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**Tracing the Origins of Ultra-Diffuse Galaxies:  
Insights from the LEWIS Project in the Hydra I  
Cluster**

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# Abstract

Ultra-diffuse galaxies (UDGs) and low-surface brightness galaxies (LSBs) represent one of the most important points in galaxy evolution. They represent the extreme end of low-mass, inefficient star formation. With sizes almost as large as the Milky Way ( $R_e \sim 1.5 - 4$  kpc) but with stellar masses of dwarfs ( $M_* \sim 10^7 - 10^9 M_\odot$ ). These systems challenge our understanding of baryonic and dark matter physics, in addition to environmental processes. Despite large progress in the latest decade, several questions remain: are UDGs born or made diffuse? If made UDG, do they "puff-up" externally or internally? Can we separate internal processes with external ones? Are they "just" the extreme end of dwarf galaxy evolution?

This thesis presents the first systematic and comprehensive study on spectroscopic properties from UDGs and LSBs for Hydra-I. We leverage the LEWIS (Looking into the faintEst With MUSE) survey and MUSE IFU spectroscopy to analyze at least 10 galaxies of the original 25 (19 UDGs, 6 LSBs) within the inner  $0.4R_e$  of the cluster, deriving stellar kinematics, integrated stellar population properties (ages, metallicities, chemical abundances) and spatially resolved metallicity,  $[\text{Mg}/\text{Fe}]$  ratios and age gradients for four of such sources.

Our integrated stellar population analysis reveals that most galaxies within the cluster follow the standard mass-metallicity relationship (MZR) for dwarf galaxies, with mean metallicities of  $\langle [\text{M}/\text{H}] \rangle \approx 0.9 \pm 0.2$  dex and intermediate-to-old ages ( $\approx 10$  Gyr). However, we find a distinct sub-population of metal-rich outliers within the core of the cluster ("early infallers") that deviate from the standard MZR. Our two-dimensional analysis for a subset of the LEWIS sample reveals complex metallicity profiles, including flat, inverted and V-shaped. We also recover  $[\alpha/\text{Fe}]$  gradients where we generally find strongly decreasing trends.

We compare these results against simulations (TNG50, NIHAO) and conclude that the "failed scenario" cannot explain the observed properties within the Hydra-I cluster, as we find no evidence for extreme metal poor stars associated with massive halos. Instead, we find a complex scenario with evidence of many galaxies being "extended" or "puffed-up" dwarfs instead. High metallicity outliers coupled with non-standard metallicity profiles show further evidence of environmen-

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tal processes contributing to the observed properties. These findings demonstrate that UDGs are not a monolithic class, but a diverse population whose extreme diffuseness arises from the coupling of internal baryonic physics with environmental history.

# Chapter 1

## LSBs and UDGs in clusters: The faint universe on extreme environments

### 1.1 Low-mass galaxies in the context of cosmology and galaxy evolution

Historically, much of extragalactic astrophysics, and in particular galaxy evolution, has been described from the perspective of massive, high surface-brightness galaxies (HSBs). Ever since the release of large scale photometric surveys such as SDSS ([York et al., 2000](#)), galaxy evolution has been studied mainly for HSBs through the investigation of colour-magnitude diagrams (e.g. [Baldry et al., 2004](#)) and morphologies (e.g. [Schawinski et al., 2014](#); see also the Hubble Tuning Fork in Fig. 1.1). In these scenarios, galaxies constitute massive systems, with highly efficient star-formation (SF). For these sources, we have seen bimodalities in morphology, colour, and spectral types, generally correlating to each-other. These data have allowed us to understand how these galaxies evolve in slow (e.g. classical slow-exhaustion of gas) versus fast paths (e.g. violent gas depletion, mergers) depending on stellar mass and environmental conditions. While this improved significantly our understanding of galaxy evolution in the past two decades, we were left with a few missing pieces due to data limitations, in particular the magnitude limits of these large-scale surveys: galaxy evolution science below  $10^9 M_{\odot}$  suffered in comparison, being limited to a few nearby sources, in particular nearby Ultra-Faint Dwarfs (UFDs, [Willman et al., 2005](#)).

This limitation deeply reshaped the way we view cosmology. According to the  $\Lambda$ CDM paradigm, structure is formed in a hierarchical manner: small dark matter halos collapse first to merge together later, forming larger structures. Dark matter-

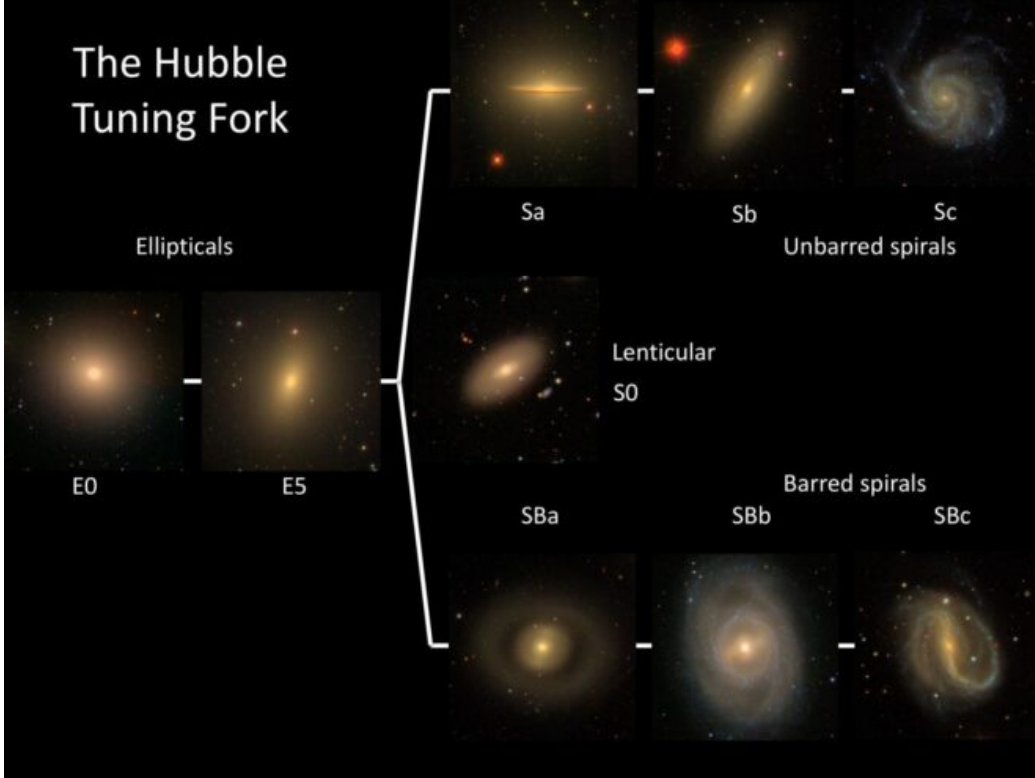


Figure 1.1: Hubble's tuning fork. Credits: [Masters et al. \(2019\)](#), Digital Sky-Survey (SDSS)

only (DMO) simulations indicate that the number of sub-halos in a Milky Way-mass halo ( $M_{\text{vir}} \approx 10^{12} M_{\odot}$ ) would have thousands of sub-halos, way beyond the count of the  $\sim 11$  "classical" satellite galaxies known at the end of the 20th century ([Klypin et al., 1999](#); [Moore et al., 1999](#)). This discrepancy was evident and termed the "Missing Satellite Problem" (MSP), which at least initially, put forth a huge challenge to the standard model of the universe. Another problem closely related to the first one, the "Too Big to Fail" issue, was brought up by [Boylan-Kolchin et al. \(2011\)](#). They found that the substructure in the DMO simulations which is the most massive is also the densest and therefore it cannot be the hosts of the bright satellites in the Milky Way that are observed. At the same time, DMO simulations predicted steep central density "cusps" ( $\rho \propto r^{-1}$ ; [Navarro et al., 1996](#)), but the measured dwarf rotation curves often led to the inference that the central regions of dwarfs have constant density "cores" (the Cusp-Core problem; [de Blok, 2010](#)).

Nevertheless, it is now known that these "small-scale problems" have been mostly solved within  $\Lambda$ CDM by taking into account baryonic physics in simu-

lations (Tegmark et al., 1997, Benitez-Llambay & Frenk, 2020). Current hydrodynamical simulations reveal that cosmic reionization provides heat to the intergalactic medium to  $\sim 10^4$  K, thus preventing gas from accreting into halos with virial temperatures less than this value ( $M_{\text{halo}} \lesssim 10^{9.5} M_{\odot}$ ; Sawala et al., 2016; Wetzel et al., 2016). As a result, most of the sub-halos that are theoretically anticipated are "dark" in nature (they are there but never go through the process of star formation). After observational completeness corrections are put in place to take into account survey biases (sky coverage, luminosity limits, surface brightness limits), the satellite counts both predicted and observed are in very close agreement (Kim et al., 2018). In their words, a recent review by Jeon et al. (2025) states that these "missing" satellites were "born to be starless" in the pre-reionization environment.

Both the TBTF and Cusp-Core issues are treated by stellar feedback in a similar way. Read et al. (2016) and Pontzen & Governato (2012) pointed out that "bursty" star formation (SF episodes followed by supernova driven outflows) result in rapid changes of the gravitational potential. This "impulsive heating" adds energy to the dark matter particles, thus making their central cusps that have been flattened into cores and lowering densities. Di Cintio et al. (2014) went as far as to measure this effect, stating that the efficiency of core formation is at the maximum for the intermediate stellar-to-halo mass ratio ( $M_*/M_{\text{halo}} \sim 10^{-2}$ ) which is exactly the area where bright dwarf galaxies are found. The same mechanisms are capable of lowering the central circular velocities of large sub-halos so that they match the observations thus providing a solution to the TBTF problem (e.g., Wetzel et al., 2016)

The baryonic solution, while achieving large success, is not completely proven. Indeed, both kinematics and stellar populations in low-surface brightness galaxies is needed to demonstrate the presence of cored DM profiles and/or strong initial quenching. A more modern "Diversity of Rotation Curves" problem states that dwarf galaxies of similar mass exhibit a wide range of central densities (both cored and cuspier; see Oman et al., 2015) that single-parameter models struggle to explain. The new findings point to differences in assembly history, environment, or AGN feedback in dwarfs (Arjona-Gálvez et al., 2024) as possible causes of this scatter. Ultra-diffuse galaxies (UDGs), being the most extreme low-surface-brightness systems, are thus critical in probing such baryonic models at their boundaries.

## 1.2 Low-surface brightness galaxies (LSBs)

*But this blinding is clearly a relative matter and we should ask to what extent we are blinded by the spiral galaxy in which we exist, faint as it may appear by comparison. I will argue that strong indirect evidence already exists that our*

*knowledge of galaxies is heavily biased by the sky background, and that the true population of extra-galactic space may be very different from the one we can see (Disney, 1976, quoted).*

A critical piece of the puzzle has been the number density and properties of the rich, low-mass population of dwarfs that are expected to compress the majority of the baryonic mass in the universe. Low surface brightness galaxies (LSBs) seem to account for nearly half of the number of galaxies with masses of  $M > 10^8 M_\odot$  and, when extrapolating to lower masses of  $M > 10^7 M_\odot$ , the fraction is expected to increase to 70 – 85% (Martin et al., 2019). We have traditionally been biased in our conception of the Universe toward only those galaxies that have high surface brightness (HSBs), simply because they are easier to detect. Very early on, Freeman (1970) pointed out that the observed disk galaxies seemed to have a uniform central surface brightness ( $\mu_{0,B} \approx 21.65 \text{ mag arcsec}^{-2}$ ), a result that Disney (1976) later argued was not a physical constant but rather an observational artifact: the "tip of the iceberg." The recognition of this fact marked the beginning of a long period of time during which scientists have been trying to locate the LSB universe (e.g., Impey et al., 1988). Since then, researchers have uncovered a huge number of galaxies whose central surface brightness is even lower than that of the night sky ( $\mu_{0,B} \gtrsim 23 \text{ mag arcsec}^{-2}$ ), reaching even fainter values for ultra-diffuse galaxies (UDGs).

Although the number density of these faint objects is critical for simulations (Martin et al., 2019), perhaps more interesting is their low star-formation efficiency. Unlike HSBs, they are often gas-rich for their mass, well below those predicted by standard scaling relations (Bothun et al., 1997, Bigiel et al., 2008) such as the Kennicutt-Schmidt (KS) law. This makes them ideal laboratories for testing the star formation laws and feedback mechanisms previously discussed. In particular, there are at least two major reasons to study LSBs from this perspective:

- In HSB galaxies, baryonic matter deeply affects the DM profile of galaxies via adiabatic contraction: stars will fall into the center, dragging DM along and thus driving a cuspier profile (de Blok & McGaugh, 1997). In contrast, baryonic mass in LSBs acts as a "massless tracer" of the original DM-dominated gravitational potential. If cores were to be found on systems without SF, strong feedback processes such as those described in Di Cintio et al. (2014) would never happen. This poses a challenge to current solutions for the Cusp-Core problem.
- Models invoking high-spin DM halos (Amorisco & Loeb, 2016) have been extensively discussed in the literature. In this case, the high angular momentum keeps the gas from imploding and forming high-density clumps;

thus, providing no need for either strong internal feedback or environmental quenching. A "high-spin" channel can be verified by finding LSBs that have maintained rotational support and show the regular, inside-out growth characteristics predicted by the models (e.g., steeper metallicity gradients). However, so far, many profiles show a flat-to-rising trend (see [Ferré-Mateu et al., 2025](#) and this work). The shape and variety in metallicity profiles challenges a single formation model and suggests the existence of environmental effects on top of the above models (see this work).

To conclude this section, we can state that LSBs provide a solid way to stress test these leading theories against real data. Thus help probing our understanding of the visibility of baryons and the structure of DM.

### 1.3 UDGs

UDGs are a distinct and intriguing class of LSB galaxies characterized by extremely low surface brightness ( $\mu_{0,g} > 24 \text{ mag arcsec}^{-2}$ ), large effective radii ( $R_e > 1.5 \text{ kpc}$ ; Fig. 1.2), and small stellar masses ( $M \sim 10^7 - 10^{8.5} M_\odot$ , see [Van Nest et al., 2022](#), for a review on UDG definition). This makes them comparable in terms of  $R_e$  to a Milky Way-like galaxy, but with stellar masses typical of dwarf galaxies ( $M_* \sim 10^7 - 10^9 M_\odot$ ). Originally detected in the 1980s (e.g., [Sandage & Binggeli, 1984](#)), these galaxies were rediscovered in large numbers in 2015 in the Coma cluster, thanks to advances in observational techniques and the development of instrumentation capable of probing LSB galaxies ([van Dokkum et al., 2015](#); [Koda et al., 2015](#)). Since then, UDGs have been found in a wide range of environments, from galaxy clusters (e.g., [Mihos, 2015](#); [Mancera Piña et al., 2018](#); [Lim et al., 2020](#); [La Marca et al., 2022a](#)) to groups (e.g., [Trujillo et al., 2017](#); [Forbes et al., 2019](#)) and field (e.g., [Martínez-Delgado et al., 2016](#); [Bellazzini et al., 2017](#)).

#### The size controversy and the Failed $L^*$ scenario

Initially, the large observed effective radii and the high GC count led to the hypothesis that UDG were "failed galaxies". This is, galaxies inhabiting Milky Way-sized halos that were quenched prematurely ([van Dokkum et al., 2015](#)). Recent studies, however, have changed this view by pointing toward the somewhat unphysical UDG definition. [Chamba et al. \(2020\)](#) and [Trujillo et al., 2020](#) suggest that  $R_e$  is essentially a measure of light concentration rather than a true size measurement. To understand why the classification of UDGs is controversial, one must distinguish between a galaxy's physical boundary and its  $R_e$ . The  $R_e$  is effectively measuring the radius enclosing half of the total light of the galaxy, and



thus is directly linked to the shape of its light profile and not the edge of the stellar component. When using physically motivated size metrics, such as the radius of the star-forming threshold or the classic Holmberg radius (Holmberg, 1958), UDGs lies directly on the expected mass-size relationship for dwarfs (Trujillo et al., 2020). Crucially, because they are physically small (despite having large  $R_e$ ), they do not require massive dark matter halos to survive tidal disruption. This favored a view in which UDGs are "extended/puffy dwarfs" rather than examples of the "failed galaxy" initial hypothesis.

The picture has become complicated recently. Dalla Vecchia & Trujillo (2025) showed that the star-forming edge is the one that most closely correlates with the Dark Matter halo virial radius, thus structurally, UDGs are living in dwarf-scale halos. However, Gannon et al., 2025 highlight a critical tension: while the kinematics and physical sizes of UDGs match these dwarf halos, their unusually high Globular Cluster counts often imply much deeper potential wells. This "paradox" makes it possible for UDGs to be in halos that are large (corresponding to the GCs) but have extremely large Dark Matter cores (corresponding to the "dwarf-like" inner kinematics).

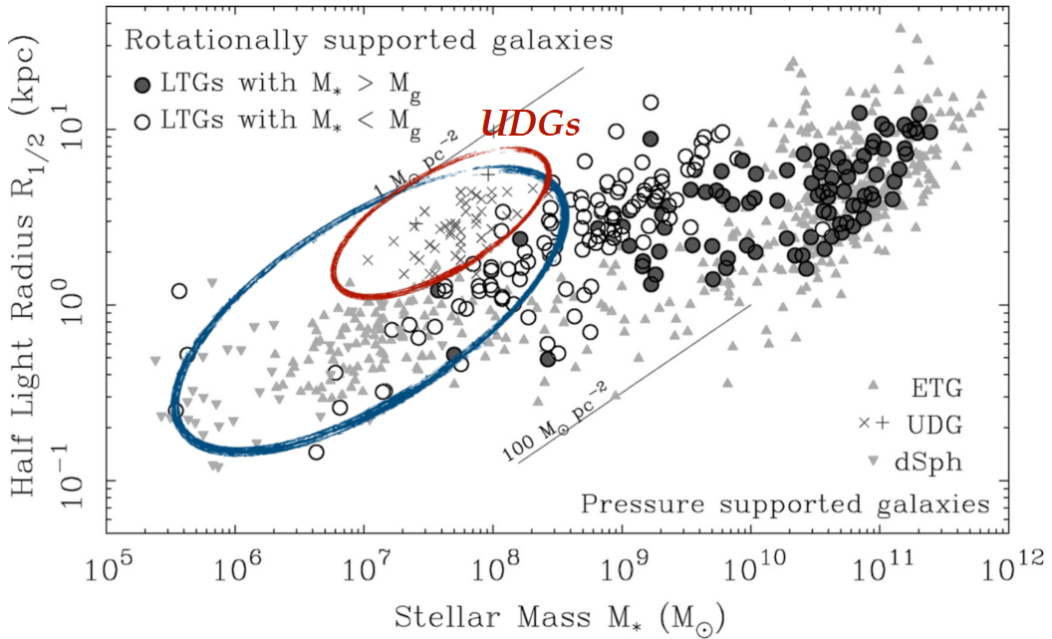


Figure 1.2: Location of Ultra-diffuse galaxies (marked with the red line) in the stellar mass versus half-light radius ( $R_e$ ) diagram. The loci of low-surface-brightness galaxies, including dwarfs, are marked with a blue line. Credits: Mc-Gaugh (2021)

### Born or made diffuse

The existence of these extremely diffuse sources poses a fundamental question: are UDGs "born" diffuse or "made" diffuse? The answer bifurcates our understanding of galaxy formation, separating the effects of internal processes from those of the external environment. If UDGs are "born" diffuse, their properties must be a result of internal baryonic physics, primarily stellar feedback. This channel is considered a leading explanation for UDGs found in low-density field environments. In this scenario, UDGs are not "failed"  $L^*$  galaxies; instead, modern simulations suggest the vast majority are "true" dwarfs, inhabiting halos of  $10^{10} - 10^{11} M_{\odot}$ . Their extreme diffuseness is proposed to be the result of intense, bursty episodes of star formation. The associated supernovae (SN) feedback drives powerful outflows that can rapidly remove gas from the galaxy's center. This rapid, non-adiabatic change in the central potential "puffs up" the stellar orbits, expanding the galaxy (Di Cintio et al., 2017). This feedback-driven expansion is not just a curiosity; it is a direct, observable prediction of the mechanism invoked to solve the Cusp-Core problem, as the gravitational fluctuations from repeated gas outflows are shown to heat the central dark matter component, transforming the primordial "cusp" predicted by DM-only simulations into the "core" that is observationally inferred in many dwarf galaxies (Read et al., 2016). In this context, UDGs are not just an anomaly, but rather the most extreme and visible examples of feedback-driven core formation, providing a key laboratory to test our models of baryonic physics.

Conversely, if UDGs are "made" diffuse, their properties are dictated by external, environmental processes. This is a compelling explanation for the large UDG populations observed in dense galaxy clusters. Several mechanisms have been proposed. One possibility is that UDGs are descendants of normal, more compact dwarf galaxies that fell into the cluster and were "puffed up" by tidal interactions, either from the overall cluster potential or from repeated high-speed encounters with other galaxies (Carleton et al., 2019). This expansion also pushes and expands the stellar component of the galaxy. Another process can happen due to ram-pressure in a dense environment: ram-pressure stripping by the hot intracluster medium (ICM) would remove the galaxy's gas reservoir, quenching its star formation and freezing it in its diffuse, "red and dead" state. An alternative model suggests that UDGs are "tidally-born" objects, formed from material stripped during galaxy interactions (see, e.g. Lelli et al., 2015; Poggianti et al., 2019)

## 1.4 Are LSBs and UDGs part of a continuum?

There is a common fundamental question that we ask ourselves when first discovering these galaxies: are they a truly distinct class of galaxies with unique formation pathways or just the extreme tail of dwarf galaxies? dwarf ellipticals (dEs), dwarf spheroidals (dSphs), and dwarf irregulars (dIrrs). This issue goes beyond semantics as it influences how we see their formation processes, their role in cosmology and their interaction with the rest of the galaxy population.

First of all, the classical dwarf galaxy populations have been well characterized, especially in the Local Group (LG). Dwarf spheroidals (dSphs), for instance, Sculptor, Fornax, and Draco, are the faint, pressure-supported satellites of the Milky Way and Andromeda. They are distinguished by low luminosities ( $M_V \geq 14$ ), old stellar populations, low metallicities, and almost complete lack of gas (see e.g. [McConnachie, 2012a](#)), comprising the red and dead population of our LC. Dwarf ellipticals (dEs), which mainly reside in galaxy clusters like Virgo and Fornax, are a bit more luminous ( $M_V \sim -13$  to  $-18$ ) and have different morphologies nucleated to non-nucleated, but they are also mostly old, inactive, and gas-poor ([Ferguson & Binggeli, 1994](#)). On the other hand, Dwarf irregulars (dIrrs) are gas-rich, star-forming galaxies with irregular morphologies and blue colors, such as the Large and Small Magellanic Clouds (LMC/SMC) and IC10 ([Hunter & Elmegreen, 2004](#)). When contrasting the above properties with what we see from UDGs, the differences are clear: UDGs still occupy a very different region of the parameter space, due their extreme diffuseness. However there is strong evidence that many UDGs and LSBs, are indeed part of a continuum, linking them to classical dwarfs. In their research of LSB galaxies in the Fornax Cluster, [Prole et al. \(2019\)](#) have shown that the transition of structural properties from classical dEs via LSBs to UDGs is gradual. The authors found that a significant overlap of stellar masses, colors, and structural parameters exists between UDGs and the faintest dEs. Additionally, [Venhola et al. \(2017\)](#) and [Leisman et al. \(2017\)](#) have demonstrated that gas-rich, star-forming field UDGs are possible; these properties are typical of dIrrs and rarely of quiescent dSphs. Similar evidence has been found for both kinematics (e.g [Beasley & Trujillo, 2016](#), [van Dokkum et al., 2019](#), [Buttitta et al., 2025](#)) and stellar population studies ([Ferré-Mateu et al., 2023](#), [Doll et al., 2025](#)) have shown a significant fraction of UDGs that adhere to the properties of regular dwarfs, both in stellar velocity dispersion, ages and metallicities. A large fraction of dynamical masses from kinematics lead to halo masses lying in the interval  $M_{200} \sim 10^{10} - 10^{11} M_\odot$ , which is the same as the halo masses of classical dwarf galaxies, indicating that many UDGs are likely to be normal dwarfs that have undergone formation in halos with higher angular momentum or more efficient feedback-induced expansion rather than failed L\* galaxies.

## 1.5 Born UDG: High spin DM halo and the role of stellar feedback

### 1.5.1 Branching from classical dwarfs

A leading proposed path to explain the observed continuity of properties of classical dwarfs with the added feature of extreme diffuseness, is the high-spin DM halo model ([Amorisco & Loeb, 2016](#)). In this picture, all low-mass galaxies form in dark matter halos with masses  $M_{200} \sim 10^{10} - 10^{11} M_{\odot}$ . The final size and surface brightness of the galaxy is then determined primarily by the dimensionless spin parameter  $\lambda$ . When  $\lambda$  is high enough, the angular momentum will make the galaxy appear more diffuse, making it evolve as a UDG instead of a classical dwarf. As detailed in a previous section, superimposed on this is the role of stellar feedback ([Di Cintio et al. \(2017\)](#)). In this model, feedback-driven expansion can act in the range of masses where UDGs are most common ( $M_{\star} \sim 10^7 - 10^8 M_{\odot}$ ), even when the galaxy is hosted by a regular sized DM halo.

The above two scenarios represent the most common and accepted paths for the formation of LSBs: LSBs could be the high-spin end and UDGs the extreme high-spin or high-feedback end. As previously suggested, however, these reasonable formation pathways are not the sole reason why UDG science became so prominent in recent years.

### 1.5.2 When are UDGs not dwarfs?

One of the most controversial topics in UDG science has to do with the extreme values of derived halo masses (via using both the GC - halo mass relationship and kinematics as independent measurements). In particular, these galaxies may form a separate branch in the UDG characterization (the "failed branch"). The most famous examples are globular-cluster rich UDGs, in particular Dragonfly 44 (Fig. 1.3; DF44, see [van Dokkum et al., 2016](#)) which has  $M_{\star} \sim 10^8 M_{\odot}$  while possessing  $\sim 70 - 100$  GCs, far more of what one would expect assuming this was a regular dwarf. Using the GC - halo mass relationship (e.g, [Forbes et al., 2018](#)) this would imply halo masses of  $M_{200} \sim 10^{11} - 10^{12} M_{\odot}$  (comparable to the Milky Way). This would reconcile with the old failed  $L^*$  scenario where UDGs are remnants of early, dark matter-dominated systems that were quenched very early in cosmic history ([van Dokkum et al., 2015](#); [Peng & Lim, 2016](#)). While this model has been difficult to reproduce in cosmological simulations, it could explain the massive dark matter halos observed in some UDGs ([Beasley & Trujillo, 2016](#); [Gannon et al., 2022](#); [Forbes & Gannon, 2024](#)). This explanation has been disputed. Various investigations have raised the point that the relationship be-

tween GC-halo mass may cease at low stellar masses because of increased scatter (Forbes et al., 2018), and that the dynamical mass estimates from GC kinematics may be biased high due to unrelaxed systems or non-virialized orbits (Laporte et al., 2019). Aside from uncertainties and scatter, the derivation of the DM halo mass is subject to potential biases from the extrapolation of the currently visible GCs, while the stellar velocity dispersion is an inherently difficult measurement due to instrumental and geometrical limitations and the possible presence of ordered motion. Some revised measurements of the integrated stellar kinematics have led to lower, more dwarf-like halo masses for these kinds of objects (e.g., Saifollahi et al., 2021). Regardless of the outcome of this discussion, this indicates that a special population of UDGs with a large number of GCs does exist (e.g., Danieli et al., 2022, Forbes & Gannon, 2024).

At the opposite end, there are a few galaxies that have generated even more controversy: the so-called "dark-matter free dwarf galaxies", such as DF2, DF4 (van Dokkum et al., 2018, van Dokkum et al., 2019) and FCC224 (Buzzo et al., 2025) for which velocity dispersions of  $\sim 10$  km/s have been measured (eg., Em-sellem et al., 2019, Danieli et al., 2019). In the case that they are confirmed, these entities would be beyond the explanation of the typical dwarf formation model that expects halos dominated by dark matter. They could be tidal dwarf galaxies that originate from the tidal debris during the collision of galaxies and inherently lack a dark matter halo (e.g., Duc et al., 2014, Montes et al., 2020), or the fragments of galaxies that have been so extensively stripped by tidal forces that their dark matter halo has been removed (Ogiya, 2018).

## 1.6 Made UDG: UDGs and their environment

From the above, systematic studies of LSBs and UDGs is critical for both isolation and cluster environments. If we are to isolate the baryonic processes such as stellar feedback from the observables, we need to disentangle the effect of environment. Many observational studies have shown that UDGs span a wide range of properties in relation to the environment where they reside. For instance, UDGs in dense environments are found to be red, quenched, and spheroidal (Koda et al., 2015; van Dokkum et al., 2015, 2016; Ruiz-Lara et al., 2018; Lee et al., 2020). On the other hand, UDGs in less dense environments, such as in the field or group outskirts, are often bluer, irregular, and gas-rich (van der Burg et al., 2016; Leisman et al., 2017; Román & Trujillo, 2017; Prole et al., 2019). UDGs have even been identified at redshift  $z \sim 0.3$ , providing evidence for their existence at earlier cosmic times (Janssens et al., 2017). The above observational evidence for the important role of environment is not surprising given that less massive galaxies are more prone to change due external influences. Clearly, environment adds another



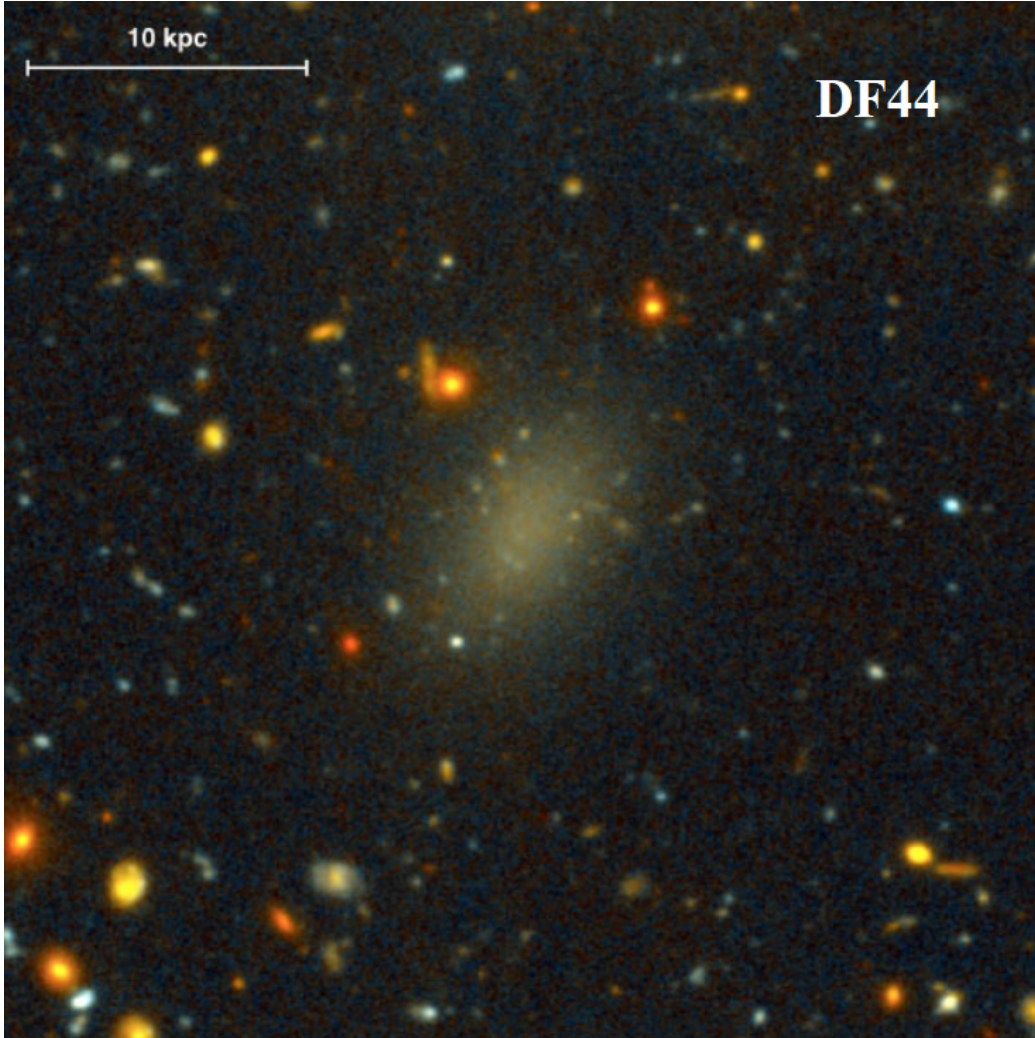


Figure 1.3: Dragonfly 44 with its globular clusters. Credits to [van Dokkum et al. \(2015\)](#)

layer of complexity. This, combined with luminosity constraints is why many UDG studies have focused on (nearby) clusters (Coma, Virgo, Perseus, Hydra-I).

This apparent bimodality points to the necessity of studying specific environmental mechanisms as formation pathways. Models invoking external environmental effects suggest that tidal forces or ram-pressure stripping from a cluster environment could strip gas and quench star formation, transforming a typical dwarf galaxy into a passive, low-surface-brightness object ([Yozin & Bekki, 2015](#); [Ogiya, 2018](#); [Bennet et al., 2018](#); [Müller et al., 2019](#); [Poggianti et al., 2019](#); [Benavides et al., 2023](#)). Among these, the most significant is ram-pressure stripping that happens when a galaxy travels through the hot, dense intracluster medium

(ICM). The ram pressure can remove the galaxy's gas reservoir in around  $\sim 100$  Myr timescales when the galaxy penetrates the cluster core, thus star formation is quenched almost completely and a gas-poor, passively evolving stellar population remains.

Complementing tidal processes are tidal stripping of the outer material and tidal heating, which dynamically expands the stellar component and lowers its surface brightness. Simulations indicate that tidal heating is very efficient for dwarfs with cored dark matter halos (which have already been puffed up by feedback), thus resulting in a natural two-stage evolution: internal feedback produces a cored halo in the field, then cluster tidal forces not only expand the galaxy but also ram pressure quenches star formation (Yozin & Bekki, 2015; Carleton et al., 2019). This can explain many of the morphological properties of observed cluster UDGs. There is also a change that some UDGs have been pre-processed in groups before falling into the cluster and hence, experiencing a two-stage quenching process with gentler stripping (Rong et al., 2017). Special cases may include backsplash galaxies. These galaxies have gone through the cluster center and are coming back to the outskirts, thus, showing up at large radii but having properties of the core-processed (e.g, Bahé et al., 2013). Moreover, galaxy harassment (a series of fast encounters) can, according to the accumulation, increase the thickness of disks and change dwarfs into spheroidal, diffuse systems (Moore et al., 1996). The overall effect of these processes is environmental stripping of gas and dark matter while expanding and heating the stellar component.

To conclude, there are at least a few branches of possible UDG formation (internal, external, and Failed  $L^*$  UDG). Our work has to do with characterizing the relative fraction and probabilities of these processes happening in a diverse set of environments. A summary figure of the most common leading models of UDG formation channels can be found in Fig. 1.4.

## 1.7 Surveys of UDGs

Large-scale photometric surveys like the Systematically Measuring Ultra Diffuse Galaxies survey (SMUDGes, Zaritsky & Behroozi, 2023) provide a broad overview of the UDG population but have limitations in directly comparing stellar populations - particularly in terms of mass and metallicity - due to inconsistencies in distance measurements and the lack of direct metallicity measurements. Recently, Buzzo et al. (2024b) has provided the most comprehensive analysis of UDGs' properties by systematically re-examining UDG samples from Buzzo et al. (2022) and Buzzo et al. (2024) alongside a new nearly ultra-diffuse galaxy (NUDGes) sample, creating a large, unified dataset for statistical studies. The authors have identified two distinct subclasses of UDGs: Class A UDGs, which

| Formation channel                                                                                                                                                                                                                                                         | Expected properties                                                                  |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| <b>failed (<math>M_* \sim 10^{11} M_\odot</math>) galaxies</b><br>(van Dokkum et al. 2015)                                                                                                                                                                                | red, quenched, metal poor & old, gas poor, DM dominated                              |
| <b><i>Internal processes</i></b>                                                                                                                                                                                                                                          |                                                                                      |
| <b>star-formation feedback</b><br>(Di Cintio et al. 2017)                                                                                                                                                                                                                 | gas rich, dwarf-like DM halo                                                         |
| <b>high-spin DM halo</b><br>(Amorisco & Loeb 2016; Rong et al. 2017; Tremmel et al. 2019)                                                                                                                                                                                 | gas rich, dwarf-like DM halo                                                         |
| <b><i>External mechanisms</i></b>                                                                                                                                                                                                                                         |                                                                                      |
| <b>gravitational interactions &amp; merging</b><br>- <i>collisional debris of a merger, i.e. TDG-like</i><br>(Lelli et al. 2015; Duc et al. 2014; Ploekinger et al. 2018)<br>- <i>ram-pressure stripped clumps</i><br>(Poggianti et al. 2019)                             | blue, dust, moderate metallicity, SF, UV emission & gas rich, DM-free                |
| <b>gravitational interactions &amp; merging</b><br>- <i>weak tidal interaction</i><br>(Conselice 2018; Carleton et al. 2021; Bennet et al. 2018; Müller et al. 2019)<br>- <i>high-velocity galaxy collisions</i><br>(Silk 2019; Shin et al. 2020; van Dokkum et al. 2022) | red, metal poor, gas free, DM free                                                   |
| <b>interaction with the environment</b><br>(Yozin & Bekki 2015; Tremmel et al. 2020)                                                                                                                                                                                      | gas poor<br>dwarf-like DM halo                                                       |
| <b>backsplash galaxies</b><br>(Benavides et al. 2021)                                                                                                                                                                                                                     | quenched, isolated, gas poor, dwarf-like DM halo, near to a high density environment |

Figure 1.4: Schematic view of the main formation channels proposed for UDGs. In the left boxes are listed the relevant physical processes. The predicted properties for UDGs, from each formation channel, are reported in the boxes on the right. From LEWIS Paper I.



are less massive, elongated, and found in low-density environments, and Class B UDGs, which are more massive, rounder, and located in denser environments. These findings suggest that Class A UDGs align with the puffed-up dwarf scenario, where internal processes such as stellar feedback and gas expulsion drive their expansion, whereas Class B UDGs may be better explained by the failed galaxy formation scenario, possibly involving early quenching in dense environments.

Spectroscopic studies of UDGs have provided further constraints on stellar population properties of UDGs. Those formed through internal feedback processes tend to have extended star formation histories (SFHs) and younger ages ( $\sim 6 - 9$  Gyr), with metallicities comparable to classical dwarfs ( $[M/H] \sim -0.8$  dex). In contrast, UDGs formed via the failed galaxy mechanism have older stellar populations ( $\sim 10 - 12$  Gyr) and much lower metallicities ( $[M/H] \sim -1.5$  dex; see e.g., [Ferré-Mateu et al., 2018, 2023](#); [Ruiz-Lara et al., 2018](#); [Levitskiy et al., 2025](#)). Studying the largest sample of UDGs with spectroscopic data yet, and covering different environments and globular cluster (GC) richness, [Ferré-Mateu et al. \(2023\)](#) found that the local environment is relevant for possible formation pathways of UDGs. In high-density environments, UDGs seem to have formed stars very early and have short quenching times ( $\sim 6$  Gyr). Conversely, UDGs in low-density environments (as groups and cluster outskirts), have younger ages and a prolonged SFH. These results are compatible with the inferred  $[\alpha/Fe]$  ratios of UDGs, which are overall elevated but particularly for the high-density environment ( $\geq 0.3$  dex). While this is not far from the typical values of metal-poor dwarfs in the Milky Way halo ([Kirby et al., 2011](#)), some outliers do push the average to higher values ([Martín-Navarro et al., 2019](#)).

In summary, having a large statistical spectroscopic sample is fundamental for studying not only the stellar population properties, but also other structural properties such as the amount of dark matter (DM), the stellar kinematics, and the stellar population properties of globular cluster content. In this thesis, we use spectroscopic data from LEWIS<sup>1</sup>.

## 1.8 Spectroscopic observables

We have extensively described some of the leading theories of formation scenarios for UDGs. The ultimate proof, however, will come from the observables. In this work we primarily work on measuring kinematics, metallicities, ages and chemical abundances for UDGs and LSBs. These are the primary ways to assess formation pathways.

<sup>1</sup><https://sites.google.com/inaf.it/lewis/home>

- **Kinematics:** Internal feedback models (e.g, [Di Cintio et al., 2017](#)) predict that strong supernova explosions would not only puff-up the stellar component but also heat the DM halo, causing the central cusp to "flatten" into a core-like pattern. Therefore, a born diffuse UDG should have low stellar velocity dispersions ( $\sigma_*$ ), which may not happen if the galaxy was puffed-up due to environmental processes, which can cause the galaxy to retain the denser, cuspy DM profile of the halo. This analysis, however, often relies on resolved 2D velocity dispersions and assumes a pressure-supported system. This is hard to do in practice due data limitations (see LEWIS Paper II). However, a simpler analysis that probes the absence or presence of coherent rotation is often feasible as it directly helps to favor certain formation scenarios over others: for example, the presence of coherent rotation directly favors less intense processes such as high-spin DM halo, in comparison to violent processes which may have disrupted the ordered motion.
- **Stellar ages and star formation histories:** Stellar ages, percentiles of the cumulative SFH distribution, and other similar quantities, when used along other chemical clocks, directly help probing the underlying quenching mechanism. Galaxies with extended feedback-driven cycles should show more prolonged SFHs with evidence for multiple episodes, whereas stronger, earlier quenching (such as the failed hypothesis) would show an early, often single peak at early epochs. We can directly test some of these properties against simulations ([Sales et al., 2020](#), [Benavides et al., 2023](#)).
- **Metallicities:** Fundamentally, metallicity can track how much gas in a galaxy was expelled in feedback processes compared to how much it currently has. Supernova feedback models predict that the efficiency of outflows is much higher for metal-rich gas, so strong outflows would primarily drive the metals out to the ISM and mostly keep the metal-poor gas, forming the failed branch. Failed galaxies would yield lower metallicities than what is expected for their mass (e.g [Buzzo et al., 2024b](#)), probing the intensity of feedback directly.
- **Chemical abundances:** They allow us to have another, clear and independent look at how fast the ancient starburst was. This is traced by the ratio of Type-Ia (primarily expelling Fe) to Type-II supernova (primarily expelling heavier elements such as Mg), which can be measured by  $[\alpha/\text{Fe}]$ , often traced by  $[\text{Mg}/\text{Fe}]$ . The failed scenario, would naturally have a high  $[\text{Mg}/\text{Fe}]$  content by comparison.

## 1.9 Insights from simulations

Simulations have provided a major advance in our understanding of UDGs. For instance, [Sales et al. \(2020\)](#) used the Illustris TNG100-1 simulation to study the formation of UDGs, distinguishing between two main populations: UDGs that are “born” diffuse (B-UDGs) and UDGs that are transformed into diffuse galaxies through tidal stripping (T-UDGs). B-UDGs are typically field galaxies that retain their low surface brightness even after being accreted into clusters, while T-UDGs have experienced significant mass loss due to tidal interactions after entering the cluster environment. According to [Sales et al. \(2020\)](#), T-UDGs are older, more metal-rich, and have lower velocity dispersions than B-UDGs. The distinction between these two populations, which has been supported by additional observational work (e.g., [Gannon et al., 2020](#); [Ferré-Mateu et al., 2018, 2023](#)), offers a powerful framework for understanding the diverse properties of UDGs across different environments.

Recently, [Cardona-Barrero et al. \(2023\)](#) and [Benavides et al. \(2024\)](#) have provided valuable insights on the expected metallicity profiles for UDGs and their implications, identifying stellar population profiles as another set of observables that directly constrain evolution models. In particular, [Benavides et al. \(2024\)](#) TNG50 simulations represent the physics of a classical galaxy formation with a high-spin DM halo, in which we expect declining metallicity profiles: star formation, happening in an inside-out manner due to the concentrated nature of the DM profile. In this way, because the center forms various generations of stars which have enriched gas, and in the outskirts the SF is lower, a negative metallicity and alpha-enhancement profiles are expected. In this process, the large angular momentum spreads the gas into extended disks, which help preserve the steeper gradients that resemble the classical “inside-out” growth pattern. Meanwhile, in [Cardona-Barrero et al. \(2023\)](#) NIHAO simulations this situation changes slightly: feedback processes at the center are so strong that it can drive the enriched metals from the center towards the outskirts in a mixing process, flattening the whole gradient.

## 1.10 Specific Objectives and the Structure of this Thesis

Our aim is to use spectroscopic tools to provide observational data and evidence for the presence or absence of the aforementioned proposed formation channels in UDGs. In particular, we focus on the UDG and LSB population in Hydra-I cluster ([Iodice et al., 2023](#)), and use it as a test of both internal, external and even the “failed-galaxy” formation mechanisms. Hopefully, our measurements provide

valuable data for future simulations, and can help pave the way for the next decade of UDG science.

In Chapter II, we present the LEWIS project, its observations and the data reduction process. We follow on Chapter III with the fundamental preliminary work of further spectroscopic analysis: the stellar kinematics. Chapter IV and V are the main original contribution of this thesis, where we explain in detail the 1D and 2D stellar population properties of this sample of LSBs and UDGs. We finalize with a summary of conclusions.

## Chapter 2

# LEWIS: project, data and observations

*The data reduction procedure and scientific methods presented here and the next chapter, are described in [Iodice et al. \(2023\)](#). Here, my main contribution was to establish the pipelines and characterize the stellar population and kinematics for a sample UDG (UDG11), laying the foundation for future work. Additionally, I was in charge of making tests and understanding the biases regarding the recovery of stellar kinematics for low S/N data. I was also part of the data reduction team and helped to set the pipeline for LEWIS. In this section, we present the main methods and data used for our studies. The data, being MUSE observations of the Hydra-I cluster, have already been presented in several papers, along with a description of the cluster (e.g. [Iodice et al., 2020a](#), [Spavone et al., 2024](#), [La Marca et al., 2022b](#)). Here, we present a comprehensive description of the cluster collected from this literature, alongside the specific methods utilised by the authors to analyse the data.*

### 2.1 The Hydra-I Cluster

The Hydra I cluster (Abel 1060,  $\alpha$  (J2000) = 10h 36m 42.7100s,  $\delta$  (J2000) =  $-27^{\circ}31'42.900''$ ) is located a distance of  $51 \pm 6$  Mpc ([Christlein & Zabludoff, 2003](#)), such that  $1'' = 247.3$  pc.. Aside from a few other options such as Coma, Virgo and Perseus, Hydra-I is one of the few options available to study galaxies at the extreme ends of the low-luminosity regime, given its relative proximity.

Compared to more distant massive clusters like Coma or Perseus, Hydra-I allow us to study cluster physics at a more modest mass and closer distances (such as the Virgo cluster) while remaining isolated enough in redshift space to minimize foreground and background contamination. In particular, previous astronomical

surveys have found a void beneath and in front our line-of-sight (LOS, [Richter et al., 1982](#), [Richter, 1987](#)) which significantly reduces the contamination from foreground and background objects, therefore making Hydra-I valuable for confirming cluster memberships and studying environmental effects.

### 2.1.1 Main properties

Hydra-I (Fig. 2.1) is rich and massive, with a virial mass of around  $1.9 - 2.1 \cdot 10^{14} h^{-1} M_{\odot}$  ([Girardi et al., 1998](#), [Tamura et al., 2000](#)). Its mean recession velocity is  $cz = 3684 \pm 46 \text{ km s}^{-1}$  with a velocity dispersion of  $\sigma = 724 \pm 31 \text{ km s}^{-1}$  ([Christlein & Zabludoff, 2003](#)). At the center of the cluster we find two bright sources: NGC3311 and NGC3309. These sources, dominating the central region of the cluster (core) are also the locus of significant X-ray emission, which maps the hot, intra-cluster gas. The X-ray emission is slightly shifted towards the northwest region of the cluster (see Fig. 2.2 and Fig. 2.3) and its bright luminosity infers a total mass that suggest a significant fraction of mass being currently "hidden". The above, given recent scientific discussions about the possibility of very faint, diffuse galaxies containing a high amount of dark matter content make the study of this cluster region particularly interesting.

Recent studies ([Spavone et al., 2024](#), [La Marca et al., 2022a](#)) point out that this cluster is in a state of ongoing mass assembly. This is suggested by the sources at the barycenter of the cluster, which hint at a recent or ongoing subcluster merger. Broadly speaking, they have separated the cluster in three main regions:

- The Core: Mostly dominated by the two bright galaxies mentioned before. The region show signs of dynamic interactions revealed by photometry: isophotes appear distorted on some of the smaller galaxies and stellar debris is found near NGC3311 ([Spavone et al., 2024](#))
- Northern group: Large amounts of intra-cluster-light (ICL) is found here. The structure is filament-like and some tidally disrupted dwarfs (e.g HCG 087) are found here.
- Southeaster group: Seem to present a foreground sub-population of galaxies which seem to be falling into the main potential of the cluster.

Each of these regions may be considered as a different laboratory as different physical processes are observed (e.g gravital interactions mostly happening at the center and northern groups while the infalling group seem mostly affected by ram-pressure stripping, further supported by detections of neutral hydrogen).



Figure 2.1: A color composite of the VST images of Hydra-I. Credits: ESO/INAF/M. Spavone, E. Iodice

### 2.1.2 Galaxy Identification and Photometric studies (VST/VEGAS Data)

The VST Early-type GALaxy Survey (VEGAS; [Capaccioli et al., 2015](#), [Iodice et al., 2021](#)) is a deep, multi-band (u,g,r,i) imaging survey which has mapped, among other environments and dwarfs, the faint and diffuse population of galaxies within the Hydra-I cluster. Using special VST capabilities, more than 200 new galaxy members have been discovered by this work in the range  $-18.5 < M_r < -11.5$  mag within the central regions of the cluster.

Recently, the focus has been placed on the extreme diffuse tail of this sample, including several UDGs ([Iodice et al., 2020a](#), [La Marca et al., 2022b](#)) which were the first step towards a subsequent study with MUSE (see next Sec. 2.2). Other than these galaxies, the intra-cluster light (ICL) has also been a topic of discussion ([Spavone et al., 2024](#)), due its possible link with past dynamic interactions. In Hydra-I this ICL has a total luminosity of  $L_{ICL} \sim 2.2 \cdot 10^{11} L_{\odot}$  which comprises  $\sim 12\%$  of the total luminosity of the surveyed area of the cluster.



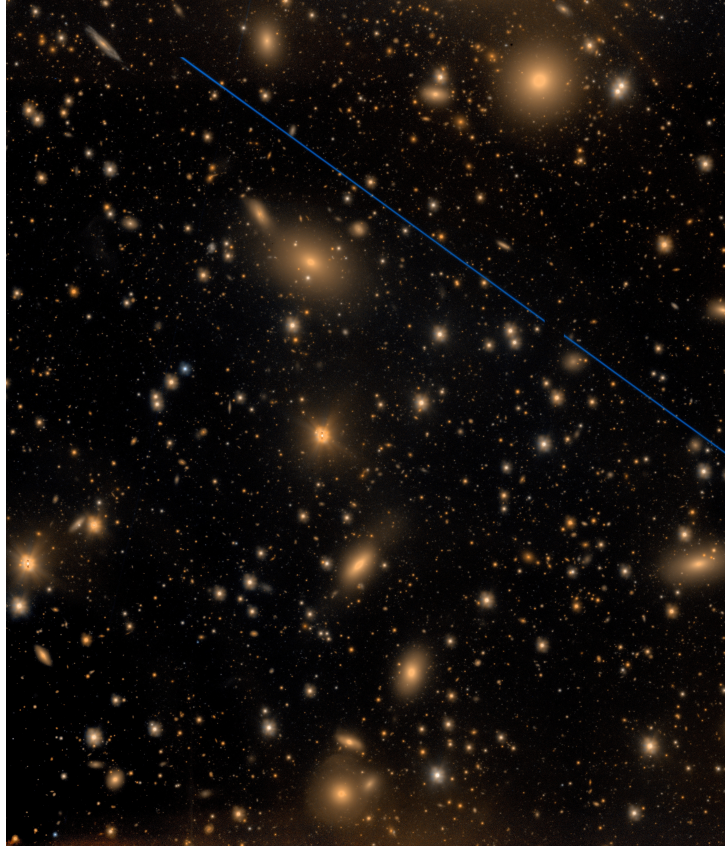


Figure 2.2: The North Group (Spavone et al., 2024)

## 2.2 Spectroscopic observables to constrain galaxy evolution and baryonic physics

The Looking into the faintEst With MUSE (P.I. E. Iodice) is an ESO Large Programme approved in 2021, with 133.5 hours granted with the Multi Unit Spectroscopic Explorer (MUSE@VLT). LEWIS data have mapped, for the first time, a sample of 30 LSB galaxies in the Hydra-I cluster. These galaxies represent the most extreme tail of the surface-brightness versus size distribution (Iodice et al., 2020a; La Marca et al., 2022a) mapped in Hydra-I from the VEGAS survey<sup>1</sup>. The majority (22) of LEWIS galaxies are classified as UDGs according to the van Dokkum et al., 2015 definition. The rest are strict LSBs, close to the UDG definition but slightly brighter and/or smaller, akin to the NUDGEs (nearly-UDGs) definition from Forbes & Gannon, 2024. Unlike most previous spectroscopic studies of UDGs, which compiled samples of galaxies from various environments (e.g.,

<sup>1</sup><https://sites.google.com/inaf.it/vegas/home>

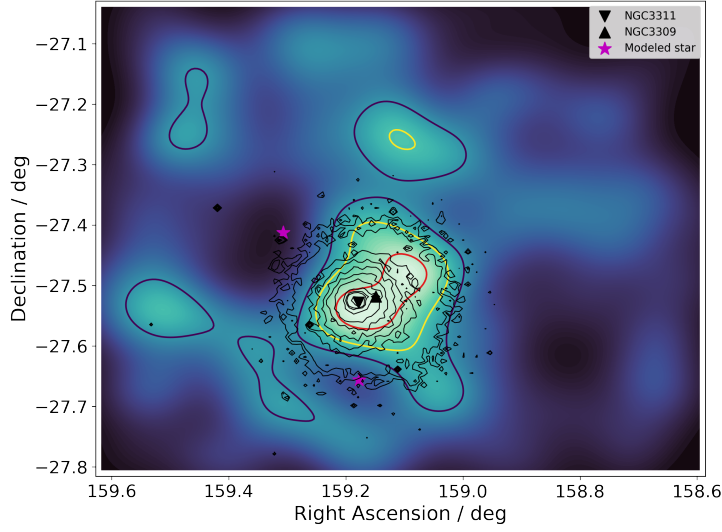


Figure 2.3: X-ray density map of Hydra-I. Adapted from [La Marca et al. \(2022b\)](#)

[Ferré-Mateu et al., 2023](#), [Gannon et al., 2024](#)) the LEWIS sample is homogeneous, allowing for the study of a substantial number of galaxies within a single environment. This is crucial for understanding how the environment affects galaxies' properties and discriminating between different classes of UDGs.

The LEWIS project has been extensively presented in [Iodice et al. 2023](#) (hereafter Paper I) together with the analysis of the location of LEWIS galaxies in the projected phase-space ([Forbes et al., 2023](#)). The LEWIS data allowed us to derive, for the first time, 2D velocity maps for a substantial sample of UDGs ([Buttitta et al., 2025](#), hereafter Paper II). In LEWIS Paper III ([Hartke et al., 2025](#)), we constrained the formation history of the intriguing UDG32, finding that it has been formed from pre-processed material (see also [Iodice et al., 2021](#)) and in Paper IV ([Mirabile et al., 2025](#)), we constrain the characteristics of globular cluster populations of four UDGs.

### 2.2.1 The science case for LEWIS

LEWIS directly addresses at least two problems, both in theoretical and observational astrophysics:

- Enlarges and deepens the amount of studied galaxies in the low density regime. In particular, the missing satellites problem posits that there seems to be a missing fraction of low-mass dwarfs at the low-mass range, contrary to expectations. Constraining kinematic properties of such galaxies and their DM content helps understand the physics at these regimes.

| Object | R.A.<br>[J2000] | DEC<br>[J2000] | $M_r$<br>[mag] | $M_*$<br>[ $10^8 M_\odot$ ] | $\mu_e$<br>[mag/arcsec <sup>2</sup> ] | $\mu_0$<br>[mag/arcsec <sup>2</sup> ] | $R_e$<br>[kpc] |
|--------|-----------------|----------------|----------------|-----------------------------|---------------------------------------|---------------------------------------|----------------|
| (1)    | (2)             | (3)            | (4)            | (5)                         | (6)                                   | (7)                                   | (8)            |
| UDG 1  | 10:37:54.12     | -27:09:37.50   | -15.48         | 1.12                        | 25.2±0.1                              | 24.2±0.1                              | 1.75±0.12      |
| UDG 2  | 10:37:34.89     | -27:10:29.94   | -14.27         | 0.55                        | 26.2±0.1                              | 25.0±0.1                              | 1.55±0.12      |
| UDG 3  | 10:36:58.63     | -27:08:10.21   | -14.70         | 1.65                        | 26.1±0.2                              | 25.2±0.2                              | 1.88±0.12      |
| UDG 4  | 10:37:02.64     | -27:12:15.01   | -16.03         | 10.6                        | 25.8±0.1                              | 24.9±0.1                              | 2.64±0.12      |
| UDG 5  | 10:36:07.68     | -27:19:03.26   | -14.66         | 1.16                        | 25.3±0.3                              | 23.7±0.3                              | 1.42±0.12      |
| UDG 6  | 10:36:35.80     | -27:19:36.12   | -14.38         | 0.32                        | 25.3±0.1                              | 24.1±0.1                              | 1.37±0.12      |
| UDG 7  | 10:36:37.16     | -27:22:54.93   | -13.72         | 0.49                        | 26.9±0.4                              | 24.4±0.4                              | 1.66±0.12      |
| UDG 8  | 10:38:14.59     | -27:24:27.07   | -14.87         | 0.53                        | 25.0±0.6                              | 23.2±0.6                              | 1.40±0.12      |
| UDG 9  | 10:37:22.85     | -27:36:02.80   | -15.16         | 1.78                        | 26.8±0.2                              | 24.2±0.2                              | 3.46±0.12      |
| UDG 10 | 10:35:27.32     | -27:33:03.86   | -13.89         | 0.26                        | 27.3±0.3                              | 24.3±0.3                              | 2.29±0.10      |
| UDG 11 | 10:34:59.55     | -27:25:37.95   | -14.75         | 0.63                        | 25.7±0.1                              | 24.4±0.1                              | 1.66±0.12      |
| UDG 12 | 10:36:45.55     | -27:48:12.73   | -14.30         | 1.19                        | 26.2±0.2                              | 25.1±0.2                              | 1.64±0.12      |
| UDG 13 | 10:36:14.49     | -27:30:26.60   | -12.73         | 0.20                        | 27.3±0.1                              | 24.2±0.2                              | 1.60±0.20      |
| UDG 15 | 10:36:02.55     | -27:36:19.57   | -11.95         | 0.06                        | 27.7±0.2                              | 25.0±0.3                              | 1.51±0.15      |
| UDG 16 | 10:36:25.30     | -27:14:14.74   | -12.84         | 0.11                        | 27.6±0.1                              | 25.9±0.2                              | 1.75±0.12      |
| UDG 17 | 10:36:41.72     | -27:16:37.48   | -13.99         | 1.20                        | 26.7±0.1                              | 24.9±0.1                              | 1.50±0.20      |
| UDG 18 | 10:36:16.82     | -27:20:16.84   | -12.28         | 0.09                        | 27.6±0.2                              | 25.6±0.2                              | 1.64±0.12      |
| UDG 20 | 10:38:04.43     | -27:29:50.18   | -12.95         | 0.14                        | 27.3±0.1                              | 26.0±0.3                              | 1.97±0.12      |
| UDG 21 | 10:36:54.17     | -27:36:55.07   | -12.78         | 0.11                        | 27.3±0.5                              | 24.0±0.4                              | 1.50±0.12      |
| UDG 22 | 10:34:40.97     | -27:42:03.27   | -13.92         | 0.36                        | 26.5±0.1                              | 25.3±0.2                              | 3.60±0.12      |
| UDG 23 | 10:35:27.70     | -27:46:16.58   | -14.11         | 0.34                        | 27.2±0.2                              | 24.3±0.3                              | 2.47±0.20      |
| UDG 32 | 10:37:04.20     | -27:42:53.92   | -14.65         | 8.00                        | 27.5±1.0                              | 26.2±1.0                              | 3.80±1.00      |

|       |             |              |        |      |          |          |           |
|-------|-------------|--------------|--------|------|----------|----------|-----------|
| LSB 1 | 10:36:00.03 | -27:28:58.17 | -12.38 | 0.06 | 26.6±0.1 | 23.9±0.2 | 0.81±0.90 |
| LSB 2 | 10:36:09.65 | -27:30:51.61 | -12.87 | 0.15 | 25.8±0.1 | 23.8±0.1 | 0.57±0.12 |
| LSB 3 | 10:36:26.55 | -27:32:41.61 | -12.03 | 0.05 | 26.6±0.8 | 23.7±0.6 | 0.70±0.12 |
| LSB 4 | 10:36:19.71 | -27:13:41.68 | -13.83 | 0.25 | 26.5±0.1 | 24.7±0.1 | 1.48±0.12 |
| LSB 5 | 10:36:41.26 | -27:48:20.54 | -13.74 | 0.40 | 25.8±0.1 | 23.9±0.1 | 1.42±0.12 |
| LSB 6 | 10:38:04.67 | -27:32:44.99 | -15.47 | 1.84 | 26.0±0.1 | 23.0±0.2 | 4.00±1.00 |
| LSB 7 | 10:36:18.70 | -27:37:17.93 | -15.68 | 2.59 | 25.3±0.1 | 22.7±0.1 | 1.97±0.10 |
| LSB 8 | 10:37:54.47 | -27:15:31.12 | -15.27 | 1.44 | 25.1±0.1 | 23.2±0.2 | 1.51±0.20 |

Column 1 reports the name of the target in the LEWIS sample. In columns 2 and 3 we list the coordinates. In columns 4 and 5 are reported the total  $r$ -band magnitude and stellar mass, respectively, derived from the  $r$ -band image. Columns 6 to 8 list the structural parameters in the  $g$  band published by [Iodice et al. \(2020b\)](#) and [La Marca et al. \(2022a\)](#): the effective surface brightness, the central surface brightness and the effective radius in kpc, respectively. Magnitudes and colours are corrected for Galactic extinction using values from [Schlegel et al. \(1998\)](#). Adapted from Paper II.

- There was a lack of a large catalogue for a single cluster environment. Recent spectroscopic studies have only been able to compile catalogues from different clusters such as Coma, Virgo and Perseus. Focusing in a single environment helps us to constrain the possible effect of the cluster in the evolution pathways of these galaxies.

### 2.2.2 Project scopes and objectives

There are three main lines of science we address at LEWIS, in particular:

- **Stellar kinematics:** in particular, stellar kinematics in low density systems allow us to constrain the dark matter content in these galaxies. Given their low baryonic density, they are essential  $\Lambda$ CDM simulations (Martin et al., 2019). While Local Group LSBs can already provide excellent constraints on DM models (e.g, Ackermann et al., 2015), it is still uncertain whether these limits are valid in a high-density environment where tidal forces and quenching mechanisms may change drastically.
- **Stellar populations:** For the first time we are able to probe age and metallicity estimates for a comparatively large sample of UDGs through a large portion of a single cluster. The MUSE spectra also allows for a 2D characterization of stellar population properties which helps constrain feedback mechanisms (inside-out versus outside-in star formation). This is the primary area of the project we address in this thesis. The first part of these results are presented in Doll et al., 2025
- **Globular Clusters:** Globular clusters allow, first of all, for another independent measurement of the DM content via the number of GCs present in each galaxy (see, e.g Burkert & Forbes, 2020). Moreover it can help constrain formation pathways as GC content has been thought to correlate with the effect of tidal interactions within the cluster (see, e.g Forbes et al., 2023)

From the above, the main properties we derive are effective velocity dispersion ( $\sigma_{eff}$ ), median age, metallicity ([M/H]) and [Mg/Fe]. For the sources with enough S/N, we also perform a 2D analysis to get velocity gradients along an axis to constrain rotation ( $\Delta V$ ) and metallicity gradients to constrain feedback processes ( $\Delta[M/H]$ ). In Fig. 2.4 we describe the main parameters to be derived by each subarea of study. In Fig. 2.5 we describe the overall flow of the whole project instead. In particular, the base of the project was the photometric characterization of the most diffuse LSB populations from VEGAS, studied in Iodice et al. (2020a) and La Marca et al. (2022b). Later on, Paper I came out and formally described the whole project, along with a cluster membership analysis and a full 1D analysis for

a single LEWIS source (UDG11). As a team, we worked in applying an improved, custom data reduction pipeline to the whole currently available sample of LEWIS galaxies. After this process, most of the collection of LEWIS papers started to appear. In this chapter, we focus on the first three blocks of this flowchart. In the next chapter, Ch. 3, we focus on the main kinematic properties of the sample, necessary for a stellar population analysis. The fourth and fifth chapter present LEWIS Paper V and VI, dedicated to 1D and 2D stellar populations respectively, while we briefly touch on some special sources for the sixth chapter.

LEWIS data targets 30 photometrically detected LSB sources from [La Marca et al. \(2022b\)](#) and [Iodice et al. \(2020a\)](#), for which we intended to derive spectra with enough quality, following a similar path from the works of [Emsellem et al. \(2019\)](#) and [Fensch et al. \(2019\)](#) for DF2. Out of these 30 galaxies, 22 are classified as UDGs and 8 LSBs and have an effective surface brightness of  $25 < \mu_g < 27.5$  mag/arcsec<sup>2</sup>. This assures a minimum S/N of 5-10 per spaxel in a 2-6 hours of integration time. Two targets were removed from the original sample of 32 LSBs (UDG14 and UDG19 in [La Marca et al. \(2022b\)](#)) due to their very low surface brightness ( $\mu_g = 28.5$  mag/arcsec<sup>2</sup>)

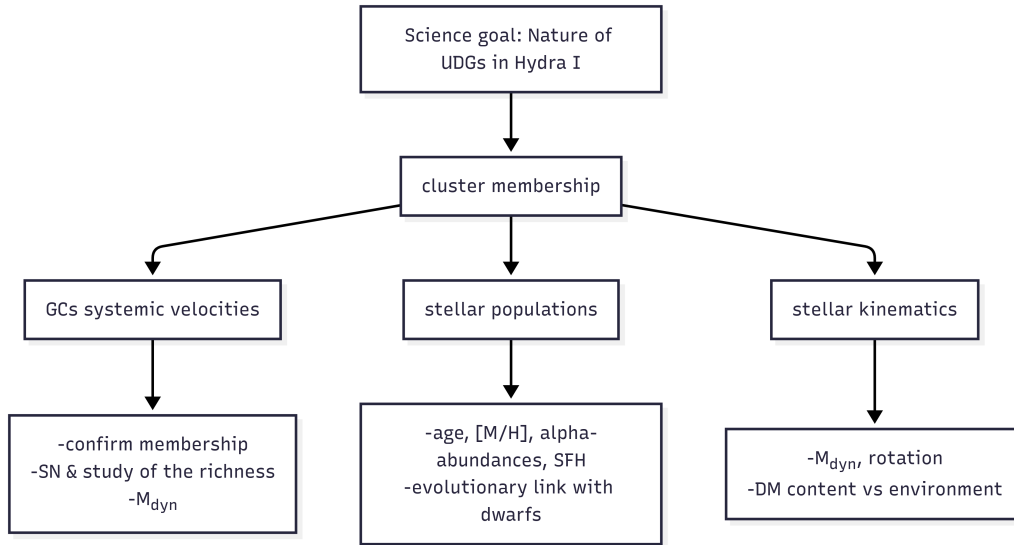


Figure 2.4: The main specific objectives of the LEWIS project. Credits: E. Iodice

### 2.2.3 Photometric parameters and the effective radius

Photometric parameters and the effective radius are derived in [Iodice et al. \(2020a\)](#) and [La Marca et al. \(2022b\)](#). Their first step in both approaches is isophote fitting,

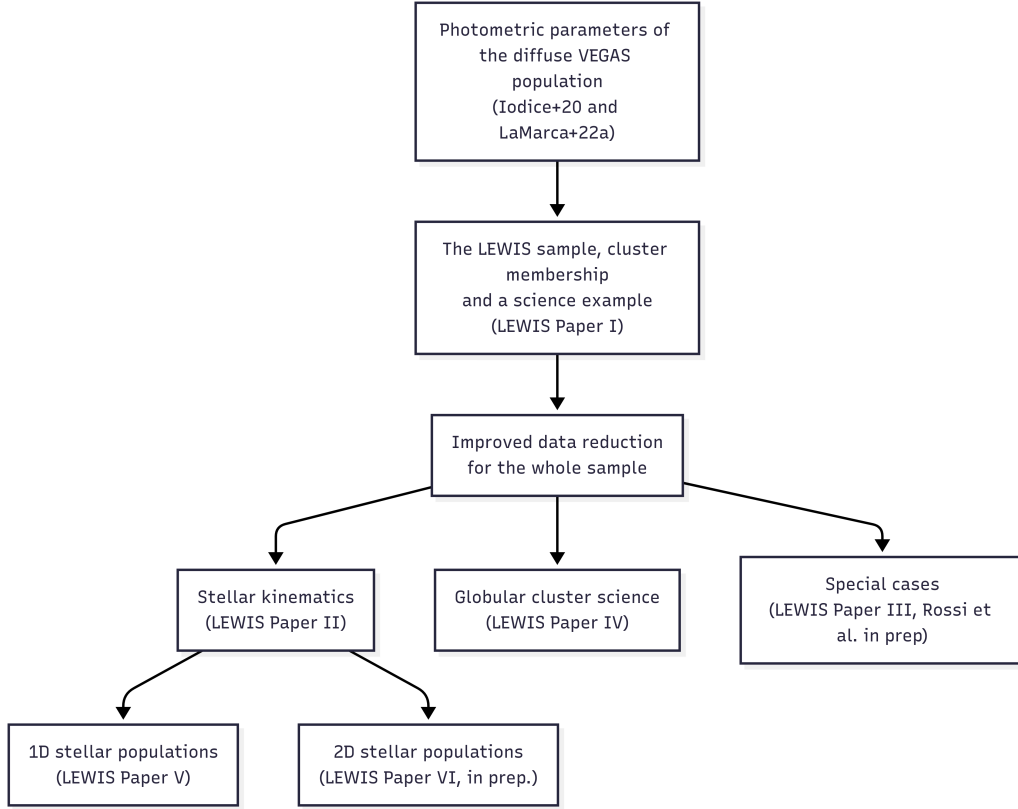


Figure 2.5: Flowchart describing the workflow of the LEWIS project, starting from the photometric selection, all the way down towards the more specific objectives.

in which they trace the regions of constant surface brightness on the galaxy images. Through this procedure, they yield azimuthally average surface brightness profiles in both  $g$  and  $r$  bands. With these profiles, total integrated magnitudes and mean  $g-r$  colors can be determined for the galaxy. When constraining parameters, they use a Sersic-profile fit of the galaxy light distribution. When modeling this function to the  $g$ -band data, they obtain two important structural parameters:

- The central surface brightness
- The effective radius ( $R_e$ ), containing half of the total integrated light from the galaxy

Finally, all computed magnitudes and colors are corrected for Galactic extinction. While most of their analysis is similar, there are a few minor differences in their approach: The 2020 study used a 2D fit on the galaxy image via GALFIT



to derive the above parameters, whereas the second work used a 1D fit to the azimuthally averaged surface brightness profile. For the isophote fitting [Iodice et al. \(2020a\)](#) and [La Marca et al. \(2022b\)](#) used ELLIPSE within IRAF and PHOTUTILS respectively.

## 2.2.4 Observing Strategy and Data Acquisition

Observations for the LEWIS survey were conducted using the Multi Unit Spectroscopic Explorer (MUSE) integral-field spectrograph at the European Southern Observatory (ESO, Program Id. 108.222P, P.I. Iodice). For this program, the instrument was engaged in Wide Field Mode, offering a field-of-view (FOV) of  $1' \times 1'$  and a spatial resolution of 0.2 arcseconds per pixel. The instrument covers a wavelength range of 4800-9300 Å with a spectral sampling of 1.25 Å/pixel and a mostly flat resolution profile (FWHM = 2.69 Å ; see Paper II for the details on the instrumental line-spread function). Observations were carried out starting in September 2021 during ESO period P108, and continued through P109 and P110. Observations were required under dark and clear sky conditions and in Service Mode. Initial priority was given to the sources that were consistent with the UDG definition of [van Dokkum et al. \(2015\)](#) and with clear GC candidates such as UDG3 and UDG11. Observations ended in a last run from January to March 2025 with the inclusion of new Observation Blocks (OBs) for UDG3, UDG17 and UDG22.

## 2.3 Data Reduction and Preparation

### 2.3.1 LEWIS sample: observations and data reduction

The LEWIS sample, previously presented in Paper I, is composed of 30 galaxies, 22 of them classified as UDGs and eight are LSBs. From these 30 galaxies of the original sample, 5 were excluded because of the presence of the Ferris wheel-like pattern, or because the exposure was heavily contaminated by the presence of a bright saturated star or nearby galaxy (see e.g. Paper II).

The observations and data reduction of the final LEWIS sample are described in detail in Paper II, but we summarize here the main steps adopted for data reduction and variations from the standard MUSE pipeline routine ([Weilbacher et al., 2020](#)), running in the ESOREFLEX environment ([Freudling et al., 2013](#)). The standard approach is adopted for the bias and overscan subtraction, lamp flat-fielding correction, wavelength calibration, determination of the line spread function (LSF), and illumination correction. The main changes are adopted to improve on the sky subtraction and the flux calibration pipelines.

For each galaxy in the sample, we built a custom mask using the white light image from the MUSE data-cube, where all the foreground/background/spurious sources, including the contribution of the target, are marked. This resulting mask is then passed to the ESOREFLEX routine, to estimate the sky in all unmasked regions of the cube. To better regulate flux fluctuations due to sky variations in the final datacube, the second step consists of normalizing each combined exposure via calibration factors. The deep-field autocalibration method in ESOREFLEX was used for every exposure in addition to a multiplicative correction at the final combination step (see Paper I and Paper II). Finally, we perform a sky line residual subtraction using the Zurich Atmospheric Purge algorithm (ZAP; [Soto et al., 2016](#)) with custom parameters (see Paper II).

### 2.3.2 MUSE Data Reduction

We present in this chapter the data reduction pipeline that we established for the MUSE observations of LEWIS galaxies. We begin with the standard data reduction within the ESOREflex environment and explain its deficiency, i.e., the severe contamination introduced by sky residuals. We then introduce our enhanced data reduction pipeline including the generation of a tailored sky mask, two-pass flux normalization using ‘deepfield’ autocalibration, and then subsequently the final, more accurate sky subtraction using the ZAP (Zurich Atmosphere Purge) algorithm. We show that this enhanced pipeline produces an enhanced final data cube allowing for more accurate scientific analysis of these difficult targets.

#### Standard ESOREFLEX Pipeline routine and ZAP

The work of studying the spectral properties of a diffuse set of galaxies like LEWIS demands an excellent data reduction quality. Being IFU observations, MUSE data offers a spectrum for each pixel within the FoV, with a three dimensional data cube (two spacial and one spectral) being the final product. The low, extended character of our targets causes their surface brightness to be very close to that of the night sky. This makes them especially prone to significant contamination from sky emission lines and other instrumental effects. Thus, it is important to have an adequate sky subtraction and correct for flux calibration over the entire field.

Data reduction was carried out initially with the standard MUSE data reduction pipeline (v2.8.3) within the ESOREflex environment (v3.9) as per the guidelines laid out in the user manual. The standard pipeline performs a set of standard processing steps:

- Bias and Dark correction: subtraction of the baseline electronic signal and thermal noise of the CCD



- Flat-fielding: Correction for pixel-to-pixel sensitivity variations
- Wavelength Calibration: Placement of a standard wavelength in each layer of the datacube via the use of arc lamp exposures.
- Illumination correction: Removal of large-scale brightness variations in the FoV via twilight flat exposures
- Flux calibration: Conversion of instrumental counts to physical flux units via a standard star observation
- Telluric Correction: Via elimination of absorption in the Earth's atmosphere

The standard procedure, while useful, had drawbacks. It quickly became apparent that the standard pipeline, and its built-in sky subtraction scripts were, not suitable for our science requirements. The produced data cubes were severely plagued by sky residuals, especially at the red part of the spectrum ( $> 7000 \text{ \AA}$ ), which would have a very detrimental effect on the analysis of crucial stellar absorption features such as the CaII triplet. This required the creation of a new pipeline especially made to counter these problems.

### Implemented Custom Routines

Our enhanced pipeline improves on the standard ESOReflex reduction with a set of custom steps aimed at ensuring maximum sky subtraction and flux normalisation. The reduction process involves five steps: (1) constructing a custom sky mask; (2) executing the ESOReflex pipeline with enhanced parameters; (3) registering and scaling each individual exposure; (4) merging the exposures into a final datacube; (5) executing a custom, high-quality sky subtraction via ZAP

#### Block 1: Creating a custom sky mask

The first, and arguably most important task in the enhanced pipeline is the creation of a custom mask to clearly identify the regions of sky within the FoV. This keeps the algorithms for sky subtraction from being influenced by starlight from the target galaxy or from any other contaminants sufficiently close in the sky. This task is managed by two scripts developed by the team, one made to create the mask, and other auxiliary script to adapt the headers of each individual file to the correct format.

The first script creates the initial mask. It begins by making a two-dimensional R-band image from an early datacube (made with the standard data reduction algorithm). Then, we use photutils ([Bradley, 2023](#)) to generate a 2D background

subtraction followed by the detection of all sources within the field using a sigma-clipping technique. Finally, we cover the central UDG using an elliptical aperture. The parameters that are to be set in the script include the position angle (PA) and ellipticity. These parameters are derived from isophotal analysis (see subsection below) and are critical for proper masking of the target source for the background identification. Contrary to the above quantities, there are variables that are not fixed, which are the exact extent of the ellipse and the exact sigma clipping threshold. These are adjusted by eye, because their optimal values can be dependent on the brightness of the sources nearby. After running the script, we are left with a FITS file in which the sky pixels are represented by 1 and all detected objects (target galaxy and foreground objects) are 0.

Finally, we run the second script, which prepares the headers. This script makes several duplicates of the master sky mask from the previous step and aligns their headers to be identical to the identifying header information for a single raw science exposure. This is particularly important as ESOREflex reduces each exposure in a separate manner. Thus is important to unambiguously pair the correct mask with the correct exposure.

## Block 2: ESOREflex Reduction

Once we have the custom sky masks from the last step, we run ESOREflex on each OB individually. Compared to the standard pipeline we ran before generating a master sky mask, we modify the following default settings:

- 'SkyMethod = auto': By changing this parameter, we instruct the pipeline to use the custom sky mask files, obtained in the previous steps, to identify the sky regions from galaxy light, rather than trying to model it using standard algorithms.
- 'autocal = deepfield': This parameter, originally thought for their use in MUSE deep fields, attempts a "slice by slice" flux calibration. This corrects for small throughput differences between these cube slices within each exposure. This prevents non-uniformity effects (e.g "striping") in the final datacube.
- 'ignore = 0.02': We instruct the sky estimation algorithm to ignore the brightest 2% of the pixels within the sky, unmasked regions. This is just to add an extra layer of security on top of the sigma-clipping algorithm from Block 1.

One important part of this new reduction procedure is that the later parts, including the final combination of exposures, is managed manually in the following Block.

**Block 3 and 4: Exposure scaling and combination**

Block 3 and 4 contain specific, custom routines that are injected into the ESOReflex environment. While this often works without issues, sometimes bugs or errors can be present (see below on exposure combination)

After the individual OB reduction from the last step, we perform a manual alignment of each exposure, by adjusting the World Coordinate System (WCS) information within the FITS headers based on a table containing all offsets from each exposure. After this, we move to the actual "exposure scaling" procedure: for each pair of overlapping science exposures, the algorithm identifies common pixels among them. Then, it solves for a linear equation in which each flux from each pixel is assumed to follow a linear relationship when compared to the other exposure. The algorithm then builds a large linear system that solves for the coefficients of these linear relationships using a least-squares method. Ultimately, this technique bring all OB's to a common photometric zero-point by applying these coefficients to the respective exposures.

After this, we use the standard exposure combination technique from ESOReflex. Sometimes, this technique would fail. In this case we apply a manual technique instead performed as contingency. For this, we create a script for the generation of a file that lists all the rescaled pixel tables. It then makes a call to the respective ESOReflex tools directly by a terminal command, instead of the more bug-prone GUI. To manage memory-related issues, common when interacting with the GUI on top of the computationally demanding, we perform the combination in three main chunks (blue, green, red) to avoid these issues. After that, we combine these chunks into one. We test these results against the GUI-based approach and confirm our pipelines succeeds in achieving the same results.

**Block 5: Final sky subtraction using ZAP**

The Zurich Atmosphere Purge (ZAP) algorithm helps us treat residual sky emission lines which are usually abundant in low signal-to-noise MUSE data. We make a specific routine to run this procedure outside the ESOReflex GUI. ZAP uses Principal Component Analysis (PCA) to model the sky residuals. It takes the spectra from all sky spaxels (by using our previous custom sky masks) and identifies common variation patterns among them. After modeling these patterns, the algorithm subtracts them from the datacube.

As the final datacube is sensitive to these subtractions, we test different configurations for the ZAP algorithm. These best parameters set up the trade off between a complete sky subtraction and the preservation of the original light from the galaxy. We determine these best parameters by manually trying different configurations, and inspecting the spectra manually to ensure that we achieve an

acceptable level of sky line residuals reduction without significantly changing the flux on the spectra, especially in the parts that are critical for stellar population analyses.

As the final product, this step produced the science-ready data cube, which improves upon the results of the standard reduction pipeline.

### 2.3.3 Cluster membership confirmation

A direct first application of integrated kinematics is the ability to confirm the presence of each source to the cluster, via the systemic velocity ( $V_{\text{sys}}$ ). Initially, a first estimation was done in Paper I, but it was later refined in Paper II, where a more detailed analysis was done along with our improved data reduction pipeline. In Fig. 2.7 we show (in blue) the systemic velocity distribution of the LEWIS sources analyzed in Paper II to Hydra-I. Most sources fall within the limits of the bright and dwarf galaxies from the catalogue of [Christlein & Zabludoff \(2003\)](#). In particular, we confirmed that 15 out of 23 observed galaxies have systemic velocities within  $1\sigma$  of the cluster mean velocity (3683 km/s) and 8 are within  $2\sigma$ . Adopting phase-space criteria and comparing with their stellar populations, we find that most galaxies are defined as very early infallers (with the earliest infall times starting at  $> 7$  Gyr). With this confirmation, we can be sure to confirm the effects of the cluster on each source, so we can investigate cluster trends.

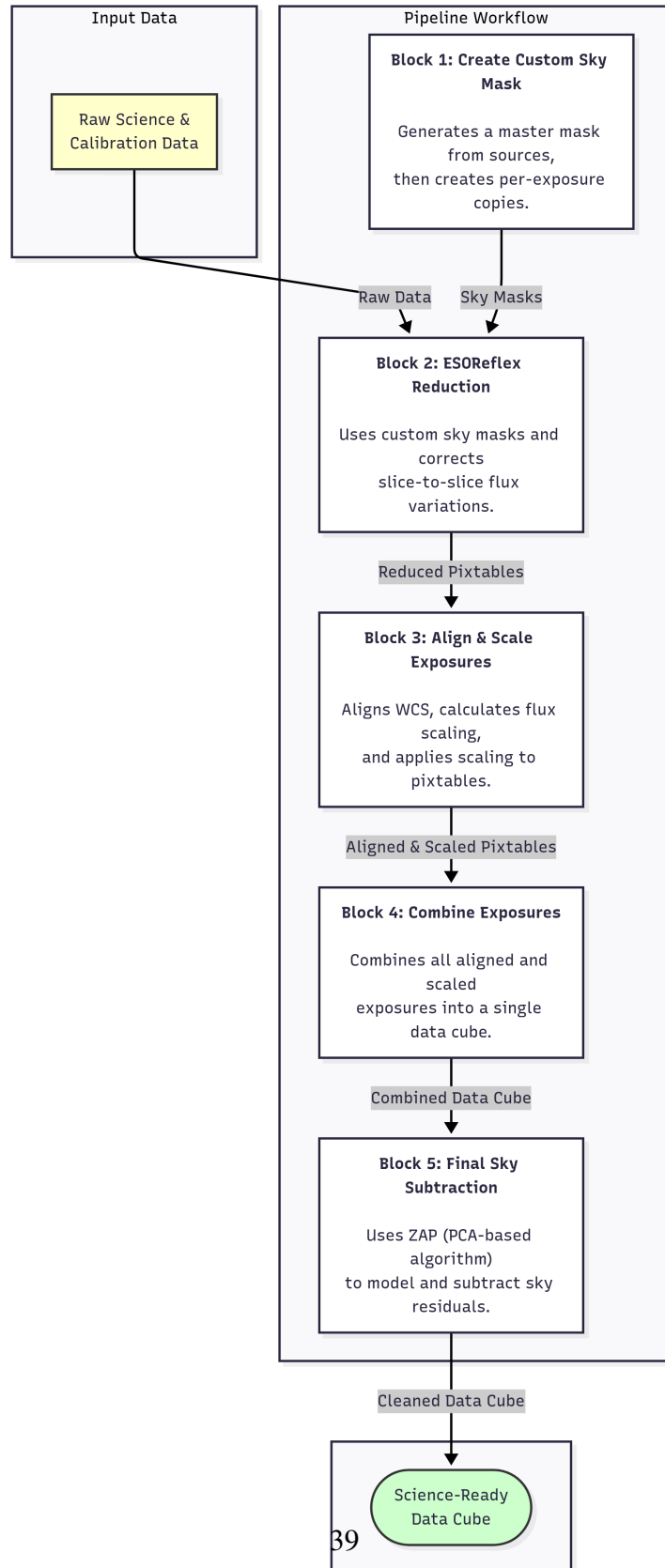


Figure 2.6: Flowchart of the LEWIS data reduction process

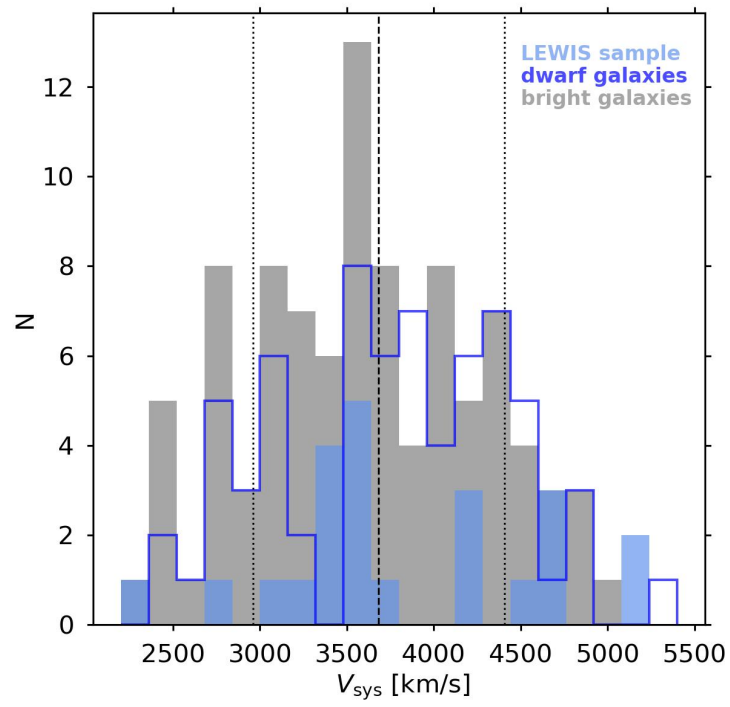


Figure 2.7: From [Buttitta et al. \(2025\)](#). Velocity distribution of the LEWIS sample within Hydra-I

# Chapter 3

## Stellar kinematics

*In this chapter we explain the methods and software we used to obtain kinematics and stellar populations measurements for all LEWIS sources. Here, my contribution was mainly on data reduction, setting up Monte Carlo routines and helping with spectral masks. We decided to include this chapter as we consider obtaining stellar kinematics to be an essential pre-requisite for stellar population work. In particular, here we are left with the task of retrieving an estimate of the effective velocity dispersion of each source, in addition to possible rotation patterns. The end result of this chapter is LEWIS Paper II ([Buttitta et al., 2025](#))*

### 3.1 Stellar Population Synthesis: Theory and Framework

Stellar population synthesis (SPS; [Tinsley, 1980](#); [Conroy, 2013](#)) models are widely used in modern Astrophysics to study both spectroscopic and photometric properties of galaxies, which allow us to ultimately derive the star formation history. SPS is based in a single important principle: the galaxy observed spectrum can be recovered by integrating, or summing up, a collection of spectra of individual stars weighted by their ages, masses, and metallicity contents. There are two main components in the SPS framework: (1) Isochrones (2) Stellar spectral libraries. We treat them separately below:

#### 3.1.1 Isochrones

These define lines of equal age on stellar diagrams, such as the Hertzsprung-Rusell (HR) diagram. They are different to evolutionary tracks in the sense that they, instead of following the complete evolutionary path of a single star or galaxy, show a snapshot, at a fixed time, of a sample population of stars with the same



age. For the spectral study of galaxies, this is a convenient concept as the SFH of galaxies is described by starbursts at few, specific look-back times. These starburst are modeled by assuming the stars are born roughly, at the same time.

The most widely used isochrones include the ones from the Padova group (Girardi, L. et al., 2000) and the BaSTI library (Pietrinferni et al., 2021). For our purposes in this work we focus on the BaSTI isochrones used in our selected templates (see subsection below).

### 3.1.2 Stellar spectral libraries

When summing up the spectra of all stars along an isochrone, a Single Stellar Population (SSP) template is created. A combination of stellar templates, then, form what is called a stellar library. As such, stellar libraries can be (1) empirical; (2) theoretical; (3) Semi-empirical. From now on, we narrow our study to empirical (e.g MILES) and semi-empirical (e.g. sMILES) models, as theoretical ones are not used in this work as they can often present systematic issues due to the complexity of modeling, for example, atmospheric physics.

Empirical models, such as the MILES templates (optical,  $\sim 100$  stars, 2.51Å resolution), have been a cornerstone for study of the stellar population in extra-galactic astronomy. Being an empirical library, they are based on spectra from real stars, often interpolated for standarization. Because they come from real data, they are free from the complex, bias-prone challenges of making a pure theoretical set of templates. Of course, there are some disadvantages: the lack of a substantial amount of spectra with known, yet uncommon and diverse abundance patterns, which can be rare inside the Milky Way as stars in it are roughly tied to the chemistry of the galaxy.

To break free of these limitations when studying extra-galactic sources such as the LSB sample from LEWIS, and given the recent literature showing UDGs having enhanced chemical patterns, we choose to work with a semi-empirical library: sMILES (UV-extended, 1680 Å - 50000 Å). They use a hybrid approach which is based on empirical data, but interpolates and extrapolates based on differential corrections to an already existing library (i.e MILES). In practise, it allows to construct a larger set of templates, with more extreme, variable levels of alpha-enhancement. Below, we summarize the properties of four important sets of templates:

#### Key libraries

- MILES (Vazdekis et al., 2010): They are high-quality, flux calibrated spectra that come in only two values of  $[\alpha/Fe] = 0, +0.4$ . It comprises around 1000 stars and cover up to 14 Gyr if using the BaSTI models.  $[Fe/H]$  ranges

from -2.7 to +1.0 dex. Originally they only comprise a narrow section in the optical range, from 3250 to 7500 angstroms at FWHM=2.51.

- sMILES ([Knowles et al., 2023](#)): It includes 801 stars. By working with the MILES templates, they apply differential corrections from theoretical modeled spectra. They span the same ranges as MILES, but with the differential corrections allowing for  $[\alpha/Fe]$  ranging from -0.2 to +0.4.
- E-MILES ([Vazdekis et al., 2016](#)): Useful for galaxies with UV data, these extend the coverage of the MILES templates up to 50000Å via a merging of different libraries (NGSL, CaT, Indo-US, IRTF).
- XSL: This is a higher resolution library (FWHM=1.3). As per their DR3, it comprises 830 spectra covering a relatively large spectral range (3000 - 25000) angstroms, supporting ages from 50 Myr up to 14 Gyr,

### 3.1.3 The Initial Mass Function

The IMF is a mathematical formulation that attempts to describe the statistical distribution of the mass of a given population of stars. These are theoretical formulas grounded in empirical data. Most modern IMF laws are taking more complex forms compared to the original Salpeter IMF, moving to a simple power-law to multi-part power-laws (e.g [Kroupa, 2001](#), [Chabrier, 2003](#)). In this work, given the wide use of the Kroupa IMF in our field, decide to work with these models.

### 3.1.4 Basic Principles of Stellar Population Synthesis Modeling

The process of synthesising a SSP spectrum, as previously said, involves summing up individual stellar contribution along an isochrone. Matematically, this is described as ([Vazdekis et al., 2010](#), [Knowles et al., 2023](#)):

$$S_{\lambda}(t, [M/H]_{SSP}, [\alpha/Fe], \Phi, I_{\alpha}) = \int_{m_l}^{m_t} S_{\lambda V}(m, t, [Fe/H], [\alpha/Fe]) \times F_V(m, t, [Fe/H], [\alpha/Fe]) \times N_{\Phi}(m, t) dm \quad (3.1)$$

The first term of this equation correspond to the result: A SSP spectrum from a given age ( $t$ ), metallicity ( $[M/H]$ ), alpha-enhancement ( $[\alpha/Fe]$ ), IMF ( $\Phi$ ) and Isochrone selection ( $I_{\alpha}$ ). The second term indicates an individual spectrum for a given star, part of the isochrone, with a cetain mass, age, metallicity and  $[\alpha/Fe]$ . The second term ( $F_V$ ) corresponds to the flux of the same star in the V-band, and

the last term ( $N_\Phi dm$ ) is the number of stars in within the differential. The integral is then summing up along the mass-space.

Once a given stellar library of SSP is built, the next step consist in their usage to solve a particular problem. One of such problems is the modeling of an extragalactic source, using tools such as pPXF. We detail such technique below.

## 3.2 Specific Techniques for Stellar Population Analysis

Before any stellar population property can be derived, it is mandatory to first determine the galaxy's stellar kinematics. This is because the observed absorption features are not completely pure: they have been convolved by both the instrumental resolution and the internal stellar velocity dispersion of its stars, in addition by the shift due to the galaxy's systemic velocity or redshift. If one were to fail to account for these effects, significant systematic effects may be introduced in the subsequent steps.

### 3.2.1 Galaxy Kinematics (systemic velocity and Velocity Dispersion)

To perform a full star formation history recovery from a stellar population fitting method, one must recover the two most important kinematic parameters of a given spectrum: the systemic velocity along the line-of-sight ( $V_{LOS}$ ) and the effective velocity dispersion ( $\sigma_{eff}$ ). This is a prerequisite for any stellar population work. For instance, if velocity dispersion were to be overestimated (either due to signal-to-noise, instrumental resolution constraints or due to a poor fit or treatment of the data), then any line depth would likely be overestimated as well, biasing the stellar population results significantly (in this case, towards younger populations and higher metallicities, if working with the  $H\beta$  and Mg and Fe lines)

We do this by performing a fitting procedure using a set of a stellar library that is justified by our science case. Specifically, a full-spectral fitting method such as pPXF works by convolving individual SSP templates from the stellar library using a test line-of-sight velocity distribution (LOSVD). The systemic velocity and the velocity dispersion are then the two free parameters recovered by the algorithm. If data quality allows, other kinematic moments may be obtained ( $h_3$ ,  $h_4$ ; [Cappellari, 2017](#))

When recovering kinematics, then, the problem reduces to recovering the LOSVD. This becomes feasible once we know the so-called line-spread-function

(LSF) of the instrument, which describes the spectral resolution (in FWHM) per pixel. The observed galaxy spectrum can be thus described as:

$$G(\lambda) = [T(\lambda) \otimes LSF_{ins}(\lambda)] \otimes L_{LOSVD}(\lambda) \quad (3.2)$$

### 3.2.2 pPXF and the SFH

From a physical point of view, one significant challenge in recovering the SFH is the age-metallicity degeneracy (Worthey, 1994). This degeneracy arises because changes in the age and metallicity of a stellar population can produce almost indistinguishable effects on its spectrophotometric properties. Specifically, an increase in age by a factor of three can mimic a decrease in metallicity by a factor of two. From a mathematical point of view, measuring the SFH has been demonstrated to be both an ill-posed and an ill-conditioned problem (Ocvirk et al., 2006): the solution is not unique (ill-posed), and the solutions can significantly change depending on quantities such as the noise level (ill-conditioned). These problems aggravate with the introduction of dust-attenuation and calibration errors.

pPXF stands for Penalized PiXel-fitting (Cappellari, 2017). Their idea is to solve the complex problem of recovering the full star formation history of an observed spectrum, and/or their main kinematic properties (velocity dispersion, systemic velocity, and other moments depending on the quality of the data). The observed spectra in pPXF are modeled as a parameterized line-of-sight velocity distribution (LOSVD) convolved with a linear combination of stellar templates or simple stellar population (SSP) spectra. The algorithm can handle gaps, masked sky lines, and irregularly sampled data because it minimizes a  $\chi^2$  function in pixel space instead of Fourier space. The addition of a penalty term to the higher-order Gauss-Hermite moments of the LOSVD is a crucial advancement of pPXF since it effectively regularizes the recovered kinematics by preventing overfitting of noisy data. In terms of stellar populations, pPXF can use regularization which is explained further in this section. Regularization can help solve degeneracies while bypassing noise systematics by picking the smoothest solutions for the weights to be recovered.

#### Calibration according to the line-spread function (LSF)

The MUSE instrument has already a standard LSF (Bacon et al., 2010). However, individual observations can often shift, or change the exact per-pixel resolution of the instrument including the exact shape of the curve. When studying low-mass sources with very low velocity dispersion ( $\sigma < 40$  km/s), an adequate characterization of the LSF becomes critical (Buttitta et al., 2025). As for the LEWIS

project, the exact shape of the LSF was carefully determined by analyzing sky-lines throughout the wavelength channels of individual observations. This was characterized as a second-order polynomial (see Eq. A.2 in [Buttitta et al., 2025](#)). Due to the variance of the LSF among observations, and given the relatively flat profile, a fixed FWHM of 2.7 Å is enough to characterize our LSF for practical purposes.

### Polynomials

Before recovering any kinematic value, one must also set a few key parameters for the fitting procedure. First, apart from the noise array from the data, a mask array ('goodpixels') is needed to instruct the algorithm which spectral pixels are to be masked. Of course, these often include noisy regions, skyline residual or in some cases, emission lines. A second important piece for the modeling are the degrees of the (often Legendre or Chebyshev) polynomials to be included in the fit. These can come in two flavors: multiplicative, and additive.

**Multiplicative polynomials** modify the convolved set of templates by multiplying by a polynomial:

$$M'(\lambda) = M(\lambda) \cdot P_m(\lambda) \quad (3.3)$$

where  $M(\lambda)$  is the template spectrum and  $P_m(\lambda)$  is a polynomial of degree  $m$ . These are wavelength-dependant and adjust the overall shape of the stellar continuum. For stellar population analyses, they are often preferred to other types of polynomials because they do not change the shapes of the stellar absorption features. The main objective of implementing a multiplicate polynomial is to offset either flux calibration uncertainties, the effects of dust reddening (if not fitted separately), and other similar effects.

**Additive polynomials**, on the other hand, can correct for strong, localized features (instead of overall continuum shape variations) by functioning in an additive way:

$$M'(\lambda) = M(\lambda) + P_m(\lambda) \quad (3.4)$$

where  $P_m(\lambda)$  represents an additive polynomial of degree  $m$ . These are ideal then for localized features such as skyline residuals, scattered light and localized noise. For stellar populations, one must be careful as they can change the depth of the absorption features, biasing stellar population results. Therefore, multiplicative polynomials are the standard choice for population studies, while additive polynomials are typically reserved for pure kinematic fits or specific data quality issues.

To perform the deconvolution, one must model the line-of-sight velocity distribution (LOSVD). The observed galaxy spectrum  $G(\lambda)$  can be described as

$$G(\lambda) = [T(\lambda) \otimes LSF_{ins}(\lambda)] \otimes \mathcal{L}_{LOSVD}(\lambda) \quad (3.5)$$

where the closed cross symbol denotes a convolution. Afterwards, one can adjust the template resolution to match the LSF of a given instrument. The second operation is made by recovering the LOSVD. In practise, this recovery is done by modeling the spectrum as (eq. 11 of [Cappellari, 2017](#)):

$$G(x) = \sum_{n=1}^N w_n \left\{ [T_n(x) * LSF_n(cx)] \sum_{k=1}^K a_k \mathcal{P}_k(x) \right\} + \sum_{l=0}^L b_l \mathcal{P}_l(x) + \sum_{j=1}^J c_j S_j(x), \quad (3.6)$$

Where multiplicative and additive polynomials are included as the multiplicative and additive term respectively. Here,  $S_j$  corresponds to the spectra of the sky. After this modeling, only two procedures remain for the computation of the LOSVD:

- LOSVD parametrization: for pPXF in particular, stellar templates use the Gauss-Hermite form, which it consists of a gaussian profile multiplied by an Hermite series ([Cappellari, 2017](#))
- Fitting procedure: pPXF, as its name suggests, uses penalization as a way to fit the spectra in a non-linear way. The fitting algorithm effectively minimizes the following functional:  $\chi_p^2 = \chi^2 + \alpha P$  where  $P$  is a penalty function. In this way, non-gaussian solutions are penalized.

Due to the complexity of the algorithm, we refer the reader to the original papers by [Cappellari, 2017](#) and [Cappellari, 2023](#) for details.

### 3.2.3 Practical challenges and caveats

#### Recovering stellar kinematics in low S/N conditions

Measuring stellar kinematics in faint LSB galaxies is challenging due to low SNR. It is well known that noise adds spurious, high frequency structure to the signal. When using a routine such as  $\chi^2$  minimization, larger solutions of  $\sigma$  are preferred to smooth-out these random fluctuations.  $\sigma$ , being positive, can only shift upwards in its distribution. For regular, higher-mass galaxies studies have already shown how exact one can recover the  $\sigma$  under low S/N conditions ([Cappellari & Emsellem, 2004](#)). Low velocity dispersion galaxies, at a very limiting resolution of 2.7Å, and at  $S/N < 20$  is a setting that requires a catered test. Therefore,

we simulate UDG spectra using E-MILES templates. Degrade the FWHM of the same spectra, inject Poisson noise, and measure the ability of pPXF to recover the velocity dispersion. Results are presented in Paper I ([Iodice et al., 2023](#))

Based on the E-MILES models, we simulate mock spectra to study how the retrieved quantities from the pPXF fit vary with the SNR of the spectrum. Firstly, we take a stellar population with  $\log(\text{Age})=10$  and  $[\text{M}/\text{H}] = 1.2$ , and construct a synthetic spectrum based on it. Next, we convolve the spectrum with an approximated version of MUSE’s line-spread function (LSF) as presented in Bacon et al. (2017). We keep this more universal implementation of the LSF for testing purposes. Finally, we further convolve it with varying kernels to simulate different velocity dispersions. Subsequently, we introduced noise by generating several mock spectra with different signal-to-noise levels, ranging from 5 to 120 per pixel, by adding Poissonian noise. This allows us to evaluate the performance of the fit at very low SNR values. We find that at around  $S/N = 15$ , results are unbiased for a  $\sigma_{LOS} > 15$  km/s. The range  $SNR = 10-15$ , however, are only reliable for  $\sigma_{LOS} > 20$  km/s. As a caveat, we remind the reader that noise shape is highly specific and may not always be best represented by regular Poissonian statistics. In particular, skyline residual can and will introduce significant biases if they are present near or at important absorption features. For this test, we use the full range of the MUSE instrument.

In [Iodice et al. \(2023\)](#), we test how these uncertainties in the velocity dispersion can translate to a possible bias in metallicity in stellar populations: In order to put a rough upper bound on the maximum degree of bias in our results, under the assumption that all of our noise is systematic, we extract a clean background region of the same size as the one used for the stacked 1D UDG11 spectrum, present on the same cube. Then, we repeat the procedures described in above, including the background spectrum (containing residual sky lines and other systematics) instead of the random noise. After 1000 simulations, we estimate a maximum systematic positive bias of around +0.1 in metallicity, and a negligible one on the mean stellar age.

### On the limitations of integrated spectra

So far, previous UDG studies have been severely limited by the lack of spacially resolved spectra, unlike IFU studies. A major challenge when interpreting the kinematics of an individual, integrated spectrum (e.g from stacking all light within an aperture, or when working with long-slit observations) is the possible presence of ordered rotation. When looking at low velocity dispersion LSB sources, if rotation is present, then it can dominate over the stellar velocity dispersion, in which case the stellar population results may also be biased. In [Buttitta et al. \(2025\)](#), we take advantage of the IFU capabilities of MUSE to confirm (or not) the



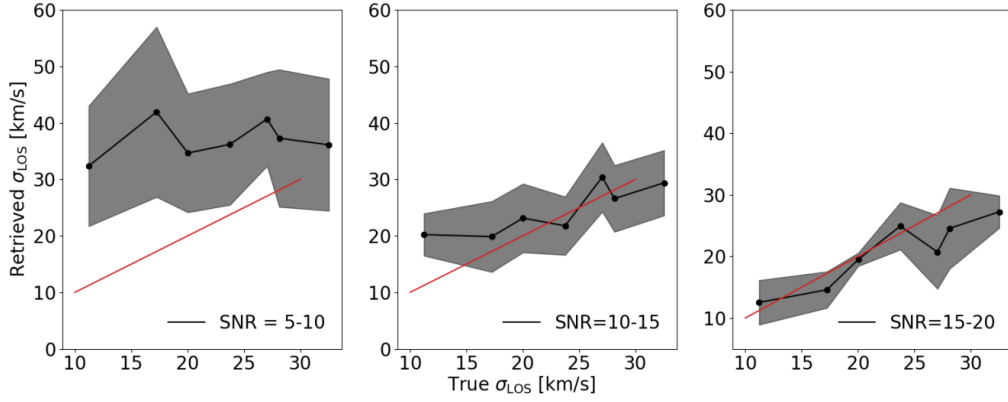


Figure 3.1: From [Iodice et al. \(2023\)](#). Simulations testing the ability of our pipeline to successfully recover a velocity dispersion of different values at low signal-to-noise (per pixel) levels, from SNR=5-10 (left panel), SNR=10-15 (middle panel), up to SNR=15-20 (right panel). Shaded areas correspond to the standard deviation of the measured values at every SNR. The red solid line corresponds to the output values equal to the input ones (unity line). In this experiment, the error is dominated by Poisson noise and no systematic sources of uncertainties have been considered

presence of rotation in these galaxies, in addition to a Voronoi-Binning based determination of the LOSDV. This effect (beam smearing) implies that the effective measured velocity dispersion is in actuality a combination of the true dispersion and the an additional rotational component:

$$\sigma_{eff}^2 \approx \sigma_*^2 + \sigma_{rot}^2 \quad (3.7)$$

Thus if rotation is comparable, or dominates over the stellar component and not accounted for,  $\sigma_{eff}$  can be overestimated. With IFU we can overcome this limitation, which may be significant for objects with significant rotation (e.g UDG1). In these cases, the best practice is to de-redshift each spacial bin before co-adding the spectra.

### 3.2.4 2D-kinematics methods

#### Isophotal analysis

Before integrating spaxels to reliably perform a global quantification of the kinematics and/or stellar population analysis, a characterization of the main geometrical parameters of the galaxy is needed. In particular, the position angle (PA) and ellipticity ( $\epsilon$ ) are needed to identify the main axes where the rotation is going to



be tested. It also serves as a reference point for any further binning procedure, including the extraction of a  $1R_e$ -stacked spectrum and the extraction from annular apertures. This is called an isophotal analysis, which studies the spatial distribution of light in an extended astronomical object as a function of its radius, based on its isophotes, or curves of constant surface brightness. The observed intensity field is processed in a manner similar to that used when applying a topographic map, so the brightness contours are distinguished and their geometry is described. In addition to characterizing these basic properties, this method has the potential to catch certain features such as bars and dynamical interactions.

For the LEWIS sample, this procedure is explained in [Buttitta et al. \(2025\)](#): starting from the final datacube and the special masks obtained from the procedures described in the data reduction section, the task `Ellipse` is used within `photutils` to fit isophotes to the galaxy.

### Voronoi-Binning and Annular Apertures

Individual spaxels in IFU observations, especially for faint galaxies such as LSBs, have a poor SNR. Moreover, for important quantities such as the effective velocity dispersion, or stellar population properties, a higher SNR is needed. Because of reasons explained above, it is useful to spacially bin spaxels while setting: (a) a minimum SNR for each bin to be analyzed (2) Make the SNR constant to mitigate any subsequent bias. Because all bins should be non-overlapped, and the galaxy has a certain shape, it is also useful to add another constrain which dictates the shape of each bin.

In the case of Voronoi-Binning ([Cappellari & Copin, 2003](#)), one tries to make the binning contiguous and uniform, where each bin is not only SNR optimized but also there is some uniformity in the bin shape. These shapes, usually compact, are a product of the inner workings of the algorithm: we define seed points and then select points nearby the seed point to be grouped, until a certain SNR is achieved. This rule, along with the constraints given by the shape of the galaxy, explains the tessellated shape of each bin. This is the approach we use in [Buttitta et al. \(2025\)](#), where we need enough bins to test the presence of rotation along a given axis.

Annular apertures, however, are a completely different way of grouping spaxels. Instead of prioritizing spacial resolution, one prioritizes the annular shape of the extraction regions. This is often needed because (1) The science case: annular symmetry is SF patterns is expected (see Chapter 2). This is rooted in the standard model of "inside-out" formation of galaxy growth, where the central parts of the galaxy tend to form their stars early and rapidly compared to the outer parts. The elliptical geometrical symmetry reinforces this view when other processes such as gas accretion or outward flows of gas also present this symmetry from both

a physical and a theoretical point of view. (2) When SNR is low, and only few bins can be made, it is natural to follow the geometric symmetry of the object instead of trying to gather information from smaller, localized bins. This method has already been tested for less massive galaxies (see, e.g. [Ferreras et al., 2019](#))

An important question is whether or not one should try to also optimize for each bin having similar SNRs between them. This is not a trivial question: as stated before, optimizing for a regular SNR has the benefit of reducing systematic biases later on, yet also inherently averages or "flattens" the measurements we are trying to get (e.g. metallicity and/or age gradients; see eg., [Yuan et al., 2013](#)). The often preferred option, is to characterize the limitations imposed by the SNR, seeing conditions and instrumental PSF (point-spread-function) and address these as best as possible (e.g. correcting for the PSF effect, and setting the number of bins correctly ensuring the minimal SNR threshold is met). We use this method later in the thesis for deriving age and metallicity gradients for a selected subset of the LEWIS sample. We estimate the average seeing and PSF of the combined MUSE observations to be around 0.8 arcseconds (averaged from the HIERARCH ESO TEL IA FWHM header keyword).

### 3.2.5 The stellar kinematics of LEWIS: main results

In [Buttitta et al. \(2025\)](#), we lay out the foundational work for the subsequent stellar population studies of the LEWIS sample. This study utilized the above methods (LSF characterization, Voronoi-Binning) to derive systemic velocities and effective velocity dispersions for the sample, in addition to 2D distributions of the  $V_{LOS}$ . The full pipeline leading to the final maps can be found in 3.2 where we use UDG1 as an example. According to the data quality, sources are classified into constrained (C), intermediate (I) or unconstrained (U)

The main results of this study is the fact that a large portion of LEWIS sample present significant, coherent and large-scale rotation with velocity amplitudes up to  $\Delta V = 25 - 40$  km/s. For the first time, we can split UDGs kinematically by the presence of rotation (rotation-supported or dispersion-supported systems). The properties of the full sample can be found in Table 3.1. Among the sample, we find three sources that present a form of rotation that does not go along the major axis.

For most of the same, we are able to catch the presence or not of rotation and thus have an estimate of the contribution of the rotational component to the effective velocity dispersion. However, two sources (UDG7 and UDG12 with  $\sigma_{eff} \sim 40 - 60$  km/s) are unconstrained in this sense, so the effective velocity dispersion may be biased upwards from this. Another caveat is that this is the first time these UDGs are confirmed to present rotation. A parameter that is also used to confirm the presence of rotation corresponds to the projected specific angular

momentum parameter, with values up to 0.25 - 0.35. Before drawing major conclusions about the DM content in these galaxies, one should revise the possibility of a good fraction of the UDGs currently studied, being rotators yet not currently classified as such.

In short, Paper II constitutes the first systematic evidence for kinematically distinct UDG populations in a cluster. The presence of both rotating and non-rotating UDGs implies several types of evolution and possibly, formation pathways. It also implies an interesting retrospective on the current assumptions of UDGs being dispersion dominated-systems, in both data analysis and simulations,.

### Dark Matter Content

UDGs in Hydra-I were found to be predominantly DM-rich [Buttitta et al. \(2025\)](#). We derived the dynamical masses from the [Wolf et al. \(2010\)](#) expression, modifying it for rotation by replacing  $\sigma_{eff}$  with the luminosity-weighted second velocity moment ( $V_{rms}$ ) whenever applicable. Our galaxies exhibit dynamical mass-to-light ratios within the 3D deprojected half-light radius of  $M_{dyn}/L_V \sim 10 - 100 M_{\odot}/L_{\odot}$ , demonstrating significantly elevated DM content compared to LG dwarf galaxies of the same luminosity.

#### 3.2.6 Correlations with environment

We studied the relationship between kinematic properties and cluster environment. We found weak trends that galaxies with lower  $\sigma_{eff}$  and higher dark matter content are located at decreasing distances from the cluster center, but those are not statistically significant due to our small sample size and radial range (out to  $\sim 0.4 R_{200}$ ). Expanding this coverage to near the full extent of the cluster's radius, in the future would guarantee more robustness in these initial trends.

It is also worth mentioning that galaxies presenting irregular morphologies (such as faint bar-like structures and tidal features) are almost exclusively late infall (and mixed times) objects, both in terms of kinematics and morphology, further pointing out to environmental mechanisms at the origin of their appearance.

| Object | $\mu_0$<br>[mag arcsec <sup>-2</sup> ] | $R_{\text{eff}}$<br>[kpc] | $\epsilon$ | Type                 | Location in Hydra I     |
|--------|----------------------------------------|---------------------------|------------|----------------------|-------------------------|
| (1)    | (2)                                    | (3)                       | (4)        | (5)                  | (6)                     |
| UDG 1  | 24.2 ± 0.1                             | 1.75 ± 0.12               | 0.28       | UDG                  | Very early infall       |
| UDG 3  | 25.2 ± 0.2                             | 1.88 ± 0.12               | 0.21       | UDG                  | Very early infall       |
| UDG 4  | 24.9 ± 0.1                             | 2.64 ± 0.12               | 0.30       | UDG                  | Late infall/Mixed times |
| UDG 6  | 24.1 ± 0.1                             | 1.37 ± 0.12               | 0.59       | UDG/cLSB             | Very early infall       |
| UDG 7  | 24.4 ± 0.4                             | 1.66 ± 0.12               | 0.14       | UDG                  | Very early infall       |
| UDG 8  | 23.2 ± 0.6                             | 1.40 ± 0.12               | 0.53       | Dwarf/Extended dwarf | Late infall/Mixed times |
| UDG 9  | 24.2 ± 0.2                             | 3.46 ± 0.12               | 0.41       | UDG                  | Very early infall       |
| UDG 10 | 24.3 ± 0.3                             | 2.29 ± 0.10               | 0.14       | UDG                  | Very early infall       |
| UDG 11 | 24.4 ± 0.1                             | 1.66 ± 0.12               | 0.30       | UDG                  | Very early infall       |
| UDG 12 | 25.1 ± 0.2                             | 1.64 ± 0.12               | 0.29       | UDG                  | Very early infall       |
| UDG 13 | 24.2 ± 0.2                             | 1.60 ± 0.20               | 0.15       | UDG/cLSB             | Very early infall       |
| UDG 15 | 25.0 ± 0.3                             | 1.51 ± 0.15               | 0.27       | UDG/cLSB             | Very early infall       |
| UDG 16 | 25.9 ± 0.2                             | 1.75 ± 0.12               | –          | UDG                  | –                       |
| UDG 17 | 24.9 ± 0.1                             | 1.50 ± 0.20               | –          | UDG/cLSB             | –                       |
| UDG 20 | 26.0 ± 0.3                             | 1.97 ± 0.12               | 0.45       | UDG                  | Late infall/Mixed times |
| UDG 21 | 24.0 ± 0.4                             | 1.50 ± 0.12               | 0.20       | Transition           | Very early infall       |
| UDG 22 | 25.3 ± 0.2                             | 3.60 ± 0.12               | –          | UDG                  | Late infall/Mixed times |
| UDG 23 | 24.3 ± 0.3                             | 2.47 ± 0.20               | 0.16       | UDG                  | Very early infall       |
| UDG 32 | 26.2 ± 1.0                             | 3.80 ± 1.00               | –          | UDG                  | Very early infall       |
| LSB 1  | 23.9 ± 0.2                             | 0.81 ± 0.90               | 0.12       | Transition           | Very early infall       |
| LSB 4  | 24.7 ± 0.1                             | 1.48 ± 0.12               | 0.35       | UDG/cLSB             | Very early infall       |
| LSB 5  | 23.9 ± 0.1                             | 1.42 ± 0.12               | 0.49       | Dwarf/Extended dwarf | Very early infall       |
| LSB 6  | 23.0 ± 0.2                             | 4.00 ± 1.00               | 0.48       | Extended dwarf       | Late infall/Mixed times |
| LSB 7  | 22.7 ± 0.1                             | 1.97 ± 0.10               | 0.26       | Extended dwarf       | Very early infall       |
| LSB 8  | 23.2 ± 0.2                             | 1.51 ± 0.20               | 0.17       | Dwarf/Extended dwarf | Late infall/Mixed times |

**Note:** From LEWIS paper II [Buttitta et al. \(2025\)](#). Column 1 reports the target name of the galaxy in the LEWIS sample. Columns 2 and 3 report the central surface brightness  $\mu_0$  and effective radius  $R_{\text{eff}}$  in the  $g$  band from [Iodice et al. \(2020b\)](#) and [La Marca et al. \(2022b\)](#), respectively. Column 4 reports the average ellipticity of the galaxy measured from the isophotal analysis performed on the MUSE reconstructed image. Column 5 reports the morphological classification of the galaxy according to the structural parameters and their uncertainties. Column 6 reports the location of the galaxy within the Hydra I cluster, according to the infall diagnostic diagram ([Forbes et al., 2023](#)). Missing values correspond to the galaxies with on-going observations (UDG16, UDG17, and UDG22). UDG32 is a special case ([Hartke et al., 2025](#)).

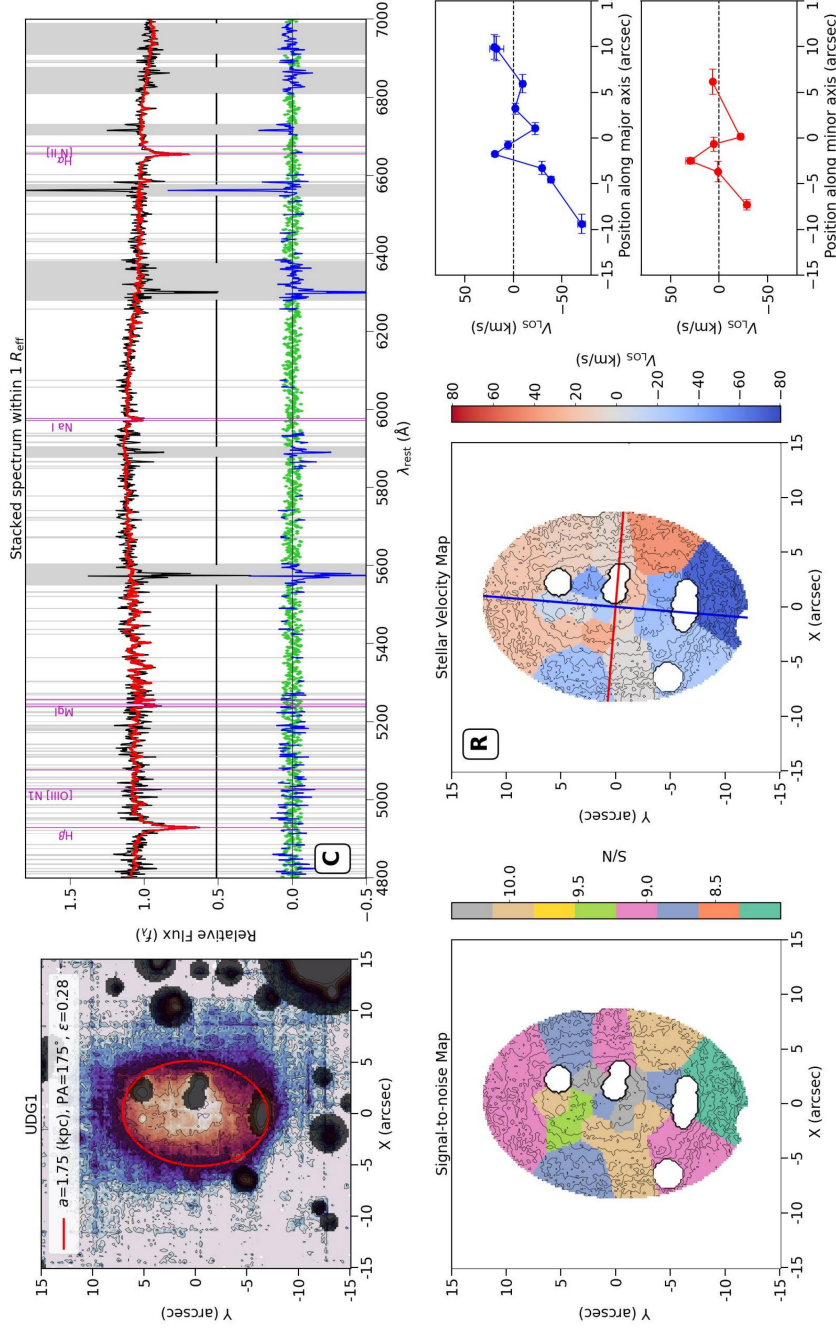


Figure 3.2: (1D) and spatially resolved (2D) stellar kinematics of UDG1. Top left panel: MUSE-reconstructed image of UDG1. The red ellipse represents the elliptical region we used to extract the stacked spectrum within  $1 R_{\text{eff}}$  and the grey circles show the masked image regions. The top label reports the values of the semi-major axis ( $a$ ), position angle ( $PA$ ), and ellipticity ( $\epsilon$ ) of the ellipse. Top right panel: MUSE 1 stacked spectrum (solid black line) for UDG1. The bottom label reports the fit type (Table 3.1). The main absorption features are marked with magenta lines and labels. The solid red line represents the best-fitting spectrum obtained with pPXF. The green points show the residuals between the observed and its best-fitting spectrum. The grey areas show the masked spectral regions that we excluded from the fit. The residual points excluded from the fit are marked in blue. Bottom left panel: Voronoi-binned map of the S/N. Bottom middle panel: Stellar velocity map subtracted from the systemic velocity. The top label reports the type of rotation (Table 3.1). The blue and red lines mark the photometric major and minor axes of the galaxy, respectively. Bottom right panel: Velocity profiles extracted along the major (top) and minor (bottom) axes and subtracted from . From Buttitta et al. (2025).

## Chapter 4

# LEWIS Paper V: Integrated stellar population properties of UDGs and LSBs in the Hydra-I Cluster

*Here, we describe the one-dimensional stellar population properties of a selected subset from the LEWIS sample. This work represent a large portion of my contribution to the project.*

### 4.1 Stellar population methods

#### 4.1.1 Line Index Analysis for Age, Metallicity, and $[\alpha/\text{Fe}]$

One perhaps simpler way to determine stellar population properties from a given observed spectrum when comparing to models is the line-index method. Here, we measure specific absorption-line indices at a certain resolution before comparing to predictions from the stellar libraries. Often, this requires to develop conventions, or systems in which the FWHM of the spectrum is fixed at a certain resolution, to homogenize and deconvolve data from different instruments to a common level. One of such systems is the Lick/IDS system ([Worthey, 1994](#)) which was formalized at FWHM $\sim 8 - 11\text{\AA}$ . The more modern LIS system ([Vazdekis et al., 2010](#)) instead works with three different resolutions depending on the science case (5,8.4,14  $\text{\AA}$ )

Some of the common lines used in these indices are the Balmer absorption lines ( $\text{H}\beta$ ,  $\text{H}\delta$ ) as age-indicators and iron ( $\text{Fe}5270$ ,  $\text{Fe}5335$ ) and magnesium ( $\text{Mg}_b$ ) as metallicity indicators ([Vazdekis et al., 2010](#)). In practice then, one should shift the spectrum to rest-frame via the LOSDV results, and then degrade the model resolution to the resolution of the data.



### Selection of Lick/IDS and other relevant indices (e.g Hb0)

Due to the spectral coverage of MUSE, only the  $H_b$  Balmer line is available as an age-estimator. Throughout this work, we exclusively use the definition found in (Cervantes & Vazdekis, 2009), the  $Hb_o$ . This definition uses a narrower bandpass, limiting the dependence on the metallicity which is especially important in old, metal-poor populations.

Aside from this age indicators, we pick three iron lines (Fe5015, Fe5270 and Fe5335) and one Magnesium line ( $Mg_b$ ) and derive indices from them on their respective bandpasses. At this point, we mention two other indices for completeness: the  $[MgFe]$  and  $[MgFe]'$  indices. The  $[MgFe]'$  index in particular, has been shown to be mostly insensitive to changes in  $[\alpha/Fe]$  (Thomas, Maraston and Bender 2003) and thus can be used as an independent metallicity indicator (e.g, Vazdekis et al., 2015). This index is computed as:

$$[Mg/Fe]' = \sqrt{Mg_b \times (0.72 \cdot Fe5270 + 0.28 \cdot Fe5335)} \quad (4.1)$$

Conversely, when age and metallicity are held relatively constant, one can use the ratio of Mg to Fe (an average of all three Fe indices can be used) to trace the alpha-enhancement.

### 4.1.2 Monte Carlo routines

Obtaining error estimates for kinematics and stellar populations, while many times not straightforward, has been done extensively in the literature (e.g, Cappellari, 2023). As stated in (Iodice et al., 2023), the sources of uncertainties are the following:

1. Quality of the data (noise and residual sky lines)
2. Uncertainty on the spectral resolution
3. Prior on the regularization (stellar populations)
4. Choice of the spectral mask
5. Calibration errors and selection of multiplicative and additive polynomials

A complete characterization of the errorbars then has to take care of all these uncertainties. We implement a common bootstrap-like procedure for both (Iodice et al., 2023, Buttitia et al., 2025) and it consists on perturbing the input parameter space (e.g noise estimation, masked regions, polynomial order, and regularization), and/or the data (e.g adding noise while keeping S/N relatively constant) to

study how sensitive are the results to these perturbations, which also represent our own uncertainties on these input parameters.

We note that for low S/N sources, both kinematic and stellar population results can significantly change depending on the selection polynomials and regularization. In particular, we often see benefits on using regularization for sources with very low S/N as the SFH can often get very sensitive to localized noise, especially if avoiding the use of additive polynomials. Thus, we use and recommend manual testing of the different configurations (Buttitta et al., 2025) and/or using tested procedures (D’Ago et al., 2023) to select the polynomial degrees that have a lesser chance to bias important results.

### 4.1.3 Practical considerations for $[\alpha/\text{Fe}]$ extremes

Since our sample may contain galaxies that have extreme  $[\alpha/\text{Fe}]$  (very low, hence having extended star formation, or very high, which would translate into rapid star formation), special care will be taken in interpreting these objects. Standard, scaled-solar SSP models would get the ages or  $[Z/H]$  wrong for such systems, because e.g., high  $[\alpha/\text{Fe}]$  increases strength of Mg lines but weakens Fe lines at a fixed  $[\text{Fe}/H]$ . Thus we will use the sMILES templates for their use in both Lick indices techniques and full stellar population fitting procedures.

### 4.1.4 LEWIS sample: observations and data reduction

Observations for the LEWIS survey were conducted using the MUSE integral-field spectrograph (Bacon et al., 2010) at the European Southern Observatory (ESO, Program Id. 108.222P, P.I. Iodice). MUSE was set to operate in Wide Field Mode without AO, offering a field-of-view (FOV) of  $1' \times 1'$  and a spatial resolution of 0.2 arcseconds per pixel. The data covers a wavelength range of 4800-9300 Å with a spectral sampling of 1.25 Å/pixel and a mostly flat resolution profile (FWHM = 2.69 Å; see Paper II for the details on the instrumental line-spread function).

The LEWIS sample presented in Paper I is composed of 30 galaxies, 22 of them classified as UDGs and eight are LSBs. From these 30 galaxies of the original sample, 5 were excluded because of the presence of Ferris wheel-like patterns, or because the exposure was heavily contaminated by the presence of a bright, saturated star or a nearby galaxy. The observations for LEWIS were completed in March 2025. The observations and data reduction of the final LEWIS sample are described in detail in Paper II.



### 4.1.5 Comparison sample

Throughout the paper, we compare our sample to both existing spectroscopic UDG and classical dwarf galaxy data in relatively well-matched stellar mass and redshift distributions. The main studies we draw comparison data from are [Ferré-Mateu et al. \(2023\)](#), [Gannon et al. \(2024\)](#) and [Buzzo et al. \(2024\)](#), as they are the largest and most complete spectroscopic and photometric samples that consistently have mass and metallicity measurements. They contain data for UDGs in both high and low-to-moderate density environments. Although LEWIS is a cluster-based sample, we include group and field UDGs in this study to better characterise how LEWIS UDGs fall in the grand scheme of UDG properties. LEWIS UDGs present a wide coverage in stellar mass ( $10^7 - 10^9 M_\odot$ , see Paper I), allowing for an adequate comparison with literature data, in particular photometric measurements. Overall, LEWIS UDGs seem to range from GC-poor to GC-rich ([Mirabile et al., submitted](#)).

Additionally, we complement our control sample with the SAMI-Fornax Dwarfs survey ([Scott et al., 2020](#); [Romero-Gómez et al., 2023](#)), which targets dwarfs down to a mass limit of  $10^7 M_\odot$  in the Fornax cluster. Like LEWIS, it employs integral-field spectroscopy to provide stellar population and galaxy kinematics properties, making it an ideal control sample for low-mass galaxy evolution studies in cluster environments.

## 4.2 Analysis

### 4.2.1 Age and metallicity

To obtain the mean stellar population properties of the LEWIS galaxies, we fit the stacked spectrum extracted from an aperture of radius equal to an effective radius  $1 R_e$  with the package Penalized Pixel Fitting (ppxf, [Cappellari, 2017, 2023](#)). The code uses single stellar population synthesis (SSP) models and allows masking of gas emission lines and low-S/N regions. Moreover, it allows multiplicative and/or additive polynomials to correct for the shape of the continuum.

As templates, we use the entire set of SSP models from sMILES ([Knowles et al., 2023](#)), with BaSTI isochrones, assuming a Kroupa initial mass function with a fixed slope of 1.3. The metallicities span from  $-1.79$  to  $+0.26$  dex, from 0.03 to 14 Gyr in age, and from  $-0.2$  to  $+0.6$  in  $[\alpha/\text{Fe}]$ . The initial setup for the fitting is based on the main results from Paper II:

- Wavelength range: we use the narrow region between  $4800 \text{ \AA} - 5400 \text{ \AA}$ . This is a relevant spectral range for stellar population studies, since it contains

age- and metallicity-sensitive absorption lines, particularly for old stellar populations. This is also the spectral range where we have the best quality of the MUSE data.

- Instrumental LSF: we adopt the LSF measured from Paper II. Given that our LSF is relatively flat, we fix the template resolution at  $2.69 \text{ \AA}$  for ease and speed of iterative computations.
- Polynomial order: The literature frequently uses multiplicative and additive polynomials to account for spectral calibration issues and template mismatching (see e.g., [Cappellari, 2017](#)). To avoid potential biases for the computation of the stellar population properties, we decided to use only multiplicative polynomials of order 6 to 10, using Paper II as a reference point.

The output of `ppxf` is a grid of weights assigned to each SSP model of the bestfit solution that allows obtaining mass or light-weighted age and metallicity of the observed galaxy's spectrum. We run a first fitting iteration at the  $4800 \text{ \AA}$ – $5400 \text{ \AA}$  on the rest-frame spectra, masking consistently noisy regions and skyline residuals. From residuals of the first iteration, we set a masking threshold of  $3\sigma$  that determines the number of pixels to be masked in a second iteration by using a simple sigma-clipping technique. To estimate the uncertainties in the stellar population properties, we follow an approach similar to the one described in Paper II: we implement a bootstrap-like procedure to generate several perturbations of the spectrum by adding Poissonian noise, which introduces a standard deviation in the S/N per pixel distribution of less than  $3\sigma$ . Then we fit the perturbed spectra by exploring a grid of randomly generated input parameters, emulating standard Monte Carlo approaches. We derive the mass-weighted metallicities and mean ages for the entire LEWIS stellar population sample, which are reported in Table 4.1.

### 4.2.2 Star formation histories

The analysis of the SFHs can reveal detailed evolutionary patterns of galaxies, offering a richer and more comprehensive understanding of their formation and evolution. Star formation (SF) quantities require a precise reconstruction of the SFH of the observed spectrum. From the output of `ppxf` it is possible to construct the SFH by collapsing the weights along the metallicity axis to generate a cumulative mass function that describes how the mass of a galaxy is built across cosmic time. Alternatively, one can construct the SFH by dividing the specific mass fraction generated by each SF episode by its associated timeframe or age bin. We follow the first approach to construct cumulative mass fraction plots and derive age percentiles for the formed stellar mass.

From the recovered SFHs, we calculate two characteristic *lookback times*: when the galaxies formed 50% ( $t_{50}$ ) and 90% ( $t_{90}$ ) of their stellar mass, respectively. The value  $t_{90}$  is often used as a proxy for the quenching time, as the point at which the SF has effectively stopped (Ferré-Mateu et al., 2023). To quantify the evolutionary phase, we define the duration of the *formation phase*, which measures the time elapsed between two stages of SF and allows us to separate the evolution of the galaxy into two phases: the first phase  $\Delta t_{50} = t_{\text{BB}} - t_{50}$  where we set  $t_{\text{BB}} = 14$  Gyr, and the second phase  $\Delta t_{90} = t_{50} - t_{90}$  (see Grèbol-Tomàs et al. 2023). In the first phase, we neglect the time that passed since the Big Bang and the onset of the first episode of SF in our galaxies, as in Ferré-Mateu et al. (2023), because LEWIS galaxies tend to be old. Lower values of  $\Delta t$  mean a rapid SF, while higher values suggest that SF proceeds more slowly.

Given that different sets of weights can replicate the observed spectrum, these inherent degeneracies are commonly addressed through a regularisation technique, which selects the smoothest solution, suppressing solutions that exhibit abrupt variations in the age-metallicity plane (Cappellari, 2017). While this introduces a potential bias, it typically generates a more realistic model. We test the effects of regularisation and find no significant difference in the median recovered metallicity and age, similarly to what was reported previously in Ferré-Mateu et al. (2023). Thus, we decide to use the non-regularised solutions: we expect these to be comparable to literature SFHs of other UDGs, despite having a slightly ‘burstier’ shape. It is important to stress that this choice, combined with the low S/N of some sources, means that the recovered SFH for any individual galaxy can be sensitive to noise. Considering that these quantities can be affected by the regularisation, we focus exclusively on the median trends of SFH rather than considering individual SFH to identify the broad differences in their evolutionary pathways.

From the mass-weighted metallicity weights, we derived the mass-to-light ( $M/L$ ) ratio for each galaxy, using the corresponding transmission curves to compute photometric measurements for our spectra. Subsequently, we also get spectroscopic stellar masses ( $M_*$ ) by combining  $M/L$  ratios with the photometric  $r$ -band luminosity (Paper I). To construct a normalised SFH, we divide each collapsed mass weight by the age width of the corresponding grid template. Appendix 6.2 presents, for each galaxy, all the relevant stellar population information, including their ppxf fit, resulting age-metallicity weights, and their derived SFH.

### 4.2.3 Chemical abundances

The chemical abundance ratios provide another independent constraint on the star formation timescale. For example, unlike the SFH lookback times, which reflect

the totality of the mass assembly, the  $[\alpha/\text{Fe}]$  ratio is a chemical clock for the phase and efficiency of the initial burst of SF. A high ratio is effectively the blueprint of a very short and intense timescale ( $< 1$  Gyr), where enrichment from Type-II supernovae (producing heavy elements such as Mg) massively outpaces the slow enrichment from Type-Ia supernovae (Worthey et al., 1992).

To characterise abundances in our sample, we measure iron and magnesium indices, along with the  $H\beta_0$  as an age indicator. Due to our wavelength selection and median S/N, we decide to work exclusively with the  $[\text{Mg}/\text{Fe}]$  abundance as a  $[\alpha/\text{Fe}]$  tracer, similarly to what has been done in the literature. The line index measurement is done with the latest version of `pyphot`<sup>1</sup>, and uncertainties are measured from perturbed spectra (injecting Poisson noise into the raw spectrum), also utilised for other error estimations. We adopt a combination of the following two methods:

1. We use the sMILES templates to construct model grids of Mg as a function of Fe (Fig. 6.1). We use a regular, arithmetic average of Fe5015, Fe5270 and Fe5335, compared to the  $\text{Mg}_b$  index, for different values of alpha enhancement ( $[-0.2, +0.0, +0.2, +0.4, +0.6]$  dex), convolved to the spectral resolution of our data. In age and metallicity, we centre these grids at the `ppxf`-derived values. We interpolate according to the position of the data within the model grids.
2. Using the scaled-solar E-MILES models (Vazdekis et al., 2016), we construct model grids of  $H\beta_0$  versus different metallicity ones, mainly Fe and Mg, to estimate the Mg and Fe enhancement on each galaxy from the proxy  $[\text{Mg}/\text{Fe}] = [Z_{\text{Mg}}/Z_{\text{Fe}}] = Z_{\text{Mg}} - Z_{\text{Fe}}$  (Vazdekis et al., 2015). However, due to the old and metal-poor nature of our sample, which makes many LEWIS measurements fall outside the range of the model grids (see Fig. 6.2, upper panel) or in a very degenerate region, we replace the  $H\beta_0$  indices by the proper light-weighted median age (Ferré-Mateu et al., 2014) from `ppxf`. This produces a more orthogonal model grid facilitating interpolation (see Fig. 6.2, bottom panel)

The associated uncertainties for the derived  $[\text{Mg}/\text{Fe}]$  are obtained from Monte Carlo simulations of the different line indices involved. Overall, we find that the estimates from both methods are consistent; hence, we use the average of both for the final  $[\text{Mg}/\text{Fe}]$  value. The only exceptions are UDG 1 and LSB 5, for which the second method did not provide reliable results, and thus we limit them to the results of method 1.

We estimate the  $[\alpha/\text{Fe}]$  abundance using the formula:

<sup>1</sup><https://mfouesneau.github.io/pyphot/>

$$[\alpha/\text{Fe}] = 0.02 + 0.56 \times [Z_{\text{Mg}}/Z_{\text{Fe}}] \quad (4.2)$$

where we assume that sMILES models (with BaSTI isochrones) behave similarly to the regular Base E-MILES models, which this formula is based on.

### 4.3 Results: stellar populations properties of LEWIS galaxies

| Object | Position in Hydra | Age            | [M/H]          | $M_*$            | [Mg/Fe]        | $t_{90}$       | $t_{50}$       |
|--------|-------------------|----------------|----------------|------------------|----------------|----------------|----------------|
|        |                   | [Gyr]          | [dex]          | $[10^8 M_\odot]$ | [dex]          | [Gyr]          | [Gyr]          |
| (1)    | (2)               | (3)            | (4)            | (5)              | (6)            | (7)            | (8)            |
| UDG 1  | Very early infall | $7.6 \pm 2.9$  | $-0.5 \pm 0.1$ | $1.73 \pm 0.43$  | $-0.8 \pm 0.2$ | $1.0 \pm 2.8$  | $13.6 \pm 7.5$ |
| UDG 4  | Late infall       | $13.7 \pm 0.2$ | $-0.9 \pm 0.1$ | $9.07 \pm 0.28$  | $0.3 \pm 0.2$  | $13.3 \pm 0.1$ | $13.7 \pm 0.1$ |
| UDG 8  | Late infall       | $8.4 \pm 0.7$  | $-1.2 \pm 0.1$ | $0.71 \pm 0.04$  | $0.1 \pm 0.2$  | $8.6 \pm 0.6$  | $9.2 \pm 0.7$  |
| UDG 9  | Very early infall | $12.7 \pm 0.6$ | $-0.7 \pm 0.1$ | $2.62 \pm 0.22$  | $1.1 \pm 0.4$  | $13.1 \pm 0.2$ | $13.3 \pm 0.5$ |
| UDG 11 | Very early infall | $7.3 \pm 0.3$  | $-1.3 \pm 0.1$ | $1.41 \pm 0.05$  | $0.4 \pm 0.2$  | $6.9 \pm 0.4$  | $7.8 \pm 0.4$  |
| UDG 12 | Very early infall | $9.0 \pm 0.5$  | $-0.9 \pm 0.1$ | $1.25 \pm 0.07$  | $0.3 \pm 0.2$  | $7.6 \pm 1.4$  | $8.0 \pm 1.0$  |
| LSB 5  | Very early infall | $8.6 \pm 1.4$  | $-0.7 \pm 0.2$ | $0.85 \pm 0.12$  | $-1.1 \pm 0.8$ | $0.8 \pm 0.2$  | $13.6 \pm 0.6$ |
| LSB 6  | Late infall       | $8.9 \pm 0.7$  | $-1.0 \pm 0.1$ | $3.55 \pm 0.24$  | $-0.1 \pm 0.2$ | $7.7 \pm 1.6$  | $9.0 \pm 0.7$  |
| LSB 7  | Very early infall | $9.2 \pm 1.0$  | $-0.7 \pm 0.1$ | $4.39 \pm 0.41$  | $-0.1 \pm 0.3$ | $9.3 \pm 0.7$  | $11.1 \pm 1.1$ |
| LSB 8  | Late infall       | $11.1 \pm 1.0$ | $-0.8 \pm 0.1$ | $3.31 \pm 0.24$  | $-0.7 \pm 0.3$ | $9.5 \pm 0.9$  | $11.1 \pm 1.4$ |

Table 4.1: Stellar populations properties of UDGs and LSBs in Hydra I. We present the results of stellar population analysis only for those galaxies which have constrained kinematics (see Table 2 from [Buttitta et al., 2025](#), for details). Column 1 reports the target name in the LEWIS sample. Column 2 reports the position of the LEWIS sample in Hydra I, according to the infall diagnostic diagram. Columns 3 to 6 report the age, metallicity, stellar masses and alpha-enhancements derived from stellar population analysis. Columns 7 and 8 report the 90th and 50th percentiles of star formation times, respectively.

In Table 4.1, we report all the quantities derived from the analysis of stellar population properties: ages, metallicities [M/H], stellar masses  $M_*$ , chemical abundances [Mg/Fe] and characteristic lookback times  $t_{50}$  and  $t_{90}$ . In addition, we report the classification in the projected phase-space (PPS) diagram as presented in Paper II.

The accuracy of the results strongly depends on the quality of the spectra and the reliability of stellar kinematics parameters. In particular, the effective velocity dispersion  $\sigma_e$  could be sensibly overestimated in poor-quality spectra, and thus cannot be used in the extraction of stellar population properties (see Paper II for details). The final LEWIS sample presented in Paper II is composed of 25 objects (19 UDGs and 6 LSBs), but only for a subsample of them, the stellar kinematics information was accurately derived. In this work, we use the same classification presented in Paper II to identify galaxies with precise measurements of stellar kinematics parameters and thus with reliable stellar population properties. The ‘C’ (constrained fit) galaxies have high-quality spectra and reliable estimates of stellar kinematics; the ‘I’ (intermediate fit) objects might have biased stellar kinematics parameters due to the presence in their spectra of sky line residuals close to absorption features, while ‘U’ (unconstrained fit) galaxies have low quality spectra and thus the spectral fitting is unreliable. In this work, we present accurate measurements for only constrained cases (10 galaxies), six of which are classified as UDGs, and the remaining four are LSB galaxies. The main conclusions presented in this work are based only on this sample, whereas results of the stellar population analysis of the intermediate cases (UDG3, UDG7, UDG10, LSB1, and LSB4) are discussed in Appendix 6.3.

#### 4.3.1 Age, metallicities and chemical abundance

Fig. 4.1 (left panel) shows the mean mass-weighted ages as a function of metallicity  $[M/H]$  for the LEWIS sample and literature data of cluster UDGs from Ferré-Mateu et al. (2023). For LEWIS, we find a mean metallicity of  $\langle[M/H]\rangle = -0.9 \pm 0.2$  dex and an average of  $\langle\text{Age}\rangle = 10 \pm 2$  Gyr for the stellar ages, consistent with these analogue studies ( $\langle\text{Age}\rangle = 8.9 \pm 2.7$  Gyr and  $\langle[M/H]\rangle = -1.0 \pm 0.4$  dex). We find that the derived ages of LEWIS UDGs are also consistent with the ages of classical dwarfs analysed in Heesters et al. 2023 (Age  $\sim 6 - 14$  Gyr), although the latter are on average more metal-poor overall ( $[M/H] = -1.9$  to  $-1.3$  dex). The dwarf galaxy sample of the SAMI-Fornax survey (Romero-Gómez et al., 2023) instead shows slightly younger ( $\langle\text{Age}\rangle \sim 8$  Gyr) and more metal-rich ( $[M/H] = -0.4$  dex) values, but a direct comparison is hard to establish since they only report luminosity-weighted quantities.

In Fig. 4.1, we marked with different colors the LEWIS galaxies belonging to the two regions of the projected phase-space (PPS), i.e. very early and late infallers (see also column 2 in Table 4.1). To remind the reader, very early infallers are those galaxies that entered the cluster at least  $\sim 7$  Gyr ago and thus are virialised with the cluster, whereas late infaller galaxies are approaching the cluster for the first time or have already passed the first pericenter (see also Rhee et al., 2017; Forbes et al., 2023). This infall diagnostic diagram allows us to highlight possible

dependencies between structural properties of the galaxies and the cluster. We notice that, except for UDG11, the majority of early infall galaxies have higher metallicity with respect to late infall ones.

Fig. 4.1 (right panel) shows the chemical abundance  $[\alpha/\text{Fe}]$  as a function of the metallicity  $[\text{M}/\text{H}]$  for the LEWIS sample and literature data of cluster UDGs from Ferré-Mateu et al. (2023). We compute the  $[\alpha/\text{Fe}]$  using Equation 4.2 to directly compare our findings with UDGs in the literature. LEWIS galaxies show values similar to the UDGs in literature from Ferré-Mateu et al. (2023), ranging from sub-solar ( $[\alpha/\text{Fe}] \sim -0.5$  dex) to super-solar ( $[\alpha/\text{Fe}] \sim +0.5$  dex) abundances. In LEWIS, UDGs are consistent with a flat metallicity versus  $[\alpha/\text{Fe}]$  trend (as in Ferré-Mateu et al., 2023, but see Gannon et al., 2024 for a discussion of a possible mild anti-correlation)

### 4.3.2 The mass-metallicity relation

Fig. 4.2 shows the mass-metallicity relation for all the LEWIS galaxies analysed in this work, compared with other works in the literature that analysed samples of UDGs and dwarf galaxies in different environments. Considering the uncertainties, 7 out of 10 galaxies analysed in this work have metallicity consistent with the relation found for the dwarf galaxies (Kirby et al., 2013) and with most of the UDGs studied by Buzzo et al. (2024) and Ferré-Mateu et al. (2023). The remaining 3 galaxies (UDG1, UDG9 and LSB5) have higher metallicities than dwarf galaxies with similar stellar mass and are located outside the  $1\sigma$  confidence region of the Kirby et al. (2013) mass-metallicity relation for dwarfs. Values are consistent with the observed scatter for the UDGs in the literature.

Different from the UDGs samples by Buzzo et al. (2024) and Ferré-Mateu et al. (2023), at stellar masses larger than  $10^8 M_\odot$ , we do not find LEWIS galaxies having metallicities lower than those expected for dwarf galaxies of comparable stellar masses, i.e.  $[\text{M}/\text{H}] \lesssim 1.5$  dex. This result can have implications for the formation channels for UDGs and will be discussed in Sec. 4.4.

Finally, according to the PPS, we notice that all late-infallers have metallicity consistent with the Kirby et al. (2013) relation for dwarfs, whereas early-infallers have either consistent or higher values.

### 4.3.3 Star formation histories and quenching times

Fig. 4.3 shows the star-formation histories (SFH) of LEWIS galaxies. According to the PPS, we analysed the SFH for the galaxies into very early and late-infall regions of the PPS. For the late infaller group (right panels), we find a median lookback time of  $t_{90} = 8.6^{+0.5}_{-1.0}$  Gyr and  $t_{50} = 9.2^{+1.6}_{-0.1}$  Gyr. The above estimates



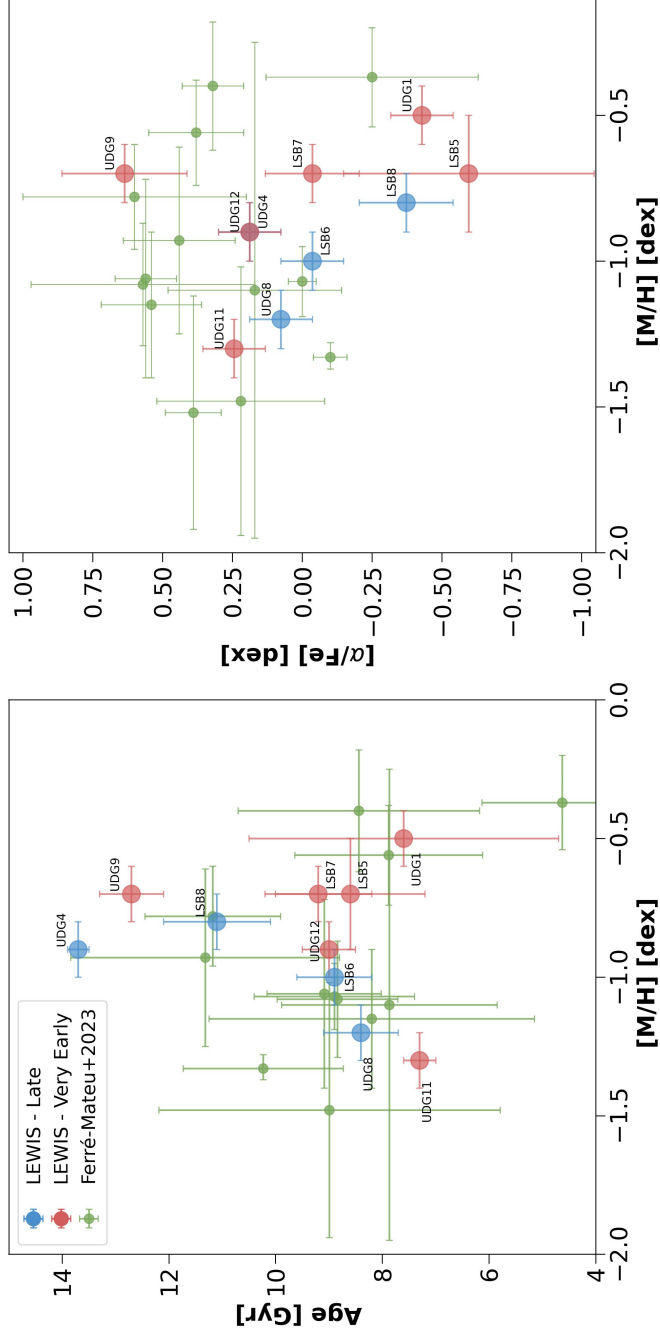


Figure 4.1: Stellar population properties of LEWIS galaxies. Left panel: Mean mass-weighted ages as a function of metallicities  $[M/H]$  for the LEWIS sample (coloured datapoints) and the literature UDGs (green circles, from [Ferré-Mateu et al., 2023](#)). The red and blue circles represent galaxies classified as very early and late infallers, respectively. Right panel: chemical abundance  $[\alpha/Fe]$  as a function of metallicities  $[M/H]$ . Datapoints are colour-coded as in the left panel.

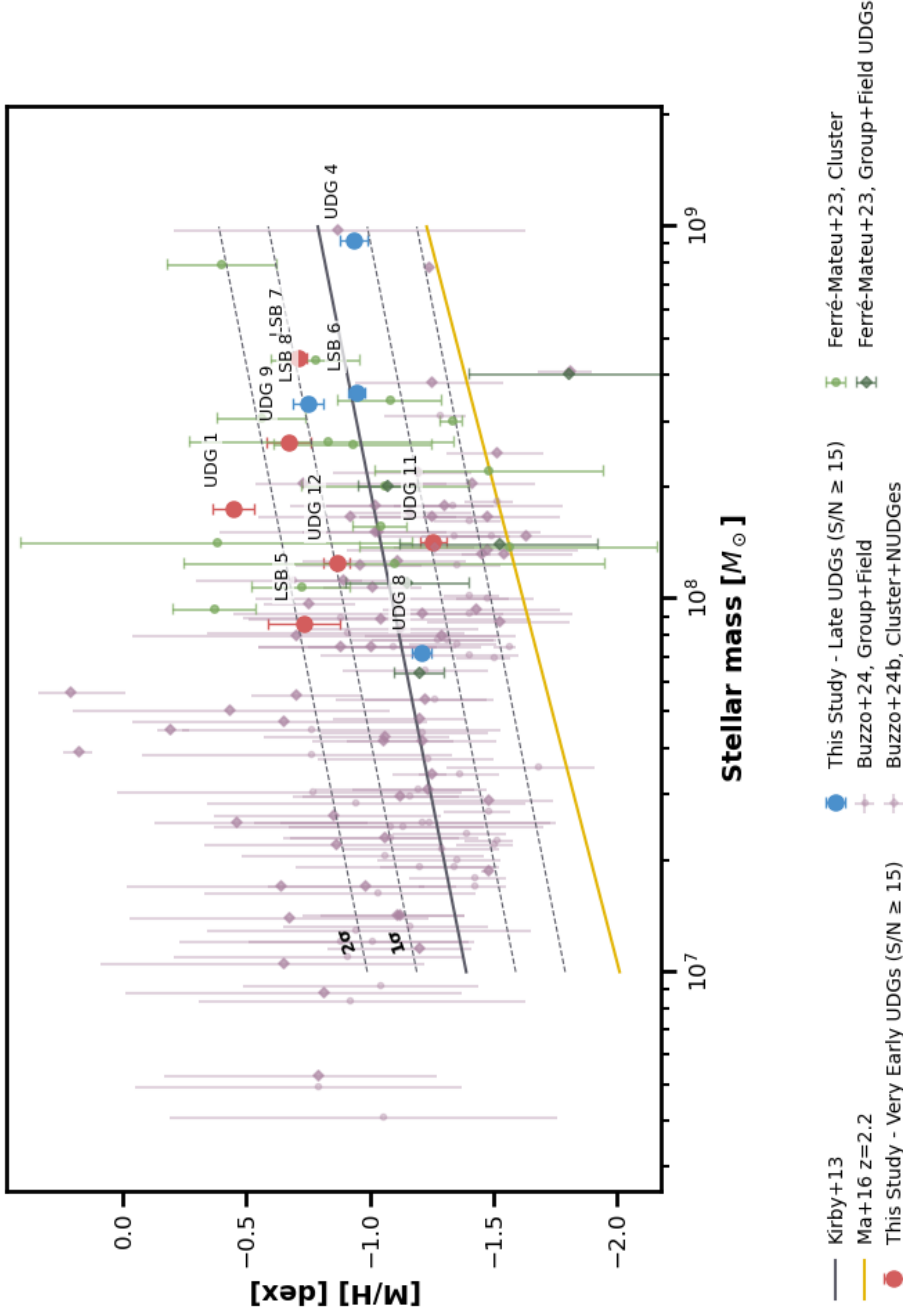


Figure 4.2: Mass-metallicity relation. LEWIS datapoints are colour-coded as in Fig. 4.1, while other coloured datapoints correspond to literature samples: UDGs in clusters (light green circles) and in low-density environments (dark green diamonds) from [Ferré-Mateu et al., 2023](#), UDGs in low-density environments (violet circles) from [Buzzo et al., 2024](#), and UDGs and nearly UDGs in high-density environments (violet diamonds) from [Buzzo et al., 2024b](#). The black solid line is the mass-metallicity relation found for dwarf galaxies assuming a constant  $\alpha$ -enhancement ([Kirby et al., 2013](#)), and the grey dashed lines represent the  $1\sigma$  and  $2\sigma$  confidence regions of the relation. The yellow line represents the evolving mass-metallicity relationship at redshift  $z \sim 2.2$  from [Ma et al. \(2016\)](#).

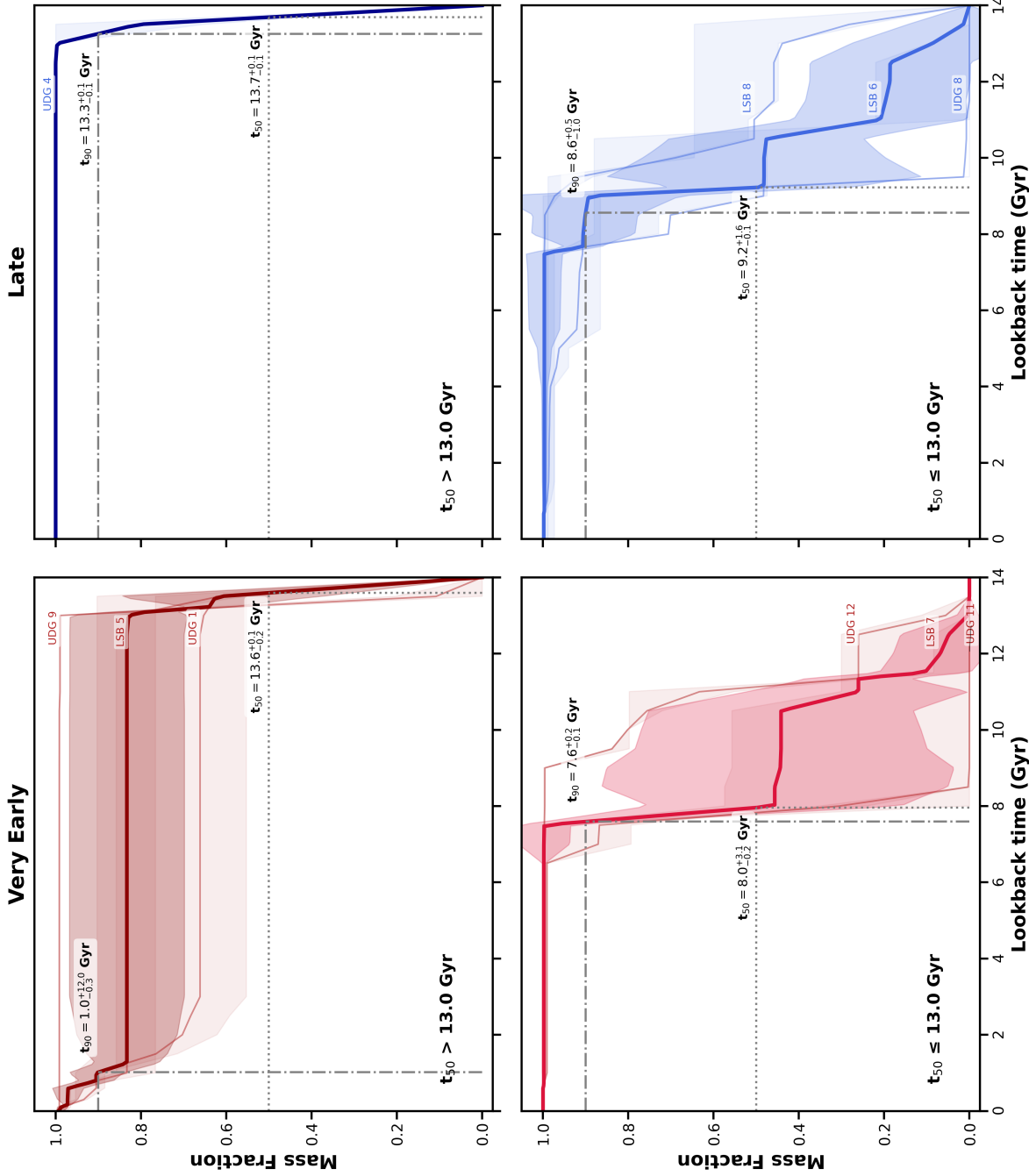


Figure 4.3: Star-formation histories of LEWIS galaxies, where we have separated very early quenching ( $t_{50} > 13$  Gyr, upper panels) from normal to late quenching ( $t_{50} < 13$  Gyr, lower panels). Lines are colour-coded as in Fig. 4.1, separating very early and late infallers. In each panel, the thin lines represent the individual SFHs of galaxies, whereas the thick solid line represents the median SFH. Grey lines represent the percentiles  $t_{50}$  and  $t_{90}$  of the mean SFHs.

exclude the UDG4, which shows a different SFH (see top-right panel of Fig. 4.3). This object quenched earlier ( $t_{90} = 13.3^{+0.1}_{-0.1}$  Gyr) and very fast ( $\Delta t_{90} \sim 0.7$  Gyr).

As noted in the mass-metallicity relation, galaxies in the early-infall region of the PPS show a bi-modality in the metallicity. Three objects (UDG11, UDG12 and LSB8) are consistent with the relation found for the dwarf galaxies (Kirby et al., 2013), and three others (UDG1, UDG9 and LSB5) have higher metallicities and are located outside the  $1\sigma$  confidence region. The two groups of galaxies also exhibit different SFH.

The metal-rich galaxies present a SF peak at an early epoch  $t_{50} = 13.6^{+0.1}_{-0.2}$  Gyr, with a subsequent slow and constant mass assembly phase (see Fig. 4.3, upper left panel), with similar  $t_{90} \sim 1$  Gyr. This behavior is atypical in galaxies located in the innermost regions of the cluster. Two of these galaxies (UDG1 and LSB5) also have low values of chemical abundance ( $[\text{Mg}/\text{Fe}] \sim -1$  dex). These findings suggest that these galaxies might be interlopers in the PPS or have suffered inefficient environmental quenching. The remaining three galaxies in the early-infall region (UDG11, UDG12 and LSB8) show a smooth trend of the SFH (see Fig. 4.3, lower left panel), where  $t_{90} = 7.6^{+0.2}_{-0.1}$  Gyr and  $t_{50} = 8.0^{+3.1}_{-0.2}$  Gyr. It is worth noting that the SFH for these three objects in the early infall region of the cluster is quite similar to that observed for the late infallers. In particular, both groups build up their mass at a similar speed during the first phase of their mass assembly, as their  $t_{50}$  estimates are consistent within uncertainties, and also, during the second phase of their formation history, driven by  $\Delta t_{90}$ , which are also comparable ( $\Delta t_{90, \text{early}} \sim 4$  Gyr and  $\Delta t_{90, \text{late}} \sim 3$  Gyr).

#### 4.3.4 Trends within the cluster environment

In Fig. 4.4 we present PPS infall diagrams colour-coded with properties derived from stellar population analysis of this work and stellar kinematics from Paper II.

In the top panels of Fig. 4.4, we show the LEWIS galaxies colour-coded according to stellar mass  $M_*$  (top left) and metallicity  $[\text{M}/\text{H}]$  (top right) derived from stellar populations analysis. We do not see any clear trend between  $M_*$  and the cluster location, but we find a mild distinction in metallicity between the two groups. Except for UDG11, the majority of very early infallers show higher values of metallicities with respect to late infall galaxies. We compute the mean metallicities values in the two groups, and we find  $\langle [\text{M}/\text{H}] \rangle_{\text{early}} = -0.8 \pm 0.1$  dex for very early-infallers, and  $\langle [\text{M}/\text{H}] \rangle_{\text{late}} = -1.0 \pm 0.1$  dex for late infallers.

In the bottom panels of Fig. 4.4, we show the LEWIS galaxies colour-coded according to the  $\alpha$  abundance (bottom left) and the presence of stellar rotation (bottom right). As already pointed out in Section 4.3.1, galaxies span a wide range of  $[\alpha/\text{Fe}]$  values, and we do not see a clear trend with the environment. Both early and late infallers show solar-like  $\alpha$  abundances. In terms of stellar rotation, except

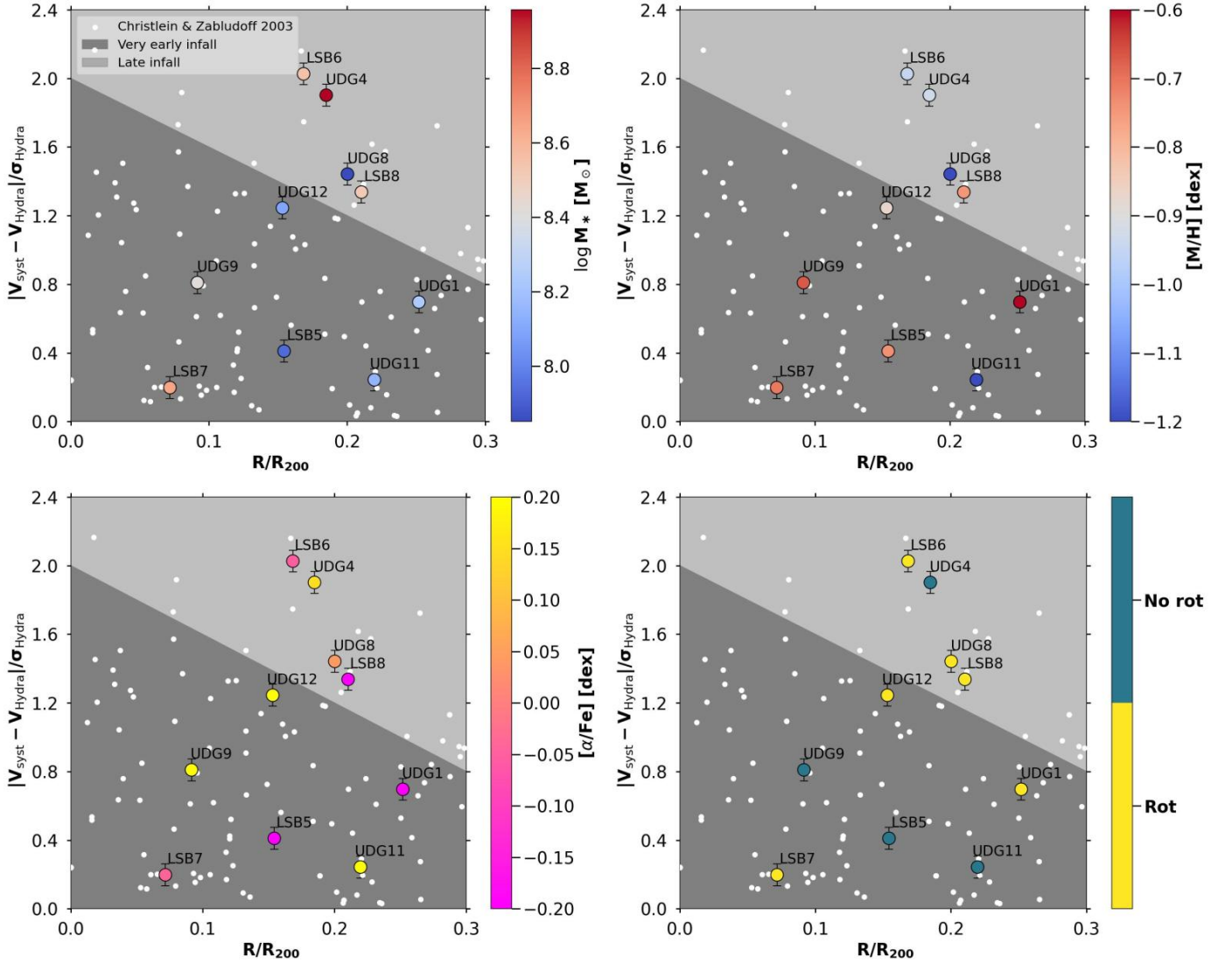


Figure 4.4: Global properties of LEWIS galaxies as a function of the cluster environment. The projected phase-space diagram (PPS) shows the relative velocity versus projected radius for the LEWIS sample (coloured points), and galaxies from [Christlein & Zabludoff \(2003\)](#) catalogue (white circles). LEWIS galaxies are colour-coded according to the stellar mass (top-left panel), metallicity (top-right panel), chemical abundance (lower-left panel), and presence of rotation (lower-right panel). Grey-shaded regions indicate different infall stages ([Rhee et al., 2017](#); [Forbes et al., 2023](#)): early infall (dark grey) and late infall (light grey).

for UDG4, galaxies in the late infall region have hints of stellar rotation, whereas in early infall regions, we find either galaxies with or without stellar rotation.

### 4.3.5 Correlation with stellar kinematic properties

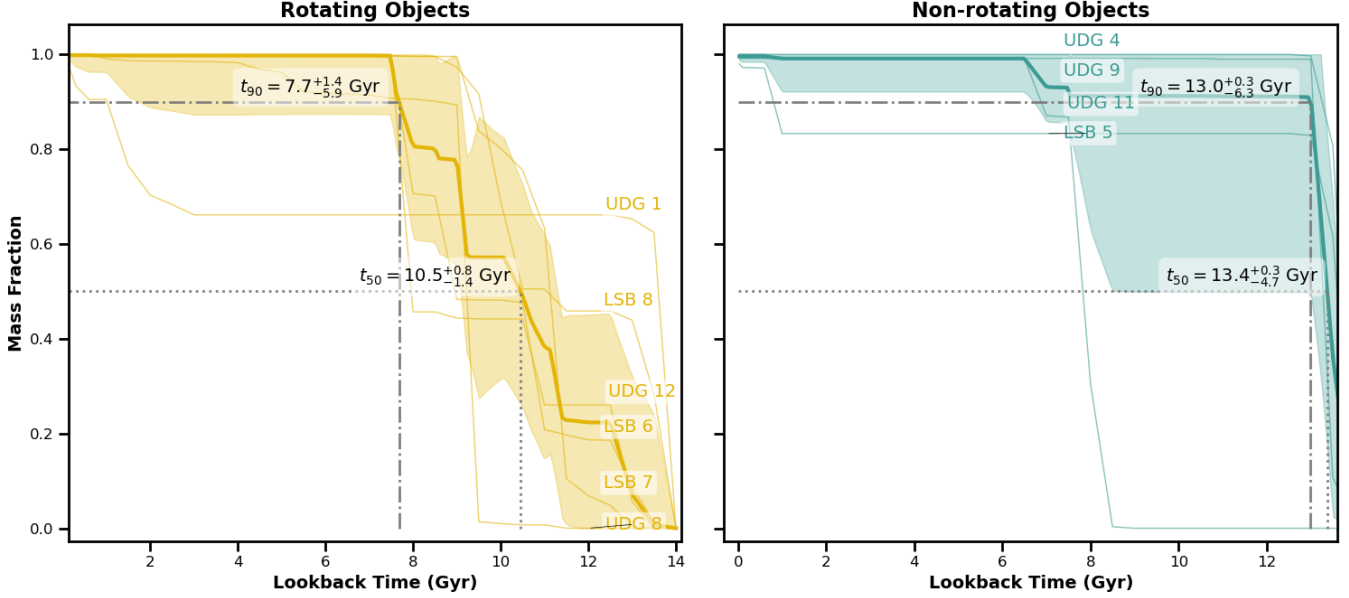


Figure 4.5: Star-formation histories of LEWIS galaxies and stellar kinematics properties. Galaxies are separated according to the kinematic type as described in Paper II: presence of rotation (left panel) vs. non-rotating objects (right panel). Thick, solid lines correspond to the average SFH for each panel, and shaded lines correspond to the standard deviation of the distribution. Similarly to Fig. 4.3, grey lines correspond to  $t_{50}$  and  $t_{90}$ , respectively.

From the stellar kinematic study of LEWIS galaxies (Paper II), we found that in the Hydra I cluster seem to exist two different kinematical classes of UDG and LSB galaxies. Almost half of the galaxies in the sample show significant stellar rotation. The remaining half of the galaxies do not rotate at all. According to the PPS, and considering that the present sample is made of only 10 objects in total, we cannot address a firm conclusion on a possible trend of the two kinematic classes with the cluster environment. We note that the early infall region of the cluster, where most of the metal-rich objects are found, is populated by a mix of rotation-supported and pressure-supported galaxies as well (Fig. 4.4, bottom-right). Three out of the four galaxies located in the late infall region are rotation-supported.

Fig. 4.6 shows values of stellar velocity dispersion extracted from the stacked spectrum in an aperture equal to  $1R_e$  ( $\sigma_e$ , see Paper II) as a function of chemical

abundance  $[\alpha/\text{Fe}]$ . On average, LEWIS galaxies cover the same region populated by other UDGs from literature data, expanding the range of measured  $[\alpha/\text{Fe}]$  from sub-solar to slightly super-solar regime. Even considering the large scatter, values for the LEWIS sample are consistent with the observed values for dwarf galaxies (Romero-Gómez et al., 2023), whose trend is marked in the figure with dashed and shaded blue region. Except for UDG1, we note that all the sub-solar objects are LSBs, whereas other sources display an enhancement consistent with regular dwarfs or slightly above, as observed in the literature data for UDGs.

In Fig. 4.5, we show the star formation histories of LEWIS galaxies for the two kinematic types. We found that galaxies without signs of rotation present an initial fast SF phase, forming 90% of their stellar masses in  $\Delta t_{90} \sim 1$  Gyr. In contrast, galaxies that rotate show slower SF, forming half of their stellar masses in  $\Delta t_{50} \sim 3$  Gyr. Some individual cases have exceptional behavior. Among the rotation-supported galaxies, UDG1 has a unique SFH, which is particularly prolonged. Interestingly, the two pressure-supported galaxies, UDG9 and LSB5, are the outliers in the mass-metallicity relation, having higher metallicities than all the other galaxies of the sample. UDG4 is the only object with a different SFH in the late infall region.

## 4.4 Discussion: on the formation history of UDGs in the Hydra I cluster

The main goal of this section is to investigate the formation history of UDGs in the Hydra I cluster by comparing the observed properties of this galaxy class, derived from the LEWIS project, with predictions from simulations on UDG formation. To this aim, we briefly summarise the main structural properties of the galaxies in the LEWIS sample.

By combining the stellar population properties (this work) with the stellar kinematics (Paper II), we found that the overall structure of UDGs and LSB galaxies in Hydra I is a function of the environment where they reside. In particular, according to the PPS (see Fig. 4.4), we found that:

- Early infallers seem to comprise at least two different types of galaxies. We found a group of galaxies with metallicities consistent within errorbars with the mass-metallicity relation (UDG11, UDG12, LSB7), with UDGs presenting the highest values of alpha abundance in the sample. Another group of galaxies, instead, has higher metallicity (UDG1, UDG9, LSB5) and is located outside the  $1\sigma$  confidence region of the mass-metallicity relation. The two groups show different trends of SFH. Metal-rich galaxies show a



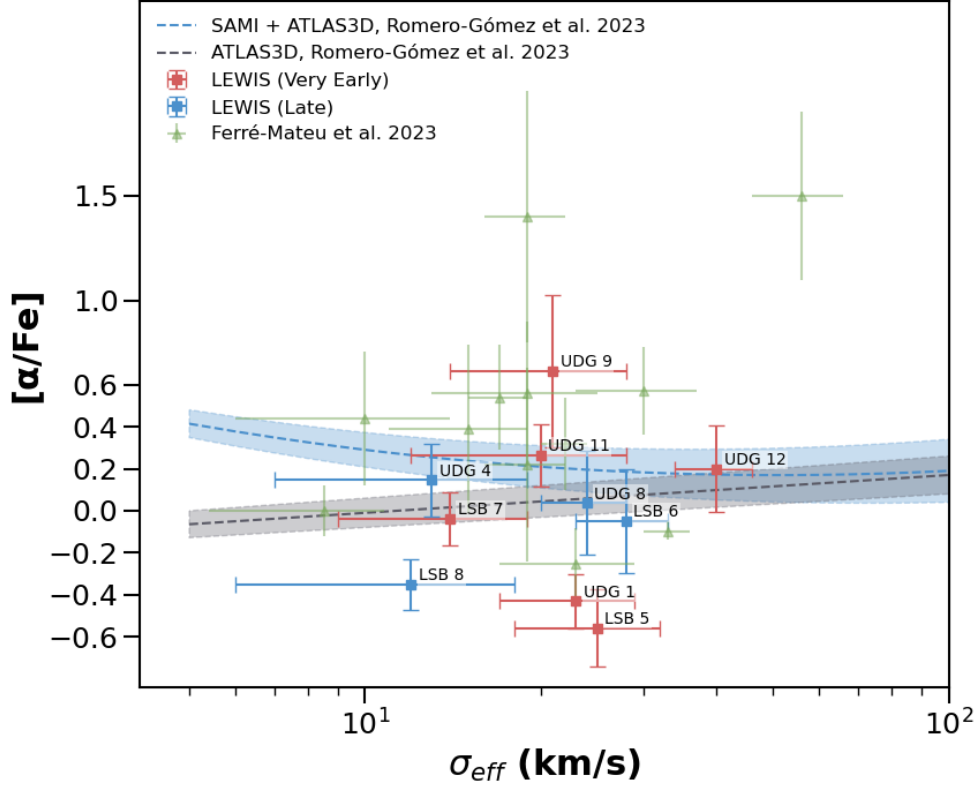


Figure 4.6: Velocity dispersion measurements as a function of alpha abundances. LEWIS galaxies are colour-coded as in Fig. 4.1. Green triangles are UDGs analysed by Ferré-Mateu et al. (2023). Values of  $\sigma_{\text{eff}}$  for LEWIS are from Paper II. The black dashed line and the corresponding shaded region represent the average trend of massive early-type galaxies from ATLAS<sup>3D</sup> survey (Cappellari et al., 2011). The light blue line and the corresponding shaded region represent the average trend ATLAS<sup>3D</sup> survey together with the sample of dwarf galaxies in the Fornax cluster from the SAMI survey (Scott et al., 2020).

fast mass assembly phase at an early epoch, with  $\Delta t_{50} \sim 0.4$  Gyr, and a prolonged ( $\sim 12$  Gyr) SF afterward, with respect to the others. In both groups, galaxies are both pressure-supported systems (UDG9, UDG11 and LSB5) or have hints of rotation (UDG1, UDG12, LSB7).

- Late infallers generally present more homogeneous properties in terms of metallicity, since they seem to follow the standard mass-metallicity relationship from classical dwarfs. Among them, only UDG4 has super-solar  $\alpha$ -abundance and does not have hints of rotation. All the other late infallers have solar-like  $[\alpha/\text{Fe}]$  and are rotation-supported systems.
- Except for metal-rich galaxies, both early and late infallers, which are consistent with the mass-metallicity relation, show a similar SFH. They build up their mass at a similar speed during the entire mass assembly period, where  $t_{90} \sim 8$  Gyrs for the early infallers and  $t_{90} \sim 9$  Gyrs for the late infallers.

A summary of the properties of the UDGs/LSB populations found in Hydra I, described above, is reported in Table 4.2.

#### 4.4.1 How do the structural properties of the LEWIS galaxies compare with dwarfs?

Since UDGs and LSB galaxies represent the faint end of the luminosity function of dwarf galaxies, we examined how the observed properties of the two classes of objects compare. This analysis has fundamental implications on the possible formation channels for UDGs in the Hydra I cluster.

Firstly, according to [La Marca et al. \(2022a\)](#), colors and structural parameters of the light distribution of all UDGs and LSB galaxies are similar to those of the parent dwarf galaxy population. With the LEWIS data we can compare the stellar kinematics and populations with same quantities derived for dwarf galaxies in a cluster environment<sup>2</sup>.

According to the standard picture of dwarf galaxy evolution ([Mistani et al., 2015](#)), very early-infallers are expected to have an increased  $\alpha$ -abundance pattern, low metallicity, old ages, and a large amount of GCs ([Forbes et al., 2023](#)). In previous literature, UDG and LSB metallicities have been shown to have only a weak correlation to clustercentric distance (e.g. [Romero-Gómez et al., 2023](#), [Ferré-Mateu et al., 2018](#)), yet low number statistics and the very limited number of studied environments (mostly Coma, Virgo and Perseus, see [Ferré-Mateu et al.,](#)

<sup>2</sup>Spectroscopic data are not available for the sample of dwarf galaxies in Hydra I cluster.

2023; Gannon et al., 2024 and references therein) have hindered strong conclusions.

Overall, in the Hydra I cluster, we observe that late infallers exhibit properties similar to those of regular dwarfs. Conversely, early infallers display a larger scatter in all properties (metallicity,  $\alpha$ -enrichment, and stellar kinematics), indicating that they likely contain galaxies that have undergone at least two distinct evolutionary paths. In particular, based on the star-formation history shape, or more specifically, the [Mg/Fe] ratio, two major populations are found.

A sub-population of the LEWIS sample resembles the properties of regular dwarfs (LSB5, LSB6, LSB7, LSB8, UDG1, UDG8) with their low-to-‘around-solar’  $[\alpha/\text{Fe}]$  ratios and extended SFHs. These could include the LSB tail of either high-metallicity dwarf-spheroidals (UDG1, LSB6, LSB7, LSB8, possibly slightly enriched by their medium yet supported by their rotation) or SF-inefficient dwarf-ellipticals (LSB5) distributions. These seem to be consistent with the mass-metallicity relationship for dwarfs, perhaps slightly enriched by the Hydra-I environment. According to the findings of Paper II, most of these galaxies, regardless of their strict UDG/LSB classification, appear to be DM-rich and exhibit rotation. In particular, as shown in Fig.5 of Paper II, the projected specific angular momentum ( $\lambda_R$ ) found for these objects are comparable with typical values derived for dwarf galaxies of similar stellar masses. The rest of the LEWIS sample is in line with the recent UDG literature, presenting solar-like or super-solar  $[\alpha/\text{Fe}]$  patterns and fast SFH shapes.

In the following section, we aim to compare the observed properties of the galaxies in the LEWIS sample, described above, to the predictions from simulations on galaxy formation.

#### 4.4.2 Comparing the observed properties with predictions from simulations

The LEWIS sample consists of galaxies located within  $0.4R_{\text{vir}}$  of Hydra I, meaning we are mapping a high-density environment. Therefore, we focus solely on comparison with theoretical predictions of UDGs in clusters. Using Illustris-TNG50 simulations, Sales et al. (2020) and Benavides et al. (2023) provided detailed properties on both stellar kinematics and stellar populations in cluster UDGs, under the assumption that all their UDGs are dispersion-supported systems. In this scenario, the T-UDGs, i.e. galaxies transformed into UDGs through tidal stripping processes, are predicted to have higher metallicity and lower velocity dispersion compared to dwarf galaxies of comparable stellar mass, and of the B-UDGs, which are field galaxies born as UDGs that later join the cluster. Since almost half of the UDGs in the Hydra I cluster are rotation-supported, a direct comparison

with predictions from [Sales et al. \(2020\)](#) can be performed only for the dispersion-supported galaxies, considering those targets having a constrained fit for the stellar kinematics (see Sec. 4.1 and Paper II). These are UDG4, UDG9, UDG11, LSB5 (see Table 4.1). Examining the mass-metallicity relation in Fig. 4.2, UDG9 and LSB5 are outliers, exhibiting higher metallicity than those for dwarf galaxies of similar stellar masses. None of these two galaxies shows a velocity dispersion  $\sigma_e$  lower than the typical values for dwarf galaxies, as predicted by the Faber-Jackson relation (see Fig.4 in Paper II). However, given the large scatter of the simulated UDGs in this relation, the tidal-stripping origin for these galaxies cannot be excluded. Both LSB5 and UDG9 are located in the early-infall region of the PPS, where tidal interactions between galaxies are clearly detected ([Spavone et al., 2024](#)), and where T-UDGs are expected to be found.

UDG4 and UDG11 have  $\sigma_e$  and metallicity that are consistent with the expected Faber-Jackson and mass-metallicity relations. Combining velocity dispersion measurements with metallicity estimates, these LEWIS galaxies might resemble the B-UDGs in the framework proposed by [Sales et al. \(2020\)](#). However, the number density of B-UDGs is larger in the cluster outskirts, with a half-number radius of about 0.5 of the virial radius. Since the LEWIS sample covers  $\sim 0.4 R_{\text{vir}}$  of the Hydra I cluster, B-UDGs might be those galaxies located at large cluster-centric distances.

UDG1, instead, has hints of stellar rotation; thus cannot be directly compared with [Sales et al. \(2020\)](#) prediction. This galaxy is a peculiar case. It is located in the very early infall region of the PPS, but differently from almost all other UDGs and LSBs in this region, it has a slow and constant mass assembly phase that does not seem to reconcile with either a tidal origin or a failed formation channel.

The metallicity of the LEWIS galaxies spans a range  $-1.3 \leq \langle [M/H] \rangle \leq -0.5$  dex, with stellar masses  $M_* \leq 10^9 M_\odot$  (see Fig. 4.2). Taking into account the error estimates, almost all LEWIS galaxies, except the three objects with the highest metallicities, show comparable values to those predicted by the simulations cited above. Therefore, considering the small scatter around the mass-metallicity relation, and the similarities in other structural properties (integrated colors, light distribution, SFH,  $\alpha$ -enhancement, stellar kinematics), all of them might reconcile with a puffed-up origin.

In the mass-metallicity relation, none of the galaxies in the LEWIS sample shows metallicity lower than  $\sim -1.5$  dex (see Fig. 4.1). As suggested by [Buzzo et al. \(2024\)](#) and [Ferré-Mateu et al. \(2023\)](#), very low metallicities, consistent with the evolving mass-metallicity relationship at redshift  $z \sim 2.2$ , are expected for the UDGs formed as the ‘failed-galaxy’ scenario (see Fig. 4.2). However, we cannot rule out their presence at the outskirts of the cluster, beyond the area covered by LEWIS.

| Properties<br>(1)                        | Very early infallers<br>(2)                                                                                                                       | Late infallers<br>(3)                                               |
|------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|
| Number of galaxies                       | 6 galaxies                                                                                                                                        | 4 galaxies                                                          |
| Metallicity                              | $[M/H] = -0.8 \pm 0.1$ dex                                                                                                                        | $[M/H] = -1.0 \pm 0.1$ dex                                          |
| $\alpha$ abundances                      | $[\alpha/Fe] = 0.0 \pm 0.2$ dex                                                                                                                   | $[\alpha/Fe] = -0.1 \pm 0.1$ dex                                    |
| Mass-Metallicity relation <sup>(a)</sup> | dwarf-like & metal-richer                                                                                                                         | dwarf-like                                                          |
| 2*Star formation history <sup>(b)</sup>  | dwarf-like: $\Delta t_{50} \sim 6$ Gyr , $\Delta t_{90} \sim 0.5$ Gyr<br>metal-richer: $\Delta t_{50} \sim 0.5$ Gyr , $\Delta t_{90} \sim 12$ Gyr | dwarf-like: $\Delta t_{50} \sim 5$ Gyr , $\Delta t_{90} \sim 1$ Gyr |
| Stellar rotation <sup>(c)</sup>          | Rotation & pressure-supported                                                                                                                     | Rotation-supported                                                  |

Table 4.2: Stellar populations properties of early and late UDG populations in Hydra I. Column 1 reports the properties of stellar population analysis from this work and stellar kinematics analysis from Paper II. Columns 2 and 3 report the values for the very early and late infallers. (a): we refer to galaxies in LEWIS for which the value of metallicity is similar (dwarf-like) or higher (metal-richer) than metallicity of dwarf galaxies of similar stellar mass according to the Kirby et al. (2013) relation. (b) we are not considering UDG4 since it has a peculiar SFH (see Fig. 4.3, top left panel).(c): in the late-infallers, three out of four galaxies have hints of stellar rotation, while the remaining one is pressure-supported. The reported classification refers to the majority of the objects in this class, although the sample size is not statistically significant.

## 4.5 Summary and conclusive remarks

In this paper, we have presented the stellar population properties for a homogeneous sample of UDG and LSB galaxies in the Hydra I cluster of galaxies observed with the MUSE integral-field spectrograph at ESO-VLT, as part of the LEWIS large programme (Iodice et al., 2023). We have derived the age, metallicity, and  $\alpha$ -abundances for 10 galaxies in the LEWIS sample (see Table 4.1). Overall, we have found that all galaxies exhibit age and metallicity consistent with typical values for dwarf galaxies of comparable stellar mass, including literature estimates for UDGs. The stellar population properties derived in this work, together with the stellar kinematics presented in Paper II, are analysed as a function of the cluster environment using the projected phase space (PPS).

In the late-infall region of the PPS, we identify a single population of galaxies with the lowest metallicities, nearly all of which are rotation-supported systems. In contrast, the early-infall region contains two types of galaxies: roughly half have metallicities consistent with the dwarf galaxy mass–metallicity relation, while the other half show higher metallicities (with  $\langle[M/H]\rangle \geq -1.0$  dex), ly-

ing outside the  $1\sigma$  confidence region of that relation. Both sub-samples include rotation- and pressure-supported systems. Galaxies in this region of the cluster also display different timescales for stellar mass assembly. Metal-rich galaxies reached 50% of their stellar mass in less than 1 Gyrs and show a prolonged and almost constant SF of more than 12 Gyr. All other galaxies exhibit a SFH similar to that found for galaxies in the late-infall region.

By comparing the observed properties for LEWIS galaxies with possible formation channels, we suggest that most of the UDGs/LSBs inside the  $0.4R_{\text{vir}}$  of the Hydra I cluster are likely puffed-up dwarfs. We propose that the high-metallicity systems have undergone significant stellar evolution driven by tidal processes, likely through interactions with nearby bright and massive galaxies. This interpretation is supported by their location in the cluster core and North group, where deep imaging has revealed clear signatures of ongoing gravitational interactions, such as tidal tails and disrupted dwarf galaxies. Finally, we do not find any galaxies consistent with the “failed-galaxy” scenario, primarily due to the absence of very low-metallicity systems in our sample. However, we cannot rule out the existence of such systems in the cluster outskirts, beyond the area covered by LEWIS.

In this work, we have attempted for the first time to correlate the spatial information from stellar kinematics (from Paper II) with age, metallicity and SFH. We expect to place even tighter constraints on the formation histories of UDGs in Hydra I by combining the structural properties derived so far (from stellar populations and stellar kinematics) with the globular cluster content ([Mirabile et al., 2025](#)).

## Chapter 5

# LEWIS Paper VI: Two-dimensional properties of LSBs and UDGs in the Hydra-I Cluster

*This is an ongoing work on the two-dimensional properties of stellar populations. This was, and is still being made in collaboration with Anna Ferré-Mateu, Jesús Falcón-Barroso and Ignacio Martín-Navarro at Instituto de Astrofísica de Canarias. This work mostly happened between January and April of 2025 and was the subject of my visit at the institute.* In this chapter, we delve into the bi-dimensional characteristics of a subset of the LEWIS sample. Due to the higher S/N demands of this work, in which we attempt to recover stellar population properties in a per-annuli basis, we are forced to focus only on the highest S/N sources in the sample, in particular: UDG1, UDG8, LSB7 and LSB8. In this way, we can be sure to retrieve the magnesium and iron lines with the quality necessary to perform a bin-to-bin comparison. In addition, throughout this chapter, we extend the spatial extent of the galaxy up to  $1.5R_e$  to improve spatial coverage and reach the necessary S/N. This choice, while somewhat arbitrary, allows one to gather enough light from the outer regions for a proper binning. This drives the S/N higher, allowing for the retrieval of a more complete stellar population gradient.

### 5.1 Preliminary considerations for 2D analysis

The methods described in this section are based on the 2D kinematics techniques described in Sec.3.2.4. In particular, we aim to separate the spatial extent of the galaxy in annular apertures using fixed radii in a way that allows us to keep a minimum S/N. As described by the previous chapters, a minimum  $S/N = 15$  is often needed to perform unbiased 1D-kinematics science on the main features



such as the Balmer lines and CaII lines. Here, we are also dealing with the often fainter magnesium and iron lines. In practice, we have empirically observed that this puts a minimum target for the study of stellar populations of  $\sim S/N = 20$  per bin. In addition to S/N constraints, we are also physically limited by the seeing, which we set at 1 arcsecond for practical purposes (this corresponds to the higher end of the measured seeing among the observation blocks). Thus, given that  $s \sim PSF \ll \delta R$ , where  $s$  is the seeing and  $\delta R$  is the bin size of any bin (inner or outer), we determine that PSF contributions, and seeing effects are for practical purposes, negligible given the small number of bins used here. The first task to retrieve useful concentric, annular bins, is to determine the number of bins to be used in all three of these sources.

### 5.1.1 Binning methodology

The underlying concept is to partition the galaxy into a sequence of concentric elliptical annuli, from which one dimensional spectra are obtained. Each annulus is specified by an inner semi-major axis ( $SMA_{inner}$ ), outer semi-major axis ( $SMA_{outer}$ ), ellipticity ( $\epsilon$ ) and a position angle ( $PA$ ) which we extract from our isophotal analysis (Paper II). The position angle (in degrees East of North in the catalog) is converted to radians counter-clockwise from the positive x-axis so that it matches the rest of the pipeline.

There are several ways to go about defining the position and extent of each annulus

#### Fixed-width method

One basic method is to cut the radial extent of the galaxy into a fixed number of annuli, each having equal semi-major axes of the ellipse. For a galaxy with a maximum radius of analysis  $R_{max}$  and a number of rings  $N$ , the outer boundary of the  $i$ -th ring is basically  $R_i = i \times (R_{max}/N)$ . While we use this method for comparison against our optimized routine, this method tends to generate very low SNR spectra in the outer annuli, which correspond to the regions of the galaxy with the lowest surface brightness.

Because of the fainter surface brightness at the outskirts of the galaxy, we are forced to either (1) Make the outer annuli larger, as these will naturally have less S/N, via having fixed inner and outer radii (2) Make the outer annuli large via systematically finding the  $sma_{inner}$  and  $sma_{outer}$  that guarantees a similar S/N throughout each annuli. This choice is not as straightforward as it sounds: uneven sampling can flatten out the very gradient we are trying to measure, because the properties of the outer regions would be averaged across a much larger area. Fixed

radii, however, while good to mitigate the effects of low S/N, are not rigourously defined. We follow the approach below:

### Adaptive Signal-to-Noise Ratio (SNR) Annuli

In order to address the drawbacks of equal-width binning, we developed a more complex adaptive binning method that is controlled by the algorithm. The objective of this program is to establish annuli of different diameters in such a way that the signal-to-noise ratio obtained from each annulus reaches one predetermined target SNR. As a result, the quality of the signal is preserved in all radial bins.

The program operates in this manner:

**Start-Up** The algorithm moves inwards from the galaxy center, i.e. the inner radius is zero ( $sma_{\text{inner}} = 0$ ). The target SNR is most often set as the median SNR obtained from all bins in an initial equal-width binning pass.

**Root-Finding Iteration** Given the inner radius  $sma_{\text{inner}}$ , the algorithm has to determine an outer radius,  $sma_{\text{outer}}$ , such that the SNR of the extracted spectrum from the annulus defined by  $(sma_{\text{inner}}, sma_{\text{outer}})$  corresponds to the target SNR. This is formulated as a root-finding problem. The objective function is defined as follows:

$$f(sma_{\text{outer}}) = \text{SNR}(sma_{\text{inner}}, sma_{\text{outer}}) - \text{SNR}_{\text{target}}$$

The algorithm utilizes Brent's method (`scipy.optimize.brentq`), an efficient numerical root-finding algorithm, to locate the value of  $sma_{\text{outer}}$  where  $f(sma_{\text{outer}}) = 0$ .

**Monotonic Radial Constraint** The physics of the situation requires that the width of the annuli generally become larger with increasing radius (as surface brightness decreases). Hence the monotonic width constraint is active. In other words, the width of the current ring,  $(sma_{\text{outer}} - sma_{\text{inner}})$ , should not be less than the width of the previous one. This condition narrows down the search bracket for the root-finding location.

**Repeating** The outer radius for the current ring, once found, is therefore the inner radius for the next one. The process is continued thus until the maximum radius of the galaxy (defined strictly as  $1.5R_e$ ) is reached.

This adaptive technique generates a set of annuli that reflect the brightness profile of each galaxy and thus provide spectra with uniform quality that can be used for comparative analysis.

### 5.1.2 Determination of Bin Size

The choice of size for each bin is not straightforward. Both relatively speaking (differences between bins) and globally speaking (overall size of the bin compared to the extent of the cube and the PSF). S/N is expected to degrade if the number of bins increases. In this preliminary test, we perform a case-by-case study on the S/N degradation for all of these four sources (see Fig. 5.2). For the two brightest LSBs of the sample, LSB7 and LSB8 we find that we are able to get as high as 6 and 5 sectors respectively before the quality of the Mg-Fe region degrades significantly. For the UDGs, we find that the choice must be within  $< 4$  sectors to prevent the weaker lines from disappearing into the noise. In practise, the lowest S/N bin we reach is about  $S/N \sim 18$ , and the S/N targets we aim to reach are  $> 20$  for UDGs and  $\sim 25$  for LSBs. Before committing to a choice of  $N_{bins}$ , we check the quality of the data by plotting the relevant lines for the different apertures of each galaxy, paying close attention to the last bin.

### 5.1.3 Spectrum Extraction and Kinematic Correction

After the definition of the annuli, a 2D boolean mask is generated to limit the extraction beyond each annulus. A final extraction mask is obtained by the logical AND of this annulus mask with a previously defined spatial mask which is used to indicate bad spaxels or foreground contaminants (this is the same spatial mask we use in Paper II and Paper V).

The correction for the internal kinematics is a very important point in the extraction process. The galaxies have internal velocity structures (for example - rotation), thus the spaxels within a single annulus are not all at the same rest frame. To just co-add their spectra would create a fake broadening of spectral lines, which in turn would be giving a false, higher velocity dispersion value and could possibly cause the stellar population parameters to be biased.

We construct the following function to handle this issue:

**Velocity Map** A 2D line-of-sight velocity ( $V_{LOS}$ ) map for each spaxel is given. These stellar velocity maps come from LEWIS Paper II.

**De-redshifting** Each spaxel within the annulus mask uses its velocity ( $V_{LOS, spaxel}$ ) to determine the Doppler shift with respect to the galaxy's systemic velocity ( $V_{sys}$ ). The wavelength solution for that spaxel's spectrum is adjusted to the galaxy's rest frame:

$$\lambda_{rest} = \lambda_{obs} \left/ \left( 1 + \frac{V_{LOS, spaxel} - V_{sys}}{c} \right) \right.$$

**Resampling and Co-addition** Linear interpolation of the spectra of each annulus is used to resample the de-redshifted spectrum to the original common rest-frame wavelength grid.

**Stacking** The final, kinematically-corrected 1D spectrum for that radial bin is obtained by co-adding the resampled, de-redshifted spectra of all spaxels in the annulus.

The noise that goes along with each extracted spectrum is calculated from the median-filtered residual of the spectrum itself. This phase's final outputs are the FITS files for each annulus, which include the wavelength array, the co-added flux array, and the estimated noise array. Fig. 5.3 illustrates this kinematic alignment procedure, using a kinematic map from LEWIS Paper II.

## 5.2 pPXF solutions on the two-dimensional stellar population analysis

We employ the methods described in the Chapter 4 to derive the stellar population properties of each bin, including the errorbars by means of the same Monte Carlo routine used in LEWIS Paper II and V. We recover, the mean metallicity, mean age, alpha-enhancement and mass-to-light ratio for all of the four sources. Similar to our previous work, we select the sMILES set of templates to cover the low alpha-enhancement found for the LSBs in the LEWIS sample. We add the caveat that this choice is not standard, and Base templates with a regular, alpha-enhanced pattern might lead to different results. This will be explored in an extension of this current work.

## 5.3 Results on the two-dimensional stellar population analysis

### 5.3.1 Overall 2D properties

Overall, for these four sources, we find complex metallicity gradients along the studied radii, which do not seem to prefer a constant decrease or increase towards the external regions. To quantify these variations, we decide to perform linear fits in two regions:  $0 - 0.75R_e$  (measuring  $\nabla_{inner}[M/H]$ ) and  $0.75 - 1.5R_e$  (measuring  $\nabla_{outer}[M/H]$ ). This allow us to (1) detect a change of sign on the gradient, (2) separate the inner, more robust inner part of the gradient to the outer region which often relies on fewer data points, and (3) use  $\nabla_{inner}[M/H]$  for a more direct comparison

with the recent work of [Ferré-Mateu et al. \(2025\)](#) which report values within the inner  $0.7R_e$ . In addition, we find a very significant decreasing pattern in alpha-enhancement for UDG1, LSB7, and LSB8 across the whole studied radii. Age gradients appear largely flat, except for UDG1 which presents a clear decreasing pattern towards the outskirts. Therefore, we only measure the global gradient across the  $1.5R_e$  for both the age and the alpha enhancement.

| Source | $N_{\text{rings}}$ | $\nabla_{\text{inner}}[\text{M/H}]$ | $\nabla_{\text{outer}}[\text{M/H}]$ | Outer Boundary |
|--------|--------------------|-------------------------------------|-------------------------------------|----------------|
|        | (1)                | (2)                                 | (3)                                 | (4)            |
|        |                    | (dex/ $R_e$ )                       | (dex/ $R_e$ )                       | ( $R_e$ )      |
| UDG1   | 3                  | $-1.1 \pm 0.5$                      | $1.5 \pm 0.4$                       | 0.70           |
| UDG8   | 4                  | $1.1 \pm 0.9$                       | $-0.5 \pm 0.7$                      | 0.60           |
| LSB7   | 6                  | $0.0 \pm 0.4$                       | $-0.3 \pm 0.5$                      | 0.60           |
| LSB8   | 5                  | $-1.3 \pm 0.6$                      | $0.1 \pm 0.8$                       | 0.75           |

Table 5.1: Inner and outer metallicity gradients for each source. Column (1) shows the number of radial rings used for the analysis. Columns (2) and (3) present the inner and outer metallicity gradients, respectively, where the inner gradient is measured from 0 to  $0.75 R_e$  (or adjusted boundary) and the outer gradient is measured from the outer boundary to  $1.5 R_e$ . Column (4) indicates the radial position of the boundary between the inner and outer regions, with values below  $0.75 R_e$  representing an adaptively adjusted boundary due to limited data coverage.

### 5.3.2 Specific gradients and comparison to 1D properties

#### UDG1 and UDG8

UDG1 was found to present a  $1R_e$  integrated mean metallicity of  $[\text{M/H}] = 0.5 \pm 0.1$  dex (see Chapter 4 of this thesis), which is compatible with our 2D results. In particular, we find a dip in metallicity at  $\sim 1R_e$  (Fig. 6.12), while elsewhere the profile seems otherwise flat or slightly increasing. The age profile of UDG1 is interesting because show significant younger populations at the outskirts of the galaxy. Additionally, the  $[\alpha/\text{Fe}]$  gradient is decreasing.

UDG8, conversely has a global metallicity of  $1.2 \pm 0.1$  dex which is somewhat compatible with the seen metallicity profile within  $1R_e$ . In particular, the gradient is positive overall (Fig. 6.13), with a sharp increase within  $0.5R_e$  but plateauing at larger radii at significantly higher metallicities ( $\sim 0.9 \pm 0.1$  dex). The overall  $[\alpha/\text{Fe}]$  gradient is negative.

### LSB7 and LSB8

LSB7 was found to present a metallicity of  $0.7 \pm 0.1$  dex, consistent with the very flat profile at  $\sim 0.6 \pm 0.1$  dex across the whole  $1.5R_e$ . The  $[\alpha/\text{Fe}]$  gradient is sharply decreasing in the inner region (Fig. 6.14), reaching very low values at the outskirts. LSB8 (Fig. 6.14) presents instead a complex situation. We find  $\nabla_{\text{inner}}[\text{M}/\text{H}] = -1.3 \pm 0.6$  dex/ $R_e$  and  $\nabla_{\text{outer}}[\text{M}/\text{H}] = +0.1 \pm 0.8$  dex/ $R_e$ , but we also see a discontinuity at  $\sim 0.6 R_e$ , where the metallicity sharply decreases. This sharp decrease create these negative gradients from an otherwise flat (or slightly decreasing) metallicity gradient.

## 5.4 Discussion on the stellar population gradients

The four sources are different enough to guarantee a case by case discussion.

UDG1, having V-shaped metallicity profile plus a decreasing age gradient is arguably the most striking pattern we see in this sample. The inner regions, up to  $0.7R_e$ , exhibit a significant and strong negative gradient of  $\nabla_{\text{inner}}[\text{M}/\text{H}] = -1.1 \pm 0.5$  dex/ $R_e$  which is consistent with the classic pattern of "inside-out" formation. This region seems to be dominated by old to old-intermediate age populations, consistent with formation early on followed by quenching. Despite the above, the profile undergoes a dramatic reversal beyond  $0.7R_e$ , with  $\nabla_{\text{outer}}[\text{M}/\text{H}] = +1.5 \pm 0.4$  dex/ $R_e$  accompanied by a sharp decrease in the mean age of the outer stellar populations. The above effect cannot be produced by a simple, continuous process. Thus, we may evoke external processes to explain the apparent rejuvenation of the outer regions, such as a tidal event or accretion process. Alternatively, this pattern may be recreated if the galaxy were to push internal material and younger stars to the outer regions. In any case, this pattern directly challenges the simpler, single SF bursts at early epochs scenarios (e.g such as "failed galaxy") and is further reinforced by the negative  $[\alpha/\text{Fe}]$  gradient of UDG1.

UDG8 presents a completely different but equally striking situation, the so called positive or "inverted" metallicity pattern. This is not the first time such a gradient has been found for an UDG (see e.g, [Villaume et al., 2022](#) for a discussion of stellar population gradients for one of the most well-studied UDGs, DF44). Recently, further evidence of this pattern in UDGs was found in [Ferré-Mateu et al. \(2025\)](#). This profile may represent a feature that separate UDGs from classical dwarf galaxies. An internal process that is commonly associated with this pattern is stellar migration (e.g, [El-Badry et al., 2016](#)), which could potentially push older, metal-rich stars outwards from the center, leading to an inversion of the original gradient. The flat age profile of this galaxy, contrary to UDG1, disfavors a tidal scenario, consistent with its relatively low overall metallicity. It instead favors

"puffy-dwarf" models and a situation where star formation happened all at once (Ferré-Mateu et al., 2025), presumably early on.

LSB7 presents another interesting case. This metallicity profile is compatible with being flat, or slightly decreasing while presenting a flat age profile. This is not too far away from the classical dwarf pattern, but we have to remark the stark  $[\alpha/\text{Fe}]$  negative gradient across the galaxy, less expected in LSBs. Akin to more massive galaxies, this galaxy may have been formed in a classical "inside-out" pattern. Alternatively, the flatness of the measured metallicity profile may indicate evidence for the effect of environmental mixing or tidal stirring. Stripped galaxies from TNG50 are consistent with this slope, which may suggest that environment may be playing a role on top of internal processes. This would not be clear from 1D analysis alone, as the source is only at  $< 1\sigma$  above the MZR. The positioning of LSB7 on the PPS, being the closest LEWIS source to the center, makes this plausible scenario appealing.

Finally, LSB8 presents some similarities to UDG1, where we find evidence for a dip in metallicity followed by an outer profile consistent with slightly positive to flat. If flat, the pattern would be consistent with tidal stripping or truncation of a more massive galaxy. This is consistent with the strong, declining  $[\alpha/\text{Fe}]$  profile, common in "inside-out" formation patterns. Alternatively, stellar migration remains a possibility due the relative increase in metallicity in the lastest bin, but a further refinement of the data quality would be needed for a stronger conclusion.

## 5.5 Comparison with simulations on gradients

Fig. 5.4 shows our measured gradients against the literature data, in particular simulations from NIHAO (Cardona-Barrero et al., 2023) and TNG50 (Benavides et al., 2024) for cluster UDGs. Following previous works (e.g, Sales et al., 2020, Benavides et al., 2024, Ferré-Mateu et al., 2025), we have normalized the absolute metallicity by applying a constant downwards shift of 0.4 dex to the TNG50 values. Thus, we do not attempt to compare the mean metallicity of the galaxies with those of the simulations (which are sensitive to a wide range of parameters) but rather the predicted gradients. The metallicity plot shows that the predictions from the TNG50 and NIHAO simulations, which are indicated by the dotted and dashed lines, correspond to a relatively small range of flat-to-mildly-negative gradients. In fact, they do not seem to match the complex and negative gradient of LSB8, the V-shaped profile of UDG1, or the inverted gradient of UDG8. The relative trend of TNG50 tidally stripped galaxies, while flatter, also does not seem to match the large variations seen for UDG1 and LSB8. While large-volume simulations such as TNG50 and zoom-in suites like NIHAO have, by and large, been very successful in reproducing global galaxy scaling relations for large statistical samples,



this paper is pointing out their limitations at the moment in being able to predict the detailed internal structures of single galaxies, especially those in the inner regions of massive galaxy clusters. The difference may point to the fact that the sub-grid physical models that regulate star formation, stellar feedback, and most importantly for this sample, environmental processes might not be of sufficient quality or resolution to consider the widest range of physical outcomes. Despite the above, we note that [Cardona-Barrero et al. \(2023\)](#), while presenting individual profiles that allow for a direct structural comparison, these simulations model isolated dwarfs, which make the comparison with our sample significantly more challenging. On the other hand, [Benavides et al. \(2024\)](#) report median trends, which may naturally wash out V-shape outlier or other complex profiles in the averaging process.

## 5.6 Summary

We conclude that our sample exhibit a wide range of metallicity gradient morphologies, including steeply negative (LSB8), flat (LSB7), V-shaped (UDG1), and inverted (UDG8). Such variety implies that galaxies residing in the same global environment have the potential to diverge significantly in their evolutionary pathways. Additionally, many of the observed properties, when added to the enhanced metallicity of some of the sources, suggest a prevalence of environmental features and processes. Some of these properties, such as the gradients in alpha-enhancements and steep metallicity gradients, disfavor some of the leading theories of UDG evolution (e.g "failed-galaxy") for our sample in Hydra-I. Finally, simulations are left with the task of being able to explain this wide range of properties. This highlights a key area for further development.

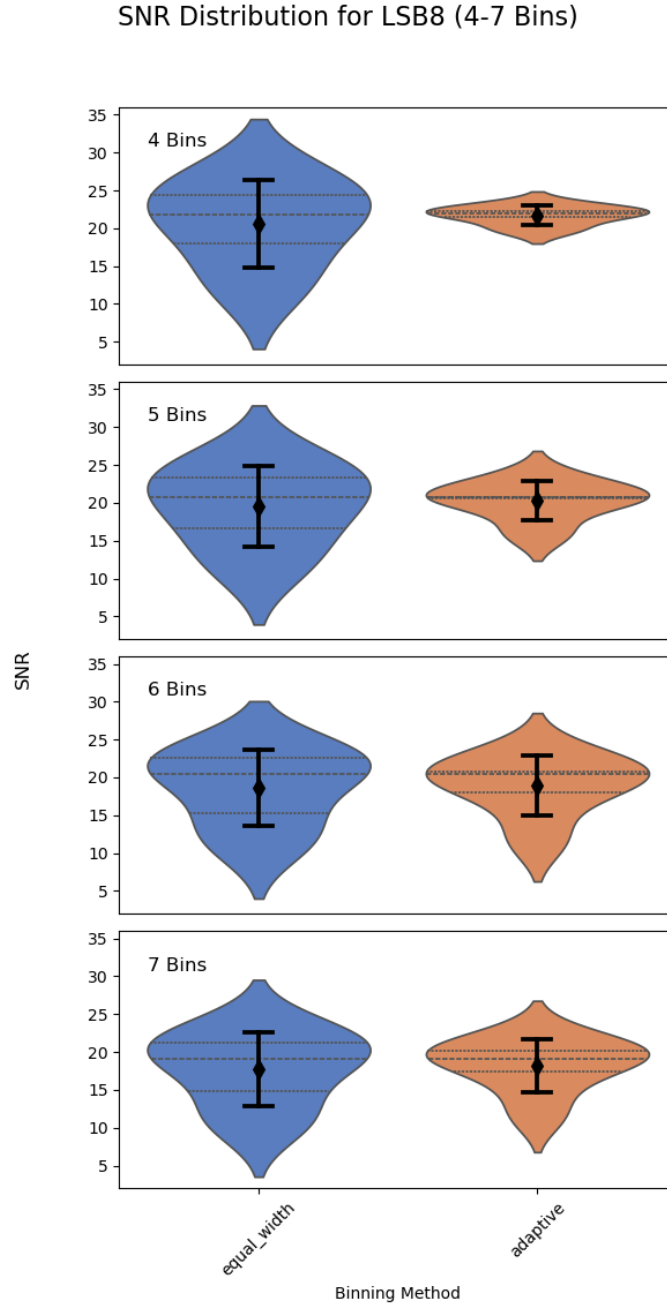


Figure 5.1: Comparison of our adaptive rings methodology for LSB8, illustrated by a violin plot. In blue and orange, we plot the SNR distribution across the number of bins for each selection of  $N_{bins}$  for the equal width partitioning method versus our implemented adaptive method. We see (1) the average of the SNR is higher for the adaptive method (2) The distribution is narrower for the adaptive method, meaning the SNR does not drop significantly in the outer regions. From the above, we conclude our method works well and is preferred for this particular analysis. The only drawback (loss of homogeneity across the spatial extent) is countered by the gain in SNR, critical for LSBs.

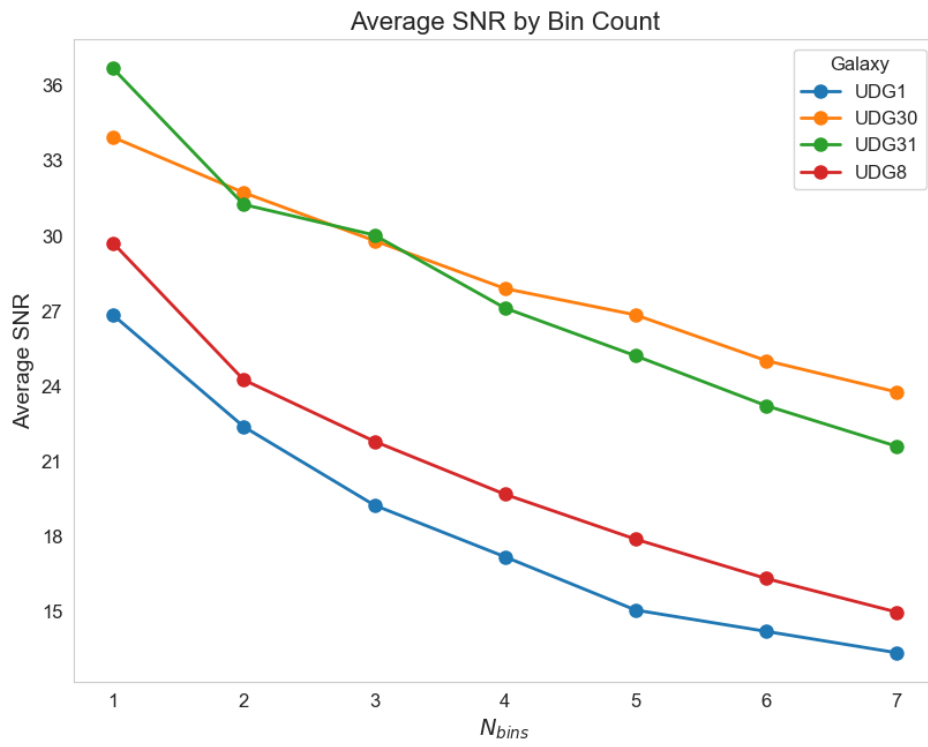


Figure 5.2: Degradation of S/N as per the number of bins for all four sources analyzed in this chapter.

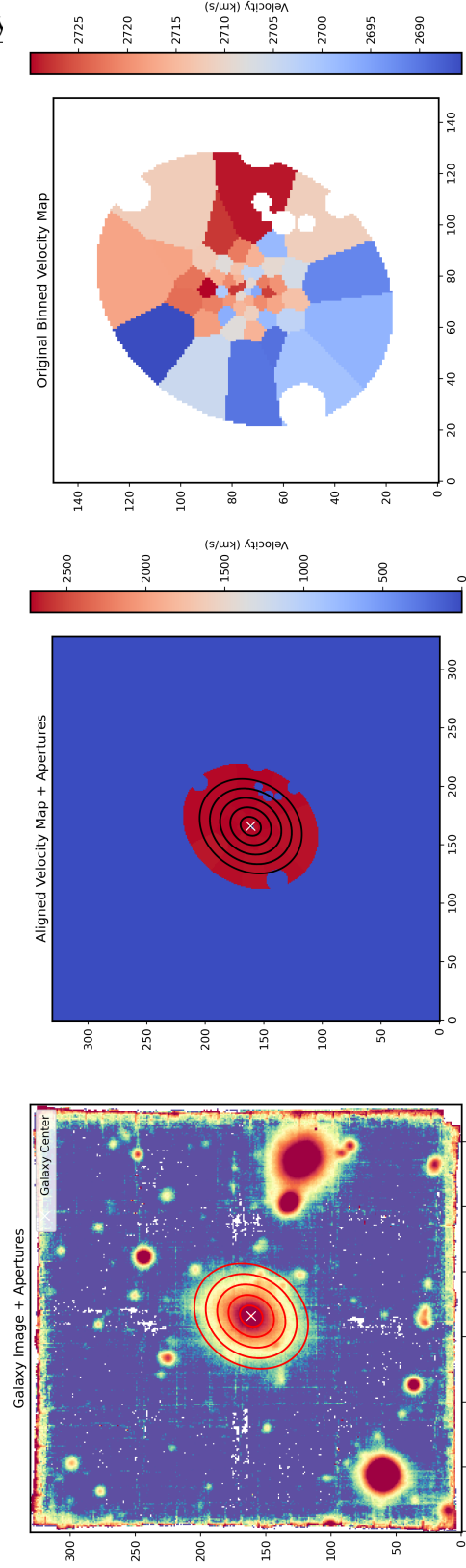


Figure 5.3: An example illustrating the kinematic alignment procedure for LSB8. The left panel shows the white MUSE image of LSB8 with the selected apertures as per our adaptive rings method (Sec.5.1.3). The right panel shows the velocity map for LSB8 as presented in LEWIS Paper II. The central panel shows the same velocity map, but corrected to achieve the same systemic velocity before co-adding the spaxels within the annuli.

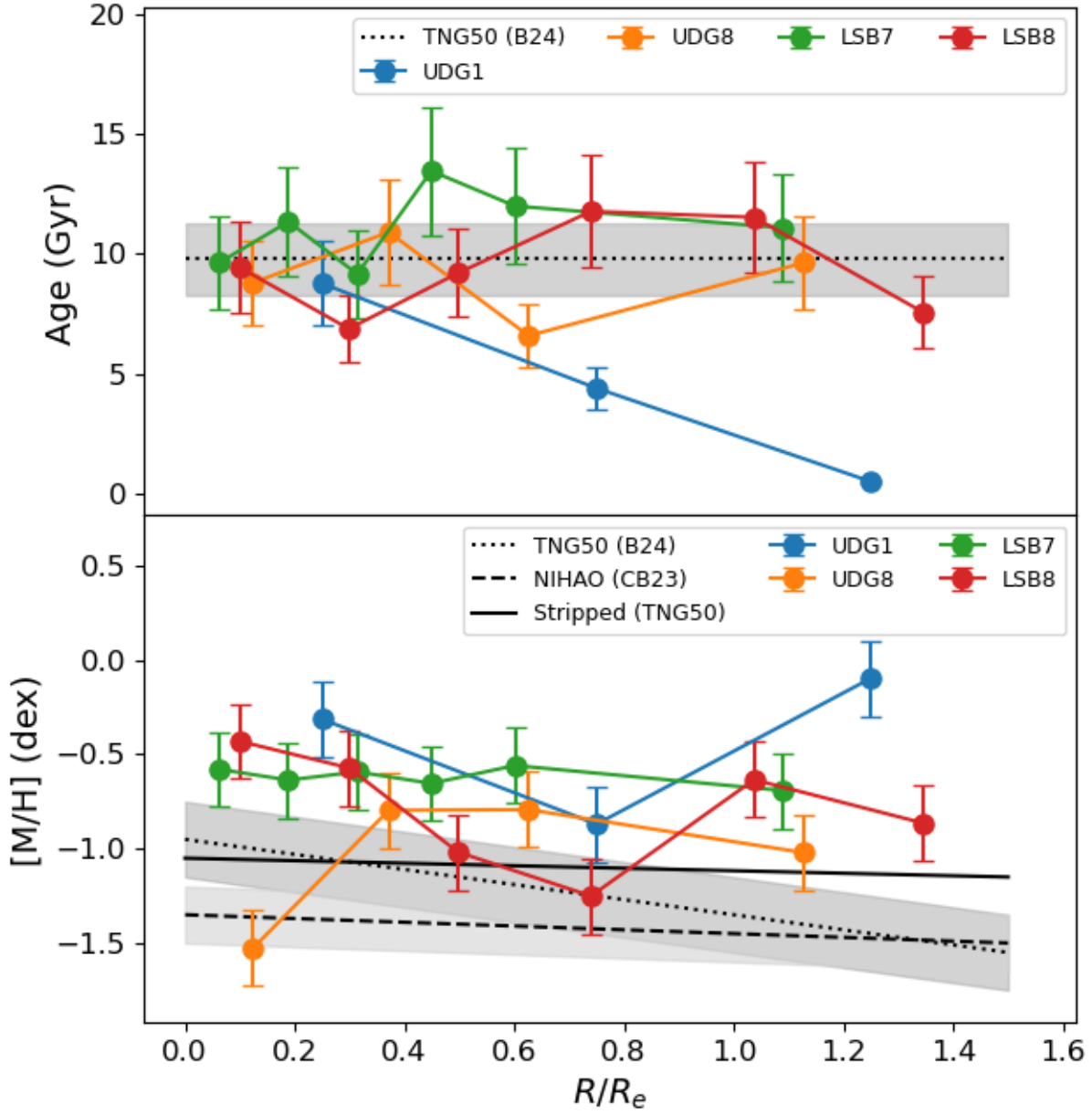


Figure 5.4: Measured gradients compared to TNG50 (dotted) and NIHAO (dashed) simulations, we have added the global metallicity trend of some of the stripped TNG50 galaxies as per [Ferré-Mateu et al. \(2025\)](#)

# Conclusions and Future Outlook

This thesis provides a first systematic characterization of local stellar kinematics, integrated stellar populations, and spatially resolved properties for a statistically significant sample of LSBs in a single cluster environment (Hydra-I). Such discoveries set important limits on the origin of LSB galaxies, their possible evolutionary routes, and the issue of small-scale problems of  $\Lambda$ CDM cosmology that they can be a part of. This sample comprises 25 galaxies (19 UDGs and 6 LSBs) located within  $\sim 0.4R_{vir}$  of the Hydra-I cluster. Out of these, we have analyzed 10 galaxies with high enough S/N and constrained kinematics to perform stellar population studies.

The bulk of the LEWIS galaxies seems to be consistent with the high-spin halo + stellar feedback model. They are located on or close to the dwarf MZR relation, with stellar masses of  $10^7 - 10^9 M_\odot$ . The  $[\alpha/\text{Fe}]$  ratios of most LEWIS UDGs are close to solar or mildly enhanced ( $\sim 0.0 - 0.4$  dex), in agreement with the shorter quenching timescales of  $\sim 1 - 6$  Gyr. Yet UDG1 and the LSBs from LEWIS present sub-solar  $[\alpha/\text{Fe}]$  instead. Their dynamics are mainly rotation-supported and their metallicity gradients, primarily either flat or negative, are compatible with a complex dwarf-like evolutionary pathway. Given to the (relatively) metal-rich quantities of our population, we fail to detect galaxies consistent with the failed scenario, at last for our studied region within the cluster. In general, when coupling the presence of rotation in several LEWIS galaxies with their slower SFH and their steep declining metallicity profile as per their  $\nabla_{inner}$  (UDG1, UDG7), we find evidence for very strong feedback processes not being ubiquitous across the whole UDG population. In particular, we isolate a population that likely retains its primordial halo structure rather than being heavily transformed by feedback. This puts constraints to the intensity and/or universality of the feedback processes that solve the Cusp-Core problem. It also implies that not every UDG can be used as a test for such processes.

We find the outliers of the MZR (UDG1, LSB5, UDG9) and galaxies with inverted/complex gradients (UDG8, LSB8) provide strong evidence for environmental transformation. In particular, pre-processing, stripping or accretion is possible for the metal-rich sources in this sample. The youngest outer populations of

UDG1 and the inverted gradient of UDG8 being not consistent with isolated evolution. They suggest tidal heating, stellar migration, or minor mergers. We find further possible evidence when we consider the rate of tidal tails and disrupted dwarfs by [Spavone et al. \(2024\)](#) in the cluster core and North Group of Hydra. Still, it is clear that ram-pressure stripping by itself is not sufficient to account for the extended SFHs of UDG1 and LSB5 where  $\Delta t_{90} \sim 12$  Gyr. The complex stellar population gradients we found suggest the need for further development in the physics and resolution of simulations, alongside expanding the studies on individual simulated profiles which are currently the most meaningful way of testing the models due statistical limitations. Studies on the effect of stellar migration and/or accretion would likely prove to be useful when testing against some of our outliers (UDG1, LSB8).

On our side, further expansion of LEWIS would be beneficial, in particular towards the outskirts of the cluster. This would allow for a better testing ground of the physical processes in a larger radius where trends can be significantly measured with these small samples. Fundamentally, such an expansion of the covered regime within the cluster will help to better separate environmental effects from internal processes. This allows for testing the discussed models much more effectively. In terms of new technology, we expect facilities such as Euclid and LSST to open new frontiers for deep photometry and future spectroscopic follow-ups in an even wider range of environments.



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et al. (2022); Danieli et al. (2022); Villaume et al. (2022); Webb et al. (2022); Saifollahi et al. (2022); Janssens et al. (2022); Gannon et al. (2023); Ferré-Mateu et al. (2023); Toloba et al. (2023); Shen et al. (2023). The authors acknowledge the use of the following Python scripts: ASTROPY (Astropy Collaboration et al., 2013, 2018), MATPLOTLIB (Hunter, 2007), MPDAF (Bacon et al., 2016; Piqueras et al., 2017), NUMPY (van der Walt et al., 2011), PHOTUTILS (Bradley et al., 2023), SCIPY (Virtanen et al., 2020), and ZAP (Soto et al., 2016).

# Chapter 6

## Appendix

### 6.1 Line indices

In this section, we show the model grids used for the computation of the  $[\text{Mg}/\text{Fe}]$  pattern and address the potential caveats of using the standard E-MILES models.

Fig. 6.1 shows a selection of sMILES model grids for all galaxies in our high-quality sample: for each one, we restrict the age and metallicity of each grid to a region centred at the `ppxf` solution of the galaxy for both their age and metallicity. Comparing the datapoints to an interpolated (or extrapolated) trend for the grid, we compute an estimate of  $[\text{Mg}/\text{Fe}]$ .

The top panel of Fig. 6.2 shows our data points on top of the E-MILES models. The bottom panel shows the actual model grids (E-MILES+`ppxf`) to derive the  $[\text{Mg}/\text{Fe}]$  pattern, using light-weighted ages as a more robust age indicator. We note that E-MILES templates are not being used for any `ppxf` fits and are solely to have another, partly independent measurement of the alpha enhancement. We strictly use variable  $[\alpha/\text{Fe}]$  sMILES templates, as these allow us to cover a larger space in the  $\text{H}\beta_0$  distribution and therefore to minimise any effect of template mismatch. We caution that two sources have an extremely low  $\text{H}\beta_0$  intensity and are not perfectly covered by any template (UDG9 and UDG12). However, the strength of the metallic lines allows us to still constrain the metallicity and alpha content of these galaxies via the alpha-enhanced sMILES templates. The age, though in a difficult position, can be constrained by the use of `ppxf`. We interpret the positioning of these sources within the grids as the effect of high levels of  $[\alpha/\text{Fe}]$ , low S/N and a possible, minor emission component, hard to decouple given the quality of these spectra.

Overall, we find the results for the  $[\text{Mg}/\text{Fe}]$  computation are fully consistent between the three methods (`ppxf`-derived, E-MILES derived, and sMILES-derived). Two minor exceptions are found: UDG1 and LSB5 have an extremely

low alpha-enhancement, going slightly beyond the template limits at the low end with the sMILES method (Fig. 6.1) and are at the corners of the grid following the method of Vazdekis et al. (2015) and Ferré-Mateu et al. (2023) using the E-MILES templates (Fig. 6.2). Thus, we are forced to slightly extrapolate outside the model grids for their computation, as the sMILES models (and thus, their ppxf results) have a hard limit at a sub-solar enhancement of  $-0.2$  dex.

## 6.2 Stellar population properties and star-formation histories

In this section, we present the stellar population properties and star-formation histories of all the galaxies in LEWIS for which both stellar kinematics and stellar population properties are accurately constrained (see Section 4.3). Figs. 6.3 to 6.11 reports the ppxf fit of the analysed spectral region for the different galaxies, along with a grid showing the median distribution of ages and metallicities obtained through our Monte Carlo procedure. Additionally, we include the cumulative mass fraction obtained by collapsing the age and metallicity weights of each Monte Carlo iteration.

## 6.3 Intermediate cases

In this section, we describe the intermediate cases, i.e., galaxies classified with ‘I’ symbol in Table 4.1. These galaxies have spectra with S/N not enough to properly resolve all major absorption features. In addition, the stellar kinematics extraction might be biased and thus affect the reliability of the results from stellar population analysis. These galaxies are UDG3, UDG7, UDG10, LSB1, and LSB4. The spectrum of UDG3 presents a very weak  $H\beta$  and lacks any major hint of iron and/or magnesium lines. We thus infer that this source is presumably old, like most of the sample. However, we cannot put a constraint on the exact age or metal content. The same holds for LSB1 and LSB4. The spectra of UDG7 and UDG10, instead, show clear Fe lines, but the poor quality of the  $H\beta$  feature makes the degeneracy of the alpha-enhancement and metallicity hard to break. The large  $[Mg/Fe]$  ratio of UDG7 would place this galaxy among the highest alpha-enhanced sources in the sample, as their iron patterns fall outside of solar-scaled model templates. We infer that UDG7 and UDG10 are old and enhanced in magnesium content, yet the large uncertainties and degeneracies due to the data quality make it hard to give significant constraints.

## 6.4 2D stellar population gradients

Fig. 6.12 through Fig. 6.15 show individual gradients for all of the four sources. We have included M/L gradients for completeness.

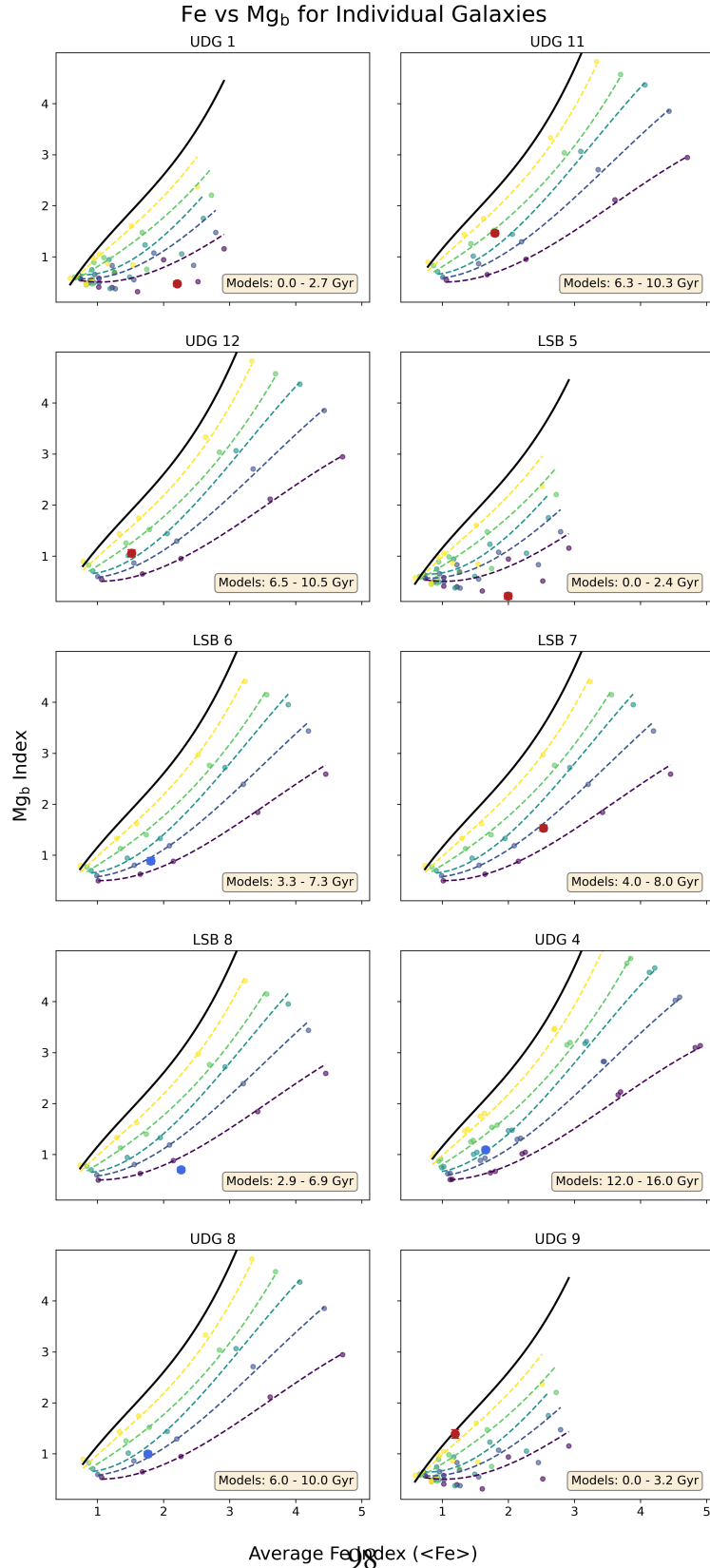


Figure 6.1: Line indices  $\langle Fe \rangle$  and  $\langle Mg_b \rangle$  for sMILES models and LEWIS galaxies. In each panel, the label shows the subset of sMILES models (coloured lines and circles) restricted in age and metallicity used to compute line indices and infer the values of  $[Mg/Fe]$  for the LEWIS galaxies, colour-coded as in Fig. 4.1. The thick solid black line represents the solar baseline ( $[Mg/Fe]=0$ ), while the different dashed lines correspond to increasing values of  $[Mg/Fe]$ .

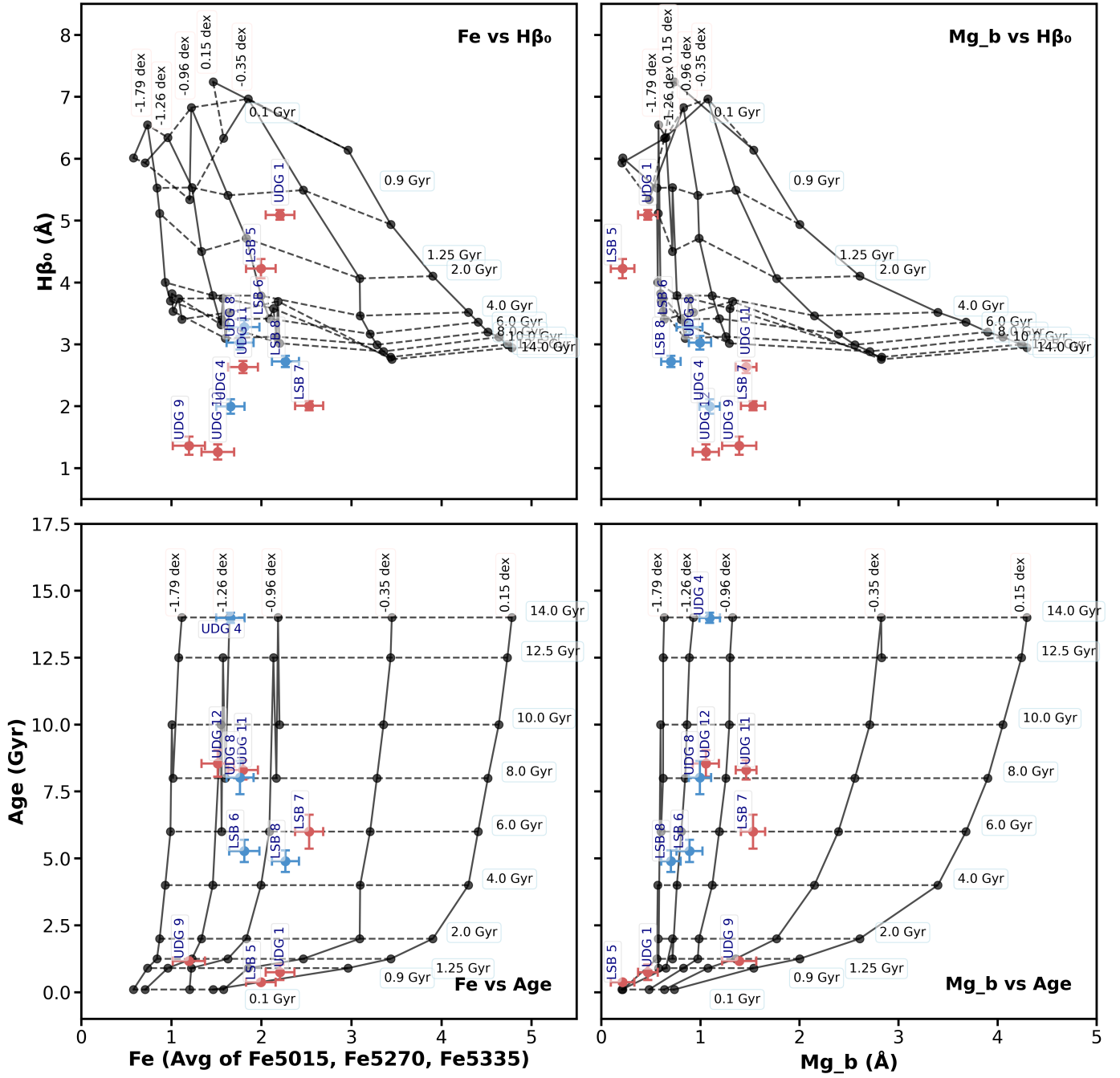


Figure 6.2: Top row: E-MILES base models compared to line indices data-points from our sample. Bottom row: E-MILES model grids used to compute the  $[Mg/Fe]$  enhancement, using the light-weighted age of the models and `ppxf` to make the grids orthogonal, and this is better defined in the old and metal-poor regime. LEWIS galaxies are colour-coded as in Fig. 4.1

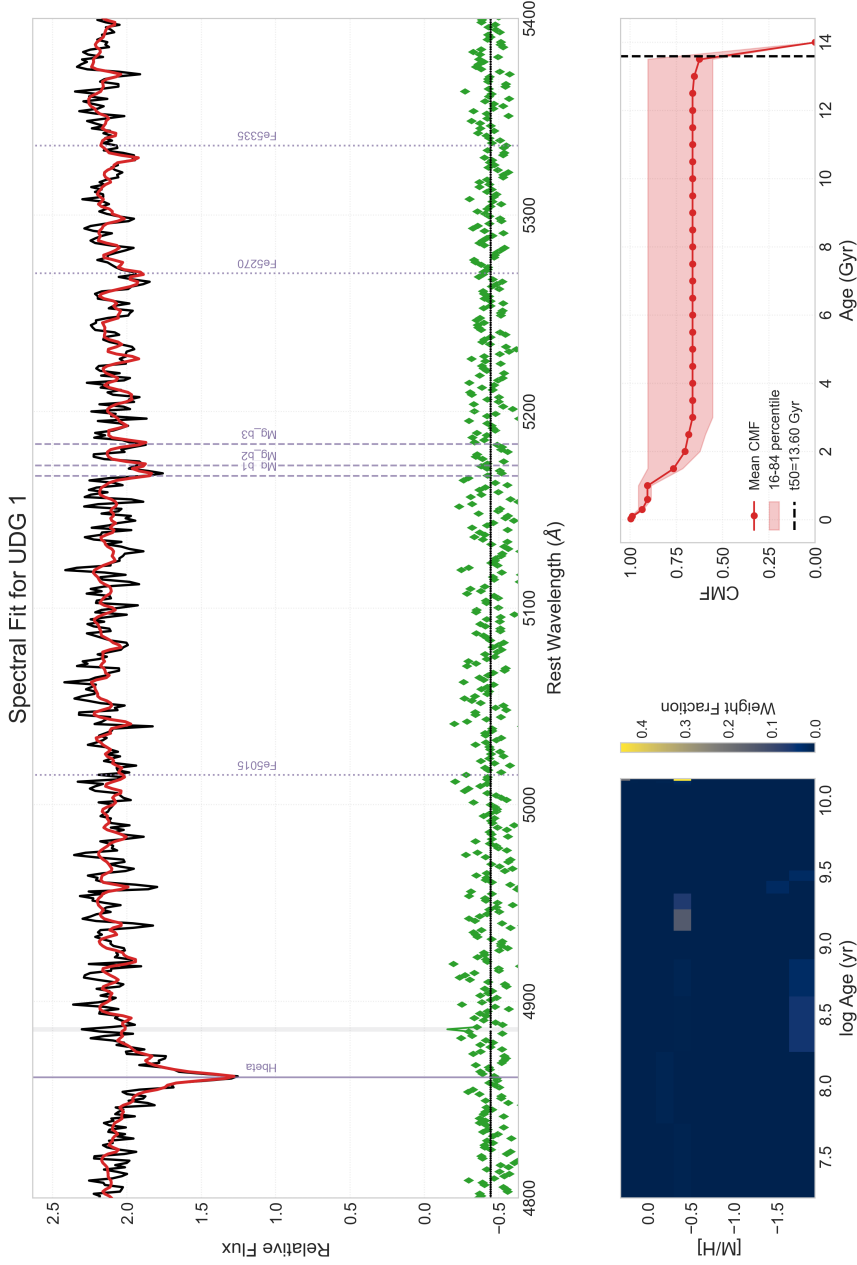


Figure 6.3: Stellar population properties and star-formation history of UDG1. Top panel: MUSE  $1 R_e$  stacked spectrum (black solid line) for UDG1. The main absorption features are marked in purple. The red solid line represents the bestfit obtained with `ppxf`. Green points are the residuals between the observed spectrum and its best-fit template spectrum. The grey areas are the masked regions excluded from the fit. Bottom left panel: Age-metallicity distribution of the MC iterations of UDG1. Bottom right panel: Cumulative mass fraction, based on the MC iterations.  $t_{50}$  marks the time at which the 50% of the galaxy mass was formed.



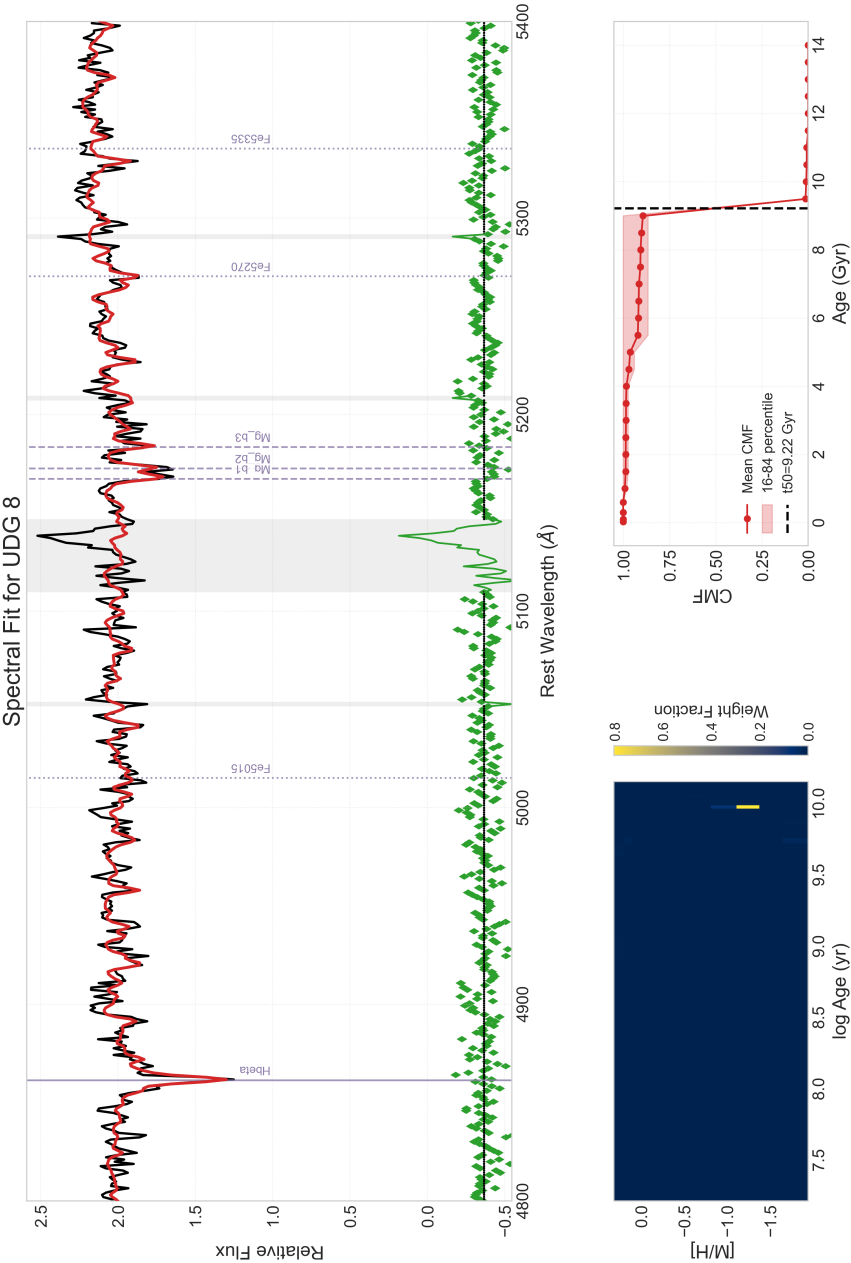


Figure 6.4: Same as Fig. 6.3, but for UDG8.

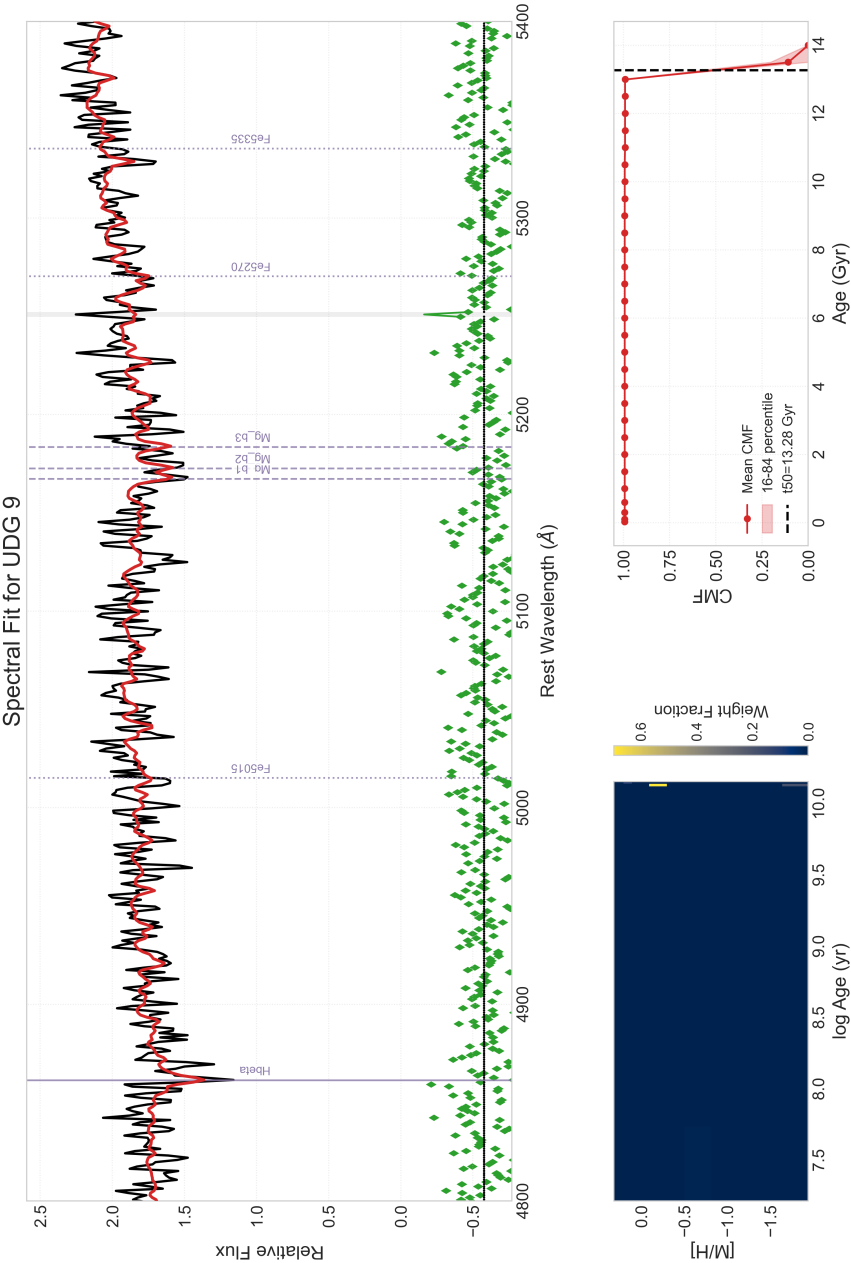


Figure 6.5: Same as Fig. 6.3, but for UDG9.

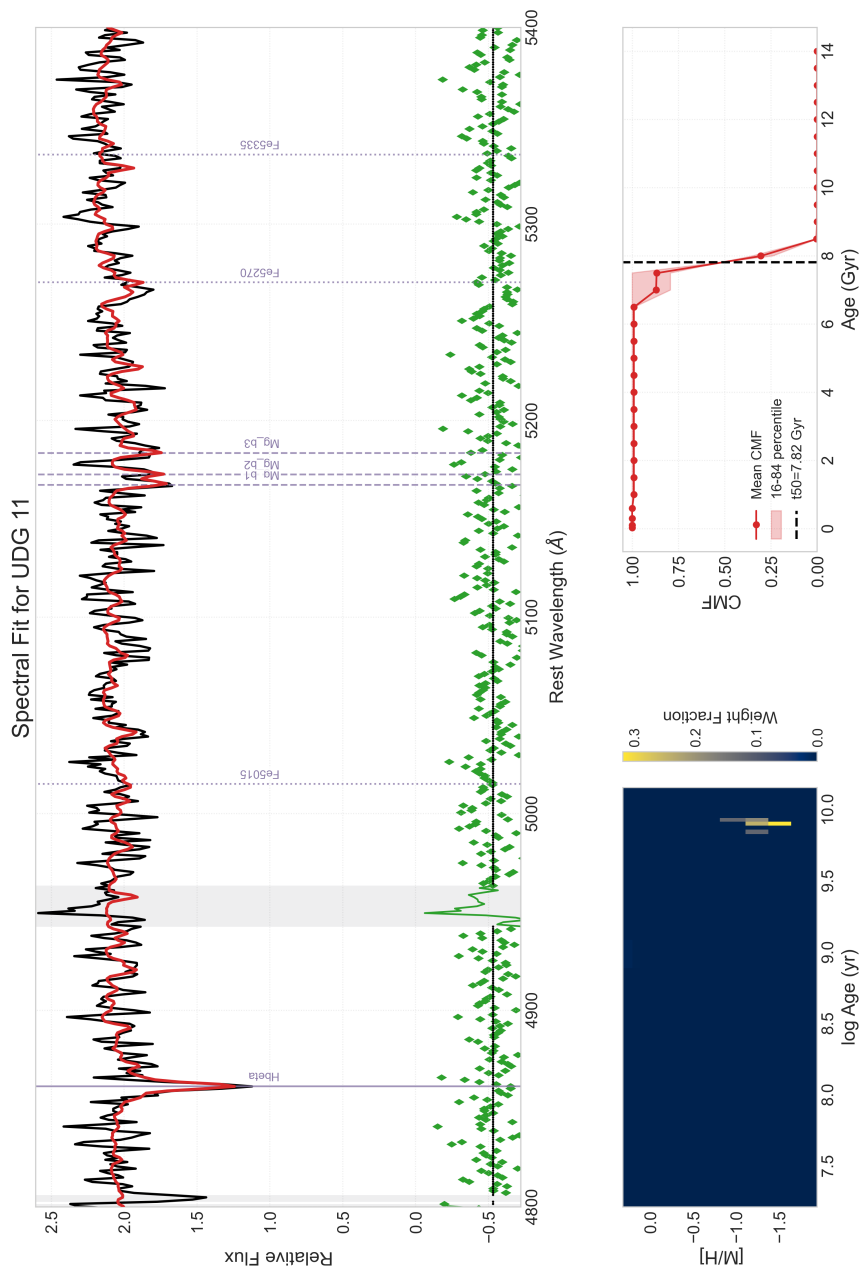


Figure 6.6: Same as Fig. 6.3, but for UDG11.

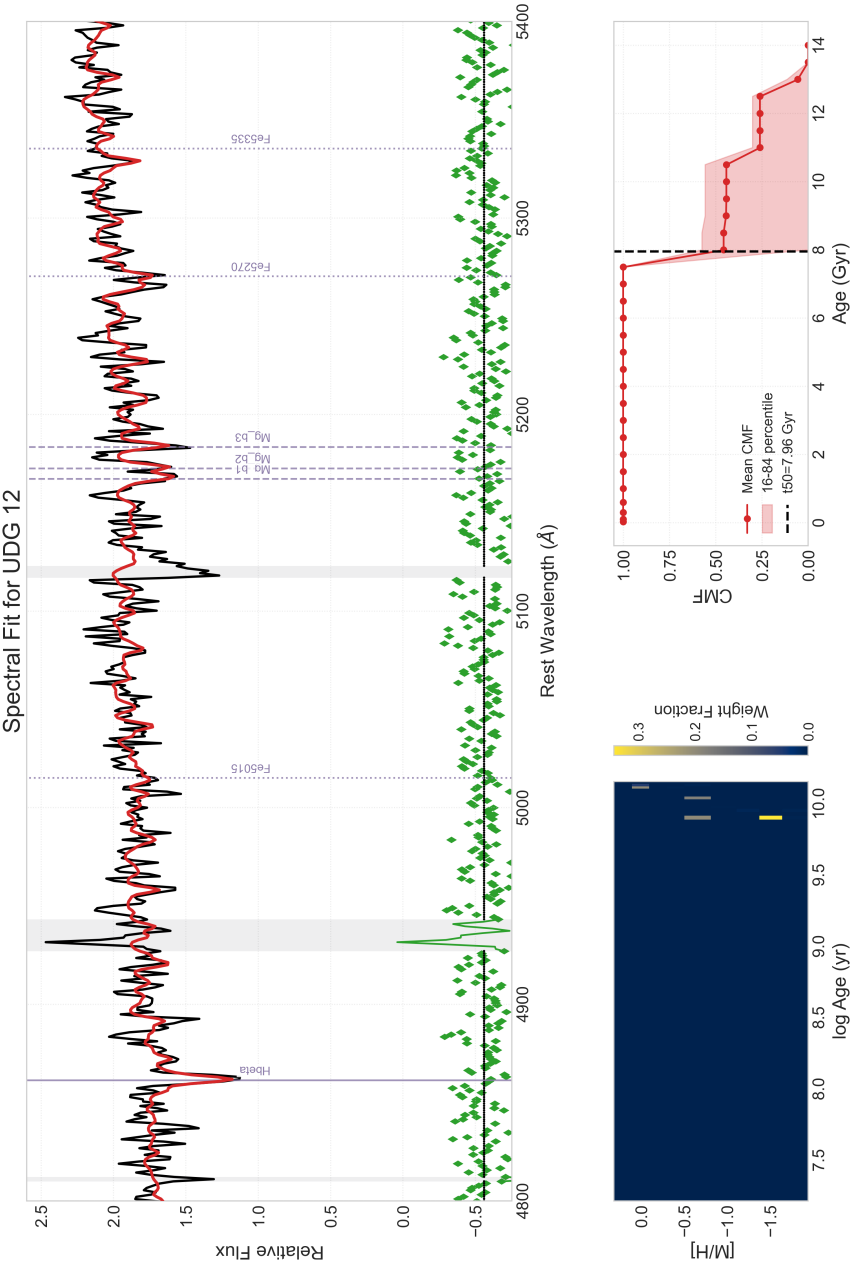


Figure 6.7: Same as Fig. 6.3, but for UDG12.

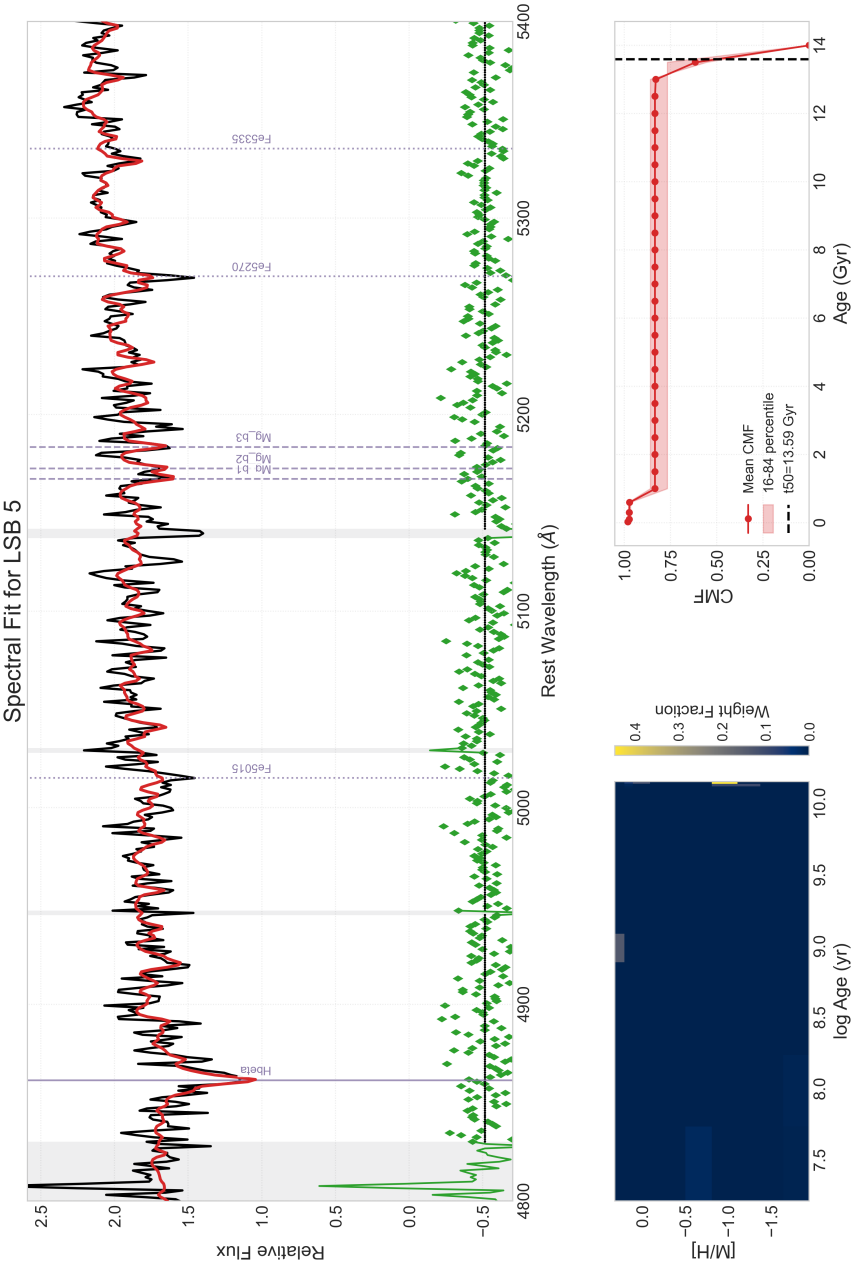


Figure 6.8: Same as Fig. 6.3, but for LSB5.

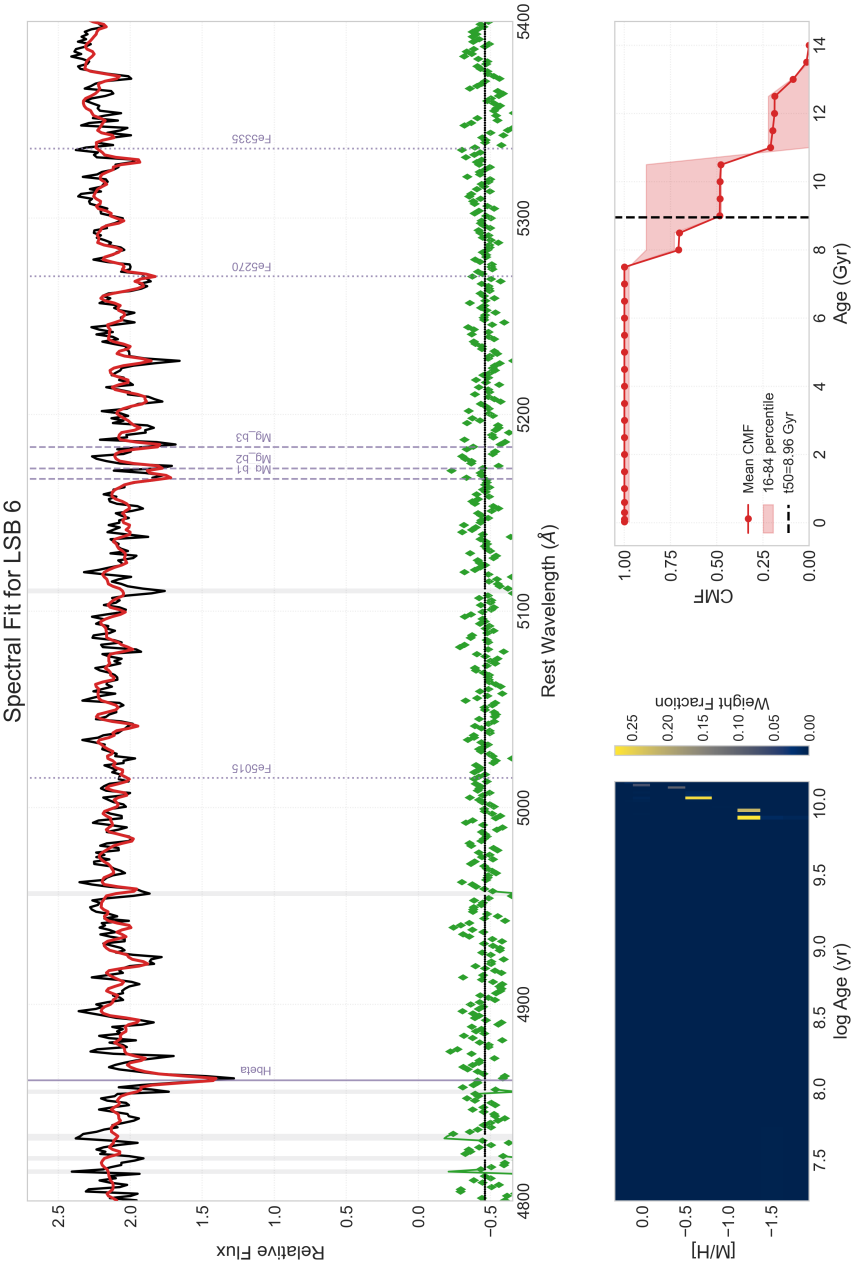


Figure 6.9: Same as Fig. 6.3, but for LSB6.

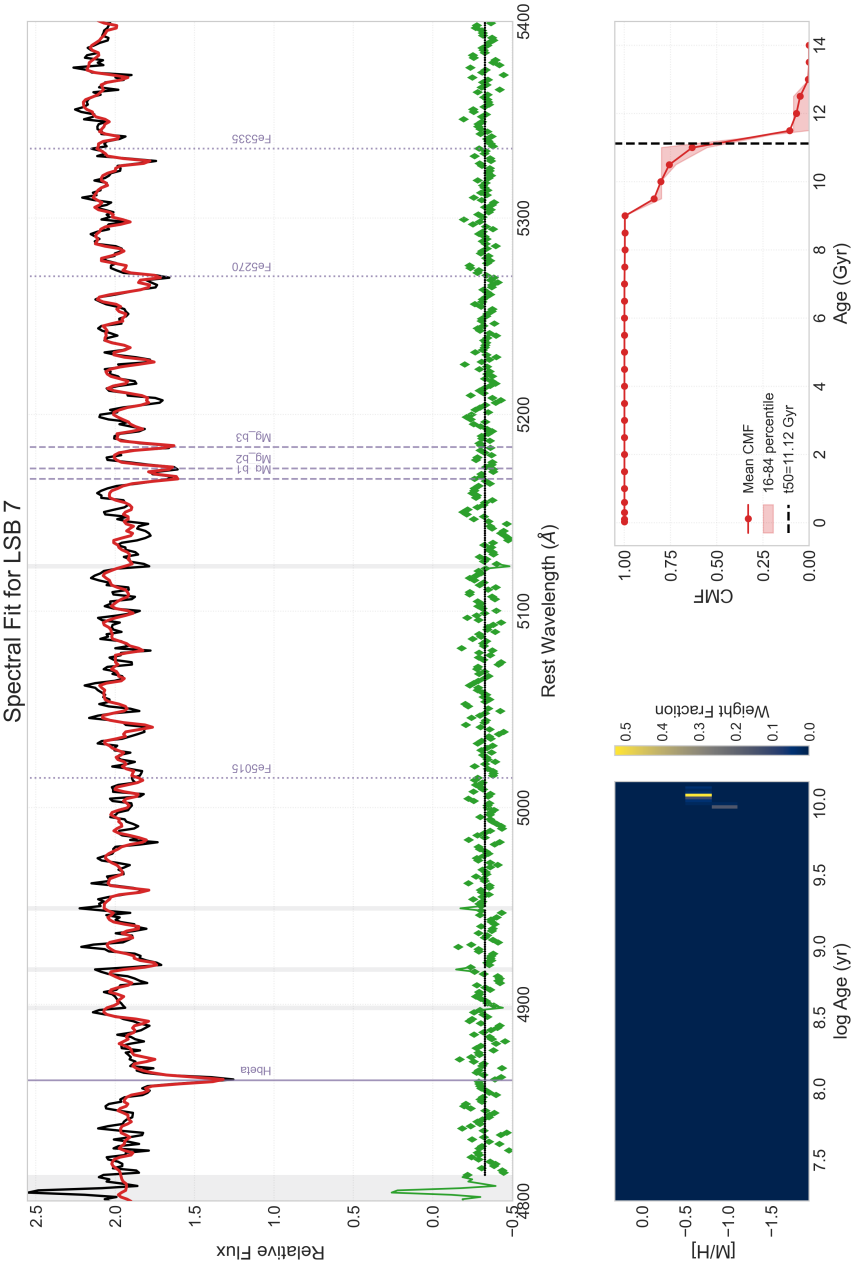


Figure 6.10: Same as Fig. 6.3, but for LSB7.

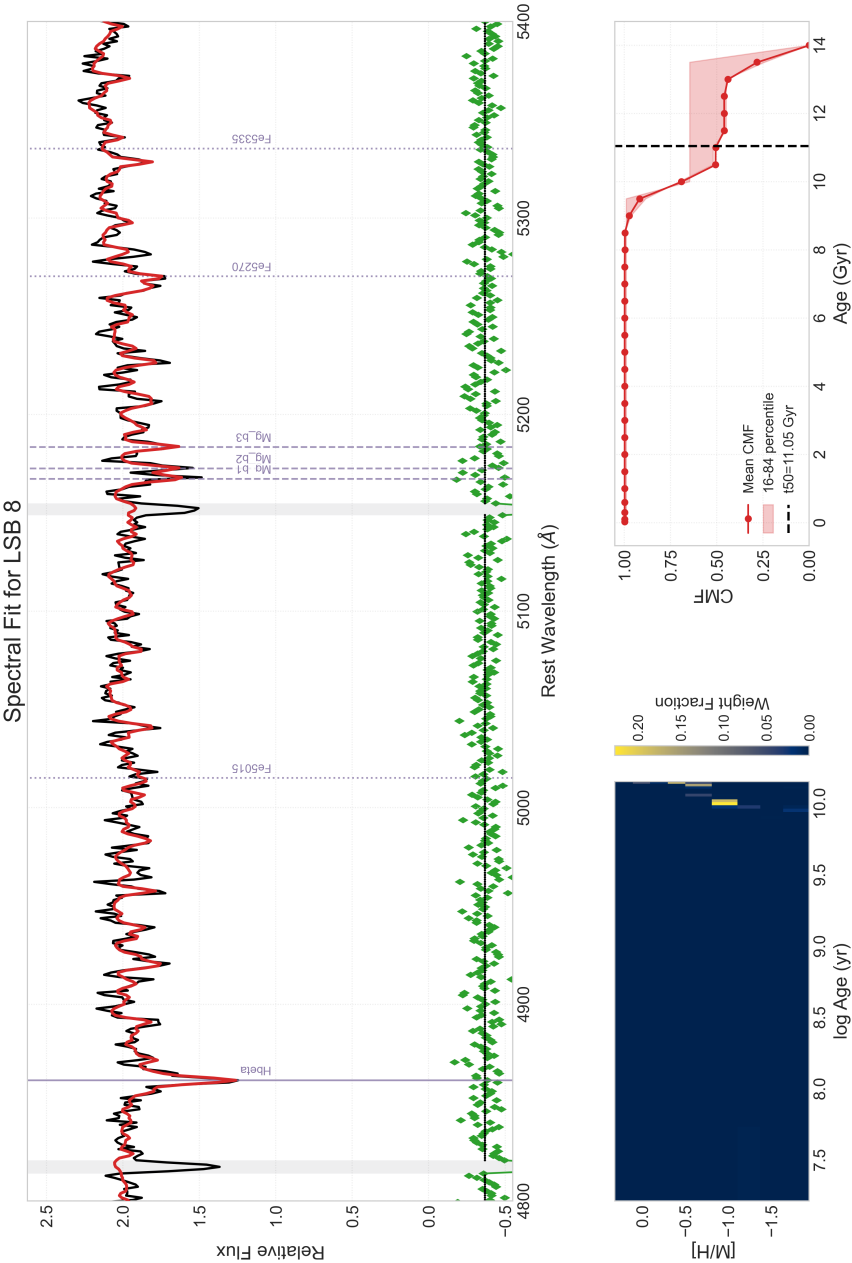


Figure 6.11: Same as Fig. 6.3, but for LSB8.



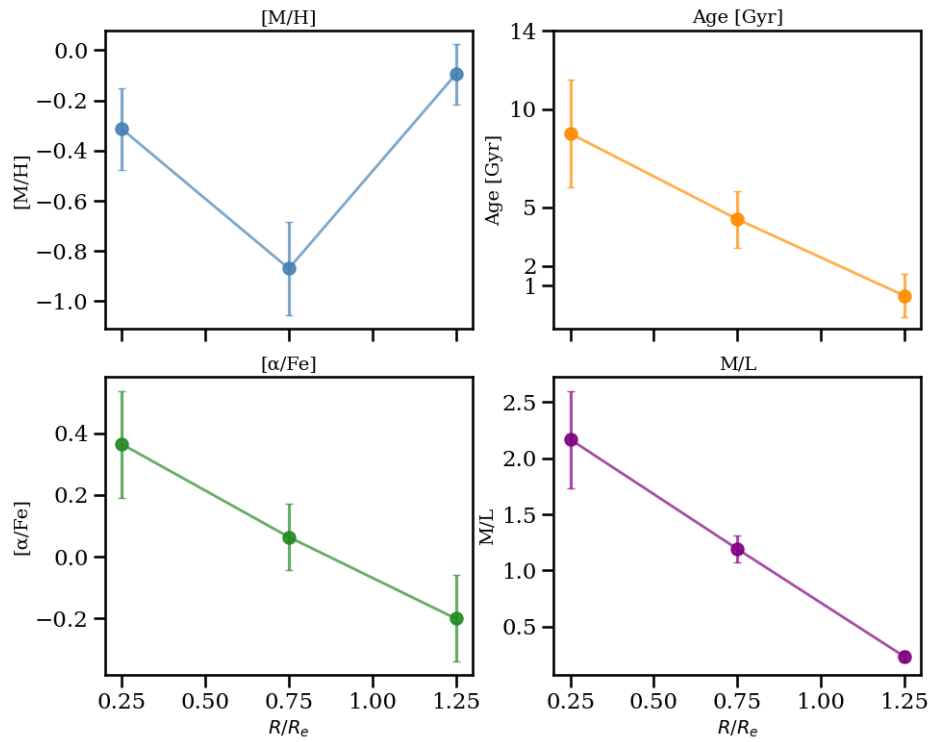


Figure 6.12: Stellar population gradients for UDG1. (upper left) Metallicity gradient. (upper right) Age gradient. (lower left)  $[\alpha/Fe]$  gradient. (lower right) M/L gradient.

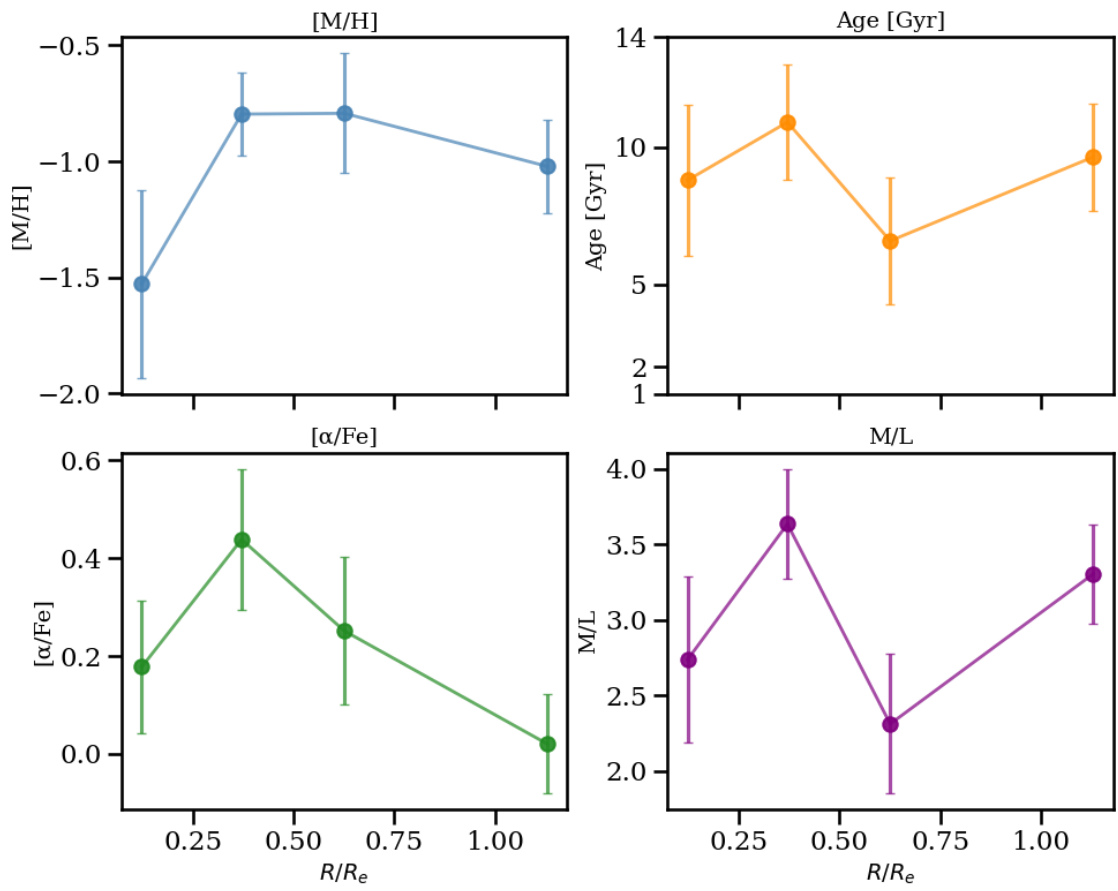


Figure 6.13: Stellar population gradients for UDG8. Panels and colors are the same as Fig. 6.12

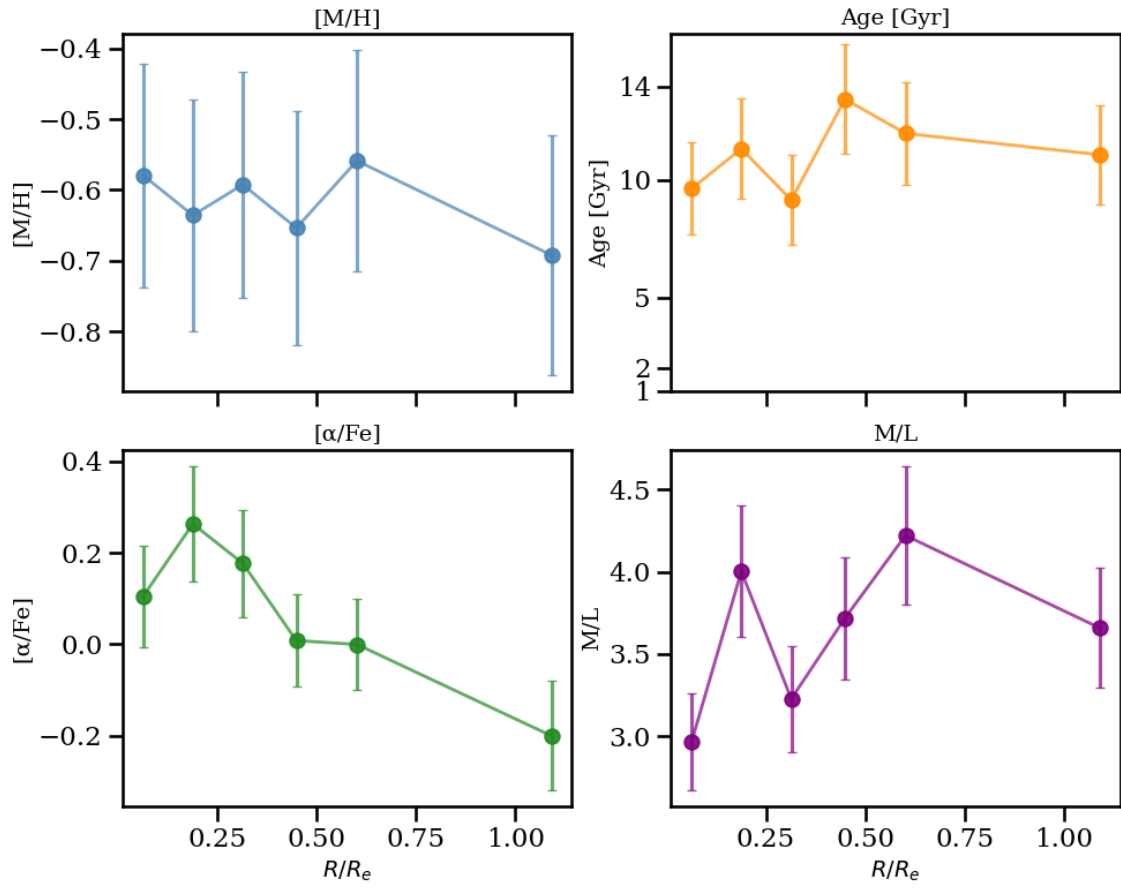


Figure 6.14: Stellar population gradients for LSB7. Panels and colors are the same as Fig. 6.12

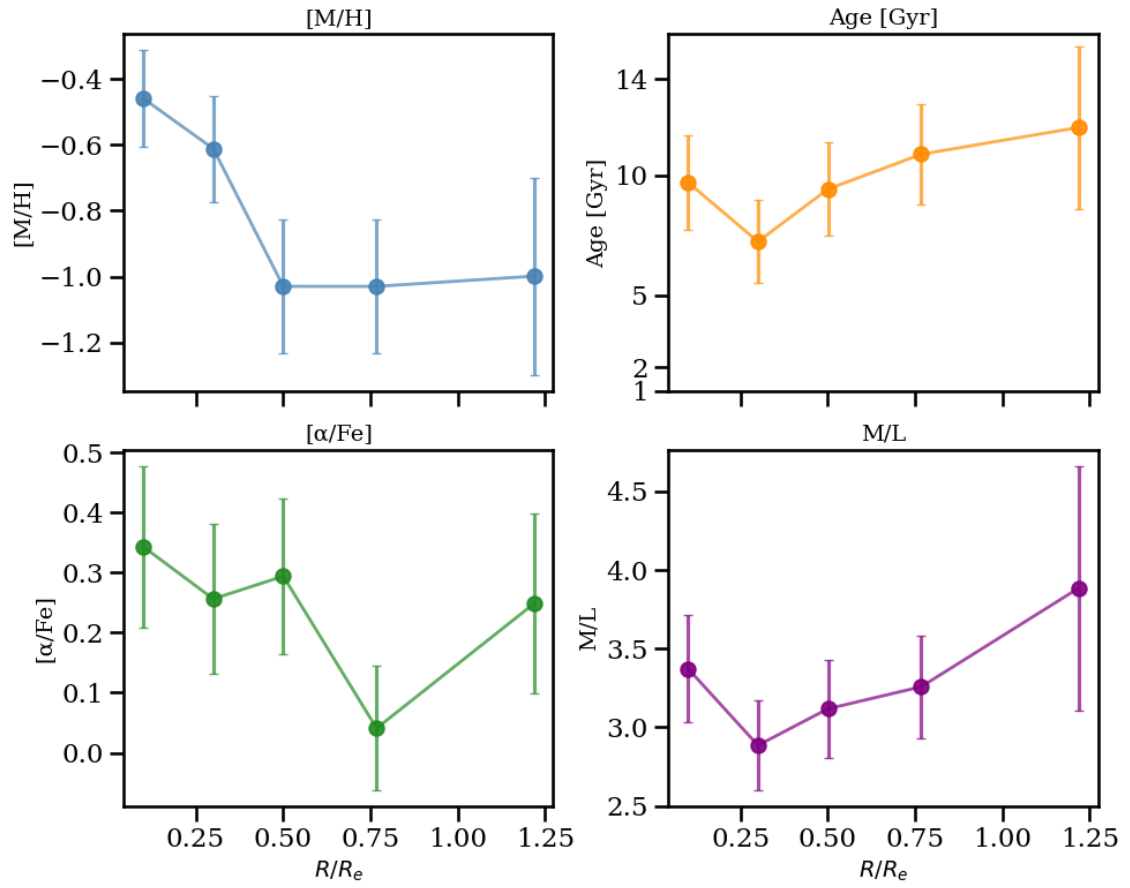


Figure 6.15: Stellar population gradients for LSB8. Panels and colors are the same as Fig. 6.12

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