

Kinematics and Shapes of Galaxies in Rich Clusters



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A thesis submitted for the degree of
Doctor of Philosophy

Hilary 2014

Statement of Originality

Declaration

I declare that no part of this thesis has been accepted or is currently being submitted, for any degree or diploma or certificate or any other qualification at this University or elsewhere.

This thesis is the result of my own work unless otherwise specified.

Parts of this thesis have been submitted for publication in (or are to be submitted to) the following refereed journals:

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Abstract

In this work we have studied the relationship between the kinematics and shapes of Early Type Galaxies (ETGs) in rich clusters. In particular we were interested to extend the kinematic morphology density relation to the richest clusters. We obtained data from FLAMES/GIRAFFE to probe the stellar kinematics of a sample of 30 ETGs in the massive cluster Abell 1689 at $z = 0.183$, to classify them as Slow Rotators (SRs) or Fast Rotators (FRs). To date, this is the highest redshift cluster studied in this way. We simulated FLAMES/GIRAFFE observations of the local SAURON galaxies to account for the bias introduced compared to the ATLAS^{3D} sample, which we used as a local comparison. We find that the luminosity function of SRs in Abell 1689 is the same as that in ATLAS^{3D}, down to the faintest objects probed ($M_K \approx -23$). The number fraction of SRs over the ETG population in Abell 1689 is $f_{\text{SR}} = 0.15 \pm 0.03$, consistent with the value found in the Virgo Cluster. However, within the cluster, f_{SR} rises sharply with the projected number density of galaxies, rising from $f_{\text{SR}} = 0.01$ in the least dense bin to $f_{\text{SR}} = 0.58$ in the densest bin. We conclude that the fraction of SRs is not determined by the local number density of galaxies, but rather by the physical location within the cluster. This might be due to dynamical processes which cause SRs (on average more massive) to sink in the gravitational potential of the cluster.

Next we explore the distribution of projected ellipticity ϵ in galaxies belonging to a sample of clusters from SDSS ($z \lesssim 0.1$) and the CLASH survey ($z \approx 0.2$). We were interested to establish whether the fraction of galaxies flatter than $\epsilon = 0.4$ (a proxy for FRs) varies from cluster to cluster. We find some significant variations. We go on to probe the projected shape as a function of projected cluster-centric radius. In both samples we find that on average galaxies have progressively rounder projected shapes at lower cluster-centric projected distance. In the SDSS sample we show that this trend exists above and beyond the trend for brighter galaxies to be more common near the centre of clusters (bright galaxies are on average rounder). In order to disentangle the trend for SRs (which are rounder) to be more common near the centre of clusters, we isolate a subsample of FRs only, by considering only galaxies with $\epsilon > 0.4$. We find that even the intrinsically flat FRs are on average rounder at lower projected cluster-centric distance. We conclude that the observed trend is due either to the dynamic heating of the stellar discs being strongest near the centre of clusters, or due to an anti-correlation of the bulge fractions with the cluster-centric distance.

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Chapter 1

Introduction

One of the first facts that the young astronomer learns is that galaxies come in different classes. On one side are rather smooth and featurless Early Type Galaxies (ETGs), on the other are Late Type Galaxies (LTGs), which present prominent substructures.

Any theory of galaxy formation and evolution has to explain how these two distinct types form, also accounting for their detailed subclassifications. According to Eggen et al. (1962), galaxies formed from the monolithic collapse of a large gas cloud, which fragmented into smaller and smaller clumps in a single burst of star formation.

However galaxies are not isolated systems, but rather form and evolve as part of their surrounding environment. This principle is the core of the theory of hierarchial formation (Toomre and Toomre 1972). According to this model galaxies form from smaller stellar systems, which merge one another growing in mass and size (hierarchical assembly).

Although the latter theory is generally accepted, there are still a number of difficulties. Whatever the mechanism, its products are today before our eyes: one of the possible approaches to understand the formation of galaxies is therefore to study in detail their present day structure.

In this thesis we concentrate on ETGs, their properties and subclassifications, and their relationship with the surrounding environment. The aim of this chapter is to put this research in a broader context, as well as introducing the conventions that will be used throughout.

1.1 Cosmology

The beginning of the last century has witnessed the birth of Cosmology as a science. Since then, our picture of the Universe has changed dramatically. It moved from a static and eternal environment, to one that is both evolving and limited in time.

The theoretical framework was set in 1917, with the publication of Einstein's work on General Relativity. At the time the dominant picture of the Universe was that of a static environment. So much so, that Einstein arbitrarily introduced the cosmological constant in order to balance the attractive force of gravity and obtain an equilibrium solution.

If we had to choose a turning point in the field, without any doubt we would pick the discovery of the expansion of the Universe (Lemaître 1927; Hubble 1929). Measuring the speed of galaxies it was found that virtually all of them are moving away from us. This phenomenon became known as the expansion of the Universe.

Our understanding of the Universe improved quite significantly since then. Indeed, the most widely accepted paradigm, the Λ CDM model (Springel et al. 2006), is also called the Standard Cosmological Model.

Reversing the expansion of the Universe we go back in time to a superdense, homogeneous and isotropic condition. From that state the Universe started to expand (Big Bang), regulated by the space-time distribution of matter and energy. According to the latest and most precise measurements (Planck Collaboration et al. 2013a,b) the Universe is composed by 68.3% of dark energy, 26.8% of Dark Matter (DM) and 4.9% of ordinary matter. The latter, which constitutes gas clouds, stars, planets and living beings, is the only part we can observe directly.

The earliest information from the Universe comes from the study of primordial photons, that constitute the Cosmic Microwave Background (CMB). It shows that the Universe was initially homogeneous and isotropic. This is in stark contrast with what we see today: the spatial distribution of galaxies forms a complex structure called the Cosmic Web. This is composed of large voids, low density filaments and high density clusters, with the latter sometimes holding thousands of gravitationally bound galaxies.

Explaining this evolution is one of the tasks of contemporary Cosmology. A satisfactory answer involves predicting the present day structures from elementary principles and from the initial conditions frozen in the CMB. Galaxies are the direct tracers of cosmological structures, therefore, almost a century since the first work, the study

of galaxies is still important in Cosmology. This is no coincidence: galaxies are the fundamental building blocks of the visible Universe. As such, a considerable amount of information concerning our Universe comes either directly or indirectly from their light.

Throughout this work, we used the well understood WMAP7 cosmology (Komatsu et al. 2011, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $h_0 = 0.71$), rather than the most recent results from the Planck Collaboration. These became available too recently to be implemented here. For the purpose of this work, the difference between the two sets of parameters is ≈ 0.10 mag in the distance modulus, and $\approx 5\%$ in the angular size. None of these differences affect our results in a significant manner.

1.2 Galaxies

Galaxies appear like diffuse, luminous objects. The detection of Cepheid variable stars in M31 and M33 allowed us to measure their distance from the Earth (Hubble 1925). This proved that “spiral nebulae” were in fact independent stellar systems analogous and external to the Milky Way.

In the years following their discovery, scientists tried to classify galaxies and understand the great variety of objects observed. The aim of galaxy taxonomy was to group related systems and to help explaining their characteristics. The classification scheme most widely used is that due to Hubble (1936). Galaxies are divided in four groups: ellipticals (E), lenticulars (S0), spirals and irregulars. The first are systems with smooth, featureless light profiles, with elliptical shapes on the sky. Lenticulars are disc systems, showing a central light concentration known as bulge. Spiral galaxies are again discs with a more or less prominent bulge, but they also exhibit spiral arms and may present a bar. Galaxies without a particular shape fit in the irregulars class (Sandage 1961).

Spiral galaxies are further divided in four subclasses, labelled with the letters *a-d*. Along this sequence, a number of physical properties vary, including the total brightness and size of the bulge with respect to the disc component, the amount of cold gas and recent or ongoing star formation, the tightness of the spiral pattern and their degree of resolution into individual stars and hydrogen clouds. Also Es and S0s have been divided into subclasses. As we shall see, however, this subdivision is less satisfactory than that of spiral galaxies. Some of the criteria clearly depend on observational

accidents, e.g. the inclination with respect to the observer. Nevertheless, a physical motivated classification is very unlikely to be achieved when a new phenomenon is discovered, and empirical criteria are often the starting point of scientific analysis.

Spirals and irregulars are collectively known as LTGs, as opposed to Es and S0s, which are called ETGs. The focus of this thesis is on the latter. ETGs have long been a focus of attention, for their relatively simple photometry hides a complex dynamical structure (Binney and Tremaine 1988). Despite being less common than LTGs, they are on average more massive and encompass roughly half of the total stellar mass in the present day Universe (Baldry et al. 2004; Renzini 2006).

The key observable of a galaxy is its spectrum S , which for each point on the sky (x, y) and for each wavelength λ yields the flux of photons $S(x, y, \lambda)$. Once S is known, any other observable can be derived.

At any point (x, y) on the sky, $S(x, y, \lambda)$ is the superposition of the spatially unresolved spectra from all the stars at (x, y) ¹. Since each class of stars has its own distinctive spectrum, galaxies with different stellar composition will in general have different spectra. In addition, the velocity distribution of the stars along the Line Of Sight (LOS) causes a measurable effect due to the superposition of their Doppler shifted spectra. By measuring this effect we can infer some of the properties of the velocity distribution. This means that S grants us access to the phase-space distribution of a galaxy.

Theoretically, the structure of a galaxy is fully described by its distribution function f , which at any time t and to any point $(\mathbf{x}, \mathbf{v})$ in phase-space associates its mass density of stars $f(\mathbf{x}, \mathbf{v}, t)$. The symmetric shapes of galaxies on the sky suggest that they are in (or close to) stationary equilibrium, so that we can drop the time dependence.

Because of their very large distances, we cannot measure parallaxes (z) nor proper motions for the stars in external galaxies (v_x, v_y). This means that S contains less information than is needed to fully recover f . If we orient the coordinates system with the z -axis along the LOS, the accessible information is expressed as:

$$f_{LOS}(x, y, v_z) \equiv \int_{-\infty}^{+\infty} dz \int_{-\infty}^{+\infty} dv_x \int_{-\infty}^{+\infty} dv_y f(\mathbf{x}, \mathbf{v}) \quad (1.1)$$

¹the existence and the importance of other sources of photons within galaxies is not relevant in this work

where it is understood that $(x, y, z, v_x, v_y, v_z) = (\mathbf{x}, \mathbf{v})$. If we assume that a galaxy is composed of a single stellar spectral class, with spectrum s , then the relationship between the spectrum S of the galaxy and f_{LOS} is:

$$S(x, y, \lambda) = \int_0^{+\infty} d\hat{\lambda} \text{LOSVD} \left(x, y, v_z(\lambda - \hat{\lambda}) \right) s(\hat{\lambda}) \quad (1.2)$$

where the LOS Velocity Distribution LOSVD is defined as:

$$\text{LOSVD}(x, y, v_z) \equiv \frac{f_{LOS}(x, y, v_z)}{\int_{-\infty}^{+\infty} dv_z f_{LOS}(x, y, v_z)} \quad (1.3)$$

The first and second order moments of LOSVD define two key kinematic quantities, that can be measured from S . The first moment is the mean velocity V_{LOS} along the LOS:

$$V_{LOS}(x, y) \equiv \int_{-\infty}^{+\infty} dv_z v_z \text{LOSVD}(x, y, v_z) \quad (1.4)$$

which is related to the shift of the spectrum with respect to its rest wavelength. The second central moment defines the velocity dispersion σ_{LOS} :

$$\sigma_{LOS}^2(x, y) \equiv \int_{-\infty}^{+\infty} dv_z (v_z - V_{LOS}(x, y))^2 \text{LOSVD}(x, y, v_z) \quad (1.5)$$

related to the additional broadening of the spectral features in S with respect of those of single stars. By adding in quadrature V_{LOS} and σ_{LOS} , we obtain the (non-central) second order moment of the LOSVD, which enters the Jeans Equations and the Virial Theorem and can be used to estimate the gravitating mass (Binney and Tremaine 1988).

By integrating S along wavelength λ , we obtain the surface brightness I^2 :

$$I(x, y) \equiv \int_0^{+\infty} d\lambda S(x, y, \lambda) \quad (1.6)$$

whose study is the domain of photometry.

1.2.1 Photometry of ETGs

The surface brightness of Es is described reasonably well by the de Vaucouleurs' $r^{1/4}$ law (de Vaucouleurs 1948). If we call $I(R)$ the source brightness at a distance R from its centre, then de Vaucouleurs' law can be written as:

$$\log[I(R)] := \log I_e + b_4 \left[1 - \left(\frac{R}{R_e} \right)^{1/4} \right] \quad (1.7)$$

²Practically, one measures the surface brightness in a limited wavelength domain, dictated by the support of the instrument response function.

where $b_4 = 7.669 \dots$ (Ciotti 1991). This is a phenomenological formula with two free parameters. Unlike in previous fitting formulas, in de Vaucouleurs' law both I_e and R_e have a precise physical meaning. $I_e = I(R_e)$, while R_e is the radius encompassing half the total light:

$$\int_0^{R_e} dR R I(R) = \frac{1}{2} \int_0^\infty dR R I(R) \quad (1.8)$$

A widely used alternative to de Vaucouleurs' law is its natural generalization, the Sérsic law (Sérsic 1963):

$$\log[I(R)] := \log I_e + b_n \left[1 - \left(\frac{R}{R_e} \right)^{1/n} \right] \quad (1.9)$$

where the number b_n is determined from Equation (1.8). For $n = 4$ we recover de Vaucouleurs' law, while for $n = 1$ Sérsic law reduces to the exponential profile typical of discs. Therefore the above formula can be used to fit any ETG.

From an observational point of view, these laws are a valuable tool to convert observables about flux in relative dimensions. When we compare the size of ETGs, we use their values of R_e , based on either the de Vaucouleurs' or Sérsic's laws.

1.2.2 The shape of ETGs

Another prominent property of ETGs is their apparent shape, as measured from the surface brightness I . As we have seen, I depends on f , so that ultimately the shape of a galaxy is determined by the distribution of its orbits. Unfortunately what we can measure from I is a projected shape only. Alone this is insufficient to infer the true, three-dimensional shape, unless additional assumptions of symmetry are made. Moreover, the observed I is convolved with the seeing, which further alters the shape.

Traditionally Es were labelled according to the ellipticity of their isophotes, having defined the ellipticity ϵ as:

$$\epsilon \equiv 1 - b/a \quad (1.10)$$

where b and a are the minor and major axis of the isophote considered. An elliptical galaxy labelled En has $\epsilon = n/10$. This definition of ϵ can be extended to S0s, which are known to have stellar discs; in this case ϵ will be sensitive to the combined projected shape of the bulge and the disc.

Even though we cannot reconstruct the three-dimensional shape of an ETG from photometry alone, we can study their intrinsic shape by adopting a statistical approach (Sandage et al. 1970). To this end, one generally assumes that galaxies are oriented randomly on the sky.

For a population of infinitesimally thin discs, the distribution of apparent ϵ is flat between 0 and 1. The observed distribution of ϵ , which is not flat, but deficient in the flattest shapes, implies that ETGs are not thin discs. For an oblate or prolate spheroid, the expected distribution is truncated at a value of ϵ equal to the intrinsic ellipticity: the projection of a spheroid cannot make it appear flatter than it is. Lambas et al. (1992) demonstrated that the ϵ distribution of Es cannot be reproduced by any population of oblate or prolate spheroids, but that (mild) triaxiality is needed.

Jorgensen and Franx (1994), investigated the ϵ distribution of a volume limited sample of galaxies in the Coma Cluster, finding a deficit of face-on S0s. They interpret this result as an indication that these objects are likely misclassified as Es.

More recently, Holden et al. (2009) investigated the ϵ distribution of a sample of cluster galaxies between $z \approx 0$ and $z \approx 1$, and found no evolution. This is at variance with the findings of morphological studies. Dressler et al. (1997) classified the galaxies in a sample of ten clusters between $0.37 < z < 0.56$, and compared the morphological fractions to what is observed in local clusters. They found that the number fraction of Es stays constant with redshift, but S0s decrease while the fraction of spirals sees a corresponding increase. The proposed explanation is that while cluster Es are already in place at $z \approx 0.5$, infalling spirals are converted into S0s between $z \approx 0.5$ and now. When looking at ETGs only, Dressler et al. (1997) sees that clusters at higher redshift include the same number of Es, but significant less S0s than local clusters. Since Es and S0s have different distributions of the projected ϵ , we expect that at higher redshift the ϵ distribution of cluster ETGs reflects the change in the morphological break-up. In particular, as intrinsically flatter S0s disappear, the average ϵ of ETGs should decrease with redshift. Holden et al. (2009) do not see this, and a possible explanation comes from challenging the accuracy of morphological classifications at $z \approx 0.5$ (Andreon 1998). For instance, while ϵ can be corrected for the effect of the Point Spread Function (PSF), the same is not true for the inferred morphologies.

Another analysis tool based on the apparent shape of ETGs is the departure of the isophotes from an ellipse. This can be measured for instance by the parameter a_4

(Bender et al. 1988). After fitting an ellipse to a galaxy surface brightness, the residuals are developed in Fourier's series, using polar coordinates (ρ, θ) . If we call a_n the coefficient of the term $\cos n\theta$, a positive value of a_4 denotes “discy” isophotes, while a negative value corresponds to isophotes that appear “boxy”. So called discyness is associated with E galaxies which contain a stellar disc. In addition, the value of a_4 anti-correlates with other physical properties of E galaxies, namely their radio and X-ray luminosities, which are invariably low for discy galaxies (Bender et al. 1989). Unfortunately, much like ϵ - and even more so - a_4 depends on observational accidents like the inclination of the galaxy on the sky and the seeing of the image.

1.2.3 Spectroscopy of ETGs

The visible spectra of ETGs are dominated by giant stars of the K spectral type (Faber et al. 1985).

From the structural point of view, the stars in S0s are arranged in a bulge and a disc, maintained in equilibrium by the rotation of the stars around the axis of symmetry of the galaxy. They are characterized by a velocity distribution which is dominated by tangential motions, with relatively little dispersion.

Es exhibit instead two opposite tendencies. On one hand are galaxies with large rotation velocities, comparable to those of S0s. On the other hand, some Es have little to no rotation. In these systems, stars follow a variety of different orbits, so that at any given point in space, the velocity distribution is comparatively wide. These galaxies are supported against gravity by the velocity dispersion σ . In the most general case σ takes the form of a tensor (Binney and Tremaine 1988). Its role in the Jeans equations is analogous to that of pressure in fluid-dynamics, therefore a σ -supported galaxy is sometimes referred to as “pressure supported”.

In order to establish the relative importance of rotation over σ , Davies et al. (1983) introduced the quantity:

$$(V/\sigma)^* \equiv \frac{V_{\max}/\sigma_0}{(V/\sigma)_{\text{OI}}} \quad (1.11)$$

where $V_{\max}$ is the maximum rotation velocity along the major axis, σ_0 is the central velocity dispersion, and $(V/\sigma)_{\text{OI}}$ is the value of the ratio for an oblate isotropic model (Binney 1978).

Based on their values of $V_{\max}/\sigma_0$, Es can be roughly divided in two more subgroups: fainter galaxies tend to have $(V/\sigma)^* \simeq 1$, while their brighter relatives show the full range of values (Davies et al. 1983). Therefore, while the first are roughly consistent

with rotationally flattened models, the flattening of the others can arise entirely from the anisotropy of the velocity dispersion.

This dynamical dichotomy of Es is all the more important as it correlates with other physical properties of ETGs, such as the radio power, X-ray luminosity and the presence of a core. This reinforces the argument for the existence of two classes of Es.

1.2.4 Scaling relations

Despite the differences that we have highlighted so far, ETGs share a number of properties that make them a rather tight family of stellar systems. Even though their masses and luminosities span several orders of magnitude, ETGs obey a number of phenomenological laws, collectively known as “scaling relations”.

These empirical relations link the structural properties of ETGs to their stellar populations. Their mere existence imposes strong constraints on the formation and evolution of ETGs, while the small observed scatter has additional implications.

Baum (1959) was the first to notice that ETGs formed a tight sequence on the color-magnitude diagram (CMD). Subsequent works (Visvanathan and Sandage 1977; Sandage and Visvanathan 1978a,b) established that this relation was almost universal, holding both in cluster and field environments. This relation is now called the Red Sequence (RS).

Since colour is to first order independent of distance, the RS can be used to infer an approximate distance of the galaxies that lie on it. However crude, this estimate can be used as a simple method to help establish if a galaxy belongs to a cluster of galaxies.

In addition to the RS, both S0’s and E’s follow a tight relation in the color- σ diagram (Bower et al. 1992). Both these relations imply that the stellar content of ETGs is remarkably uniform, and that it evolved without recent star formation (passive evolution). The small scatter around the best fit relation sets a precise constraint on the formation redshift for the bulk of the stellar content, at $z > 2$ (Bower et al. 1992). In addition, the tightness and slope of the relation pose constraints on the amount and type of mergers that ETGs might have undergone: gas poor mergers (dry mergers) increase both luminosity and σ , but leave colors unchanged, so to change the slope of the relation. Gas rich mergers (wet mergers) on the other hand make

the galaxy bluer, thus flattening and broadening the relation even more (Bower et al. 1998).

Perhaps the most important scaling relation is the Fundamental Plane (FP, Dressler et al. 1987; Djorgovski and Davis 1987). It couples three key observables, the radius R , the velocity dispersion σ and the surface brightness I :

$$\log R = a \log \sigma + b \log I + c \quad (1.12)$$

The relation is understood to stem from the Virial Theorem. However the measured value of the coefficients a and b is different from the virial prediction, a problem known as the tilt of the FP. The tilt is understood to originate from an additional dependence of c on σ , through the mass-to-light ratio of the galaxies (Cappellari et al. 2006). Since the mass-to-light ratio depends both on the DM and stellar content of a galaxy, the FP can be used to constrain the structure and the star formation history of ETGs (Ciotti et al. 1996).

The picture that emerges is that, as tight as they are, the scaling relations leave room for further subclassifications of ETGs. As we have seen, Hubble already distinguished between Es and S0s, based solely on morphology. Later, more accurate and extended observations became possible, and Es were further divided in two subgroups: massive, pressure supported systems and relatively low mass galaxies, where rotation is comparatively more important. These dynamical differences represent a link with the assembly history of ETGs. Galaxies are not isolated, and there is overwhelming evidence of their mutual interaction. Therefore the question of their mass assembly involves understanding and quantifying the effect of the surrounding environment.

1.3 The role of the environment

The first observational evidence that environment plays a role in the formation and evolution of galaxies came from measuring the fraction of ETGs in clusters of galaxies. Hubble and Humason (1931) found that cluster members are more likely to be ETGs than their field counterparts. The fraction of Es correlates with the degree of dynamical relaxation: clusters with regular symmetric contours, a strong degree of concentration and a dominant cD galaxy are more likely to have a higher fraction of Es (Oemler 1974). In addition, within clusters, the fraction of spirals increases with the cluster-centric distance, so that - all other conditions being equal - Es and S0s dominate the galaxy population near the centre of clusters. The outskirts, instead,

have a higher spiral fraction, more in line with the field.

The first large study of environment was done by Dressler (1980), who studied the morphology of ≈ 6000 galaxies in a sample of 55 nearby clusters ($z \lesssim 0.06$). He concluded that morphology correlates with the local density around each galaxy, as expressed by the surface density of galaxies within the circle encompassing the ten closest neighbours (Σ_{10}). The fraction of spirals decreases with Σ_{10} , while the fraction of ETGs increases. This is known as the morphology-density ($T - \Sigma$) relation. Its validity extends to higher redshift (Dressler et al. 1997).

These results all underline that environment is a key factor in shaping galaxies, but we are still far from a complete picture. Whitmore et al. (1993) argue that cluster cores all have the same fraction of Es, irrespective of the local density value. It is unclear whether the key correlation is with the cluster-centric radius (Whitmore and Gilmore 1991; Whitmore et al. 1993) or with projected density, as advocated by Dressler et al. (1997). The two variables are degenerate, in that higher densities are generally found close to the cluster centre.

To complicate matters even further, there is no universal definition of environment, and different techniques commonly used measure different properties (Muldrew et al. 2012). For this reason, Houghton et al. (2013) introduced two definitions: the Global Host Environment (GHE) and the Local Point Environment (LPE). The former depends on the large scale structure surrounding a galaxy, such as field, group or cluster of galaxies. It is best traced by aperture methods, which count the number density of galaxies inside a circle of fixed radius. The LPE is measured instead using variable size apertures, as done by Dressler (1980), and is sensitive to the local conditions around a galaxy. Although the GHE and LPE are not independent, in that clusters of galaxies are more likely to host regions of high local density, the two definitions are nevertheless useful. For instance, some physical processes depend on the LPE, while others are linked to the GHE.

1.4 Integral Field Spectroscopy: the SAURON and ATLAS^{3D} surveys

The advent of Integral Field Spectroscopy (IFS) brought a wealth of information about ETGs. IFS effectively delivers the spectrum S of a galaxy, both as a function

of wavelength and as a function of the spatial position on the sky. As we have seen, knowing S we can probe the internal kinematics of galaxies, and - by using the Jeans equations - can link the kinematics to the dynamics.

The first IFS survey takes its name from the instrument **SAURON**. Its sample comprised 72 galaxies, including 48 ETGs, chosen in both cluster/groups and field environments. The targets were selected to sample nearly uniformly the three morphological classes Es, S0s and spirals, as well as the M_B vs ϵ plane (de Zeeuw et al. 2002).

The **SAURON** survey revealed that ETGs can be alternatively classified based on the morphology of their kinematic maps (Fig. 1.1). Since the kinematics are connected directly to the internal dynamics, this new classification scheme reflects a physical difference among ETGs. Two main classes of objects are identified. Systems characterized by disc-like rotation maps are called Fast Rotators (FRs). Their velocity maps are smooth, and present an unambiguous axis of rotation, which coincides with the minor axis (in green in Fig. 1.1). In contrast Slow Rotators (SRs) exhibit little to no rotation. Instead they often present counter rotating discs, as well as Kinematically Decoupled Cores (KDCs, Emsellem et al. 2007).

Most importantly, the division between FRs and SRs crosses the traditional morphological boundary between Es and S0s: as can be seen in Fig. 1.1, there are a number of FRs which are morphological Es.

The ATLAS^{3D} survey is the volume limited follow-up to the **SAURON** survey (Cappellari et al. 2011a). In the target region of the sky, ATLAS^{3D} obtained IFS observations of all the ETGs within 42 Mpc, and brighter than $M_K = -21.5$ mag. The resulting sample consists of 260 ETGs, of which 68 are Es and 192 are S0. After classifying these galaxies according to the FR/SR paradigm, Emsellem et al. (2011) finds that there are 36 SRs and 224 FRs. When comparing this result to the traditional morphological classification, one concludes that 45/68 of the Es are FRs, while 13/192 of the S0s are SRs.

From the dynamical point of view, FRs are more similar to the S0s than they are to SRs, which constitute instead the “true” Es. Regardless of their traditional morphological classification as either E or S0, FRs present the same range of disc fractions as spiral galaxies, and are consistent with being oblate. On the other hand, SRs have rounder projected shapes, implying that they are intrinsically round stellar systems. This evidence lead ATLAS^{3D} to advocate the revision of the traditional morphological paradigm (Fig. 1.2; Cappellari et al. 2011b), in line with other works

(van den Bergh 1976; Kormendy and Bender 2012).

Practically, a critical aspect for the classification is the inclination of the galaxy with respect to the LOS. If a FR galaxy is exactly face on (inclination $i = 0$), then its rotation velocity will be entirely in the plane of the sky, and its kinematic map will appear similar to that of a SR. However, even a small angular difference from face on translates into a velocity along the LOS

$$V_{\text{LOS}} = \|\mathbf{V}\| \sin \Delta i \underset{\Delta i \rightarrow 0}{=} \|\mathbf{V}\| (\Delta i + O((\Delta i)^3)) \quad (1.13)$$

where Δi is the difference from face on. Given the typical rotation velocity of FRs ($\approx 200 \text{ km s}^{-1}$) and the precision of SAURON (6 km s^{-1}), one can still detect residual V_{LOS} down to a few degrees inclination. By comparison, the effect on both the axis ratio and the LOS disc thickness is much smaller, viz.

$$\propto \cos \Delta i \underset{\Delta i \rightarrow 0}{=} 1 - \frac{1}{2}(\Delta i)^2 + O((\Delta i)^4) \quad (1.14)$$

As a result, IFS can detect the presence of a stellar disc more reliably and at lower inclinations than photometric methods (Cappellari et al. 2013a, Fig. 4). This can be understood qualitatively by looking again at the velocity maps of the SAURON sample (Fig. 1.1). While it is clear which galaxies are FRs from the appearance of the velocity field, their isophotes (in black in Fig. 1.1) can be as round for some FRs as they are for SRs.

In order to break the degeneracy between the physical parameters and the inclination on the sky, Emsellem et al. (2007) introduced the λ vs ϵ diagram. They define a proxy for the projected angular momentum per unit mass λ , which in the notation of Equations 1.5-1.1 becomes:

$$\lambda' \equiv \frac{\int d\mathbf{x} I(\mathbf{x}) \|\mathbf{x}\| |V(\mathbf{x})|}{\int d\mathbf{x} I(\mathbf{x}) \|\mathbf{x}\| \sqrt{V(\mathbf{x})^2 + \sigma(\mathbf{x})^2}} \quad (1.15)$$

where V and σ are short for V_{LOS} and σ_{LOS} . While the numerator of Equation (1.15) is $\propto |\sin(i)|$, and occupies the y-axis of the λ vs ϵ diagram, ϵ - which depends on $\cos i$ - is plotted on the x-axis.

Emsellem et al. (2011) found that the λ vs ϵ diagram conveniently captures the dichotomy between SRs and FRs. The former all lie below the line of equation $\lambda = 0.31 \sqrt{\epsilon}$ and are not compatible with disc-like rotation.

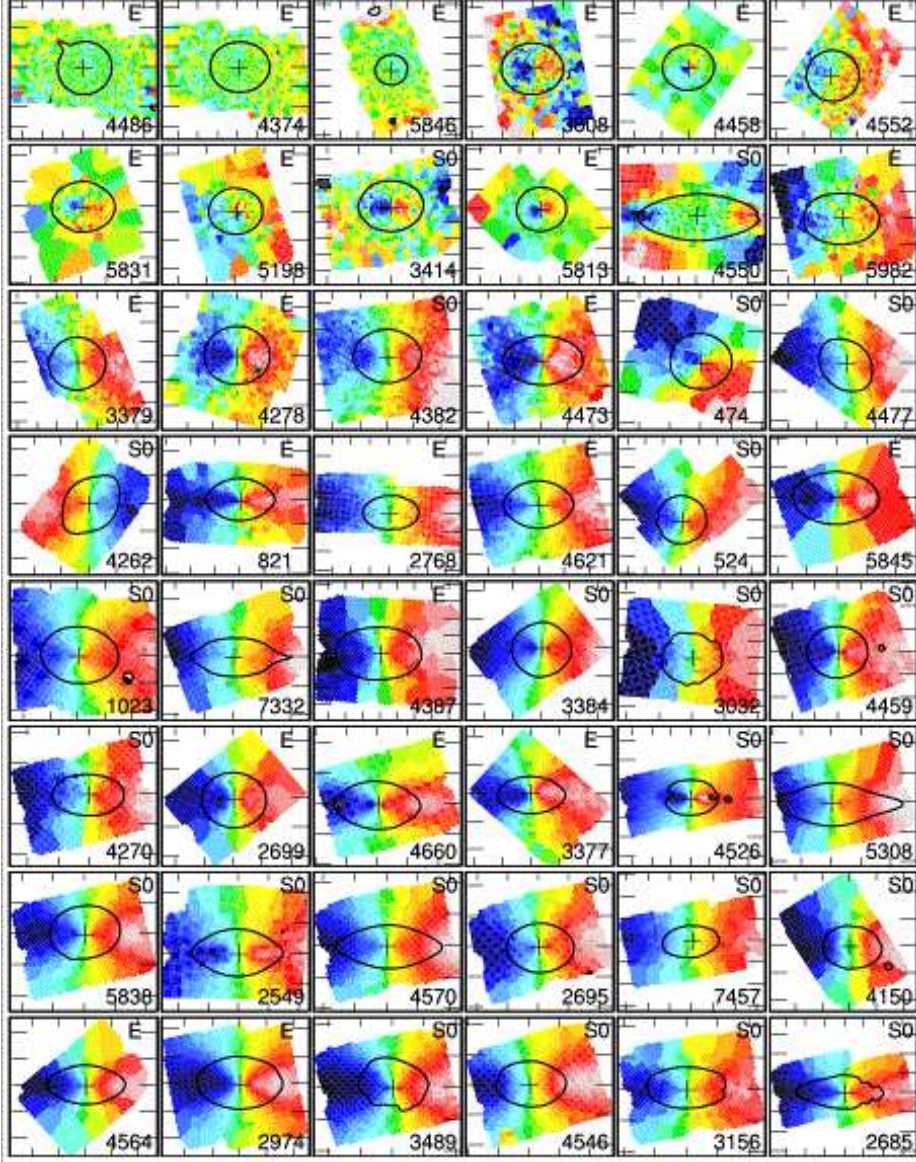


Figure 1.1: Stellar velocity fields for the ETGs in the SAURON sample. Each galaxy is labelled according to its NGC designation (lower right), as well as its Hubble morphological type (upper right). The color scale is tuned to highlight eventual structures, while the ticks correspond to 10 arcsec. Galaxies are ordered from top to bottom based on increasing values of λ , a proxy for the projected angular momentum. Notice several Es galaxies exhibiting disc-like rotation patterns identical to the patterns found in S0s. [After Emsellem et al. (2007)]

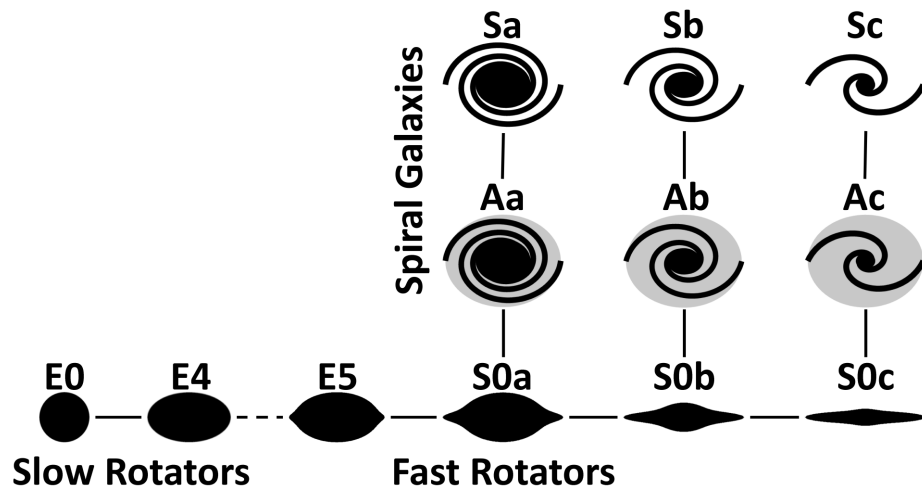


Figure 1.2: The comb diagram, reflecting the empirical link between FRs (E5-S0s) and the link between S0s and spirals. Intrinsically round SRs (E0-4) are physically distinct, form from different mechanisms and therefore are separated from FRs by a dashed line. Notice the decrease of the B/D ratio of FRs from E5 to S0c galaxies. [After Cappellari et al. (2011b)]

1.5 This study

The SRs/FRs divide points to two different paths of galaxy assembly. In particular, FRs must have formed the bulk of their stars through dissipative collapse, so that the mass now locked up in stars was accreted in the form of dense, cold gas (Cappellari 2013).

SRs, on the other hand, might form through non-collisional processes, which involves accretion of mass that has already formed stars. This might happen either via several minor mergers or fewer major mergers, which one is not yet clear (Bois et al. 2011).

Based on the observation that FRs share their dynamical structure with S0s, a revised classification paradigm has been proposed (Cappellari et al. 2011b). Here FRs and S0s are analogous systems, differing mainly in their Bulge-to-Disc (B/D) ratio. SRs instead, although appearing similar in projection, are intrinsically round systems belonging to a physically distinct class (Fig. 1.2).

Cappellari et al. (2011b) found that the fraction of SRs with respect to the total number of galaxies stays constant over a range of LPEs, corresponding to ≈ 4 orders of magnitude in Σ_3 . In the core of the Virgo Cluster instead the fraction of SRs increases sharply. This phenomenon is called the kinematic morphology-density

relation (kT- Σ).

We have seen, however, that LPE and GHE are strongly correlated, in that cluster of galaxies reach denser LPE than groups and fields. Since ATLAS^{3D} probed only one cluster, it is not clear if the increase in the fraction of SRs is linked to high density found in the core of Virgo (LPE) or instead to the special spatial location represented by the core of a cluster of galaxies (GHE).

In this study, we aim to improve our knowledge of the relationship between environment (GHE and LPE) and ETGs, as viewed through the prism of the SR/FR classification. In the next chapter we describe our IFS observations of the massive cluster Abell 1689 (Chapter 2), where we search for SRs in the densest environment available. The results are shown in Chapter 3. Building on our findings, we describe our study of the ϵ distribution of galaxies in nearby clusters ($z \lesssim 0.2$, Chapter 4) and the relevant results (Chapter 5). The last chapter (Chapter 6) summarizes the main achievements of this work.

Chapter 2

Abell 1689 FLAMES/GIRAFFE data

ATLAS^{3D} studied the fraction of SRs over the total number of galaxy, as a function of local environment. They found that the fraction of SRs stays constant for several orders of magnitude with the projected number density of galaxies. In the densest region probed, the core of the Virgo Cluster, the fraction of SRs rises sharply. This result can be interpreted in two ways: either the increase happens when the local density reaches a threshold value, or it happens in the particular spatial location represented by the core of a cluster of galaxies. ATLAS^{3D} probed only one cluster, and could not answer this question.

Here we break the degeneracy between local galaxy density (LPE) and global environment (GHE), by probing the densest environment available using IFS. Since the most dense galaxy clusters are rare, we need to go beyond the local Universe, to fainter objects. As a consequence, and to be efficient, the instrument of choice needs to implement multiplexing, the ability to observe more than one target in a single exposure. Our choice fell on the FLAMES/GIRAFFE spectrometer at the Very Large Telescope (VLT). The cluster targeted was Abell 1689, because of its very high projected density and of the good amount of additional data already available through public archives.

We open this chapter introducing the cluster of galaxies Abell 1689 (Section 2.1). We then give a brief description of the instrument used (Section 2.2), which is necessary to understand the sample selection (Section 2.3). The observations and the data reduction process are described in Section 2.4 and Section 2.5 respectively. In Section 2.6 we illustrate the analysis of the IFS data, and conclude describing the ancillary data, alongside the additional measurements required for the following analysis

(Section 2.7).

2.1 The cluster of galaxies Abell 1689

The cluster of galaxies Abell 1689 is a very rich, massive system at redshift $z=0.183$ (Struble and Rood 1999) (Fig. 2.1). Its X-ray luminosity of $20.74 \times 10^{44} \text{erg s}^{-1}$ is almost three times that of the Coma Cluster, the richest nearby cluster (Ebeling et al. 1996). Because of both its physical characteristics and its relative proximity, Abell 1689 has been the subject of several studies in the past. Its mass has been estimated using different methods, however the results do not agree.

Andersson and Madejski (2004) used X-ray data. They assumed spherical symmetry and hydrostatic equilibrium and fitted a NFW model to the mass distribution (Navarro et al. 1996). They found a total mass $M = 0.20 \pm 0.03 \times 10^{15} h^{-1} M_{\odot}$ within a radius $R = 0.25 h^{-1} \text{Mpc}$. The ratio between the mass of the gas and total mass is 0.072 ± 0.008 , significantly lower than the typical value of 0.108 ± 0.014 found for relaxed clusters (Allen et al. 2003). The X-ray emitting gas presents asymmetries in both the redshift and temperature distributions, supporting the case for recent merging activity. In contrast, the smooth, almost circular, X-ray isophotes suggest that Abell 1689 has already reached hydrostatic equilibrium.

The histogram of the LOS velocities of galaxies within 2 Mpc from the centre of Abell 1689 is multimodal, however none of the galaxies can be considered an outlier (Łokas et al. 2006). Depending on the interpretation of the velocity histogram and on the adopted cut, the estimated mass can vary by an order of magnitude. The hypothesis that all the galaxies with redshift 0.1832 ± 0.05 are gravitationally bound to the cluster and follow a Gaussian velocity distribution leads to a very large dynamical virial mass $M_v = 33 \times 10^{15} M_{\odot}$ and a virial radius $r_v = 8.3 \text{Mpc}$. Using data from numerical simulations, Łokas et al. (2006) further show that a velocity histogram does not necessarily separate structures that are aligned by chance.

Models based on strong and weak gravitational lensing predict total masses of order $M = 2 \times 10^{15} M_{\odot}$. This value is an order of magnitude smaller than the prediction from the velocity distribution of galaxies, and indeed an order of magnitude larger than the prediction of X-ray studies (Broadhurst et al. 2005a,b).

A possible interpretation of this discrepancy is that Abell 1689 is elongated along the LOS. This hypothesis is supported also by recent studies using the Sunyaev-Zeldovich (SZ) effect. The optical depth of the intra cluster medium as measured through its effect on the CMB photons is much higher than that inferred from X-ray emission. By combining X-ray emission, strong lensing, weak lensing and SZ data in a Bayesian framework, and assuming an NFW model, Sereno et al. (2013) obtain an axial ratio of 0.5 ± 0.1 , a mass $M_{200} = (1.3 \pm 0.2) \times 10^{15} M_{\odot}$ and the concentration parameter $c_{200} = 8 \pm 1$.

The value of the concentration parameter c_{200} for Abell 1689 is particularly high (but still consistent with theoretical predictions Sereno et al. 2013). This property makes Abell 1689 an extremely dense environment, and the ideal testing ground where to investigate the effects of environment on ETGs.

With the adopted WMAP7 cosmology, Abell 1689 comoving distance is 741 Mpc, corresponding to 1 arcsec per 3.0 kpc.

2.2 The FLAMES/GIRAFFE spectrograph

FLAMES is a multi-object spectrometer at the Unit Telescope 2 (UT2) of the European Southern Observatory (ESO) Very Large Telescope (VLT). It covers the whole visible band, from intermediate to high resolution. A fibre positioner, hosting two plates, limits the setup time between subsequent observations to less than 15 minutes: when one plate is observing, the other one can be prepared for the next scheduled observation. The spectrometer GIRAFFE is fed by means of optic fibres. It is capable of observations from $\lambda \approx 3600 \text{ \AA}$ to $\lambda \approx 9400 \text{ \AA}$, with resolutions from $R \approx 6000$ to $R \approx 48000$, depending on the exact configuration. FLAMES can be used in three independent observing modes. IFU mode provides 30 deployable mini Integral Field Units (IFU), 15 per plate. Each one is capable of Integral Field Spectroscopy (IFS) observations (with a Field of View (FOV) of $\approx 3 \times 2 \text{ arcsec}^2$), ideal to observe several galaxies per exposure. The large FOV of FLAMES (25 arcmin in diameter), combined with the multiplexing capability of the IFU mode, makes FLAMES/GIRAFFE an excellent tool to observe galaxies in low redshift clusters ($z \lesssim 0.2$), ensuring an optimal usage of telescope time. At the distance of Abell 1689, the GIRAFFE deployable IFUs sample up to $1 R_e$ for most galaxies.

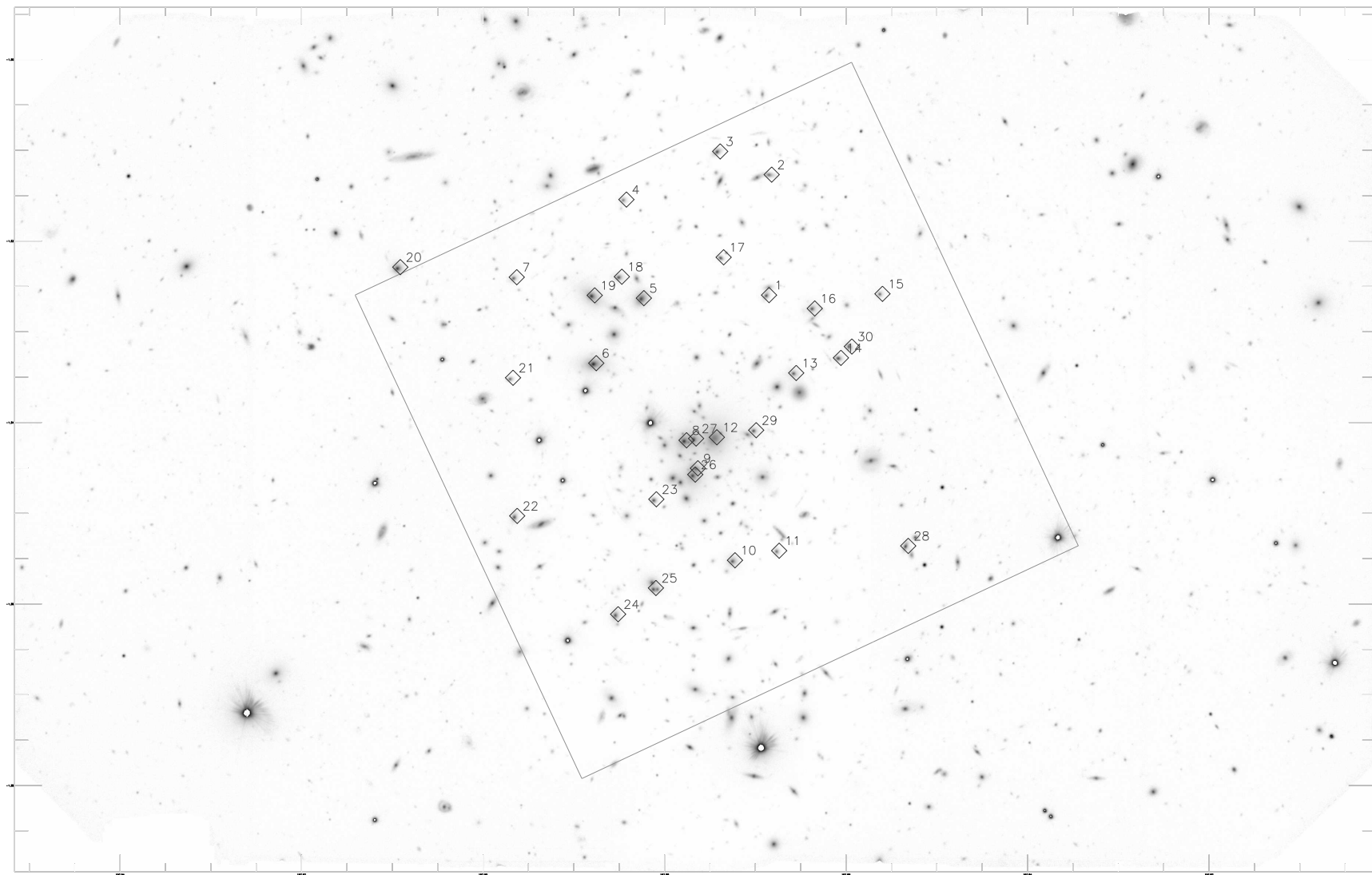


Figure 2.1: Gemini GMOS g' -band image of Abell 1689. The black square is HST ACS footprint, and the numbered diamonds mark the galaxies in our sample (see Table 2.1). North is up, East to the left. The image size is $9.0 \times 5.6 \text{ arcmin}^2$.

2.2.1 FLAMES/GIRAFFE IFU mode

When in IFU mode, FLAMES/GIRAFFE provides 30 independent mini IFUs, deployable anywhere on the focal plane. They are arranged in two positioner plates, each hosting 15.

Each mini IFU is positioned and held in place by a magnetic button, with an accuracy better than 0.08 arcsec¹. The field acquisition, crucial to the accuracy of the positioning of the mini IFUs, is achieved using four Field Acquisition Coherent Bundles. These are four additional dedicated IFUs, and are used to obtain images of four fiducial stars. A single object mini IFU contains an array of 20 square microlenses of 0.52 arcsec side each, arranged in 4 rows of 6 (with 4 empty “dead” corners) for a total aperture of 3.12×2.08 arcsec². Each lenslet is then connected to the spectrometer with a dedicated optical fibre. A mechanical system called retractor ensures that every fibre is maintained at constant tension throughout the observation. Alongside the 15 mini IFUs, each positioner plate also houses 15 sky dedicated fibres. These are fully deployable just like the former, but carry only one lenslet.

Since the magnetic buttons are larger (10 arcsec) than the IFU FOV, they cannot be deployed closer than a minimum distance corresponding to 11 arcsec: targets closer than this must be allocated on different plates.

The output spectra of the twenty IFU fibres plus a single sky fibre constitute an IFU subslit. In total, the IFU mode slit is composed of fifteen subslits.

On the chip, the centre-to-centre distance between the spectra in each subslit is 1.47 times the fibre diameter core, corresponding to six pixels. In uniform illumination conditions, the contamination between adjacent fibres is about 10% of incoming photons².

¹FLAMES User Manual, Section 3.3.1 <http://www.eso.org/sci/facilities/paranal/instruments/flames/doc/VLT-MAN-ESO-13700-2994.v94.pdf>

²FLAMES User Manual, Section 3.4.4 <http://www.eso.org/sci/facilities/paranal/instruments/flames/doc/VLT-MAN-ESO-13700-2994.v94.pdf>

2.3 The Abell 1689 sample

The number of galaxies we need to observe in Abell 1689 is dictated by the best compromise between the constraints on the telescope time and the need to overcome Poisson noise in the number of SRs. Previous studies found an f_{SR} in the range $0.15 \lesssim f_{\text{SR}} \lesssim 0.30$, depending on the environment considered (Cappellari et al. 2011b). With a sample of 15 randomly selected galaxies, we expected 2.25 ± 0.7 SRs for $f_{\text{SR}} = 0.15$ and 4.5 ± 0.5 SRs for $f_{\text{SR}} = 0.30$. Increasing the sample size to 30 gives 4.5 ± 0.5 SRs and 9.0 ± 0.3 SRs respectively. Since the IFU mode of FLAMES/GIRAFFE permits the observer to target 15 objects simultaneously, we chose to target 30 galaxies as a compromise between sample size and integration time. Our selection was based on the catalogue from Halkola et al. (2006), which used high resolution HST imaging. In order to gain the maximum possible signal-to-noise ratio (SNR), we initially selected the 30 ETG with the highest surface brightness within R_e (but we included the central cD galaxy regardless of its surface brightness). This initial sample was then subject to the FLAMES/GIRAFFE proximity constraint of 11 arcsec (Section 2.2.1), which ruled out some targets in the most crowded regions and forced us to re-select from a reserve list. This left us with 29 galaxies, therefore the final sample includes one target outside the HST FOV (galaxy 20 in Table 2.1).

2.4 FLAMES/GIRAFFE data

The observations were carried out between 24 May 2009 and 29 May 2009, as detailed in Table 2.2, which also lists the observing conditions. The value quoted for the seeing Full Width at Half Maximum (FWHM) is the FWHM of the telescope guide star, taken from our own on site records. The official figure for the seeing, provided in the archival data, is higher (on average by 0.5 arcsec). This discrepancy is well known (Sarazin et al. 2008), and the first value is the appropriate one.

We used FLAMES/GIRAFFE in IFU mode, setup with the L612W filter, which gives a wavelength range of 5732-6515 Å and a resolution R of 11800 (the minimum allowed at these wavelengths). For a target at redshift $z=0.183$, the rest frame wavelength interval is 4858-5521 Å, which includes prominent absorption features of old stellar populations (for comparison, SAURON has a wavelength range of 4800-5380 Å).

Here we stress that the seeing was excellent, with a PSF Full Width at Half Maximum (FWHM) comparable in width with the lenslet size (0.52 arcsec).

Table 2.1: Our sample of 30 bright galaxies in Abell 1689.

Galaxy	Halkola	RA	DEC	M_K	R_e	Q	ϵ_e	PA
		(deg)	(deg)	(mag)	(arcsec)	(1-3)		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	17	197.86780	-1.32543	-23.28	0.65 ± 0.29	2	0.286	20
2	3	197.86746	-1.31217	-23.16	1.27 ± 0.57	1	0.583	163
3	12	197.87312	-1.30963	-23.57	0.71 ± 0.32	2	0.363	47
4	34	197.88345	-1.31490	-22.58	1.15 ± 0.51	2	0.032	235
5	22	197.88155	-1.32575	-24.97	2.84 ± 1.24	2	0.219	113
6	47	197.88679	-1.33293	-25.41	2.39 ± 1.04	2	0.330	266
7	65	197.89554	-1.32343	-22.99	0.85 ± 0.38	2	0.108	311
8	31	197.87683	-1.34142	-24.86	2.74 ± 1.20	3	0.090	196
9	38	197.87562	-1.34447	-24.28	7.51 ± 3.28	3	0.077	-41
10	43	197.87158	-1.35463	-23.87	1.69 ± 0.74	2	0.049	-157
11	37	197.86674	-1.35358	-22.75	0.74 ± 0.33	2	0.217	-41
12	32	197.87358	-1.34107	-26.18	13.92 ± 6.08	3	0.149	-62
13	14	197.86484	-1.33403	-23.64	1.58 ± 0.69	2	0.107	44
14	6	197.85991	-1.33236	-23.48	0.62 ± 0.28	2	0.361	88
15	2	197.85533	-1.32531	-22.81	0.93 ± 0.42	2	0.029	83
16	7	197.86275	-1.32691	-23.63	1.81 ± 0.79	2	0.138	0
17	20	197.87279	-1.32127	-23.04	0.46 ± 0.21	2	0.558	138
18	41	197.88396	-1.32339	-23.55	0.95 ± 0.42	2	0.174	198
19	35	197.88699	-1.32541	-25.13	2.27 ± 0.99	2	0.246	180
20	-	197.98916	-1.15270	-24.38	1.55 ± 0.19	2	0.040	98
21	69	197.89596	-1.33452	-22.56	0.52 ± 0.23	2	0.278	278
22	75	197.89558	-1.34971	-23.47	0.86 ± 0.38	2	0.301	193
23	61	197.88025	-1.34790	-23.19	0.57 ± 0.25	2	0.055	292
24	70	197.88451	-1.36054	-23.66	1.19 ± 0.52	2	0.245	-124
25	60	197.88029	-1.35769	-23.64	0.85 ± 0.37	2	0.261	-41
26	29	197.87596	-1.34520	-24.91	4.64 ± 2.02	3	0.116	-26
27	42	197.87584	-1.34122	-24.94	3.36 ± 1.47	3	0.154	-53
28	8	197.85258	-1.35308	-23.54	0.83 ± 0.37	2	0.617	-35
29	28	197.86925	-1.34030	-23.63	0.69 ± 0.31	2	0.081	96
30	4	197.85870	-1.33110	-23.35	0.93 ± 0.41	2	0.265	70

Column (1): galaxy ID number used throughout this work. Column (2): galaxy ID from Halkola et al. (2006). Column (3): right ascension in degrees and decimal (J2000.0). Column (4): declination in degrees and decimal (J2000.0). Column (5): K -band galaxy magnitude derived from the apparent r' -band magnitude and corrected as detailed in Section 2.7.1. Column (6): R_e obtained with a curve of growth method and masking nearby objects, see Section 2.7.2. Column (7): quality of the R_e determination. A value of 1 is only given to the best fits. Values of 3 are assigned to objects with severe contamination. Column (8): ellipticity determined with the method of moments, inside the isophote of area πR_e^2 . Column (9): position angle determined with the method of moments, inside the isophote of area πR_e^2 .

Table 2.2: A summary of the VLT/FLAMES GIRAFFE/IFU spectroscopy. The seeing FWHM was measured on site using the telescope guide stars.

Frame	Plate	Date D/M/Y	night	Time min	Seeing arcsec
1	1	24 May 2009	1	120	0.60
2	1	25 May 2009	1	120	0.60
3	1	25 May 2009	2	120	0.60
4	1	26 May 2009	2	120	0.60
5	1	27 May 2009	3	120	0.60
6	2	25 May 2009	1	120	0.50
7	2	26 May 2009	3	120	0.60
8	2	27 May 2009	3	120	0.60
9	2	27 May 2009	4	120	0.80
10	2	28 May 2009	4	120	0.65

Table 2.3: Calibration data

Frame	Number	Number (per night)	Time [s]	Fits keyword
Bias	15	3	0.0	BIAS
Flat Field	9	3	96.2	LAMP,FLAT
Arc Lamp	3	1	127.6	LAMP,WAVE
Twilight	5	N/A	N/A	OBJECT,OzPoz
Science	5	N/A	7200	OBJECT,OzPoz

2.5 Data reduction

The data reduction is the set of all processes needed to produce a spectrum on a uniform wavelength grid starting from the raw science frames. The main steps of the data reduction are:

- bias subtraction
- flat fielding
- wavelength calibration
- rectification of the spectra

We used the standard pipeline provided by ESO³ and followed the guidelines ESO offers⁴. The GIRAFFE pipeline is organized in nine distinct applications, called recipes. Some of these have a large number of user configurable parameters and it is impractical to list them all in here. Therefore we only specify the values of those parameters where we did not use the default choice.

The four data reduction steps listed above are executed by the recipe *giscience*. However, before launching *giscience*, a number of auxiliary calibration frames have to be provided. This is done using three additional recipes, *gimasterbias*, *gimasterflat* and *giwavecalibration*. The remaining five recipes were not used.

Each morning a number of raw calibration frames were taken. These include bias, lamp flats and arc lamp frames, as listed in Table 2.3.

The first task of the data reduction process is the creation of a master bias frame, using the recipe *gimasterbias*. We created a distinct master bias frame for each observing night, using as input the five raw bias frames of the following morning. The default method *average* is inadequate in eliminating cosmic rays, so we used the method *ksigma* instead, with the keywords *ksigma.low* and *ksigma.high* both set to 3.0.

The next recipe, *gimasterflat*, uses three lamp flat frames to create the master flat frame. In addition, it performs the fibre localization. The latter is necessary because on the raw science frames the spectra are not aligned with the rows and columns of

³<http://www.eso.org/sci/software/pipelines/giraffe/giraf-pipe-recipes.html>

⁴<ftp://ftp.eso.org/pub/dfs/pipelines/giraffe/giraf-manual-2.8.7.pdf>

the CCD. In order to extract the spectra it is necessary to trace their position. This task is best done for a very high SNR frame, therefore the recipe combines the three lamp flat frames. At each spectral pixel on the combined frame the recipe determines the locations, in the cross-dispersion direction, of the light peaks corresponding to the centre of each fibre signal. A polynomial is fitted to each profile, and is stored as the trace shape. We used the standard unweighted summation to extract the spectra (we set the keyword *extraction.method* to *SUM*). This is against the manual recommendation of setting the keyword to *OPTIMAL*, however this often caused the program to crash. The keyword *biasremoval.method* was set to *PROFILE+CURVE*, as advised by ESO on the website, while the keywords *fibres.spectra* and *fibres.nspectra* were modified to take into account the occurrence of both broken and unused fibres. The manual indicates that, using *SUM*, the contamination between neighboring spectra is less than 10% of the counts. The recipe also determines the pixel-to-pixel variation corrections and the fibre-to-fibre transmission variations.

The wavelength calibration was done separately for each night using the recipe *giwavecalibration*. We determined the precision of the wavelength solution by comparing the observed sky lines with high precision measurements obtained with FLAMES/UVES (Hanuschik 2003). We selected a subset of prominent, singlet lines in the relevant wavelength range, and used the MINPACK-1 (Moré et al. 1980) Levenberg-Marquardt nonlinear least-squares optimization algorithm to fit a Gaussian to each of them. The resulting accuracy (mean displacement between measured and nominal line centers) is $0.01 \pm 0.03 \text{ \AA}$. The resolution (mean FWHM of the lines) is $0.61 \pm 0.07 \text{ \AA}$. This corresponds to a velocity dispersion $\sigma = 12.7 \text{ km s}^{-1}$, more than adequate to determine the velocity dispersion of massive ETGs ($\sigma \simeq 200 \text{ km s}^{-1}$ for a galaxy with mass $M \geq 3 \times 10^{10} M_{\odot}$ Cappellari et al. 2013a).

The science spectrum was extracted using the recipe *giscience*. The keyword *extraction.method* was set again to *SUM*. This recipe uses the fibre localization from *gimasterflat* and the wavelength solution from *giwavecalibration* to rebin the spectra in a regular grid in wavelength. Formal errors are also returned.

2.5.1 Post processing

giscience produced a frame of data (and a frame of errors) for each of the input science frames. We had 5 frames per night, and combined them to increase the SNR and to eliminate cosmic ray hits. We used a custom implementation of the ksigma rejection method, with the value of ksigma set to 3.

The resulting two frames (one per plate) were then rescaled using the twilight exposures. Finally we separated the science fibres from the sky ones, and arranged the science data into “cubes”, fits files with 3-dimensional arrays, where the dimension represent the two spatial dimensions on the sky and the wavelength.

The median SNR for all the spaxels for all the galaxies is 4.5, while the dispersion around this value is 2.6.

2.6 Data analysis

2.6.1 Kinematics extraction

We used the program pPXF (penalized PiXeL Fitting, Cappellari and Emsellem 2004) to extract the stellar kinematics from the reduced spectra. pPXF fits a model to the LOSVD. It takes as input the galaxy spectrum to fit, an initial guess for the parameters and a library of stellar template spectra. The fit is performed by convolving a linear combination of the stellar template spectra with an LOSVD expressed by the truncated Gauss-Hermite series:

$$\mathcal{L}(v) = \frac{e^{-(1/2)y^2}}{\sigma\sqrt{2\pi}} \left[1 + \sum_{m=3}^M h_m H_m(y) \right] \quad (2.1)$$

where $y = (v - V)/\sigma$ and the H_m are Hermite polynomials (van der Marel and Franx 1993; Gerhard 1993). In practice, because we are primarily interested in V and σ , we truncated the expansion of $\mathcal{L}$ and fitted a Gaussian function only. We therefore did not use the penalizing feature which gives the name to pPXF, as it is meant to detect deviations from Gaussianity.

Since the LOSVD can be approximated reasonably well by a Gaussian, we can use the value of σ in Equation (2.1) as an estimate of the velocity dispersion (Equation 1.5). In principle one can use the Gauss-Hermite expansion to express the velocity dispersion as a function of σ and h_m , but in practice the adopted approximation is sufficient for our purposes (Cappellari et al. 2006, 2007, 2013b).

pPXF performs the fit in the velocity space, therefore the spectra provided have to be sampled in a regular velocity grid. At a wavelength λ , a difference in wavelength $\Delta\lambda$ corresponds to a difference in velocity Δv given by:

$$\Delta v = c \frac{\Delta\lambda}{\lambda} \quad (2.2)$$

where c is the speed of light. Therefore, a regular grid in v corresponds to a logarithmic grid in λ . All the input spectra are binned on a grid with constant $\Delta\lambda$, therefore they

have to be rebinned logarithmically before pPXF can use them. This is done using the dedicated function included in the pPXF package.

The SAURON and ATLAS^{3D} collaborations used the stellar template library MILES (Sánchez-Blázquez et al. 2006), with a spectral resolution of 2.54 Å FWHM (Beifiori et al. 2011). The resolution of our FLAMES/GIRAFFE data is much higher (see Section 2.5), therefore, in order to match the resolution of MILES, one needs to reduce it. Since this reduction involves a convolution, which introduces correlations between adjacent pixels, we decided to use a different library. Our choice fell on the high-resolution version (R=40000) of the ELODIE template library (Prugniel and Soubiran 2001), which has a spectral FWHM of 0.13 Å. The stellar templates in ELODIE cover a good range in age and metallicity; in particular, they include old and metal rich spectral types that dominate the populations of massive ETGs. All ELODIE template spectra have a gap at $\lambda \approx 5414$ Å, so we cut the galaxy spectra at 5300 Å. For each galaxy we have 20 distinct spectra, one for each lenslet in the FLAMES/GIRAFFE mini-IFU; we computed a weighted average (with sigma clipping rejection) of all the 20 spectra, and fed it to pPXF along with all the 1959 templates available in ELODIE. This resulted in ≈ 15 templates being selected for each galaxy, and we use this subset to fit the individual fibre spectra of the galaxy, thus speeding the fitting process and ensuring its robustness. We used formal errors derived by pPXF (as we did not exploit the penalizing functionality of the algorithm). These are typically of the order of 15 km s⁻¹ for V and 17 km s⁻¹ for σ , but they do not take into account the correlation introduced when log-rebinning. Due to the high spectral resolution and low SNR, we decided not to subtract the sky, but rather to fit it simultaneously with the stellar templates. Like Weijmans et al. (2009), we provided pPXF with all the simultaneous sky spectra and let the maximum likelihood algorithm rescale them to best fit the data.

Fig. 2.2 shows a spectral fit for galaxy number 1 (Table 2.1).

We conducted further tests to assess the reliability of the results. We introduced one at a time the following changes and repeated the fit. We added a random fraction between 0. and 0.1 to the starting values for pPXF; we changed the degree of the (additive) polynomial between 2 and 6; we matched the spectral resolution of the science frames to that of MILES, and used this library instead of ELODIE. The results were the same within the errors. The last test also demonstrates that our choice of the ELODIE spectral library does not bias the kinematics.

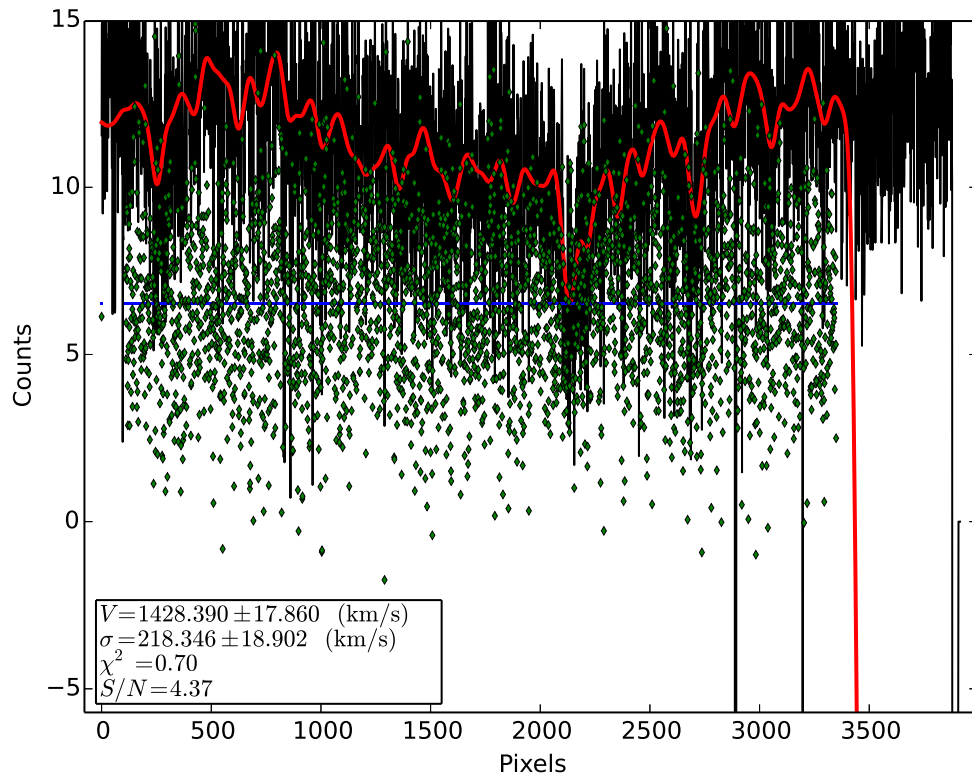


Figure 2.2: pPXF fit for a spectrum of galaxy number 1 (Table 2.1). The galaxy spectrum is in black, the red line is the best fit, the blue horizontal line is the domain where the spectrum was fitted and the green diamonds are the residuals, shifted up for illustration purposes.

2.7 Archival data

We used archival photometry from the Hubble Space Telescope (HST) as well as Gemini-North Telescope. The HST data consisted of a single F625W-band image from the Advanced Camera for Surveys (ACS); it was obtained as part of the ACS Guaranteed Time Observation programme 9289 (P.I. H. Ford). Gemini data comprised two images in the g' - and r' -band, taken with the Gemini Multi Object Spectrograph (GMOS-N). A detailed description of this data, as well as the data reduction process, is available in the literature (Houghton et al. 2012).

2.7.1 Parent sample

We used the g' and r' -band Gemini imaging to create the parent sample for Abell 1689. We extracted a list of the sources in the images using the program **sExtractor** (Bertin and Arnouts 1996). This is achieved in two separate stages. In the first stage, we detected all the sources in the g' -band image, because of its better spatial resolution. The second step measures the photometric parameters (including aperture and Petrosian magnitudes). In this stage we used as input both the r' -band and g' images, the latter convolved with a suitable Gaussian function to match the resolution of the former. The resulting list of sources has been trimmed by excluding all stars (**sExtractor** parameter $\text{STAR} > 0.99$), as well as spurious or unreliable detections (we applied cuts in the error on the magnitudes, $\sigma_{r'}, \sigma_{g'} < 0.1$ mag). We further eliminated all galaxies with Petrosian r' -band magnitudes fainter than $r' = 22$, that are of no interest in this work.

The ATLAS^{3D} parent sample is volume limited, and complete down to $M_K = -21.5$ mag, where the magnitude is measured in the K_S band and Vega system. Following Houghton et al. (2012) we converted our observed r' magnitudes into K_S band absolute magnitudes by applying a fixed correction of -42.20 . This included the distance modulus $d = 39.72$, a k -correction of 0.18 and a colour correction $r' - K_S = 0.835$. The latter has been computed using Maraston (2005) models, assuming an age of 10.4 Gyr (Houghton et al. 2012) and passive evolution. A further correction of $\Delta m_{\text{AB-Vega}} = 1.83$ takes into account the difference between the AB and Vega magnitude systems. We obtained the parent sample for Abell 1689 from the **sExtractor** catalogue, by applying a magnitude cut at $M_K = -21.50$.

The resulting catalogue has been used to compute the number density of galaxies (Section 3.5), the cluster Luminosity Function (LF) (Section 3.6) and the cluster RS

(Section 3.6.1).

2.7.2 Effective radius and ellipticity

In order to measure the effective radii R_e and the ellipticities ϵ for the 30 galaxies in our sample, we used the high resolution F625W-band HST image. In practice one galaxy (number 20 in Table 2.1) lies partially outside the ACS field of view, and takes its photometric parameters from the r' Gemini image.

Since a large fraction of our sample is found in very dense regions, the surface photometry can be contaminated by that of a neighbour. Consequently all of our photometric measurements are made on processed post-stamp images of each galaxy, where any contamination has been masked out (Houghton et al. 2012). The regions masked have been “reconstructed” by symmetrization with respect to the centre of the galaxy, viz. by mirroring and adding up the image.

The values of R_e were measured using a curve of growth method developed by Houghton et al. (2012), imposing a de Vaucouleur’s light profile. It is very hard to characterize the error introduced by the masking process. This is reflected by a “quality” flag Q, running from 1 to 3 for relatively clean to heavily contaminated galaxies (Houghton et al. 2012). The resulting R_e and Q are listed in Table 2.1.

Following Emsellem et al. (2007) we adopted the method of moments to determine the ellipticities. We used the algorithm `findgalaxy` from M. Cappellari to identify 100 isophotes, between a flux F_0 equal to two times the sky flux and the flux F_{100} of the peak. We call I_k the set of all pixels that have flux $f > F_k$ $k \in \{0, \dots, 99\}$. `findgalaxy` associates to the k -th isophote an ellipse ϵ_k , by computing the second order moments of the light distribution within I_k . From the second order moments we derive the major and minor axes, the position angle PA_k , the ellipticity ϵ_k . The latter is defined as

$$(1 - \epsilon_k^2) \equiv \frac{\sum_{i \in I_k} f_i y_i}{\sum_{i \in I_k} f_i x_i} \quad (2.3)$$

where f_i is the flux associated with the i -th pixel and the coordinates (x, y) are drawn from the galaxy centre. We further associate to the k -th isophote a circle of radius R_k , defined by $R_k \equiv \sqrt{A_k/\pi}$, where A_k is the area of I_k .

SAURON and ATLAS^{3D} based their classification on values relative to the isophote of equivalent radius $R = R_e$, determined on the reconstructed spectrograph image. Because the spatial resolution of our observations is much coarser, we used instead HST imaging. The bias introduced by measuring the kinematics and photometry with different spatial resolutions is discussed in Section 3.3.

The associated ellipses of equivalent radius $1 R_e$ are used also as apertures to compute σ_e . In practice, because some galaxies are larger on the sky than the IFU FOV, for some galaxies we used smaller apertures, as detailed in Table 2.1.

Chapter 3

Abell 1689 IFS results

3.1 Kinematic maps

Fig. 3.1 shows the kinematic maps for the sample of 30 galaxies in Abell 1689. The first plot shows HST photometry, with the IFU footprint superimposed. The black compass arrows denote the North and East. The second plot shows the image reconstructed from the spectrograph, by integrating along the dispersion direction. Each square corresponds to an IFU spaxel and a lenslet in the instrument. The third and fourth plots depict the velocity and velocity dispersion respectively. The colourbar limits for the latter two plots are given in units of km s^{-1} .

3.2 Dynamical classification

As explained in Chapter 1, ETGs can be assigned to two dynamically distinct classes: SRs and FRs. This division arises naturally from the appearance of their kinematic maps, in that FRs exhibit ordered, large scale rotational patterns that are absent in SRs (Fig. 1.1). In this section we will use the FLAMES/GIRAFFE IFS data to classify the galaxies in our sample.

3.2.1 The λ vs ϵ diagram as a classification tool

In their study of the SAURON sample of galaxies, Emsellem et al. (2007) introduced the λ vs ϵ plot, where λ is a proxy for the projected angular momentum per unit mass and ϵ is the projected ellipticity. The combination of kinematic and projection information conveniently captures the dichotomy between FRs and SRs, in that SRs occupy a region of the diagram that is incompatible with disc-like rotation.

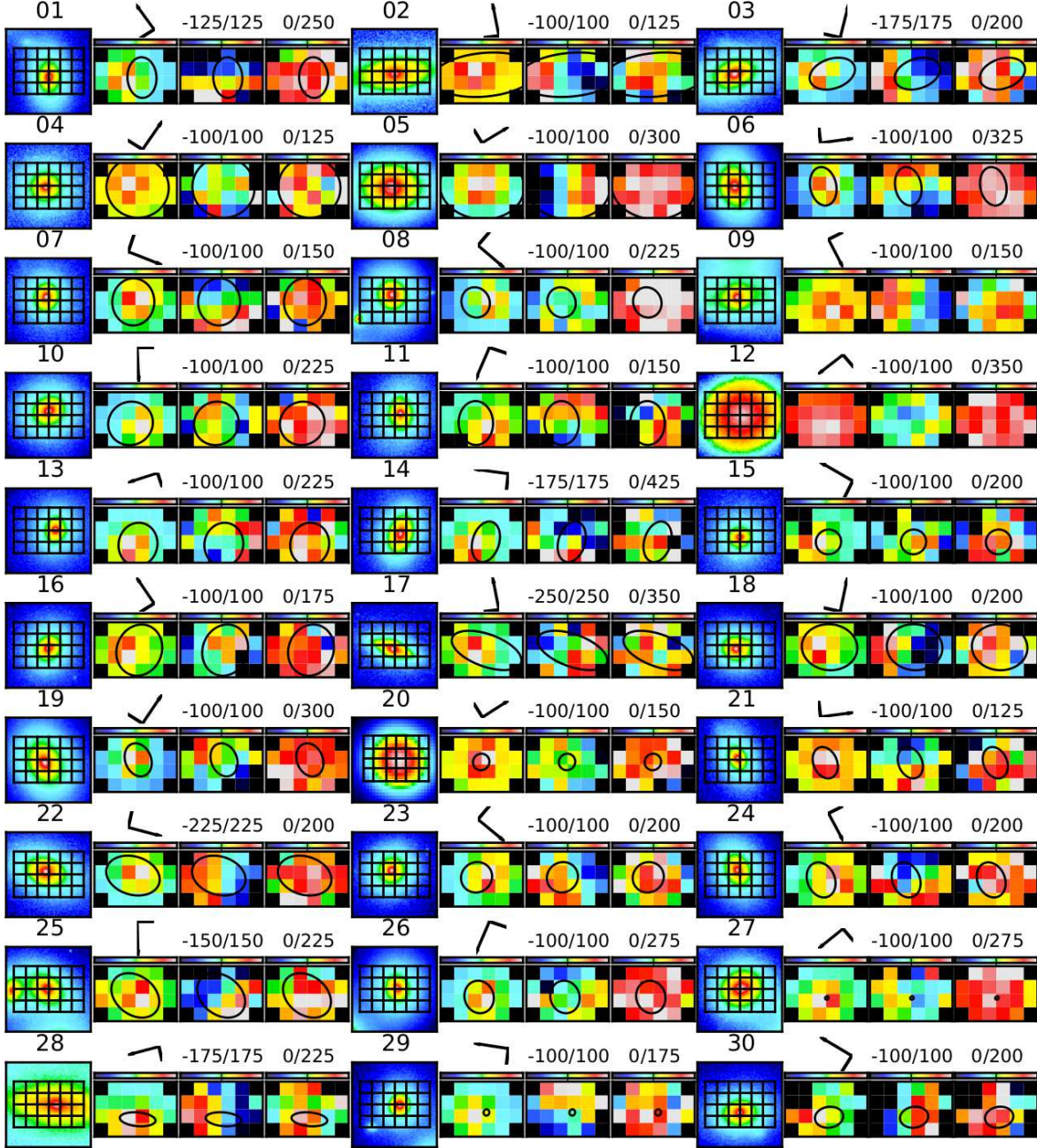


Figure 3.1: Kinematic maps of the 30 galaxies in the Abell 1689 sample. Each horizontal set of four images depicts one galaxy. The first plot shows HST photometry (Gemini photometry for target 20). Superimposed is the FLAMES/GIRAFFE footprint. In the second plot we show the reconstructed image from FLAMES/GIRAFFE, where each square is a spaxel, corresponding to a lenslet in the instrument. Superimposed is an isophote at either R_e , or the closest fraction that fits into the IFU footprint. The four black corners correspond to unused “dead” corners, while other black spaxels (seen in 11, 15 and 30) correspond to broken or unused fibres. Velocity and velocity dispersion maps are depicted in the third and fourth plots. The black compass arrows show North and East. Colourbar limits are given in km s^{-1} .

The galaxies of the ATLAS^{3D} sample were classified as SRs and FRs using *kinemetry*¹ (Krajnović et al. 2006) and visual inspection (Krajnović et al. 2011). Subsequently, Emsellem et al. (2011) placed them on the λ vs ϵ plot. They determine empirically the line of equation $\lambda = 0.31 \times \sqrt{\epsilon}$, which separates FRs (above it) from SRs (below it, see Fig. 3.3). Emsellem et al. (2011) warn against using the λ vs ϵ plot to classify ETGs and assign them to the SR and FR classes. Specifically, they point out that the distribution of galaxies on the plot might depend on the properties of the sample and of the instrument used, and in particular on the aperture adopted. However, with careful control of systematics, it presents an ideal tool, free from the biases associated with visual inspection. In addition, it allows a robust error analysis.

Given the practical limitations inherent to observations at higher redshift, we have no alternative.

3.2.2 Measurements of λ : introducing $\lambda(IFU)$

According to the SAURON prescription, to each galaxy we associate a set of concentric ellipses parametrized by their equivalent radius R (Section 2.7.2). Operatively, we define $\lambda(R)$ as:

$$\lambda(R) \equiv \frac{\sum_{i=0}^N f_i R_i |V_i|}{\sum_{i=0}^N f_i R_i \sqrt{V_i^2 + \sigma_i^2}} \quad (3.1)$$

where f_i , R_i , V_i and σ_i are respectively the flux, distance from the galaxy centre, velocity and velocity dispersion associated with the i -th spaxel, and the sum is carried out inside the ellipse of associated radius R . This is a discretized version of Equation (1.15).

The values that enter the λ vs ϵ plot must be derived from the reconstructed spectrograph image and computed within the same ellipse of equivalent radius R_e (Emsellem et al. 2007, 2011). However, the largest galaxies in our sample have R_e larger than the IFU FOV, while the smallest R_e 's are unresolved by the GIRAFFE lenslets. For this reason we cannot follow the ATLAS^{3D} prescription precisely.

We introduced instead $\lambda(IFU)$, defined as the value of λ computed on the whole IFU FOV. In order to compute $\lambda(IFU)$, the sum of Equation (3.1) is extended to all available spaxels in the IFU. The difference between our definition and that of the ATLAS^{3D} group comes alongside inherent dissimilarities in the observations. Our

¹www.davor.krajnovic.org/idl

galaxies are significantly farther, and the spatial resolution is accordingly coarser. Having to resort to a multiplexing instrument, we also lacked the flexibility needed to tile different exposures; as a consequence, we observe galaxies of different physical size with the same fixed aperture.

3.3 Simulated FLAMES/GIRAFFE observations of the SAURON sample

Having in mind the ATLAS^{3D} sample as the local term of comparison for our study, we must take into account the differences in the two datasets. In order to gauge the effect of higher redshift and coarser spatial resolution, as well as to test $\lambda(IFU)$ as a proxy of $\lambda(R_e)$, we set up simulated FLAMES/GIRAFFE observations.

We used publicly available data from the original SAURON survey². For each galaxy we created a kinematic model using *kinemetry*. We then projected the galaxy at the distance of Abell 1689, convolved it with a seeing of $0.8''$ and “observed” it with FLAMES/GIRAFFE. We created 10000 random realizations of each galaxy, adding random Gaussian noise with mean 15 km s^{-1} and 17 km s^{-1} for V and σ respectively, to reproduce the noise observed in the real FLAMES/GIRAFFE data. We then proceeded to measure λ .

We define $\Delta\lambda$ as the difference between $\lambda(IFU)$ and the published value of $\lambda(R_e)$ from Emsellem et al. (2007). In the upper panel of Fig. 3.2 we plot $\Delta\lambda$ against R_e for the SAURON sample. This information can be used to estimate the correction and the uncertainties that we need to apply to $\lambda(IFU)$ in order to recover the value of $\lambda(R_e)$. In particular, the difference between the two quantities decreases with R_e . We therefore divide the SAURON sample in three subsets, based on the value of R_e . The separations fall at $R_e = 1.15''$ and $R_e = 1.70''$, which naturally divide the sample (vertical lines in the lower panel of Fig. 3.2). We find the following mean offsets and systematic errors: for galaxies with $R_e < 1.15''$, $\Delta\lambda = -0.06 \pm 0.09$; for galaxies with $1.15 \leq R_e < 1.70''$, $\Delta\lambda = -0.01 \pm 0.04$, and for the remainder $\Delta\lambda = 0.01 \pm 0.02$.

We use these bias measurements to correct $\lambda(IFU)$ into $\lambda(R_e)$: for each galaxy we sum the relevant offset (depending on the galaxy’s R_e) to the measured value of $\lambda(IFU)$, and add the errors in quadrature. This correction is not exact, but rather has to be interpreted in a statistical fashion: on average, galaxies with $R_e < 1.15''$ will have a $\Delta\lambda = -0.06$ and it is this value that we add to $\lambda(IFU)$ to obtain $\lambda(R_e)$.

²<http://www.strw.leidenuniv.nl/sauron/>

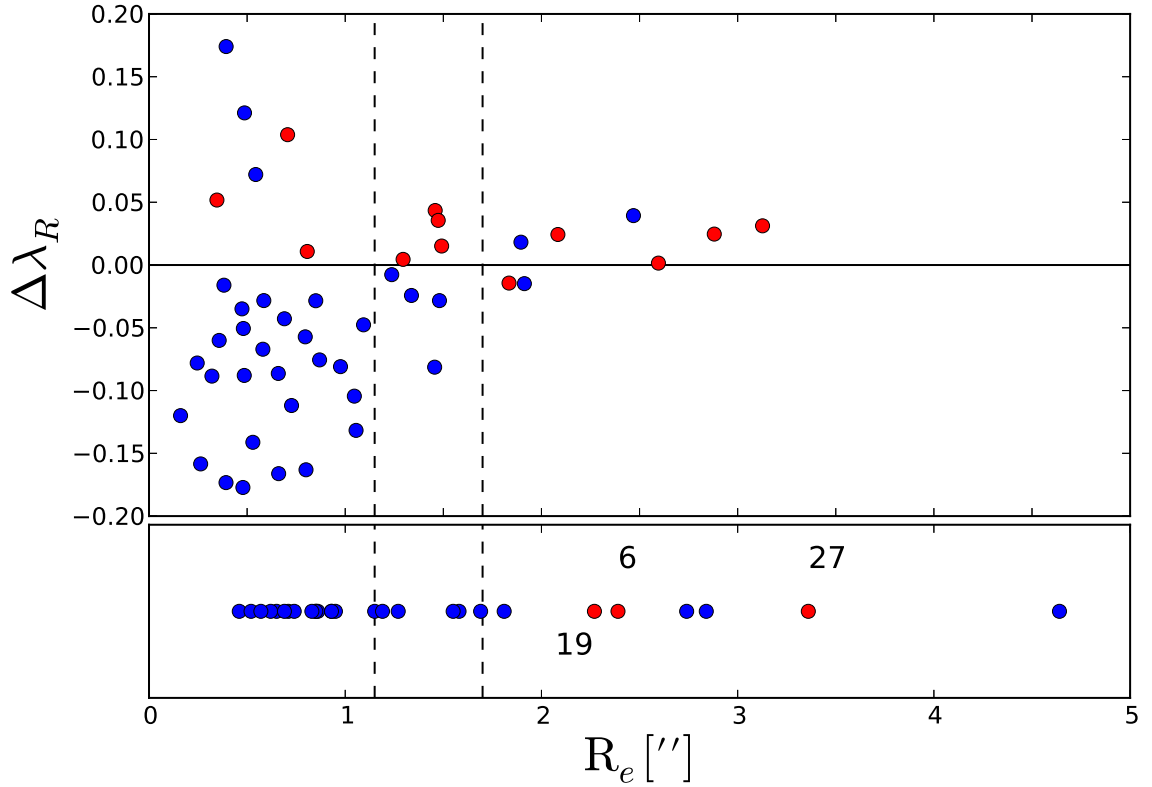


Figure 3.2: Upper panel: $\Delta\lambda$ as a function of R_e for the simulated observation of the galaxies in the SAURON sample. We moved the SAURON galaxies at the distance of Abell 1689, and resampled the velocity field according to the characteristics of FLAMES/GIRAFFE. $\Delta\lambda$ is the difference between the average measured value of $\lambda(IFU)$ and the published value of $\lambda(R_e)$ (Emsellem et al. 2007). The vertical dashed lines denote three arbitrary subsets, corresponding to natural partitions of the data. Red and blue dots mark slow and fast rotators respectively. Lower panel: R_e for the sample of 30 galaxies in Abell 1689. For each galaxy in this sample, we applied a correction to the measured value of $\lambda(IFU)$ based on the value of R_e .

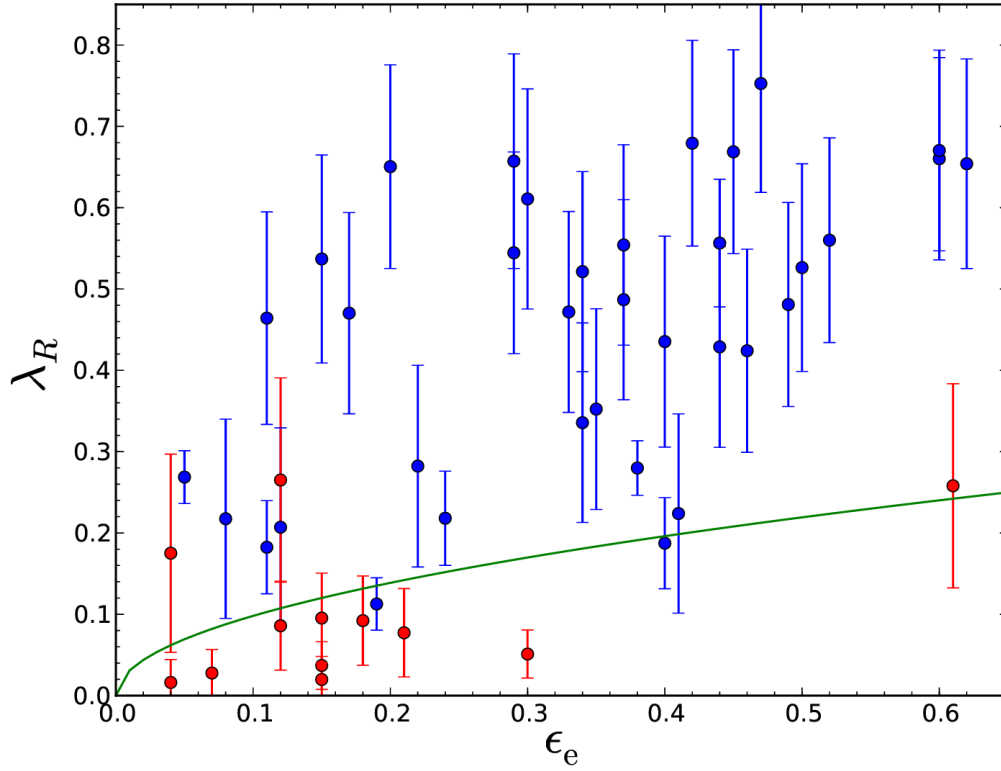


Figure 3.3: $\lambda(R_e)$ against ϵ_e for the 48 galaxies in the simulated FLAMES/GIRAFFE observations of the SAURON sample. The value of $\lambda(R_e)$ derives from measurements of $\lambda(IFU)$, which we corrected using the true values measured by Emsellem et al. (2007). Red and blue dots correspond to slow and fast rotators in the original classification of Emsellem et al. (2007). The green line of equation $\lambda = \sqrt{0.31} \times \epsilon$ separates the two groups, therefore any red dot above it or blue dot below it results in a misclassified galaxy.

In Fig. 3.3 we plot the resulting λ vs ϵ plot: **SAURON** galaxies are denoted by blue or red dots according to the published classification (Emsellem et al. 2007). If we use the green line of equation $\lambda = 0.31 \times \sqrt{\epsilon}$ to separate FRs from SRs, then misclassified objects correspond to blue dots below the line or red dots above it. Despite deriving $\lambda(R_e)$ from a different aperture, and combining it with ϵ_e (which is measured at $1 R_e$ for all galaxies), there is little misclassification. Observing the **SAURON** sample of galaxies with FLAMES/GIRAFFE instrument results in an error on f_{SR} of about 10%.

Given the use of the λ vs ϵ plot to classify SRs and FRs, and the size of the error bars, we can calculate the probability that a given galaxy is a SR. We adopt a Monte Carlo approach: we assume for each galaxy Gaussian errors in λ , truncated so that $0 \leq \lambda_R \leq 1$ and sample 100000 times. The resulting fraction of SRs is 12.3 ± 1.7 , where the true value is 12.

3.4 Dynamical classification of the Abell 1689 galaxies

Having asserted the effect of our observing setup on $\lambda(R_e)$, we now proceed to study the Abell 1689 sample. For each galaxy we computed $\lambda(IFU)$ and applied the correction derived in the previous section to convert it to $\lambda(R_e)$. The results are shown in Fig. 3.4, where we plot $\lambda(R_e)$ against the measured value of ϵ_e . The error estimated through the simulated observations of the **SAURON** galaxies was summed in quadrature to the results. We plot in red and in blue the dots lying respectively below and above the green line of equation $\lambda = 0.31 \times \sqrt{\epsilon}$. To each galaxy we assign a probability of being a SR according to the method discussed above.

Within the errors, the galaxies populate the same regions as the ATLAS^{3D} sample, in that the top left and bottom right corners are empty.

In order to estimate the uncertainty due to sampling, we adopt a Bayesian approach. Let $p(k|f_{\text{SR}}, N)$ be the probability of observing k SRs in a sample of N galaxies, where f_{SR} is known. $p(k|f_{\text{SR}}, N)$ can be expressed by the binomial distribution:

$$p(k|f_{\text{SR}}, N) = \binom{N}{k} f_{\text{SR}}^k (1 - f_{\text{SR}})^{N-k} \quad (3.2)$$

Bayes theorem states that the probability distribution of f_{SR} is:

$$p(f_{\text{SR}}|k, N) \propto p(k|f_{\text{SR}}, N)p(f_{\text{SR}}) \quad (3.3)$$

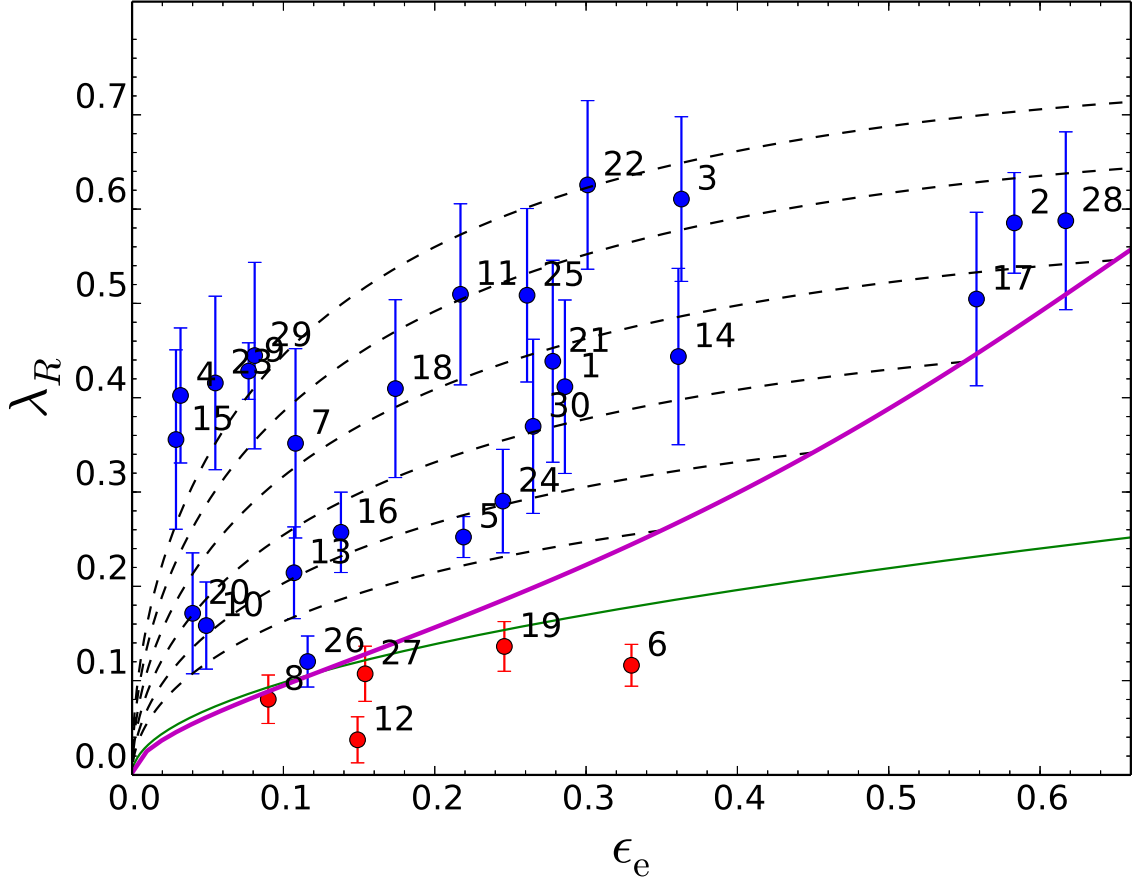


Figure 3.4: $\lambda(R_e)$ against ϵ_e for the 30 galaxies in the FLAMES/GIRAFFE sample of Abell 1689. The value of $\lambda(R_e)$ derives from a direct measurement of $\lambda(IFU)$, which we have corrected using simulated observations of the SAURON sample. The green line separates SRs (below it) from FRs (above it). However we assign to each galaxy a probability of being a SR, as described in the text.

where we adopted a so called uninformative prior, setting $p(f_{\text{SR}})$ constant in the interval $[0; 1]$ and 0 otherwise. Given that for each galaxy we know its probability of being a SR, we can determine $p(k)$ for the whole sample (or for a given subset, e.g. a magnitude or density bin). We then marginalise over k and obtain:

$$p_i(f_{\text{SR}}|N_i) \propto \sum_{0 \leq k \leq N_i} p_i(k|f_{\text{SR}}, N_i) p_i(k) \quad (3.4)$$

where the subscript i denotes the i -th magnitude or density bin, and N_i is the number of galaxies in that bin.

In Fig. 3.6 we plot the LF for the SRs in our sample. The probability of being a SR can be translated in the probability to measure a certain fraction f_{SR} of SRs in each magnitude bin. The resulting LF is compatible, within the errors, with the LF of the ATLAS^{3D} Virgo galaxies. In particular we confirm that SRs are more likely to be massive systems, even in extreme environments such as Abell 1689.

3.5 Environment density

In order to investigate the kT- Σ relation, we determined the local density around each galaxy in the sample. We started from the parent sample introduced in Section 2.7.1, where we eliminated all galaxies with $M_K > -21.5$ mag to match the ATLAS^{3D} selection. Following Cappellari et al. (2011b), for each target we measured Σ_3 , defined as the projected number density of galaxies in the circular area (in Mpc^2) encompassing the three closest neighbors.

Because (unlike Cappellari et al. 2011b) we do not possess the redshift of every galaxy in the parent sample, we cannot identify interlopers. We used instead a fixed correction, estimated as follows. We randomly selected one hundred 1 arcmin^2 fields from the Sloan Digital Sky Survey Data Release 7 (Abazajian et al. 2009), with a cut in r -band Petrosian magnitude of $r \leq 20.705$ to match our (converted) K-band limit of $M_K = -21.5$. We counted the number density of galaxies in each field, and took their mean. The result is $0.49 \pm 0.86 \text{ galaxies arcmin}^{-2}$, which we subtracted from our measurements of Σ_3 . For comparison, the minimum density found in our sample is $3.83 \text{ galaxies arcmin}^{-2}$.

This estimate does not take into account the presence of structures in the distribution of galaxies. A more accurate determination by Yasuda et al. (2001) gives a number density of 0.94 arcmin^{-2} , which is statistically compatible with our result.

In Fig. 3.5 we show f_{SR} plotted against $\log\Sigma_3$. Our results are shown by the red solid line, while those from the ATLAS^{3D} survey are in green. The core of the Virgo cluster, corresponding to the densest environment probed by the ATLAS^{3D} survey, has $f_{\text{SR}} = 0.25$. This value is double that typically found in less dense environments, where $f_{\text{SR}} \approx 0.12$.

We probe environments with $\log\Sigma_3$ between 2.06 and 3.75 (here Σ_3 is expressed in Mpc^{-2}). The minimum is comparable to the core of Virgo, while the maximum is 1.7 dex higher. In this respect, our study starts exactly where ATLAS^{3D} finished.

We find a sharp increase of f_{SR} with density, rising from $f_{\text{SR}} = 0.01$ in the least dense bin to $f_{\text{SR}} = 0.58$ in the densest environment. Comparing this result with the one of ATLAS^{3D}, we find that the least dense regions of Abell 1689 have a f_{SR} lower than that of the field/group environments. In the densest regions of Abell 1689 f_{SR} is much higher than in the core of Virgo.

The overall value of f_{SR} averaged on the whole sample is 0.15 ± 0.03 (red square in Fig. 3.5). This is the same value that we would measure for Virgo when sampled in the same way (green square in Fig. 3.5) and is in line with f_{SR} of field/group environments.

3.6 Bias discussion

In Fig. 3.6 we compare the LF of Abell 1689 (as determined from the GMOS r-band image, blue circles) to the LF of our sample (yellow squares). We also show the LF of the Virgo Cluster, as determined by the ATLAS^{3D} group and the LF of the RS. It is clear how our sample sees bright galaxies overrepresented with respect to faint ones. In addition, we do not probe the faint end of the LF. This means that our sample is not representative of the galaxy population of Abell 1689. Therefore, before drawing inferences from our results, we have to determine the effect of the sample selection.

3.6.1 Red Sequence bias

Our sample falls entirely on the RS of Abell 1689, even though we did not impose such constraint. This is a result of our selection criteria (we selected the galaxies with the highest surface brightness in the HST FOV) and the fact that the RS includes all such objects in the cluster core.

We know that the RS does not trace, in general, the ETGs population of a cluster of galaxies, because the correlation between colour and morphological type is strong but has some scatter. The RS includes red spirals and omits blue ellipticals.

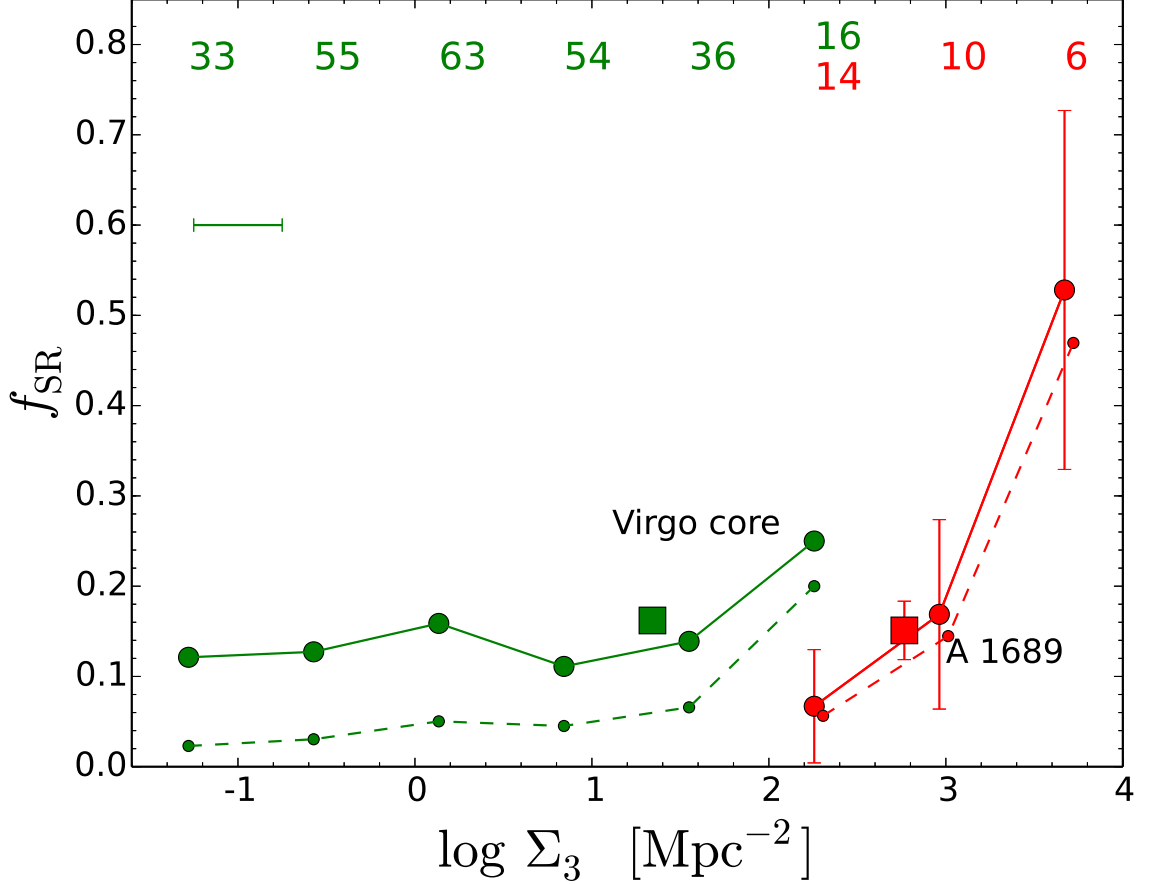


Figure 3.5: The fraction of SRs f_{SR} against the local environment density, expressed by $\log \Sigma_3$, where Σ_3 is in units of Mpc^{-2} . The red solid line and big circles represent the values measured from our sample of 30 galaxies in Abell 1689, while the green solid lines show the results from the ATLAS^{3D} survey (Cappellari et al. 2011b). The dashed lines show the fraction of SRs computed against the total number of galaxies, i.e. including LTGs. The green and red solid squares mark the average density and f_{SR} for the Virgo Cluster (from ATLAS^{3D}) and for Abell 1689. Uncertainties in f_{SR} derive from both classification errors (Section 3.4) and sampling uncertainties (Section 3.4), while the error bars in $\log \Sigma_3$ were estimated generating a random distribution of points of fiducial density equal to $\log \Sigma_3$, and then measuring the actual distribution of $\log \Sigma_3$ for 10000 random realisations. The solid lines represent f_{SR} measured against the total number of ETGs, while the dashed lines represent f_{SR} measured against the total number of galaxies. The solid squares denote f_{SR}

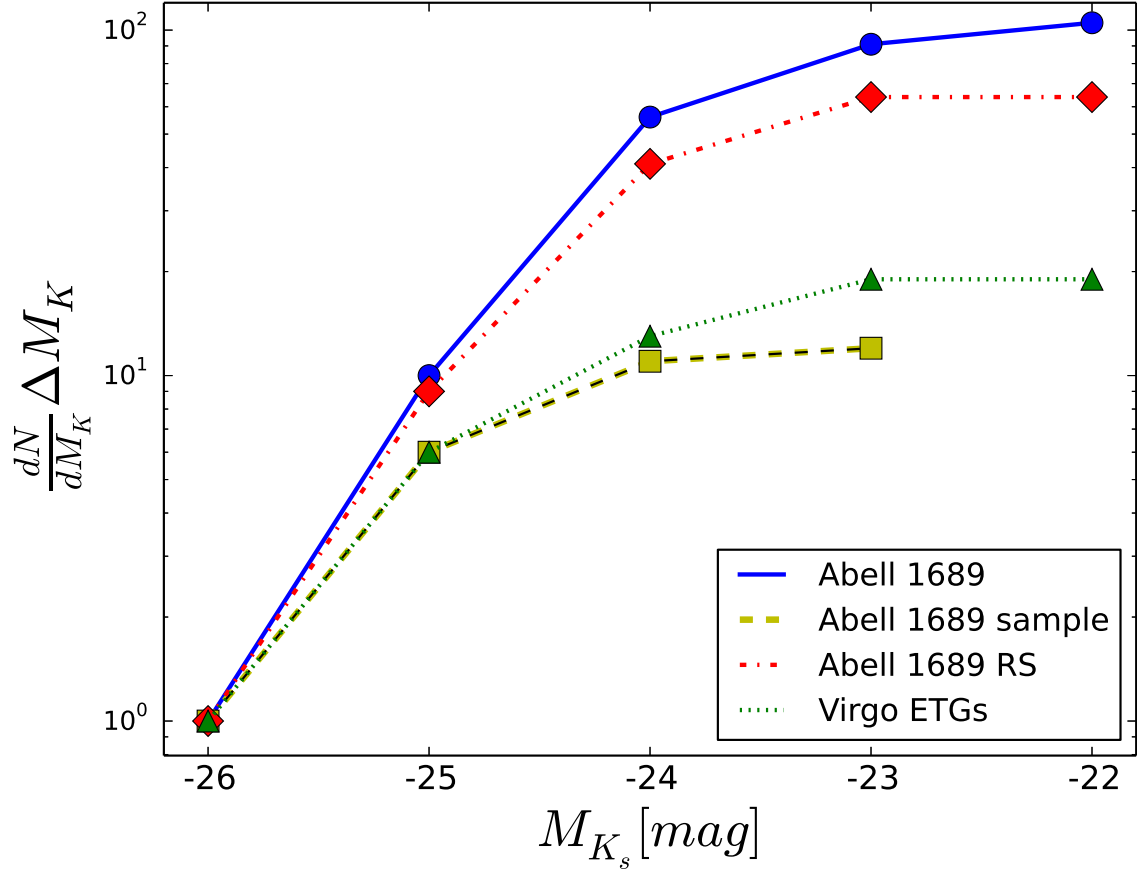


Figure 3.6: K-band LF of Abell 1689 (blue circles) and the Virgo cluster (green triangles, from Cappellari et al. 2011b). The yellow squares are the LF of the FLAMES/GIRAFFE sample of 30 galaxies in Abell 1689. The LF of the RS is also shown (red diamonds). The photometry for Abell 1689 is based on GMOS r' -band measurements. The conversion to K-band magnitudes is described in Section 2.7.1.

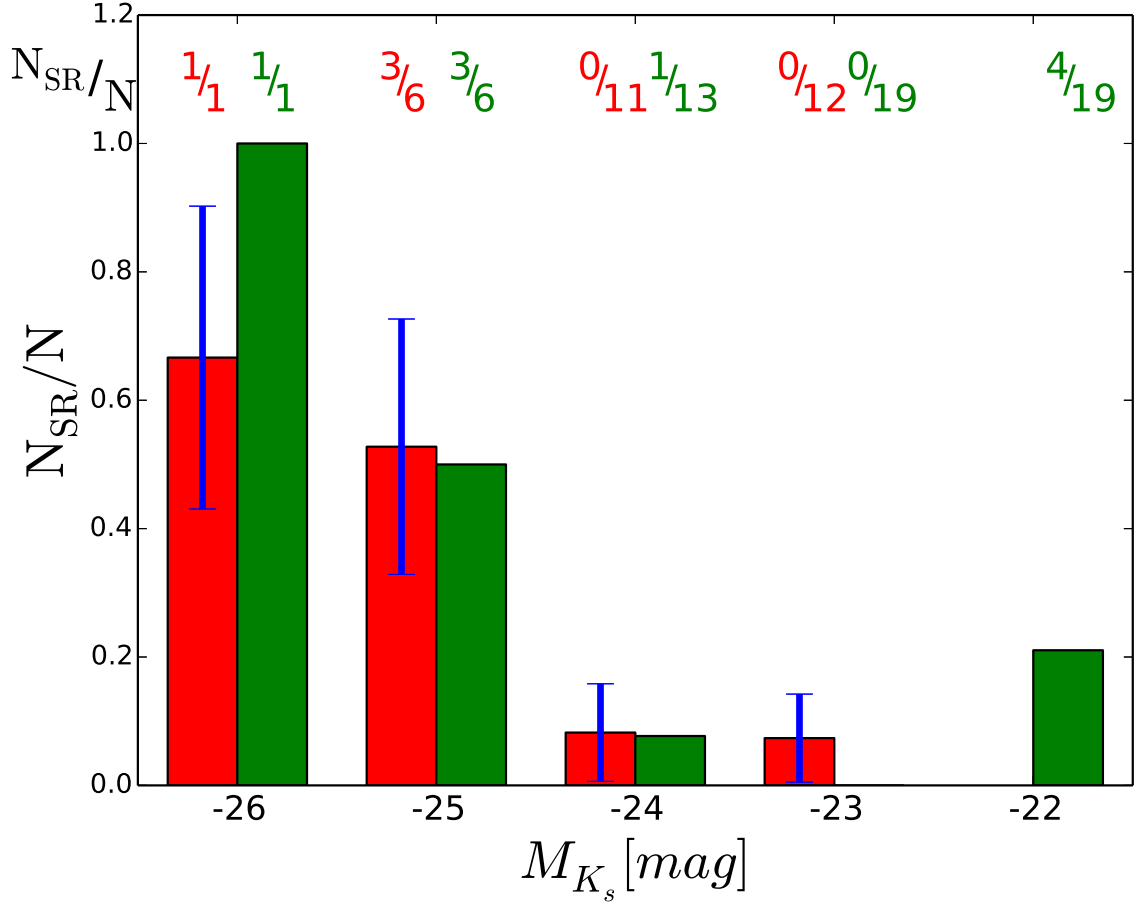


Figure 3.7: The fraction of SRs f_{SR} for the Abell 1689 sample (red histogram) and the Virgo ETGs population (green histogram, Cappellari et al. 2011b). The x-axis shows K-band magnitudes, based on converted r' -band measurements (Abell 1689) or on 2-MASS measurements (ATLAS^{3D}). The numbers at the top are the number of SRs and the number of galaxies in each bin. For Abell 1689 the number of SRs has been rounded off (Section 3.4).

Abell 1689 is a rich, relaxed cluster and comprises a very small fraction of spirals, particularly so in the core. We visually inspected the 30 galaxies in the sample, and found that there were no red spirals.

This leaves us with the question of how many ETGs lying off the RS have we left out. The ratio between the LF of the RS and the cluster LF goes from 1 at the bright end to 0.7 at $M_K = -22.5$ mag (Fig. 3.6). We estimated that in order to remove the RS bias, we have to include 10 “blue” ETGs.

These faint galaxies are more likely to be FRs (see Fig. 3.7, and Cappellari et al. 2011b). Therefore the colour bias leads us to overestimate f_{SR} . If we assume that these galaxies are all FRs, and that they are distributed spatially much like the observed targets, we can determine the k-T Σ relation for a colour “fair” sample (Fig. 3.5, smaller red dots and red dashed line).

The good overlap between the ETGs and RS populations in Abell 1689 causes f_{SR} to stay the same, whether the fraction is computed against the RS or the overall galaxy population. This is not true in a less relaxed, spiral rich cluster like Virgo, where f_{SR} changes considerably between the ETGs and overall populations (Fig. 3.5, solid and dashed green lines).

As a final remark, if we consider that blue galaxies tend to populate the least dense regions, the observed trend in f_{SR} with $\log \Sigma_3$ is even reinforced.

3.6.2 Magnitude selection

In Fig. 3.7 we show f_{SR} as a function of K-band magnitude. Our results are represented in red, while those from the ATLAS^{3D} study of Virgo are in green. f_{SR} is identical in the Virgo and Abell 1689 clusters, down to the faintest magnitude in our sample. However we know that the two clusters have different LFs, in that Abell 1689 is relatively richer in faint galaxies (Fig. 3.6). What bias does this introduce in the measured value of f_{SR} ? There is no independent evidence about the dependence of the LF of SRs with redshift or environment. Given the results shown in Fig. 3.7, we assume that f_{SR} as a function of M_K is the same for Virgo and Abell 1689.

We can conduct simulated observations of the Virgo cluster to assess how the particular sample selection affects the results. We further assume that the galaxies were selected based on their magnitudes only. Although this is not true for the FLAMES/GIRAFFE sample (see Section 2.3), it is still reasonable given the randomness introduced by the proximity constraint.

We drew 10000 random subsamples from the ATLAS^{3D} Virgo ETGs population based on the LF of the FLAMES/GIRAFFE sample, and measured f_{SR} for each of them. This yielded $f_{\text{SR}} = 0.16 \pm 0.01$, in agreement with the actual value of 0.16.

Despite being biased towards brighter galaxies, our sample still yields the true value of f_{SR} . This happens because, as we have seen, the distribution of f_{SR} with M_{K_s} in the Virgo Cluster has a peak both at the bright and faint end. Our magnitude cut happens to be in the region of the diagram where SRs are least common, and $f_{\text{SR}} \approx 0.15$ both above and below the cut (Fig. 3.5).

3.6.3 Other factors

In Section 3.5 we worked under the implicit assumption that Abell 1689 is spherical. However there are indications that this is not the case, and that the cluster is in fact elongated along the line of sight (Oguri et al. 2005; Corless et al. 2009). Therefore the measured Σ_3 is higher than what we would measure from any other point of view.

If the cluster length along the line-of-sight direction were γ times longer than the diameter of the sky projection, then the measured value of Σ_3 would be $\approx \gamma$ times the unbiased value. Since the maximum reasonable value is $\gamma \approx 3$, the values of $\log \Sigma_3$ in Fig. 3.5 are overestimated by at most ≈ 0.5 dex, which does not affect significantly our results.

In Section 3.3 we applied a correction to $\lambda(IFU)$: had we applied no correction, we would have had 3.8 ± 1.0 SRs, so an even lower value of f_{SR} .

Finally, we remark that the distribution of projected ellipticities ϵ_e of our sample is different from that observed in the Virgo cluster. Since SRs are generally rounder (Emsellem et al. 2011), our sample can be biased towards higher values of f_{SR} .

This observation prompted us into investigating the distribution of projected ellipticities of the parent populations, a matter that is the subject of the following chapters.

3.7 Discussion

Our work represents the first attempt to classify SRs and FRs beyond the local Universe. We have established that - within the magnitude cut adopted - the LF of SRs in Abell 1689 is the same as observed locally (Section 3.4). f_{SR} increases with

K-band luminosity (and therefore mass). SRs comprise half the ETGs population at $M_K \approx -25$, and virtually all galaxies with $M_K \leq -26$ (Fig. 3.7).

By relating f_{SR} with the environment, we demonstrated that SRs are on average as common in Abell 1689 as they are in the environments probed by the ATLAS^{3D} survey. However, when breaking down f_{SR} according to the local environment density, we find that f_{SR} increases with the projected number density of galaxies Σ_3 , going from ≈ 0.1 to ≈ 0.5 (Fig. 3.5). When compared to the average value of f_{SR} , the least dense regions (which trace the outer regions of our sample) are depleted of SRs, while the densest regions (corresponding to the cluster core) are enhanced.

The picture that emerges is that of some sort of segregation of SRs in the core of Abell 1689, a view that is confirmed by observations of the Virgo Cluster in the ATLAS^{3D} survey (Cappellari et al. 2011b) and of the Coma Cluster (Houghton et al. 2013).

It remains to be established whether SRs form preferentially in the centre of clusters or if they gather there due to secular evolution of the host cluster.

The first hypothesis fails to explain why on average f_{SR} is the same across a large variety of environments: if we accept that more SRs form in the core of clusters and less form in the outer regions, it is difficult to explain why the overall fraction would be the same in the completely different environment represented by the field.

If we instead invoke secular evolution, we have to determine what process generates the observed segregation when compared to FRs. Dynamical friction (invoked by e.g. Cappellari et al. 2011b) has been ruled out by Scott et al. (2014), who used a mass-matched sample of SRs and FRs in the Virgo Cluster to show that the two have different spatial distributions.

Numerical simulations suggest that SRs are not the outcome of major dry mergers alone. In this case, the orbital angular momentum of the parent galaxies is retained in the final configuration; the resulting products include a fraction of prolate SRs which is ruled out by the ATLAS^{3D} survey (Bois et al. 2011).

Khochfar et al. (2011) uses semi-analytical models to trace the mass assembly history of SRs and FRs. They find that SRs accrete between 50% and 90% of their mass through minor mergers, which tend to destroy pre-existing discs and to lower the overall angular momentum. The conditions for this to occur are most favourable in the centre of deep DM potential wells, therefore SRs are expected to be associated with extended DM haloes. If this were the case, the effective mass for dynamical

friction would be significantly higher than the values adopted in Scott et al. (2014).

The data presented in this work is insufficient to disentangle the scenarios proposed. Future observations should focus on dynamically old groups and clusters, where any secular process would have proceeded even further than in the available samples.

Chapter 4

Ellipticity of ETGs

The SAURON survey introduced the concepts of FRs and SRs. This is a physical subdivision of ETGs, one that is almost completely robust to observational accidents (viz. inclination, see Section 1.4). Although they are very different in their kinematics, FRs and SRs have comparatively similar projected shapes (Krajnović et al. 2006). This means that - in general - they cannot be separated without the help of IFS. Since this type of observation is time consuming, it is desirable to investigate the viability of alternative tools. In addition, the boundary between FRs and SRs crosses that between the traditional morphological classes of Es and S0s. It is therefore necessary to review our previous knowledge in light of the new results that IFS made possible.

We know that FRs are roughly oblate spheroids, spanning the full range of ϵ of ETGs, while SRs are intrinsically rounder and have $\epsilon < 0.4$ (Emsellem et al. 2007). Here we propose to study the ϵ distribution of cluster ETGs. We start explaining and justifying our definition of ϵ (Section 4.1). We then introduce the sample of cluster of galaxies (Section 4.2), which is divided in a local (Section 4.3) and non-local (Section 4.4) subsample. The results are presented instead in the following chapter.

4.1 Projected ellipticity ϵ

Since - to first order - most ETGs are smooth and featureless, their shape is measured by the projected ellipticity ϵ . This can be done in three ways:

- measuring the axis ratio of a specified isophote (Equation 1.10)
- computing the second moments of x and y

- fitting a model to the data, and using the model ϵ

The first method involves an arbitrary choice of the isophote to be fitted. In practice however the other methods also employ some sort of truncation, because even though at sufficiently large radii the light contribution from the galaxy becomes negligible, the same is not true for the sky noise (and for the light from other objects). In principle methods 1 and 2 measure the same thing, however it is common to compute second order moments weighted with some function (e.g. the measured flux). Depending on the exact nature of the weight functions, the method of moments is sensitive to the shape of different regions of the galaxy.

In Chapter 2 we have used the method of moments, following the recommendation of Emsellem et al. (2007). However the galaxies in the **SAURON** and **ATLAS^{3D}** samples are mostly isolated objects, with the highest density attained in the core of the Virgo cluster. In order to avoid the additional complications found in dense environments (Section 2.7.2), in this chapter we decided to resort to the third method. This gives two advantages over the other methods. Firstly, model fitting allows for simultaneous fit of overlapping galaxies. Moreover, it is possible to take into account the effect of the PSF.

4.2 Cluster selection

We conducted a preliminary analysis of the ϵ distribution of two cluster of galaxies. In our pilot project we selected Abell 1689 and Abell 1656 (the Coma Cluster) because we already had the necessary photometric data. In particular, we used Gemini/GMOS and HST/ACS photometry for Abell 1689 (see Chapter 2) and SDSS DR7 data for the Coma Cluster (Abazajian et al. 2009).

We then expanded our sample to include clusters at redshift comparable with Coma ($z=0.023$) and Abell 1689 ($z=0.183$) respectively. It follows that our sample of galaxy clusters consists of two parts. The first one spans the redshift range $0 \leq z \leq 0.1$, and relies on SDSS DR10 photometry (Ahn et al. 2013). We refer to this subsample as the local sample. For the second half, covering $z \approx 0.2$, SDSS does not have sufficient spatial resolution, and we resorted to HST/ACS data. We call this subsample the non-local sample.

Since the two sets use different data, we treat them separately in the remainder of this chapter.

4.3 The local sample

The local sample of clusters was based on the catalogue of Rich Clusters of Galaxies (Abell et al. 1989), which included more systems at lower redshifts ($z \lesssim 0.04$) than any other work. We selected all clusters with available SDSS photometry, and further requested richness $R \geq 2$, as the subset of rich clusters is less likely to suffer from incompleteness issues. We discarded the ones which had no redshift measurements available, or which had $z > 0.10$. The resulting subset contains 23 entries (Table 4.1) (See Section A for SDSS images).

We queried the SDSS DR10 database to retrieve all the galaxies within a projected distance of 1.5 Mpc from the cluster coordinates, and down to a magnitude limit of $M_r = -18.0$ mag. The magnitude cut was chosen as the best compromise between sample size and reliability of the photometry. We found that a more generous cut in magnitude increased the sample size but also the scatter in the RS, which is undesirable. The conversion between physical and observed quantities has been done using the available redshifts, and ignoring any effect of the unknown cluster peculiar velocity as well as the K-correction.

We excluded all objects with a radius $deV Rad^1 \leq 0.3''$ (corresponding to 0.5 kpc at $z = 0.1$). We also rejected all objects with errors on *modelMag* and *fiberMag* greater than 0.2 and 0.3 mag respectively. These constraints filter out both artifacts and measurements affected by bad photometry.

4.3.1 Data analysis

4.3.2 Red Sequence selection

Since the galaxies in our sample do not have, in general, reliable redshift measurements, we resort to a colour selection to assess the membership. We constructed the CMD for each cluster, using $g - r$ aperture colours (*fiberMag*) and r -band total magnitudes (*modelMag_r*).

From the parent population we excluded all galaxies with $g - r \notin [0.0, 2.5]$, and with errors in colour greater than 0.1. These constraints ensure that outliers, artifacts or measurements affected by large errors do not affect the results.

We used the Gaussian mixture model of Houghton et al. (2012) to identify the RS. The algorithm fits two superimposed Gaussian models: one for the RS population,

¹We denote in italics the columns of the tables in the SDSS database.

Table 4.1: The local sample of clusters. [After Abell et al. (1989), unless otherwise specified.]

ACO	RA	DEC	z	r	R	B-M	kT	L_X
(1)	(J2000) (2)	(J2000) (3)	(4)	(mag) (5)	(arcsec) (6)	(7)	(keV) (8)	(10 ⁴⁴ erg/s) (9)
16*	0:16:46.30	6:44:39.84	0.084	19.88	16.09	III	-	-
168*	1:15:9.79	0:14:50.64	0.045	18.48	28.52	II-III	2.60	1.09
736*	9:3:10.56	52:12:7.19	0.062	19.19	21.23	III	-	-
1035	10:32:7.20	40:12:33.12	0.080	19.77	16.80	II-III	3.60	1.51
1186	11:13:51.36	75:23:39.84	0.079	19.75	16.95	II-III	-	-
1190	11:11:46.32	40:50:41.28	0.079	19.75	16.89	II	3.60	1.48
1367	11:44:29.52	19:50:20.40	0.021	16.83	58.29	II-III	3.50	1.63
1399*	11:51:9.60	-3:5:41.28	0.091	20.08	14.89	III	-	-
1650	12:58:46.32	-1:45:10.80	0.085	19.90	15.97	I-II	5.50	7.81
1656	12:59:48.72	27:58:50.52	0.023	16.99	54.13	II	8.00	7.21
1775	13:41:55.68	26:21:53.28	0.072	19.54	18.38	I	4.90	2.90
1795	13:49:0.48	26:35:6.72	0.062	19.20	21.14	I	5.10	11.12
1904	14:22:7.92	48:33:22.32	0.071	19.49	18.76	II-III	-	-
2029	15:10:58.80	5:45:42.12	0.077	19.68	17.43	I	7.80	15.35
2065	15:22:42.72	27:43:21.36	0.072	19.54	18.40	III	8.40	4.95
2142	15:58:16.08	27:13:28.56	0.090	20.04	15.10	II	11.00	20.74
2151	16:5:14.88	17:44:54.60	0.037	18.04	34.41	III	3.50	0.87
2198*	16:28:4.80	43:49:25.68	0.080	19.77	16.81	III	-	-
2199	16:28:36.96	39:31:27.48	0.030	17.59	41.80	I	4.70	3.65
2244	17:2:43.92	34:2:48.48	0.099	20.27	13.82	I-II	7.10	9.09
2255	17:12:30.96	64:5:33.36	0.081	19.80	16.61	II-III	7.30	4.79
2256	17:3:43.44	78:43:2.63	0.060	19.12	21.82	II-III	7.50	7.05
2670	23:54:10.08	-10:24:18.00	0.076	19.66	17.56	I-II	3.90	2.55

Column (1): cluster ID. Clusters marked with an * have been discarded from the analysis, because of an unreliable/undetectable RS. Column (2): right ascension in degrees and decimal. Column (3): declination in degrees and decimal. Column (4): cluster redshift from Ebeling et al. (1996), or from Abell et al. (1989) when available. Column (5): magnitude cut adopted, SDSS *r*-band. Column (6): cut in the projected distance, corresponding to 1.5 Mpc. Column (7): Bautz-Morgan class. Column (8): X-ray temperature, when available (Ebeling et al. 1996) Column (9): X-ray temperature, when available (Ebeling et al. 1996)

the other for the underlying galaxy background (and foreground). The mean $g - r$ of the RS Gaussian is allowed to vary linearly with the magnitude r , while the amplitude and dispersion are constant with r . For the background Gaussian, all parameters are independent of r .

The algorithm returns the slope m and intercept c of the RS (mean of the RS Gaussian), as well as its scatter Δ (standard deviation of the RS Gaussian). In addition, for each galaxy on the CMD the algorithm gives also the probability p that it belongs to either the RS or the background, and we define galaxies with $p > 0.5$ as members of the RS.

After fitting the RS of all the 23 clusters, the average results are:

$$\begin{aligned}\langle m \rangle &= -0.036 \pm 0.005 \\ \langle \Delta \rangle &= 0.035 \pm 0.007\end{aligned}\tag{4.1}$$

In Fig. 4.1 we show the results for six clusters. The upper four panels are examples of reliable algorithm results, where m and Δ are close to the average values $\langle m \rangle$ and $\langle \Delta \rangle$. In the bottom two panels we show two examples of clusters that were discarded based on the RS selection. In the bottom right panel is Abell 2198, where no RS was identified. In the bottom left panel we show the CMD of Abell 16, where the algorithm converged but the result is unreliable, as the RS is too different from the average results. (See Fig. B.1 for the results of the whole sample of local clusters).

Changing the initial parameters, or the selection criteria on the parent population does not change the results on the bad fits. This may happen either because the cluster's RS is too weak, viz. the colour of most galaxies is still dominated by comparatively young stars, or because the superposition of two Gaussian populations is insufficient to describe the CMD, for example because there is heavy contamination from foreground/background structures.

4.3.3 Reliability of the RS

We base our analysis on the assumption that all RS galaxies are cluster members. For this reason, we have to reject from our sample clusters Abell 2198 and Abell 16 (Fig. 4.1), as well as Abell 736, Abell 168 and Abell 1399. In practice we reject all clusters whose RS parameters m and Δ do not lie within 3σ of the respective sample statistics (Equation 4.1).

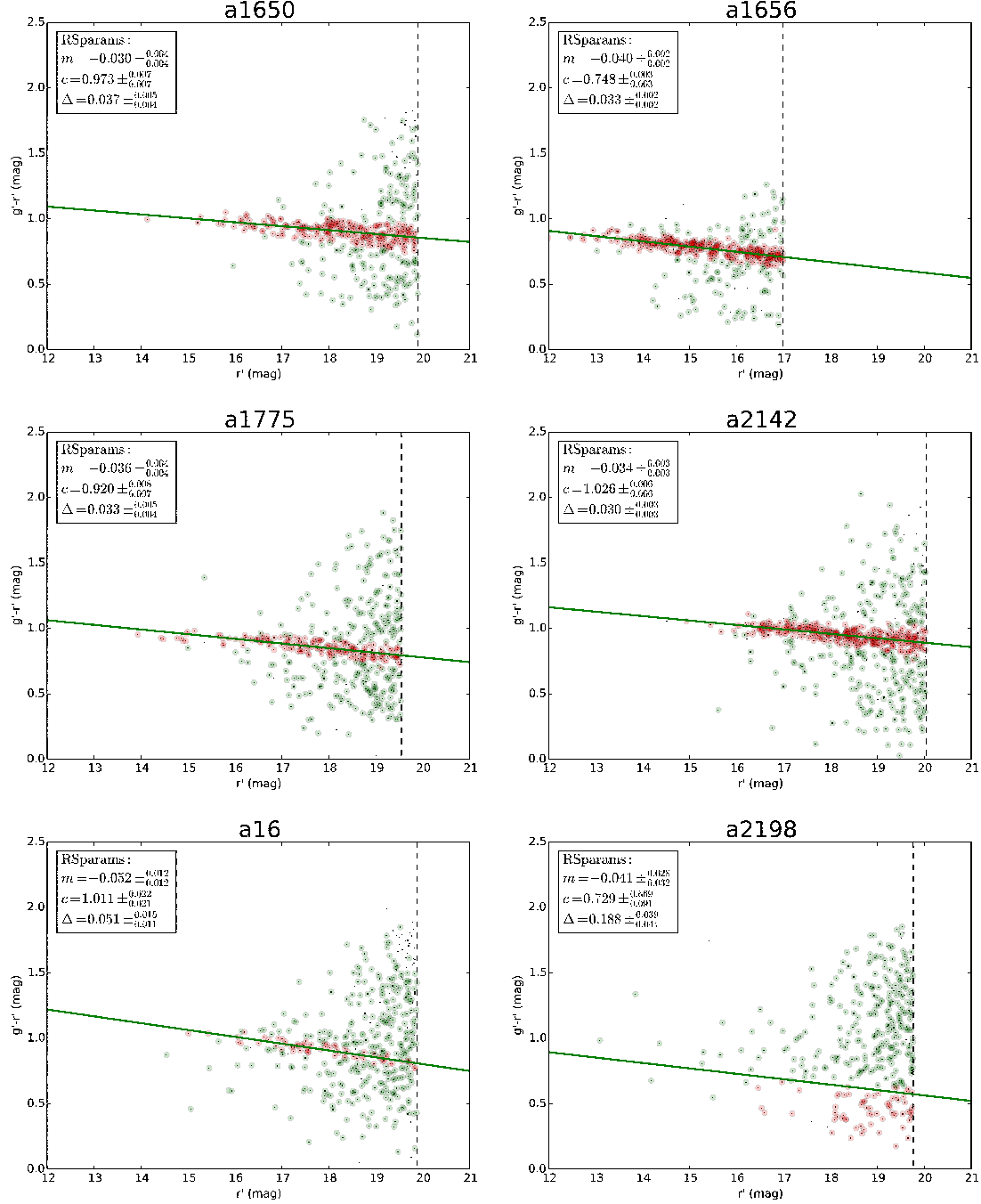


Figure 4.1: CMD for six clusters in the local sample. Galaxies are marked with black dots. Galaxies circled in red are RS members, while galaxies circled in green are non RS galaxies. Galaxies that are not circled have been ignored by the algorithm because of large uncertainties or because they fall in regions below the magnitude cut. The upper four panel show examples of good detections of the RS. The two bottom panels show a questionable detection (left) and an incorrect detection (right) of the RS.

In order to assess the reliability of our analysis, it is important to estimate the level of contamination of our parent samples. This is the fractional number of interloping objects lying inside the circular aperture of 1.5 Mpc used to retrieve the samples.

We selected a new sample of galaxies from Abell 1650, Abell 1656 and Abell 2142. We used the same selection criteria of the original samples, but we added the constraint that all galaxy entries have a redshift measurement available in NED.

We matched these new samples to the original ones, and assigned cluster membership by using a cut in redshift, imposing that $4\sigma/(cz_{\text{cluster}}) \leq 1$ (The velocity dispersions of Abell 1650, Abell 1656 and Abell 2142 are taken from Pimbblet et al. 2006; Price et al. 2011; Struble and Rood 1999, respectively). The fraction of interlopers in the RS is 0.20 for Abell 1650, 0.04 for Abell 1656 and 0.11 for Abell 2142. In the Blue Cloud (BC, defined as the set of galaxies below the RS) the fraction of interlopers rises to 0.33, 0.09 and 0.37 respectively. It is worth noticing that the higher value found in Abell 1650 is explained by the presence of another structure along the LOS, at a different but similar redshift of ≈ 0.12 .

Next we proceeded to assess the effect of the interlopers on the RS. For each of the three clusters we considered only spectroscopically confirmed members, and determined again the RS. Within the errors, the new values of m and Δ are identical to the previous ones.

4.4 The non-local sample

For the non local sample of clusters we relied on the archival data taken as part of CLASH survey (Postman et al. 2012). It consists of multi-band HST/ACS HST/WFC images of 25 cluster of galaxies, in the redshift range $0.18 < z < 0.89$. According to the selection criteria specified in Section 4.2, we selected all the clusters with redshift $z < 0.25$. The redshift cut was chosen to avoid the possible effect of evolution on the galaxy population. Our initial sample consists of the five clusters Abell 209, Abell 383, Abell 1423, Abell 2261 and RXJ2129.7+0005 (Table 4.2).

4.4.1 Data analysis

Our previous experience on the galaxies in Abell 1689 (Chapter 3) demonstrated that the presence of a close neighbour can affect the measured photometric properties. Since all the clusters in the non-local sample comprise several instances of galaxies with overlapping light profiles, we had to take this into account.

Table 4.2: The non-local sample of clusters. [After Postman et al. (2012)]

Name	RA (J2000)	DEC (J2000)	z	kT (keV)	L _{Bol} (10^{44}erg/s)
Abell 209	01:31:52.57	-13:36:38.8	0.206	7.3 ± 0.54	12.7 ± 0.3
Abell 383	02:48:03.36	-03:31:44.7	0.187	6.5 ± 0.24	6.7 ± 0.2
Abell 1423	11:57:17.26	+33:36:37.4	0.213	7.1 ± 0.65	7.8 ± 0.2
Abell 2261	17:22:27.25	+32:07:58.6	0.224	7.6 ± 0.30	18.0 ± 0.2
RXJ2129.7+0005	21:29:39.94	+00:05:18.8	0.234	5.8 ± 0.40	11.4 ± 2.0

GALAPAGOS, Galaxy Analysis over Large Areas: Parameters Assessment by GALFITting Objects from SExtractor, is a software that conducts automatic source detection and modelling for multiple images simultaneously (Barden et al. 2012).

GALAPAGOS uses SExtractor to detect sources, and uses GALFIT to perform a two dimensional Sersic fit. The results are then combined into an output catalogue. Crucially for our purposes, GALFIT includes PSF convolution and simultaneous fitting of neighbouring galaxies. It represents the best software available in this respect (Häussler et al. 2007).

We used all the available ACS bands to perform the fit, however ϵ is held constant across all wavelengths. In addition, we always fit a single Sérsic profile, rather than including multiple components.

Each cluster typically takes 240 hours computation time on the available machine, but we had to manually abort the fit for a few (≈ 10) galaxies, with prohibitively large fitting times. This happens when the object has $\gtrsim 15$ neighbours. In addition we ran out of time and were not able to finish our work on RXJ2129.7+0005, which is therefore excluded from any further consideration.

4.4.2 RS selection

For the clusters in the non-local sample the CMD was constructed using aperture colours from SExtractor and GALFIT total magnitudes taken from GALAPAGOS. The bands used are F475W and F625W. From the parent population we excluded all galaxies with colour $F475W - F625W \notin [0.0, 2.5]$, and with errors in colour greater than 0.1.

We used the same algorithm of Section 4.3.2. Results are plotted in Fig. 4.2.

After fitting the RS of all the 4 clusters, the average results are $\langle m \rangle = -0.025 \pm 0.006$, and $\langle \Delta \rangle = 0.064 \pm 0.011$. By inspecting the CMD and the RS fit for Abell

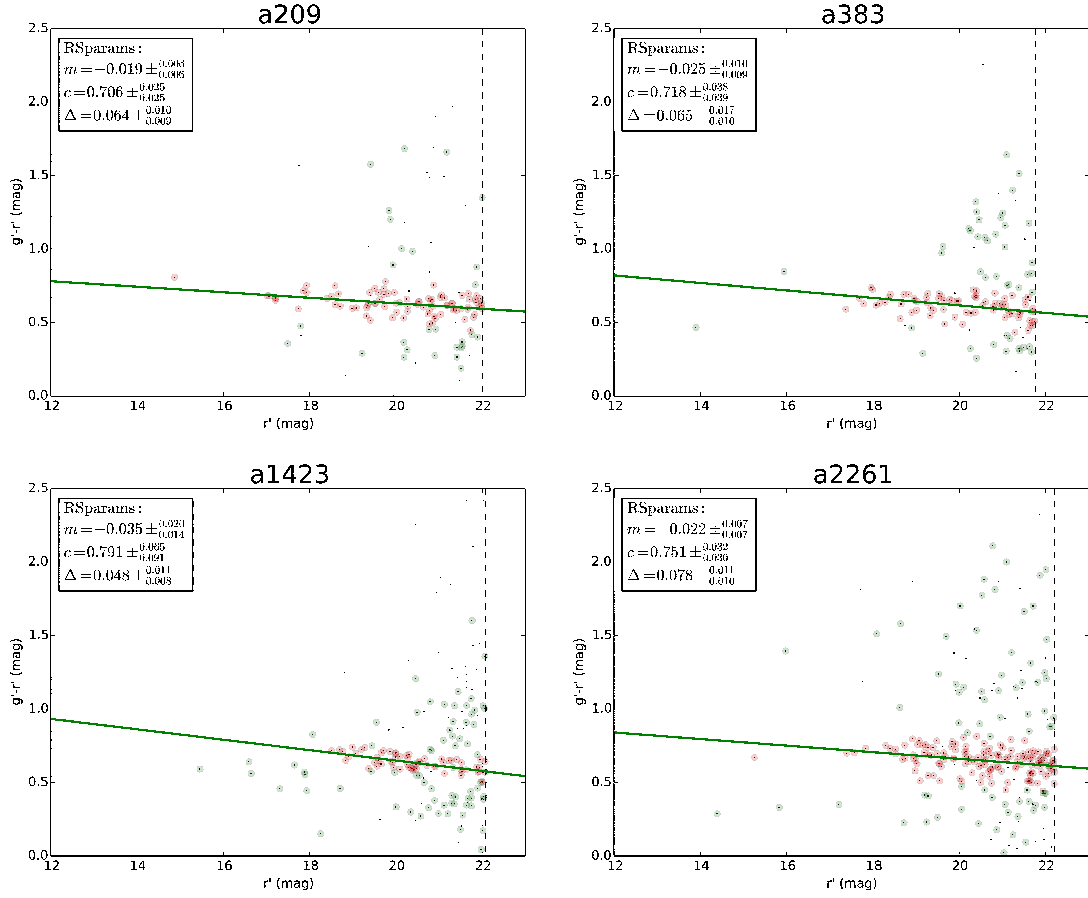


Figure 4.2: CMD for the four clusters in the non local sample. Galaxies are marked with black dots. Galaxies circled in red are RS members, while galaxies circled in green are non RS galaxies. Galaxies that are not circled have been ignored by the algorithm because of large uncertainties or because they fall in regions of no interest of the CMD.

1423, we notice that the results of the fit are unreliable, in that the RS determined by the algorithm does not include the brightest galaxies (Fig. 4.2) Excluding that cluster, the results become $\langle m \rangle = -0.022 \pm 0.002$, and $\langle \Delta \rangle = 0.069 \pm 0.006$, and the values of m and Δ for Abell 1423 are more than 3 standard deviations away from the mean. Rejecting the minimum and maximum values of m and Δ and recomputing the mean and standard deviation, we find the same result, namely that the fit for Abell 1423 is more than 3 standard deviations away from the mean values. The reason for this discrepancy remains unclear. A possible explanation is that the brightest galaxies, including the cD galaxy, are considerably bluer than the attendend value from the extrapolation of the faint end RS. We therefore exclude this cluster from future considerations.

Chapter 5

Ellipticity of ETGs: Results

5.1 Local sample of clusters

5.1.1 ϵ distribution

We constructed a reference galaxy population as the union of all the galaxies from all the clusters in the local sample. In the left panel of Fig. 5.1 we plot the ϵ distribution of this reference population (green histogram), alongside the distributions of the RS (in red) and the BC (in blue). Each histogram has been normalized so that:

$$\int_0^1 n(\epsilon) d\epsilon = 1 \quad (5.1)$$

For the parent distribution we find an average ellipticity $\langle\epsilon\rangle$ and standard deviation σ_ϵ of 0.40 and 0.22 respectively. For the RS we find $\langle\epsilon\rangle = 0.35$ and $\sigma_\epsilon = 0.23$ while the values for the BC are $\langle\epsilon\rangle = 0.43$ and $\sigma_\epsilon = 0.23$.

As we have seen, different morphological and kinematic classes have different intrinsic shapes. In principle, different morphological fractions can be reflected in different ϵ distributions. We therefore used a Kolmogorov-Smirnoff (KS) test to check the null hypothesis that any cluster has the same ϵ distribution as the reference one. The results are summarized in Table 5.1, where for each cluster we report the probability that its overall ϵ distribution is the same as the reference population (left column) and the probability that the ϵ distribution of a cluster's RS is the same as the ϵ distribution of all the clusters RSs (right column). Probability values less than 0.05 are highlighted in red, while values between 0.05 and 0.10 are highlighted in orange. Two clusters, Abell 1367 and Abell 1656, have a different overall ϵ distribution than the reference population. For the RS, it is Abell 1656 and Abell 2142 who are incompatible with the reference distribution's RS.

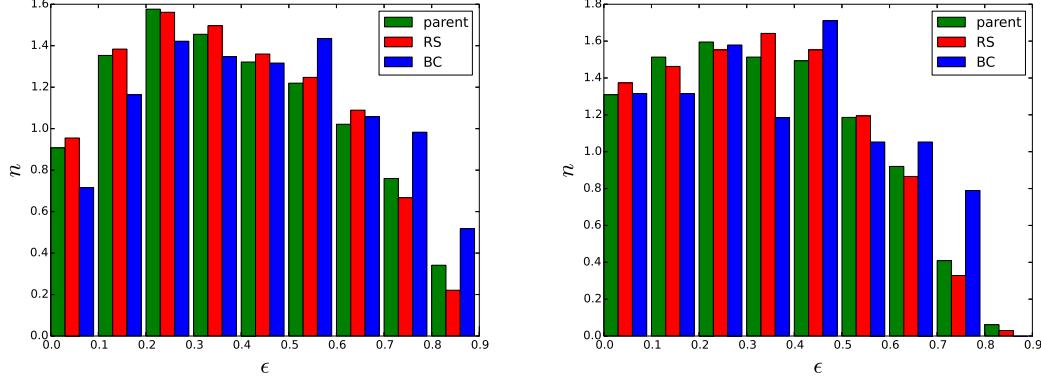


Figure 5.1: Left: ϵ distribution for the reference galaxy population of the local sample. n is the relative number of objects, normalized as in Equation (5.1). The reference population comprises galaxies from all the clusters in the local sample, and is depicted in green. The RS and the BC are denoted in red and blue respectively. Right: ϵ distribution of Abell 1656, with the same colour conventions.

If we suppose that the distributions are equal, then the KS test is expected to give a probability of p in a fraction p of the tests. Therefore, if one draws N samples from a population, the KS test is expected to return a probability of $p = 0.01$ in 1% of the samples. If N is large enough, a number of the tests can be expected to fail. Since our sample of cluster has 18 members, if all the distributions were the same, we would expect $18 \times 0.10 \approx 2$ clusters to have p value of 0.10 or less, $18 \times 0.01 \approx 0$ clusters to have p of 0.01 and so on. Since more than one cluster has $p = 0.01$ or less, the differences highlighted by the KS test are statistically significant.

When compared with the reference population, Abell 1656 is deficient in the most flattened objects ($\epsilon \approx 0.9$, Fig. 5.1, right panel). It is worth noticing that Abell 1367 and Abell 1656 have an overall average ellipticity $\langle \epsilon \rangle = 0.35$, the lowest for any cluster in the sample. All the other clusters have $\langle \epsilon \rangle \approx 0.4$. A possible explanation is that the difference arises from the fact that Abell 1367 and Abell 1656 have the lowest redshift in the local sample. Since the volume of the cone with base radius 1.5 Mpc increases linearly with the distance, and since the cut in the apparent magnitude also increases, these two clusters might have the lowest fraction of interlopers. For Abell 2142 the discrepancy remains unexplained.

Only three out of 23 clusters exhibit significant differences from the reference sample. We therefore conclude that there is only marginal evidence of incompatibility between the ϵ distribution of different clusters.

	Parent	RS
Abell 1035	0.204	0.597
Abell 1186	0.713	0.217
Abell 1190	0.693	0.186
Abell 1367	0.000	0.060
Abell 1650	0.258	0.736
Abell 1656	0.001	0.010
Abell 1775	0.681	0.454
Abell 1795	0.214	0.059
Abell 1904	0.809	0.078
Abell 2029	0.180	0.685
Abell 2065	0.420	0.726
Abell 2142	0.662	0.016
Abell 2151	0.600	0.485
Abell 2199	0.136	0.275
Abell 2244	0.067	0.416
Abell 2255	0.165	0.117
Abell 2256	0.208	0.512
Abell 2670	0.624	0.798

Table 5.1: Kolmogorov-Smirnoff test results for the ϵ distribution of the galaxies of the local sample. For each cluster we tested the null hypothesis that its ϵ distribution is the same as the ϵ distribution of the whole galaxy population, obtained adding up the galaxies from all clusters. The probabilities that the null hypothesis is true are reported in the left column. The test has been repeated for the galaxies in the RS (right column). We highlighted in red the tests rejected with confidence less than 0.05. Values between 0.05 and 0.10 are highlighted in orange.

5.1.2 $\langle \epsilon \rangle$ and environment

We now focus on trends within each cluster, as opposed to comparing the clusters to one another. For each cluster, we divided the galaxies in ten bins according to their cluster centric distance d . The bins were equally spaced in $\log d$, between $\log d = 1$ and $\log d = 3.5$. In Fig. 5.2 we plot $\langle \epsilon \rangle$ as a function of $\log d$ for the reference galaxy population of the local sample (top left), as well as other clusters that are considered representative. For each bin we plot the average ϵ of all the galaxies in that bin (empty bins are not plotted). The green diamonds show the results for the whole galaxy population in each cluster, while the red circles and blue crosses represent the RS and BC respectively. Error bars are an estimate computed assuming a flat distribution in ϵ between 0.0 and 1.0, which has a standard deviation $\sigma = 1/\sqrt{12}$. We further divided σ by the square root number of galaxies at each point in $\log d$. Since the real ϵ distribution is hardly flat (Fig. 5.1), this is a conservative estimate. The green, red and blue lines are a least squares linear fit to the data. The value of the slope is written in the lower left box, with the relevant error.

For most of the clusters in the local sample, the $\langle \epsilon \rangle$ of the RS increases with $\log d$. This trend is most pronounced in Abell 1650, Abell 1656, Abell 1775, Abell 2255 and Abell 2256, all of which have a slope that is more than 3 standard deviations away from 0. Only one cluster shows a decreasing trend of $\langle \epsilon \rangle$ with $\log d$, but the slope of the best fit relation is compatible with a flat trend. The BC does not show any general trend: there are examples of flat, decreasing and increasing with $\log d$, but in general the slope is compatible with 0 within 3 standard deviations. Two exceptions are represented by the BCs of Abell 1367 and Abell 2151, both of which show an increasing trend with $\log d$.

The parent population tends to mirror the trend of the RS. This is a consequence of the fact that at the adopted magnitude cut, typically $\gtrsim 50\%$ of the galaxies within the area sampled fall on the RS. In Fig. C.1 we report the results for all the local clusters with an accurate RS determination.

We repeated the same analysis using $\log \Sigma_3$ in place of $\log d$. Again we observe a general trend, where $\langle \epsilon \rangle$ of the RS decreases with increasing $\log \Sigma_3$ (Fig. 5.3). A linear fit reveals that only two clusters, Abell 1650 and Abell 1656, have a trend that is more than 3 standard deviations away from a flat line. In this sense we are unable to disentangle the effect of the LPE ($\log \Sigma_3$) from those of the GHE ($\log d$), but the trend is strong with GHE. The results for all the local clusters with an accurate RS determination are plotted in Fig. C.2.

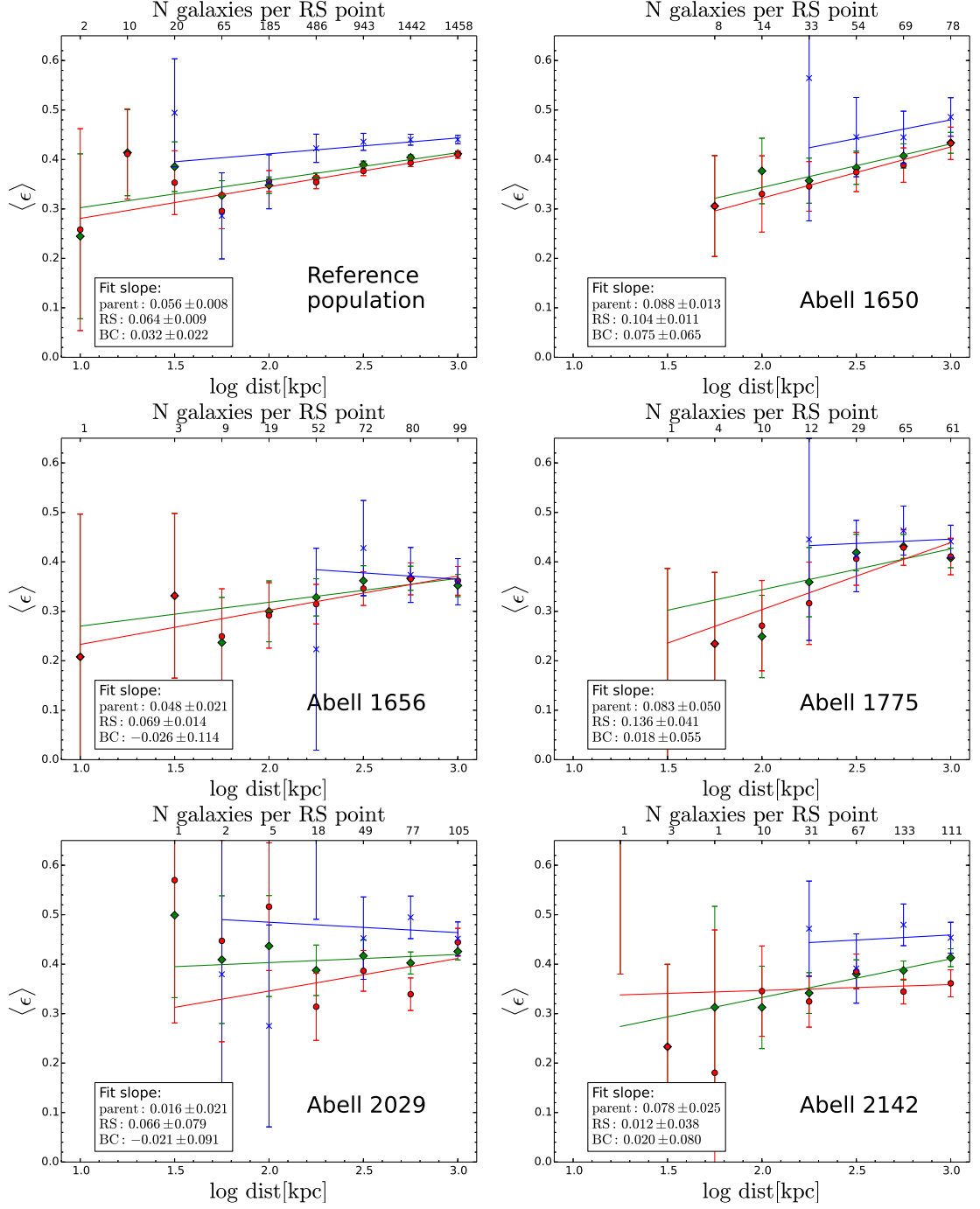


Figure 5.2: $\langle \epsilon \rangle$, the average ϵ of the galaxies as a function of $\log d$, where d is the distance to the cluster centre in kpc. The top left plot (labeled “Reference”) shows the reference population for the local sample, while the remaining plots show a selection of the clusters in the local sample. The green diamonds refer to the parent galaxy population, the red dots are the RS and the blue crosses are the BC. The lines are a linear fit to the data. The slope of the fit and its standard deviation is reported for each plot in the bottom left box. For most clusters $\langle \epsilon \rangle$ decreases towards the cluster centre. There are five cases (including Abell 1650, Abell 1656 and Abell 1775) where the slope of the best fit line for the RS is more than three standard deviations away from 0. Conversely, there are clusters where the slope is less than a standard deviation from 0 (Abell 2029 and Abell 2142 are shown).

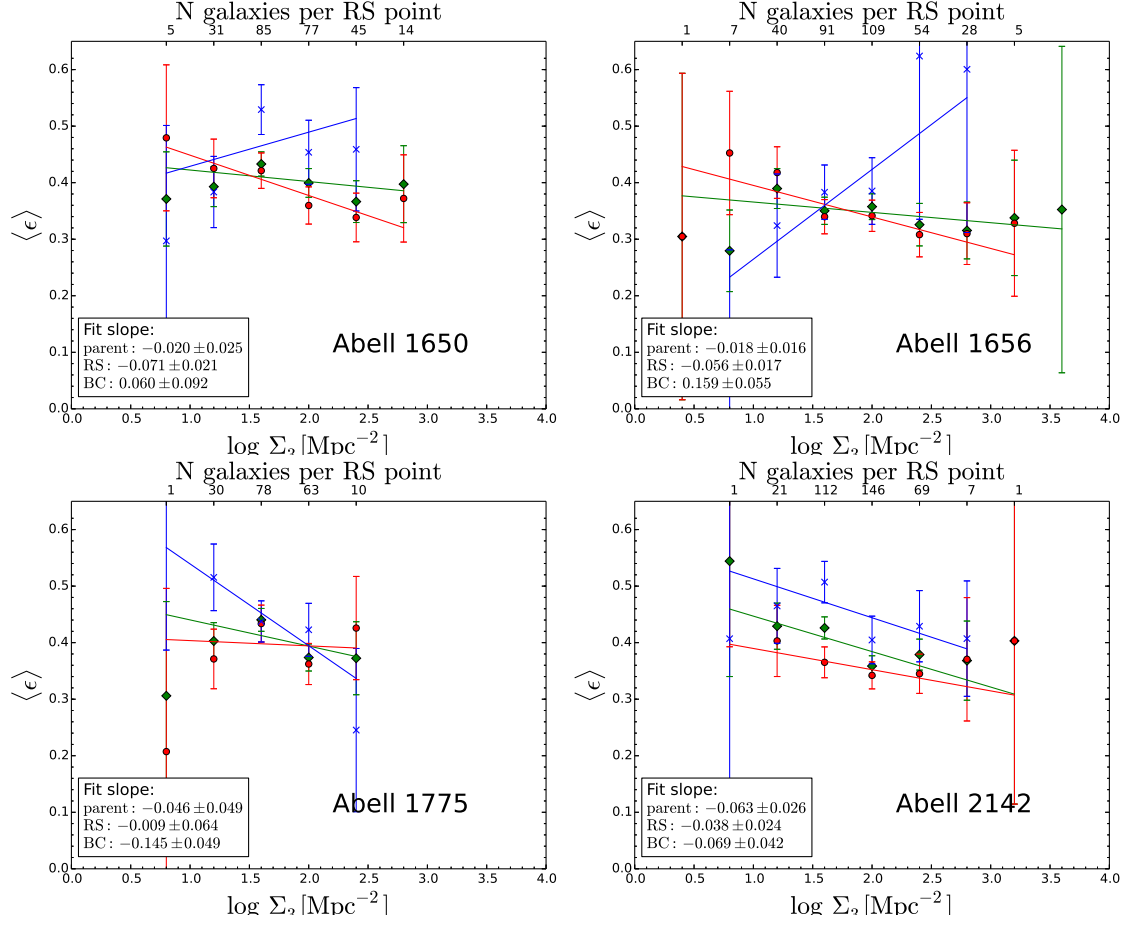


Figure 5.3: $\langle \epsilon \rangle$, the average ϵ of the galaxies as a function of $\log \Sigma_3$, where the projected number density Σ_3 is in units of Mpc^{-2} . The green diamonds refer to the parent galaxy population, the red dots are the RS and the blue crosses are the BC. The lines are a linear fit to the data. The slope of the fit and its standard deviation is reported for each plot in the bottom left box. For most clusters $\langle \epsilon \rangle$ decreases towards regions of higher projected density. There are two cases (Abell 1650 and Abell 1656) where the slope of the best fit line for the RS is more than three standard deviations away from 0. Conversely, there are clusters where the slope is compatible with no trend (Abell 1775 is shown). Most clusters have a negative slope, but its value is less than three standard deviations away from 0 (Abell 2142).

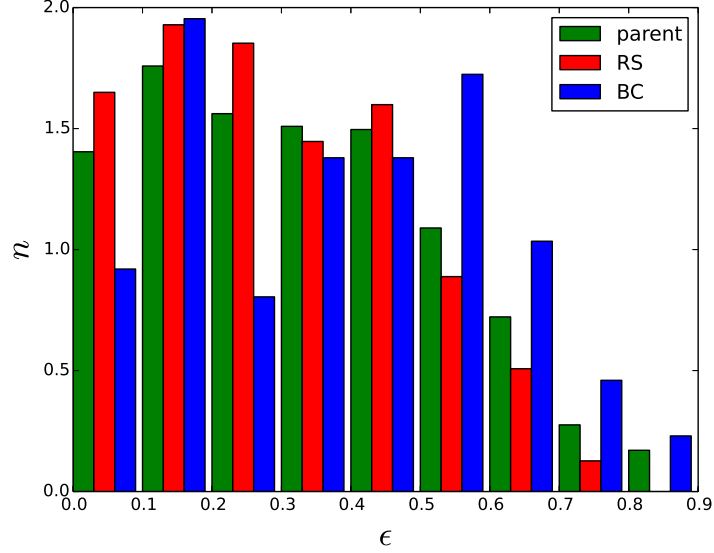


Figure 5.4: ϵ distribution for the reference galaxy population of the non-local sample. The reference population comprises galaxies from all the clusters in the non-local sample, and is depicted in green. The RS and the BC are denoted in red and blue respectively.

5.2 Non-local sample

5.2.1 ϵ distribution

We repeated the above analysis for the non-local sample. The first step was to construct the reference galaxy population, made up of all the galaxies from all the clusters in the non-local sample.

The ϵ distribution of this reference population is shown in Fig. 5.4 (green histograms). The blue and the red histograms pertain instead galaxies in the BC and RS respectively. For the normalization of the histograms see Equation (5.1).

The reference galaxy population has $\langle \epsilon \rangle = 0.36$ and $\sigma_\epsilon = 0.22$, while for the RS and BC we measure $\langle \epsilon \rangle = 0.32$ and $\sigma_\epsilon = 0.18$ and $\langle \epsilon \rangle = 0.39$ and $\sigma_\epsilon = 0.24$

A KS test does not reveal any differences between the ϵ distribution of any of the clusters in the non-local sample and the reference population. We find that the null hypothesis cannot be rejected in any case with a confidence better than 0.64 (parent samples) and 0.78 (RS samples).

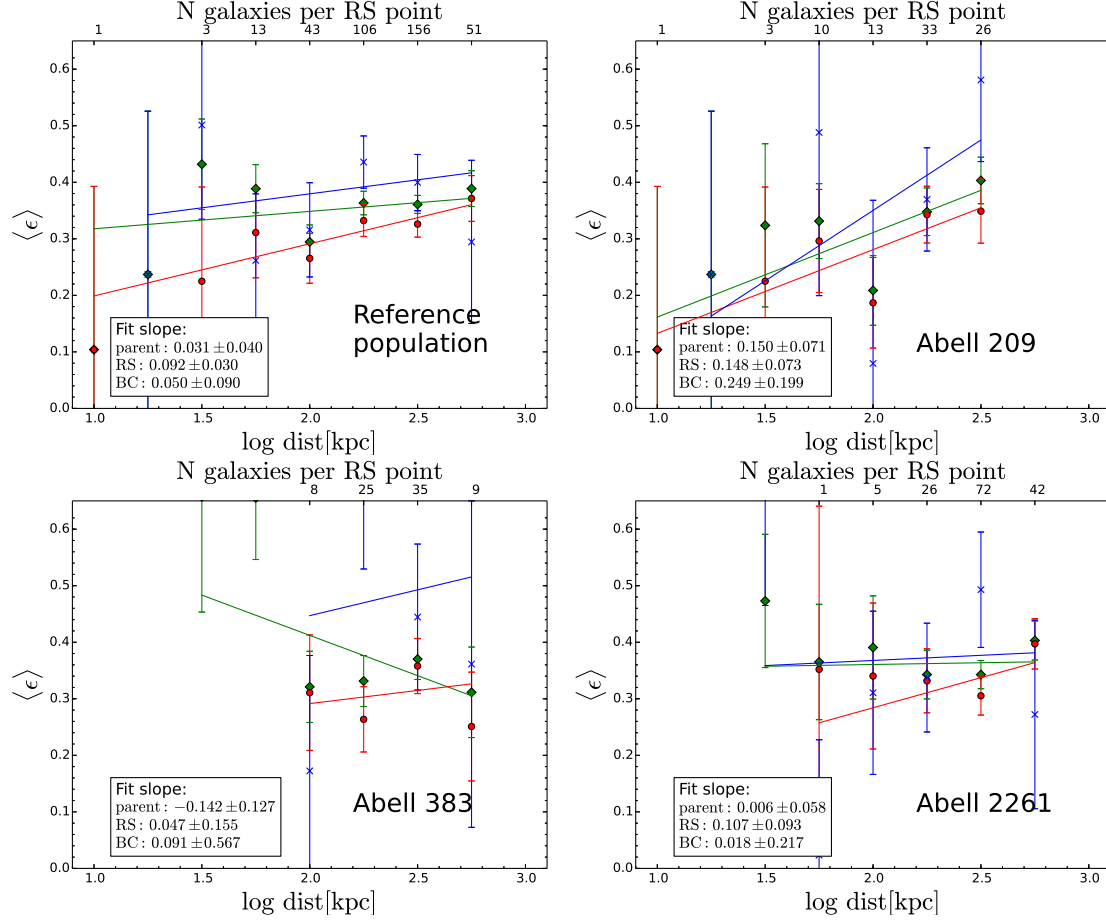


Figure 5.5: Same as Fig. 5.2, but for the non-local sample.

5.2.2 $\langle \epsilon \rangle$ and environment

We now analyse the trend of ϵ with local environment. Again we divided the samples in 11 bins, equally spaced in $\log d$, and proceeded to plot $\langle \epsilon \rangle$ for each bin (Fig. 5.5). Error bars are estimated as in Equation (5.1.2), and represent a conservative estimate.

For the reference galaxy population (top left panel in Fig. 5.5) the RS shows a clear trend with $\log d$, and the slope of the best fitting linear relation is more than three standard deviations away from 0. No such trends are observed for the parent and BC populations, which are compatible with a flat behaviour within the errors.

When it comes to the single clusters, the general trend of the population is generally compatible with a flat line, within one or two standard deviations. The same behaviour is observed for the galaxies on the RS.

Once again, repeating the analysis substituting $\log \Sigma_3$ for $\log d$ does not change the general picture, with RS galaxies having lower $\langle \epsilon \rangle$ in regions with higher values of $\log \Sigma_3$, but errors do not rule out a flat slope of the best fitting line.

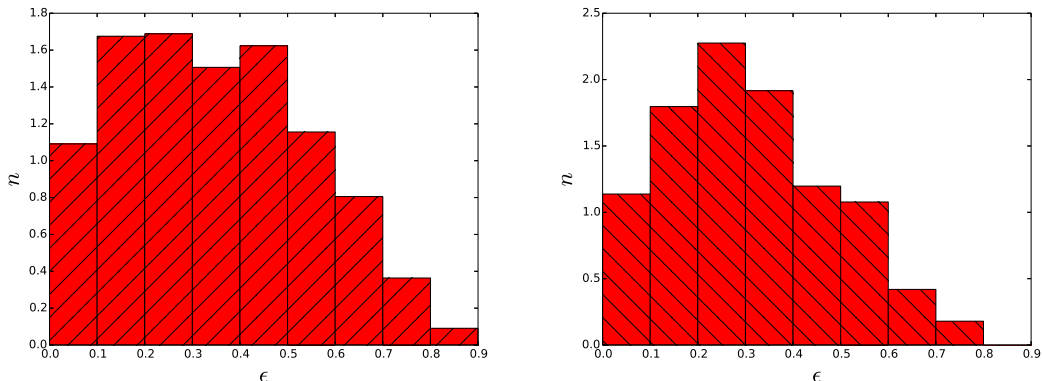


Figure 5.6: Left: ϵ distribution for the RS galaxies in the local sample of clusters, when $\log d < 2.5$. Right: same diagram for the non-local sample. The normalisation of n is the same as in Fig. 5.1.

5.3 Comparison of the two samples

It is natural to ask whether the distribution of projected ϵ changes between the local and the non-local samples. However the local and non-local samples probe the clusters to different projected radii. As we have seen Chapter 3, SRs (intrinsically round) are more abundant in the inner regions, skewing the ϵ distribution to lower values. In order to eliminate this bias, we considered the subsample of the local RS galaxies within $\log d(\text{kpc}) = 2.5$ from the centre. The new subsample consists of 770 galaxies, and covers the same physical region of the clusters as the non-local sample. It has average ellipticity $\langle \epsilon \rangle = 0.35$ and standard deviation $\sigma_\epsilon = 0.20$, while the corresponding values for the non-local sample are $\langle \epsilon \rangle = 0.32$ and $\sigma_\epsilon = 0.18$, Section 5.1.1). The ϵ distribution of the two subsamples is shown in Fig. 5.6. A KS test rejects the possibility that the two samples are drawn from the same distribution, with confidence $\gtrsim 0.995$. The two distributions are therefore different, at variance with the results of Holden et al. (2009).

There are however a number of caveats. The methods adopted to measure the ellipticity are equivalent, but not identical. They however take into account the effect of a different PSF between the local sample (SDSS) and the non-local sample (HST), which is the main source of systematics (Holden et al. 2009). Most importantly, the two subsamples of galaxies have been selected based on colours, rather than on morphology and redshift, as done in Holden et al. (2009). Finally, the clusters in the two samples have been selected from two different parent populations. The non-local sample spans a much larger volume than that available (by definition) to

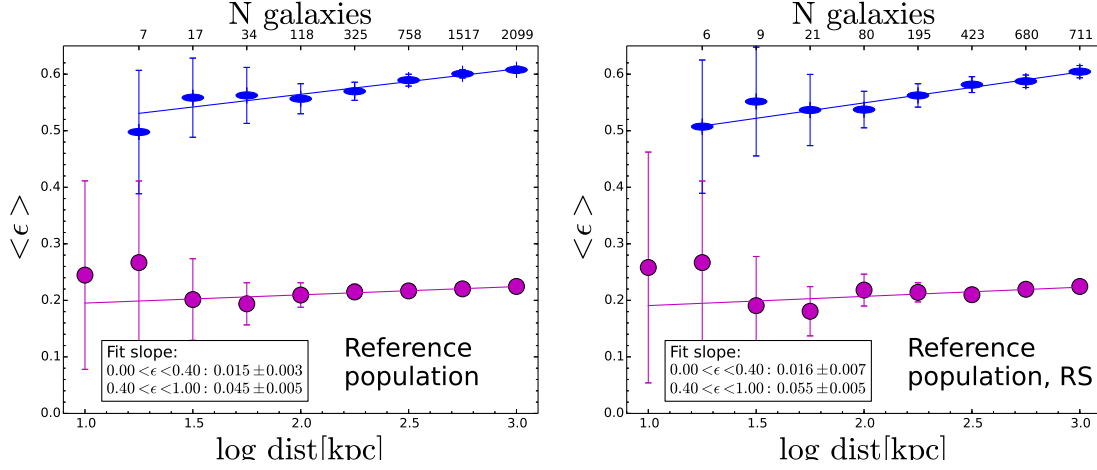


Figure 5.7: $\langle \epsilon \rangle$, the average ϵ of the galaxies as a function of $\log d$, for the reference galaxy population of the local sample (left) and the local sample RS (right). We divided the parent population in two subsets, separated at $\epsilon = 0.4$. The subset of galaxies with $\epsilon < 0.4$ is denoted by the magenta circles, while the blue ellipses correspond to the subset of galaxies with $\epsilon > 0.4$. The lines are determined using the least squares method, and highlight the presence of a strong trend in the subset of flattened objects.

the local sample. In addition, the non-local sample consists of the most massive and centrally concentrated clusters: in this respect they represent an extreme of their parent population, and are not directly comparable to the clusters in the local sample.

5.4 Constraints on the SRs and FRs fraction

Emsellem et al. (2011) found that no SR has $\epsilon > 0.4$. We therefore divided the galaxies in each cluster accordingly. In this way, the subsample with $\epsilon > 0.4$ contains only FRs.

In Fig. 5.7 we show the results for the reference galaxy populations of the local sample, for both the parent population (left panel) and the RS (right panel). We plot $\langle \epsilon \rangle$ as a function of $\log d$ for the two subsets: the subset of (apparently) round galaxies (with $\epsilon < 0.4$) is denoted by the magenta circles; the blue ellipses represent the subset of the galaxies having $\epsilon > 0.4$. We also plot the best linear fit to the points for both the round and flat subsamples. Indeed, both the round and flat subsamples show a trend of decreasing $\langle \epsilon \rangle$ with decreasing $\log d$. For flat galaxies the trend is stronger, and it can be observed also in single clusters (seven clusters from the local sample have the slope of the best fit linear relation more than 3 standard deviations away from 0).

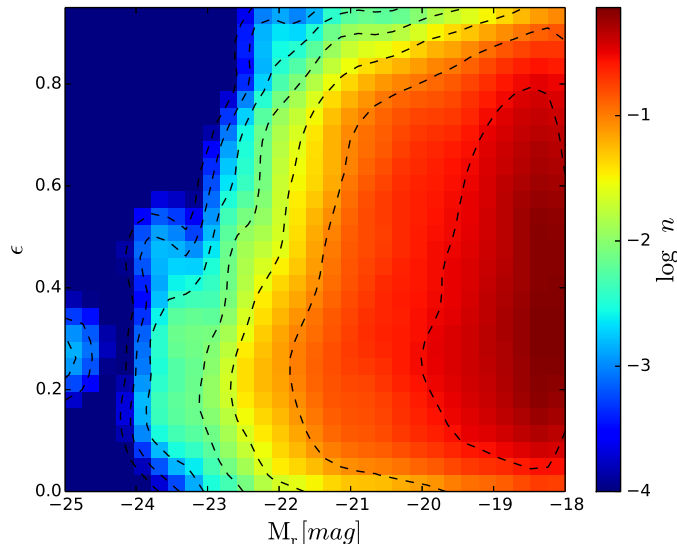


Figure 5.8: Distribution of the galaxies in the local sample in the magnitude- ϵ plane. $\log n$ is the number density of galaxies. The shape of the contours shows clearly that galaxies with $M_r \lesssim -21$ are on average rounder than the other galaxies.

5.5 Bias discussion

5.5.1 Trends with magnitude

It is well known that the most luminous galaxies are intrinsically rounder. This is evident for example in Fig. 5.8, where we plot the projected ellipticity ϵ against the absolute r -band magnitude of all the galaxies in the local sample of clusters. We have already mentioned that the ϵ distribution of rotation ellipsoids is truncated at the value of the projected ϵ equal to the intrinsic ellipticity. From the figure it is evident how the luminous end of the LF is deficient of flattened objects, evidence for a modest intrinsic flattening. This simple observation is backed by a KS test, where we consider the null hypothesis that the luminous end of the LF has the same ϵ distribution as the faint end.

On the other hand, it is known that more luminous galaxies are more likely to be found in dense environments, such as the centre of galaxy clusters. It is therefore possible that the trend of ϵ with cluster-centric radius stems from the above facts.

We considered the subsample of all galaxies with absolute r -band magnitude in the interval $[-19.5; -19.0]$, in order to eliminate the trend of ϵ with M_r . Repeating the tests performed above on this smaller subsample confirms the results ob-

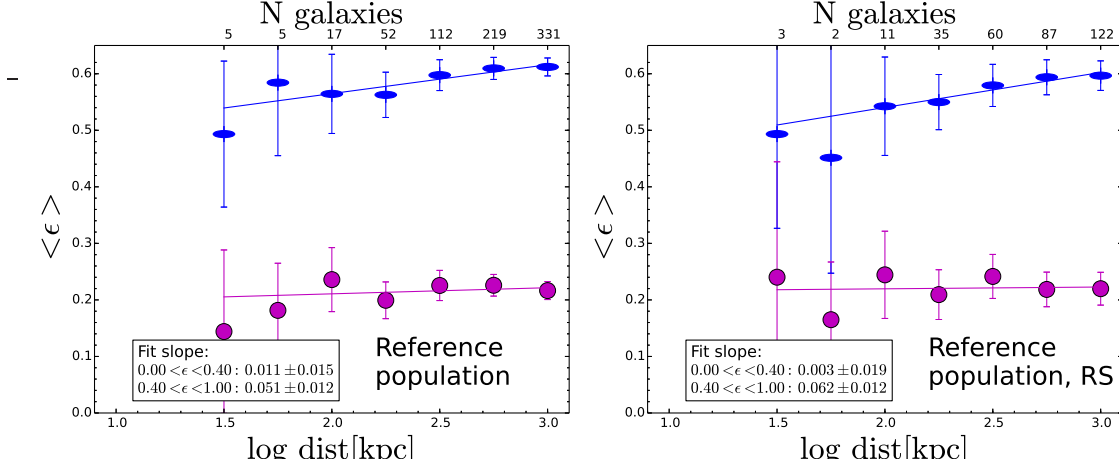


Figure 5.9: $\langle \epsilon \rangle$, the average ϵ of the galaxies as a function of $\log d$ for the reference galaxy population of the local sample (left) and for the galaxies on the RS only (right). Here we used only galaxies with $-19.5 < M_r < -19.0$. This eliminates the trend of ϵ with environment due to the combination of the trend of M_r with environment and the trend of ϵ with M_r . The blue and magenta data points refer to the subsets with $\epsilon > 0.4$ and $\epsilon < 0.4$ respectively. Even though the trend due to M_r has been eliminated, there remains a relative overabundance of round galaxies at small cluster-centric radii.

tained (Fig. 5.9).

5.6 Effect of interlopers

We have seen that the RS selection is not enough to discard all the interloping galaxies from a sample (Section 4.3.3). In general interlopers come from field galaxies, and we can assume that the shape of the average interloping galaxy does not depend on the particular region of the sky. This does not mean, however, that our results are not affected. Since in a cluster the projected density of member galaxies increases towards the centre, there is a corresponding decrease in the fraction of interlopers, assumed to have constant surface density. This can produce exactly the trend observed in Section 5.4.

In order to test this, we used a redshift selected sample of galaxies from Abell 2142 to repeat the test of Section 5.4. We find that, again, the average ϵ of flat ($\epsilon > 0.4$) RS galaxies increases with d , even though we have removed any interlopers.

5.7 Discussion

We have shown how ϵ , the projected ellipticity of galaxies, can be used to investigate the properties of cluster FRs.

Despite the large uncertainties due to projection, we find a trend of increasing $\langle\epsilon\rangle$ both with the projected cluster-centric radius d and with the projected number density of galaxies Σ_3 . This is observed in almost all clusters (17 out of a sample of 18 clusters for which the RS could be reliably identified). However, due to the associated noise, only five clusters present a statistically significant result ($3\text{-}\sigma$ confidence). When we stack all the galaxies in the local sample, we get a much higher confidence ($7\text{-}\sigma$).

This can be explained by a superposition of concurring trends. The brightest galaxies are on average intrinsically rounder, and only present in the central regions of clusters. However, the observed trend is still present if we consider a narrow bin in magnitude, where this bias is negligible. An alternative possibility is that the trend is due to the morphology-density relation: Es, which are on average rounder than S0s and LTGs, are more common in the central region of clusters. Although this is certainly the case, it must be kept in mind that the observed properties of ETGs are heavily affected by misclassification, with $\approx 66\%$ of Es being intrinsically flat FRs.

If we restrict our analysis to galaxies flatter than $\epsilon = 0.4$, which are known to be FRs, we find the same trend of increasing $\langle\epsilon\rangle$ with d . This result is robust against misclassification, and applies to all FRs because the set with $\epsilon > 0.4$ is a random subset of the FRs population.

The observed trend can be interpreted in two ways. The Bulge to Disc fraction (B/T) might decrease with d , affecting $\langle\epsilon\rangle$ because bulges are intrinsically rounder than discs. In alternative, stellar discs might become thicker closer to the cluster centre. The first scenario implies a connection between the current position of a galaxy inside a cluster and its assembly history. The second scenario instead can be explained by the interaction between galaxies inside clusters, which can heat the stellar disc.

Answering these questions can be done with a B/T decomposition. However it is not clear to what extent these techniques are reliable. Our preliminary analysis of ATLAS^{3D} B/T fractions suggests a dependence on the galaxy inclination, which in turn points to possible systematics in the decomposition.

A careful investigation of this matters is deferred to a future work.

Chapter 6

Conclusions

The SAURON and ATLAS^{3D} surveys have opened a new window on the structure of ETGs. In particular they showed that the Hubble morphological classification in disc-like S0s and spheroid-like Es does not necessarily reflect a physical difference between the two groups. Two thirds of the Es have stellar kinematics dominated by large scale, ordered rotation, which makes them closer to S0s than to the remaining Es. In addition, the classification is subject to additional errors for S0s viewed at high inclination, which are prone to be classified as Es.

The new classification paradigm proposed in Cappellari et al. (2011b), which separates ETGs in SRs and FRs, is based instead on the stellar kinematics, and is almost independent of inclination. It is directly linked to the formation and evolution history of ETGs, and provides a crucial constraint for models of galaxy formation.

In addition, ATLAS^{3D} discovered that the fraction of SRs with respect to the total ETGs population is a function of the environment. This confirmed previous knowledge that the formation and evolution of galaxies are influenced by their surroundings. However this result was based on observations of only one cluster of galaxies, the Virgo Cluster. As such, and because of the degeneracy between GHE and LPE, ATLAS^{3D} could not determine precisely the relevant environment scale.

It became necessary to review previous results such the $T - \Sigma$ relation in light of the new classification scheme.

In this thesis we focused on the relationship of SRs and FRs with the surrounding environment, and addressed some of the open questions. In this final chapter, I will summarize our results (Section 6.1 and Section 6.2) and describe the future steps of this research work (Section 6.3).

6.1 SRs and environment

In Chapters 2 and 3 we studied a sample of 30 ETGs in the massive cluster Abell 1689. We used archival HST and Gemini photometry, as well as IFS data from FLAMES/GIRAFFE at the VLT.

- a) We classified the galaxies according to the new SR/FR paradigm, thus demonstrating the feasibility of this kind of study beyond $z = 0$. To date, this work remains the highest redshift study of this kind.
- b) In order to compare our results with those of the ATLAS^{3D} survey, we developed new analysis tools. In particular we simulated observations of the SAURON sample of galaxies using FLAMES/GIRAFFE.
- c) The LF of SRs was found to be the same as in the Virgo Cluster within the sample magnitude cut.
- d) Our sample of 30 ETGs in Abell 1689 shows a fraction of SRs $f_{\text{SR}} = 0.15 \pm 0.03$, the same fraction as in the Virgo Cluster, when sampled in the same way.
- e) Within the cluster, the fraction of SRs rises sharply towards the centre. The overall picture is that of an enhanced core (with respect to the average fraction) and of depleted outskirts. This is analogous to what found in the Virgo Cluster.

A possible explanation is that SRs form everywhere in the same numbers, but later converge in the centre of cluster of galaxies, via relaxation processes like dynamical friction. However, assuming ordinary mass-to-light ratios, their mass is insufficient to explain this phenomenon. However, if SRs formed at the bottom of very large DM potential wells (e.g. at the centre of groups and protoclusters) then their DM haloes might be massive enough to justify our hypothesis.

6.2 FRs and environment

Emsellem et al. (2007) found that no SRs have $\epsilon > 0.4$, while FRs span the full range of projected ellipticities. This means that SRs are intrinsically rounder as opposed to FRs, which are flatter.

We studied the distribution of ϵ in a photometric sample of cluster of galaxies with $0 \lesssim z \lesssim 0.2$.

- a) We found that the average ellipticity increases with the cluster-centric radius.

- b) The local and non-local samples exhibit qualitatively similar behaviours
- c) This trend exists above and beyond that of brighter galaxies (which are on average rounder) to be more common in the centre of clusters.
- d) The average ϵ of FRs increases with the cluster-centric radius. The trend observed in a) exists therefore above that of SRs (which are on average rounder) to be more common in the centre of clusters.
- e) The distribution of projected ϵ in the local and non-local sample are different, even when sampling within the same physical radius.

The observed trends of ϵ with projected cluster-centric radius have two possible explanations. One is that towards the centre of galaxy clusters, stellar discs are thicker, thereby determining a lower intrinsic ellipticity. This can be caused by violent but short interactions between galaxies, which dynamically heat the discs.

The other explanation is that the B/D ratio increases towards the centre of clusters, either as a result of a different stellar assembly history, or as a result of the suppression of the disc (for example by removing the peripheral gas before it could form stars).

6.3 Future works

In order to fully address the question of the link between environment and dynamical structure of ETGs, we need to use IFS to fully sample the range of available galaxy environments. In particular, the traditional probes of environment, such as $\log \Sigma_3$, do not do justice to the different GHEs of galaxies.

In order to better understand the formation and evolution histories of SRs, it is necessary to explore the full range of cluster ages. If SRs form at the centre of DM potential wells, we will find them already in place in the centre of galaxy groups.

On the other hand, if the hypothesis that SRs migrate towards the centre of clusters were correct, they would be likely to merge with one another. This prediction can be tested by measuring the fraction of SRs in dynamically old clusters, a project that has been awarded time at the VLT.

We have seen how FRs are themselves sensitive to the conditions of their surroundings, even using an inaccurate tracer as the projected cluster-centric radius. In

order to distinguish between the effect of increasing B/D ratios versus intrinsic thickening of the disc, we need to directly investigate the dynamical structure of FRs in clusters.

Appendices

Appendix A

The Local Sample of Clusters

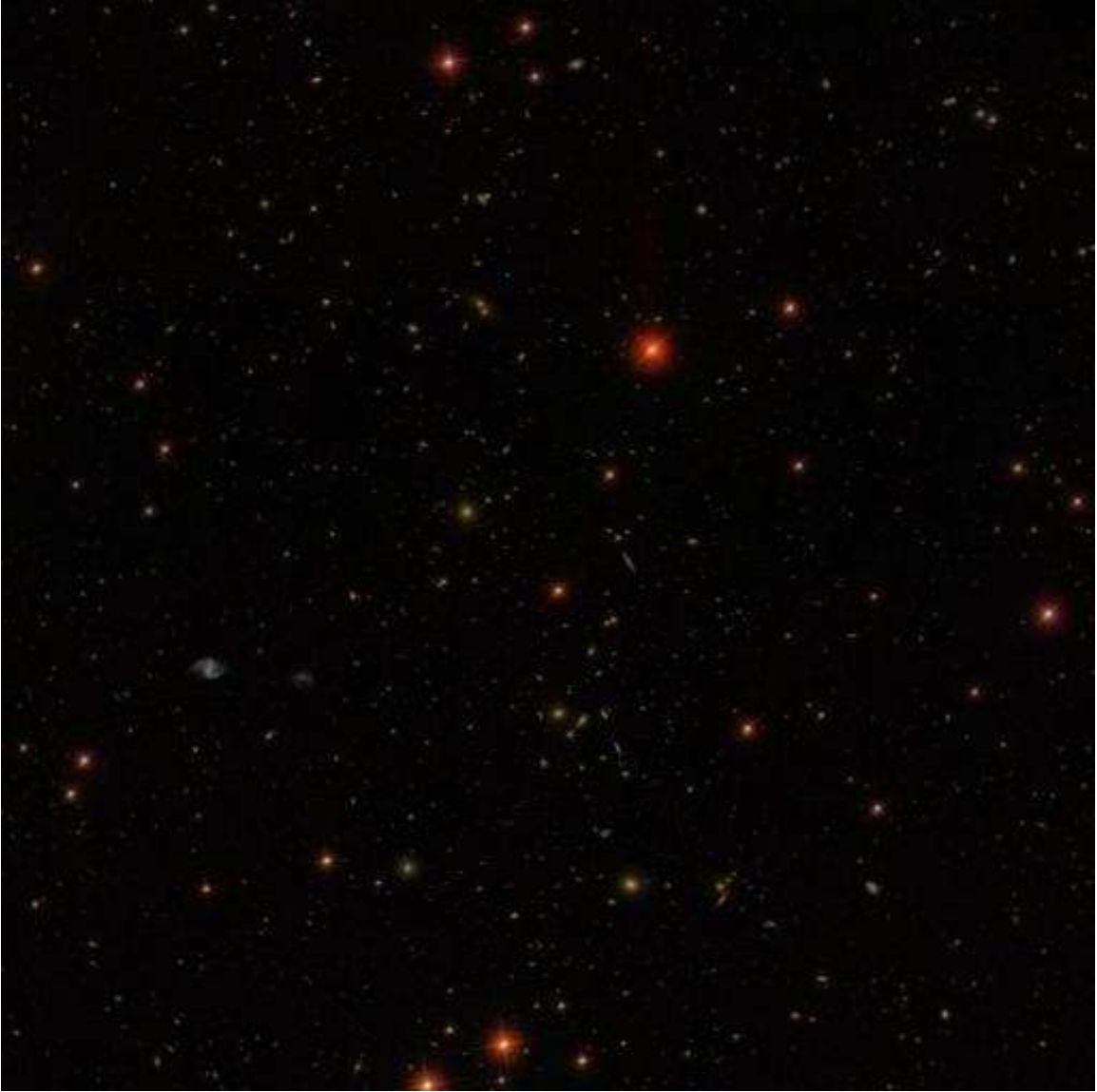


Figure A.1: Abell 16, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

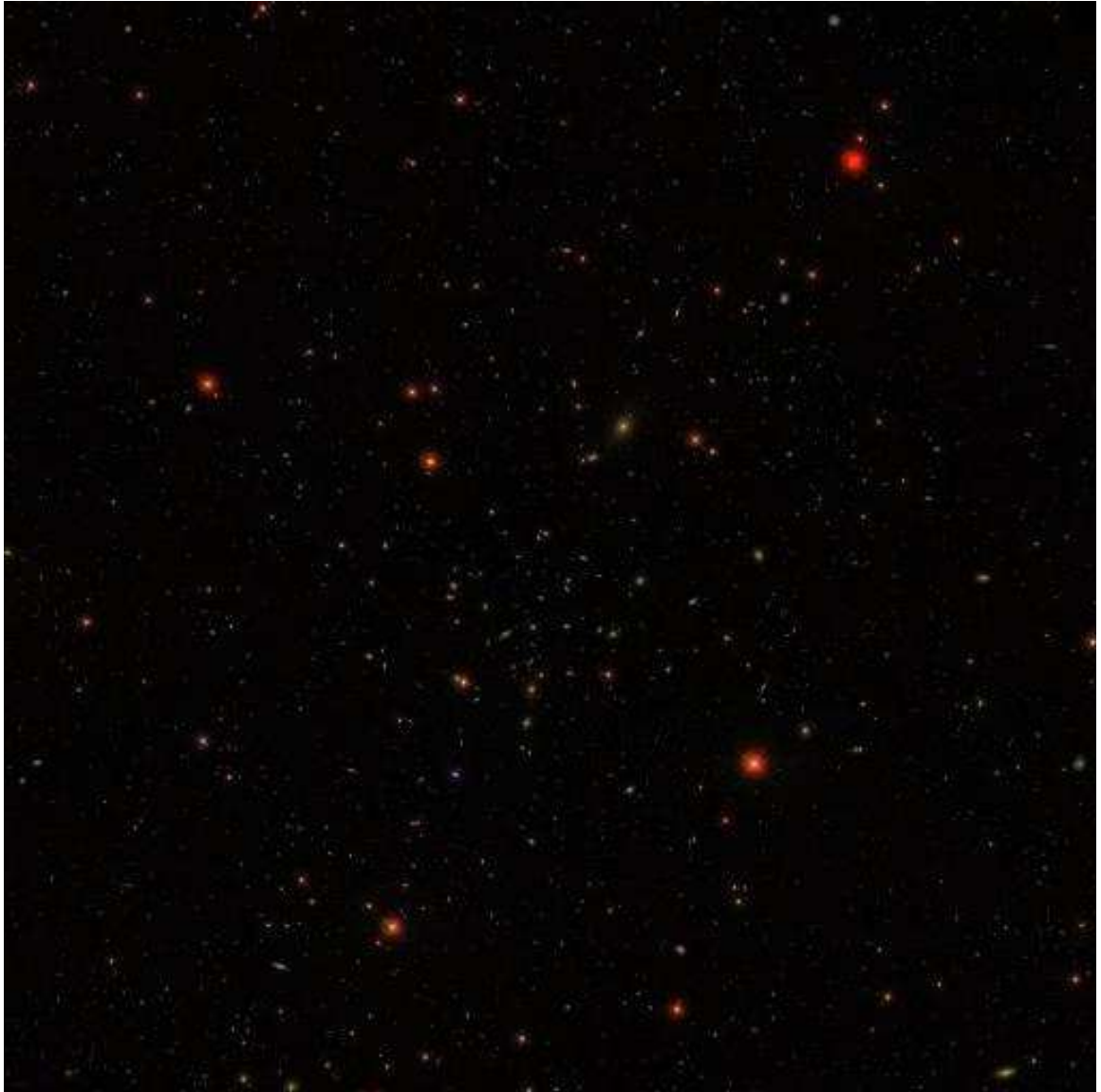


Figure A.2: Abell 168, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

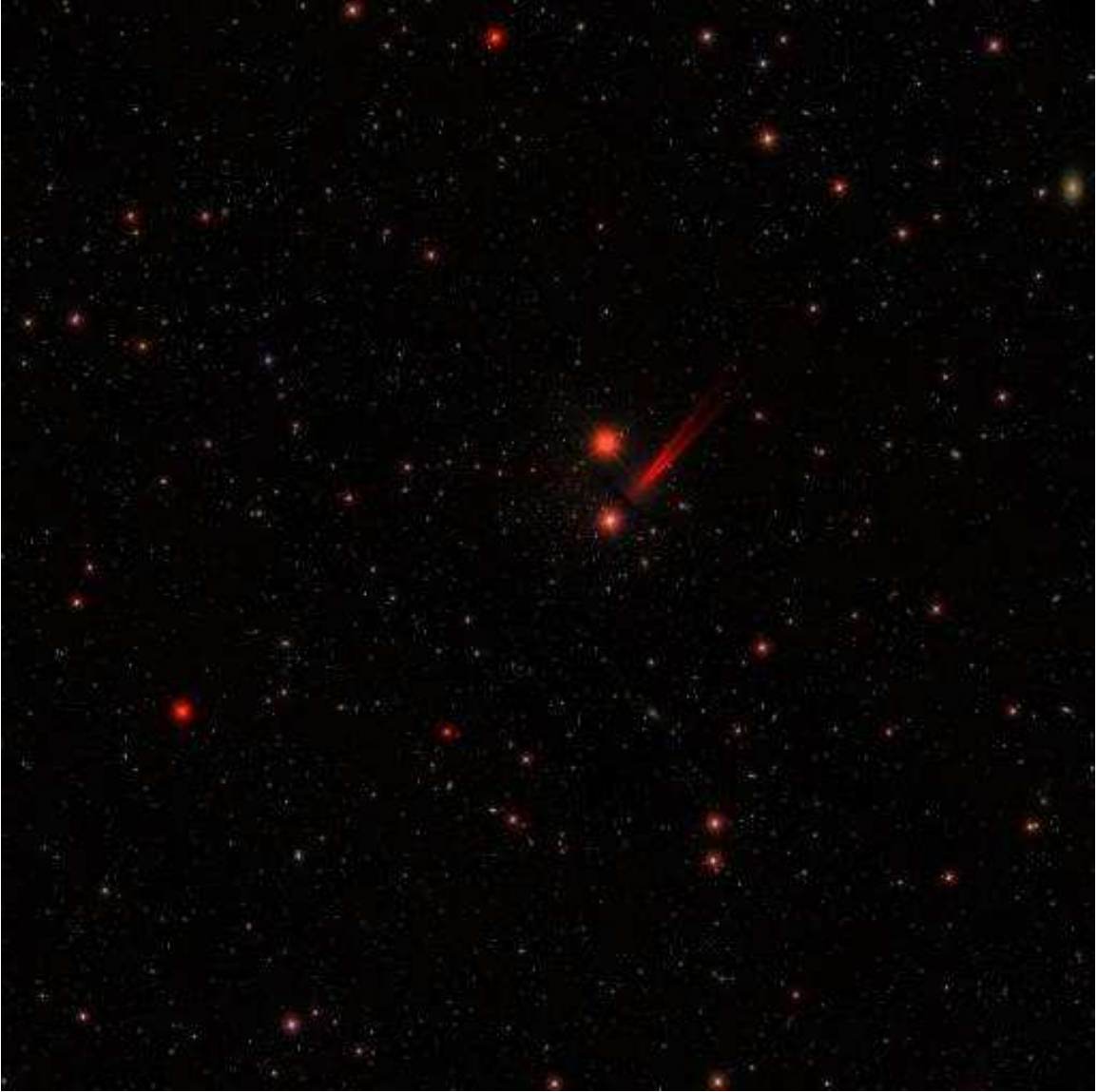


Figure A.3: Abell 736, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

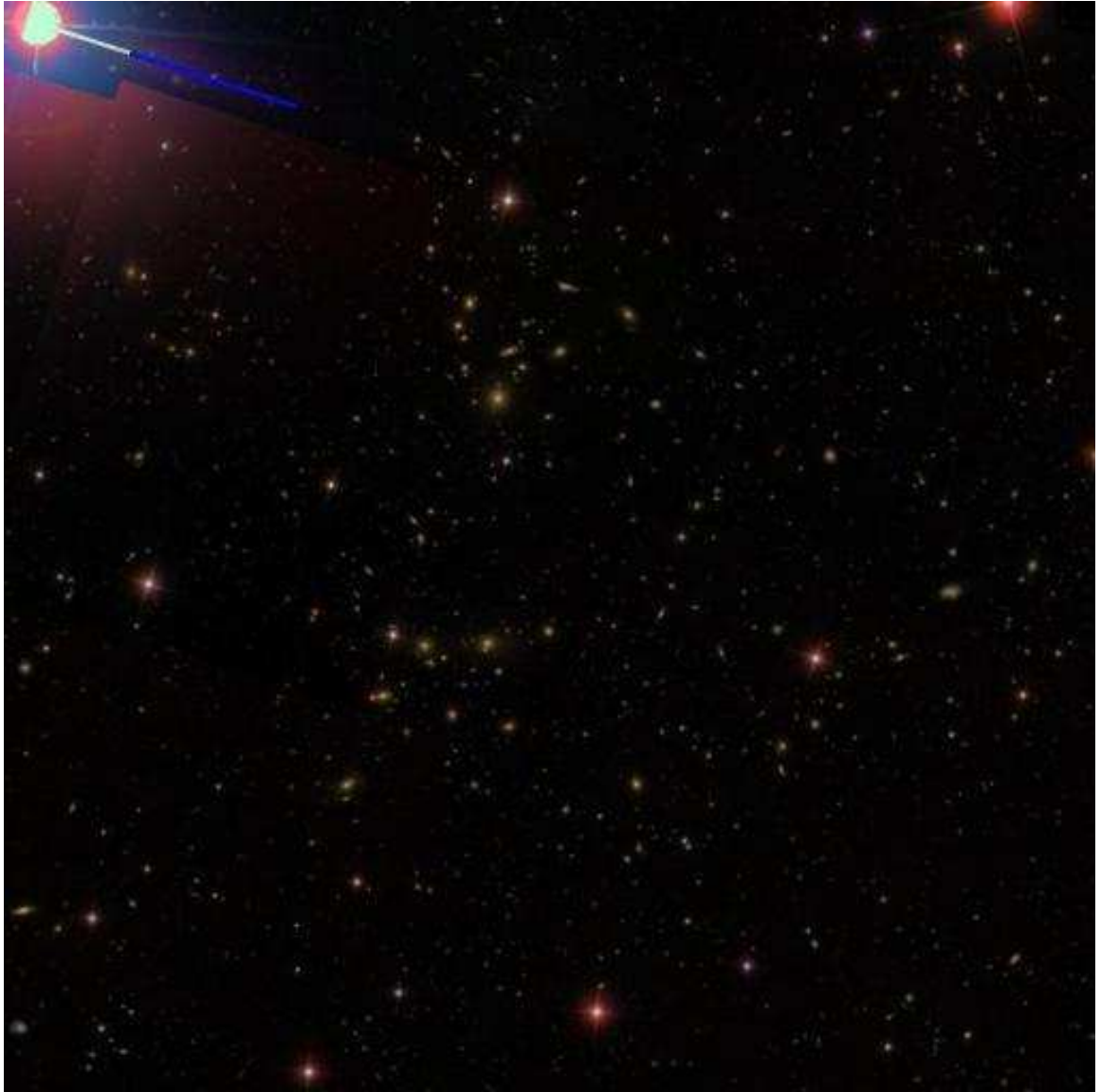


Figure A.4: Abell 1035, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

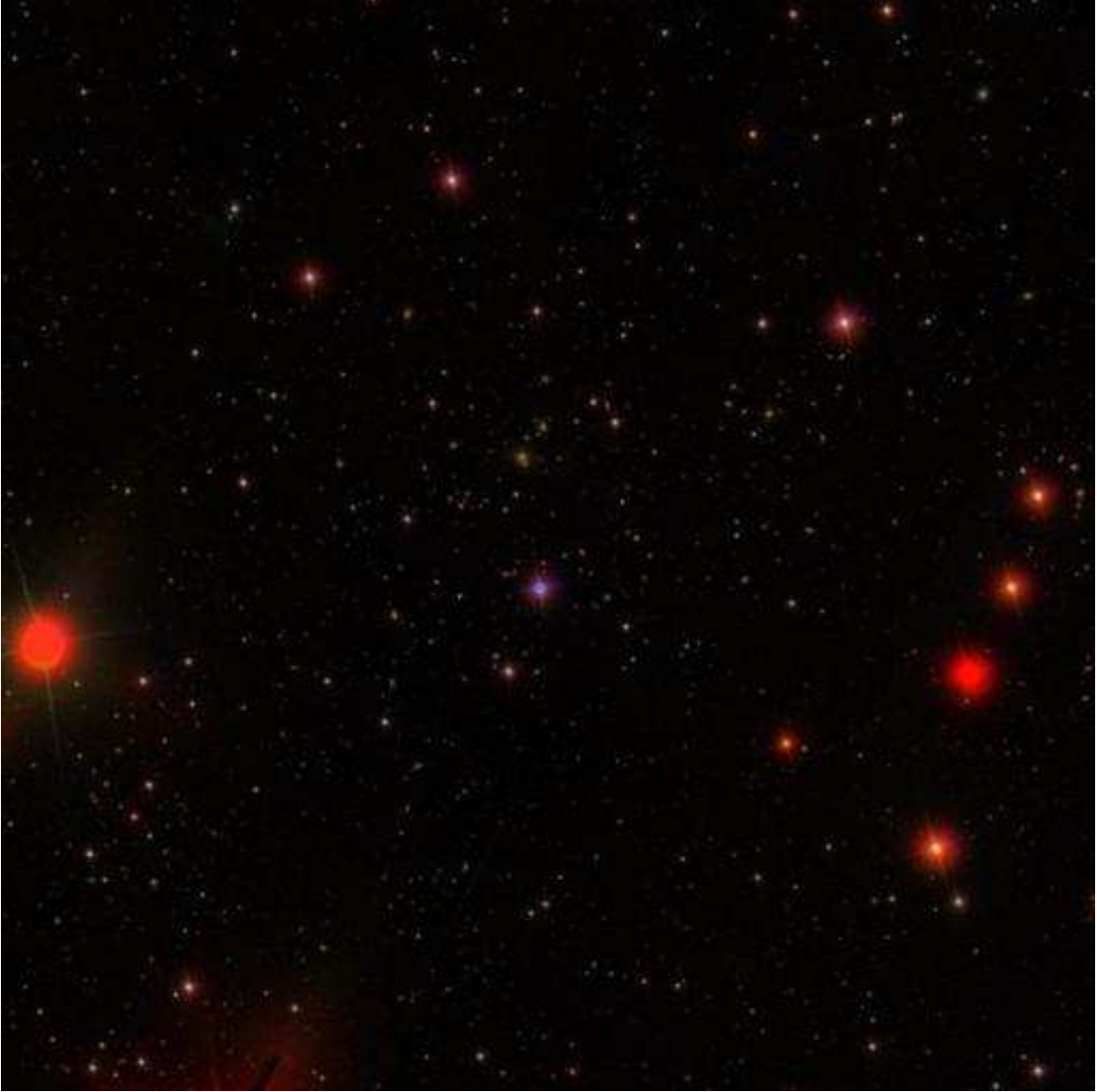


Figure A.5: Abell 1186, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

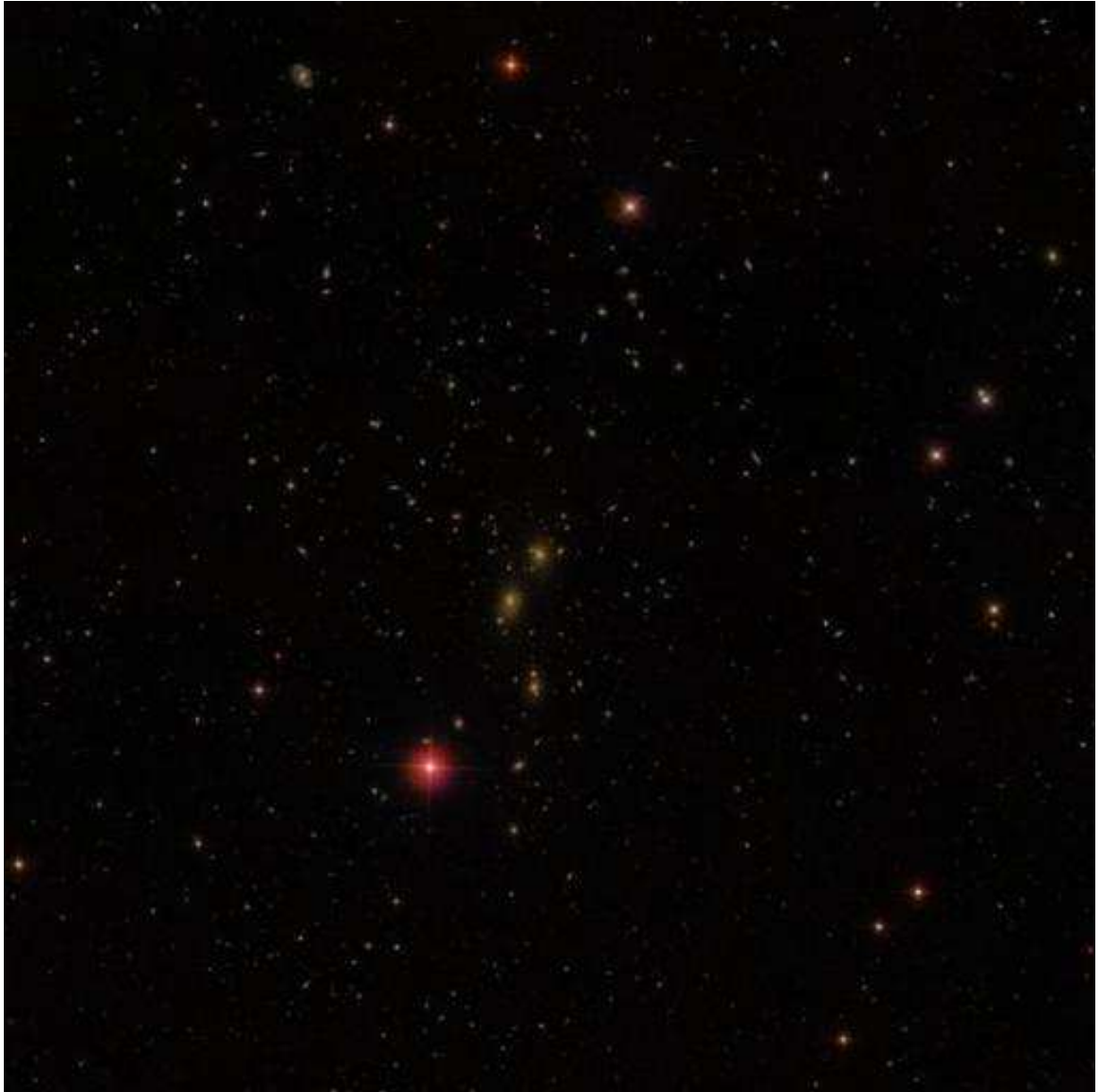


Figure A.6: Abell 1190, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

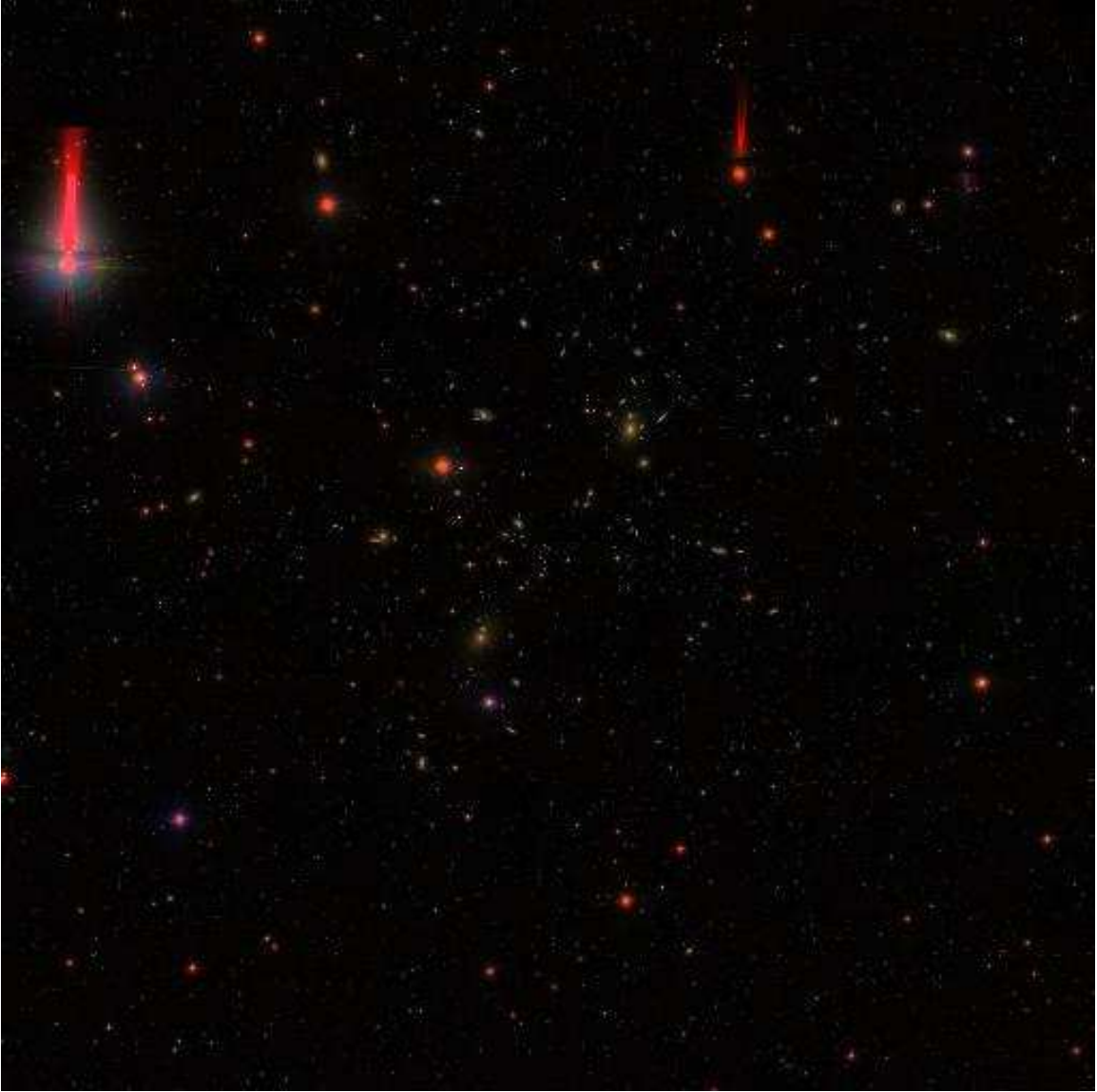


Figure A.7: Abell 1367, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

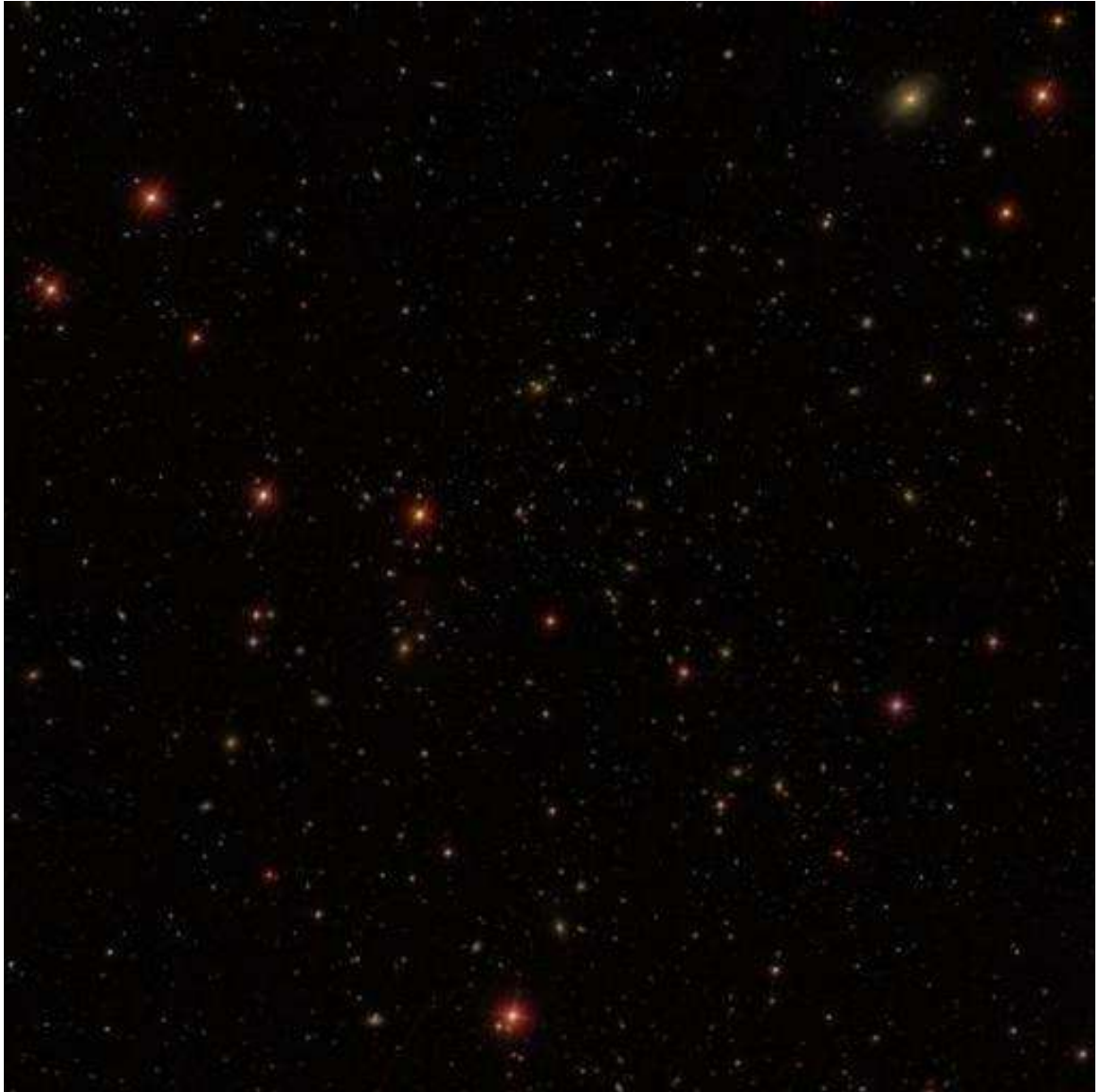


Figure A.8: Abell 1399, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

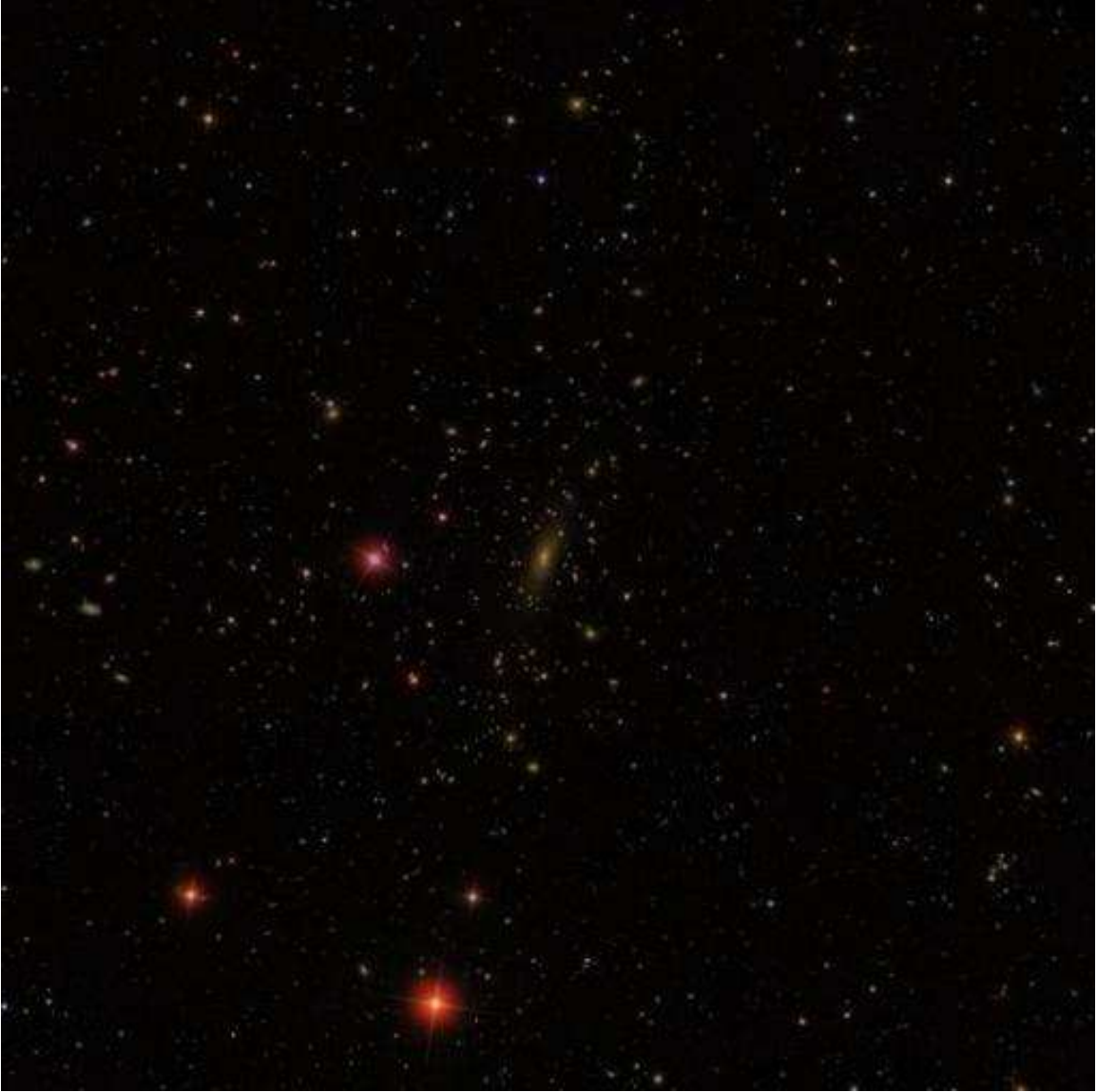


Figure A.9: Abell 1650, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

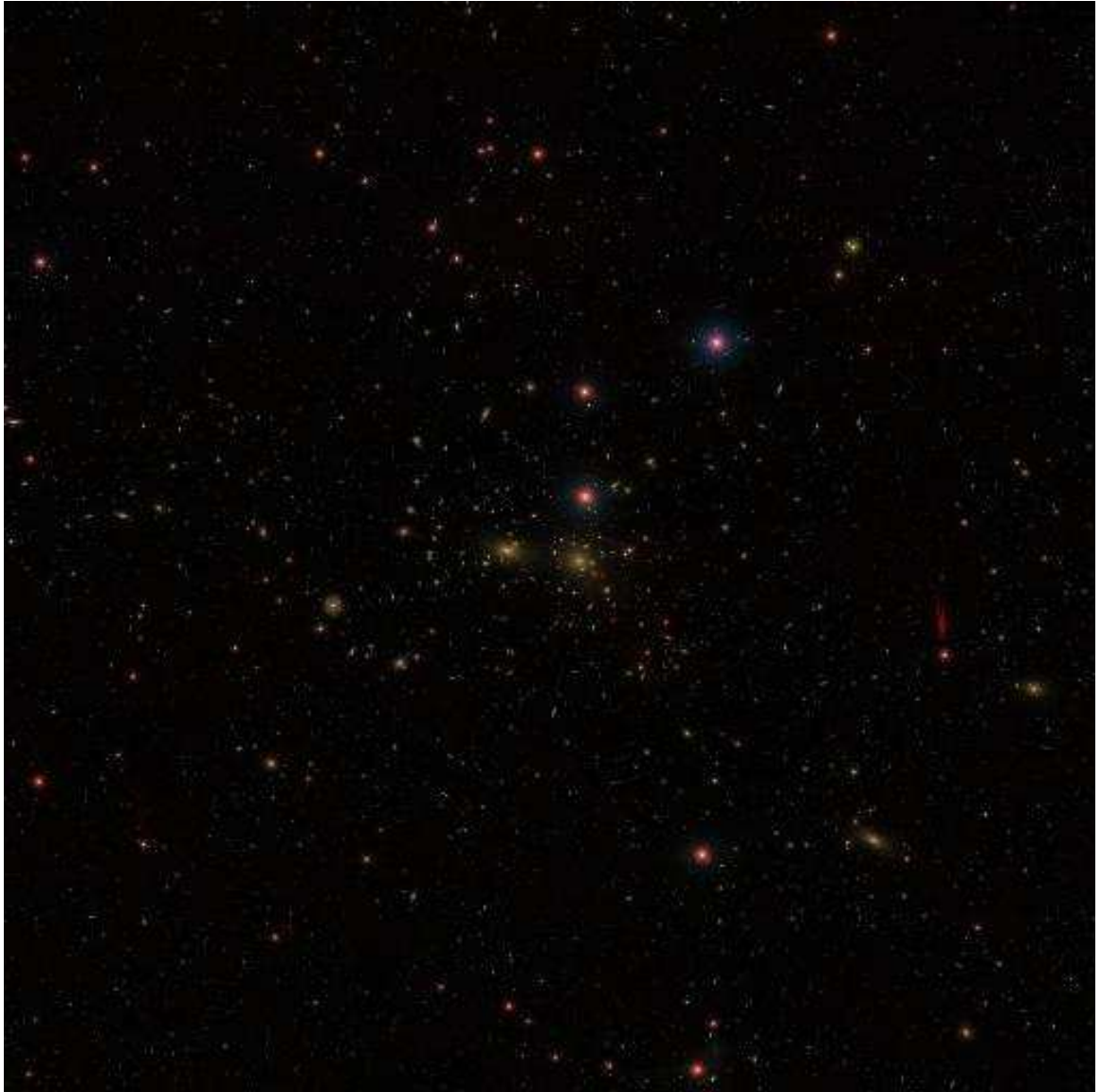


Figure A.10: Abell 1656, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

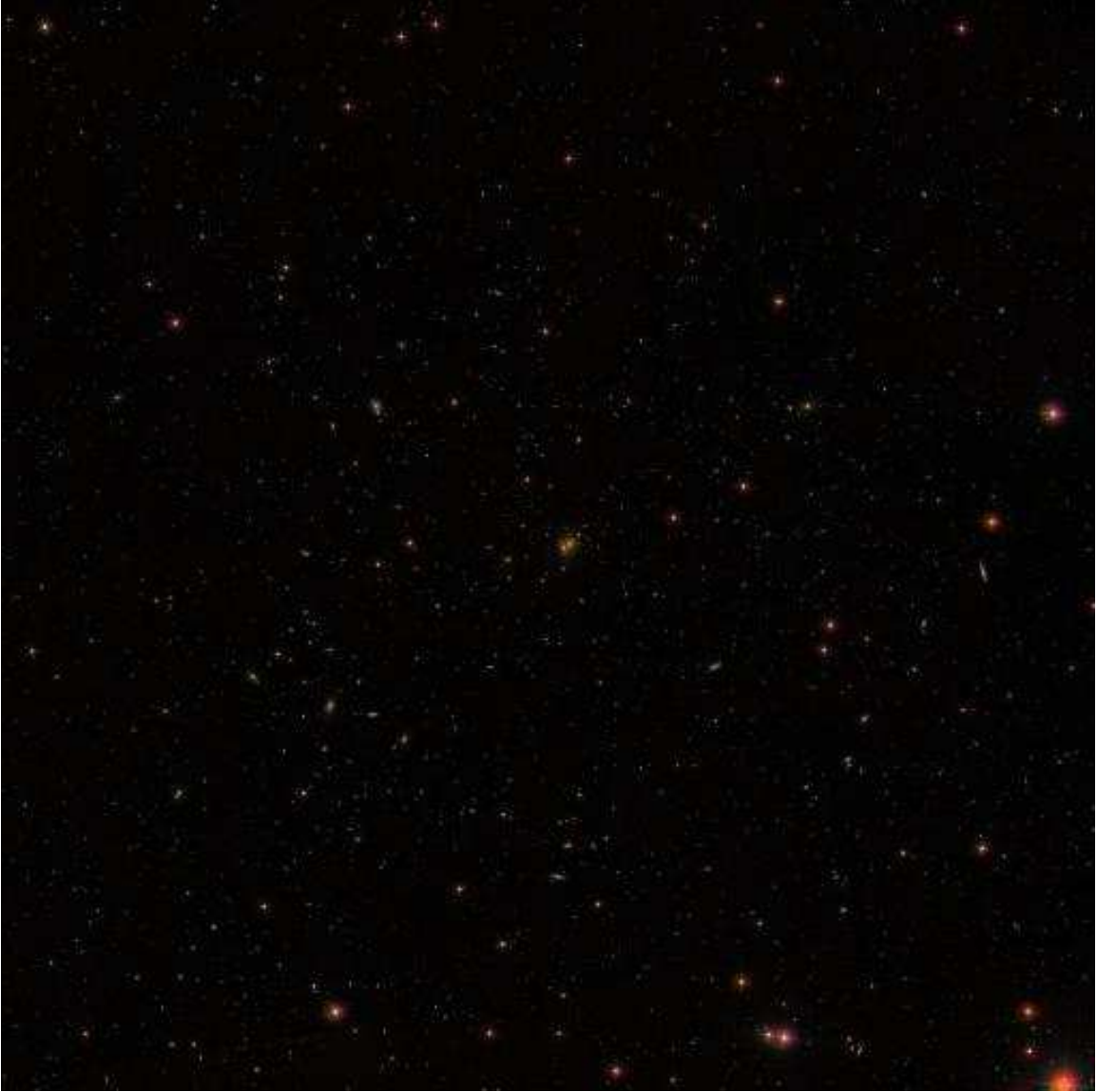


Figure A.11: Abell 1775, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

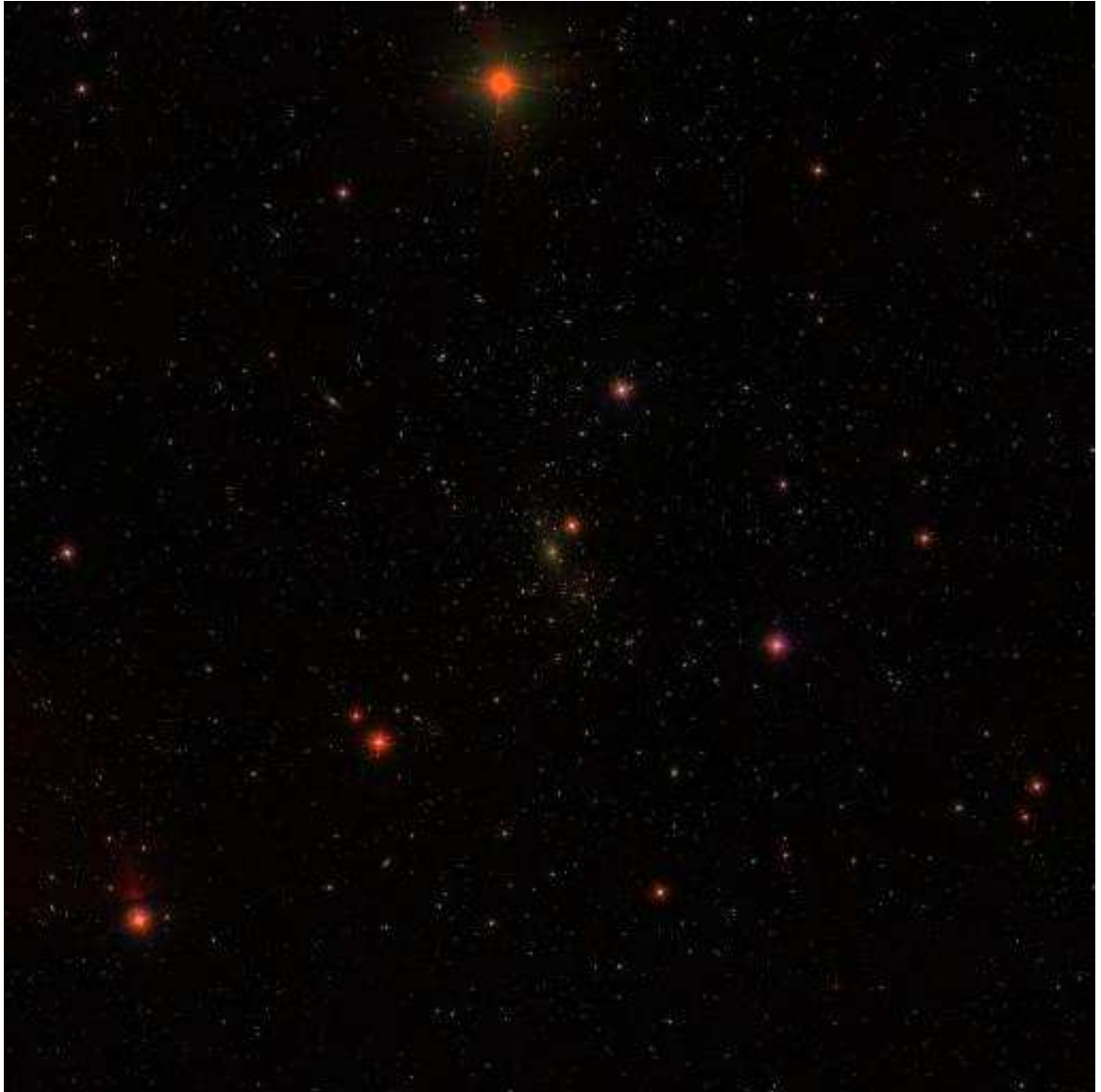


Figure A.12: Abell 1795, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

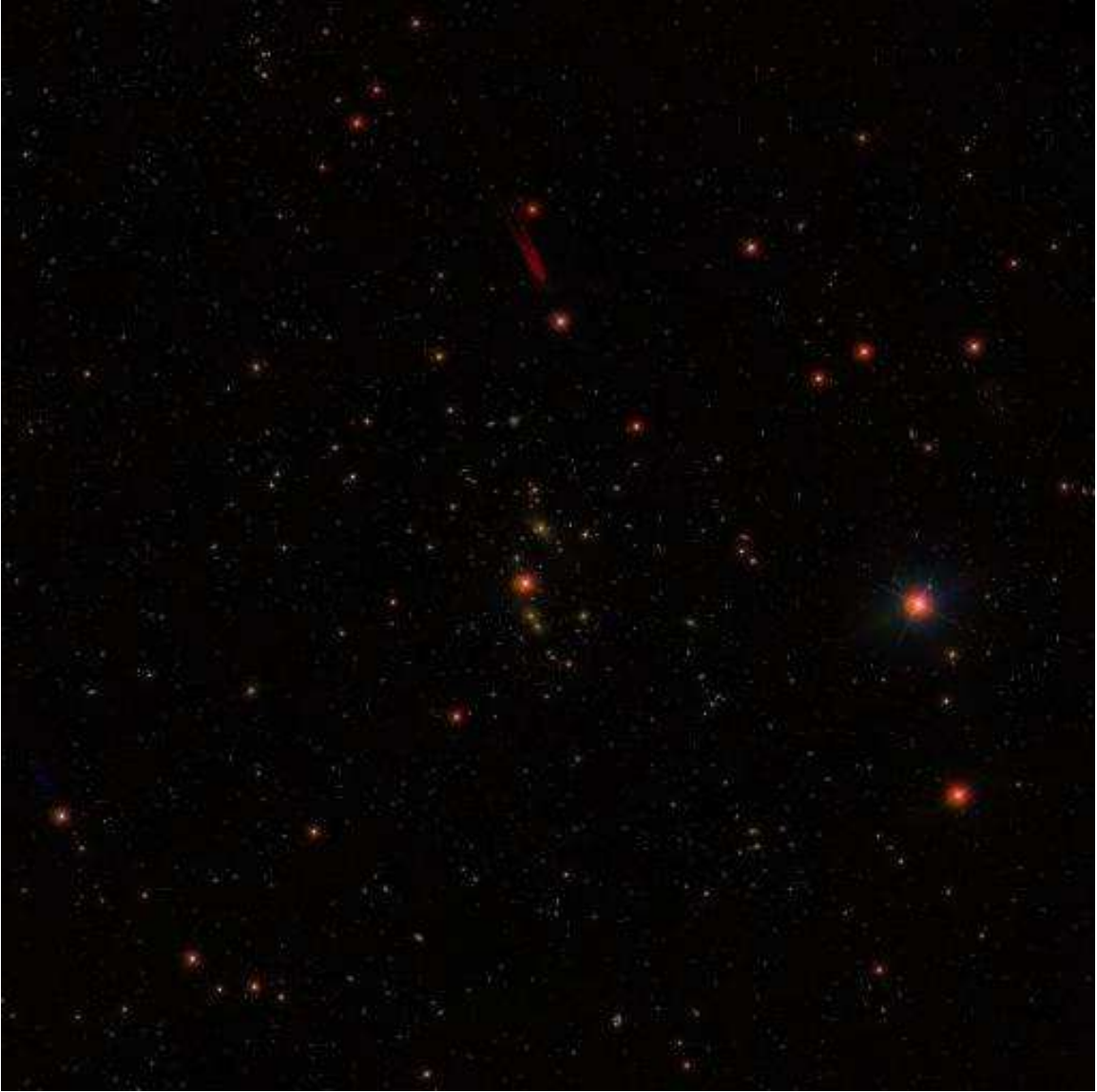


Figure A.13: Abell 1904, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

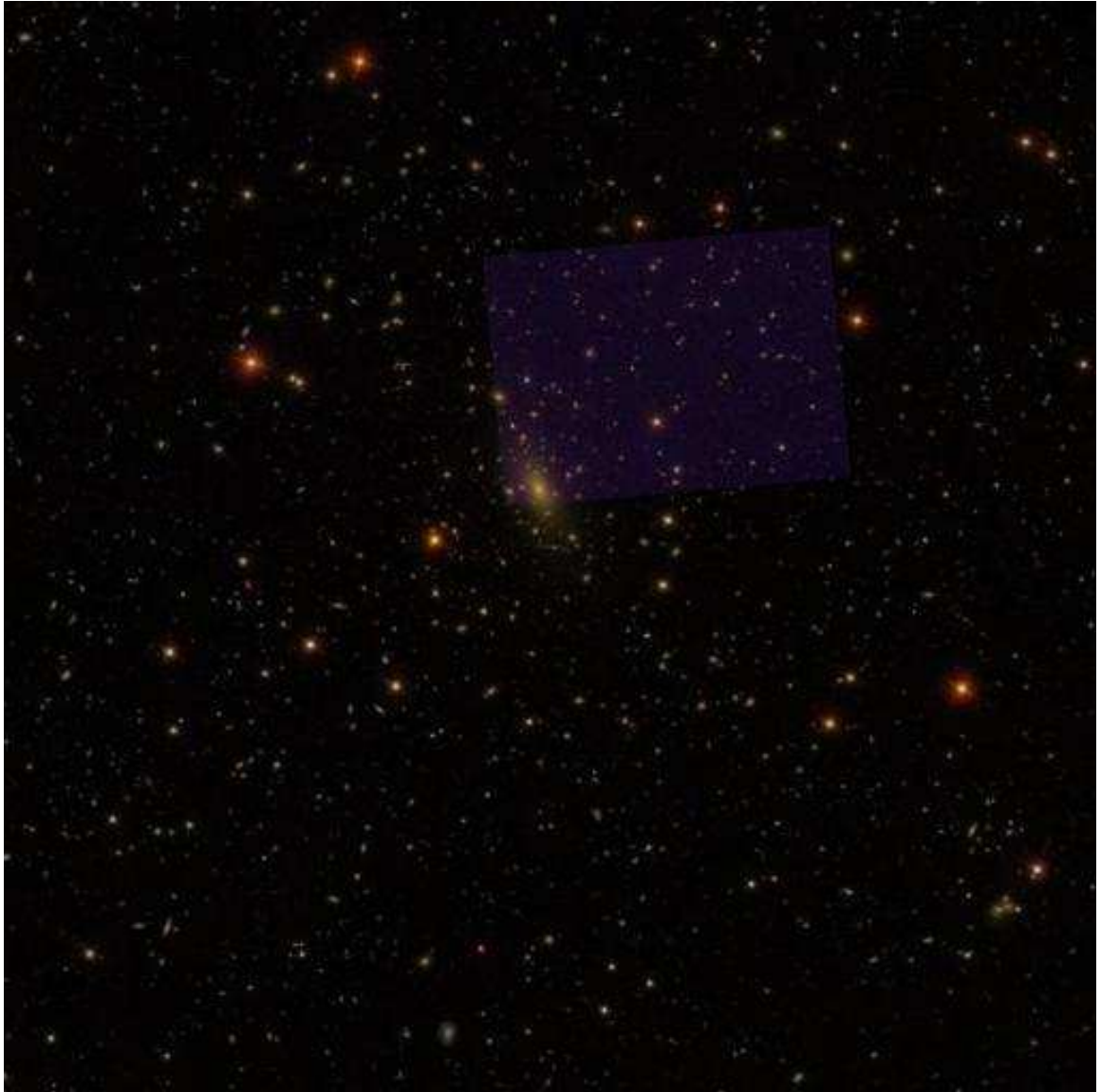


Figure A.14: Abell 2029, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

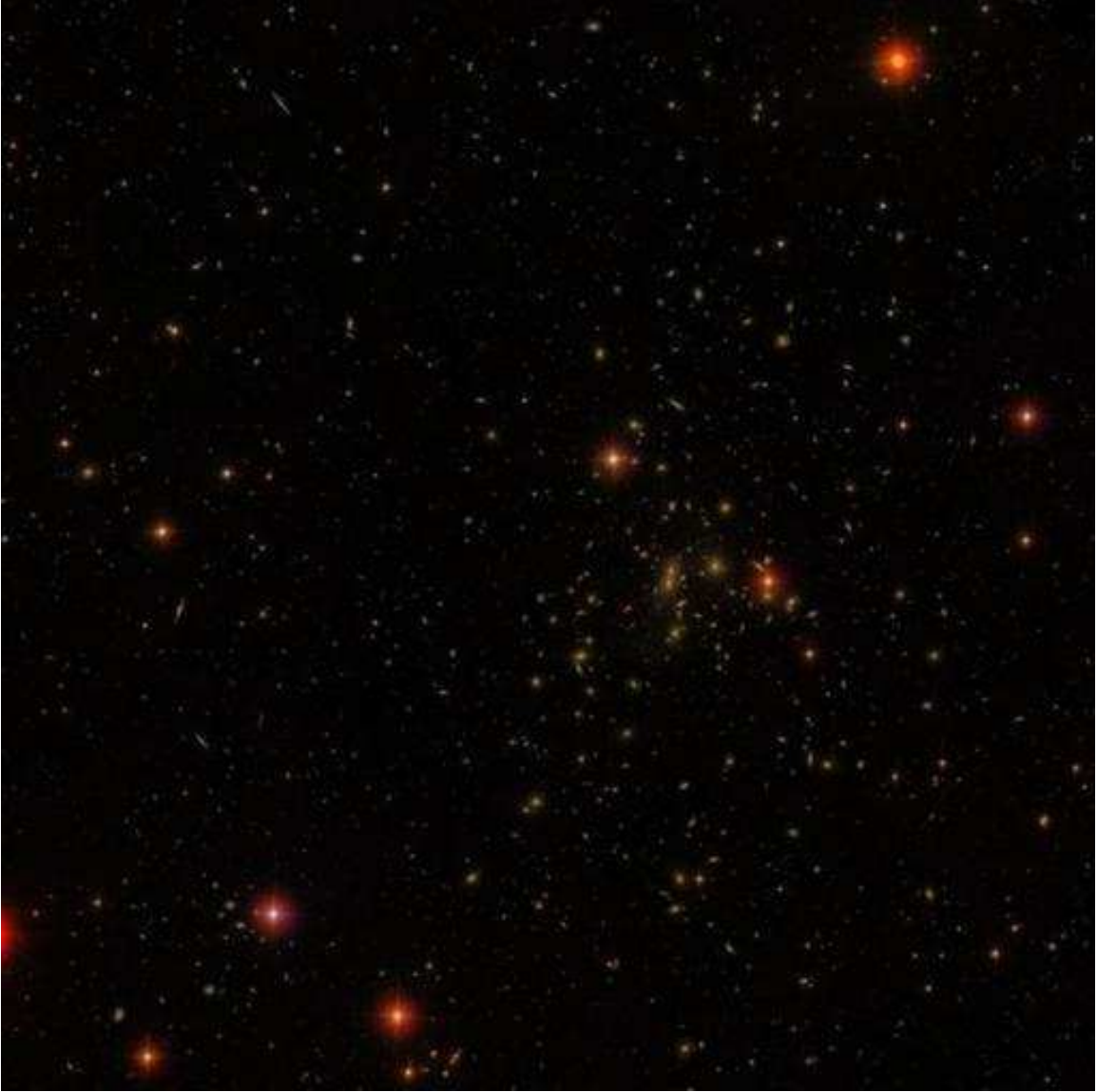


Figure A.15: Abell 2065, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

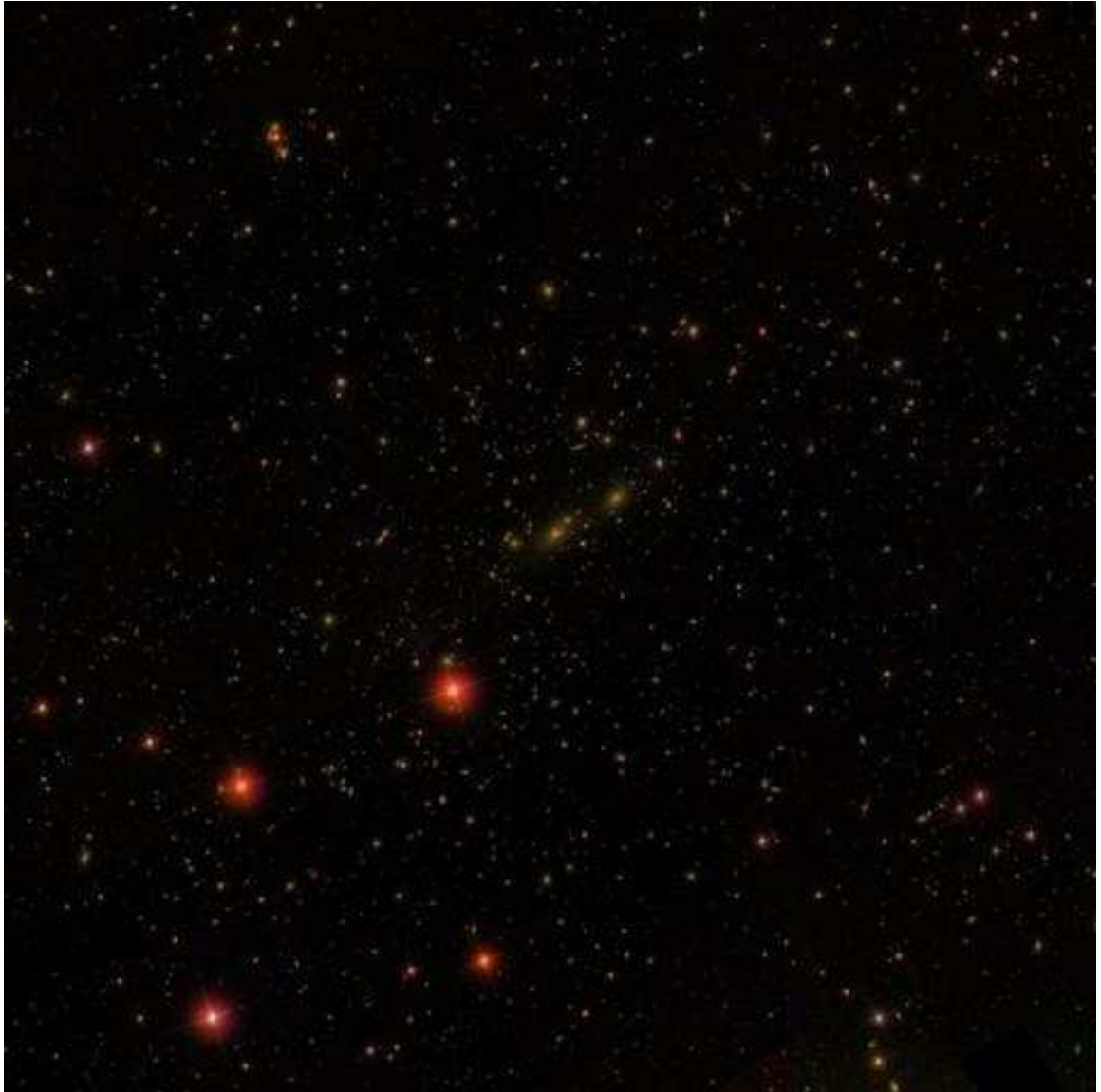


Figure A.16: Abell 2142, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

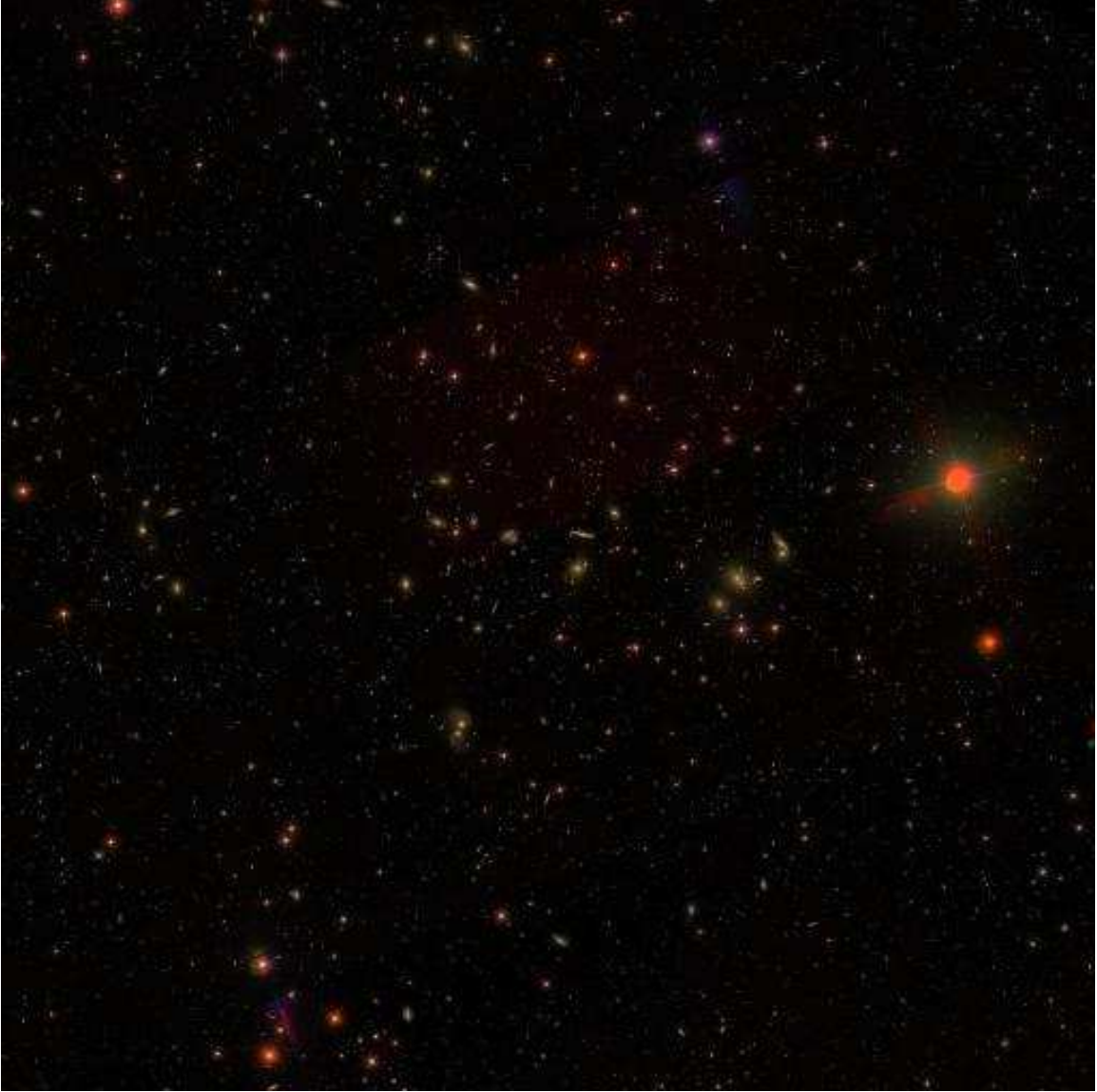


Figure A.17: Abell 2151, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

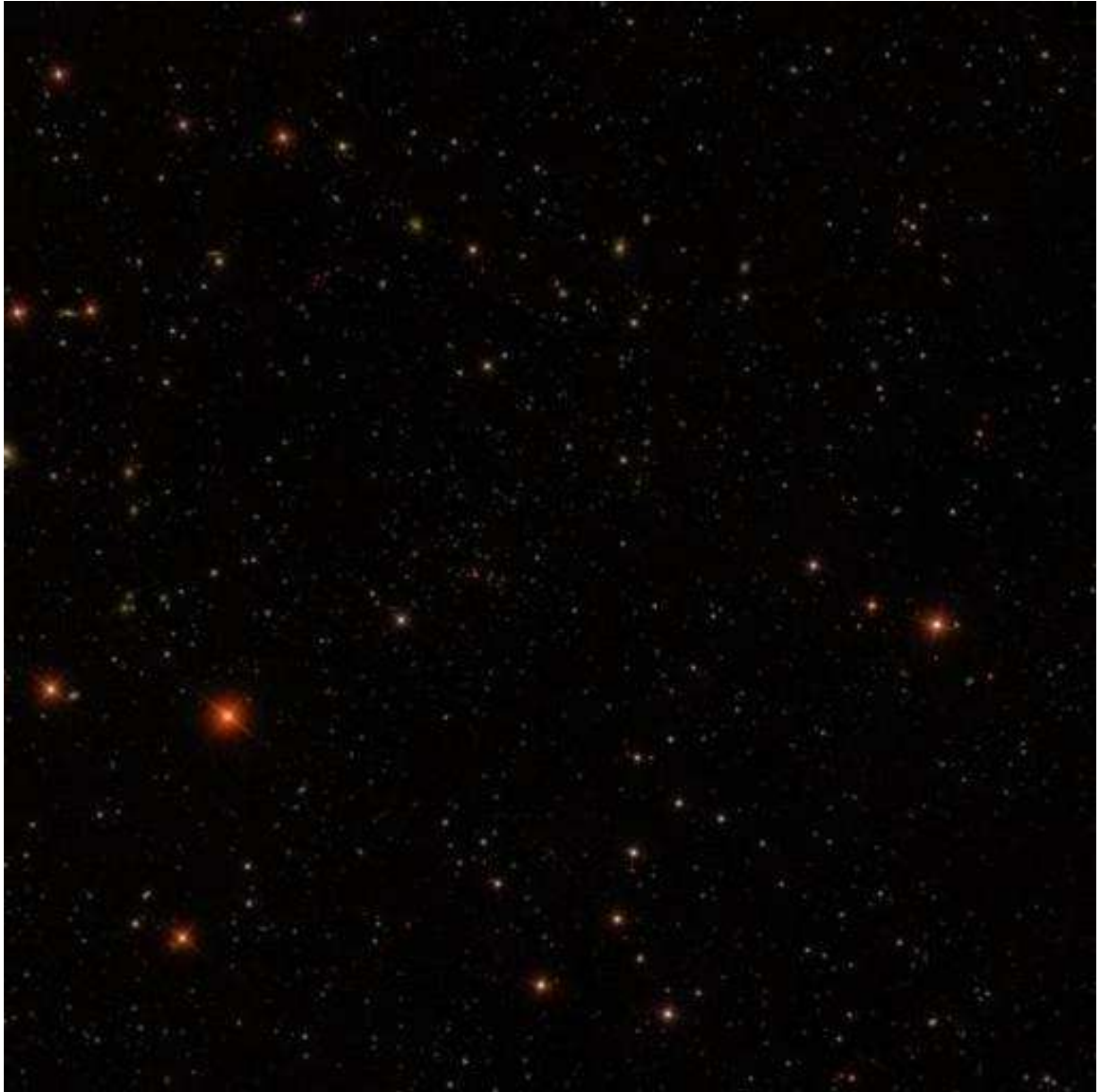


Figure A.18: Abell 2198, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

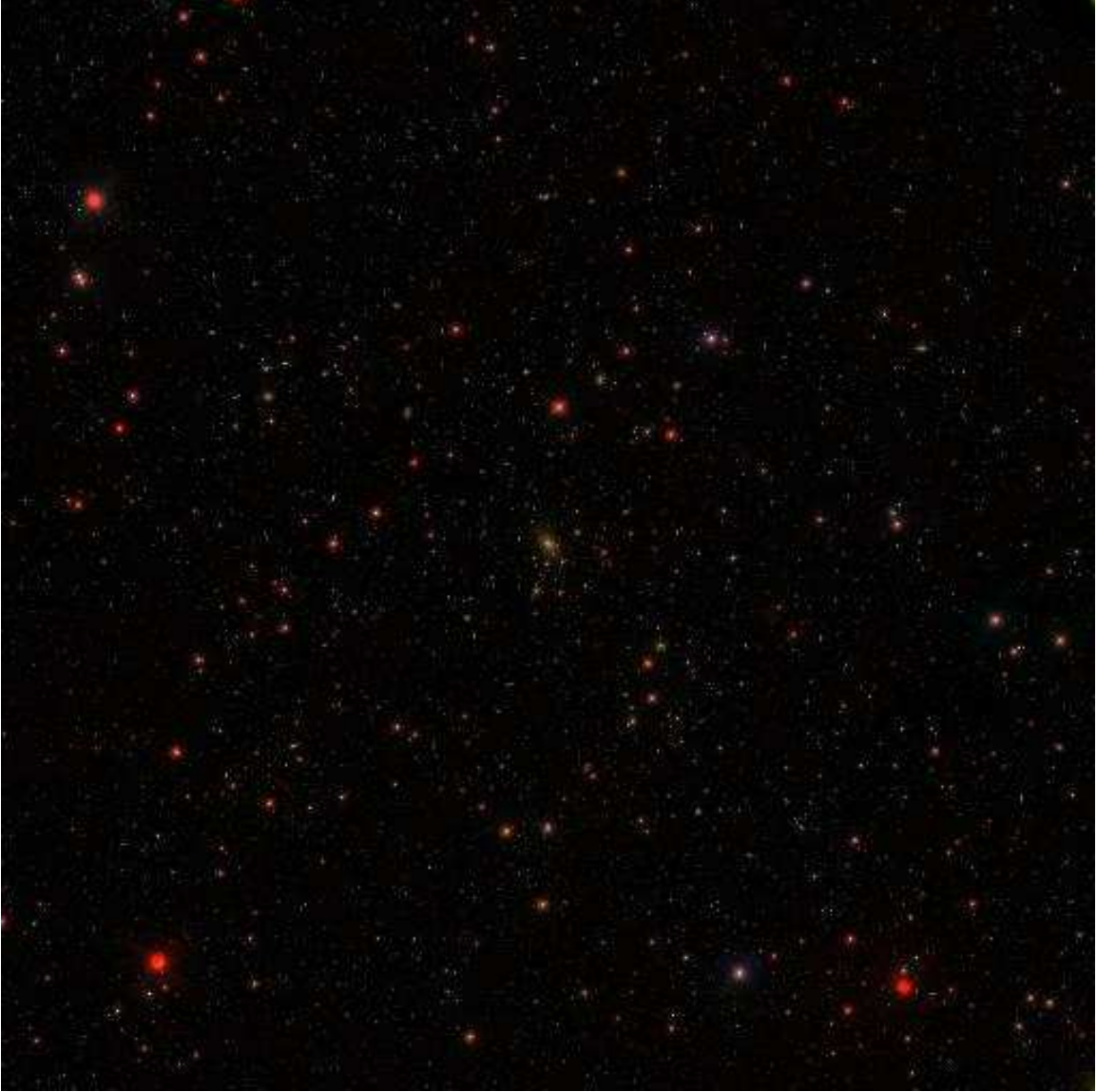


Figure A.19: Abell 2199, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

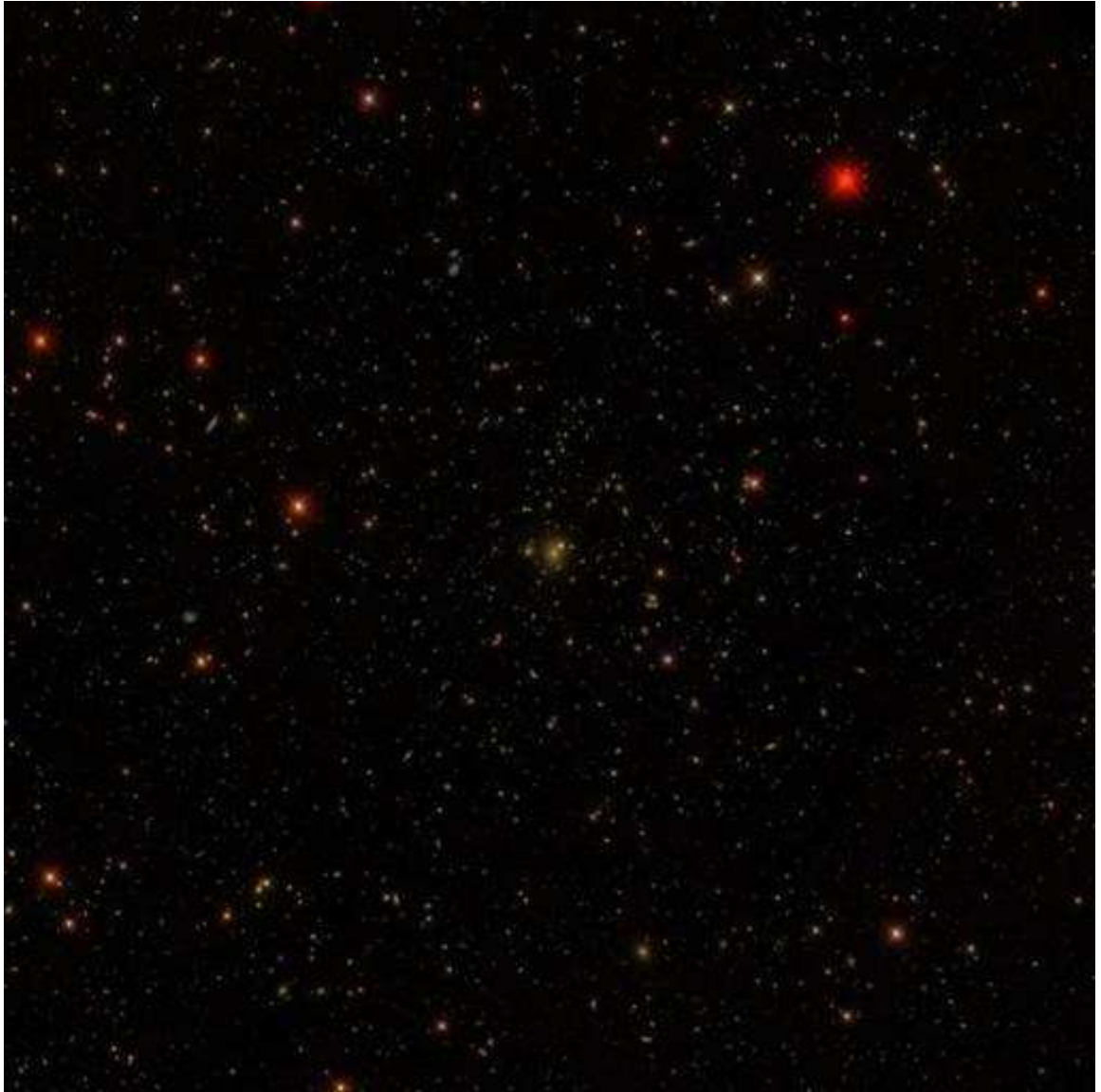


Figure A.20: Abell 2244, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

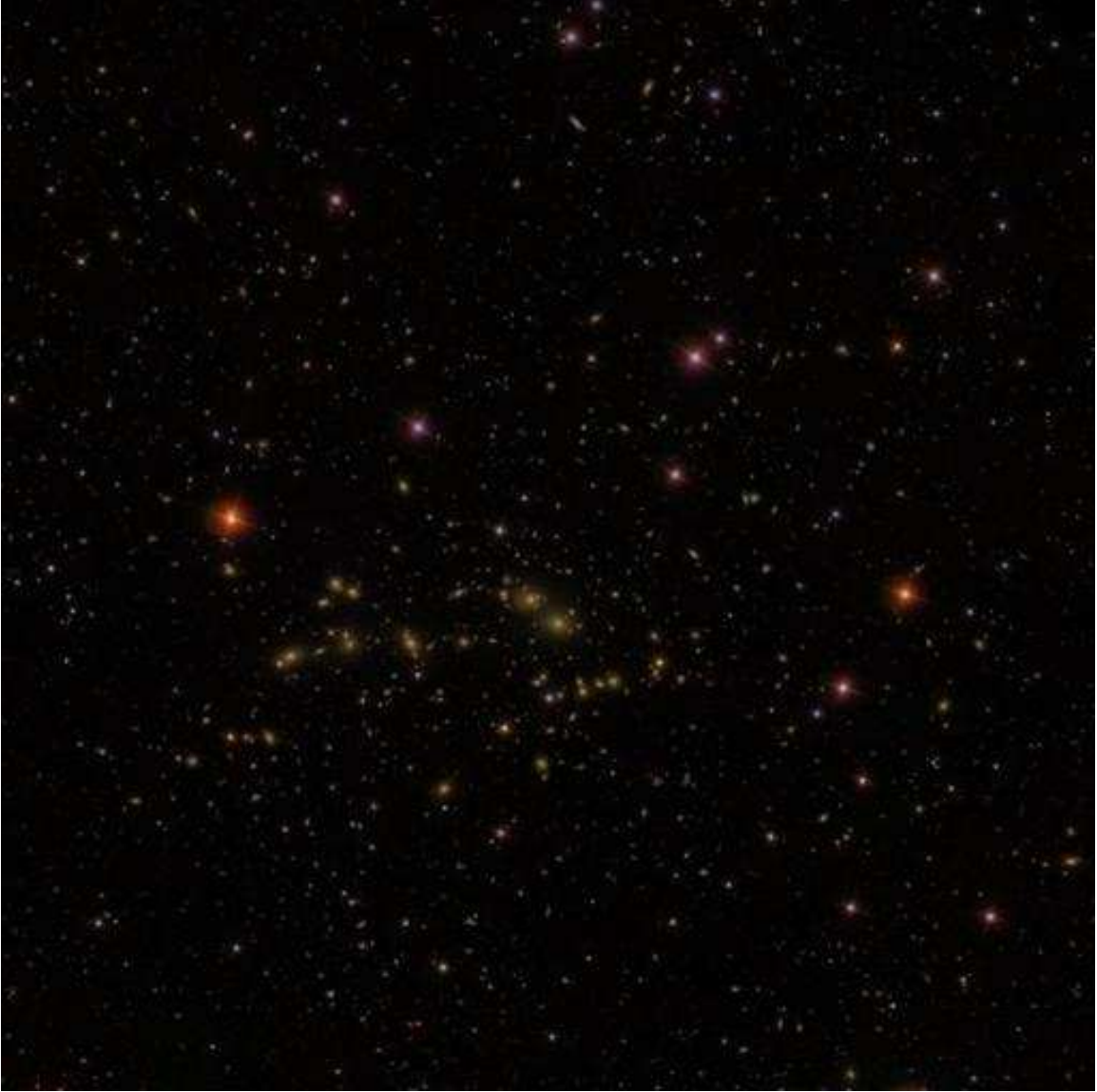


Figure A.21: Abell 2255, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

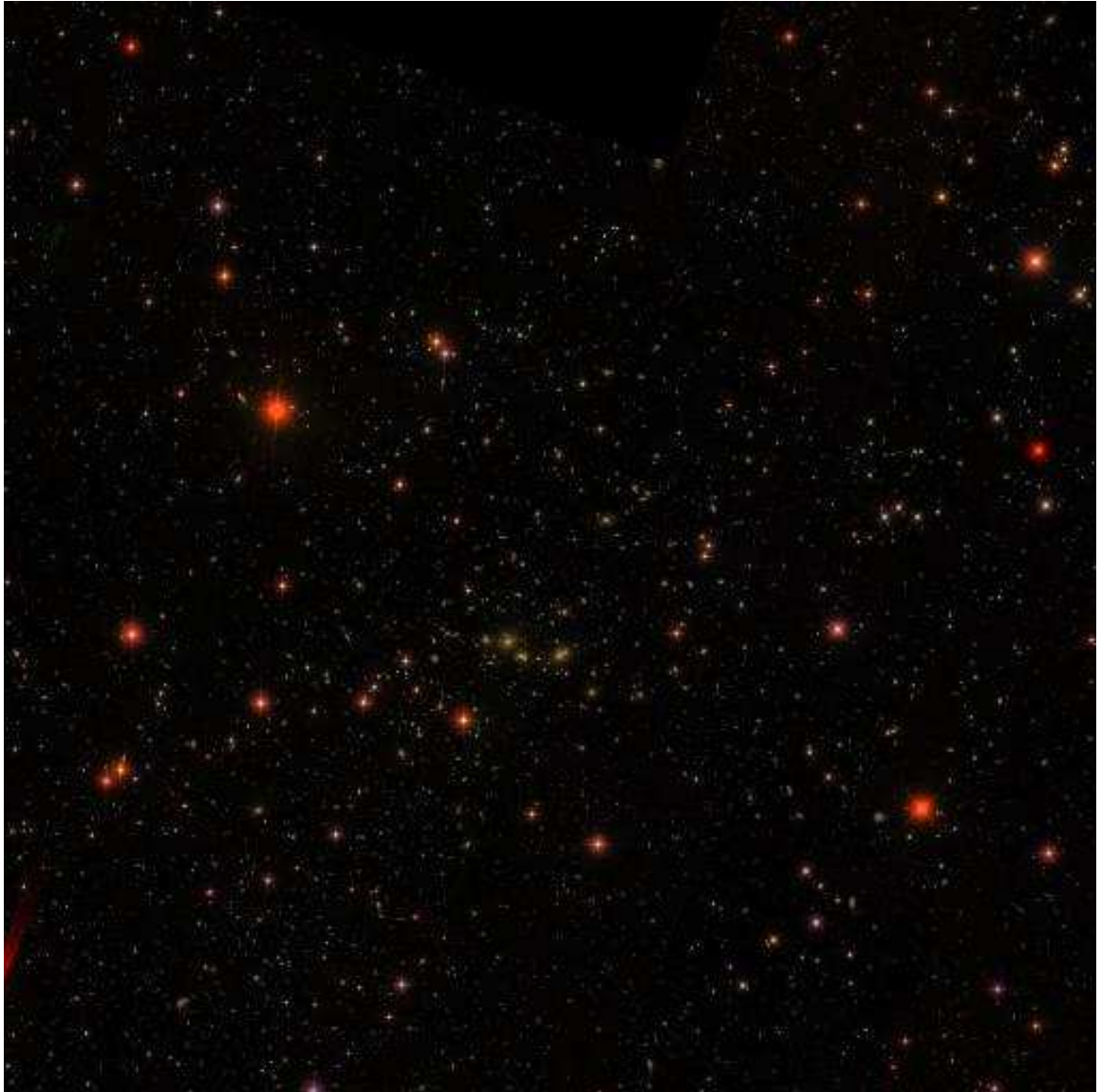


Figure A.22: Abell 2256, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

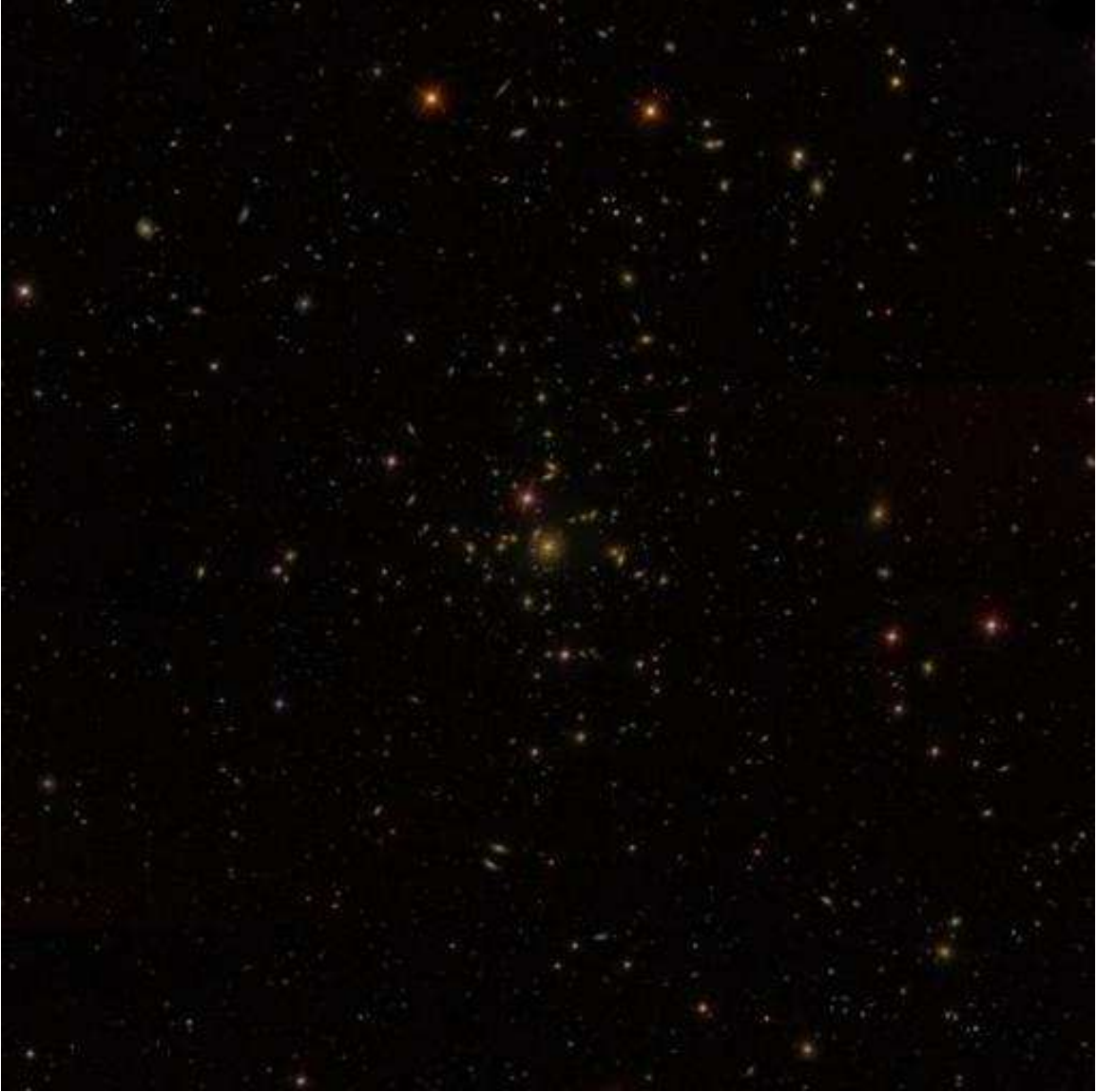


Figure A.23: Abell 2670, using SDSS DR10 imaging. North is up, East to the left. The image side is equal to $2 \times R$, where R is the aperture radius (see Table 4.1).

Appendix B

Red Sequence of the Local Sample of Clusters

APPENDIX B. RED SEQUENCE OF THE LOCAL SAMPLE OF CLUSTERS

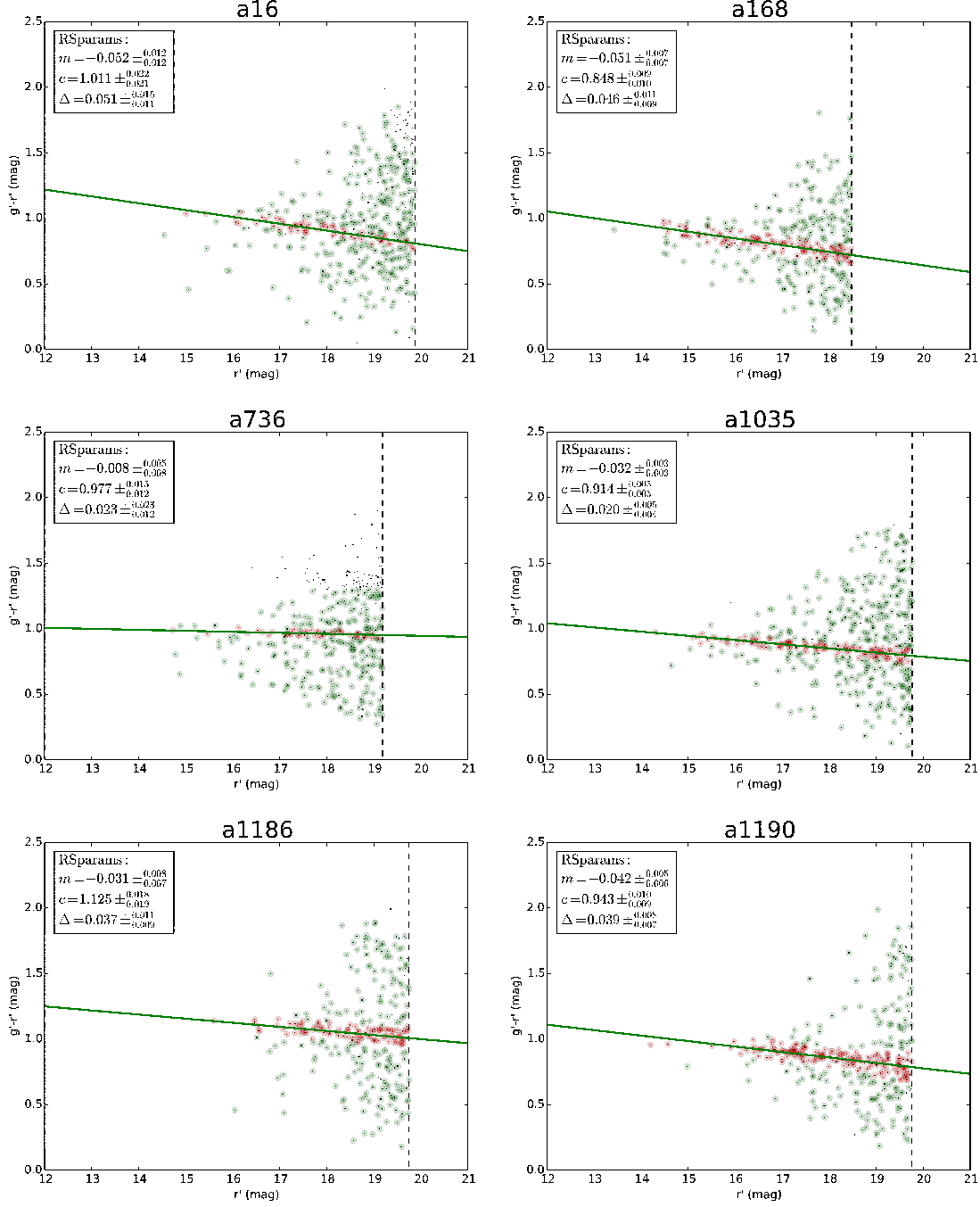


Figure B.1: CMD for all the clusters in the local sample. The symbols are as in Fig. 4.1.

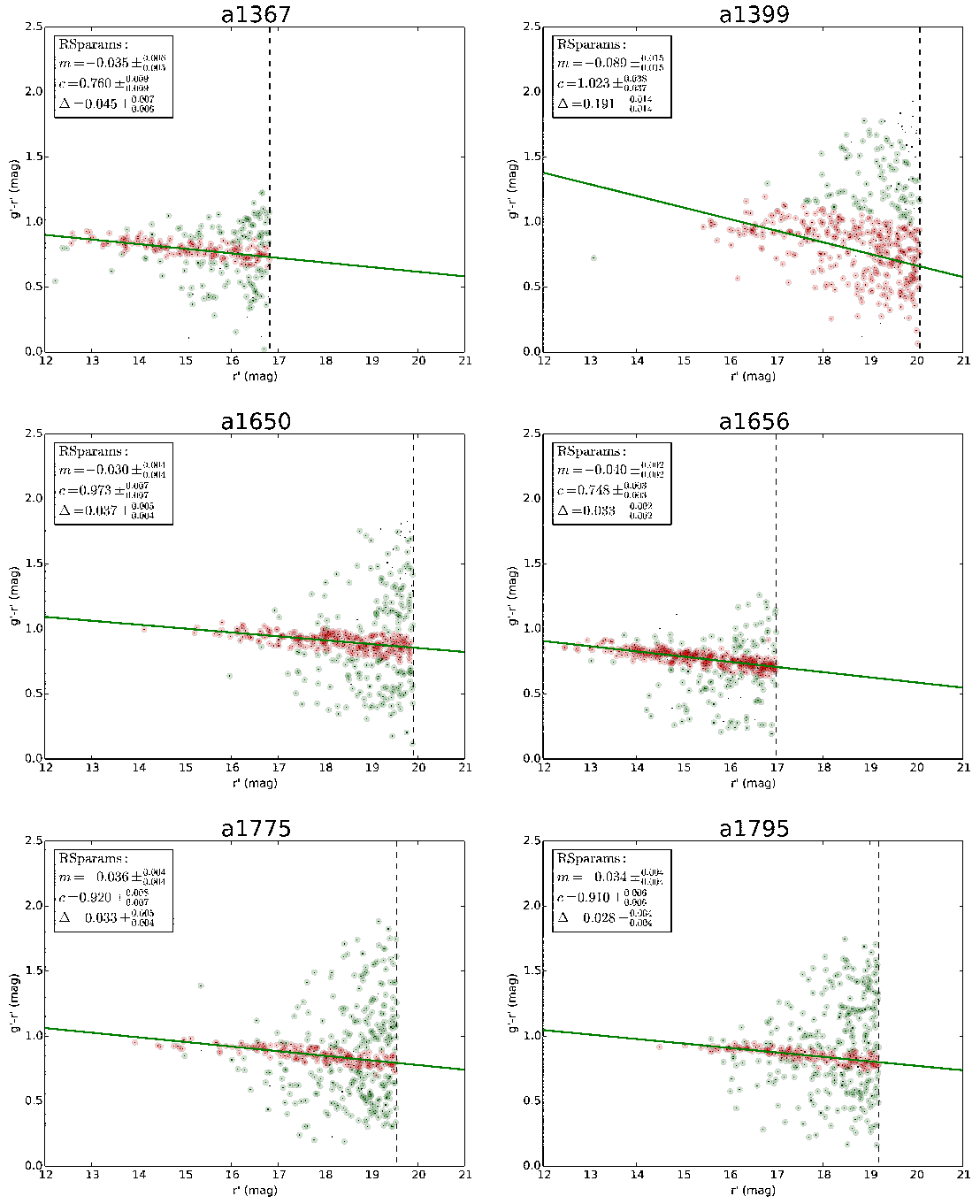


Figure B.1: (continued)

APPENDIX B. RED SEQUENCE OF THE LOCAL SAMPLE OF CLUSTERS

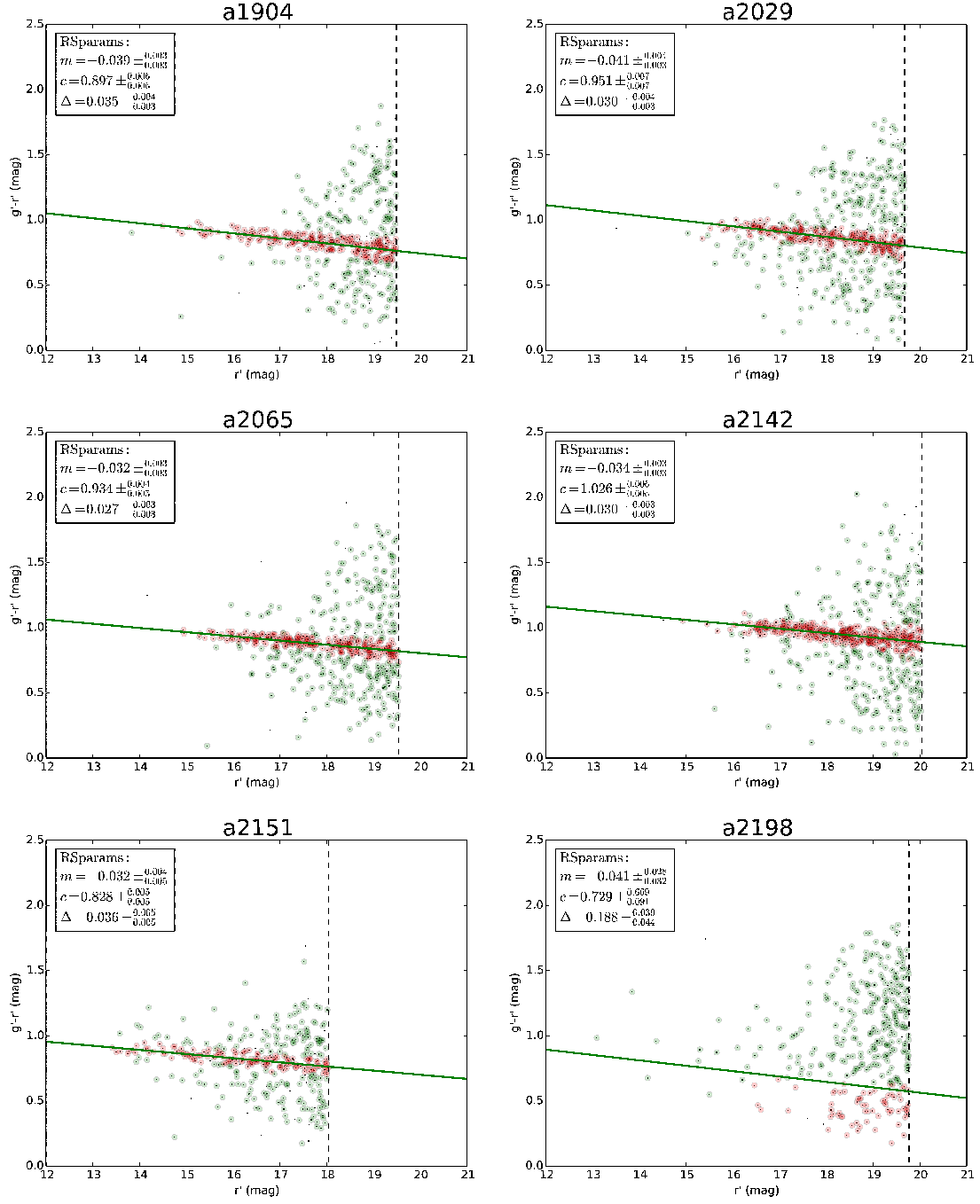


Figure B.1: (continued)

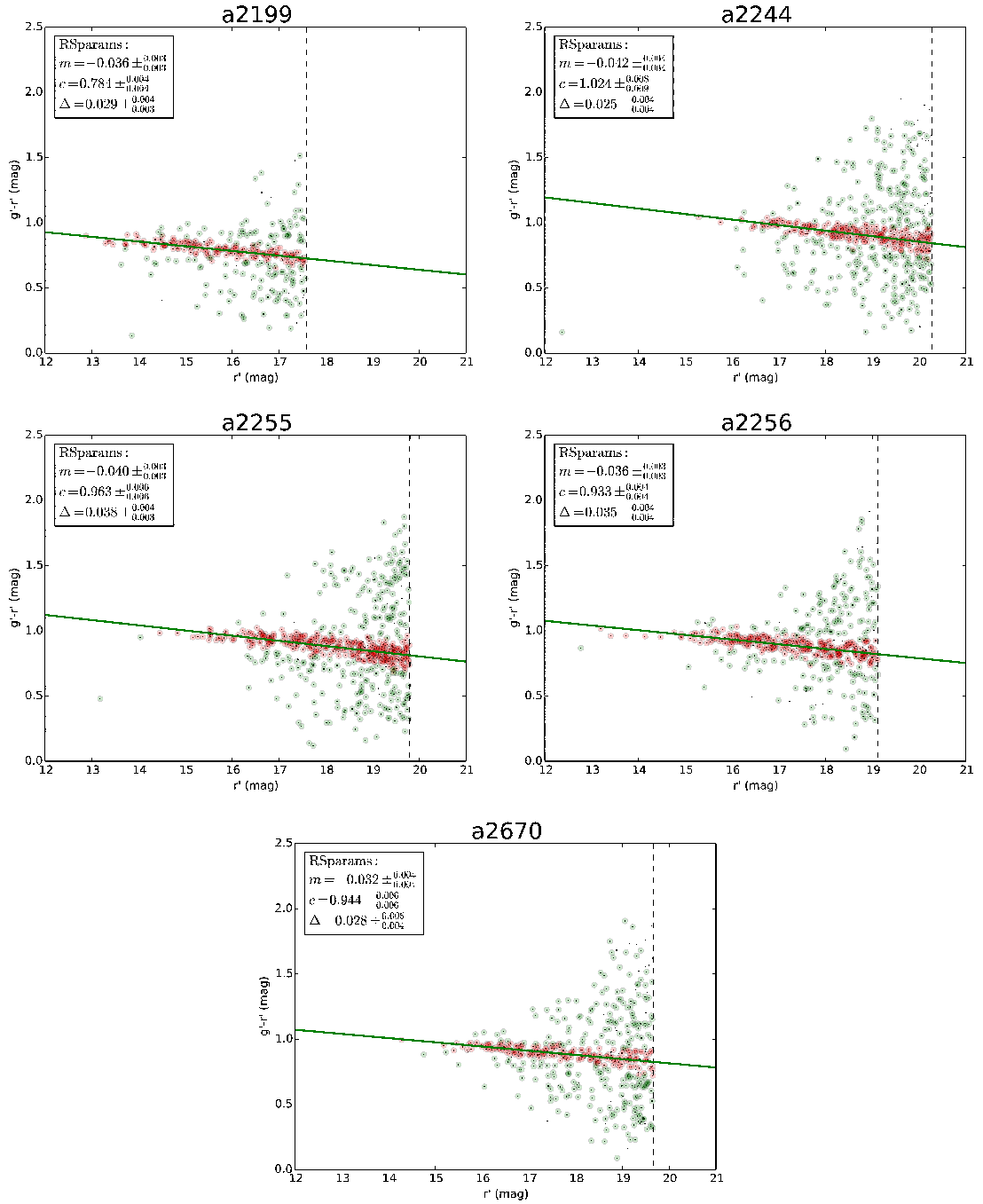


Figure B.1: (continued)

APPENDIX B. RED SEQUENCE OF THE LOCAL SAMPLE OF CLUSTERS

Appendix C

Average ellipticity for the Local Sample of Clusters

APPENDIX C. AVERAGE ELLIPTICITY FOR THE LOCAL SAMPLE OF CLUSTERS

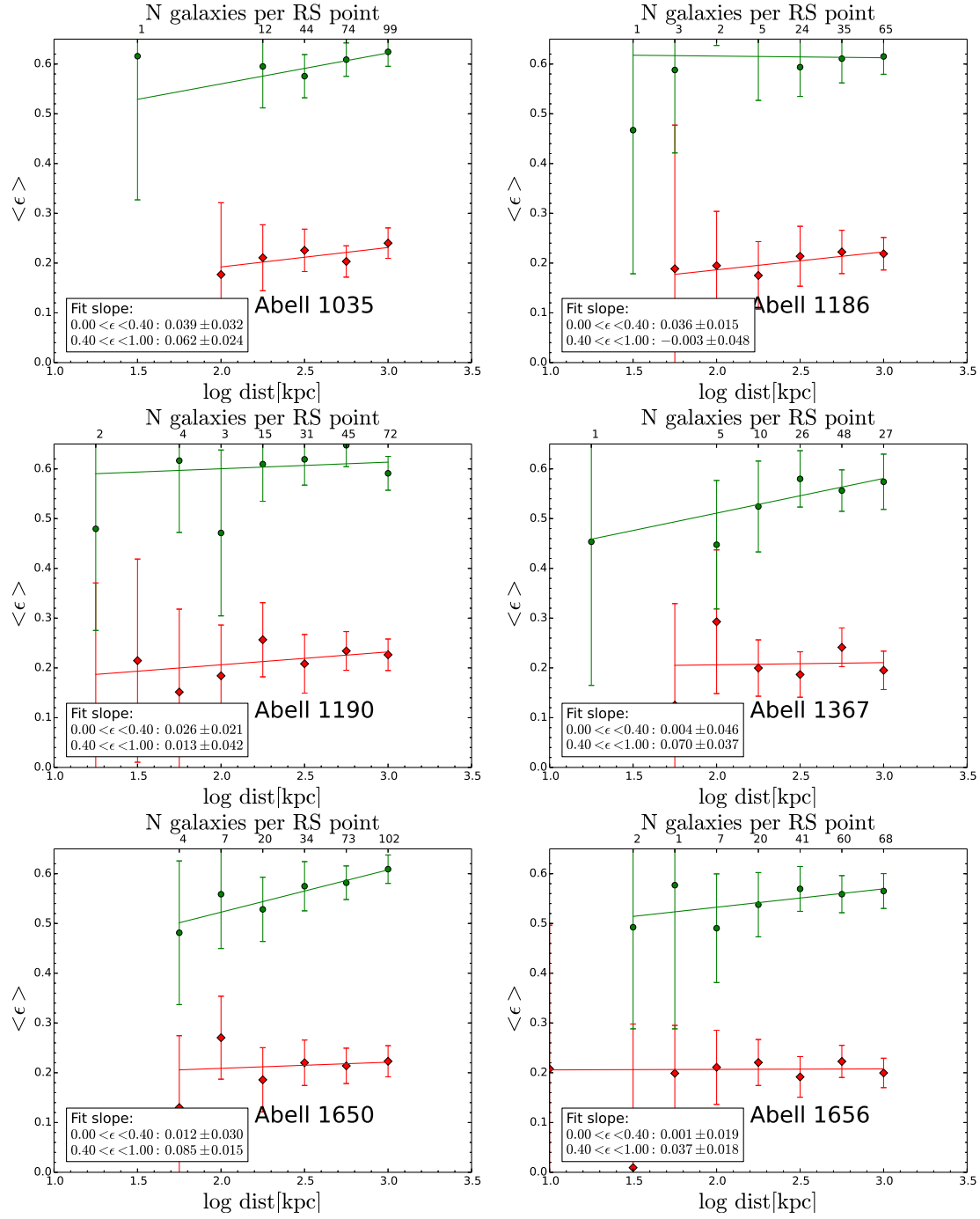


Figure C.1: $\langle \epsilon \rangle$ as a function of $\log d$, same as Fig. 5.2 but for all the local clusters with a reliable RS.

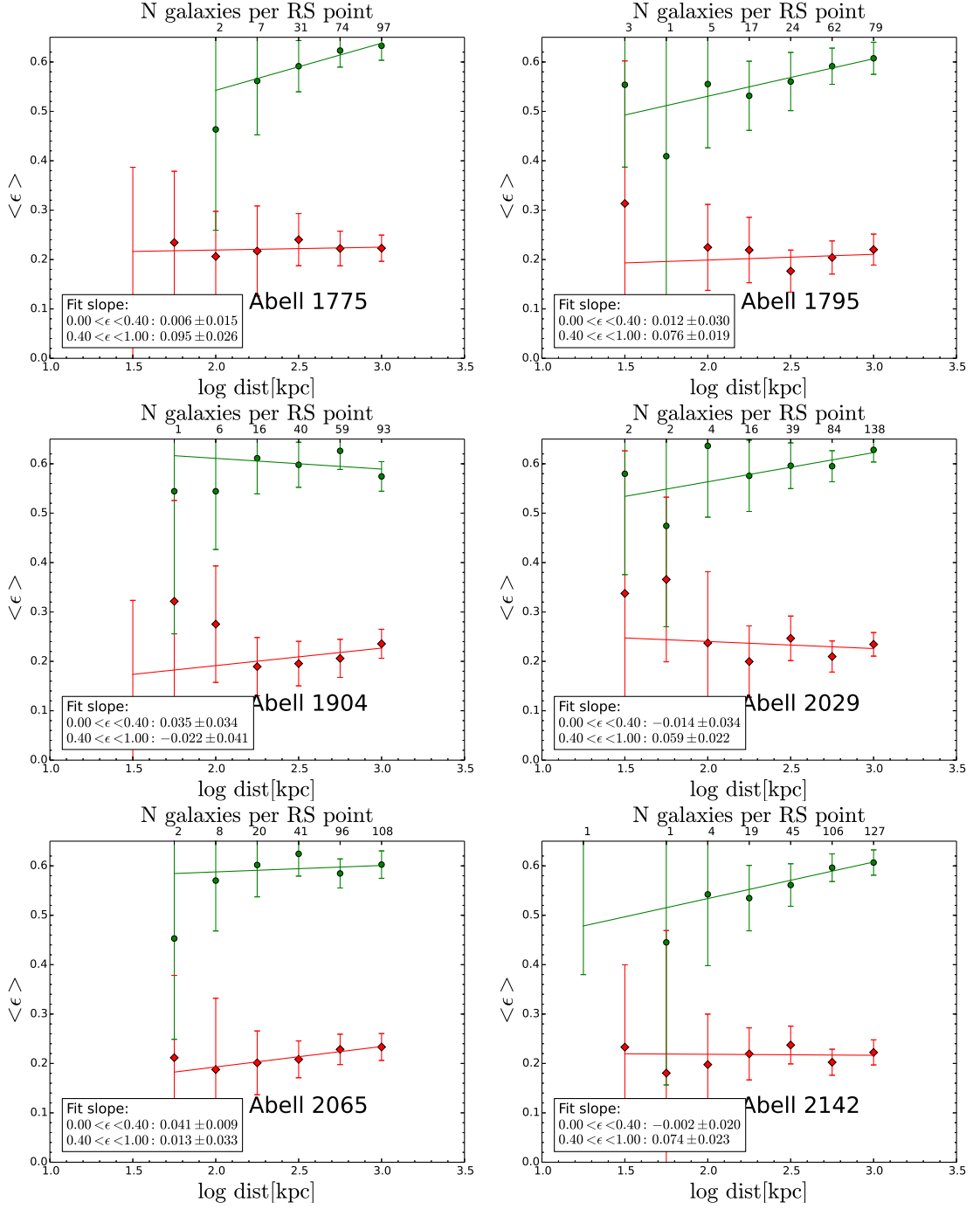


Figure C.1: (continued)

APPENDIX C. AVERAGE ELLIPTICITY FOR THE LOCAL SAMPLE OF CLUSTERS

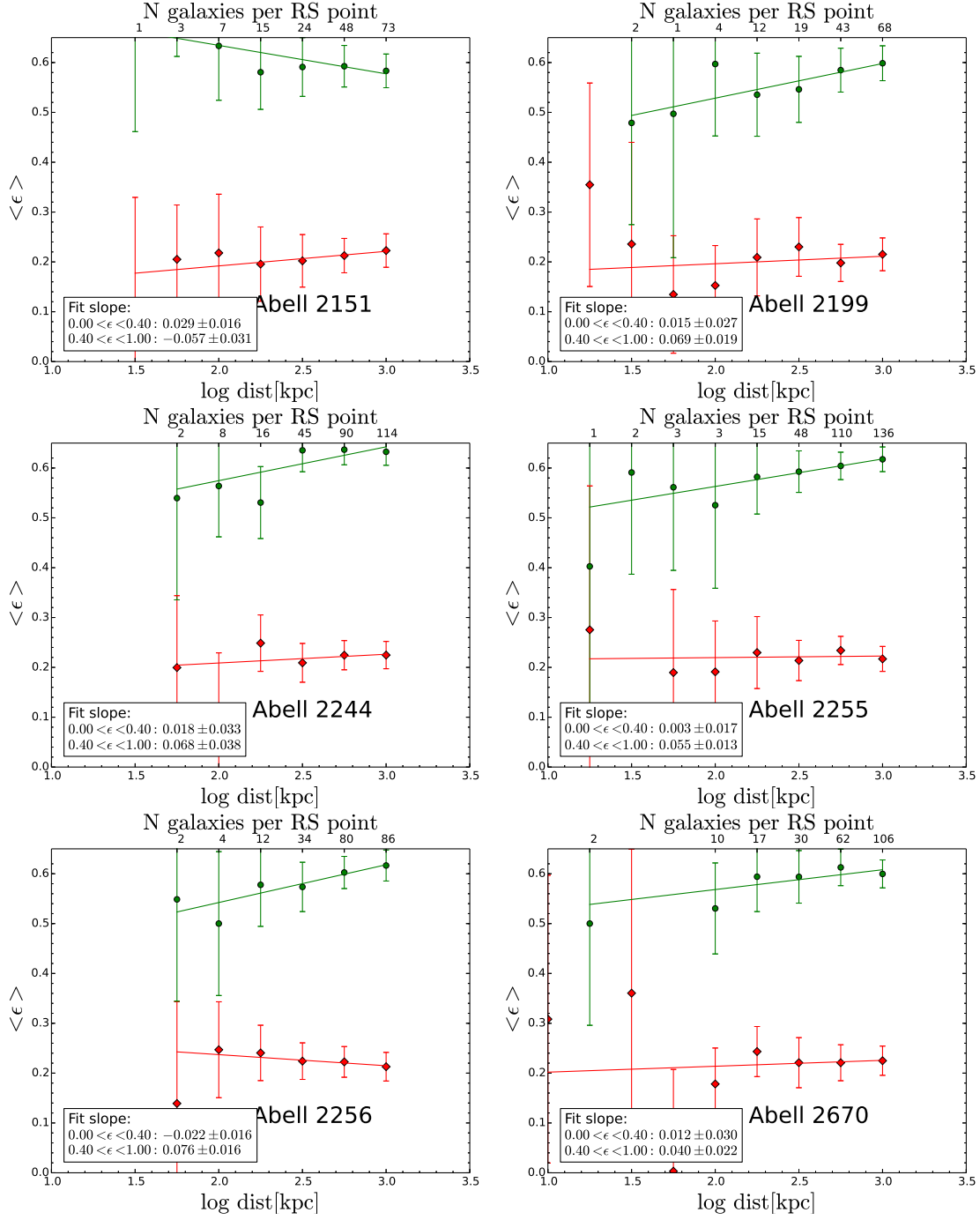


Figure C.1: (continued)

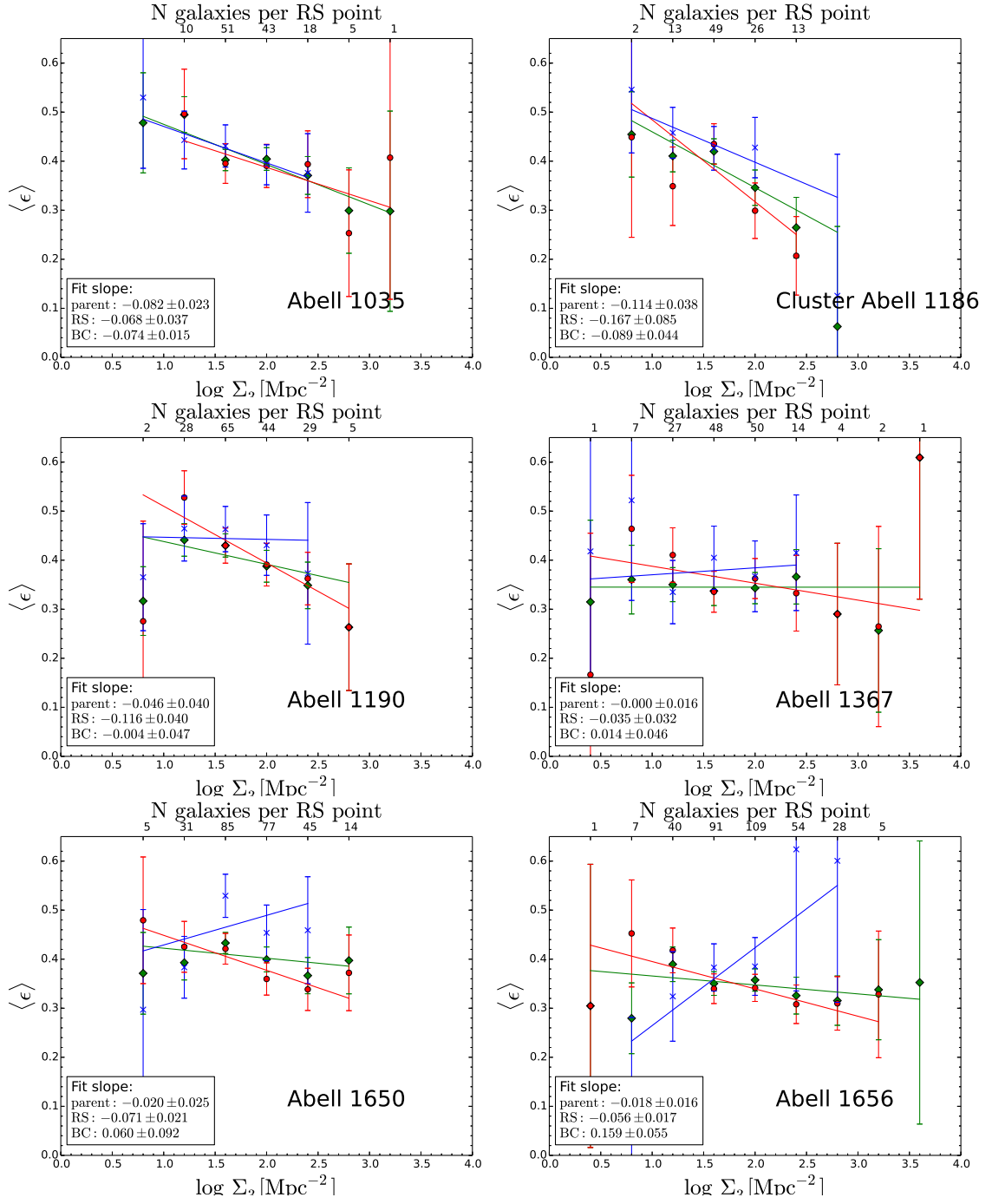


Figure C.2: $\langle \epsilon \rangle$ as a function of $\log \Sigma_3$, same as Fig. 5.3 but for all the local clusters with a reliable RS.

APPENDIX C. AVERAGE ELLIPTICITY FOR THE LOCAL SAMPLE OF CLUSTERS

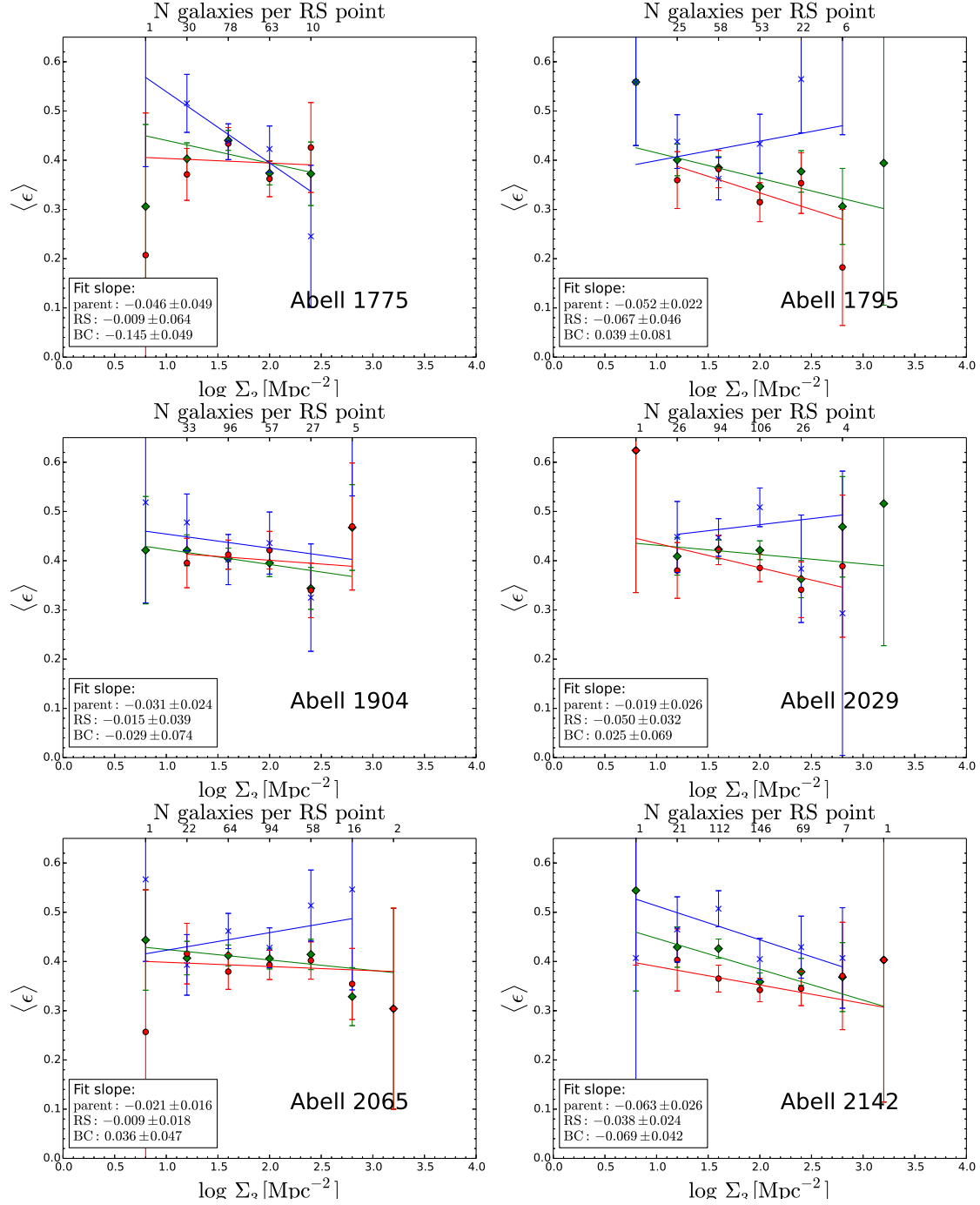


Figure C.2: (continued)

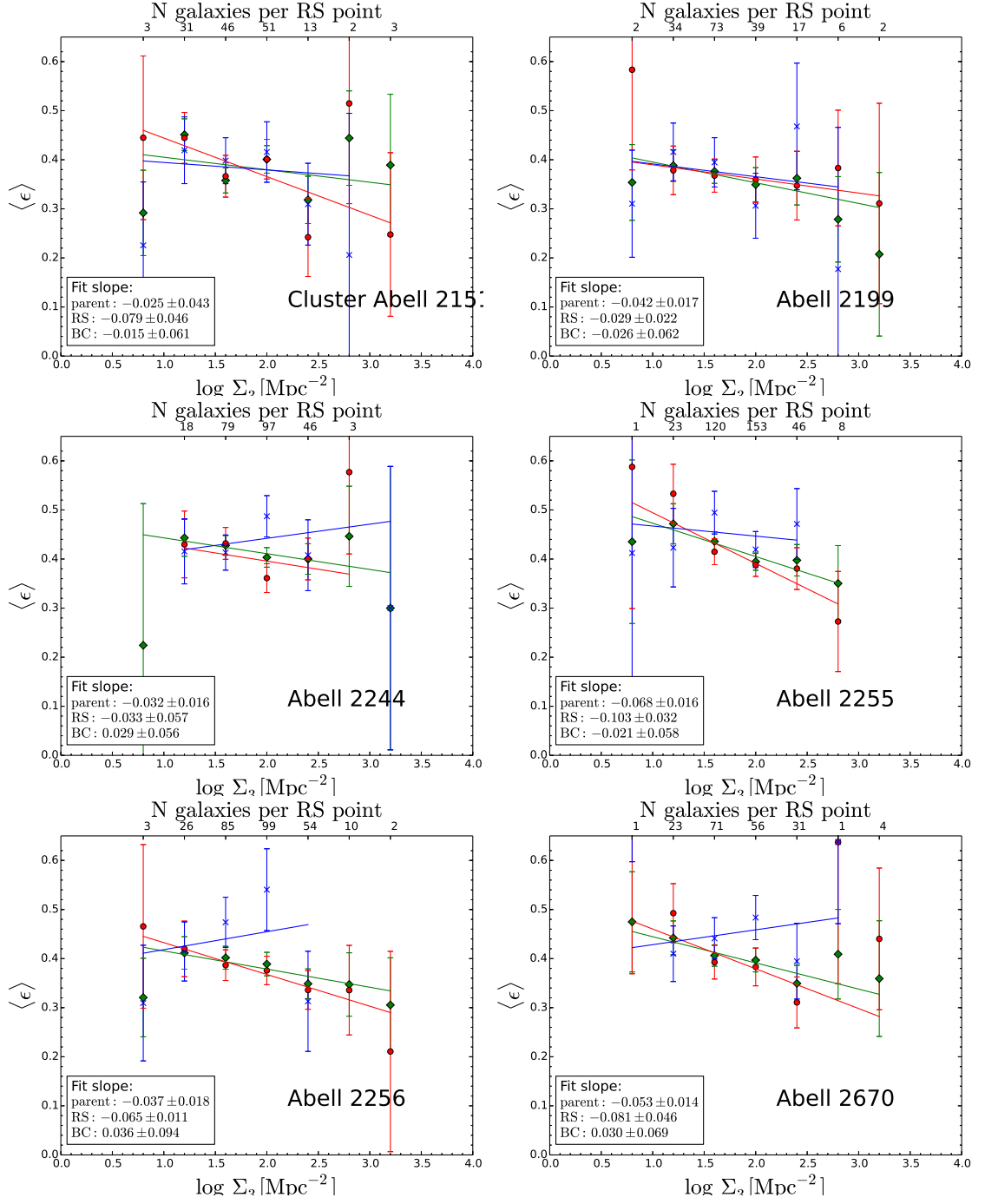


Figure C.2: (continued)

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