONS r-band images. Since UNIONS is an ongoing survey, the amount of r-band imaging data available and preprocessed increased while the work described in this thesis was being completed. Multiple data products such as shape catalogues and associated calibration catalogues were developed. Two processing pipelines have been carefully developed to generate galaxy shape catalogues, ShapePipe and lensfit (Guinot et al., 2022). Throughout this thesis, we will use the lensfit v1.0 shape catalogue which used the THELI processing pipeline and lensfit software (Miller et al., 2007). The lensfit shape catalogue contains 109 million galaxy sources with shape measurement over an area of $\sim 2,100 \text{ deg}^2$ (Li et al., 2024). We note that the lensfit shape catalogue does not have redshift estimates for each individual sources, and therefore a calibration catalogue of a subset of 65,896 sources with spectroscopic redshift measurements is used. This calibration catalogue is used to estimate the average redshift distribution of the entire source

sample, $n(z)$ (Li et al., 2024).

A mask map made by the [UNIONS](#) collaboration is used in making the lensfit shape catalogue. Some regions of the current [UNIONS Canada France Imaging Survey \(CFIS\)](#) r-band survey footprint are not included in these masks since [UNIONS](#) data analysis and acquisition is still ongoing and therefore these regions do not have galaxy shape measurements available. A full-sky mask map in [Hierarchical Equal Area isoLatitude Pixelation \(HEALPix\)](#) format allows us to find regions where masking is available. We therefore will restrict our search for [UDGs](#) to be within the $\sim 2,100 \text{ deg}^2$ footprint covered by the lensfit catalogue.

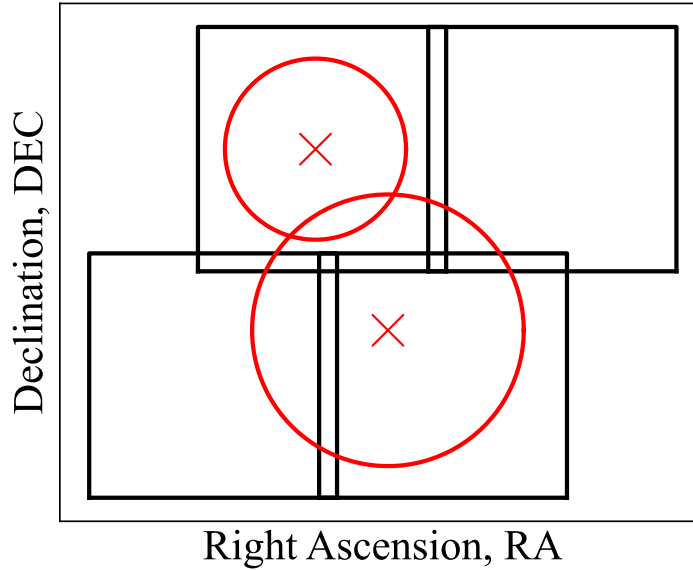


Figure 2.1: Diagram of tile layout with tile edges shown with solid black lines. Tile overlap causes duplicate sources to be found and is multiplied by a factor of five for visibility purposes in the diagram. Two clusters (red solid line) are shown to overlap. Sources within this overlapping region are considered to have a secondary cluster.

2.2 Galaxy Cluster Catalogues

To find as many galaxy clusters as possible with [UNIONS CFIS](#) r-band [LSB](#) imaging and lensfit galaxy shape measurements available, we use two galaxy cluster catalogues which

overlap with the survey footprint; the [red-sequence Matched-filter Probabilistic Percolation \(redMaPPer\)](#) ([Rykoff et al., 2014](#)) and [Meta-Catalogue of X-ray detected Clusters of galaxies \(MCXC\)](#) ([Piffaretti et al., 2011](#)) catalogues.

The [redMaPPer](#) catalogue is made by applying a cluster finder algorithm on 10,400 deg² of multi-band photometric data from the [SDSS DR8](#) ([York et al., 2000](#); [Aihara et al., 2011](#)), and makes use of spectroscopic data from the [SDSS DR9](#) ([Ahn et al., 2012](#)) to calibrate their algorithm. The algorithm works iteratively, first using spectroscopic red galaxies as “seeds”, then searching for overdensities of galaxies of the same color, then calibrating the search based on these newly found galaxies and running the search again ([Rykoff et al., 2014](#)). The [redMaPPer](#) cluster catalogue provides an estimated richness λ for each clusters based on the properties of the cluster galaxy members such as color, i-band magnitude and position. It can be effectively described as follow

$$\lambda = \sum_{R < R_c(\lambda)} \frac{\lambda u(\mathbf{x}|\lambda)}{\lambda u(\mathbf{x}|\lambda) + b(\mathbf{x})} \quad (2.1)$$

where $\mathbf{x}$ is a vector describing the observable properties of the galaxies, $u(\mathbf{x}|\lambda)$ is the normalized cluster density profile, $b(\mathbf{x})$ is the background density, R the radial distance from the cluster center and $R_c(\lambda) = (1.0h^{-1} \text{ Mpc})(\lambda/100.0)^{0.2}$. The richness is calculated for each cluster by solving numerically equation 2.1, and we note that extra corrections are applied to this estimate to account for cases with clusters near one another ([Rykoff et al., 2014](#)). This richness parameter has the advantage of relying only on photometric data alone and has been shown to be tightly correlated with the total halo mass of the cluster ([Spitzer, 2022](#)). The [redMaPPer](#) catalogue contains 26,111 galaxy clusters with redshifts in the range $0.0811 \leq z \leq 0.5983$. Since it is based on [SDSS](#) data, it has good overlap with [UNIONS](#) footprint.

The [MCXC](#) catalogue is a combination of many cluster catalogues made using X-ray data primarily from the [ROSAT All-Sky Survey \(RASS\)](#) ([Voges et al., 1999](#)). These clusters are found based on their X-ray emission. The [MCXC](#) catalogue contains 1,743 galaxy clusters with redshifts in the range $0.0031 \leq z \leq 1.261$. Since it is based on all-sky observations it fully overlaps with [UNIONS](#) footprint. Each clusters in this catalog contain a halo mass M_{500} and halo size R_{500} which are measured based on X-ray properties of the clusters. We note that for our purposes we will need the halo mass M_{200} and corresponding size R_{200} instead of M_{500} and R_{500} which are better measured using X-ray observations (see section 2.6 for details). One key difference between the [redMaPPer](#) and [MCXC](#) catalogues

is that we expect the X-ray emission of galaxy clusters used in the [MCXC](#) catalogue to better trace the center of the gravitational potential of the clusters than the photometric data used in the [redMaPPer](#) catalogue ([Rykoff et al., 2008, 2014](#)).

2.3 Maximum Redshift Considered

Our ability to properly detect [UDGs](#) is limited to relatively low redshifts. At low redshifts, further away galaxies will have smaller projected angular sizes. Our search for [UDGs](#) requires to be able to reliably measure morphological parameters of galaxies with half-light radius of at least 1.5 kpc (section 3.6.1). The median seeing of the r-band imaging data we use is $\sim 0.65''$, which if we assume a simple Gaussian profile for the corresponding [PSF](#) which effectively blurs our imaging data, gives a half-light radius of $\sim 0.33''$ for the [PSF](#). At a redshift of $z = 0.3$, this corresponds to a half-light radius of our [PSF](#) of 1.5 kpc which is the same as the minimum size as our [UDGs](#). In practice, we are not able to detect and measure accurately [UDGs](#) at such a high redshift and limit ourselves to a maximum redshift of $z = 0.1$, where the half-light radius of our [PSF](#) corresponds to 0.6 kpc.

Another important consideration is the effect of cosmological dimming ([Tolman, 1930, 1934](#)), which causes the measured surface brightness to decrease rapidly as a function of redshift by $10 \log(1+z)$ mag/arcsec². Up to a redshift $z = 0.1$, this corresponds to 0.4 mag/arcsec² while at a redshift of $z = 0.3$ it is 1.1 mag/arcsec² which is significantly dimmer. Since our [UDG](#) search relies on our ability to measure the faintest sources possible in [UNIONS](#), this dimming will affect our ability to detect [UDGs](#) which contributed to our decision to limit our search to a maximum redshift of $z = 0.1$.

We also considered the effect of interloper contamination on our sample of [UDGs](#) which we found to be highly dependent on redshift. Interloper contamination is an unavoidable result of our method which relies on detecting [UDGs](#) in clusters, where interlopers are galaxies which are not necessarily at the same redshift as the cluster but are in the line of sight of it (see section 3.9 for details). We estimated the interloper contamination fraction in our [UDG](#) detection pipeline at $z = 0.2$ and found a much higher interloper contamination compared to at $z = 0.1$, and therefore limited our search for [UDGs](#) up to $z = 0.1$ to ensure a relatively low interloper contamination fraction of 0.468. We note that the fast increase in interloper contamination as a function of redshift can be seen in Figure 3.10 (see section 3.9 for details). We discuss in depth the importance of interlopers on our

measurements in sections 3.9, 5.1.

By considering the angular size, cosmological dimming and estimated interloper fractions, we decided to limit our search for UDGs to within galaxy clusters up to a redshift of $z \leq 0.1$, similar to other UDG studies in clusters (S18). This selection reduces the number of galaxy clusters available from the MCXC catalogue to 663 clusters and from the redMaPPer catalogue to 169 clusters. This selection criteria removes the most galaxy clusters out of all other criteria describe below. The redshift distribution of galaxy clusters considered is shown in Figure 2.2.a, where we see that, primarily from the redMaPPer catalog, many more galaxy clusters would be available using the same catalogues if we were able to search for UDGs at higher redshifts.

2.4 UNIONS Mask

As described in section 2.1, we are limiting our UDG search to within the $\sim 2,100 \text{ deg}^2$ sky area with both the UNIONS r-band LSB tiles and the lensfit shape catalogue available. We use the UNIONS full-sky mask map in HEALPix format to determine sky regions with masking information available, and therefore background galaxy shape measurements available. We exclude galaxy clusters in regions with no mask information available which reduces the number of clusters with $z \leq 0.1$ for MCXC clusters from 663 to 71 and for redMaPPer clusters from 169 to 24.

2.5 Galactic Cirrus and Dust Contamination

To limit galactic cirrus and dust contamination in the line of sight of our sample of galaxy clusters which could be mistaken as LSB galaxies (Zaritsky et al., 2021), we use the τ_{353} (Planck Collaboration et al., 2014) and Wide-field Infrared Survey Explorer (WISE) $12 \mu\text{m}$ (Meisner & Finkbeiner, 2014) full-sky dust emission maps. We select the τ_{353} and WISE $12 \mu\text{m}$ full-sky maps in HEALPix format with resolutions of $\sim 1.7 \text{ arcmin/pix}$ and $\sim 0.9 \text{ arcmin/pix}$ respectively, which is more than enough resolution for our purposes. Since these dust maps do not vary significantly over the angular scale of our clusters, we measure the dust emission at the center of each cluster and keep clusters with $\tau_{353} \leq 0.05$ and WISE $12 \mu\text{m} \leq 0.1 \text{ MJy/sr}$ (Zaritsky et al., 2021). The τ_{353} and WISE $12 \mu\text{m}$ emission at our cluster centers is shown in Figure 2.2.b. This selection reduces the number of MCXC clusters from 71 to 55 and the number of redMaPPer clusters from 24 to 20. We note that the rejection

due to dust contamination is relatively small (23% and 17%) as expected since [UNIONS](#) survey footprint is designed to avoid sky regions with large amounts of galactic cirrus.

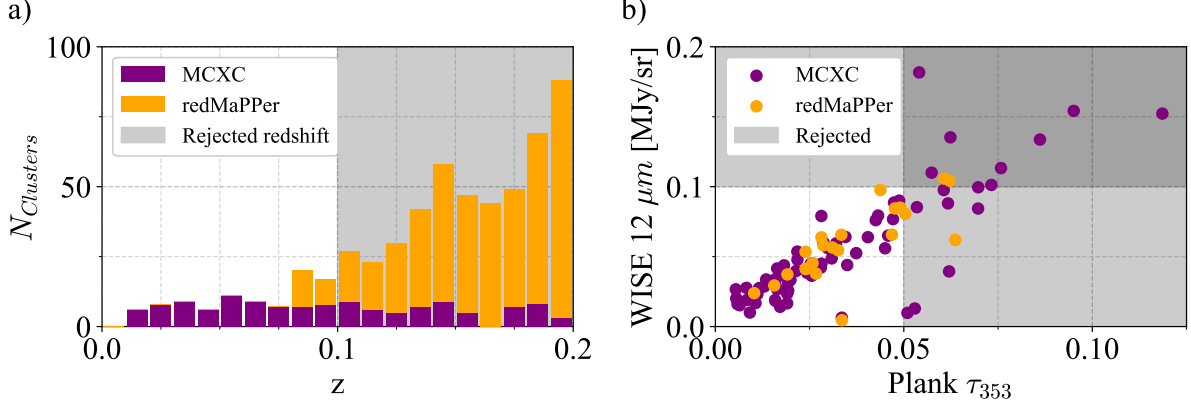


Figure 2.2: a) Total number of galaxy clusters within the [UNIONS CFIS](#) r-band [LSB](#) survey footprint with available [UNIONS](#) masks, $N_{clusters}$ per redshift bins of $\Delta z = 0.01$ as a function of redshift z . Only clusters with redshifts up to $z \leq 0.1$ are kept (rejected redshifts shown in grey shaded area). We see that more [redMaPPer](#) (orange) galaxy clusters are available at higher redshift than [MCXC](#) (purple) galaxy clusters. b) [WISE](#) 12 μm vs Planck τ_{353} emission at galaxy cluster centers with $z \leq 0.1$ within the [UNIONS CFIS](#) r-band [LSB](#) survey footprint with available [UNIONS](#) masks. Clusters with higher dust emission are more likely to contaminate our UDG selection, we therefore only keep clusters with $\tau_{353} \leq 0.05$ and [WISE](#) 12 $\mu m \leq 0.1$ MJy/sr ([Zaritsky et al., 2021](#)) to limit this contamination (rejected clusters shown in grey shaded area). Both the [MCXC](#) clusters (purple) and the [redMaPPer](#) clusters (orange) are shown.

2.6 M_{200} and R_{200} Estimates

Both the [MCXC](#) and [redMaPPer](#) galaxy cluster catalogues contain different information on their clusters, but neither contain the cluster R_{200} and M_{200} . In general, we can define R_{Δ} as the radius at which the average mass density within the cluster is Δ times the critical density of the universe at the cluster redshift, $\rho_{crit}(z)$, and M_{Δ} as the total mass enclosed within R_{Δ} . We are interested in calculating both R_{200} and M_{200} for our galaxy clusters since they are a good approximation of the virial radius and virial mass of the cluster halo. Both these values will be necessary in our analysis to define the projected angular size

of our clusters as well as estimate the completeness of our sample. Assuming spherically symmetric clusters, we can express M_Δ as a function of R_Δ such that

$$M_\Delta = \frac{4\pi}{3} \Delta \rho_{crit}(z) R_\Delta^3 \quad (2.2)$$

Since the focus of this work is at relatively low redshift, we can ignore the small contribution from radiation energy density and express the critical surface density as follows:

$$\rho_{crit}(z) = \frac{3H_0^2 (\Omega_{\Lambda,0} + \Omega_{m,0}(1+z)^3)}{8\pi G} \quad (2.3)$$

where the dark energy density $\Omega_{\Lambda,0} \approx 1 - \Omega_{m,0} = 0.70$ and the gravitational constant $G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$.

For the [MCXC](#) clusters, M_{500} and R_{500} are provided since these values are better measured than M_{200} and R_{200} when using X-ray observations. In order to convert these R_{500} and M_{500} values to R_{200} and M_{200} , we need a description of the cluster density as a function of radius, $\rho(r)$. To describe our galaxy cluster halos we adopt the common [Navarro–Frenk–White \(NFW\)](#) density profile ([Navarro et al., 1997](#)) which was first developed using N-body simulations. This profile can fully characterize our clusters using two parameters such that

$$\rho(r) = \frac{\rho_0}{r/r_s(1+r/r_s)^2} \quad (2.4)$$

where r_s is the scale radius and ρ_0 is the density at the center of the cluster which can be expressed in terms of the concentration of the cluster, c_{200} or c_{500} , such that

$$\rho_0 = \frac{200\rho_{crit}(z)c_{200}^3}{3 \left[\ln(1+c_{200}) - \frac{c_{200}}{1+c_{200}} \right]} = \frac{500\rho_{crit}(z)c_{500}^3}{3 \left[\ln(1+c_{500}) - \frac{c_{500}}{1+c_{500}} \right]} \quad (2.5)$$

Note that the scale radius can be defined in terms of either R_{200} or R_{500} :

$$r_s = \frac{R_{200}}{c_{200}} = \frac{R_{500}}{c_{500}} \quad (2.6)$$

Therefore, to convert the cluster R_{500} and M_{500} values to R_{200} and M_{200} , we need to assume a concentration. We use the halo mass to c_{200} concentration relation from [Duffy](#)

et al. (2008) which was found by fitting an exponential function to N-body simulations and allowed to vary as a function of redshift such that

$$c_{200} = 5.71 \left(\frac{M_{200}}{2 \times 10^{12} h^{-1} M_{Sun}} \right)^{-0.084} (1+z)^{-0.47} \quad (2.7)$$

Combining equations 2.2-2.7 and solving numerically, we are able to calculate R_{200} and M_{200} for each clusters in the MCXC catalogue.

For the redMaPPer clusters, a richness estimate λ is provided as described in section 2.2. This richness parameter is extremely useful since it is based on photometric data and is tightly correlated with the total mass of the clusters. We use the halo-mass-to-richness relation measured using weak gravitational lensing from Spitzer (2022):

$$\log(M_{200m}/M_{\odot}) = 1.43 \log(\lambda/40) + 14.41 - \log(h) \quad (2.8)$$

where $h = H_0/(100 \text{ km/s/Mpc})$. This halo-mass-to-richness relation allows us to calculate the mass M_{200m} for each redMaPPer clusters. Unlike M_{200} , this mass is defined based on the average matter density of the universe at the cluster redshift, $\rho_m(z)$, which we can express as

$$\rho_m(z) = \frac{\Omega_{m,0} \rho_{crit}(z) (1+z)^3}{\sqrt{\Omega_{\Lambda,0} + \Omega_{m,0} (1+z)^3}} \quad (2.9)$$

The associated radius R_{200m} , defined as

$$M_{200m} = \frac{4\pi}{3} R_{200m}^3 200 \rho_m(z) \quad (2.10)$$

is calculated from this mass M_{200m} . Lastly, the scale radius can be expressed as the ratio of this radius and associated concentration such that

$$r_s = \frac{R_{200m}}{c_{200m}} \quad (2.11)$$

Combining equations 2.2-2.7, 2.9-2.11 and solving numerically, we calculate R_{200} and M_{200} for each cluster in the redMaPPer catalogue.

2.7 Cluster Duplicates

We check for overlap between the 55 [MCXC](#) and 20 [redMaPPer](#) clusters using 3D cluster center distances. We find that 2 galaxy clusters in the [MCXC](#) clusters are within a physical distance of 3 Mpc to a [redMaPPer](#) cluster. We consider these to be duplicates and remove the 2 clusters from the [redMaPPer](#) clusters.

To further check for duplicate clusters, we look for clusters which overlap with one another in sky-projection using R_{200} as the edge of the cluster. We find that 7 [redMaPPer](#) clusters are completely overlapping with a [MCXC](#) cluster, and that these pairs have similar redshifts with a difference of at most 0.006 in redshift. While this redshift difference is relatively small and comparable to the precision of the redshifts in the [redMaPPer](#) cluster catalogue ([Rykoff et al., 2014](#)), it can lead to a 3D distance between clusters much larger than 3 Mpc. We consider these 7 [redMaPPer](#) clusters to be duplicates and remove them.

This leaves us with a total of 66 galaxy clusters, of which 10 clusters overlap slightly in sky-projection. It contains 55 clusters from the [MCXC](#) catalogue and 11 from the [redMaPPer](#) catalogue. We note that for the 9 total duplicate clusters, we keep the [MCXC](#) cluster center coordinates rather than the [redMaPPer](#) center coordinates since we expect the [MCXC](#) cluster position to better trace the center of the gravitational potential of the cluster’s halo (see section 2.2).

2.8 Sample Purity and Completeness

Both the completeness and purity of the [redMaPPer](#) cluster catalogue has been estimated in detail in [Rozo & Rykoff \(2014\)](#) by comparing the catalogue to many other cluster catalogues, including the [MCXC](#) catalogue. The completeness of the entire [redMaPPer](#) catalogue, which is the fraction of [MCXC](#) clusters present in the [redMaPPer](#) catalogue, has been estimated as a function of cluster X-ray luminosity L_{500} down to a redshift of $z = 0.1$. Based on the mean luminosity of the 55 [MCXC](#) clusters in our sample $\langle L_{500} \rangle = 0.46 \times 10^{44}$ ergs/s, the completeness of [redMaPPer](#) clusters in our sample is $\sim 95\%$. This means that we would expect most of the [MCXC](#) clusters in our sample to have a [redMaPPer](#) counterpart. However, since the overlap of [UNIONS](#) with the footprint of the [MCXC](#) catalogue is larger than that of the [redMaPPer](#) catalogue, and since the [MCXC](#) catalogue extends to lower redshifts than the [redMaPPer](#) catalogue, we found only 9 duplicate clusters out of

our final 55 [MCXC](#) clusters (see section 2.7).

The purity of the entire [redMaPPer](#) catalogue, which is the fraction of [redMaPPer](#) clusters which are not X-ray detected and therefore not in the [MCXC](#) catalogue, has been estimated as a function of cluster richness λ down to a redshift of $z = 0.1$ ([Roza & Rykoff, 2014](#)). Based on the mean richness of the 11 [redMaPPer](#) clusters in our sample $\langle \lambda \rangle = 29.9$, the purity of [redMaPPer](#) clusters in our sample is $\sim 60\%$. This means that we expect a significant fraction of the [redMaPPer](#) clusters to not have been X-ray detected and therefore not included in the [MCXC](#) catalogue, which explains the 11 remaining [redMaPPer](#) clusters in our final cluster sample.

Our final cluster sample contains 55 [MCXC](#) clusters and 11 [redMaPPer](#) clusters. The 11 galaxy clusters which are found in the [redMaPPer](#) catalogue have a similar median mass as the 55 clusters found in the [MCXC](#) catalogue of $M_{200} = 10^{14.10} M_{\odot}$. The total halo mass M_{200} of our sample of 66 clusters ranges from $10^{13.34} M_{\odot}$ to $10^{14.83} M_{\odot}$. The redshifts of our final cluster sample ranges from 0.018 to 0.100, with a mean redshift of 0.064. All 66 galaxy clusters in our final sample are analysed together and in the same way throughout the rest of this thesis. A summary of the selection criteria for our galaxy cluster sample is provided in Table 2.1.

Selection Criteria	MCXC	redMaPPer	Total
Total	1,743	26,111	27,854
$z \leq 0.1$	663/1,743	169/26,111	832/27,854
UNIONS Mask available	71/663	24/169	95/832
Low Dust Contamination	55/71	20/24	75/95
Duplicate removal	55/55	11/20	66/75

Table 2.1: Selection criteria applied to the [MCXC](#) and [redMaPPer](#) cluster catalogues. We show the resulting number of clusters for each catalogues as well as the total number of clusters which pass each selection criteria. Each row shows the combination of all selection criteria of the rows above it. We have a final sample of 66 galaxy clusters.

Chapter 3

Ultra-diffuse Galaxy Catalogue

In this chapter, we describe the search for [UDGs](#) within our galaxy cluster sample from chapter 2. We first describe the [UNIONS](#) r-band photometric data used and how we estimate the [PSF](#) in the survey. We describe the source extraction and fitting method used to extract parameters for each source. We then apply a set of selection criteria, including a visual selection, and find a sample of 545 potential [UDGs](#) within our clusters. We estimate the fraction of interlopers, which are the sources within the clusters line of sight which are not associated with the clusters, and define a catalogue of field interlopers in [UNIONS](#).

3.1 Photometric Data

We use the [UNIONS](#) photometric survey to detect [UDGs](#). More specifically, we use the preprocessed r-band [LSB](#) tiles which combines contains the stacked images taken from the [CFHT](#) (see section 2.1 for details). A typical example tile and associated weight map are shown in Figure 3.1.a and 3.1.b respectively. For each of the 66 galaxy cluster in our sample, we find which tiles overlap with a region around the cluster extending to the projected cluster R_{200} . We find a total of 213 unique tiles containing our cluster sample.

3.2 Variable Point Spread Function

The rapidly changing atmospheric distortions of our ground-based observations effectively blurs our data. This effect, combined with distortions due to the optics of the instruments,

must be accounted for with an accurate measurement of the **PSF** which will be necessary to extract physical properties of our **UDGs**. We expect the **PSF** to vary across each tile, sometimes sharply, due to the stacking of different images. To model this variation, we use the **PSF Extractor (PSFEx)** software (Bertin, 2011) which allows us to extract the **PSF** and model its variation using a low-order polynomial. **PSFEx** automatically detects candidate point sources (i.e. stars) from an input catalogue with image cutouts, then fit a variable **PSF** which we choose to allow variations as a function of pixel coordinates using a second order polynomial, which is the default **PSFEx** setting. To generate the input catalogue in FITS_LDAC binary format, which is the needed file type for **PSFEx**, we use the source detection software **Source Extractor (SExtractor)** (Bertin & Arnouts, 1996) with the parameters recommended by **PSFEx** on each of our tiles. We have a set of 213 measured **PSF**, one for each of our tiles, which can be reconstructed at any pixel location on each tile.

The reconstruction of the **PSF** at any pixel coordinate within a tile from the **PSFEx** output is non-trivial and described here. With the default **PSFEx** parameters and the **PSF** in **PSFEx** allowed to vary as a function of pixel coordinates (x, y) in each tile using a second order polynomial, **PSFEx** will fit for the best possible **PSF** across a given tile. We note that we set the **PSF** output pixel scale to be the same as the pixel scale of our images using the parameter `PSF_SAMPLING = 1` which simplifies the reconstruction step. The **PSFEx** output file contains six 25×25 pixels “moments” of the **PSF**, A_i , for each combination of X and Y up to second order provided in the following order: 1, X , X^2 , Y , XY , and Y^2 . These X and Y parameters can be calculated from the pixel coordinates (x, y) as follow:

$$X = \frac{x - \text{POLZERO1}}{\text{POLSCAL1}} \quad Y = \frac{y - \text{POLZERO2}}{\text{POLSCAL2}} \quad (3.1)$$

where `POLZERO1`, `POLSCAL1`, `POLZERO2`, `POLSCAL2` are parameters available in the output **PSFEx** file. A 25×25 pixels **PSF** at any given pixel coordinates (x, y) , $\text{PSF}_{(x,y)}$ can then be reconstructed by summing all moments weighted differently such that

$$\text{PSF}_{(x,y)} = \sum_{i=1}^6 C_i A_i \quad (3.2)$$

where the coefficients $C_i = \{1, X, X^2, Y, XY, Y^2\}$.

3.3 Faint Source Extraction

To detect **UDGs** within our data, we again use the **SExtractor** software on each individual tile. We use optimized parameters to detect these very faint and extended sources based

on the [van der Burg et al. \(2016\)](#) and S18 previous [UDG](#) studies within galaxy clusters. We note that our data is shallower than that from these studies, with an average exposure time from the same MegaCam camera on [CFHT](#) approximately ten times shorter. While these optimized parameters have the advantage to detect extremely faint and large sources, they also increase the number of false detection and artifacts in our resulting catalogues, which will need to be carefully removed. The non-default [SExtractor](#) parameters used along with a reasoning for the choices made can be found in [Table 3.1](#). [SExtractor](#) output catalogues contain basic information on each sources. Each source parameters used in our analysis is described in [Table 3.2](#). Furthermore, [SExtractor](#) outputs an estimated variable background across the entire tile, shown in [Figure 3.1.c](#) as well as a segmentation map which assigns each pixels to a single object in the catalogue or to the background.

We run [SExtractor](#) on all 213 tiles and extract a total of 5.8×10^6 sources, with an average of 2.7×10^4 sources per tile or 28.4 sources/arcmin². We restrict our search to sources within the projected R_{200} of our sample of galaxy clusters, which leaves a total of 1.7×10^6 sources. The half-light radius and total magnitude measured by [SExtractor](#) of all the sources detected within our projected clusters R_{200} is shown in [Figure 3.2](#).

Parameter Name	Default	Used	Description	Reasoning
DETECT_MINAREA	5 pix	20 pix	Minimum number of pixels above threshold	Reduce contamination from small and faint detection
DETECT_THRESH	1.5σ	0.7σ	Minimum threshold for a detection	Increase number of faint sources detected, at the cost of a lower Signal-to-Noise Ratio (SNR)
Gaussian Filter Width	2 pix	5 pix	Filter convolved with data to improve source detection	A wider filter improves detection of large sources
BACK_SIZE	64 pix	150 pix	Background mesh size, which sets the size of the area used to estimate background	Subtracts only large scale variation, ensures UDGs are not mistaken as background variation
BACK_FILTERSIZE	3 pix	5 pix	Size of the filter used to estimate background	Improve detection of larger sources

Table 3.1: Non-default [SExtractor](#) parameters used in detecting [UDGs](#) in the [UNIONS CFIS](#) r-band [LSB](#) tiles. The parameter name, default and used values as well as a description and reasoning for the choice of parameter used is provided.

Parameter Name	Description
X_IMAGE (Y_IMAGE)	x(y)-coordinates of the source
FLUX_RADIUS	Half-light radius of the source
MAG_AUTO	Total magnitude of the source
FLAGS	SExtractor flag for the source
MAG_APER	Aperture magnitudes for a 2'' and 7'' diameter aperture for each source

Table 3.2: [SExtractor](#) output parameters used in our [UDGs](#) detection pipeline. Parameter names and description of the parameters is provided.

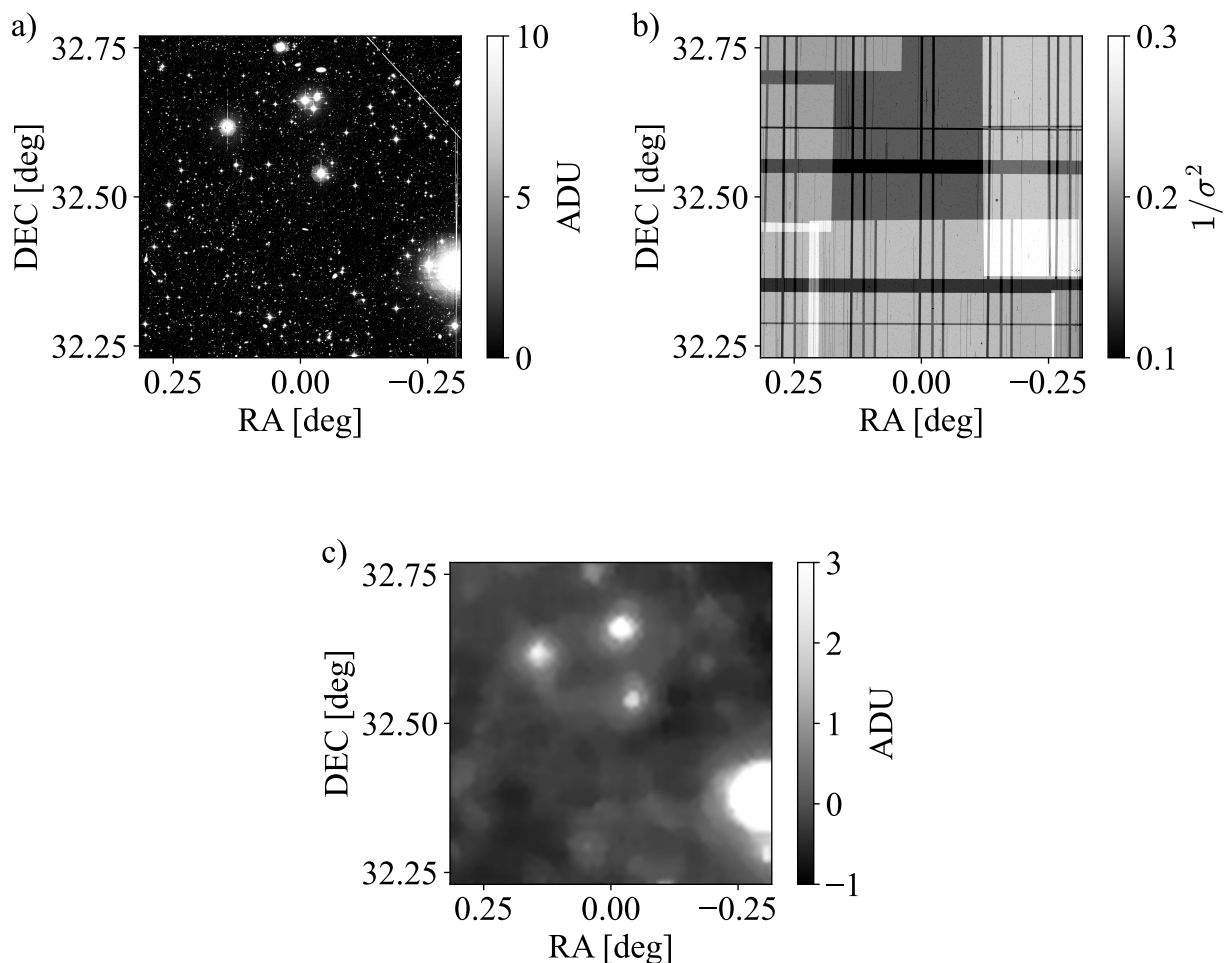


Figure 3.1: a) Example [LSB](#) tile and b) weight map from [UNIONS](#) r-band which combines many r-band images taken from [CFHT](#) using the MegaCAM wide-field camera. Each tile and associated weight map is $0.5^\circ \times 0.5^\circ$. c) Example variable tile background measured by [SExtractor](#) for the shown tile. The various total exposure varies across the tile due to different images combined as well as chip gaps which can be clearly seen in the weight map. The background map shows large scale variations over the entire tile, especially around bright saturated stars.

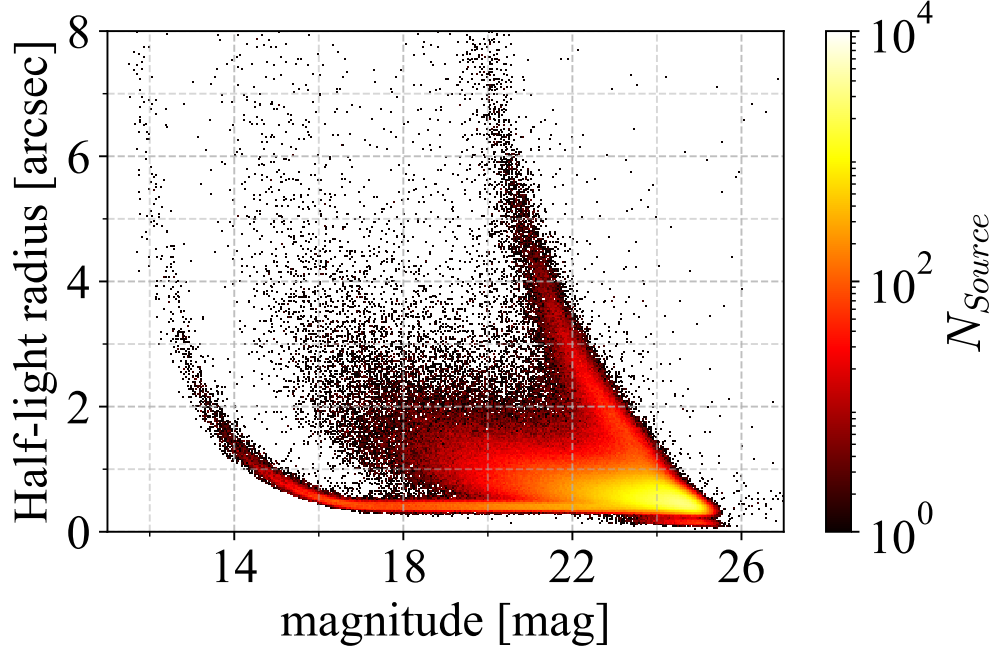


Figure 3.2: Half light radius R_e in arcseconds compared to the total apparent magnitude of the 1.7×10^6 sources detected within the cluster R_{200} of our sample of 66 galaxy clusters by [SExtractor](#).

3.4 Initial Source Selection

We apply an initial aperture selection to remove stars, compact sources, false-detections and some artifacts from the sample. Our selection criteria is as follows:

$$m_{2''} > m_{7''} + 0.9 \text{ mag} \quad (3.3)$$

where $m_{2''}$ ($m_{7''}$) is the r-band magnitude within a circular aperture of $2''$ ($7''$) diameter. This effectively remove sources which are not contributing enough light pass a $2''$ diameter radius using a robust and simple [SExtractor](#) measurement ([van der Burg et al., 2016](#)). The $2''$ and $7''$ aperture magnitude for our sources within the projected clusters R_{200} are shown in Figure 3.3. This aperture selection reduces significantly our sample from 1.7×10^6 sources to 1.8×10^5 sources.

We show the half-light radius and total magnitude measured by [SExtractor](#) for the remaining sources after this aperture selection in Figure 3.4 for comparison to Figure 3.2. The key difference between these figures is that most of the smaller and brighter sources have been removed.

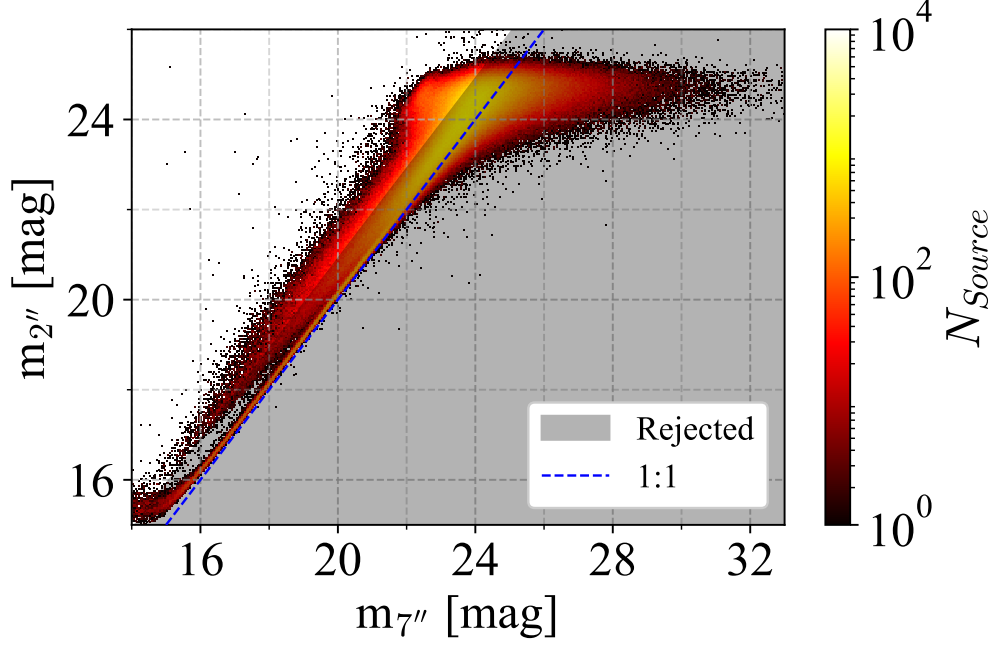


Figure 3.3: Apparent magnitude within a 2'' and 7'' aperture of the 1.7×10^6 sources detected within the cluster R_{200} of our sample of 66 galaxy clusters by [SExtractor](#). The rejected parameter space from the criteria in equation 3.3 is shown (grey area). The one-to-one line (blue dashed line) is shown for clarity.

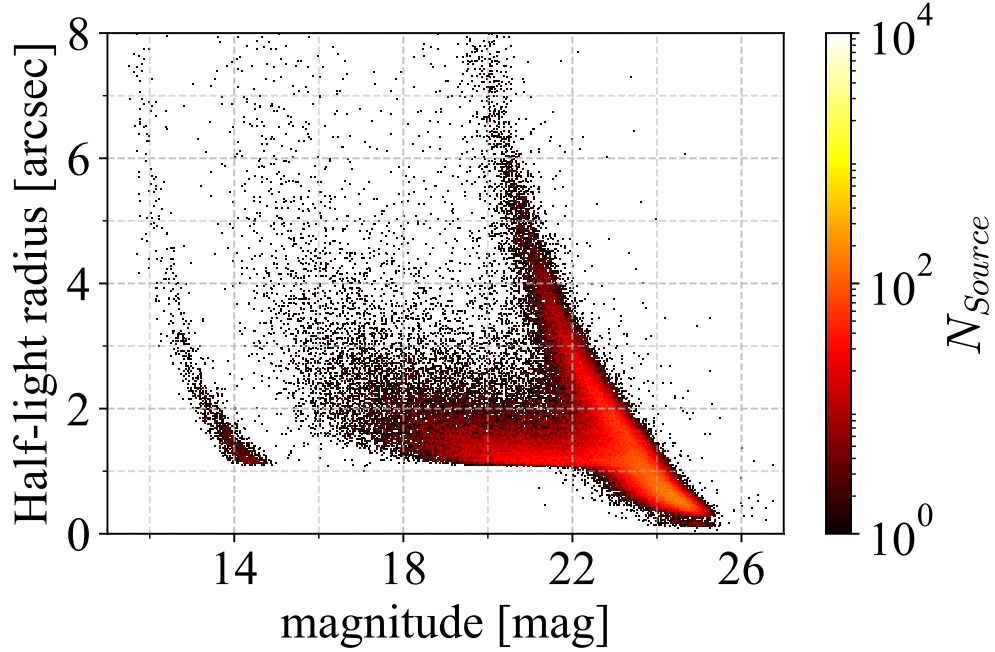


Figure 3.4: Half light radius R_e in arcseconds compared to the total apparent magnitude of the 1.8×10^5 sources detected by [SExtractor](#) which pass our initial source selection based on aperture magnitudes (see equation 3.3).

3.5 Fits

3.5.1 Sérsic Profile

While [SExtractor](#) is a powerful tool for detecting sources and performing fast photometry, we fit a light profile to our sources in order to have a more accurate size and surface brightness measurement on which we define our [UDGs](#). This extra fitting step is especially important for the faint and low signal-to-noise [UDGs](#) which we are trying to find. Most previous searches for [UDGs](#) use a Sérsic profile ([Sersic, 1968](#)) as it is found to describe well the light profile of [UDGs](#) ([van Dokkum et al., 2015a](#); [Yagi et al., 2016](#)). This profile has

the following form:

$$\mu(r) = \mu_{\text{eff,m}} + \frac{2.5b_n}{\ln(10)} \left[\left(\frac{r}{r_{\text{eff}}} \right)^{1/n} - 1 \right] \quad (3.4)$$

where $\mu(r)$ is the surface brightness in mag/arcsec^2 at a given radius r in arcseconds, r_{eff} the “effective” or “half-light” radius within which 50% of the total profile light is enclosed, $\mu_{\text{eff,m}}$ the measured surface brightness at r_{eff} , and n the Sérsic index. b_n can be calculated by solving numerically the following:

$$\Gamma(2n) = 2\gamma(2n, b_n) \quad (3.5)$$

where Γ and γ are the complete and incomplete Gamma functions respectively.

3.5.2 Set Sérsic Index

While most [UDG](#) searches let the Sérsic index be a free fitting parameter when modeling the light profile ([van der Burg et al., 2016](#); [Mancera Piña et al., 2019](#); [Yagi et al., 2016](#)), we find this free parameter adds little improvement in our fits, as measured from the residual chi-square. This is likely due to the relatively low [SNR](#) of our faint sources. The Sérsic index for [UDGs](#) is typically measured to be around $n = 1$ ([Mancera Piña et al. \(2019\)](#) measures a mean $\langle n \rangle = 1.01$). We choose to fit a Sérsic profile with a set Sérsic index $n = 1$ (i.e an exponential light profile), similarly to [van Dokkum et al. \(2015a\)](#), which reduces equation [3.4](#) to

$$\mu(r) = \mu_{\text{eff,m}} + 1.822 \left[\left(\frac{r}{r_{\text{eff}}} \right) - 1 \right] \quad (3.6)$$

3.5.3 Cutout Preparation

To perform our fits, we first create a 150×150 pixel ($27.9'' \times 27.9''$) tile cutout centered on each source in our sample after applying our initial cuts. Each tile cutout has an associated weight map cutout. We first subtract a background cutout made from the [SExtractor](#) estimated variable background map for the tile in which the source was found. While a flat background has already been subtracted for the tile in the preprocessing stage when combining different exposures, we found a strong sensitivity of our extracted morphological parameters on the background and therefore subtract this variable background measured

with [SExtractor](#) to remove more subtle fluctuations. For each source, we reconstruct the [PSF](#) at the source (x,y)-coordinate using the measured variable [PSF](#) from [PSFEx](#) for the corresponding tile. Most tile cutout contains multiple sources of light within this $27.9'' \times 27.9''$ window. To hide these extra sources from our analysis, we use the segmentation map generated by [SExtractor](#) for each tile, and create a matching cutout at the location of the source we want to fit. All sources in the cutout other than the source of interest at the center and the background are masked by generating a mask cutout. We found the [SExtractor](#) segmentation to be in some cases too small, meaning that light from the masked sources “bleed” out of the masked area. To correct for this effect, we apply a 2-dimensional smoothing Gaussian filter with $\sigma = 2$ pixels to our mask (with pixel value of 0 for background and source of interest, and pixel value of 100 for sources to hide) and hide all values above a threshold of 1. This expands the mask around each extra sources to a point where the “bleeding” light no longer affects significantly the fitted parameters for the source of interest. An example set of the cutouts needed for the fit to a single source is shown in [Figure 3.5](#) for clarity.

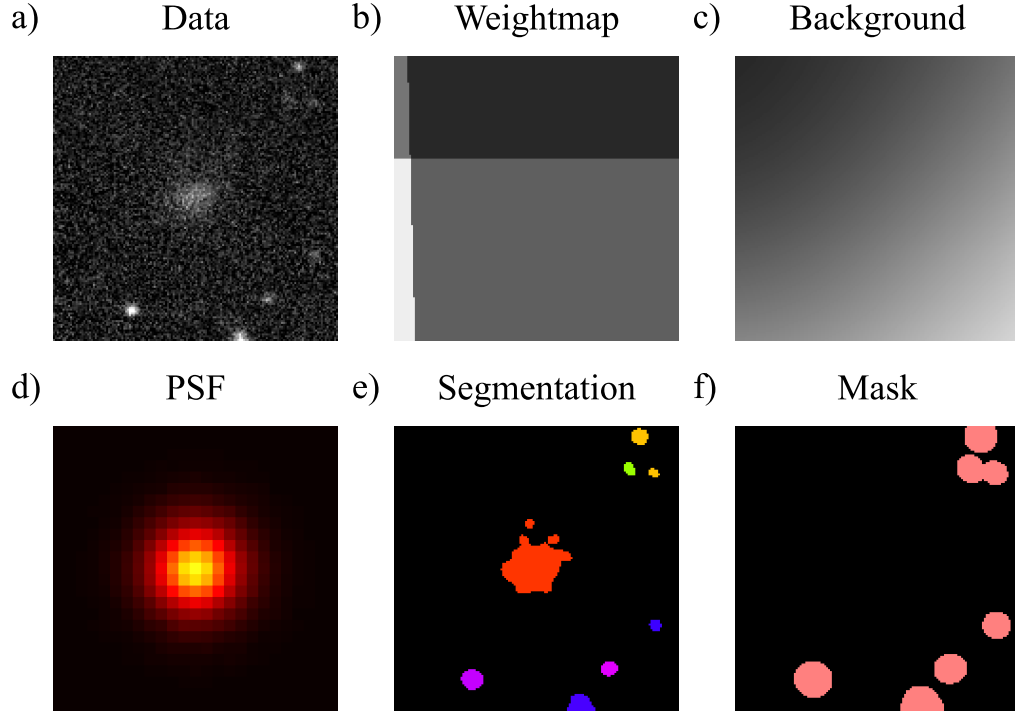


Figure 3.5: Example 150×150 ($27.9'' \times 27.9''$) cutouts generated for a source. a) r-band [LSB](#) tile cutout and b) Associated weight map cutout. c) Variable background cutout measured with [SExtractor](#). d) Variable [PSF](#) measured using [PSFEx](#) reconstructed at the source center location. e) Segmentation map generated by [SExtractor](#) and f) associated mask map we generate.

3.5.4 Background Fit

Despite using preprocessed data with a flat background subtracted as well as a variable background measured by [SExtractor](#) subtracted, we still find the need to include a free parameter in our model to correct for small residual flat background in our cutouts. This residual background measured is likely due to local under or over estimate of the variable background by [SExtractor](#), which is set to only vary on scales larger than our cutouts. This extra parameter increases the accuracy in the extracted morphological parameters of our sources. We note that this flat background β in units of $\text{count}/\text{pix}^2$ which we add to our model can be either positive or negative since it is applied to already background

subtracted cutouts.

3.5.5 Least-square Fitter

We fit 183,825 sources to a Sérsic profile with a set Sérsic index $n = 1$ (see equation 3.6) convolved with our measured PSF and allowing for a flat background offset β . In equation 3.6, the radial distance r effectively incorporates multiple fitting parameters that described the elliptical shape that we allow for our sources, such that in the pixel coordinates (x, y) of the cutout,

$$r = \sqrt{q [(x - x_0) \cos \theta + (y - y_0) \sin \theta]^2 + [-(x - x_0) \sin \theta + (y - y_0) \cos \theta]^2 / q} \quad (3.7)$$

where (x_0, y_0) is the source center, q is the semi-minor axis b to semi-major axis a ratio (i.e. $q = b/a$), and θ the position angle with respect to the x-axis in a counter-clockwise direction. We choose to give our fits more flexibility by allowing the source center position to vary from the one measured by SExtractor since we found the SExtractor source center to be sometimes offset from the true center of our faint sources.

We use the AutoProf python package (Stone et al., 2021) to perform relatively efficient least-square fits with the Levenberg-Marquardt χ^2 minimization method (Levenberg, 1944; Marquardt, 1963). AutoProf takes as input the tile cutout and associated weight map, convolves the model described in equations 3.6 and 3.7 with the input PSF cutout, and masks extra sources with our input mask. Furthermore, AutoProf automatically provides initial guesses for the fitting parameters of our model. This least-square method also provides a measure of a symmetric 1σ uncertainty in all of our parameters. We note that this fitting procedure is one of the most computationally demanding parts of our analysis which highlights the need for an initial source selection. Our model contains seven free fitting parameters shown in Table 3.3. A set of example fit cutouts, models and residuals are shown in Figure 3.8. We note that despite the source pre-selection, a significant number of the fitted sources in our sample of 183,825 objects are artifacts which will be removed as described in sections 3.6.2 and 3.6.5.

Fitting Parameter	Description
r_{eff}	Effective or "half-light" radius defined as $r_{\text{eff}} = \sqrt{ab}$.
q	Axis ratio defined as $q = b/a$.
θ	Position angle measured counter-clockwise from the positive x-axis.
x_0	Ellipse center along x-axis within the cutout.
y_0	Ellipse center along y-axis within the cutout.
$\mu_{\text{eff,m}}$	Measured surface brightness at the effective radius $\mu(r_{\text{eff}})$.
β	Flat background surface brightness on the already background subtracted cutout.

Table 3.3: Free fitting parameters for our model. A description of each of the seven parameters is provided.

3.5.6 Physical Properties

Now that we measured the morphological properties of the sources projected on the tiles, such as their angular size and surface brightness, we can convert these to physical properties needed to define UDGs by assuming a distance for the sources. We assume that each source belongs to the cluster on which it is projected within the cluster R_{200} and therefore has the same redshift as the cluster, a common assumption for UDG studies (Mancera Piña et al., 2019; van der Burg et al., 2016; Sifón et al., 2018b). This assumption will only be correct for a subset of sources, while all sources whose true position is either in front of or behind the cluster along the line of sight are referred to as interlopers. While with our method it is impossible to disentangle the interlopers from true cluster members, the effects of these interlopers on our weak gravitational lensing analysis results will be corrected for (see sections 3.9 and 4.4) and discussed in depth (see section 5.1).

Given each source redshift, we compute the effective radius in kpc, and correct the measured surface brightness at the effective radius $\mu_{\text{eff,m}}$ for cosmological dimming (Tolman, 1930, 1934) such that

$$\mu_{\text{eff}} = \mu_{\text{eff,m}} - 10 \log_{10} (1 + z) \quad (3.8)$$

where μ_{eff} is the corrected surface brightness at the effective radius on the cutout. We do not apply the color-dependent and redshift-dependent K-correction (Humason et al., 1956; Oke & Sandage, 1968; Hogg et al., 2002) to our measurements. Based on estimates using

the online K-correction calculator (Chilingarian et al., 2010; Chilingarian & Zolotukhin, 2012) and assuming a constant colour for our sample of $g - r = 0.61$ based on the cluster UDG measurement of Mancera Piña et al. (2019), this correction affects μ_{eff} by at most 0.2%. The change in surface brightness at the effective radius $\Delta\mu_{\text{eff}}$ ranges from 0.02 to 0.05 over the redshift range of our sample. The 1σ scatter in $g - r$ color from Mancera Piña et al. (2019) is ± 0.12 , which at the mean redshift of our sample $\langle z \rangle = 0.07$ can affect our surface brightness measurements $\Delta\langle\mu\rangle$ ranging from 0.04 to 0.06. The uncertainty in our sources' $g - r$ colour which corresponds to an uncertainty in a K-correction is similar to the range of K-correction on our sample due to its redshift dependence. We therefore do not apply this small correction which is expected to not affect our results significantly.

3.6 UDG Selection Criteria

3.6.1 UDG Definition

With the morphological parameters measured for each of our sources, we can now apply selection cuts on the sample and define our UDGs. As described in section 1.2.1, the definition of UDG can vary significantly across the literature, due in part to the fact that these galaxies appear to be a continuation of the dwarf galaxy population in the surface brightness and size parameter space. In all cases, UDGs are defined to be physically large, above some threshold size value, with a very low surface brightness, below a chosen threshold, which makes them ultra-diffused. In practice these size and surface brightness thresholds, as well as the definitions of size and surface brightness, vary throughout the literature between different UDG studies.

One notable difference in defining a UDG is the definition of surface brightness used, which can vary significantly depending on if we consider the central surface brightness μ_0 , the surface brightness at the effective radius μ_{eff} , or the mean surface brightness within the effective radius $\langle\mu\rangle$. Both the central surface brightness and mean surface brightness within the effective radius can be expressed in terms of the surface brightness at the effective radius for a Sérsic profile with $n = 1$ as follow:

$$\mu_0 = \mu_{\text{eff}} - 1.822 \quad (3.9)$$

$$\langle\mu\rangle = \mu_{\text{eff}} - 0.698 \quad (3.10)$$

These surface brightness definitions for the same exponential profile are compared in Figure 3.6, where it is clear that μ_0 , μ_{eff} and $\langle\mu\rangle$ can be significantly different for a single object,

and that by definition $\mu_0 < \langle \mu \rangle < \mu_{\text{eff}}$. Furthermore, the definition of effective radius for an ellipse varies throughout the literature as either the semi-major axis of the ellipse $r_{\text{eff}} = a$, or the circularized radius $r_{\text{eff}} = \sqrt{ab}$, which in turn will affect the quoted surface brightness. We select a size and surface brightness definition similar to that of S18 and [van der Burg et al. \(2016\)](#), based on the circularized radius $r_{\text{eff}} = \sqrt{ab}$ and mean surface brightness within the effective radius $\langle \mu \rangle$ in the r-band to have a more comparable [UDG](#) sample to that of S18. To ensure the sources we consider [UDGs](#) are in fact extended sources, we add the requirement that the measured size is more than 1σ larger than the minimum threshold. Our [UDGs](#) are defined as:

$$r_{\text{eff}} - \Delta r_{\text{eff}} \geq 1.5 \text{ kpc} \quad (3.11)$$

$$\langle \mu \rangle \geq 24.0 \text{ mag/arcsec}^2 \quad (3.12)$$

where Δr_{eff} is the 1σ uncertainty in our measurement. Applying this definition leaves us with a sample of 5,552 potential [UDGs](#).

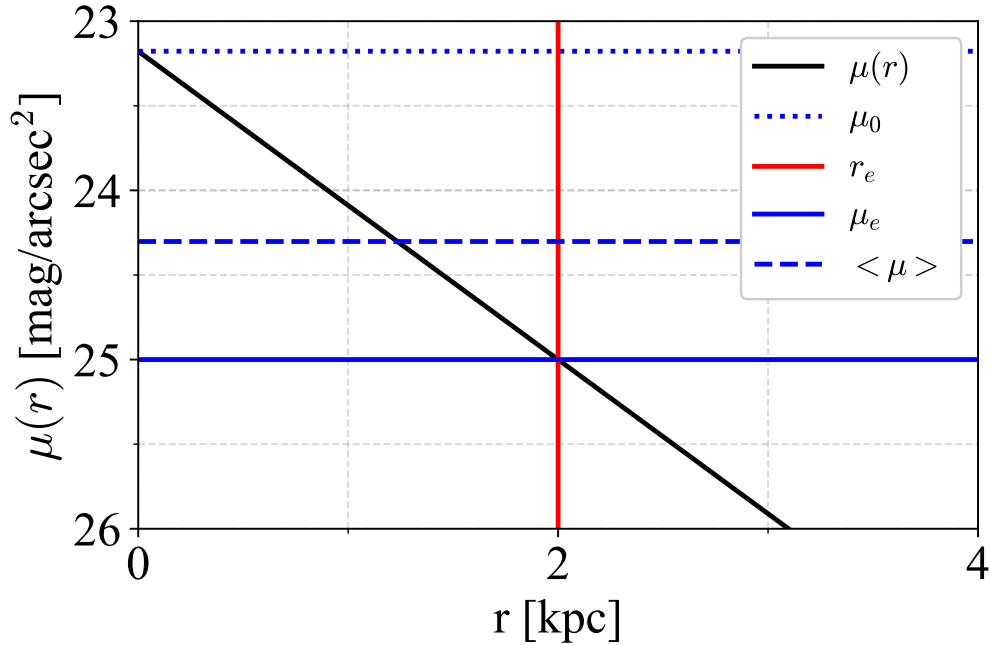


Figure 3.6: Sérsic profile with a set Sérsic index $n = 1$ (i.e. exponential profile) $\mu(r)$ is shown (black line). We compare different surface brightness definitions for the same effective radius $r_{\text{eff}} = 2$ kpc. The central surface brightness, μ_0 (blue dotted line) is always brighter than the mean surface brightness within r_{eff} , $\langle\mu\rangle$ (blue dashed line) which is always brighter than the surface brightness at r_{eff} , μ_e (blue solid line).

3.6.2 Sample Purity Improvement

Due to the low detection thresholds we used for our sources as well as our focus on the faintest objects in our data, most of the 5,552 potential UDGs in our sample are image artifacts, false detections or the results of bad fits. To improve the purity of this sample, we apply another set of selection criteria. Most of these selection criteria are based on those from [van der Burg et al. \(2016\)](#) which were tested on simulated images to improve purity while ensuring completeness, while some other criteria were decided based on visual inspection of a subset of our sample. The criteria are applied to the 5,552 fitted sources which meet our UDG definition and described in Table 3.4. Applying the seven criteria listed in Table 3.4 improves significantly the purity of our sample, and reduces the number of potential UDGs from 5,552 sources to 750 sources.

Criteria	Description
SExtractor FLAGS = 0	Extraction flags from SExtractor software which are non-zero if the aperture photometry is biased by neighbor sources or bad pixels, if the source contains saturated pixels or if the source is too close to the tile edge (Bertin & Arnouts, 1996).
Failed Fit	AutoProf output to confirm that the fit has converged and is therefore successful (Stone et al., 2021).
$\Delta(x, y) < 7 \text{ pix}$	The shift in source center measured by SExtractor compared to that measured by the AutoProf fit is smaller than 7 pix (1.3") (van der Burg et al., 2016).
$A_{Mask} < 6000 \text{ pix}^2$	The total masked area in the mask cutout, A_{mask} is less than 6,000 pix^2 out of the total cutout area of 22,500 pix^2 . This criteria was found based on visual classification of a subset of sources and selects against potential UDGs in crowded regions or near bright extended sources such as galaxies or stellar halos, which results in an inaccurate background measurement.
$r_{\text{eff}} < 7 \text{ kpc}$	The maximum allowed size for UDGs in our sample (van der Burg et al., 2016). We confirm visually on a subset of sources that objects with measured r_{eff} larger than this threshold either over-estimate their true size or are image artifacts.
$\langle \mu \rangle < 26.5 \text{ mag/arcsec}^2$	The dimmest allowed mean surface brightness within the effective radius for UDGs in our sample (van der Burg et al., 2016) since detection below this threshold become unreliable due to the depth of the tiles.
UNIONS Mask = 0	The UNIONS mask used in our cluster selection is also used in improving our UDG sample purity. We keep only UDGs where the UNIONS mask value is zero at the center.

Table 3.4: Selection criteria used to improve the purity of our sample of 5,552 potential [UDGs](#). A description and reasoning for each of the seven criteria used is provided.

The application of our [UDG](#) definition in size on the 183,825 fitted sources using Au-

toProf is shown in Figure 3.7.a. The rejected region is shown in grey and highlights that most fitted sources are measured to be too small to be considered UDGs. We show the surface brightness compared to size measured for all 183,825 fitted sources in Figure 3.7.b. The rejected region shown in grey includes both the definition of UDG used (see equation 3.11) as well as the extra criteria applied to improve the purity of our sample by limiting the size to $r_{\text{eff}} < 7$ kpc and the surface brightness to $\langle \mu \rangle < 26.5$ mag/arcsec² (see Table 3.4 for details). These figures highlight that most of the sources fitted using AutoProf are found to be either too small or too bright to pass the selection, as expected.

The selection based on total masked area in the mask cutout A_{Mask} and that based on the shift in the source center measured by SExtractor compared to the one measured by AutoProf $\Delta(x, y)$ (see Table 3.4 for details) is shown in Figure 3.7.c for the 5,552 sources which passed our UDG definition (see equation 3.11 and section 3.6.1). Once again the rejected region is shown in grey. We note that many of the 5,552 potential UDGs have a relatively large $\Delta(x, y)$, sometimes comparable to or even larger than the cutout size of 150×150 pixels. This shows fits which do not capture correctly the physical properties of the source of interest near the center of the cutout, likely due to not finding the central source, and highlights the importance of this selection criteria. Furthermore, Figure 3.7.c reveals two population of objects along the $\Delta(x, y)$ with a divide at $\Delta(x, y) \approx 7$ pixels, which shows the fits which do find the source at the center and the fits which do not and is therefore a natural cutoff point at which to place our selection criteria $\Delta(x, y) < 7$ pix.

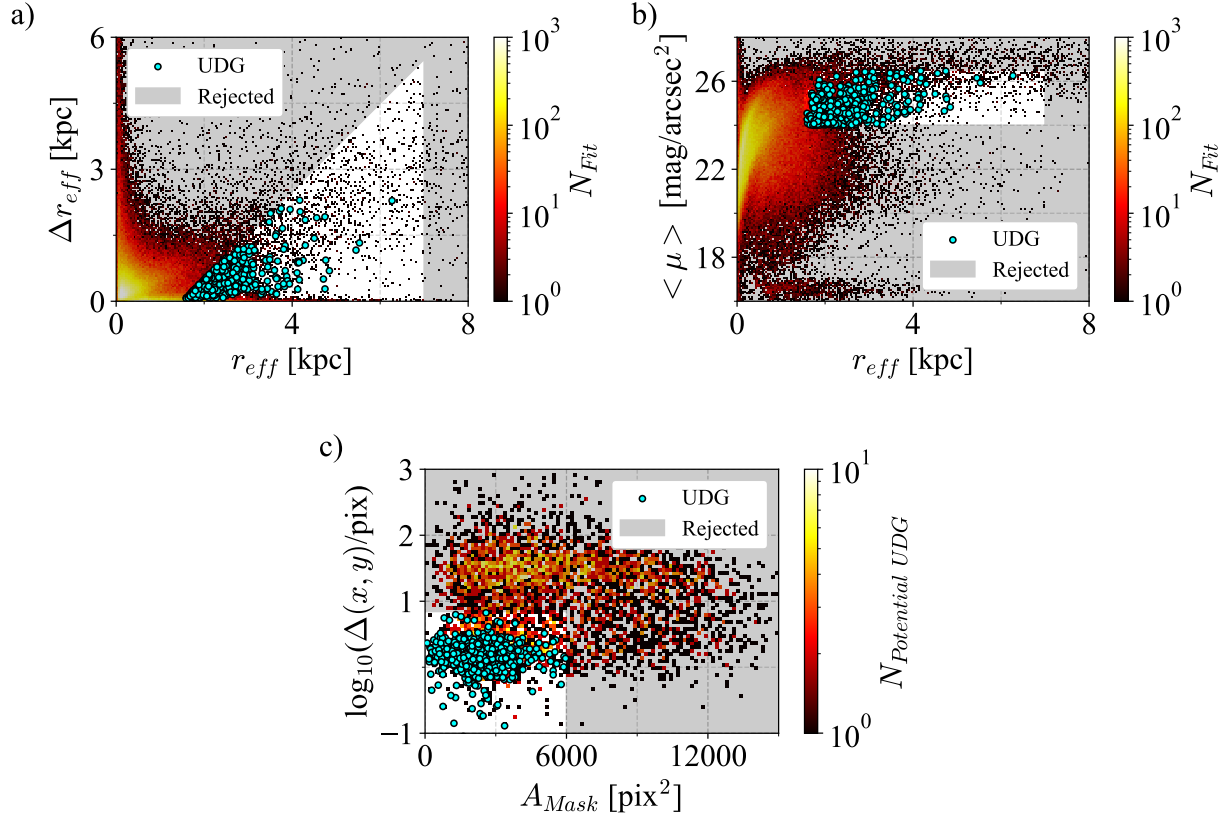


Figure 3.7: a) Effective radius r_{eff} vs 1σ uncertainty in effective radius Δr_{eff} and b) r_{eff} vs surface brightness within the effective radius $\langle \mu \rangle$ are shown for all 183,825 sources fitted with AutoProf. Region which is rejected based on the UDG definition from equation 3.11 are shown (grey shaded region) as well as the final visually classified sample of 545 UDGs (cyan circles). c) Cutout mask area A_{Mask} is shown against the shift in center position between SExtractor and AutoProf $\Delta(x,y)$ for all 5,552 potential UDGs which passed the UDG definition criteria from equation 3.11. The rejected region based on these parameters is shown (grey shaded region) as well as the final sample of UDGs (cyan circles).

3.6.3 Tile Overlap

The tiling strategy used by the [UNIONS](#) collaboration results in the preprocessed $0.5^\circ \times 0.5^\circ$ tiles which we analysed to have an additional 28.5'' of overlap with neighboring tiles as described in section 2.1, which is depicted in Figure 2.1. This overlap leads to duplicate sources in our catalogue of potential [UDGs](#) for sources which are found in the overlapping region between two adjacent tiles. We correct for these duplicates by cross-matching our potential [UDGs](#) catalogue with itself based on source RA and DEC and remove duplicates within 1'' of each other's center. Out of the 750 potential [UDGs](#), 15 duplicates are found and removed, leaving a total of 735 potential [UDGs](#).

3.6.4 Cluster Overlap

We found 10 of the galaxy clusters in our cluster sample to overlap slightly in sky-projection with another cluster (see section 2.7 for details). We depict such overlap in Figure 2.1 where the edge of two galaxy clusters (red solid line), defined as the cluster R_{200} within which we limit our [UDG](#) search, overlap with one another. Sources detected within this region of overlap between clusters are assigned to a primary cluster based on which cluster center the source is closest to. The cluster-centric distances are defined in units of each cluster's R_{200} . The redshift of the primary cluster is used to calculate the physical property of the source. We find 32 potential [UDGs](#) in our sample with a secondary cluster and use a separate flag to keep track of them in our catalogue.

3.6.5 Visual Selection

The final step in creating the catalogue of [UDGs](#) is to visually inspect each of the 735 potential [UDGs](#) in order to remove image artifacts and other false detections from our sample. This ensures a pure sample necessary for the interpretation of our weak lensing signal in chapter 4. Some works do not rely on visual inspections of their final sample such as [van der Burg et al. \(2016\)](#), which while likely decreasing sample purity allows for a more repeatable and scalable analysis. While other recent works have used automated machine learning methods to improve [LSB](#) sample purity ([Thuruthipilly et al., 2024](#)), many [UDG](#) analysis still rely on visual inspection ([Sifón et al., 2018b](#); [Mancera Piña et al., 2019](#)). We decided to visually inspect our sample given its relatively small size. For each potential

UDG, we inspect the tile cutout, the weight map cutout, the associated mask map, and a residual of the tile cutout with the subtracted Sérsic model. Each potential UDG is classified into three categories: Yes, Maybe, No. We either accept (Yes) or reject (Maybe, No) potential UDGs into our final sample. A general overview of the reasons for rejections are listed below, with rejections generally made if one or more of the following applies:

- Near image edges: Due to the flat and therefore imperfect background subtraction of each exposure during the pre-processing of each tile, sharp changes in the surface brightness of the background can be seen, which can be mistaken by our selection as one large galaxy within the cutout. These sources are rejected since they are an artifact of the LSB tiles processing.
- Within chip gaps: Faint and rectangular artifacts can be found in some tiles due to different exposures around and within the chip gaps of MegaCam for one image which is covered by another combined image with imperfect background subtraction. Such rectangular artifact can be mistaken for large, faint sources in our analysis. These sources are rejected since they are an artifact of the LSB tiles processing.
- Proximity to bright source: Some sources are found near the halo of saturated stars or large, bright galaxies. The background can have a strong gradient throughout the cutout which leads both SExtractor and our fitting model to not properly account for it. These sources are rejected since the resulting fitting parameters are deemed unreliable.
- Within stellar spikes or cosmic rays: Some bright and thin lines in our cutouts such as that from spikes around saturated stars or cosmic rays are broken into a set of small sources by the SExtractor segmentation map, resulting in all but one small part of the artifact to be hidden by the cutout mask. These sources are rejected since they clearly are not UDGs and a result of the source detection software.
- Not well described by model: Some of the faint sources have very non-circularly symmetric shapes not well represented by an ellipse, while other have light-profiles which do not follow well a Sérsic profile. This leads to easily identifiable bright and dark features in the residual cutouts of these sources. These sources are rejected since the resulting fitting parameters are deemed unreliable.
- Grouped during segmentation: The SExtractor segmentation sometimes combines multiple smaller and brighter sources together into one. These sources are rejected since they clearly are not UDGs and a result of the source detection software.

The visual selection keeps 545 out of the 735 potential UDGs (26% rejected). Figure 3.8 shows example UDGs in our final sample which passed our visual selection spanning the redshift range of our sample from $z = 0.023$ to $z = 0.100$. We summarize the selection process and properties of the remaining 545 UDGs in section 3.8.

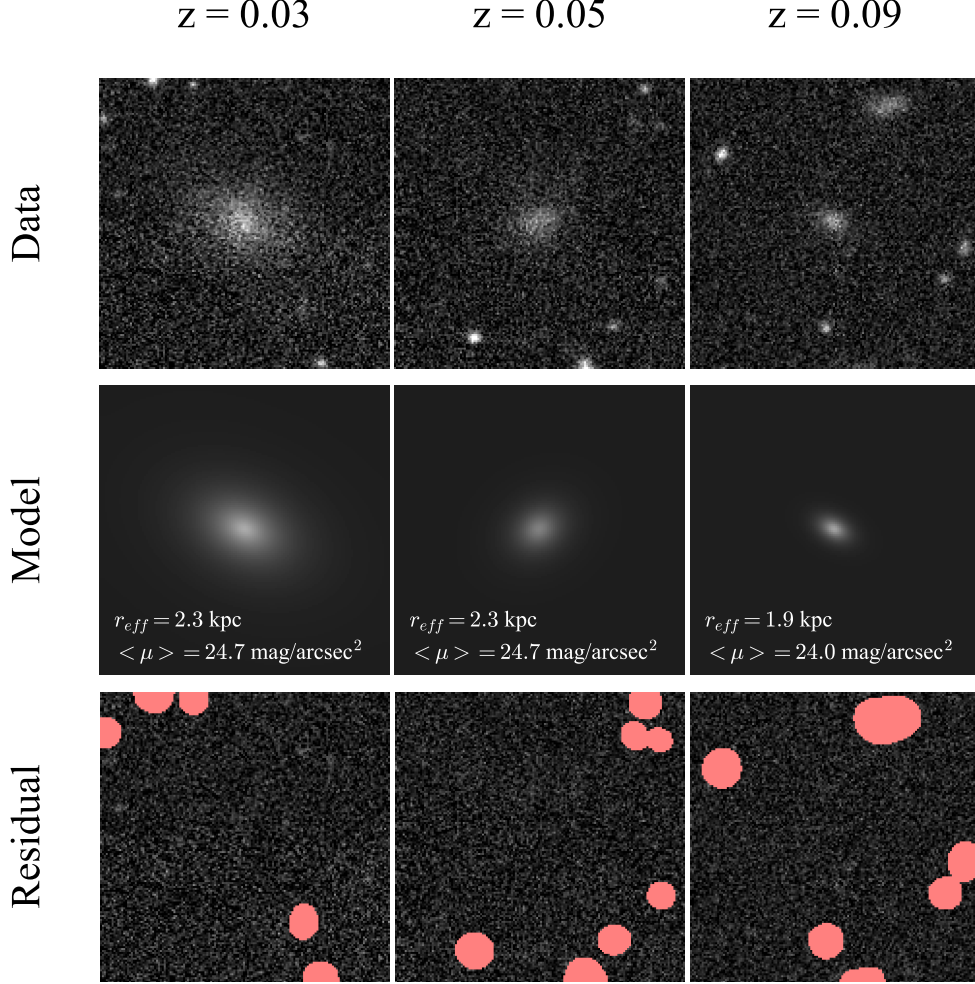


Figure 3.8: Example UDGs in UNIONS CFIS r-band imaging. Top, middle and bottom rows show the data, fitted model and residual respectively. Left, middle and right columns show an example UDG at redshift 0.03, 0.05 and 0.09 respectively. The masks applied during the fits are shown in pink in the residual plots. The cutouts are 150×150 pixels ($27.9'' \times 27.9''$) in size.

3.7 Stellar Mass

Having an estimate for the stellar mass of the [UDGs](#) in our sample is both necessary to properly understand the sources we consider and interpret our halo mass measurements with respect to other [UDG](#) works and galaxies as a whole. Firstly, the total apparent and absolute magnitude, m and $\mathcal{M}$ respectively, of each source can be calculated such that

$$m = \langle \mu \rangle - 2.5 \log_{10} (\pi r_{\text{eff}}^2) - 0.753 \quad (3.13)$$

$$\mathcal{M} = m - 5 (\log_{10} (d_{pc}) - 1) \quad (3.14)$$

where r_{eff} is the effective radius in units of arcseconds and d_{pc} the luminosity distance of the source in units of parsecs. From this, the luminosity L of each source can be calculated such that

$$\log_{10} (L/L_{\odot}) = -0.4(\mathcal{M} - \mathcal{M}_{\odot,r}) \quad (3.15)$$

where $\mathcal{M}_{\odot,r} = 4.64$ is the AB absolute magnitude of the Sun in the [CFHT](#) r-band filter ([Willmer, 2018](#)) and $L_{\odot}$ the luminosity of the Sun. We use the colour-dependent stellar Mass-to-Light ratio from [Bell et al. \(2003\)](#) which is based on the [Two Micron All Sky Survey \(2MASS\)](#) ([Skrutskie et al., 2006](#)) and [SDSS](#) ([York et al., 2000](#)) observations. Since our [UDG](#) sample is found in the r-band, we assume a mean $g - r$ colour of 0.61 for our [UDGs](#) which is the mean $g - r$ colour of a sample of [UDGs](#) found in a set of galaxy clusters by [Mancera Piña et al. \(2019\)](#), and is similar to the $g - r$ color measured for the S18 and [van der Burg et al. \(2016\)](#) [UDG](#) samples within galaxy clusters. This allows us to estimate the stellar mass M_* of each [UDG](#) given the luminosity calculated above such that

$$\log_{10} (M_*/M_{\odot}) = -0.306 + 1.097(g - r) + \log_{10} (L/L_{\odot}) \quad (3.16)$$

3.8 UDG Sample Properties

We show in this section the properties of our final sample of 545 [UDGs](#) we found in [UNIONS](#) r-band imaging. We first detected sources using the [SExtractor](#) software on a set of 213 preprocessed [LSB](#) tiles which contained our sample of 66 galaxy clusters (see section 3.3). After an initial selection based on fixed aperture magnitudes (see section 3.4), we fitted a light profile to the remaining sources using the AutoProf python package (see section 3.5). Using these extracted parameters, we applied our definition of [UDGs](#) (see section 3.6.1) as well as a set of criteria to improve the purity of our sample (see section 3.6.2). We then

remove duplicate sources (see section 3.6.3) and visually classified each of the remaining potential UDGs to improve further the purity of the sample (see section 3.6.5). This leaves us with a final sample of 545 UDGs. A summary of all selection criteria from the initial source detection to the final sample of UDGs is shown in Table 3.5. We show this final sample of 545 UDGs in Figure 3.7 (cyan circles) to visualize where our final sample of UDGs lies in these parameter space compared to the 183,825 fitted sources.

Selection Criteria	Total Discarded	Unique Discarded
within Cluster R_{200}	N/A	4,136,461/5,801,794
$m_{2''} > m_{7''} = 0.9$ mag	N/A	1,481,508/1,665,333
$r_{\text{eff}} - \Delta r_{\text{eff}} \leq 1.5$ kpc	170,377/183,825	7,896/183,825
$\langle \mu \rangle \geq 24.0$ mag/arcsec ²	130,312/183,825	47,961/183,825
SExtractor FLAGS = 0	2,636/5,552	430/5,552
Failed Fit	11/5,552	5/5,552
$\Delta(x, y) < 7$ pix (1.3'')	3,110/5,552	84/5,552
$A_{\text{Mask}} < 6000$ pix ²	2,004/5,552	76/5,552
$r_{\text{eff}} < 7$ kpc	2,751/5,552	17/5,552
$\langle \mu \rangle < 26.5$ mag/arcsec ²	1,465/5,552	83/5,552
UNIONS Mask = 0	1,743/5,552	129/5,552
Duplicates	N/A	15/750
Visual Classification	N/A	545/735

Table 3.5: Overview of the selection criteria applied from initial source detection to the final sample of UDGs. The total discarded column refers to the number of sources rejected by the criteria, while the unique discarded column indicates the number of sources rejected only by that criteria.

We note that while this final sample of 545 UDGs has a high purity with as few artifacts as possible, it remains contaminated by interlopers. By limiting our search to within galaxy clusters and assuming that all sources in the line of sight of the cluster are at the cluster redshift, we introduce a source of contamination which are interlopers. These interlopers are the sources we would find if we were to apply our UDG detection pipeline to field data instead of galaxy clusters and assumed a redshift for all the sources in the line of sight. These interlopers are sources in our final UDG sample which pass all our selection criteria

but are not guaranteed to be at the clusters redshift.

Various measured properties of the final [UDG](#) sample are shown in Figure 3.9. By design, the [UDG](#) sample’s r_{eff} ranges from 1.5 kpc to 7 kpc, with a median r_{eff} of 2.2 kpc. We note that the r_{eff} distribution in Figure 3.9.a peaks at about 2 kpc instead of at the lower end of our minimum size criteria of 1.5 kpc, unlike other cluster [UDG](#) studies ([Mancera Piña et al., 2019](#); [Sifón et al., 2018b](#)). This difference is caused by our modified minimum size definition (see equation 3.11) which requires our [UDGs](#) to be 1σ larger than 1.5 kpc. While this selects against most sources smaller than 2 kpc, it gives us more confidence that the selected [UDGs](#) are large and extended (see Figure 3.7.a). The sample $\langle\mu\rangle$ ranges from 24 mag/arcsec² to 26.5 mag/arcsec² with a median $\langle\mu\rangle$ of 24.6 mag/arcsec². The median axis ratio of the sample is $q = 0.73$. We estimate a median stellar mass of $3 \times 10^8 M_{\odot}$ with a scatter of 0.2 dex, which is comparable to the [UDG](#) samples of S18 with median stellar mass of $2 \times 10^8 M_{\odot}$ and [Mancera Piña et al. \(2019\)](#) with median stellar mass $1.3 \times 10^8 M_{\odot}$.

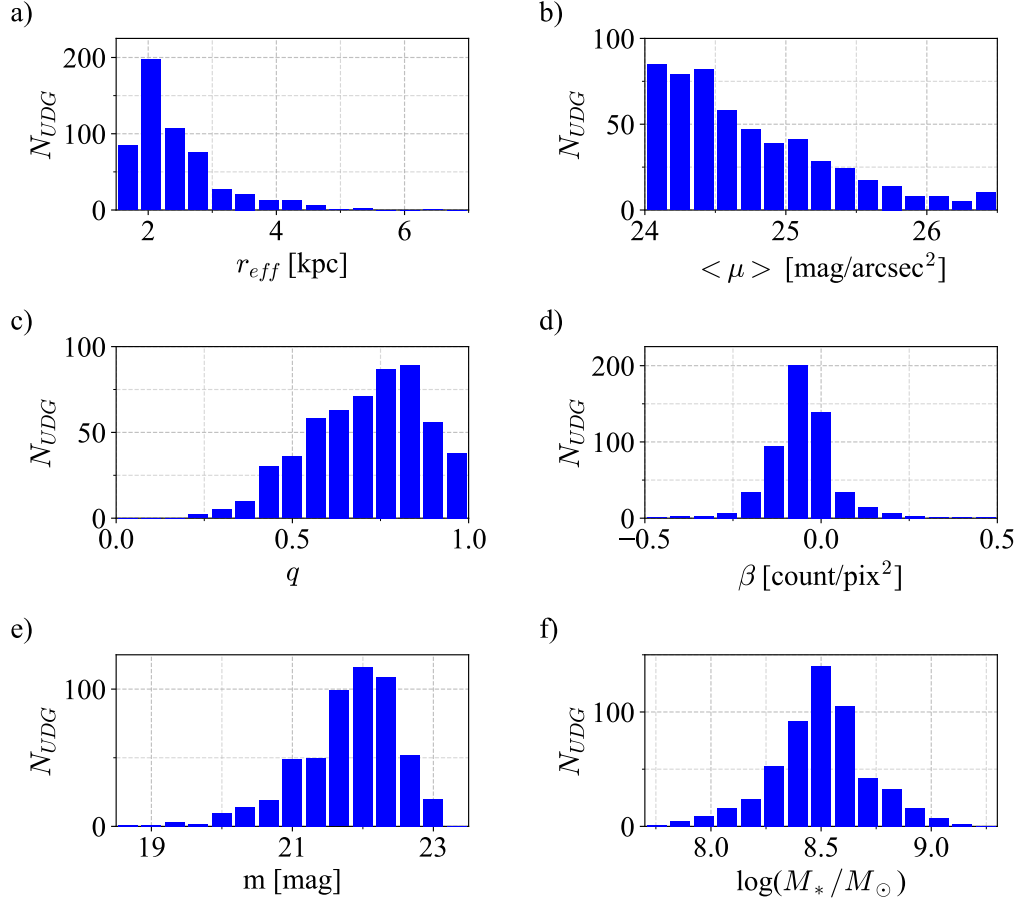


Figure 3.9: Properties of the final sample of 545 UDGs found in UNIONS. We show the histogram of a) effective radius r_{eff} , b) mean surface brightness within the effective radius $\langle \mu \rangle$, c) axis ratio q defined as the ratio of the semi-minor axis b to the semi-major axis a , d) flat background fitting parameter β , e) apparent magnitude m , and f) estimated stellar mass M_* assuming a color $g - r = 0.61$.

3.9 Interlopers

The assumption that every source within the line of sight of a cluster belongs to that cluster is incorrect. Only a subset of the sources is guaranteed to belong to the cluster while some sources will either be in front of or behind the cluster, which we refer to as interlopers.

While we cannot distinguish in our sample of 545 **UDGs** which sources are interlopers and which are true **UDGs**, we can estimate the interloper contamination fraction by analysing field data. For clarity, we will refer to the sample of 545 **UDGs** found as our contaminated **UDG** sample.

We select a new set of 286 “field” tiles which corresponds to 76.1 deg^2 on which we run our **UDG** search. These tiles are selected at random within the **UNIONS** r-band survey footprint, excluding tiles which overlap with our cluster sample, tiles for which no **UNIONS** masks are available, or tiles for which the dust emission measured at the center of the tile from the τ_{353} and **WISE** $12 \mu m$ full-sky maps is above our threshold (see section 2.5). Since **UDGs** are defined based on physical properties, we assume all sources to be at the same redshift and rerun our analysis in steps of $\Delta z = 0.001$ with assumed redshifts ranging from $z = 0.018$, the lowest cluster redshift in our sample, up to the maximum redshift we consider for our cluster selection of $z = 0.100$. This corresponds to a total of 83 redshifts considered.

A total of 7,635,871 sources are detected using **SExtractor**, of which 755,845 pass our initial source selection based on aperture magnitude and are fitted using AutoProf. We apply both our redshift-independent selection criteria (i.e. **SExtractor** FLAGS, Failed Fit, $\Delta(x, y) < 7 \text{ pix}$ ($1.3''$), $A_{Mask} < 6,000 \text{ pix}^2$, **UNIONS** Mask = 0) and redshift-dependent selection criteria (i.e. $r_{\text{eff}} - \Delta r_{\text{eff}} \leq 1.5 \text{ kpc}$, $\langle \mu \rangle \geq 24 \text{ mag/arcsec}^2$, $r_{\text{eff}} < 7 \text{ kpc}$, $\langle \mu \rangle < 26.5 \text{ mag/arcsec}^2$) for each of the 83 redshifts we consider. We do not check for duplicate sources in this sample since we expect few to no tiles being adjacent. A total of 8,225 sources pass all these criteria in at least one assumed redshift. We refer to these sources as our sample of potential interlopers since they have not yet been visually checked.

For each cluster redshift, we estimate the number density of potential interlopers per sky area, from which we calculate the number of potential interlopers per cluster. Assuming that the visual selection of **UDGs** is redshift-independent, we now have the distribution of interlopers as a function of redshift in our contaminated **UDG** sample. In order to create a sample of unique interlopers which correctly represent the interlopers in our contaminated **UDG** sample, we assign a redshift to a subset of 3,000 potential interlopers out of the 8,225 potential interlopers found. This redshift is assigned by drawing from the estimated interloper redshift distribution. We apply our visual selection to this sample of 3,000 potential interlopers, of which 1,952 (65.1%) are accepted and are part of our final interloper sample. We note that the precision of our interloper correction could be improved by using a larger sample of field interlopers. We analysed 76.1 deg^2 of field data, which is a very small fraction of the $\sim 2,100 \text{ deg}^2$ of **UNIONS** r-band data we considered in our analysis

(see section 2.1). However, the current limitation of our method is the time-consuming visual selection and therefore we do not attempt to increase the size of our sample of 1,952 field interlopers. Furthermore, increasing the interloper sample size would offer little to no improvement on our final weak lensing measurements (see 4.4.1 for further discussion).

Figure 3.10.a shows the number density of sources in the field which pass our UDG selection as a function of redshift, calculated from our interloper sample. From this, we estimate the number of interlopers in each cluster we analysed based on the cluster redshift and projected area. A total of 255.2 interlopers are estimated to be in our sample of 545 contaminated UDGs, which corresponds to a 46.8% interloper contamination fraction. Figure 3.10.b shows both the total number of interlopers (red) and of true UDGs (green) in our contaminated UDG sample (blue) as a function of redshift. The UDG density from our contaminated UDG sample as a function of cluster-centric distance R_{200} is shown in Figure 3.10.c. This figure is made using only sources within the 56 clusters which have no overlap with other clusters for simplicity. The estimated interloper number density, independent of R_{200} , is also shown in red. From this figure, it is clear that an overdensity of sources is associated with the clusters, which confirms the presence of true UDGs with correctly assumed redshifts in our final sample. Furthermore, the density of our contaminated UDG sample decreases for increasing R_{200} and approaches the field interloper density at larger cluster-centric distance as expected. We note that while we do not know the true redshift of the field interlopers, a subset of them may be in the redshift range where they would classify as field UDGs which do not belong to a galaxy cluster. We make no attempts at estimating the fraction of field UDGs in our interloper sample.

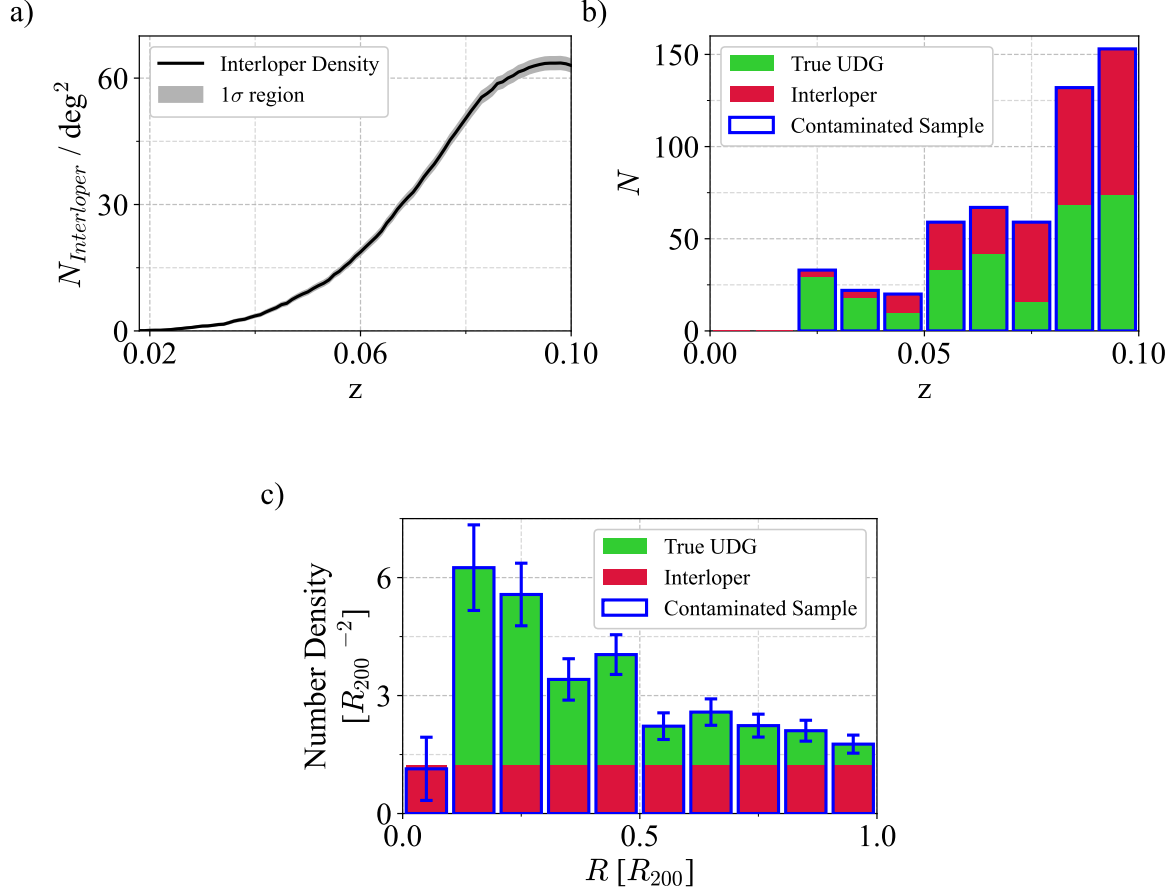


Figure 3.10: a) Number density of field interlopers which pass our [UDG](#) selection pipeline estimated from 76.1 deg^2 of field r-band data. The 1σ region is estimated assuming an uncertainty in the number of interlopers of $\sqrt{N_{\text{Interloper}}}$. b) Number of contaminated [UDGs](#) as a function of redshift. c) Number density of contaminated [UDGs](#) as a function of cluster-centric distance R_{200} shown from cluster center ($R = 0 R_{200}$) to cluster R_{200} ($R = 1 R_{200}$). The contaminated [UDGs](#) (blue outline) is composed of interlopers (red) as well as true [UDG](#) (green). Blue error bars in c) show the 1σ uncertainty estimated assuming an uncertainty in the number of contaminated [UDG](#) in each bin of $\sqrt{N}$.

Chapter 4

Weak Gravitational Lensing

In this chapter, we describe the weak gravitational lensing measurement made on our set of [UDG](#) lens catalogues using the [UNIONS](#) source catalogues. We proceed to describe the projected dark matter halo profile used to model these gravitational lensing measurements and the results of the fits.

4.1 Source Catalogue and Redshift Distribution

Careful shape measurements and calibration on the [UNIONS](#) survey's r-band imaging have been made ([Guinot et al., 2022](#)). In this work, we use the lensfit catalogue which contains 109,025,910 shape measurements over the [UNIONS](#) survey footprint as described in section 2.1. Each source in the catalogue has a position (RA, DEC), an ellipticity measurement (e_1, e_2), and an assigned weight w_s . While the lensfit shape catalogue does not have redshift estimates for the sources, a subset sources have a spectroscopic measurement which allows for accurate redshift estimate. A total of 65,896 sources have spectroscopic redshifts available, which is used to recover the average redshift distribution of the entire source sample, $n(z)$ ([Li et al., 2024](#)). These calibration measurements can be incorporated into our excess surface density measurement such that

$$\Delta\Sigma = \frac{\sum_{ls} w_s \langle \Sigma_{crit}^{-1}(z_l) \rangle e_t}{\sum_{ls} w_s \langle \Sigma_{crit}^{-1}(z_l) \rangle^2} \quad (4.1)$$

$$\langle \Sigma_{crit}^{-1}(z_l) \rangle = \int \Sigma_{crit}(z_l, z_s) n(z_s) dz_s \quad (4.2)$$

This results in only needing to know the redshifts for our lens catalogue. Since we defined our contaminated [UDG](#) lens sample by assuming that these galaxies were at the same distance as the clusters within which we found them, we can use this same distance estimate in our weak lensing analysis.

4.2 $\Delta\Sigma$ Measurements

The excess surface density can be measured using our source catalogue, calibration catalogue and lens catalogue. The uncertainty in our measurements is estimated using 400 fields for jackknife resampling ([Quenouille, 1949](#)). All excess surface density computations from a source and lens catalogue as well as the jackknife resampling are handled using the `dsigma` python package ([Lange & Huang, 2022](#)).

4.2.1 Contaminated UDG Sample Signal

We first measure the excess surface density $\Delta\Sigma$ around our contaminated sample of 545 [UDGs](#). We note that this sample contains both true [UDGs](#) which are cluster members, and interlopers for which we cannot confirm their redshift. Our contaminated [UDG](#) sample is measured to be composed of 53% true [UDGs](#) and 47% interlopers using field data. The mean redshift of our sample is $\langle z \rangle = 0.073$ and mean projected cluster-centric distance $\langle d_c \rangle = 0.69\text{Mpc}$. The stacked excess surface density is measured ranging from a distance from the lens, r_p , of 0.02 Mpc up to 3 Mpc over 11 bins in logarithmic scale. The resulting excess surface density $\Delta\Sigma_{UDG+I+C}$ is shown in Figure 4.1.a, where the subscript I and C refer to the Interloper and Cluster respectively.

We note that up to a lens distance of $r_p \approx 300$ kpc, the measurement is consistent with zero which indicates no detected mass overdensity. A signal is detected at distances larger than $r_p \approx 300$ kpc which is the excess surface density caused by the offset host galaxy clusters. The exact details of this host cluster halo contribution depend on the average halo mass, sizes and mass distribution of the galaxy clusters as well as the radial distribution of our contaminated [UDG](#) lenses around the cluster centers. While modeling this signal contribution can be difficult and require accurate measurements of the cluster properties, we can more easily subtract it with a set of random lenses.

4.2.2 Azimuthal Randoms Signal

The host galaxy clusters’ contribution to the excess surface density measurement for our contaminated [UDG](#) sample can be directly measured and subtracted using “azimuthal randoms”. For each lens in our contaminated sample, we generate 70 azimuthal angles uniformly in the range $0 < \theta \leq 2\pi$, which we then place at the same projected cluster-centric distance d_c of the lens’ host cluster with an offset azimuthal angle θ from the lens. We assign the same redshift for these random lenses as their corresponding contaminated sample lens. This results in a sample of 38,150 azimuthal random lenses with the same radial distribution about the cluster centers and redshift distribution as the contaminated [UDG](#) sample. These random lenses allow us to recover the effect of clusters on the excess surface density measured for the contaminated [UDG](#) sample.

The excess surface density measurement is made on this sample of azimuthal random lenses with the same binning described in section 4.2.1. The resulting excess surface density $\Delta\Sigma_C$ is shown in Figure 4.1.b. The host cluster contribution can be clearly seen at larger projected radius r_p . We selected 70 azimuthal random lens per contaminated [UDG](#) lens as it was found that adding more lenses did not improve on the measurement error for the excess surface density. We note that this method relies on knowing the cluster center’s position which can be difficult to measure or define accurately. However, our cluster sample is mostly composed of [MCXC](#) clusters which are based on X-ray measurements which we expect to more reliably trace the true center of the cluster’s mass distribution ([Rykoff et al., 2008, 2014](#)) (see sections 2.2 and 2.7 for details).

4.2.3 Interloper Sample Signal

The contaminated [UDG](#) sample measurement is composed of both true [UDGs](#) and interlopers. We carefully generated a sample of interlopers representative of the interlopers in our contaminated [UDG](#) sample (see section 3.9 for details) to correct for their effect on our excess surface density measurement. We measure the excess surface density of our interloper sample with the same binning described in section 4.2.1. The resulting excess surface density $\Delta\Sigma_{I+Bias}$ is shown in Figure 4.1.c. We note that this measurement might be slightly biased due to the source and lens selection, which we correct for as described in the next section.

The measured excess surface density is consistent with zero over the entire radial distance range $0.02 \text{ Mpc} < r \leq 3 \text{ Mpc}$. Since the interlopers are measured in the field, we do

not see a signal from offset galaxy clusters, as expected. We note that the redshift assigned to the interloper sample is arbitrary to match the interlopers found in our contaminated UDG sample, and likely not the true redshift of these sources. Since the excess surface density relies on knowing the redshift of the lens (see equation 4.1), the measured excess surface density for interlopers is not the actual excess surface density of these objects, but rather the effect on the excess surface density of our contaminated UDG sample.

4.2.4 Interloper Randoms Sample Signal

To correct for any bias in our interloper sample measurement, we generate a set of random lenses. These random lenses are distributed uniformly over the 286 tiles analysed in making the interloper sample. For each tile, we generate 1,000 random lenses. An arbitrary redshift is assigned to each random lens by drawing from the interloper sample’s redshift distribution. This results in a sample of 286,000 random lenses with the same redshift distribution as the interloper sample.

The excess surface density measurement is made on this sample of random lenses with the same binning described in section 4.2.1. The resulting excess surface density $\Delta\Sigma_{Bias}$ is shown in Figure 4.1.d. The measured excess surface density is consistent with zero over the entire radial distance range $0.02 \text{ Mpc} < r \leq 3 \text{ Mpc}$ and show no bias in our measurement. We generated 1,000 random lens per tile since we found that the measurement error for the excess surface density did not decrease significantly for larger random lens samples.

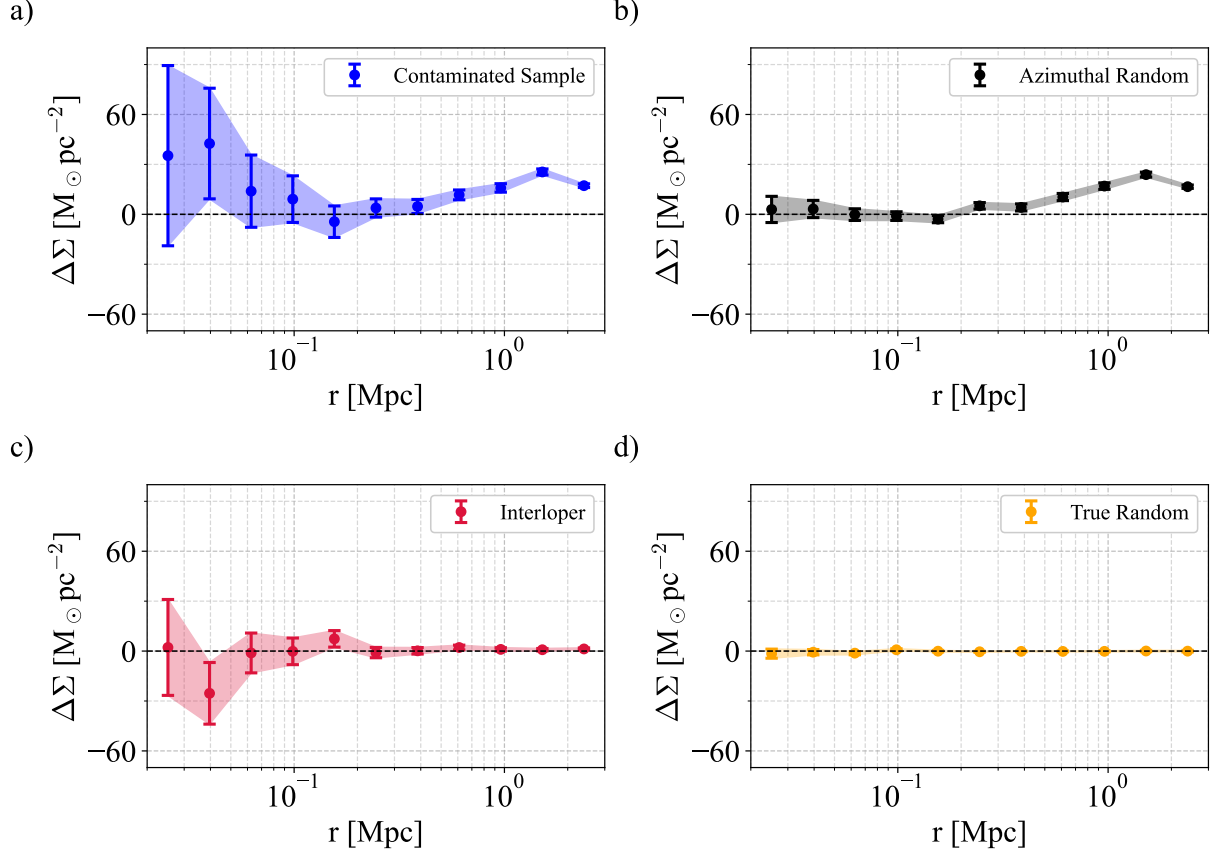


Figure 4.1: We show the excess surface density $\Delta\Sigma$ measurements as a function of radial distance from the lens r for a) the sample of 545 contaminated **UDGs** lenses found within 66 galaxy clusters, b) the associated 38,150 azimuthal random lenses which capture the effect of the galaxy clusters at larger r , c) the sample of 1,952 field interlopers lenses, and d) the associated 286,000 random lenses for the field interlopers.

4.3 Boost Factor Correction

An important correction to our excess surface density measurement arises from the fact the both our contaminated **UDG** sample and azimuthal random sample are in galaxy clusters. Since many of the galaxies in the galaxy clusters are part of our source samples, an excess number of sources is measured in the radial bins closer to our lenses. Since in this case

both the lenses and sources are in the same galaxy clusters, they have the same redshift and the gravitational field of the lenses cannot shear the sources. Therefore, an excess of sources which do not contribute to the shear measurement are diluting the true shear measurement from our lenses. This effect can be corrected with a boost factor correction $\mathcal{B}$ (Mandelbaum et al., 2005) such that

$$\Delta\Sigma_{Correct} = \mathcal{B}\Delta\Sigma_{Measure} \quad (4.3)$$

We count the total number of lens-source pairs, n_p , for each of the 11 radial bins in our excess surface density measurements for both our contaminated UDG sample and azimuthal random sample. The lens-source pair density for the i^{th} radial bin, η_i can then be calculated as follow:

$$\eta_i = \frac{n_{p,i}}{\pi (r_{i+1}^2 - r_i^2)} \quad (4.4)$$

where r_i is the i^{th} radial bin's outer edge and $n_{p,i}$ the number of lens-source pairs in the i^{th} bin. With a total of 11 radial bins, we define the boost factor for each radial bin $\mathcal{B}_i$ as the ratio of the lens-source pair density of the bin to that of the last bin, such that

$$\mathcal{B}_i = \eta_i / \eta_{11} \quad (4.5)$$

This effectively will boost the excess surface density measurement by comparing the pair density of a given bin to that of the “field” value assumed to be reached in the last radial bin. We measure this boost factor for both the contaminated sample, $\mathcal{B}_{UDG+I+C}$, and the azimuthal random sample $\mathcal{B}_C$, shown in Figure 4.2. The 1σ error shown are calculated assuming an uncertainty in the number of lens-source pairs in each bins such that $\sigma_{n_p} = \sqrt{n_p}$. This correction boosts the excess surface density of our contaminated UDG sample and azimuthal random sample by at most 15% and 4.3% respectively.

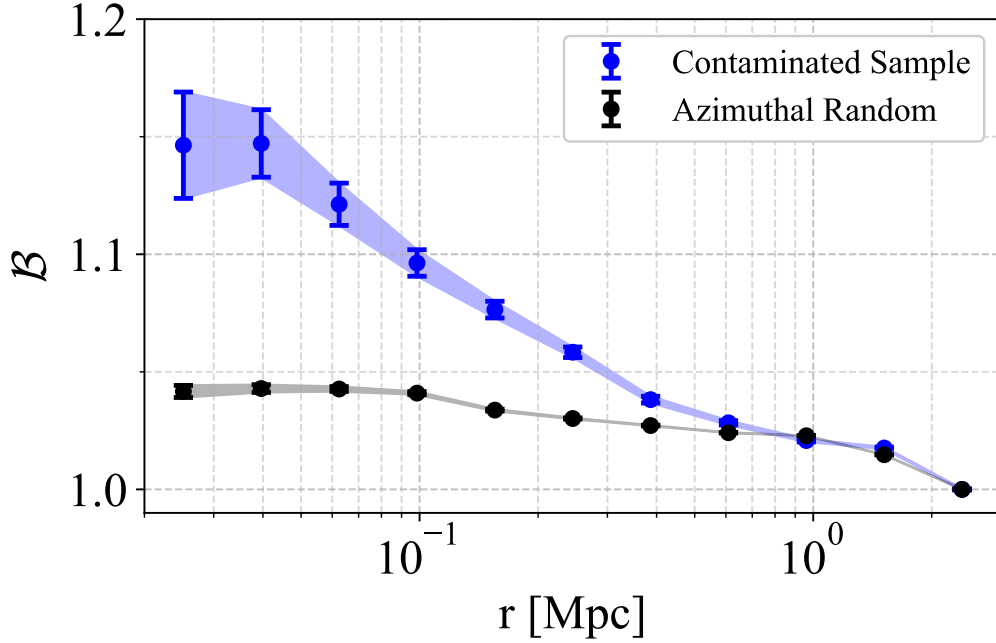


Figure 4.2: Boost factor correction $\mathcal{B}$ as a function of projected lens distance r for the contaminated [UDG](#) lens sample (blue) and associated azimuthal random lens sample (black). Error bars and shaded regions show the 1σ uncertainty in the measurements.

4.4 Combining Measurements

All the excess surface density measurements and associated boost factor measurements can be combined together to recover the signal from only the true [UDGs](#) in our sample, which will allow us to directly measure the average halo mass of [UDGs](#). Furthermore, we compare and combine our excess surface density measurements with the measurement of S18 to improve the constraint on the halo mass of [UDGs](#) as described below.

We note that while we combine our excess surface density measurements to recover the signal from only the true [UDGs](#) in our sample as described in section 4.4.1, a similar approach could be taken in terms on the measured tangential shear γ_t which is directly proportional to the excess surface density $\Delta\Sigma$ as described in equation 1.3.

4.4.1 True UDG Signal

We first apply the boost factor correction to both the contaminated UDG sample and azimuthal random sample, and then subtract the azimuthal random sample measurement from the contaminated UDG sample measurement. This corrects for the dilution of the signal caused by an overdensity of sources within the clusters as well as removes the excess surface density contribution at larger projected radial distances from the host clusters.

$$\Delta\Sigma_{UDG+I} = \mathcal{B}_{UDG+I+C} \Delta\Sigma_{UDG+I+C} - \mathcal{B}_C \Delta\Sigma_C \quad (4.6)$$

We then subtract any potential bias in our field interloper measurements measured using field randoms.

$$\Delta\Sigma_I = \Delta\Sigma_{I+Bias} - \Delta\Sigma_{Bias} \quad (4.7)$$

Since we measured the interloper fraction in our contaminated UDG sample, $f_I = 0.468$, and therefore know how much they are contributing to the signal, we can subtract the interloper contribution to the excess surface density of the contaminated UDG sample such that

$$\Delta\Sigma_{UDG} = \frac{\Delta\Sigma_{UDG+I} - f_I \Delta\Sigma_I}{1 - f_I} \quad (4.8)$$

We can similarly propagate the uncertainty in these measurements such that

$$\sigma_A = \mathcal{B}_{UDG+I+C} \Delta\Sigma_{UDG+I+C} \sqrt{\left(\frac{\sigma_{\Delta\Sigma_{UDG+I+C}}}{\Delta\Sigma_{UDG+I+C}}\right)^2 + \left(\frac{\sigma_{\mathcal{B}_{UDG+I+C}}}{\mathcal{B}_{UDG+I+C}}\right)^2} \quad (4.9)$$

$$\sigma_B = \mathcal{B}_C \Delta\Sigma_C \sqrt{\left(\frac{\sigma_{\Delta\Sigma_C}}{\Delta\Sigma_C}\right)^2 + \left(\frac{\sigma_{\mathcal{B}_C}}{\mathcal{B}_C}\right)^2} \quad (4.10)$$

$$\sigma_{\Delta\Sigma_{UDG+I}} = \sqrt{\sigma_A^2 + \sigma_B^2} \quad (4.11)$$

$$\sigma_{\Delta\Sigma_I} = \sqrt{\sigma_{\Delta\Sigma_{I+Bias}}^2 + \sigma_{\Delta\Sigma_{Bias}}^2} \quad (4.12)$$

$$\sigma_{\Delta\Sigma_{UDG}} = \frac{\sqrt{\sigma_{\Delta\Sigma_{UDG+I}}^2 + (f_I\sigma_{\Delta\Sigma_I})^2}}{1 - f_I} \quad (4.13)$$

We note that the final uncertainty in the excess surface density of **UDGs**, $\sigma_{\Delta\Sigma_{UDG}}$, is dominated by the $\sigma_{\Delta\Sigma_{UDG+I}}$ term and increased significantly by a factor of $\frac{1}{1-f_I} = 1.88$. The interloper term $\sigma_{\Delta\Sigma_I}$ increases the uncertainty by only 2%. This fact contributed to the decision of limiting the size of our field interloper sample to the selected 1,952 sources, since improvements in the uncertainty of this interloper measurement would not result in a significant improvement of the uncertainty in the final **UDG** signal. This signal could be further improved by either reducing the interloper fraction f_I of our contaminated **UDG** sample or increasing the size of our contaminated **UDG** sample. This combined measurement for the signal from the true **UDGs** only is shown in Figure 4.3.a.

4.4.2 Results from Sifón et al. (2018)

A previous direct measurement of the halo mass of **UDGs** with weak gravitational lensing was made by Sifón et al. (2018b) (referred to as S18). We discuss the relevant differences between the S18 work and our work in this section, which is relevant to combine both our and the S18 measurement (see section 4.4.3) and improve the constraint on **UDG** halo mass.

S18 used the **MENaCS** survey (Sand et al., 2012) which uses the MegaCam instrument on **CFHT** for r-band imaging, the same instrument as the r-band imaging of **UNIONS**. S18 used a sample of 18 galaxy clusters with redshifts up to $z \leq 0.09$. They found a contaminated **UDG** sample of 784 galaxies, with an estimated interloper fraction of 36.5%, which is slightly larger than our contaminated **UDG** sample of 545 galaxies with an interloper fraction of 46.8%. The combined r-band imaging used in S18 for each cluster has a total exposure time of ~ 40 minutes (van der Burg et al., 2016), compared to the **UNIONS** r-band imaging’s typical total exposure of ~ 4 minutes. This results in a more complete **UDG** sample found by S18 compared to our work. This combined with the different preprocessing of the images as well as slightly different **UDG** selection means that it is difficult to compare the interlopers in S18 to the interlopers in our sample. We therefore treat the “S18 interlopers” as a different population of objects than the interlopers in our work. We find no overlap between the 66 galaxy clusters in our cluster sample and the 18 galaxy clusters in the S18 cluster sample. This means that our excess surface density measurements of **UDG** is completely independent from the measurement of S18.

One key difference between the S18 and our results is the interloper correction which we apply to recover the signal only from our true **UDGs**. Due to the nature of the **MENeaCS** survey, which focuses on nearby galaxy clusters, little imaging of the field was available under the same imaging conditions as the clusters analysed, therefore S18 does not measure a separate excess surface density on field data to correct for interlopers as we described in our work. The excess surface density measurement of the contaminated **UDG** sample from S18, $\Delta\Sigma_S$, has been extracted from Figure 2 of S18 using an online plot digitizing tool¹. This measurement is shown in Figure 4.3.c.

Two other differences which we will account for is the smaller projected radius r_p distance used and the fact that the galaxy cluster contribution to the signal is not subtracted in S18. Again, since the **MENeaCS** survey focuses on clusters only, the S18 measurement goes up to $r_p < 1$ Mpc in 9 logarithmic bins. This is smaller than the maximum radial distance of 3 Mpc we selected in this work to clearly see the excess surface density of the galaxy clusters at larger radial distances. We also generated a sample of azimuthal randoms to subtract the signal directly from our excess surface density measurements (see section 4.2.2). Instead, S18 includes this signal into their fitted model to the excess surface density. Similarly to our work, the S18 cluster signal only contribute significantly at radial distances larger than $r_p \approx 400$ Mpc.

4.4.3 Combined Signal

Since both our and the S18 **UDG** measurements are made on two independent cluster samples, we combine these two measurements to get the tightest constraint possible on the average halo mass of **UDGs**. To do so, we remake our excess surface density measurements with the same radial binning as S18. We only combine the first 7 of 9 bins, up to $r_p \approx 400$ Mpc to avoid including the cluster signal in the S18 measurement. We chose to combine our interloper corrected **UDG** measurement, $\Delta\Sigma_{UDG}$, with the contaminated **UDG** sample measurement from S18, $\Delta\Sigma_S$, which contains both true **UDGs** and “S18 interlopers”. For our **UDG** measurement, we estimate a true **UDG** fraction $f_{UDG} = 1 - f_I = 0.532$, which corresponds to $N_{UDG} = 289.8$ true **UDGs** in our contaminated **UDG** sample of 545 sources. The S18 sample contains $N_S = 784$ contaminated sources which contribute to the excess surface density measurement, of which $N_{UDG,S} = 498$ are true **UDGs** and $N_{I,S} = 286$ are S18 interlopers. A weighted average of the samples is made based on the inverse variance

¹<https://plotdigitizer.com/>

in the excess surface density measurements such that

$$\Delta\Sigma_{UDG+S} = \frac{\Delta\Sigma_{UDG}}{1 + (\sigma_{\Delta\Sigma_{UDG}}/\sigma_{\Delta\Sigma_S})^2} + \frac{\Delta\Sigma_S}{1 + (\sigma_{\Delta\Sigma_S}/\sigma_{\Delta\Sigma_{UDG}})^2} \quad (4.14)$$

with associated measurement uncertainty

$$\sigma_{\Delta\Sigma_{UDG+S}} = \sqrt{\left(\frac{\sigma_{\Delta\Sigma_{UDG}}}{1 + (\sigma_{\Delta\Sigma_{UDG}}/\sigma_{\Delta\Sigma_S})^2}\right)^2 + \left(\frac{\sigma_{\Delta\Sigma_S}}{1 + (\sigma_{\Delta\Sigma_S}/\sigma_{\Delta\Sigma_{UDG}})^2}\right)^2} \quad (4.15)$$

where $\sigma_{\Delta\Sigma_S}$ is the uncertainty in the S18 measurement. The combined excess surface density is shown in Figure 4.3.e. This combined measurement is effectively composed of our and S18 true UDGs, $N_{UDG} + N_{UDG,S} = 787.8$ and S18 interlopers, $N_{I,S} = 286$.

4.5 Excess Surface Density Model

In order to extract the total halo mass of UDGs, we fit a model similar to that in S18 to the excess surface density measurements described above. In this section, the details of the model used, as well as the fitting procedure is described.

4.5.1 Projected NFW Profile

We assume the dark matter halo of UDGs can be described by a NFW dark matter profile (Navarro et al., 1997), projected along the line of sight into an excess surface density as follow (Wright & Brainerd, 2000):

$$\Delta\Sigma_{NFW} = \bar{\Sigma}_{NFW}(x) - \Sigma_{NFW}(x) \quad \text{where} \quad x = \frac{r_p}{r_s} \quad (4.16)$$

$$\bar{\Sigma}_{NFW}(x) = \begin{cases} \frac{4r_s\rho_0}{x^2} \left[\frac{2}{\sqrt{1-x^2}} \operatorname{arctanh} \sqrt{\frac{1-x}{1+x}} + \ln\left(\frac{x}{2}\right) \right] & \text{if } x < 1 \\ 4r_s\rho_0 \left[1 + \ln\left(\frac{1}{2}\right) \right] & \text{if } x = 1 \\ \frac{4r_s\rho_0}{x^2} \left[\frac{2}{\sqrt{x^2-1}} \operatorname{arctan} \sqrt{\frac{x-1}{1+x}} + \ln\left(\frac{x}{2}\right) \right] & \text{if } x > 1 \end{cases} \quad (4.17)$$

$$\Sigma_{NFW}(x) = \begin{cases} \frac{2r_s\rho_0}{x^2-1} \left(1 - \frac{2}{\sqrt{1-x^2}} \operatorname{arctanh} \sqrt{\frac{1-x}{1+x}}\right) & \text{if } x < 1 \\ \frac{2r_s\rho_0}{3} & \text{if } x = 1 \\ \frac{2r_s\rho_0}{x^2-1} \left(1 - \frac{2}{\sqrt{x^2-1}} \operatorname{arctan} \sqrt{\frac{x-1}{1+x}}\right) & \text{if } x > 1 \end{cases} \quad (4.18)$$

where r_p is the projected radial distance from the lens, ρ_0 depends on the halo concentration c_{200} as described in equation 2.5 and the critical density of the universe at a given redshift as described in equation 2.3, and

$$r_s = \left(\frac{3m_{200}}{800\pi\rho_{crit}(z)} \right)^{1/3} \frac{1}{c_{200}} \quad (4.19)$$

where m_{200} is the dark matter halo mass of UDGs. This dark matter halo mass m_{200} is defined based on the critical density of the universe $\rho_{crit}(z)$ (see section 2.6 for details). We note that our model ignores the contribution of baryonic mass to the total halo mass since the median stellar mass was measured for both our and the S18 contaminated UDG samples to be $M_* = 10^{8.5}M_\odot$ and $M_* = 10^{8.3}M_\odot$ respectively, which is much lower than the halo masses we can constrain with our excess surface density measurements. Using the mean redshift $\langle z \rangle$ of our samples to calculate the critical density, we can fully describe the excess surface density measurements of our true UDG sample $\Delta\Sigma_{UDG}$ with the total halo mass m_{200} and the NFW profile concentration c_{200} .

4.5.2 Halo Mass - Concentration Relation

To further constrain our model, we assume the Molin   et al. (2017) mass-concentration relation for UDGs. This concentration relation, derived from the Via Lactea II (Diemand et al., 2008) and Exploring the Local Volume in Simulations (ELVIS) (Garrison-Kimmel et al., 2014) N-body simulations, describes the dark matter halo concentration of subhalos (i.e. the UDGs) within host halos (i.e. the galaxy clusters) as a function of subhalo mass m_{200} and 3D cluster-centric distance such that

$$c_{200}(m_{200}, x_{sub}) = 19.9 \left(1 + \sum_{i=1}^3 \left[a_i \log \left(\frac{m_{200}}{10^8 h^{-1} M_\odot} \right) \right]^i \right) (1 - 0.54 \log(x_{sub})) \quad (4.20)$$

where $a_i = \{-0.195, 0.089, 0.089\}$ and $x_{sub} = r_{3D}/R_{200}$ is the ratio of the 3D cluster-centric distance of the UDGs to the cluster radius. This concentration relation, used by S18 for

their model, is expected to provides a more realistic concentration estimate of the dark matter halo of UDGs in galaxy clusters than that of [Duffy et al. \(2008\)](#) which we used to describe the concentration of our galaxy clusters. The resulting concentration from [Moliné et al. \(2017\)](#) is higher over all ranges of halo mass considered than that of [Duffy et al. \(2008\)](#) by a factor of ~ 2 , which can be explained by the outskirts of the subhalo being stripped as it interacts with the host halo ([Moliné et al., 2017](#); [Springel et al., 2008](#)). We note that [Moliné et al. \(2017\)](#) assumed a NFW profile in measuring the subhalo concentration c_{200} , therefore the definition of c_{200} is the same which has been used throughout this work (see equation 2.6) which is defined for non-stripped halos.

We estimate the average 3D cluster-centric distance of our sample $\langle r_{3D} \rangle$ based on the 2D projected distance as described in [Sifón et al. \(2018a\)](#), where the most probable 3D distance is estimated as follow:

$$\langle r_{3D} \rangle = \frac{\sum_i n(r_{2D,i}) r_{2D,i}}{\sum_i n(r_{2D,i})} \quad (4.21)$$

where $\sum_i$ is the sum over bins of 0.1 Mpc width over the entire range of r_{2D} in our samples, and $n(r_{2D,i})$ the number of objects in that bin. We describe the concentration for the average of our sample using $x_{sub} = \langle r_{3D} \rangle / \langle R_{200} \rangle$ where $\langle R_{200} \rangle$ is the average cluster size R_{200} weighted by the number of objects in each cluster.

4.6 Fit Results

We perform a single parameter χ^2 fit to our measurements. We step uniformly in logarithmic space the total halo mass m_{200} in the range $8.4 < \log(m_{200}/M_\odot) < 13.0$. At each step, we calculate the χ^2 such that

$$\chi^2 = \sum_{r_p \text{ bins}} \left(\frac{\Delta \Sigma_{UDG} - \Delta \Sigma_{NFW}(m_{200})}{\sigma_{\Delta \Sigma_{UDG}}} \right)^2 \quad (4.22)$$

The halo mass m_{200} corresponding to the minimum χ^2 , χ_{min}^2 is the most likely halo mass, the 1σ and 2σ limits for the fit are the halo masses corresponding to $\chi_{min}^2 + 1.0$ and $\chi_{min}^2 + 4.0$ respectively.

We apply our fit to our true UDG sample measurement $\Delta \Sigma_{UDG}$, with an average redshift $\langle z \rangle = 0.074$, $\langle r_{3D} \rangle = 0.46$ Mpc, $\langle R_{200} \rangle = 1.16$ Mpc. The resulting 1σ and 2σ regions

of the fit as well as the calculated χ^2 are shown in Figures 4.3.a and 4.3.b respectively. The resulting most likely halo mass measured is $\log(m_{200}/M_\odot) = 11.89 \pm_{0.4}^{1.1}$ (1σ uncertainty) with a 2σ upper limit of $\log(m_{200}/M_\odot) < 12.51$. Since the measured mass is consistent with zero to the 2σ limit, we do not have a strong enough signal to claim a detection. We therefore limit our discussion and interpretation of these results to the 2σ upper bound measured. We note that this measurement is made on an interloper corrected sample, meaning that the true **UDG** fraction is effectively 100%.

We test of fitting model on the excess surface density measurement from S18, $\Delta\Sigma_S$, using only the first 7 bins to exclude the clusters' contribution. For the S18 sample, the average redshift is $\langle z \rangle = 0.065$, $\langle r_{3D} \rangle = 0.93$ Mpc, $\langle R_{200} \rangle = 1.78$ Mpc. The resulting 1σ and 2σ regions of the fit as well as the calculated χ^2 are shown in Figures 4.3.c and 4.3.d respectively. Once again, we do not see a detection since the resulting most likely halo mass measured is consistent with zero to the 1σ limit. We measure a 2σ upper limit of $\log(m_{200}/M_\odot) < 11.80$. This 2σ upper limit is the same that was measured in S18 and shows that while our model ignores the cluster contribution to the signal at large r_p , we are still able to recover the same upper limit.

Finally, we apply our fitting model to the combined sample measurement $\Delta\Sigma_{UDG+S}$. For this sample, $\langle z \rangle = 0.066$, $\langle r_{3D} \rangle = 0.81$ Mpc, $\langle R_{200} \rangle = 1.62$ Mpc. The resulting 1σ and 2σ regions of the fit as well as the calculated χ^2 are shown in Figures 4.3.e and 4.3.f respectively. Once again, we do not see a detection since the resulting most likely halo mass measured is consistent with zero to the 1σ limit. We measure a 2σ upper limit of $\log(m_{200}/M_\odot) < 11.80$. This measured mass is the same that was found for the S18 sample alone, most likely because while the uncertainty in the $\Delta\Sigma$ data points slightly decreased which we expect would result in a lower upper limit, the average values of $\Delta\Sigma$ data points slightly increased which would increase the upper limit, resulting in a net change of zero. The key difference is that this new measurement is based on a sample which effectively is more pure, with a true **UDG** fraction of 73%, compared to the S18 sample alone with a true **UDG** fraction of 64%.

For a more direct comparison with the S18 upper limit, we measure a 2σ upper limit of $\log(m_{200}/M_\odot) < 12.12$ on our contaminated **UDG** sample $\Delta\Sigma_{UDG+I}$, which is higher than that of S18. We also tested combining both our contaminated **UDG** sample and S18 contaminated **UDG** sample, which results in a 2σ upper limit of $\log(m_{200}/M_\odot) < 11.71$, which is lower than the S18 upper limit by 0.1 dex. Unfortunately, combining directly our contaminated **UDG** sample and the S18 contaminated **UDG** sample results in having

three different types of sources combined: the true UDGs, our interlopers, and the S18 interlopers. This significantly complicates the interpretation of the measurements and we therefore focus on only three upper limit measurements: our true UDGs, S18 contaminated UDGs and the combination of our true UDGs with S18 contaminated UDGs. We interpret the meaning of these upper limits for the halo mass of UDGs in chapter 5, paying special attention to the effects of S18 interloper contamination on our results.

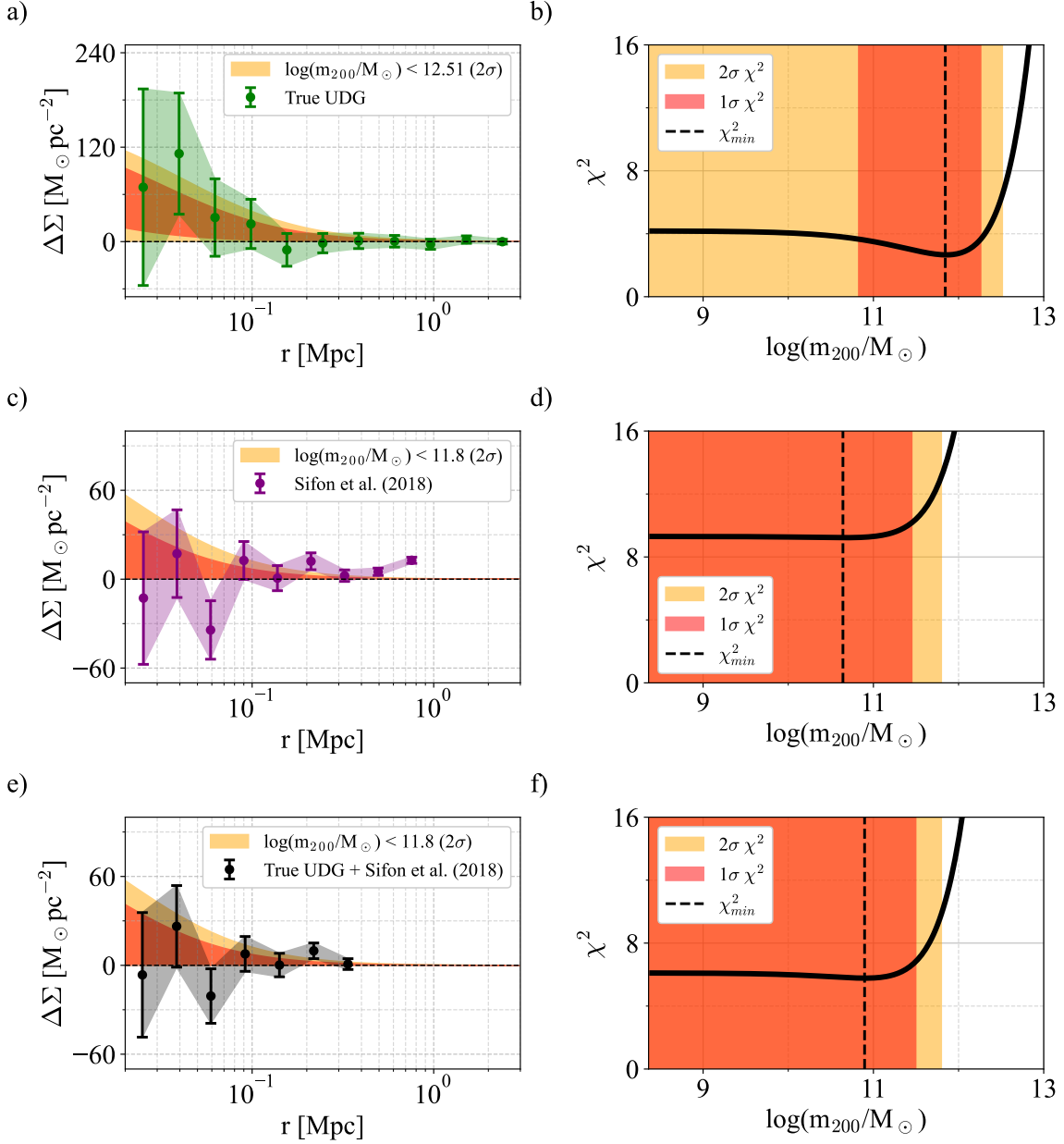


Figure 4.3: Excess surface density $\Delta\Sigma$ and associated χ^2 fits as a function of halo mass m_{200} for a-b) our true UDGs, c-d) Sifón et al. (2018b) contaminated UDGs, and e-f) the combination of our true UDGs and Sifón et al. (2018b) contaminated UDGs. The 1σ (2σ) regions are shown in red (orange) and the best fit halo mass is shown (black dashed line).

Chapter 5

Discussion and Summary

In this chapter, we discuss in depth the effect of interlopers on the upper limit measurements of the average dark matter halo mass of [UDGs](#). When modeling for this effect, we have a reliable upper limit of $\log(m_{200}/M_{\odot}) < 12.05$. We consider this constraint on the broader context of [UDG](#) formation mechanisms. Potential improvements and future works which could constrain further the halo mass of [UDGs](#) are discussed. Finally, a summary of the main takeaways from the thesis is presented.

5.1 Effect of Interlopers

We consider the measured upper limit on the halo mass of [UDGs](#) using three different samples:

- True [UDG](#) sample: We corrected our measurement for the effect of interlopers from field data, resulting in an effective true [UDG](#) fraction of 100% and a directly measured 2σ upper limit of $\log(m_{200}/M_{\odot}) < 12.51$.
- S18 sample: This contaminated [UDG](#) sample which could not be corrected for interlopers due to the lack of field data has an effective true [UDG](#) fraction of 64% and a directly measured 2σ upper limit of $\log(m_{200}/M_{\odot}) < 11.80$.
- True [UDG](#) + S18 sample: This combined sample is still contaminated by S18 interlopers, however the addition of our true [UDG](#) sample increases the effective true [UDG](#) fraction to 73% and has a directly measured 2σ upper limit of $\log(m_{200}/M_{\odot}) < 11.80$.

Because the measurement of the true **UDG** sample contains effectively no interlopers, it informs us directly about the halo mass of these galaxies. However, the measurements from the S18 sample and combined sample do not directly teach us about the halo mass of **UDGs** since the effect of S18 interlopers on the upper limit needs to be considered.

If the S18 interlopers in the sample bias the results high, then the upper limit measured is a conservative one which we can use to constrain further **UDG** masses. However, if the S18 interlopers bias the results low, then the upper limit is biased low and therefore is not reliable. In S18, an argument is made based on the relatively low redshift of the clusters studied, up to $z < 0.09$, and a bias towards more highly concentrated galaxies, that these interlopers are more likely to be background galaxies. Therefore, they are intrinsically brighter and assumed to reside in more massive dark matter halos. These interlopers are then assumed to bias the weak lensing mass measurements high, meaning that the upper limit of $10^{11.80} M_{\odot}$ can be trusted.

We are not willing to make the same assumption that the interlopers residing in more massive background halos bias the results high. Since the excess surface density is directly proportional to the shear and scaled by $\Sigma_{crit}(z_l, z_s)$ (see equations 1.3 and 1.4), using a wrong assumed lens redshift z_l for the interlopers will result in an either lower or higher “effective mass” measured which will depend on both the source redshift distribution of the sample and z_l . Furthermore, assuming the wrong z_l will lead to the wrong projected radius r_p , which is converted to a physical scale at the lens distance, significantly complicating the problem of how more massive and distant halos would affect the $\Delta\Sigma$ measurement and its associated uncertainty $\sigma_{\Delta\Sigma}$. We note that these complications are not present when subtracting the field signal of interlopers from our original contaminated sample of 545 potential **UDGs** since any effect of assuming the wrong lens redshift is identical in both our field interloper measurement and our contaminated **UDG** sample measurement and therefore corrected for.

Since the S18 interlopers may bias low our upper limit measurement, we attempt to determine the largest possible negative bias to recover a reliable upper limit on **UDG** mass. Disregarding the interloper assumptions made in S18 described above, we will only assume that the halo mass of these galaxies is greater than zero. Since we are directly measuring the excess surface density $\Delta\Sigma$ with weak gravitational lensing centered on the galaxies, and $\Sigma_{crit} > 0$ for all (z_l, z_s) , this assumption means that $\Delta\Sigma_{I,S} > 0$ for any assumed z_l . We first generate a projected **NFW** profile $\Delta\Sigma_{UDG+I}$ for the combined sample with the mass at the measured 2σ upper limit of $10^{11.80} M_{\odot}$. We describe this signal as the weighted sum

of two components, the **UDG** component $\Delta\Sigma_{UDG}$ for N_{UDG} true **UDGs** and the interloper component $\Delta\Sigma_I$ for N_I interlopers such that

$$\Delta\Sigma_{UDG+I} = \frac{N_{UDG}}{N_{UDG} + N_I} \Delta\Sigma_{UDG} + \frac{N_I}{N_{UDG} + N_I} \Delta\Sigma_I \quad (5.1)$$

We then split the $\Delta\Sigma_{UDG+I}$ profile into these two components by selecting a fraction of the measured signal α that the interloper component contributes to

$$\Delta\Sigma_I = \alpha \Delta\Sigma_{UDG+I} \quad (5.2)$$

where the corresponding fraction of the signal which the **UDGs** contribute to is constrained by equation 5.1 such that

$$\Delta\Sigma_{UDG} = \left[1 + \frac{N_I}{N_{UDG}} (1 - \alpha) \right] \Delta\Sigma_{UDG+I} \quad (5.3)$$

We note that this fraction α can either be $\alpha < 1$ in which case the interlopers are biasing the signal low, or $\alpha > 1$ where the interlopers are biasing high. These resulting excess surface density profiles are then fitted separately using the same fitting model described in sections 4.5 and 4.6, which provides a measurement for the **UDG** mass $m_{200,UDG}$ and for the “effective” interloper mass $m_{200,I}$. We note that this effective interloper mass is not the physical mass of this population of objects due to the complications which arise when assuming an incorrect lens redshift as described earlier, but simply is used as a way to quantify the bias of interlopers on the excess surface density measurement. We then repeat this procedure for a range of fractions $10^{-3} < \alpha < 10$ which we found covers well the regime where interlopers bias low (i.e. $\alpha < 1$) to the regime where they bias high (i.e. $\alpha > 1$).

We apply the technique to both the S18 sample and the combined true **UDG** with S18 sample. The resulting $m_{200,UDG}$ vs $m_{200,I}$ curves are shown in Figure 5.1. The curves show clearly two asymptotic behaviors; one for larger interloper effective mass where to compensate the **UDG** mass must become much lower and approach zero, and one for lower interloper effective mass where the **UDG** mass must become higher to compensate for the low biasing effect. When the fraction $\alpha = 1$, both the effective interloper mass and **UDG** mass are the same, which is the measured upper limit $10^{11.80} M_\odot$ in both the S18 and combined samples. Since we are interested in the effect that a low bias from interlopers has on our measured upper limit, we look at the horizontal asymptote which shows the upper limit on **UDG** mass if the interloper effective mass goes to zero. In the case of the

S18 sample, this upper limit which accounts for low biasing by interlopers on the halo mass of **UDGs** is $\log(m_{200}/M_{\odot}) < 12.17$. For the combined sample which includes our true **UDGs** and the S18 sample, this upper limit is reduced to $\log(m_{200}/M_{\odot}) < 12.05$.

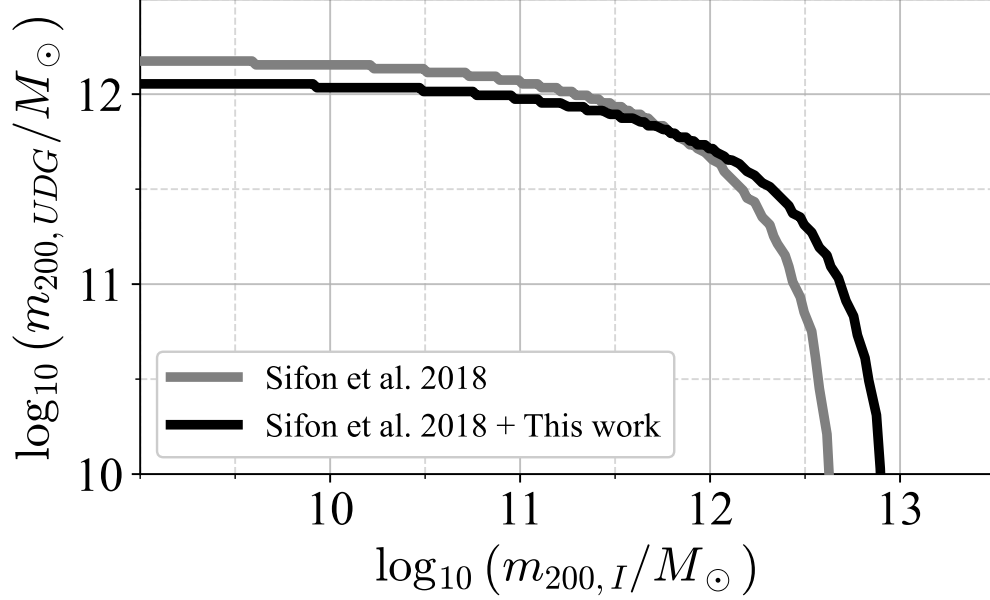


Figure 5.1: We show here an estimate of the biasing effect that interlopers have on the S18 contaminated **UDG** sample (solid grey line) and on our true **UDG** combined with the S18 contaminated **UDG** sample (solid black line). We split the upper limit measured into a signal from the true **UDG** and from the interloper contaminants (see equation 5.1) then fit our excess surface density model to these components. We show the allowed effective interloper masses measured $m_{200,I}$ as a function of the true **UDG** halo masses $m_{200,UDG}$. The horizontal asymptote reveals the maximum $m_{200,UDG}$ possible in the limit that $m_{200,I}$ goes to zero.

5.2 Broader Context of UDG Halo Mass

By combining our **UDG** measurement with that of S18, and accounting for the potential low biasing of S18 interlopers, we estimated an upper limit on the halo mass of **UDG** of

$\log(m_{200}/M_\odot) < 12.05$. We note that this upper limit is not as constraining as the one from S18 since we did not make the assumption that interlopers would bias high the results. While we are able to constrain the mean halo mass on our large sample of UDGs, these measurements are only sensitive to the mean of the galaxy population studied, and therefore can still have outliers with more massive dark matter halos.

For instance, the halo mass of the well-studied UDG DF44 in the Coma cluster has been measured, both dynamically and using the GNHR, to be $M_h = 10^{11.2} M_\odot$ (van Dokkum et al., 2019b) and is one of the more massive and dark matter-dominated UDG found to date. However, this example is larger and therefore likely more massive than the mean of our sample, with $r_{\text{eff}} = 4.6$ kpc (van Dokkum et al., 2016) compared to the mean size of combined true UDG with S18 contaminated UDG sample of $\langle r_{\text{eff}} \rangle = 3.0$ kpc. Other relatively massive UDGs have been found, such as NGC 5846 UDG1 in the NGC 5846 galaxy group with an estimated halo mass of at least $M_h > 10^{10.9} M_\odot$ (Forbes et al., 2019) and VCC 1287 in the Virgo cluster with a halo mass of $M_h = 10^{10.9} M_\odot$ (Beasley et al., 2016), both estimated from GNHR. These UDGs, while being some of the most massive and dark matter-dominated found to date, are within the upper limit on the mean of UDGs we studied. These galaxies are likely the more extreme examples of UDGs masses. Other dynamical mass estimates of well studied UDGs such as DF2 and DF4 in the Coma cluster revealed possible halo masses for UDGs as low as $M_h < 10^{8.2} M_\odot$ (van Dokkum et al., 2018, 2019a). Such low mass and dark matter-deficient galaxies, which are well within the bound of halo masses we measured, are likely another extreme of the UDG population.

Some UDG studies have focused on the mean halo mass of this population of galaxies rather than individual ones. Amorisco et al. (2018) showed that, using HST imaging to measure globular clusters and the GNHR, the median halo mass of their sample of 54 UDGs in the Coma cluster is $M_h = 10^{10.74} M_\odot$. Using scaling relations for galaxy size, brightness and velocity dispersion, Zaritsky et al. (2023) was able to estimate the halo mass of a sample of 585 UDGs across environments to be in the range of $10^{10} M_\odot < M_h < 10^{11.5} M_\odot$, which was consistent with a subset of 6 UDG halo mass measurements made using the GNHR. These halo masses are once again within the upper limit of $M_h < 10^{12.05} M_\odot$ we measured for UDGs and shows consistency across the literature. While these measurements, combined with our upper limit, point towards not overly massive dark matter halos, they do not exclude the possibility for the more massive “failed” galaxy formation scenarios.

To put these measurements in the context of galaxy formation and evolution, we look at where UDGs lie in the Stellar Mass to Halo mass Relation (SMHR). We estimate a

weighted mean stellar mass for the combined sample of our own and S18 UDGs, in logarithmic space, of $\langle \log(M_*/M_\odot) \rangle = 8.34$. Combined with our halo mass upper limit, we estimate a maximum halo-mass-to-stellar-mass ratio of $M_h/M_* < 5.13 \times 10^3$. We show the SMHR in Figure 5.2 for galaxies from Wang et al. (2015). Results from the dwarf galaxies in the Numerical Investigation of a Hundred Astrophysical Objects (NIHAO) hydrodynamical zoom-in simulations (Wang et al., 2015) are over-plotted with the expected SMHR from abundance matching measurements at present day in Λ CDM from Behroozi et al. (2013), Moster et al. (2013) and Kravtsov et al. (2018). We show the UDG masses allowed within the 1σ scatter of our sample’s stellar mass given our 2σ upper limit on UDG halo mass (purple rectangle). This region highlights that, based on our measurement, UDGs can still very well reside either at the expected SMHR given their stellar mass which would imply dwarf-like dark matter halo masses, to the left of this relation which would imply dark matter-deficient UDGs or to the right of this relation which would imply dark matter-dominated UDGs.

From the Behroozi et al. (2013) SMHR we expect a halo-mass-to-stellar-mass ratio for galaxies in dwarf-like halos with the same stellar masses as our UDG sample to be in the range of $2.2 \times 10^2 < M_h/M_* < 4.6 \times 10^2$. DF44, NGC 5846 UDG1 and VCC 1287 have estimated halo-mass-to-stellar-mass ratios of $M_h/M_* = 3.7 \times 10^2$ (van Dokkum et al., 2019b), $M_h/M_* > 8 \times 10^2$ (Forbes et al., 2019), and 3×10^3 (Beasley et al., 2016) respectively, and are shown in Figure 5.2 for comparison. The median halo-mass-to-stellar-mass ratio of the sample of 54 UDG from Amorisco et al. (2018) is $M_h/M_* = 3.5 \times 10^3$, with the median UDG halo mass and stellar mass shown in Figure 5.2. We note that both DF2 and DF4 have a halo mass so low that they are outside the bounds of Figure 5.2 and given their stellar masses of $M_* = 10^{8.3} M_\odot$ and $M_* = 10^{8.2} M_\odot$ respectively (van Dokkum et al., 2018, 2019a), their halo-mass-to-stellar-mass ratios are close to unity. This highlights that within the bounds of our upper limit on the halo mass of UDGs, a wide range of stellar mass to halo mass ratio is still allowed, ranging from very dark matter-dominated to dark matter-deficient galaxies and that some individual UDGs have been measured and shown to cover this wide range.

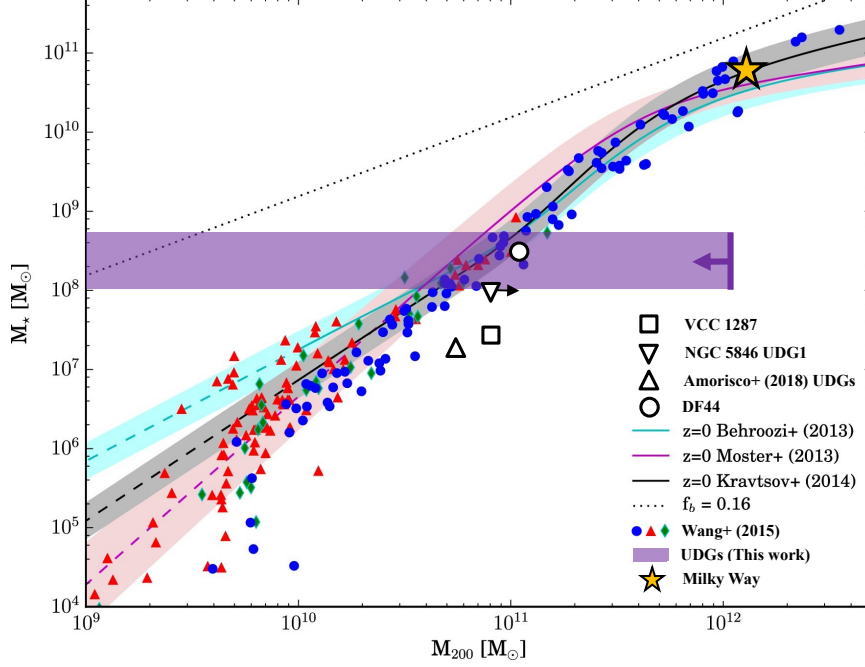


Figure 5.2: Modified Figure 5 from Wang et al. (2015) showing stellar mass M_* as a function of halo mass M_{200} at present day for the galaxies in the NIHAO hydrodynamical zoom-in simulations (blue circles, red triangles, green diamonds). The expected SMHR from abundance matching measurements from Behroozi et al. (2013) (cyan solid line), Moster et al. (2013) (pink solid line), and Kravtsov et al. (2018) (black solid line) are shown as well as the cosmic baryon fraction of mass associated with the dark matter halos f_b (black dotted line). We added the allowed UDG halo masses within our 2σ upper limit measurement (purple rectangle). The stellar mass range is given by the 1σ scatter in our sample. We show the Milky Way (yellow star) for comparison (Licquia & Newman, 2015; Posti & Helmi, 2019). UDGs VCC 1287 (Beasley et al., 2016), NGC 5846 UDG1 (Forbes et al., 2019), and DF44 (van Dokkum et al., 2019b) are shown (black square, triangle and circle respectively) as well as the median UDG of the Amorisco et al. (2018) sample (black triangle).

While there is a clearly measured large scatter in UDG halo masses, studies of the mean halo masses of this population of galaxies is necessary to constrain the main formation mechanisms of UDGs. Based on our upper limit on the halo mass, we cannot

conclusively reject or accept models proposed for the formation of UDGs due to the large range of dark matter allowed, from dark matter-dominated to dark matter-deficient. A weak lensing detection would provide a direct measurement of the halo mass of UDGs which would constrain further both models which require dark matter-deficient or dark matter-dominated UDGs, while a tighter upper bound would allow to constrain better whether or not UDGs are dark matter-dominated galaxies. Due to the observational difficulty of dynamical mass measurements, many studies have relied on globular clusters and the GNHR or other scaling relations to estimate halo masses, which is assumed to apply to UDGs and not yet well constrained in this regime. Our weak gravitational lensing approach has allowed us to not rely on these scaling relations. While we were able to provide an upper limit on the halo mass of UDGs, we expect future works to be able to provide a direct measurement of the halo mass of these galaxies.

5.3 Future Improvements

To further improve on our understanding of UDGs, tighter constraints on their halo mass will be needed. In this section, we discuss potential improvements to our method and future datasets which will allow to measure more accurately the halo mass of UDGs using weak gravitational lensing.

5.3.1 Analysis Improvements

Since UNIONS is an ongoing survey, both imaging data and data products continued to be released while the work described in this thesis was being produced. A photometric redshift catalogue was developed for the sources in UNIONS. Such photometric redshift information for every source galaxy could be used, as opposed to the calibrating redshift distribution we described in section 4.1. We expect this would improve slightly the constraining power of our sample of UDGs.

The main improvement to our measurement would be to increase the number of lenses we stack, since the uncertainty in the excess surface density decreases by a factor of $1/\sqrt{n}$ for a lens sample n times larger. Due to the definition of UDGs relying on physical size estimate, we limited our search to within 66 galaxy clusters which covered only 16 deg² out of the entire 4,800 deg² which UNIONS imaged. While this approach is common for estimating UDG distances from photometric data alone, “distance by association” techniques

have been applied by [Zaritsky et al. \(2022\)](#) in searching for [UDGs](#) where they estimate distances using the spectroscopic redshift of nearby galaxies. Such method could be applied to the [UNIONS](#) data to find sources in environments less dense than clusters. However, we note that interloper contamination, which we showed plays an important role in the weak lensing measurement, would likely increase for less dense environments compared to our current approach and estimates of the interloper fraction could become more complicated.

Deeper imaging has the potential to reveal more [UDGs](#) within the clusters we studied. We found an average of 4.4 true [UDGs](#) per cluster in our sample of 66 galaxy clusters while S18 found an average of 27.7 true [UDG](#) per cluster in their sample of 18 galaxy clusters. We note that the median halo mass of our cluster sample is $10^{14.1} M_{\odot}$ which is lower than that of S18 with a median halo mass of $10^{14.9} M_{\odot}$. While details of the S18 [UDG](#) selection differ from our selection, one of the main reasons for this difference in number of [UDG](#) per cluster found is the deeper imaging that S18 used, with a total exposure time ~ 10 times longer on the same instrument and telescope. Based on the number of [UDG](#) to host halo mass relation ([Karunakaran & Zaritsky, 2023](#)), we estimate that we found only 8% of the total number of [UDGs](#) in the clusters we studied, while we estimate that S18 found 13% which is a factor of ~ 1.5 increase. With multiple [UNIONS](#) bands now available over a large area, performing our [UDG](#) detection on combined bands imaging could improve the depth and therefore increase the total number of [UDGs](#) found ([van der Burg et al., 2016](#)). We note that this would result in a color-dependent selection.

5.3.2 Euclid

Ultimately, larger datasets with deeper imaging and higher resolution will be needed to improve on the weak lensing measurement of the halo mass of [UDGs](#). Fortunately, Euclid, a space based telescope mission of the European Space Agency optimized for weak gravitational lensing, successfully launched on July 1, 2023 and has started to acquire data. One of the main deliverables of Euclid is the [Euclid Wide Survey \(EWS\)](#) which will cover 15,000 deg^2 in the span of six years ([Euclid Collaboration et al., 2022](#)). This survey is significantly larger than [UNIONS](#) by a factor of three. Images are also expected to be deeper, with surface brightness limits in the visible band I_e of 29.8 mag/arcsec^2 for diffuse sources compared to 28.4 mag/arcsec^2 in the [UNIONS](#) r-band we used. Furthermore, unlike [UNIONS](#) which was limited by the blurring of the atmosphere due to being a ground-based survey, Euclid has a higher resolving power. The median seeing of [UNIONS](#) r-band imaging was 0.65'' with a similar [FWHM](#) for its [PSF](#), which is larger by a factor of four compared to

Euclid’s PSF, with a FWHM of $0.18''$. The density of sources with shape measurements in the EWS is expected to be $30/\text{arcmin}^2$ at an average redshift of $\langle z_s \rangle \approx 1.0$, which is twice as many as that of the UNIONS source catalogue we used in our analysis with $14/\text{arcmin}^2$ at an average redshift of $\langle z_s \rangle \approx 0.6$.

The deeper imaging combined with the higher resolving power of Euclid will allow to detect UDGs at redshifts higher than the maximum redshift of $z < 0.1$ we explored with UNIONS data (see section 2.3). For instance, if we assume a Gaussian profile for the PSF of UNIONS r-band imaging, the half-light radius of this PSF is $\sim 0.33''$ which corresponds to a physical size of 0.6 kpc at $z = 0.1$. By comparison, Euclid’s PSF will have a half-light radius of $\sim 0.09''$ assuming a Gaussian profile, which would correspond to a size of 0.6 kpc at the much higher redshift of $z = 0.6$. The improvement in depth of 1.4 mag/arcsec^2 compared to the UNIONS data we analysed would allow to explore higher redshift despite the effects of cosmological dimming. A cosmological dimming effect of 1.4 mag/arcsec^2 would be present at a redshift of $z = 0.4$ (see section 2.3), which means that UDGs could be detected at much higher redshifts than our current limit of $z = 0.1$. We note however that one of the limiting factor for exploring higher redshifts in our analysis was the increase in interloper fraction as a function of redshift which is difficult to predict for another survey depth and resolution. Conservatively assuming we can push UDG detection up to a redshift $z < 0.2$ in Euclid, many more clusters will be available to study.

We see in Figure 2.2.a that within the $\sim 2,100 \text{ deg}^2$ of UNIONS r-band imaging we analysed, considering clusters up to a redshift of $z < 0.2$ rather than $z < 0.1$ would increase the number of galaxy clusters available by a factor of ~ 4 , where most of these clusters would be from the redMaPPer cluster catalogue. We note that the redMaPPer cluster catalogue is based on the SDSS photometric data and therefore overlaps well with the UNIONS survey. For the purposes of this discussion we assume that the galaxy cluster catalogues which will be developed within the EWS (Euclid Collaboration et al., 2019) contain a similar number density of clusters up to $z < 0.2$. Therefore, since we analysed an area of $\sim 2,100 \text{ deg}^2$ compared to the EWS area of $\sim 15,000 \text{ deg}^2$, we expect a factor of ~ 29 increase in the number of clusters within which we can search for UDGs in the EWS. This would correspond to a sample of 1,919 clusters compared to our sample of 66 clusters.

Furthermore, the increased depth of Euclid data compared to UNIONS data will allow for more UDGs per galaxy clusters to be found. We estimated in section 5.3.1 that we found only 8% of the UDGs that exist within the clusters we studied. For simplicity, we

can consider the magnitude limit scales as $1.25 \log(t_{\text{eff}})$ where t_{eff} is an effective exposure time. Based on the 1.4 mag/arcsec^2 improvement in depth from [UNIONS](#) r-band imaging to Euclid imaging, this is equivalent to an increase in effective exposure time from [UNIONS](#) r-band imaging by a factor of ~ 13 . This 13 times longer effective exposure time is similar to the exposure time of the S18 data which was observed using the same telescope and instrument as [UNIONS](#) r-band data (see section 4.4.2). If we assume that an improvement in limiting surface brightness of 1.4 mag/arcsec^2 for the data we analysed corresponds roughly to the depth of the data analysed by S18, we find an increase in the average number of true [UDGs](#) detected per clusters by a factor of ~ 1.5 , from 4.4 to 6.6 true [UDGs](#) per clusters of the same average mass (see section 5.3.1). This would correspond to a total of $\sim 12,800$ [UDGs](#) within the 1,919 clusters we expect in the [EWS](#) up to $z < 0.2$. This estimate demonstrates the potential of Euclid to find a many more [UDGs](#) than have been discovered to date, and corresponds to a factor of ~ 44 times more true [UDGs](#) than we detected.

The larger area, deeper imaging and higher resolution that Euclid will offer through the [EWS](#) will allow for ~ 2 times more background sources shape measurements with a higher average source galaxy redshift of $\langle z_s \rangle \approx 1.0$ as well as ~ 44 times more [UDG](#) lenses to be used in a weak lensing analysis compared to the analysis described in this thesis. The increased average redshift of background sources from $\langle z_s \rangle \approx 0.6$ to $\langle z_s \rangle \approx 1.0$ in the [EWS](#) affects $\Sigma_{\text{crit}}(z_l, z_s)$ which, for [UDG](#) lenses at $z_l = 0.2$, corresponds to a $\sim 20\%$ improvement in excess surface density measurements. Since the uncertainty in the excess surface density measurement depends on the number density of background source n_b which scales approximately as $1/\sqrt{n_b}$ as well as the number of lenses n which scales as $1/\sqrt{n}$, Euclid will significantly improve on our current measurement of the excess surface density profile of [UDGs](#) by reducing the uncertainty by a factor of ~ 10 , which will very significantly constrain the mean halo mass of [UDGs](#). The improvements that Euclid will offer when compared to [UNIONS](#) in measuring the mean halo mass of [UDGs](#) highlights the potential that the method described throughout this thesis has at differentiating between models of [UDG](#) formation.

5.3.3 Automated Classification

One key aspect of many [UDG](#) studies is the visual classification of these galaxies to remove various artifacts and false detection from a final [UDG](#) sample ([van Dokkum et al., 2015a](#); [Mancera Piña et al., 2019](#)) which can be both time consuming and subjective making reproducibility of studies more difficult. Some studies of [UDGs](#) within galaxy clusters do not

include such visual checks to make the UDG selection more reproducible (van der Burg et al., 2016), however this step is very relevant for weak gravitational lensing measurements where we need a high purity sample to ensure the results are not biased (Sifón et al., 2018b). While we visually classified all the potential UDGs detected within our cluster sample as described in section 3.6.5, this visual classification was a limiting factor in creating our sample of field interlopers as explained in section 3.9. With future surveys expected to increase the number of potential UDGs to visually inspect to many tens of thousands, automated classification and artifact removal will become necessary.

Such automated selection which removes the need for classification by eye have been developed for UDGs. For instance, Zaritsky et al. (2019) used the pretrained DenseNet-201 deep learning model (Huang et al., 2016) and retrained it on a set of 59"x59" cutouts of 1,071 potential UDG which were classified by eye. Similarly, Zaritsky et al. (2021) trained the EfficientNetB1 model (Tan & Le, 2019) on their set of 2,665 potential UDGs, which was later applied to a non-visually checked sample of 5,860 potential UDGs by Zaritsky et al. (2022). These models are examples of Convolutional Neural Network (CNN)s which are typically used in astronomical image classification. Other machine learning models such as transformers (Vaswani et al., 2017) were used on the DES data release 1 by Thuruthipilly et al. (2024) to automatically separate LSB galaxies from image artefacts which allowed for the discovery of 317 UDGs. Various machine learning models have shown the ability to automate classification and improving the purity of potential UDG samples and these methods will be necessary for UDG identification in upcoming larger surveys such as the EWS.

5.4 Summary

Observed LSB galaxies push our understanding of galaxy formation to lower stellar masses where the effects of various feedback processes and environmental mechanisms are not as well constrained by observations. UDGs, a relatively new subclass of LSB galaxies defined to be very large and extremely diffuse, have been studied intensely over the last decade both through simulations and observationally. This push was in part driven by the large population of UDGs found in the Coma cluster by van Dokkum et al. (2015a) and the improvement of telescopes and instruments which allowed for deeper surveys over very large sky areas. The wide variety of properties of UDGs and their abundance across environments has fuelled debates on the potential formation pathways of these galaxies. Many formation models have been proposed which predicts a wide variety of dark matter halo

masses ranging from completely dark matter-free to dark matter-dominated galaxies. An accurate measurement of the halo mass of UDGs is needed to disentangle between formation scenarios and explain how this class of galaxies formed.

The main objective of this thesis was to address the problem how UDGs form, making use of the ongoing UNIONS deep r-band imaging and UNIONS data products developed for weak gravitational lensing analysis. Our approach was to first find as many UDGs as possible within UNIONS, then use the galaxy-galaxy weak gravitational technique to directly measure the total halo mass, including dark matter, of UDGs.

Due to distance information being required to both define UDGs and perform a weak gravitational lensing analysis, we restricted our search for UDGs to within galaxy clusters where we assumed that every galaxies in the line of sight of the clusters were at the same redshift as the clusters. In chapter 2, we described in detail the selection of galaxy clusters we used. We combined both the redMaPPer and MCXC cluster catalogs, limited our search to clusters where UNIONS shape catalogues were available, applied selection criteria based on redshift and galactic dust maps, and corrected for duplicates in the combined cluster sample. We found a total of 66 galaxy clusters which met our criteria, for which we estimated a size R_{200} and corresponding halo mass M_{200} based on various scaling relations.

In chapter 3, we searched for UDGs within these galaxy clusters. We first measured a variable PSF across each of the 213 data tiles in UNIONS which contained our galaxy clusters. We applied the SExtractor software to the LSB r-band photometric data tuned for detection of large LSB sources to extract as many potential UDGs as possible and detected 4.1×10^6 sources. After a pre-selection needed to reduce the amount of computing power required, we prepared image cutouts around each source and fitted 1.8×10^5 Sérsic profiles with the AutoProf software to extract morphological parameters. We then developed a series of selection criteria to both define UDGs as well as significantly improve the purity of our sample resulting in a sample of 735 potential UDG. Nonetheless, we visually classified the remaining 735 potential UDGs which left us with 545 UDGs found in UNIONS. However, the assumption we made that every source within the clusters line of sight is at the clusters distance is incorrect, and this sample of 545 UDGs is contaminated by interlopers.

Interlopers are sources which if assumed to be at the cluster distance pass all our selection criteria but are not part of the overabundance of sources seen in the cluster when

compared to the field. We carefully analysed field data to estimate an interloper contamination fraction of 46.8% and selected a sample of 1,952 field interlopers representative of the interloper contamination within our clusters.

In chapter 4, we used the [UNIONS](#) shape catalogue and the `dsigma` python package to measure the excess surface density profile of both our contaminated [UDG](#) sample and our field interloper sample. We generated a sample of 38,150 azimuthal random lenses to measure and correct for the contribution of the offset host cluster halo to our contaminated [UDG](#) sample measurement. Applying a bias correction, boost factor correction and combining our measurements allowed us to recover the excess surface density signal of the true [UDGs](#) in our sample. We then defined a projected [NFW](#) model which, using the halo mass - concentration relation for subhalos from [Moliné et al. \(2017\)](#), reduced our model to depend on a single fitting parameter, the halo mass m_{200} . We fitted this model to our true [UDGs](#) for which we found no significant detection and measured a 2σ upper limit of $\log(m_{200}/M_\odot) < 12.51$.

To improve on this constraint, we combined our true [UDG](#) measurement with the only other weak gravitational lensing measurement of [UDGs](#) from [Sifón et al. \(2018b\)](#). However, the measurement from [Sifón et al. \(2018b\)](#) on a sample of 784 contaminated [UDGs](#) has not been corrected for interlopers and therefore contains both true [UDGs](#) and interlopers. We fitted our model to this combined sample and once again found no significant detection but measured a 2σ upper limit of $\log(m_{200}/M_\odot) < 11.80$. In chapter 5, we modeled for the possible low biasing that interlopers can have on our results and estimated a corrected upper limit for the halo mass of [UDGs](#) of $\log(m_{200}/M_\odot) < 12.05$. While this upper limit on the halo mass of [UDGs](#) is not as constraining as the one reported by [Sifón et al. \(2018b\)](#), we demonstrated the importance of accounting for the effect of interlopers in weak gravitational lensing measurements of [UDGs](#).

This upper limit on the average halo mass of [UDGs](#) places a constraint on the average ratio of halo mass to stellar mass of [UDGs](#) in our sample of $M_h/M_* < 5.13 \times 10^3$ which is very dark matter-dominated for galaxies of this stellar mass. We conclude that our measurement is not constraining enough to disentangle between different formation mechanisms of [UDGs](#). A tighter upper limit would allow to constrain better dark matter-dominated models while a detection would allow to place a lower bound on the halo mass of [UDGs](#) and constrain dark matter-deficient models. We note that our method measures the average halo mass of [UDGs](#) and that some [UDGs](#) can be above our measured upper limit.

Lastly, we discussed potential improvements to our methodology and the future of UDGs halo mass measurements which will be significantly improved using upcoming wide surveys from telescopes such as Euclid. Overall, we demonstrated the ability to find UDGs in UNIONS with an optimized UDG detection pipeline and perform a galaxy-galaxy lensing analysis to constrain their halo mass while accounting for the effect of interloper contaminants. We expect similar measurements on future surveys with more constraining power will help disentangle the mystery of UDG formation.

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