

Variation of Stellar Populations and Dark Matter of Galaxies with Time and Environment



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This dissertation is submitted for the degree of

Doctor of Philosophy

Hertford College

April 2017

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

Chapter 2 and Chapter 3 are presented as published in the following journals respectively:

Shravan Shetty and Michele Cappellari, 2014, ApJL, 786:L10

Shravan Shetty and Michele Cappellari, 2015, MNRAS, 454, 1332-1357

Shravan Shetty

April 2017

Acknowledgements

Though I am technically the author of this thesis, I must admit that this thesis wouldn't be possible without the continuous support and encouragement by many people. First and foremost of these is my supervisor Prof. Michele Cappellari without whom I wouldn't have successfully produced a thesis that I can be proud of. Working with him has been a continuous journey for learning new things and discovering new unknowns. I appreciate his patience with me and thank him for all that he has taught me. I would also like to thank my examiners, Prof. Roger Davies and Prof. Ricardo Schiavon, for their valuable inputs on the thesis and for making my thesis defence a truly pleasant and enjoyable experience.

I would also like to thank Bipana Bantawa. She always ensured that I was focused and without her support and guidance made the write up phase pleasant and helped me complete the thesis in a timely manner.

I would also like to thank my friends, who never let my time in Oxford be a dull one. Particularly I would like to thank Edward Gillen, Thibaut Louis and Jean Teyssandier who added significant amount of spice to my life and left me with wonderful stories to tell in a pub. I would also like to thank Vikaran Khanna and Challenger Mishra with whom I have spent many a nights goofing around.

Finally, but most importantly, I would like to thank my parents for giving me the opportunity to follow my dreams and making all of this possible. Though this thesis is authored by me, it is in fact the result of the love, patience and hard work of my parents. For this and everything in my life, I am forever grateful to them.

Abstract

In this thesis, I probe the stellar and dark matter component of galaxies in order to infer their evolutionary histories. I am doing this by studying two distinct galaxy population samples: (i) a high redshift sample at $z \sim 1$, and (ii) a high density environment sample of galaxies in the nearby Coma cluster. By comparing these samples to a sample of galaxies in the local Universe in a low density environment, I infer variation in their properties as a function of time and environment.

For both samples, I create accurate dynamical models to infer the stellar Mass-to-Light ratios of the galaxies and their dark matter fractions. Furthermore, I model the stellar population of the galaxies using a full-spectrum technique while reproducing their star formation history in a non-parametric manner. In addition, I use IFS data for a subset of galaxies in the high density sample to create detailed dynamical models that strengthen the results found in that sample.

Based on the quantities derived from these analyses, I present results on the IMF normalisation and dark matter fraction of galaxies in both samples. Furthermore, I studied the scaling relations of these galaxies and compared them to that observed for the ATLAS^{3D} sample, which serves as a low density sample of the Local Universe, to infer variation in galaxy properties as a function of time and environment.

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Chapter 1

Introduction

Galaxies have been used as tools for Cosmology, Astrophysics and Particle Physics since their discovery as objects distinct from the Milky Way. A study of the recession velocities of galaxies was the pioneering discovery that led to the currently accepted paradigm of an expanding Universe, while the Active Galactic Nuclei of galaxies provides insights into high-energy physics and particle physics that cannot be studied on Earth. However, the formation and evolution of galaxies themselves have remained shrouded in dust. Great progress has been made in understanding the formation and evolutionary processes that effect the evolution of galaxies however, no conclusive paradigm has been established. In this Chapter, I present the context upon which I have carried out my research to probe the evolution of galaxies. The initial section presents the Cosmological context which led to the formation of galaxies. This is followed by a brief summary of what we understand of their evolution. The third section provides details on the methods used in this study, and is followed by an outline of the remainder of the thesis.

1.1 Λ CDM Paradigm

1.1.1 Cosmological Background

The process of galaxy formation is one that is closely entangled with the formation of the Universe. At present, the Λ CDM paradigm for Cosmology is the widely accepted model of the Universe we live in (Hinshaw et al., 2013; Planck Collaboration et al., 2014, 2015). Within this paradigm, the observable universe, i.e. the baryonic matter observed in galaxies, stars, gas etc., constitutes $\sim 5\%$ of the Universe while the rest is composed of mysterious dark matter and dark energy. Dark matter is as of yet, unobserved by any telescope or instruments, however this hypothetical matter is required to explain the observed kinematics of the stars and gas in galaxies and galaxy clusters (e.g: Zwicky, 1933; Rubin et al., 1985; van Albada et al., 1985). Despite the lack of direct observations, several contenders for what this matter may consist of have been proposed, such as weakly interacting massive particles (WIMPs), axions, sterile neutrinos etc (Bergström, 2009; Feng, 2010). The temperature of dark matter particles plays an important role in the formation and evolution of the large scale structure of the Universe. The two primary models for this are the warm dark matter and cold matter. Assuming a cold dark matter particle, the Λ CDM model has been highly successful in modelling the structures that astronomers observe today (White & Rees, 1978; Blumenthal et al., 1984). One such example is presented in Fig. 1.1 where the simulated large-scale structure of the Universe appears statistically indistinguishable from its observations.

As per the Λ CDM paradigm, this matter constitutes $\sim 25\%$ of the energy density of the Universe. The remaining $\sim 70\%$ of the energy density of the Universe is comprised of dark energy. Though the source of this energy density is yet to be determined, its effect is observed in the accelerating rate of expansion of the Universe as observed by Supernovae surveys, CMB etc (Riess et al., 1998; Perlmutter, Turner & White, 1999; Eisenstein et al., 2005; Percival et al., 2010; Mortonson, Weinberg & White, 2014).

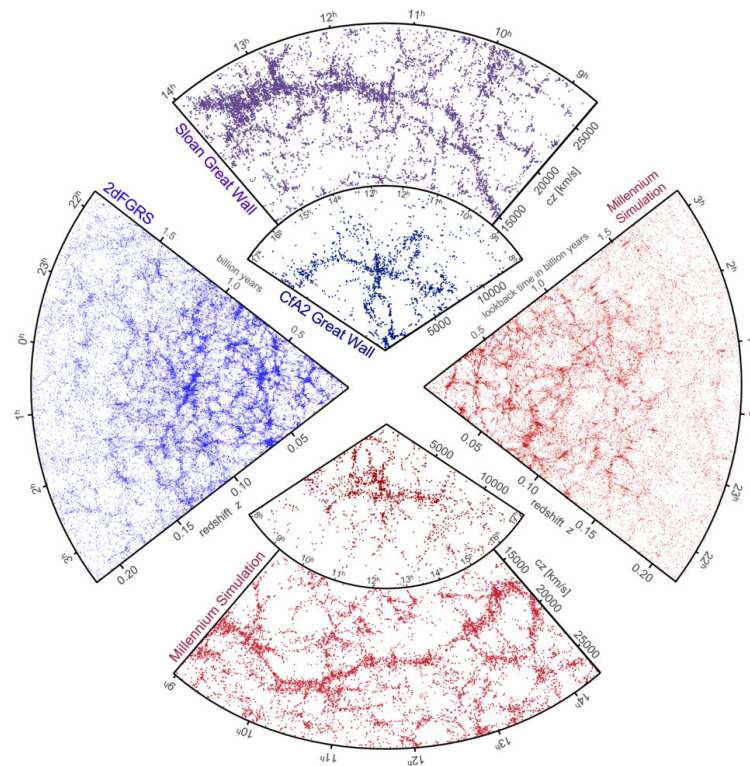


Fig. 1.1 In this plot, the top cone depicts the large scale structure of the Universe in the northern sky, as seen by the CfA2 (small cone) (Geller & Huchra, 1989) and SDSS (larger cone) (York et al., 2000). The left presents similar observations made of the southern sky by the 2dFGRS (Colless et al., 2001). The cones in the bottom and the right represent mock galaxy surveys made using semi-analytical techniques applied on the cosmological dark matter simulation of the Millennium simulation. [Credit: Springel, Frenk & White (2006)]

It is commonly accepted today that the Universe began ~ 13.8 Gyrs ago in a singularity event known as the Big Bang (Dodelson, 2003). Not much is understood of the event itself, however today cosmologists have a firm understanding of the evolution of the Universe after 10^{-35} seconds after. Due to the high energies involved, the Universe at this phase was radiation dominated and, due to Thomson scattering, opaque. At this time the Universe underwent an epoch of rapid expansion that froze the quantum density fluctuations of the time as perturbations of density in the Universe. Due to the coupling of the baryonic matter and the radiation, these over-densities were in a state of fluctuating equilibrium as the collapse of the matter due to gravity was compensated by the pressure due to the photon-matter interactions. These fluctuations later gave rise to the Baryonic Acoustic Oscillations that are observed today (Sakharov, 1966; Peebles & Yu, 1970; Sunyaev & Zeldovich, 1970). At 10^{11} seconds after the Big Bang, the free electrons in the Universe combined with nucleons in the Universe that formed at $\sim 10^2$ seconds. This led to the decoupling of the radiation from the baryonic matter as the mean free path of the photons grew and hence made the Universe transparent for the first time. These photons are observed today as the Cosmic Microwave Background and provide us with a glimpse of the Universe at that stage (Hinshaw et al., 2013; Planck Collaboration et al., 2014, 2015). This decoupling allowed the baryonic matter to collapse within the density perturbations, which eventually led to the formation of galaxies.

1.1.2 Galaxy Formation

As the baryonic gas in the early Universe decoupled from radiation, this gas collapsed into the gravitational potentials of the dark matter halos and began forming stars (Blumenthal et al., 1984). At this time the baryonic physics, such as stellar formation, feedback, cooling, metallicity enrichment, AGN feedback etc., began influencing the evolution of the galaxies (White & Rees, 1978; Springel, Di Matteo & Hernquist, 2005), making it difficult following their evolutionary path to present day.

There are two proposed models for the formation of galaxies that are observed today: the Monolithic model (Eggen, Lynden-Bell & Sandage, 1962; Larson, 1975) and the Hierarchical Model (White & Rees, 1978; Blumenthal et al., 1984; Cole et al., 2000). The Monolithic model proposes that the galaxies we observe today formed in a single event of star formation, wherein a large cloud of primordial gas collapsed instantaneously to form the galaxies we observe today. However in light of recent observations, this model is no longer widely accepted. The second model, the Hierarchical model, proposes that the galaxies formed in a “bottom-up” manner, i.e. galaxies grew by the merger of smaller galaxies. Though there is a growing evidence for this model, such as observed mergers of galaxies and evolution of scaling relations of galaxies that are explained by the Hierarchical model (such as the size growth of galaxies etc), many aspects of galaxy formation within the hierarchical model remain unclear.

One approach to distinguish between the two models is through cosmological scale hydrodynamical simulations, that evolve a large volume of space from what is known of the initial conditions of the Universe up to the present day. However, such a simulation would require parsec scale resolution to resolve the complexity of the baryonic physics and would require a volume of a few Mpc^3 to derive sufficient statistics on galaxy populations. Such a simulation is practically limited by today’s technology and technical knowledge, however recent simulations using a phenomenological implementation for the core process that affect galaxy evolution have been successful in predicting some of the scaling and cluster relations of galaxies, e.g: ILLUSTRIS (Vogelsberger et al., 2014), EAGLE (Schaye et al., 2015), FIRE (Hopkins et al., 2014), ezr (Davé et al., 2013) etc.

In light of this, astronomers have developed other innovative techniques to reduce the computational requirements for galaxy simulations. The most popular amongst those are Semi-Analytical Models (SAMs) (Kauffmann et al., 1999; Gonzalez-Perez et al., 2014; Lu et al., 2014; Porter et al., 2014) and Zoom simulations. Both of these simulations build upon

the results of cosmological dark matter simulations, which follow the evolution of the dark matter in the Universe since their formation to present day. Based on the assembly history of these dark matter halos, SAMs use an analytical prescription to translate the dark matter halo distribution of the simulation into a set of galaxy predictions which can then be compared to observations. As expected, these simulations greatly reduce the needed computational resources to create a simulated cosmological prediction. However, it does so using simplified analytical prescriptions for complex physical processes, which are then fine-tuned to ensure that simulated galaxies reproduce observations. Zoom simulations on the other hand select regions of interest within pre-existing cosmological dark matter simulations, based on the research question being studied, and run a full hydrodynamical simulation for these regions. Such an approach is efficient when studying particular galaxy population, however the limited number of simulated galaxies don't permit the interpretation of general galaxy properties from such simulations.

Due to these limitations of numerical simulations, a complete picture of galaxy formation and evolution cannot be attained using only theoretical arguments. However, the simulations have been successful in narrowing down the dominant processes that influence galaxies and, taken together with observations of galaxies, promise to place strong constraints on the models.

1.2 Observations

1.2.1 Stellar Populations

Most observations of galaxies are comprised of the light emitted by the stars that inhabit the galaxies, hence it is critical that the stellar populations of galaxies are well understood before a strong interpretation of galaxy evolution can be made through observations. Furthermore, studying the mass assembly of galaxies can give insights into the formation and evolution

history of the galaxies. The stellar mass assembly history of galaxies can be probed using a number of techniques.

Lilly et al. (1996) used spectroscopic and photometric survey of galaxies at redshift $0 < z < 1$ to study their rest-frame UV luminosity function, the number density of galaxies as a function of their absolute luminosity. The result showed that an evolving luminosity density, wherein the rest frame UV luminosity declined with lowering redshift. This result can be interpreted as a decrease in the star formation rate of galaxies since redshift of $z \sim 1$. Expanding on this work, a number of studies measured the luminosity function of galaxies at different redshifts and in other regions of the wavelength spectrum. These works concluded that the star formation history of the Universe peaked at $z \sim 2$, and that more than half of the observed stellar mass today was formed in $z > 1$ (Madau, Pozzetti & Dickinson, 1998).

Another technique to study the stellar populations of the galaxies is to model them. Early works was based on studying the colour-central velocity dispersion relations of galaxies (Bower, Lucey & Ellis, 1992) however such work was based on significant assumptions. Gradually, the reliability of the stellar population model increased with the use of empirical stellar libraries and an understanding of the alpha-abundances of galaxies. This led to the confirmation of results on the stellar mass assembly by Heavens et al. (2004) (see Fig. 1.2). It should be noted that the modelling of stellar populations is vulnerable to a degeneracy between the age and metallicities of the galaxies (Worthey, 1994) and hence one must be careful when interpreting results of such analysis.

Astronomers attempted to further examine the stellar populations of galaxies, and study the correlations of their parameters of age, metallicity, and alpha-abundances with the physical properties of galaxies. Since these parameters effect all features in a galaxy spectrum, disentangling their effect has proven to be difficult in a galaxy-by-galaxy case, and hence, most results are based on large number statistics and deal with mainly ETGs due to their simpler populations (Schiavon, 2007; Thomas et al., 2010; Johansson, Thomas & Maraston,

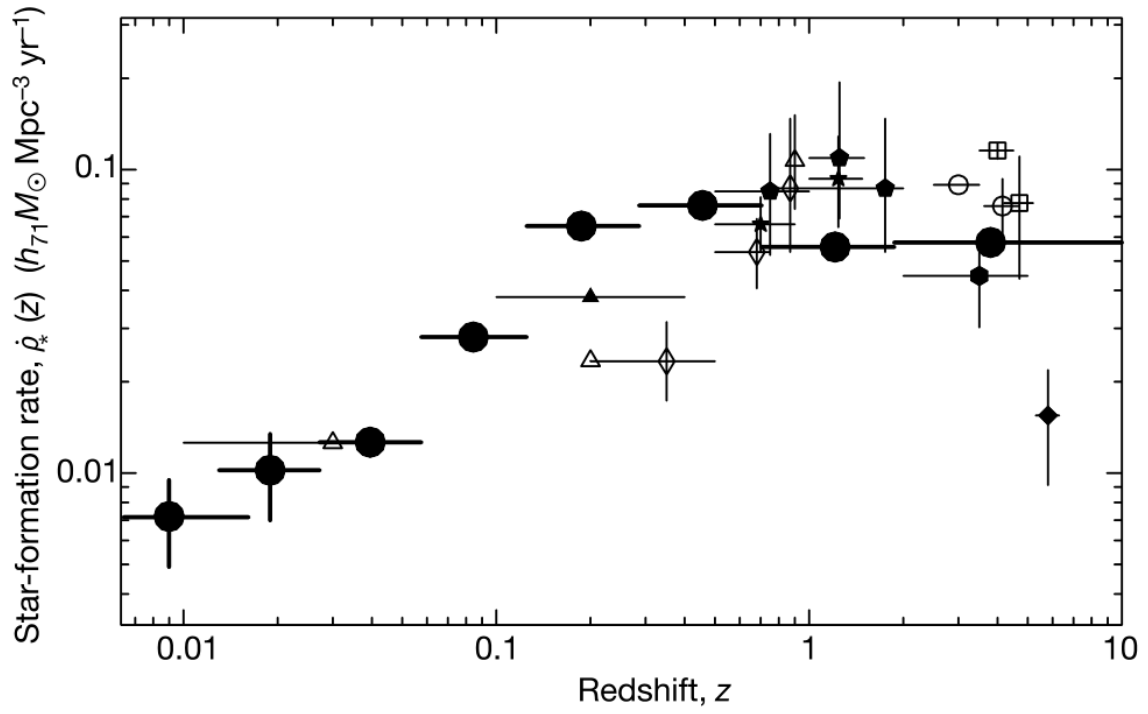


Fig. 1.2 This plot is fig. 1 of Heavens et al. (2004), where the authors analysed the spectra of 96,545 nearby galaxies to determine their star formation histories to conclude that most of the star in nearby galaxies formed at $z < 2$, with the star formation history peaking at $z \sim 0.3 - 0.8$. [Credit: Heavens et al. (2004)]

2012). These studies demonstrate that the mean luminosity-weighted age of galaxies are correlated to their stellar mass, in that the most massive galaxies tend to have older populations. This scenario is known as “downsizing” (Cowie et al., 1996; Brinchmann & Ellis, 2000; Bundy, Ellis & Conselice, 2005). Meanwhile the [Fe/H] metallicity of galaxies demonstrate almost no trends, though the total metallicity and alpha-abundance present a strong positive trend similar to that found in the stellar ages. These results have been confirmed by Conroy, Graves & van Dokkum (2014), where the authors have used a sophisticated stellar spectrum fitting code, that is robust to the varying the abundance ratios of galaxies and their IMF.

Attempts have been made to complement these results with that from high redshift. A study of the high redshift quiescent galaxies illustrate that there has been very little metallicity evolution since $z \sim 1$ (Schiavon et al., 2006; Choi et al., 2014; Gallazzi et al., 2014). However, a comparison of their ages with their local counterparts suggest that the quiescent galaxy population has had small amounts of star formation since $z \sim 1$ (“frosting”) or recently quenched star-forming galaxies, with metallicities close to that of quiescent galaxies, have recently joined the quiescent galaxy population.

1.2.2 Initial Mass Function

The main tool that astronomers use to study the stellar populations of galaxies are the synthetic stellar populations models. Additionally, these models are crucial for the development of simulations of cosmological simulations, and for the comparison of the models with observations. However, these models and their implementation are based on certain explicit and implicit assumptions and it is important that these assumptions are tested and understood to ensure that the results of stellar population analysis are interpreted accurately. One assumption used in stellar population modelling of galaxies is that of the universal Initial Mass Function (IMF) of galaxies (See Bastian, Covey & Meyer 2010 for review).

The IMF is the functional form of the distribution of the stars formed within bins of stellar mass during a single event of star formation. This function was first studied by Salpeter (1955) over 50 years ago. Using direct star counts in star clusters within the Milky Way, Salpeter (1955) showed that the IMF is an universal function of the form:

$$\frac{dN}{dm} \propto m^{-\alpha} \quad (1.1)$$

where m is the stellar mass, N is the number of stars within mass bin, dm and $\alpha \approx -2.35$ for $m > 0.4M_{\odot}$.

Evidence based on the observation of stars in the Milky Way and other nearby galaxies demonstrated an universal IMF within the Milky Way (Kroupa, 2001; Bastian, Covey & Meyer, 2010, and references therein) described accurately by the Chabrier IMF (Chabrier, 2003) and the Kroupa IMF (Kroupa, 2001), which differ from a Salpeter IMF due to a smaller fraction of low mass stars. This universality was further supported by extragalactic studies, where authors have used sub-maximality arguments for the disks of spiral galaxies to rule out Salpeter IMF for these galaxies.

Early results based on gravitational lensing suggested that ETGs may have Salpeter-like IMF mass normalisation (Auger et al., 2010). These studies however could not rule out a Chabrier-like IMF due to the degeneracy in these results between the IMF normalisation of the galaxies and their dark matter fraction. A solution for this degeneracy was provided by van Dokkum & Conroy (2010) who used spectral features sensitive to low mass stars (Schiavon, Barbuy & Singh, 1997; Schiavon et al., 1997; Schiavon, Barbuy & Bruzual A., 2000; Cenarro et al., 2003) in the spectra of 8 ETGs to discover that these galaxies are very abundant in such stars and that this abundance cannot be explained by the IMF found in the disk of the Milky Way. Furthermore, application of this method on globular clusters found that the IMF of these clusters were consistent with that of Chabrier-like IMF.

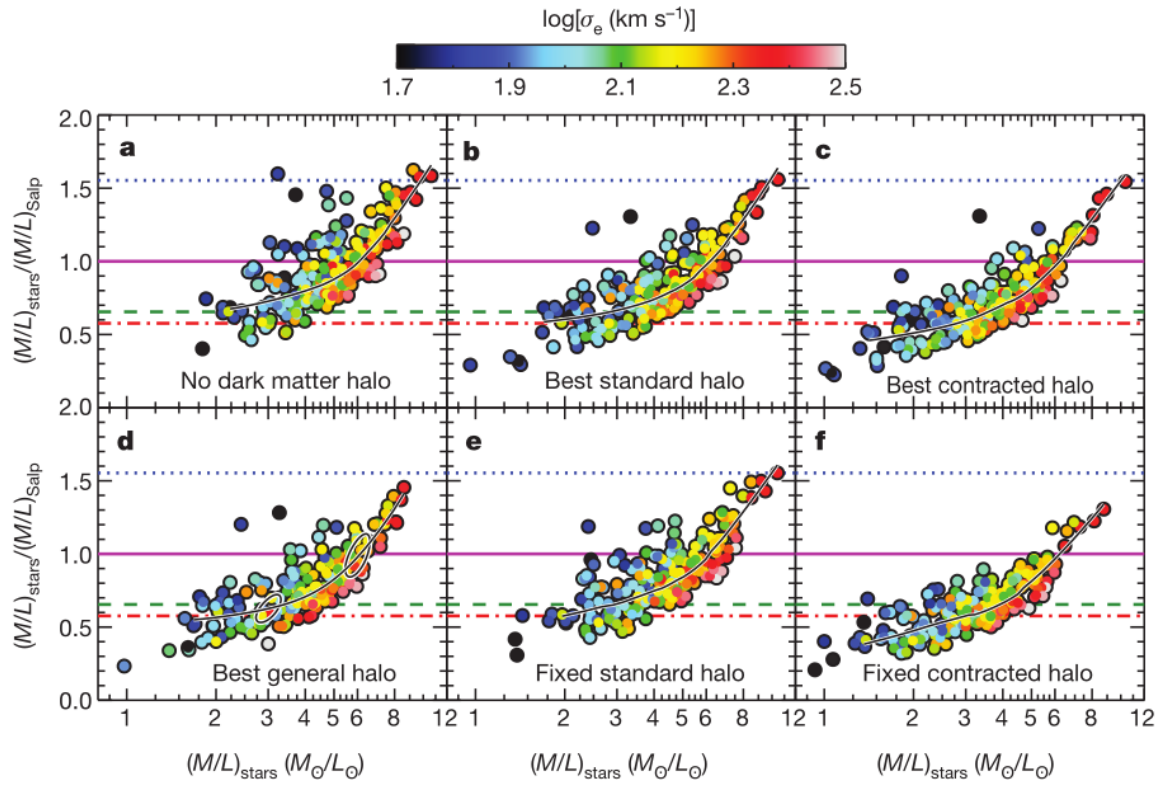


Fig. 1.3 Each panel in this figure represents the stellar Mass-to-Light ratio of 260 early type galaxies derived via stellar population modelling (y-axis) and dynamical modelling (x-axis), for various assumptions of their dark matter content. Independent of the dark matter model used, the panels demonstrate a non-universal IMF that varies as a function of the velocity dispersion of the galaxies, depicted by the colour trend. [Credit: Cappellari et al. (2012)]

Using the dynamical modelling of 260 ETGs, Cappellari et al. (2012) explained these results as part of a systematic variation of the IMF normalisation of external galaxies, as demonstrated in Fig. 1.3. These models robustly accounted for the dark matter fraction of the galaxies and show that a systematic variation in the IMF of galaxies is required to reproduce the observed kinematics of galaxies. Since then, this result has been confirmed by other authors using other techniques such as lensing, dynamical modelling and stellar population modelling (e.g: Spiniello et al., 2012; Ferreras et al., 2013; Tortora, Romanowsky & Napolitano, 2013). Nonetheless, the study of IMF variation remains a very interesting and actively debated topic, with a variety of unsolved issues and inconsistencies between different approaches (e.g: McDermid et al., 2014; Smith, 2014).

1.2.3 Dark Matter

Dark matter is the most dominant form of matter in the Universe, outweighing baryonic matter by factor of five. As mentioned in Section. 1.1.1, the dark matter creates the foundation upon which the galaxies form and evolve. Since its discovery by Zwicky (1933), Astronomers have observed evidence for the presence of dark matter in the observations of gas and stellar kinematics in the outer regions of galaxies, where the contribution by stars and gas to the gravitational potential drops significantly (Rubin et al., 1985; van Albada et al., 1985). In addition, X-ray observations of hot interstellar gas and gravitational lensing by galaxies and galaxy clusters have independently suggested the presence of dark matter (Walsh, Carswell & Weymann, 1979; Soucail et al., 1988).

For over a decade, there has been a convergence of the cosmological simulations of dark matter in the Universe which has resulted in significant improvement in our understanding of the growth of structure in the Universe (e.g: Springel et al., 2005). Despite their success, discrepancies exist between observations and simulations, particularly in the small scales.

One such problem has to do with the over-prediction of the number of the massive subhaloes that a Milky-Way-like halo would host in present day (Boylan-Kolchin, Bullock & Kaplinghat, 2011, 2012). Unless the Milky Way halo is an anomaly in the sample, the brightest dwarf galaxies around the Milky Way would require dark matter haloes ~ 5 times more massive than that observed to be consistent with the theoretical predictions. Another such issue is regarding the shape of the dark matter distribution of dwarf spheroidal and low surface brightness galaxies, whose observed kinematics are not consistent with that predicted by the cusp-like distribution predicted by these simulations (Flores & Primack, 1994; de Blok, 2010; Kuzio de Naray & Kaufmann, 2011). Though there are indications that these discrepancies between the models and observations could be resolved by the inclusion of baryonic physics in the simulations, so far such attempts have been unsuccessful (Garrison-Kimmel et al., 2013; Chan et al., 2015; Dutton et al., 2015a)

1.3 Methodology

1.3.1 Stellar Kinematics

To model the observed spectra of galaxies during this thesis, I used the penalised pixel fitting *pPXF* method and code by Cappellari & Emsellem (2004)¹. This code fits the observed galaxy spectra with a set of template spectra in pixel space using a Gaussian-Hermite parametrisation for the line-of-sight velocity dispersion (LOSVD) of the galaxy (Gerhard, 1993; van der Marel & Franx, 1993). The code solves for:

$$G(x) = \sum_{k=1}^k w_k [B * T_k](x) + \sum_{l=0}^L b_l P_l(x), \quad w_k \geq 0 \quad (1.2)$$

Where the galaxy spectra (G) is modelled as the summation of each template (T_k) convolved to the LOSVD of the model (B) and multiplied by its weight (w_k). The additive

¹<http://purl.org/cappellari/software>

term accounts for the variation in the continuum of the galaxy spectra and that of the template spectra due to the fact that the observed galaxy spectra is a combination of millions of stellar spectra, all of which cannot be accounted for. In *pPXF*, this is done using the Legendre polynomial (P_l) of order l and coefficient b_l . In addition to this, *pPXF* also permits the use of multiplicative Legendre polynomials to account for the variations in the continuum shape of the templates and galaxies that are due instrumentation systematics as the template and observed spectra are not observed by the same instruments.

1.3.2 Dynamical Modelling

Classically, dynamical models of galaxies are based on the Jeans equations (Jeans, 1922). These equations are the solution to the collision-less steady state Boltzmann equation

$$\sum_{i=1}^3 \left(v_i \frac{\partial f}{\partial x_i} - \frac{\partial \Phi}{\partial x_i} \frac{\partial f}{\partial v_i} \right) = 0 \quad (1.3)$$

Where the distribution function of the stars (f) is a function of their position (x_i) and velocity (v_i) along each spatial dimension (i), and Φ describes the gravitational potential in which the stars exist. In cylindrical coordinates, and the assumption of axial symmetry, this equation can be rewritten as:

$$\frac{\overline{v v_R^2} - \overline{v v_\phi^2}}{R} + \frac{\partial(\overline{v v_R^2})}{\partial R} + \frac{\partial(\overline{v v_R v_z})}{\partial z} = -v \frac{\partial \Phi}{\partial R} \quad (1.4)$$

$$\frac{\overline{v v_R v_z}}{R} + \frac{\partial(\overline{v v_z^2})}{\partial z} + \frac{\partial(\overline{v v_R v_z})}{\partial R} = -v \frac{\partial \Phi}{\partial z} \quad (1.5)$$

These equations however are not sufficient to uniquely solve for the kinematics of the galaxies, further assumptions are required to converge on a specific solution. Previously, this additional constraint assumed that the velocity ellipsoid of the galaxies were circular, implying that $\overline{v_r^2} = \overline{v_z^2}$ and $\overline{v_r v_z} = 0$. This assumption provided unique solutions to the Jeans

equations and were used widely (e.g: Nagai & Miyamoto, 1976; van der Marel, Binney & Davies, 1990; Carollo et al., 1995; Cappellari et al., 2006). However observations of the dynamical structure of galaxies have demonstrated that the velocity ellipsoid of fast rotator and spiral galaxies are not circular, but are in fact flattened along the axis parallel to the axis of symmetry (Cappellari et al., 2007; Thomas et al., 2009). Making this assumption simplifies the equations to:

$$\frac{bv\overline{v_z^2} - v\overline{v_\phi^2}}{R} + \frac{\partial(bv\overline{v_z^2})}{\partial R} = -v \frac{\partial\Phi}{\partial R} \quad (1.6)$$

$$\frac{\partial(v\overline{v_z^2})}{\partial z} = -v \frac{\partial\Phi}{\partial z} \quad (1.7)$$

Where b represents the velocity anisotropy of the stars and is defined as $\overline{v_R^2} = bv_z^2$. The models also take advantage of the multi-Gaussian expansion formalism (MGE; Further details are provided in Section. 1.3.3) that provide a simple description of the luminosity density and gravitational potential of the galaxy (Emsellem, Monnet & Bacon, 1994):

$$v(R, z) = \sum_{k=1}^N \frac{L_k}{(\sqrt{2\pi}\sigma_k)^3 q_k} \exp \left[-\frac{1}{2\sigma_k^2} \left(R^2 + \frac{z^2}{q_k^2} \right) \right] \quad (1.8)$$

$$\Phi(R, z) = -\sqrt{2/\pi}G \int_0^1 \sum_{j=1}^M \frac{M_j \mathcal{H}(u)}{\sigma_j} du, \quad (1.9)$$

$$\mathcal{H}(u) = \frac{\exp \left\{ -\frac{u^2}{2\sigma_j^2} \left[R^2 + \frac{z^2}{1-(1-q_j^2)u^2} \right] \right\}}{\sqrt{1-(1-q_j^2)u^2}} \quad (1.10)$$

The Jeans Anisotropic Modelling (*JAM*)² method (Cappellari, 2008) uses these equations to solve Eq.(1.6)-(1.7) and predicts the second moments of velocity, $\overline{v_{los}^2}$, for a given MGE parametrisation of the surface brightness and mass distribution, the velocity anisotropy and inclination of a galaxy. In addition, the code can take into account the effect due to seeing

²<http://purl.org/cappellari/software>

and aperture size to make practical predictions of the line of sight velocity moment of the galaxies. In Cappellari et al. (2007), the authors demonstrate that $V_{\text{rms}} = \sqrt{V^2 + \sigma^2}$, where V and σ are the velocity and velocity dispersion, is a good approximation to this prediction.

1.3.3 Photometric Parametrisation

Traditional methods used to parametrise galaxy photometry have been based on fitting the observed galaxy light profile to pre-established models, such as 2D Sérsic profile for elliptical galaxies. These models are generally based on empirical fits to the galaxies and its parametrisation can be used to infer information on the galaxies (e.g: Graham et al., 2001).

However, in this study I have used the Multi-Gaussian Expansion (MGE) formalism to parametrise the light profile of galaxies (Monnet, Bacon & Emsellem, 1992; Emsellem, Monnet & Bacon, 1994; Cappellari, 2002). This technique fits the observed galaxy photometry using a series of 2D Gaussian functions and, due its multiple degrees of freedom, can robustly fit for galaxies with multiple components. In addition, this formalism allows the user to take the effect of the point spread function of the instrument, and the deprojection of the observed light into three dimensional distributions in a trivial manner. The latter is particularly helpful when creating dynamical models for the galaxies. For my work I use the robust MGE fitting method and code by Cappellari (2002)³.

1.4 Thesis Outline

In this chapter, I have presented a summary of our understanding of galaxy evolution, particularly that of the stellar populations and dark matter in the central regions of galaxies. In this thesis, I attempt to further probe the stellar populations and dark matter content of galaxies to get a better understanding of the evolution of galaxies. I have done this in two

³<http://purl.org/cappellari/software>

parts; by probing the stellar populations and dark matter of galaxies at redshift $z \sim 1$ via dynamical and stellar population modelling, and by studying galaxies at dense environments using similar tools.

Accordingly, the research conducted during the course of this doctoral study is presented in three chapters. A summary of these chapters are provided below:

- **Chapter 2 :** This chapter highlights the results on the IMF normalisation of galaxies at $z \sim 1$. Here, I have used dynamical modelling of 68 galaxies, based on the anisotropic Jeans equations which in recent years has been demonstrated to be a good assumption when modelling the dynamics of most ETGs. Based on these models and the stellar population modelling of galaxies, I have derived an accurate estimate of the IMF normalisation of massive ETGs ($M_* > 10^{10} M_\odot$). This chapter is a published manuscript and can be found at Shetty & Cappellari 2014 (*ApJL*, 786, L10).
- **Chapter 3 :** This chapter develops the work carried out in the previous chapter. In the chapter, I have developed the dynamical models of these 68 ETGs by including dark matter halos for these galaxies. These models are based on Abundance Matching techniques and further strengthen the results presented in the previous chapter. In addition, this chapter expands the original sample of 68 galaxies to 154. For this expanded sample, I have analysed the star formation history of galaxies at these redshifts and their scaling relations. This chapter is also a published manuscript and can be found at Shetty & Cappellari 2015(*MNRAS*, 454, 1332).
- **Chapter 3 :** This chapter presents the analysis of galaxies in the Coma cluster. This project has observed 53 galaxies in the Coma cluster using the SAURON IFS and publicly available photometric data from SDSS. In addition to this, I have also had access to an additional 100 galaxies in the Coma cluster with spectral and photometric data from SDSS. For this project, I have created detailed dynamical models for 42

galaxies of the original 53 galaxies, along with the less sophisticated modelling for the additional sample. Taken together, and along with the stellar population modelling of the galaxies using SDSS spectra, I have derived the most accurate IMF normalisation for galaxies. I also present results on model free dark matter fractions of these galaxies, and their morphology-density relation based on their dynamical models. This work is in the final stages of its completion and its results are currently being written up in Shetty et al. (*in prep.*).

- **Chapter 4 :** In this chapter, I bring together the results of this thesis and present the current state of the field. I shall also be highlighting the areas where further development is required and how such developments can be made.

Chapter 2

Salpeter normalization of the Stellar Initial Mass Function for massive galaxies at $z \sim 1$

The stellar initial mass function (IMF) is a key parameter to study galaxy evolution. Here we measure the IMF mass normalization for a sample of 68 field galaxies in the redshift range 0.7 to 0.9 within the Extended Groth Strip. To do this we derive total (stellar + dark matter) mass-to-light $[(M/L)_{\text{dyn}}]$ using axisymmetric dynamical models. Within the region where we have kinematics (about one half-light radius), the models assume: (i) that mass-follows-light, implying negligible differences between the stellar and total density profiles; (ii) constant velocity anisotropy ($\beta_z \equiv 1 - \sigma_z^2/\sigma_R^2 = 0.2$); (iii) that galaxies are seen at the average inclination for random orientations (i.e. $i = 60^\circ$, where $i = 90^\circ$ represents edge-on). The dynamical models are based on anisotropic Jeans equations, constrained by HST/ACS imaging and the central velocity dispersion of the galaxies, extracted from good-quality spectra taken by the DEEP2 survey. The population $(M/L)_{\text{pop}}$ are derived from full-spectrum fitting of the same spectra with a grid of simple stellar population models. Recent dynamical modelling results by the ATLAS^{3D} project and numerical simulations of galaxy evolution

indicate that the dark matter fraction within the central regions of our galaxies should be small. This suggest that our derived total $(M/L)_{\text{dyn}}$ should closely approximate the stellar M/L . Our comparison of $(M/L)_{\text{dyn}}$ and $(M/L)_{\text{pop}}$ then imply that for galaxies with stellar mass $M_ \gtrsim 10^{11} M_{\odot}$, the average normalization of the IMF is consistent with a Salpeter slope, with a substantial scatter. This is similar to what is found within a similar mass range for nearby galaxies.*

Published : Shravan Shetty and Michele Cappellari, 2014, ApJL, 786:L10

2.1 Introduction

Knowledge of the stellar mass of galaxies has long been pivotal to the study and testing of galaxy formation and evolution theories, but an economical method for it's estimation has remained elusive to astronomers for decades (see Courteau et al., 2014, for a review). The main reason for this is the fact that the galaxy photometry doesn't sufficiently constrain the stellar mass, which is dependent on both the stellar populations of the galaxy and the stellar Initial Mass Function (IMF) of those populations. The IMF represents the distribution of stellar masses at a single star formation event. The form of the IMF is critical for estimating the mass of the galaxies and in understanding the stellar feedback and the chemical enrichment processes taking place within them.

It is currently accepted, from direct star counts, that the IMF shape in our Milky Way can be approximated by a power-law $dN/dm \propto m^x$ with the Salpeter (1955) slope $x \approx -2.35$, above a stellar mass $m \gtrsim 0.5 M_{\odot}$ and a more shallow slope below $m \lesssim 0.5 M_{\odot}$ (Kroupa, 2001; Chabrier, 2003). Though this IMF seems universal within the Milky Way its applicability to external galaxies has been uncertain for decades (see Bastian, Covey & Meyer 2010 and Kroupa et al. 2013 for recent reviews).

Early attempts, comparing the dynamical mass-to-light ratio M/L to the value inferred from stellar population synthesis, concluded that at least some spiral galaxies (Bell & de Jong,

2001; Kassin, de Jong & Weiner, 2006; Bershadsky et al., 2011; Dutton et al., 2011; Brewer et al., 2012) and ETGs (Cappellari et al., 2006; Ferreras, Saha & Burles, 2008; Thomas et al., 2011) require an overall Kroupa/Chabrier mass normalization of the IMF like the Milky Way. By studying the variation of the average M/L of galaxies in clusters at different redshifts, Renzini (2006) concluded that a Salpeter IMF slope was required for the mass range of $1 < M < 1.4 M_{\odot}$.

More recently van Dokkum & Conroy (2010, 2011) studied near-infrared spectral features, where the contribution from dwarf stars is easier to measure. They concluded that massive elliptical galaxies have a **dwarf dominated IMF**, unlike the Milky Way. Auger et al. (2010) studied the IMF by comparing stellar masses from strong gravitational lensing to stellar masses from population synthesis. Their models assume massive ETGs are spherical, satisfy a power law dependence of IMF normalization with galaxy mass, have dark halos following the mass-concentration relation predicted by simulation and the total to stellar mass derived by halo abundance matching. They concluded massive ETGs as a class have a Salpeter-like mass normalization of the IMF.

Cappellari et al. (2012) used more general axisymmetric dynamical models allowing for the IMF, the stellar profiles, the halo slope and the stellar fraction to freely vary in different galaxies to reproduce the data. The models were constrained by integral-field stellar kinematics for a sample of 260 ETGs spanning a large range of masses and σ . They found a systematic trend in the IMF normalization. The average IMF varies from Kroupa/Chabrier to Salpeter and heavier with increasing σ , which was shown to trace the bulge fraction (Cappellari et al., 2013a).

A number of recent works appear so far consistent with a systematic IMF variation. These used either spectral synthesis to study absorption features (e.g. Spiniello et al., 2012; Conroy & van Dokkum, 2012; Smith, Lucey & Carter, 2012; Ferreras et al., 2013; La Barbera et al., 2013), dynamical scaling relations (Dutton et al., 2013) or approximate spherical dynamical

models (Tortora, Romanowsky & Napolitano, 2013). However quantitative agreement between the different approaches has not yet been achieved and full consensus has not been reached (e.g. Maraston, 2013).

The study of IMF in galaxies at high redshift is so far dominated by dynamical mass derivations using the virial estimator (e.g. Renzini, 2006; van de Sande et al., 2013). In this study, we constrain the IMF normalization at redshift $z \sim 1$ using axisymmetric dynamical models and compare the results with findings in the local universe. This is one of the few studies to attempt dynamical modelling at higher redshift (van der Marel & van Dokkum, 2007; Cappellari et al., 2009) but is the first to place constraints on the IMF normalization of galaxies at high redshift.

In section 2, we give a description of the data used for this study and a description of the galaxy set. We describe our methodology in section 3, while we present our results in section 4. In section 5, we discuss the results. We used the following cosmological constants: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2.2 Data and Sample

2.2.1 Spectral Data

The 1-D spectrum of the galaxies was obtained from the DEEP2 spectrographic survey (Newman et al., 2013c). It is a magnitude limited, $R_{AB} \leq 24.1$, galaxy redshift survey. In this study, we use the Extended Groth Strip (Groth et al., 1994) field of the survey due to the availability of HST imaging (Davis et al., 2007). The data was taken by the DEIMOS multi-object spectrograph, mounted on the Keck-2 telescope, with a observed wavelength range of 6500-9100Å, in a spectral resolution of $R \sim 6000$ at 7800Å. The typical total exposure time for each galaxy is 1 hour, with average seeing of 0.85". The 2-D spectra of the galaxies were observed using slitlets of dimensions $1'' \times 7''$. 1-D spectra of the galaxies

were then derived using the **boxcar** technique, within extraction windows of $\sim 1'' \times 1''$. Due to the design of the survey, the spectra of the objects are divided into 2 halves. For our study, we use the blue half of the wavelength range so as to observe the CaK and G stellar lines for our given redshift range.

2.2.2 Photometric Data

A HST/ACS survey of the EGS was done by the GO program 10134 [P.I: M. Davis] (Davis et al., 2007). The survey was done with the F606W (V) and F814W (I) filters, at 5σ magnitude limits of $V_{\text{F606W}} = 26.23(AB)$ and $I_{\text{F814W}} = 25.61(AB)$. The observations were done in a four point dither pattern, which was processed by the STSDAS MultiDrizzle package to produce a final mosaic of the field with a pixel scale of $0.03''$.

2.2.3 Selection

The DEEP2 survey has observed $\sim 49,000$ galaxy spectra. For this study, our initial selection criteria are: the galaxies have reliable redshift between $0.7 < z < 0.9$ and have high-resolution HST photometry. This meant selecting galaxies with “secure” and “very secure” redshifts in the DEEP2 catalog. These criteria reduced the sample to $\sim 1,350$.

The galaxy spectra were then logarithmically rebinned to 60 km s^{-1} per spectral pixel and a signal-to-noise (S/N) > 3 cut-off was applied. We visually inspected the spectra after their initial spectral fits (Section 2.3.1) and retained galaxies showing clear and well-fitted stellar absorption lines. This reduced the sample to ~ 200 .

After the photometric analysis (Section 2.3.2), a visual inspection of the contour fits of the galaxy photometry and the model was done to ensure that the models accurately reproduce the galaxy photometry, removing galaxies with non-axisymmetric features, e.g. disturbed morphology or strong dust. This reduced our sample to 87.

Another selection criterion implemented on our galaxy sample was that of luminosity-weighted age of the galaxies, derived by identifying the best-fitting single stellar population model with solar metallicity via full-spectrum fitting. Galaxies with best-fitting template age < 1.2 Gyr were removed. A similar selection was made by Cappellari et al. (2012, 2013a) who found that young galaxies have strong stellar population gradients, hence breaking the assumption of constant stellar M/L. Finally we removed galaxies with strong evidence for multiple population using full-spectrum fitting (Section 2.3.3), leading to a final sample of 68 galaxies.

These galaxies consists of massive ETGs (stellar masses $10^{11} \lesssim M_*/M_\odot \lesssim 10^{12}$), except for seven galaxies at lower masses. More information on these galaxies will be given in a follow up paper.

2.3 Methods

2.3.1 Velocity dispersion measurements

To create dynamical models for our galaxies, we first extracted reliable velocity dispersion for the galaxies, using the pPXF code¹ (Cappellari & Emsellem, 2004). The spectrum fitting was done with a subset of 53 stellar spectra taken from the Indo-US Library of Coudé Feed Stellar Spectra Library (Valdes et al., 2004). These spectra were selected so that: (i) each spectrum is gap-free and (ii) the subset is a good representation of the library’s atmospheric parameter range (T_{eff} vs $[Fe/H]$). During the fitting process, the telluric features in the galaxy spectra were masked, along with any significant gas emission feature. Examples of spectral fits are given in Fig. 2.1.

A bootstrapping technique was used to estimate the real errors on the derived single aperture velocity dispersions. The technique involved re-sampling the residuals between the

¹Available at: <http://purl.org/cappellari/idl>

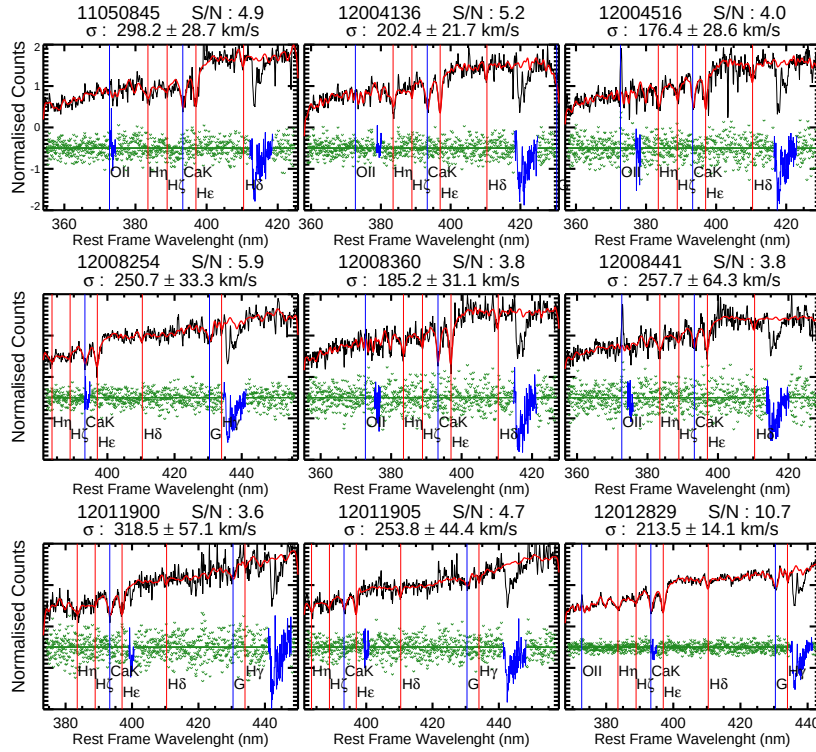


Fig. 2.1 Summary plots of spectrum fitting for 9 galaxies. The galaxy spectrum is shown in black, while the best-fit is in red. The galaxy spectrum has been rebinned to 60 km s^{-1} spectral pixel resolution and gauss-smoothed to make the absorption features clearer to the eye. The green dots below the galaxy spectrum are the residuals of the fit while the blue features are the masked pixels. The portion of the spectrum around ~ 3800 and ~ 4100 are the telluric features that have been masked.

observed spectrum and an initial best fit. The bootstrapped spectra are then fitted with an “Optimal” template which is the summation of the templates used for the initial fit of the spectrum, multiplied with their respective weights. The process was iterated 500 times, and the distribution of the stellar kinematic values was used to estimate the velocity dispersion and its error.

We compare our derived velocity dispersion with that of Fernández Lorenzo et al. (2011), for our 40 common galaxies, using the `LTS_LINEFIT` routine¹, modified to constrain the slope to 1. We find that our velocity dispersion are consistent with those of Fernández Lorenzo et al. (2011) with negligible offset of 0.013 ± 0.013 dex and an observed rms scatter of 0.094 dex.

2.3.2 Calculating Dynamical M/L

The photometry of our galaxies was parametrized using a Multi-Gaussian Expansion (Emmellem, Monnet & Bacon, 1994), using the `mge_fit_sectors`¹ code of Cappellari (2002). To ensure that our MGE fits reflect the underlying mass distribution of galaxies, we adopt the technique used by Scott et al. (2013) (Section 3.2.1). We also force the surface brightness profile at the largest observed radius to have an outer slope of R^{-4} . Examples of MGE fits are shown in Fig. 2.2.

We create our dynamical models using the JAM method¹ (Cappellari, 2008) which solves the anisotropic Jeans equations for a given light and mass profile of axisymmetric galaxies, while allowing for orbital anisotropy. The code also allows for rigorous application of seeing and aperture effects.

We adopt this method over the more commonly used virial estimates based on Sérsic spherical Jeans models since spherical models cannot reproduce the variety in the stellar kinematics of galaxies (Cappellari et al., 2013b, Fig. 1). In addition, Cappellari et al. (2013b,

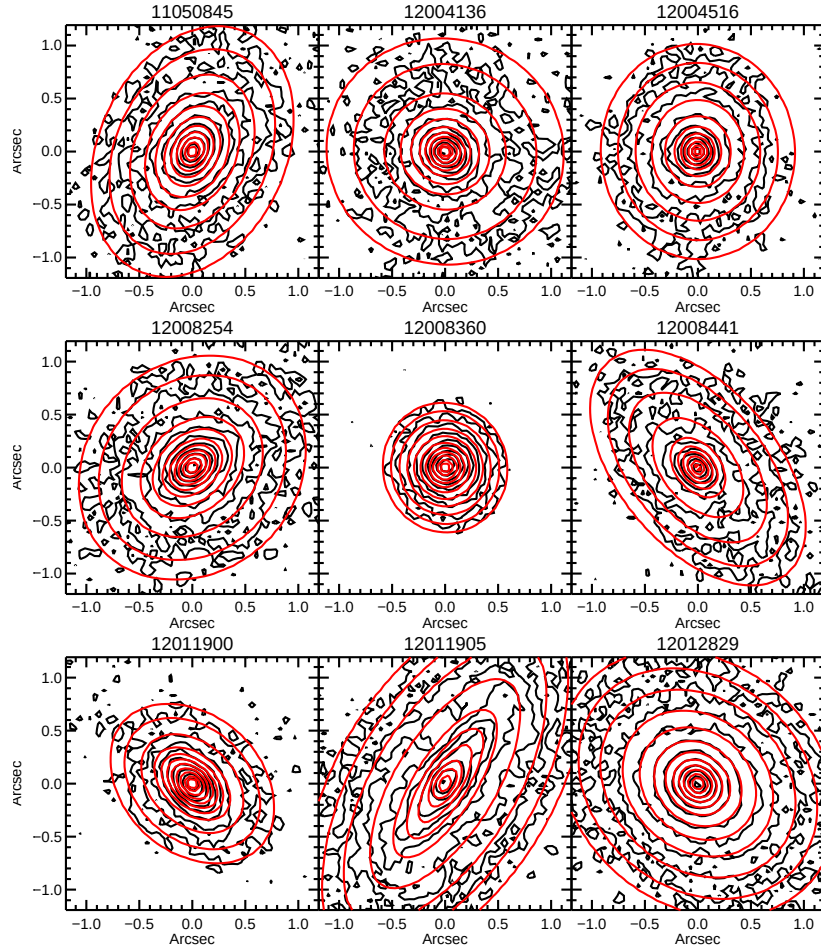


Fig. 2.2 Summary plots of the MGE fits for 9 galaxies. The black contour lines represent the observed light distribution of the galaxies, while the red represents the model. Since we calculate the $(M/L)_{\text{JAM}}$ for the inner regions of the galaxies, it is important to reproduce the inner light profile accurately.

Fig.14), show that virial estimates suffer from large scatter and potential biases in the absolute M/L normalization, which is critical for our work.

We assume for all galaxies the average inclination $i = 60^\circ$ for random orientations ($i = 90^\circ$ being edge-on). For a few galaxies for which this inclination is not allowed by the deprojection of the MGE model, we assign the lowest allowed inclination. We adopt an anisotropy $\beta_z \equiv 1 - \sigma_z^2/\sigma_R^2 = 0.2$ which is the typical value, within one half-light radius R_e , for early type galaxies in the local universe (Cappellari et al., 2007; Gerhard et al., 2001). Previous studies have shown the M/L to be very weakly sensitive to the adopted inclination (Cappellari et al., 2006, Fig. 4). However, our quoted errors do not include the effect of our constant anisotropy assumption.

Given our lack of spatially resolved data, we are unable to separate luminous and dark matter in our galaxies. Hence we use mass-follow-light models, which were shown to robustly recover the *total* M/L within $1R_e$, even when dark matter is present (Cappellari et al., 2013b), when the data extend out to the same radius. The dynamical M/L of our galaxies is given by $(M/L)_{\text{JAM}} = (\sigma/V_{\text{rms}})^2$ (Table 1), where σ is measured within the DEEP2 $1''$ slit (Table 1) and V_{rms} is the value predicted by the JAM model within the same aperture for $M/L = 1$.

The extensive modelling study of Cappellari et al. (2013b) measure a low dark matter fraction ($< 30\%$), within $1R_e$, for nearby galaxies of similar mass as ours. Numerical simulations by Hilz, Naab & Ostriker (2013) provide a general argument as to why dark matter should further decrease with increasing redshift. These results indicate that the dark matter fraction in the central regions of our galaxies should be negligible, hence indicating that our $(M/L)_{\text{JAM}}$ should closely approximate the stellar M/L . Without this assumption, our M/L would only provide an upper limit to the IMF mass normalization.

We use the parametrization of the photometry and the redshift of the galaxies to derive their absolute magnitude. Since the F814W filter observes the rest frame B band for galaxies

DEEP2 ID No.	Redshift	M_B	R_e	σ	$\Delta\sigma$	$(M/L)_{\text{JAM}}$	$(M/L)_{\text{Sal}}$
			(")	(km/s)	(km/s)	$(M_\odot/L_\odot)$	$(M_\odot/L_\odot)$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
11050845	0.840	-21.76	0.40	298	28	6.10	3.55
12004136	0.812	-21.62	0.50	202	21	3.09	2.92
12004516	0.820	-21.44	0.44	176	28	2.85	1.97
12008254	0.745	-21.51	0.41	250	33	4.92	4.32
12008360	0.828	-20.97	0.18	185	31	2.63	2.39
12008441	0.832	-21.34	0.53	257	64	9.26	1.79
12011900	0.719	-20.88	0.23	318	57	9.75	4.46

Column (1): DEEP2 galaxy identifier. Column (2): DEEP2 estimated redshift. Column (3): Absolute B (Vega) band magnitude. Column (4): Effective radius as derived from MGE (without re-scaling). Column (5): Aperture velocity dispersion. Column (6): Error on aperture velocity dispersion. Column (7): Dynamical mass-to-light ratio with a median error of 0.11dex. Column (8): Population mass-to-light ratio with a scatter of 0.08dex.

Table 2.1 Results of dynamical models and multiple population fitting. The table is published in its entirety in the electronic edition of the letter. A portion is shown here for guidance regarding its form and content. Please refer to Appendix. A to view the table in its entirety.

at redshift ~ 0.8 , all magnitudes and (M/L) s presented in this study are in the B (Vega) system.

2.3.3 Calculating Stellar Population M/L

We derive the population M/L of the galaxies using the MILES stellar evolutionary models (Vazdekis et al., 2010). These models use the MILES empirical stellar spectral library (Sánchez-Blázquez et al., 2006) to derive single age and metallicity models for the entire optical wavelength range. We use the Salpeter IMF as the reference IMF for this study.

The full-spectrum fittings were done using pPXF with a template grid of 40 logarithmically spaced ages, between 0.089 to 7.9 Gyrs, for metallicities $[M/H]$ of -0.4, 0.00 and 0.22. The upper limit of the age was constrained to the age of the universe at the adopted redshift while the metallicity range is justified by the results of Schiavon et al. (2006) who find that galaxies at $0.7 < z < 0.9$ have nearly solar metallicities. The $(M/L)_{\text{Salpeter}}$ in the B (Vega) band was calculated as

$$(M/L)_{\text{Salpeter}} = \sum_j \frac{w_j M_{\star}^{\text{nogas}}}{w_j L_B}, \quad (2.1)$$

where w_j is the weight of each template, $M_{\star}^{\text{nogas}}$ is the mass of stars and stellar remnants, and L_B is the B (Vega) band luminosity of the model.

To test the robustness of our results to model selection, the $(M/L)_{\text{Salpeter}}$ was calculated using 2 different template sets: (i) unregularized fitting with solar metallicity templates and (ii) a regularized fitting with the entire SSP model grid. The M/L derived from these template sets are offset by only 0.07 dex and have an intrinsic scatter of 0.08 dex. We find that our results are robust to variations of this scale and so we present our results here using the latter set.

2.4 Result

In this study, we derive accurate total dynamical $(M/L)_{\text{JAM}}$ and stellar population $(M/L)_{\text{Salpeter}}$ for 68 galaxies. In Table 2.1, the reader will find the list of physical parameters derived in the study.

Our results allow us to compare the M/L from detailed models with the virial estimate:

$$(M/L)_{\text{virial}} = 5.0 \times \frac{R_e \sigma_e^2}{GL}, \quad (2.2)$$

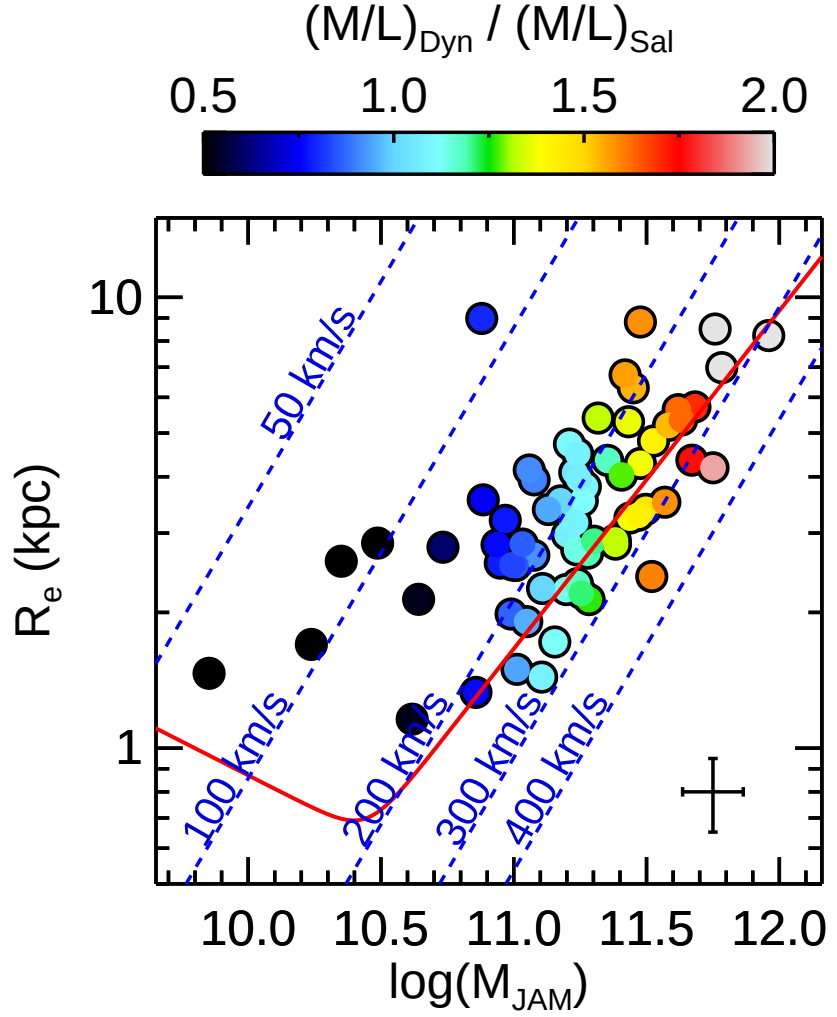


Fig. 2.3 Mass Plane (R_e vs Stellar Mass) of our final galaxy set, with R_e rescaled using the offset observed between $(M/L)_{\text{JAM}}$ and the virial estimate. The thick red line represents the Zone of Exclusion from Cappellari et al. (2013a), which approximates the 99% boundary for the nearby galaxy population. The colored diagonal dashed lines are predicted lines of constant velocity dispersion according to the scalar virial equation. Part of the trend in mass normalization with mass must be due to the correlation between M_{JAM} and $(M/L)_{\text{Dyn}}$.

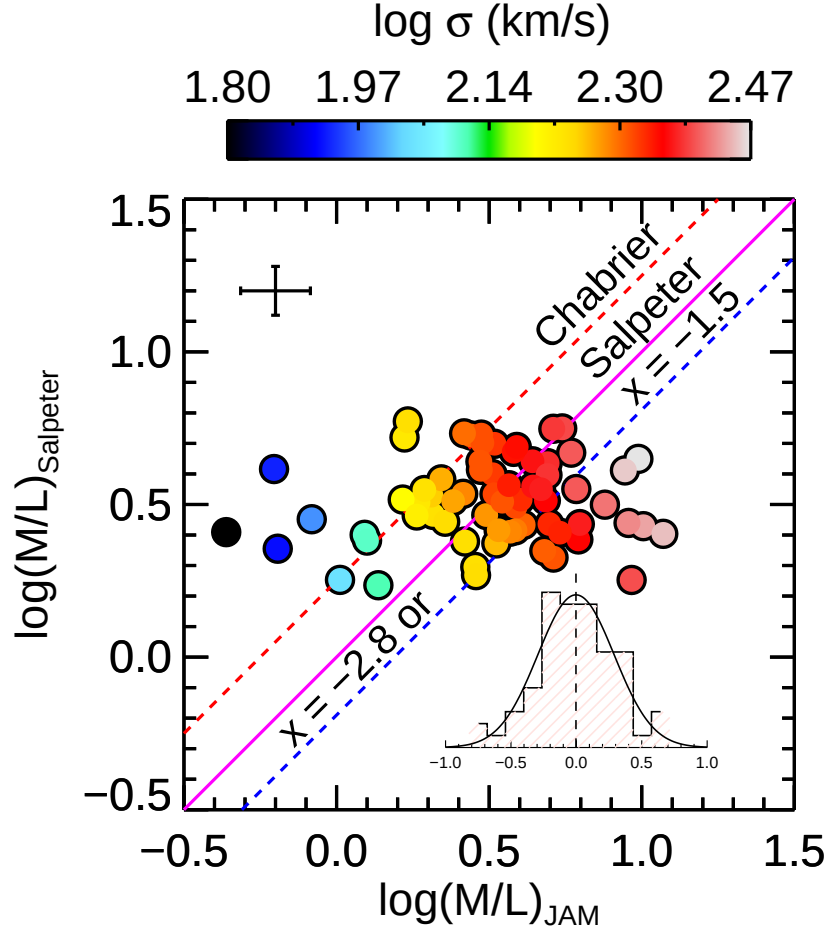


Fig. 2.4 $\log(M/L)_{\text{JAM}}$ versus $\log(M/L)_{\text{Salpeter}}$. The **thick magenta** line represents the Salpeter IMF. The **dashed red** line represents the Chabrier IMF, while the **dashed blue** line represents a single power-law with a slope of -2.8. The points are color coded to the velocity dispersion smoothed with LOESS method of Cleveland (1979). Though there is an indication of a trend of the mass normalization with the velocity dispersion of galaxies, part of this must be due to the correlation between σ and $(M/L)_{\text{JAM}}$. A representative error bar is shown at the top left. The histogram on the bottom-left shows the $\log((M/L)_{\text{Dyn}} / (M/L)_{\text{Sal}})$. The best-fitting Gaussian peaks at 0.00 and has a dispersion of 0.29. We note that part of the trend of velocity dispersion with $(M/L)_{\text{JAM}}$ is likely due to correlated errors.

where σ_e is the measured velocity dispersion within R_e (Cappellari et al., 2006). In our study, we have measured the R_e using MGE and use the aperture correction for the velocity dispersion as given in of Cappellari et al. (2006, Eq. (1)). We use a virial coefficient of 5.0 since Cappellari et al. (2013b, Fig. 13) shows that it is applicable to virial mass estimations that use MGE derived R_e . We find that the equation (2.2) under estimates the dynamical masses by 0.16 dex with an rms scatter of 0.04 dex.

We investigated the origin of the offset via a process of elimination. Since the virial estimate, using the MGE derived sizes better reproduces the dynamical mass of galaxies than a non-homology dependent virial coefficient (Cappellari et al., 2013b, Fig. 14), we argue that the structural evolution of galaxies can not account for this offset. An under-estimation in velocity dispersion and luminosity will have the same effect on both quantities, apart from effects of seeing, which is only accounted for in the models. Hence our investigation suggests that the offset observed is mostly caused by an under-estimation of the R_e , specifically due to shallow observations of galaxy photometry and our non-extrapolated radii.

In Fig. 2.3, we show the mass plane (R_e vs Stellar Mass) of the galaxies. The R_e used in the plot is rescaled to match the $(M/L)_{\text{JAM}}$ and $(M/L)_{\text{virial}}$ estimates. It is an attempt to recover the true R_e of the galaxies, but this is assumption dependent. Regardless, none of our results on the IMF mass normalization are dependent on this. A number of galaxies appear slightly smaller than local galaxies, and lie below the zone-of-exclusion of Fig. 1 of Cappellari et al. (2013a). This illustrates that our S/N selection criterion tend to select dense and massive galaxies.

By comparing the M/L calculated via the two independent methods, dynamical modeling and stellar populations, we are able to study the IMF normalization of the galaxies. In Fig. 2.4 we have plotted the M/L calculated by the two methods, along with a color code to represent velocity dispersion. The velocity dispersion is smoothed using the LOESS method

of Cleveland (1979)² to ease comparison of the plot with the results of the local universe, as done in Cappellari et al. (2013a).

The analysis of our results show that, on *average*, massive ($10^{11} \lesssim M_*/M_\odot \lesssim 10^{12}$) galaxies at $z \sim 0.8$ are more consistent with a Salpeter-like, than a Milky Way-like, IMF mass normalization provided our assumption of negligible dark matter in the central regions of the galaxies is valid. The IMF scatter appear larger than our error estimate, suggesting it must be intrinsic. However the extreme cases must be driven by systematics in our σ determinations. Fig. 2.4 can be directly compared to Fig. 11 of Cappellari et al. (2013a) representing the local galaxy sample. The two plots look qualitatively similar, and in both cases they are characterized by a nearly complete lack of correlation between the dynamical and population M/L for galaxies with the largest σ .

2.5 Summary

We used the JAM modeling method to derive dynamical $(M/L)_{\text{JAM}}$ for 68 massive galaxies ($M_* = 10^{11} - 10^{12} M_\odot$) at redshifts $z = 0.7 - 0.9$. Our results show that using the virial equation at high redshifts can lead to severe under-estimation in the dynamical masses of galaxies, which is likely due to the under-estimation of the R_e . The under-estimation must depend on the depth of the photometry as well as on the adopted extrapolation of the profiles, making the virial estimates assumption dependent (see also Cappellari et al., 2013b). The $(M/L)_{\text{JAM}}$ doesn't suffer for this problem as it only requires the knowledge of the light and mass distribution within a region comparable to where the stellar kinematics are available.

Our result suggests that stellar population estimates of stellar masses of massive galaxies at high redshift should assume a Salpeter IMF normalization for more accurate results,

²As implemented in the CAP_LOESS_2D routine of Cappellari et al. (2013b), available from <http://purl.org/cappellari/idl>

instead of the Kroupa/Chabrier IMFs which are often adopted. This IMF normalization is the same inferred for nearby galaxies of similar masses.

Chapter 3

Observed trend in the star formation history and the dark matter fraction of galaxies at redshift $z \approx 0.8$

We study the star formation history for a sample of 154 galaxies with stellar mass $10^{10} \lesssim M_ \lesssim 10^{12} M_\odot$ in the redshift range $0.7 < z < 0.9$. We do this using stellar population models combined with full-spectrum fitting of good quality spectra and high resolution photometry. For a subset of 68 galaxies ($M_* \gtrsim 10^{11} M_\odot$) we additionally construct dynamical models. These use an axisymmetric solution to the Jeans equations, which allows for velocity anisotropy, and adopts results from abundance matching techniques to account for the dark matter content. We find that: (i) The trends in star formation history observed in the local universe are already in place by $z \sim 1$: the most massive galaxies are already passive, **while lower mass galaxies** have a more extended star formation histories, and the lowest mass galaxies are actively forming stars; (ii) we place an upper limit of a factor 1.5 to the size growth of the massive galaxy population; (iii) we present strong evidence for low dark matter fractions within $1R_e$ (median of 9 per cent and 90th percentile of 21 per cent) for*

galaxies with $M_* \gtrsim 10^{11} M_\odot$ at these redshifts; and (iv) we confirm that these galaxies have, on average, a Salpeter normalisation of the stellar initial mass function.

Published : Shravan Shetty and Michele Cappellari, 2015, MNRAS, 454, 1332-1357

3.1 Introduction

Currently, one of the key quests of Astrophysics is to understand and model the processes that guide the formation and evolution of galaxies. Great strides have been made over the past few decades and with the advancement of technology, such as ever larger telescopes taking ever larger surveys of thousands of galaxies within an ever larger redshift range (e.g. York et al., 2000; Colless et al., 2001; Le Fèvre et al., 2005; Newman et al., 2013c; Coil et al., 2011; Kochanek et al., 2012), the advent of new techniques such as gravitational lensing (e.g. Bolton et al., 2006a; Heymans et al., 2012), and galaxy surveys using integral field spectroscopy (e.g. de Zeeuw et al., 2002; Cappellari et al., 2011a; Sánchez et al., 2012; Scott et al., 2015; Bundy et al., 2015).

Recent observational evidence suggests that the star formation rate of the universe peaked at $z \sim 2.5$ and that by $z \sim 1$ half of the stellar mass of the universe today was already in place (Bundy, Ellis & Conselice, 2005; Mortlock et al., 2011; Muzzin et al., 2013). The decreasing star formation rate, referred to as quenching, is mass dependent with the more massive galaxies being quenched earlier. Also, the comparison of the most massive galaxies ($M_* \gtrsim 10^{11} M_\odot$) at high and low redshifts show that these quiescent galaxies have undergone a size evolution; with the size of the galaxies increasing with decreasing redshift (Daddi et al., 2005; Trujillo et al., 2006; van der Wel et al., 2008; Bezanson et al., 2009; van Dokkum et al., 2010). This size evolution has been associated with minor mass growth, suggesting that these growths may be driven by minor merger where the size of the galaxy grows to the second power of the added mass through virial arguments, unlike major mergers where the size grows linearly to the increase in mass (Naab, Johansson & Ostriker, 2009; Bezanson et al., 2009;

van der Wel et al., 2009). Additionally, **recent work have pointed out that a significant part of the observed size growth in the populations of quiescent galaxies**, especially at lower masses, may be due to progenitor bias, wherein the addition of large recently quenched galaxies contribute to the observed increase in the mean size of the population (e.g. Carollo et al., 2013; Poggianti et al., 2013).

Regardless of what the process for the growth of the galaxy size, and its stellar mass may be, there is strong evidence indicating that, for the most massive galaxies, most of the additional stellar mass is added to the outskirts of the galaxies, while the central regions remain mostly unperturbed (Trujillo et al., 2006; Bezanson et al., 2009; van Dokkum et al., 2010). **As a result of these mergers the most massive galaxies in the nearby universe are slow rotators (Emsellem et al., 2011; Cappellari et al., 2013a), have cores in their surface brightness profiles (Faber et al., 1997; Ferrarese et al., 2006; Krajnović et al., 2013), and are embedded in extended stellar envelopes (Kormendy et al., 2009).**

The situation appears radically different for less massive ($M_* \lesssim 10^{11} M_\odot$) passive galaxies. At the present day, they are structurally different, and appear to have followed a different evolution path (Cappellari et al., 2013a). They are axisymmetric (Krajnović et al., 2011), they contain disks like spiral galaxies (Cappellari et al., 2011b) and are dominated by rotation (Emsellem et al., 2011; Cappellari et al., 2013a). These fast rotating galaxies follow the same mass-size relation, and have the same mass distribution, both in dense clusters as in the field (Cappellari, 2013), indicating they experienced an insignificant amount of merging during their evolution, in agreement with redshift evolution studies (van Dokkum et al., 2013).

Due to the recent advances in the techniques of stellar population modelling and redshift surveys, a key addition to this emerging picture of galaxy evolution is provided by studies of the stellar populations of galaxies through cosmic time.

The work of Schiavon et al. (2006), using spectra from the DEEP2 survey (Newman et al., 2013c), compared to local SDSS (York et al., 2000) results, suggests that the evolution

of the red-sequence galaxy population is not consistent with a passive evolutionary model. Instead, they propose that the red-sequence population should either continue to host some level of star formation (“Frosting”) to present day or have newly quenched galaxies joining the red-sequence galaxies between $z \sim 0.9$ and today.

Choi et al. (2014) study quiescent high redshift galaxies via a full spectrum fitting of stacked galaxy spectra to derive the stellar ages and elemental abundances of Fe, Mg, C, N and Ca. The work uses optical spectra of local galaxies taken from the SDSS and spectra from the AGES (Kochanek et al., 2012) survey within a redshift range of $0.1 < z < 0.7$. They find negligible evolution in elemental abundances at fixed stellar mass. For the most massive galaxies they measure an increase in stellar age consistent with passive evolution since $z \approx 0.7$. While at masses below $\sim 10^{10.5} M_{\odot}$, the data permit the addition of newly quenched galaxies.

Gallazzi et al. (2014, Hereafter G14) study a sample of 70 quiescent and star-forming galaxies at $z \approx 0.7$, above a stellar mass of $10^{10} M_{\odot}$. They derive the stellar age-mass relation of the galaxies, **which they compare** with that derived in a similar manner in the local universe. They find that taken as a whole, passive evolution cannot represent the evolution of galaxies in the last ~ 6 Gyr. In fact, although the shape of the stellar age-mass relationship between the two redshifts is similar, the offset is inconsistent with passive evolution. **This is in agreement** with their observed metallicity differences with redshift. They propose a mass-dependent star formation history (SFH) to explain the observations.

Here we use full-spectrum fitting to explicitly determine trends in the star formation history of a sample of 154 galaxies at $0.7 < z < 0.9$. Furthermore, we investigate the correlation between the stellar population and the physical parameters of the galaxies. We also present results on the dynamical modelling of a subset of 68 galaxies. This subsample is the same we analysed in our previous work (Shetty & Cappellari, 2014), where we studied the Initial Mass Function (IMF) mass normalisation and concluded it is consistent with a

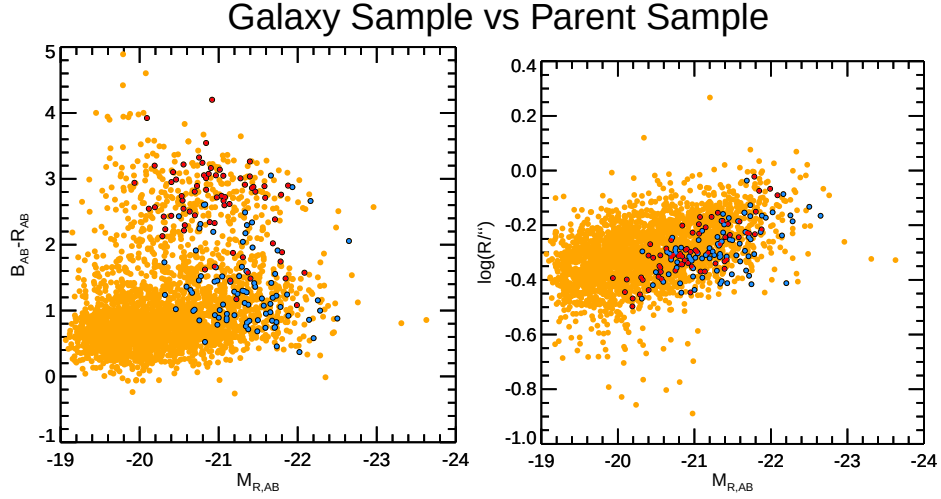


Fig. 3.1 In this plot, we compare our galaxy samples: 68 galaxies in our secondary sample (red points) and 154 galaxies in our full sample (blue and red points), against the parent sample of 2,896 galaxies in the same redshift range and field from the DEEP2 survey (orange points). In the left panel, we present the colour-magnitude plot where we can distinguish between the red sequence and blue cloud of the parent sample. It is evident that our galaxy samples have a measurably higher magnitude cut-off, compared to the parent sample, which is due to our selection criteria. Within this higher magnitude cut-off, our full galaxy sample provides a good representation of both the red sequence and the blue cloud. We also notice that our secondary galaxy sample is a good representation of the red sequence, while also including a few very luminous galaxies of the blue cloud. If we assume that the R_{AB} magnitude is a tracer of stellar mass, the right panel can be approximated as a stellar mass-size plot for the galaxies. We see here that our galaxy samples mainly consist of galaxies above a certain surface brightness.

Salpeter (1955) slope. Here, we improve upon the dynamical models by accounting for the dark matter of the galaxies via abundance matching techniques.

In Section 2 of the paper, we describe the observational data that we use within this study while in Section 3 we discuss the selection criteria that have been implemented in the course of this analysis, along with a comparison of our galaxy sample with the parent sample. In Section 4, we present the various methods used to analyse the data followed by a discussion of the results in Section 5. In Section 6, we provide a summary of the results.

In this study, we assume a flat universe with the following cosmological parameters: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

3.2 Data

3.2.1 Spectral Data

The spectral data used in this study was taken from the DEEP2 survey. The survey is an apparent magnitude limited, $R_{AB} = 24.1$, spectroscopic redshift survey of 4 fields covering an area of 2.8 deg^2 across the sky characterised by low extinction. The observation targets for the survey were selected using an algorithm based on the Canada-France-Hawaii Telescope (CFHT) observed object size, luminosity, (B-R) and (R-I) colours (Coil et al., 2004) and a surface brightness cut-off which eliminated wrongly classified objects (Newman et al., 2013c). Of the four fields of DEEP2, only the Extended Groth Strip (EGS; Groth et al. (1994)) has the required high resolution *HST* data to construct dynamical models and accurately measure galaxy size. Hence this study is restricted to this field of the DEEP2.

The observations for the survey were done using the DEIMOS spectrograph on the Keck-2 telescope, covering an observed wavelength range of $6,100\text{\AA} - 9,100\text{\AA}$. The highest resolution grating, $1,200 \text{ line mm}^{-1}$, was used to achieve a spectral resolution of $R \sim 6,000$ within the $1'' \times \sim 7''$ slitlets of the instrument. The observations were taken in 3 exposures of 20 minutes each, with the FWHM generally ranging between $0.5''$ and $1.2''$ due to seeing.

The reduction of the 2D spectrum of each galaxy and the extraction of its 1D spectra was done by the DEIMOS *spec2d* pipeline. In our study we use the 1D spectra extracted via the Boxcar technique from the central $\sim 1'' \times 1''$ window. Due to the design of the survey, the observed 1D spectra is divided into 2 halves along wavelength. Here we use the blue half of the two, since the CaK ($3,934\text{\AA}$) and G band ($4,304\text{\AA}$) stellar lines fall within this half for galaxies in the redshift range that we are studying.

3.2.2 Photometric Data

Our photometric data was taken from the AEGIS data product (Davis et al., 2007), specifically from the *Hubble Space Telescope (HST)* GO program 10134 (P.I.: M. Davis). These are *HST*/ACS images taken in the F606W (V band) and F814W (I band) filters. The observations are limited to 5σ measurements of $V_{\text{F606W}} = 26.23(AB)$ and $I_{\text{F814W}} = 25.61(AB)$ within a circular aperture of $0.3''$. This program covered 0.197 deg^2 of the EGS, overlapping entirely with the region observed by DEEP2. The observations were made in a four point dither pattern, which was processed by the STSDAS MultiDrizzle package to produce a final mosaic of the field with a pixel scale of $0.03''$. In this work, we use the F814W photometry as this translates to the vega B band at the redshifts that we are studying.

3.3 Galaxy Samples

In this study we use two samples extracted from the large DEEP2 survey catalog. The first one consists of 154 galaxies and was used to measure trends in the galaxies star formation histories via full-spectrum fitting. The second one is a subsample of 68 galaxies of the first, for which we construct dynamical models. Details of the adopted selection criteria are presented below.

3.3.1 Selection Criteria

Our first selection criterion is based on the quality flags provided by the DEEP2 survey catalogue, i.e. we selected galaxies that have either “secure” or “very secure” redshift estimation based on the automated and visual spectral redshift estimation by the DEEP2 team. We select galaxies with redshift $0.7 < z < 0.9$. In this study we have only used galaxies in the EGS field due to the lack of availability of high resolution *HST* photometry in the remaining fields. By extracting $9'' \times 9''$ thumbnails, from the AEGIS mosaics, centred at the

galaxy coordinates provided by the DEEP2 catalogue, we visually confirm the presence of photometry of the galaxies. These thumbnails are later used to parametrize the photometry of the galaxies and further details on this is provided in Section 3.4.3. From a total of 43,569 galaxies in the DEEP2 Galaxy Redshift survey 1,249 galaxies passed this stage of the selection process. Of these, 1,240 (99.3%) galaxies have an apparent $I_{F814W} < 24(AB)$.

The second selection criterion is based on the quality of the galaxy spectra. We calculate the mean signal-to-noise (S/N) of a galaxy spectrum as the median flux in the galaxy spectrum divided by the standard deviation of the residuals of the spectral fit to that spectrum. In this instance, the spectral fitting was done with a set of empirical stellar spectral library, while masking gas emission features. Further details on this spectral fitting is presented in Section 3.4.1. We only select galaxies with $S/N > 3$. We further eliminate galaxies that do not appear to have significant absorption features, i.e. clear spectral absorptions which stood out visually above the noise. This selection criteria reduced the galaxy sample to 175 galaxies. To give the reader a sense of the quality our spectral data, in Appendix C we present the reader with the spectra of our final sample.

Our third selection criteria is based on the visual inspection of the thumbnails of the galaxies, taken from the F814W images by the *HST*/ACS. We have removed 21 irregular galaxies from our final sample as these galaxies are likely to be disturbed and would confuse the trends being investigated in this study. The selection criteria based on the galaxy spectra and imaging quality, dramatically reduces our galaxy sample to 154 galaxies.

In this study, we also create dynamical models for our galaxy sample, however this requires some additional selection criteria. To create the dynamical models we need to parametrize the photometry of our galaxies to high accuracy within the central regions from which the stellar kinematics are observed. We exclude galaxies that have disturbed photometry, such as dust lanes, or non-axisymmetric features, and hence this galaxy subsample is biased towards early-type galaxies with smooth light profiles. Further details on this selection

criterion is given in Section 3.4.3. We also provide the reader with contour plots representing the quality of the photometric parametrization in Appendix B for our secondary galaxy sample, for which we have successfully created dynamical models.

Also, the dynamical modelling of galaxies assume a spatially constant stellar mass-to-light ratio (M/L), however this assumption becomes inaccurate for galaxies with multiple significant star formation events. Therefore, after deriving the SFH of our galaxies, we eliminate galaxies that require more than one significant star formation episode to reproduce their spectrum. In addition to this, the ATLAS^{3D} group found that young galaxies, as inferred by their strong $H\beta$ absorption feature, tend to show strong gradients in the stellar M/L . For this reason, these galaxies were removed from their IMF studies (Cappellari et al., 2012, 2013b, hereafter C13b). In this study, we use full-spectrum fitting to the galaxy spectra to identify the best fitting single stellar population (assuming solar metallicity) of the galaxies. We then classify any galaxy with the best fitting population of 1.2 Gyrs or younger as a young galaxy and eliminate them from our secondary sample. This narrows our secondary galaxy sample to 68 galaxies for which dynamical models were created. This sample is identical to that used in Shetty & Cappellari (2014).

3.3.2 Sample Bias

Given our strict selection criteria, our sample cannot be representative of the general galaxy population at $z \sim 1$. To illustrate the effect of the selection criteria on the sample, in Fig. 3.1 we compare our galaxy samples to a larger parent sample of galaxies. This parent sample contains 2,896 galaxies selected to have “*secure*” or “*very secure*” redshift $0.7 < z < 0.9$ in the EGS field of the DEEP2 survey. We compare the galaxy samples using data from the photometric catalogue provided by the DEEP2 survey, which is derived from Coil et al. (2004). The catalogue contains the observed B_{AB} , R_{AB} and I_{AB} magnitudes of the galaxies calculated from observations made by Canada-France-Hawaii Telescope using the CFH12K

camera. The catalogue also contains an estimate of the Gaussian radius of the galaxies which we use as a proxy for the size of the galaxies. For further details on the the catalogue, we refer the reader to Coil et al. (2004).

In the left panel of Fig. 3.1, we compare the $B_{AB} - R_{AB}$ colour of the galaxies against their absolute R_{AB} observed band magnitude. The plot depicts the R_{AB} magnitude limit of the DEEP2 survey and clearly separates the blue cloud and red sequence of the field. The plot demonstrates that our sample have a higher R_{AB} cut-off than the DEEP2 which can be explained by the S/N cut-off that we place on our galaxy spectra. This is further demonstrated in the right panel of Fig. 3.1, where we plot the R_{AB} of the galaxies against a measure of the size of the galaxies. Due to the design of the survey, particularly the fact that each galaxy has a fixed exposure of 3×20 minutes and fixed aperture size, galaxies with lower surface brightness will be of lower quality. **Hence, our S/N cut-off** can be roughly approximated as a surface brightness cut-off.

The left panel of Fig. 3.1 also demonstrates that our secondary sample, indicated by the red points in the plot, is a good representation of the red sequence along with a few galaxies in the blue cloud. This is likely the consequence of the additional selection that we place on the secondary sample, whereby only galaxies with smooth light profiles and without significant star formation younger than 1.2 Gyrs are selected. Our full sample, indicated by the red and the blue points, appears to represent all but the bluest galaxies over a certain magnitude cut-off. This under-representation may be the result of the visual inspection of the galaxy spectra, where the presence of hydrogen emission or apparent high frequency noise make the spectrum fits look unreliable.

3.4 Methods

3.4.1 Spectrum Quality Criteria

We measure the mean S/N by fitting the observed galaxy spectra with an empirical stellar spectral library. Our choice for an empirical stellar library, rather than population models, to estimate the S/N is done to allow for maximum freedom to the optimal template combination, especially for very young ages. This avoids potential bias in the stellar velocity dispersion, which is also extracted during this step. However our results are quite insensitive to this choice, due to the rather low S/N of our spectra. The spectral fitting is done using the pPXF method and code (Cappellari & Emsellem, 2004) which uses a penalised maximum likelihood fitting technique in pixel space. Before fitting we logarithmically rebin the observed galaxy spectrum to 60 km s^{-1} per pixel. As templates we use a subset of empirical stellar spectra taken from the Indo-US Library of Coudé Feed Stellar Spectra Library (Valdes et al., 2004). The subset of 53 templates is made such that: (i) each spectrum is gap-free and (ii) the subset is a good representation of the library’s atmospheric parameter range (T_{eff} vs $[Fe/H]$). We use pPXF to fit for the velocity and velocity dispersion of the galaxies using 4 additive and one multiplicative polynomial. During the fit of the galaxy spectra gas emission features are masked. The residuals of the fits are found to be random, suggesting that our spectral fitting is not biased by template mismatch.

Using these fits, we derive the S/N of each galaxy spectra as the ratio of the median of the galaxy spectra and the standard deviations of the residuals. We remove galaxies that have $S/N < 3$ from our final sample as we found the fits to their spectra unreliable.

3.4.2 Recovering Star Formation History

We derive the star formation history of our main sample of 154 galaxies via a full-spectrum fitting technique using the pPXF code (Cappellari & Emsellem, 2004). For our templates,

we use the MILES stellar population models (Vazdekis et al., 2010). These models are based on the MILES empirical stellar spectra library (Sánchez-Blázquez et al., 2006) and have a resolution of $2.5 \text{ \AA}$ FWHM (Falcón-Barroso et al., 2011). To ensure realistic fits of the galaxy spectrum with the template models, we placed certain constraints on our template grid. We use stellar population models logarithmically spaced into 40 age bins within the age range of 0.08–7.9 Gyrs to restrict the age of stellar populations to that less than the age of the universe at the redshift under study. We have also restricted our template metallicities to $[M/H]$ of -0.4, 0.0 (Solar metallicity) and 0.22. **This constraint** is based on results by Schiavon et al. (2006) where the authors studied the absorption line strengths of stacked spectra of the DEEP2 sample at redshifts $0.7 < z < 1$ and concluded that these galaxies have metallicities close to solar. Since Schiavon et al. (2006) use $[Fe/H]$ to measure their metallicities, we should note that for our template models the $[M/H]$ is equivalent to $[Fe/H]$ (Vazdekis et al., 2010). For this analysis we adopt the Salpeter IMF (Salpeter, 1955) for our stellar population models, however the derived trends in the SFH are insensitive to the IMF choice, as demonstrated in Panter et al. (2007).

In this study, we do a full-spectrum fitting for the spectral features and continuum shape of the observed galaxy spectra. In order to account for the effect of dust in the galaxy and the uncertainties in the calibration of the detectors used to observe the galaxy and stellar template spectra, we use a fourth order multiplicative polynomial during the fitting process. The fractional weight assigned to each template indicates the fraction of the galaxy spectrum contributed by that stellar population. We do not use any additive polynomials when fitting for the stellar populations as these polynomials can artificially change the line strengths of the model templates. During the fitting with pPXF, the code convolves the model spectra with a Gaussian Line-Of-Sight Velocity Distribution (LOSVD), which is optimized to best fit the spectrum.

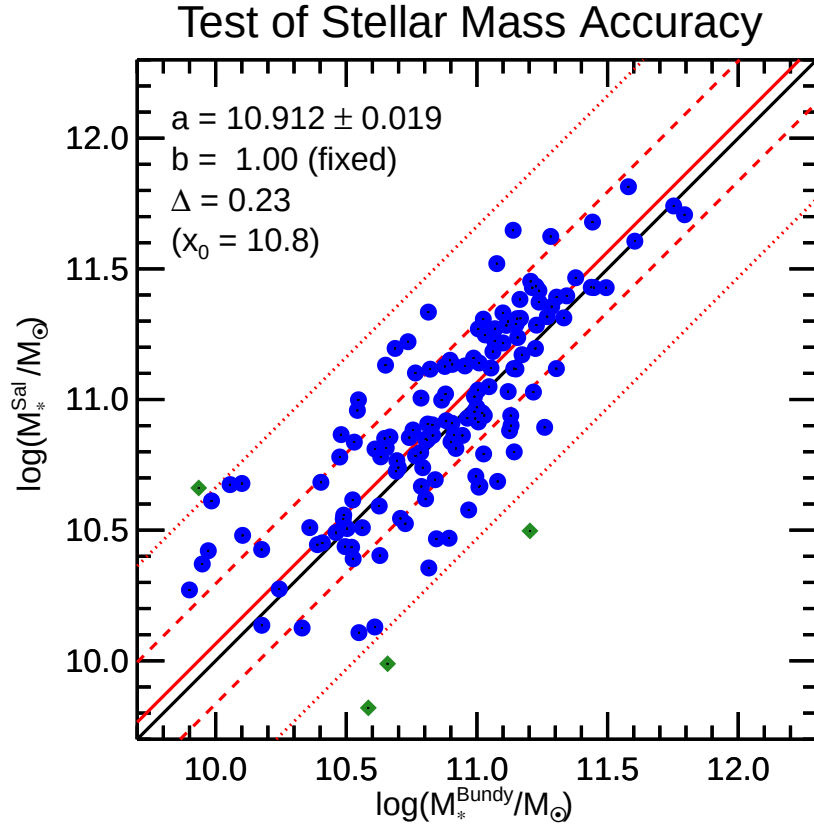


Fig. 3.2 Here we present a comparison between the stellar mass derived via our population modelling with the same derived by Bundy et al. (2006). The linear fitting is done via Least Trimmed Square fitting described in C13b with the code modified to fit the slope at one. The best-fitting coefficients for the fitted relationship, $y = a + b(x - x_0)$, are presented in the top left corner of the plot. The solid red line is the best fitting relation between the two quantities, while the dashed and dotted red lines enclose regions of 1Δ and 2.6Δ respectively, where Δ is the observed rms scatter around the relation. For comparison, the solid black line represents the one-to-one relation between the quantities.

We derive the star formation history of the galaxies by fitting their spectra with the above mentioned template grid while enforcing a smoothness criterion on the distribution of the weights in a mass weighted manner. This smoothness criterion is enforced by penalising the χ^2 for weight distributions with non-zero second partial derivatives. In this way, for infinite regularization, the 2-dimensional solution converges to a plane. Regularization is a standard method to solve general ill-posed inverse problems (e.g. Engl, Hanke & Neubauer, 1996) like the recovery of the SFH from a spectrum. It is implemented in pPXF using the classic linear-regularization approach as in equation (19.5.10) of Press (2007) and is enforced via the *REGUL* keyword in pPXF. The value assigned to the *REGUL* keyword specifies the strength of the penalisation of the χ^2 . A common guideline is to penalise the model till $\Delta\chi^2 = \chi^2 - \chi_{\text{unregul}}^2 = \sqrt{2 \times N_{\text{DoF}}}$, where χ_{unregul}^2 is the χ^2 of the model without penalisation and N_{DoF} is the number of degrees of freedom (Press, 2007, section 19.5).

We should note that the regularization approach is not similar to smoothing the solution after the fit. In fact regularization *does not* prevent sharp features in the recovered star formation or metallicity distribution, as long as these are required to fit the data. The regularization only influence the weight distribution when the solution is degenerate and many different and noisy ones can fit the data equally well. In this case the smoothest solution is preferred over the noisy ones. This is a general feature of all regularization approaches.

For a few galaxies, we find the value of *REGUL* is poorly constrained by the $\Delta\chi^2$ criterion, due to the rather large noise in the galaxy spectra. For this reason pPXF is able to fit the spectrum using a perfectly smooth weight distribution before $\Delta\chi^2 = \sqrt{2 \times N_{\text{DoF}}}$. Hence, to be conservative, and to avoid our results from being driven by the regularization, we lowered the requirement on $\Delta\chi^2$ from the standard one mentioned above to $\Delta\chi^2 = \sqrt{2 \times N_{\text{DoF}}}/10$.

As a consistency check, we have compared the stellar masses of 151 common galaxies derived in this study and that of Bundy et al. (2006), where the authors use BRIK colour to derive the stellar mass for a sample of $\sim 8,000$ galaxies in the DEEP2 survey under the

assumption of a Chabrier IMF (Chabrier, 2003). We calculate our galaxy stellar mass ($M_{\star}^{Sal}$) by multiplying the absolute luminosity of the galaxies by the $(M_{\star}/L)$ inferred from the spectral fits

$$(M_{\star}/L)_{\text{Sal}} = \frac{\sum_j w_j M_{\star,j}^{\text{nogas}}}{\sum_j w_j L_{B,j}}, \quad (3.1)$$

where w_j is the weight attached to the j th template by the regularised mass-weighted fit to the galaxy spectrum, $M_{\star,j}^{\text{nogas}}$ is the mass of the template that is in stars and stellar remnants, and $L_{B,j}$ is the B -band (Vega) luminosity of the template. **Note that all M/Ls derived in this study are in the B (Vega) band.** We derive this luminosity using the MGE parametrization of the *HST*/ACS galaxy thumbnails, mentioned in Section 3.4.3, using the galaxy redshift and equation (10) of C13b.

The comparison between the 151 common galaxies is shown in Fig. 3.2, where we compare the two stellar masses using the LTS_LINEFIT method¹ (C13b) which has been modified to derive the best fit with a fixed slope. The solid red line in the plot represents the best fitting unitary-slope relation to the points, with the coefficients presented in the top left corner. The Δ parameter is the observed rms scatter around the relation, while the dashed and dotted red lines indicate the Δ and 2.6Δ deviations from the best-fit. The solid black line indicates the one-to-one relation of the quantities. We see that a relation with slope unity is a good fit between the two datasets, though there is a significant offset of 0.11 dex and some scatter. The cause of the scatter and offset is likely the effect of differences in the assumed IMF between the two quantities, ie this study assumes a Salpeter IMF while Bundy et al. (2006) assume a Chabrier IMF, and the differences between the photometry and its analysis. Also, the work by Gallazzi & Bell (2009) found that based on the techniques used to model the $(M_{\star}/L)$ of the galaxies, uncertainties and systematics of the order 0.1–0.2 dex are expected.

¹Available at <http://purl.org/cappellari/software>

Given that the stellar masses derived in this study and that of Bundy et al. (2006) are completely independent, use very different data and approaches, and suffer from different systematics, we adopt $\Delta/\sqrt{2} = 0.16$ dex as our very conservative errors in the estimation of the stellar mass of an individual galaxy via stellar population modelling.

To estimate a conservative uncertainty in our derived $(M_*/L)_{\text{Sal}}$, we derive our (M_*/L) under 2 model sets and fitting conditions: (i) a regularised fitting to the complete model grid of 120 single stellar population models and, (ii) a non-regularised best fit to the model grid limited to 40 models with solar metallicities. Our comparison of the two in Fig. 3.3 shows a linear relation between the two values. The observed scatter is $\Delta = 0.12$ dex, which corresponds to an error of $\Delta/\sqrt{2} = 0.08$ dex or 22% in each (M_*/L) , assuming their errors are comparable.

For comparison we also derived the error on the derived $(M_*/L)_{\text{Sal}}$ via a more standard bootstrapping technique. We reshuffled the residual and repeated the determination of $(M_*/L)_{\text{Sal}}$ multiple times. This yielded a median error of 0.05 dex in $(M_*/L)_{\text{Sal}}$ for the full sample, which is smaller than the error of 0.08 dex derived above. To be conservative, and to account at least in part for systematic effects, in this study we adopt the intrinsic scatter of 0.08 dex between the two quantities as the error in the derived (M_*/L) .

3.4.3 Photometry Parametrization

To study the scaling relations, we measure the luminosities and size by parametrising the photometry of the galaxies. In this study, we choose the F814W photometry taken by the *HST*/ACS to do so. The need for *HST* photometry comes from the requirement, in the dynamical models, of an accurate description of the tracer population producing the observed kinematics. This also motivates our choice for the F814W filter, which is as close as possible to the wavelength range from which the stellar kinematics is obtained.

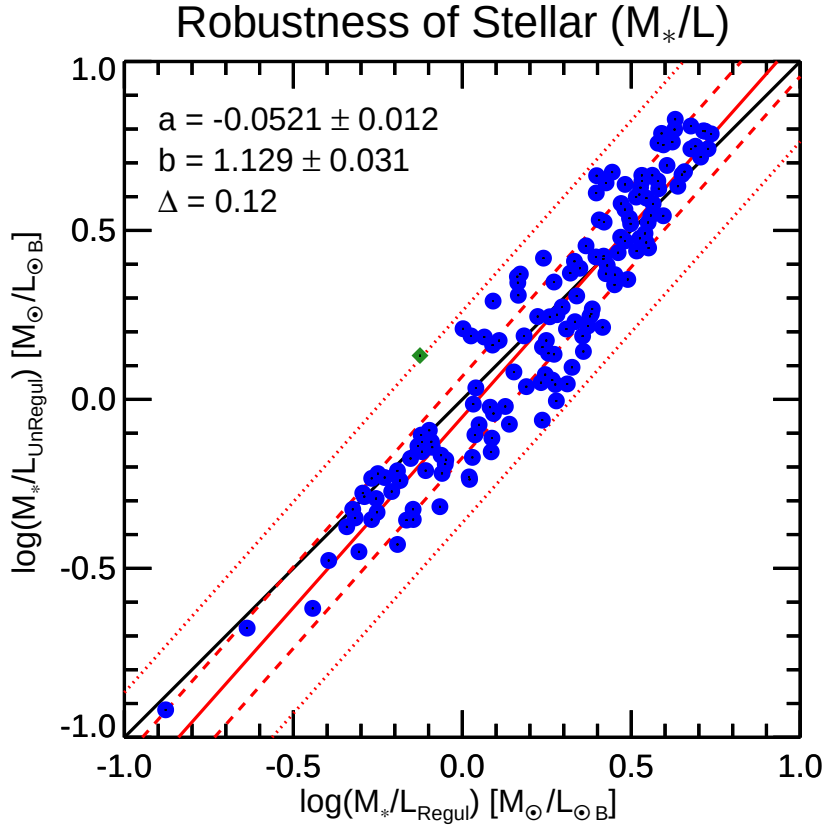


Fig. 3.3 In this plot, we compare the stellar M/L derived under two different assumptions for the stellar population of the galaxies. The comparison between the derived quantities is done using the Least Trimmed Square (LTS) fitting described in C13b. The best-fitting coefficients for the fitted relationship, $y = a + bx$, are presented in the top left corner of the plot. The solid red line is the best fitting relation between the two quantities, while the dashed and dotted red lines enclose regions of 1Δ and 2.6Δ respectively, where Δ is the observed rms scatter around the relation. The solid black line is the one-to-one relation between the quantities. The independence of the quantities of systematic bias indicates that our fits do not suffer from template mismatch.

We parametrize the photometry of the galaxies using the Multiple-Gaussian Expansion technique (Emsellem, Monnet & Bacon, 1994; Cappellari, 2002). This technique fits a series of two dimensional Gaussians, each defined by an amplitude, standard deviation and axial ratio, to the observed surface brightness of the galaxy image in a non-parametric manner, i.e. without the use of a predefined light profile function like the Sérsic profiles. The advantage of this technique is that the convolution and deprojection (i.e. conversion of the 2D model into the intrinsic 3D luminosity distribution) of the MGE models is analytically simple. The fit is performed with the robust method and software (see footnote 1) by Cappellari (2002).

In this study, we use the MGE parametrisation of the photometry to construct our dynamical models. These models assume axisymmetry, but galaxies can show non-axisymmetric features, such as bars. Scott et al. (2013, Sec. 3.2.1) tried to reduce the effect of bars in the models by essentially ignoring them during the fits, while forcing the MGE to only describe the light distribution of the underlying galaxy disk. In this study, we also adopted the same approach for all galaxies.

The luminosity of the galaxies are calculated from the analytic sum of the Gaussian luminosities equation (10) of C13b, while the projected half-light radii (R_e) were computed from the circularised Gaussians using equation (11), of C13b. For our galaxies, we also calculate the R_e^{Maj} , the major axis of the isophote containing half of the light of the galaxy as these are found to be a more robust measurement of the galaxy size due to its lower dependency on galaxy inclination (Hopkins et al., 2010, C13b). We derive this value as described in section 3.3.1 of C13b. The quality of the MGE fits to the galaxy photometry is illustrated by contours plots in Appendix B.

In Shetty & Cappellari (2014) we show that, for the subset of 68 galaxies for which we construct dynamical models, the R_e derived using the MGE parametrization are consistently offset from the R_e one can predict from the virial equation $M_{\text{vir}} = 5.0 R_e \sigma_e^2 / G$, when using the coefficient of Cappellari et al. (2006). We found that those galaxies required a 0.16 dex

increase in R_e , for M_{vir} to match the M_{JAM} derived via JAM models. Since we use the same data, at the same redshift, for all 154 galaxies, we apply the same fractional correction to the R_e and R_e^{Maj} of all galaxies of this study. Since the F814W filter approximates to the B band at the redshift range of our galaxies, we state all luminosity and photometric quantities in the B band.

3.4.4 Dynamical Modelling

To further understand the evolution of galaxies since $z \sim 1$, we created dynamical models for a subsample of our galaxies. In this study we use the Jeans Anisotropic Modelling (JAM; see footnote 1) method and code of Cappellari (2008), which solves the Jeans (1922) equations under the assumptions of axisymmetry, while allowing for orbital anisotropy and rigorously accounting for seeing and aperture effects.

The models require as input an accurate description of the projected light distribution of the galaxy and a parametrization for the unknown total mass. As the galaxy inclination is generally unknown, we assume a standard inclination of 60° , the average inclination for a set of random orientations. When this inclination is not allowed by the MGE model, we adopt the lowest allowed one. Here an inclination of 90° corresponds to an edge-on view. Another quantity required by JAM is the velocity anisotropy $\beta_z \equiv 1 - \sigma_z^2 / \sigma_R^2$, where σ_z and σ_R are the velocity dispersion along the symmetry axis and along the cylindrical radius, respectively. In this study, we adopt $\beta_z = 0.2$ as this is found to be a typical value for ETGs in the local universe (Gerhard et al., 2001; Cappellari et al., 2007). Tests by Cappellari et al. (2006) and Lablanche et al. (2012) show that the derived M/L through the JAM code is weakly sensitive to the effects of inclination and spatially constant velocity anisotropy.

The 68 galaxies in our modelling subsample are the same for which we created dynamical models in Shetty & Cappellari (2014), and we adopt the stellar velocity dispersion from that study. The stellar kinematics were derived from the DEEP2 spectra within a 1 arcsec slit. In

Shetty & Cappellari (2014) our JAM models assumed the total mass is distributed like the luminous one, hence our derived dynamical M/L incorporates the effect of stellar and dark matter.

Here we improve our dynamical models by explicitly including dark matter using results from the abundance matching techniques. This infers a relation between the stellar and halo mass by matching simulated dark halo mass functions to observed galaxy luminosity functions, under the assumption that the most massive galaxies reside in the most massive halos (e.g. Kravtsov et al., 2004; Conroy, Wechsler & Kravtsov, 2006; Vale & Ostriker, 2006; Vale & Ostriker, 2008).

Here we try two different relations between the stellar and halo mass. The first is taken from Leauthaud et al. (2012), where the authors fit a log-normal Stellar-to-Halo mass relation (SHMR), with a log-normal scatter, to the results of weak galaxy-galaxy lensing, galaxy clustering and galaxy number density analysis of the COSMOS survey (Scoville et al., 2007). We use equation (13) of Leauthaud et al. (2012) and the parameter values for model *SIG_MOD1* within the relevant redshift bin to derive the halo mass associated with a galaxy of given stellar mass. The second SHMR we use is equation (2) of Moster, Naab & White (2013). Here the authors use high resolution N-body simulations to derive the dark halo mass function at different redshifts, and match them to the observed galaxy stellar mass functions, hence allowing one to derive the halo mass for a galaxy of a given stellar mass.

We further assume that the dark matter of our galaxies is distributed spherically with an NFW profile (Navarro, Frenk & White, 1996). We constrain the concentration of the halo using equation (12) of Klypin, Trujillo-Gomez & Primack (2011), where the authors study the evolution of the concentration of the galaxies with redshift using the Bolshoi simulation. Using the above equations, we calculate the NFW density profile, which is fit using the one dimensional MGE fitting code of Cappellari (2002, see footnote 1), to use in JAM.

In practice, starting from a trial $(M_*/L)_{\text{JAM}}$ for a galaxy, we compute the total stellar mass by multiplication with the total luminosity. We then associate a corresponding dark halo mass using the SHMR, and a NFW profile using the halo mass versus concentration relation mentioned above. For given stellar and dark matter distributions we use JAM to predict the stellar $V_{\text{rms}} = \sqrt{V^2 + \sigma^2}$, integrated within the adopted slit and convolved by the seeing. The model V_{rms} is matched to the observed velocity dispersion by varying the only free parameter, (M_*/L) of our model, using a root finding algorithm. In this manner we account for the dark matter content of the 68 galaxies in our sample, and derive their dynamical stellar (M/L) $((M_*/L)_{\text{JAM}})$.

3.5 Results

3.5.1 Observed Star Formation History

In Fig.3.4, we have plotted the SFH of the galaxies after having collapsed them along the metallicity axis. The galaxies are sorted along the x-axis of the plot in order of increasing stellar mass as derived by stellar population modelling. In the top panel, we present the regularised SFH and we can clearly see that there is a gradual trend in the presented SFH with stellar mass. It appears that galaxies with low stellar mass tend to have a significant mass fraction of their stellar populations younger than 1 Gyr, unlike the typical SFH of high stellar mass galaxies, where the significance of this young stellar population weakens.

For comparison in the bottom panel we have presented the unregularised mass distribution for the full-spectrum fitting of the galaxies. In this case the weights distribution is much noisier and consists of discrete peaks, as expected. But the main trend in SFH with galaxy mass can still be recognized. This shows that the recovered trend is robust.

To further illustrate this trend, we have coadded the galaxy spectra into 3 bins: $10^{11.1} < M_*^{\text{Sal}}, 10^{10.75} < M_*^{\text{Sal}} < 10^{11.1}$ and $M_*^{\text{Sal}} < 10^{10.75}$. The full-spectrum fitting of these coadded

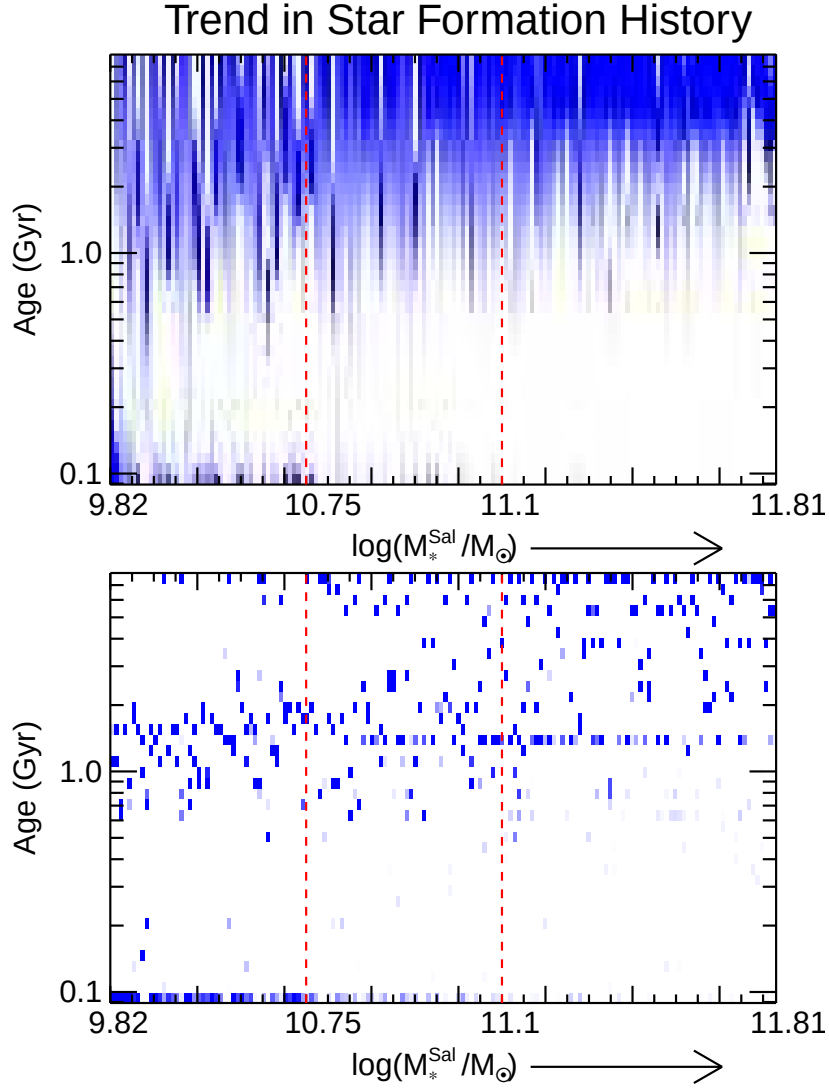


Fig. 3.4 These plots illustrate the fraction of mass represented by stellar populations of different ages for each galaxy. Along the y-axis are stellar populations of different ages, while along the x-axis are the stellar masses of the galaxies, sorted such that the stellar masses increases from the left to right. The intensity of the blue shade represents the fraction of mass of the galaxy composed of stellar populations of a certain age. The top panel represents the SFH of the galaxies derived through the mass-weighted regularised full-spectrum fitting of the galaxy spectra to the entire template grid, while the bottom panel represents the mass distribution from a mass-weighted unregularised full spectrum fitting to the stellar populations with only solar metallicities. Both plots demonstrate that galaxies with lower stellar mass tend to have a significant fraction of young stellar populations unlike those with the highest stellar masses where the bulk of their stellar populations are formed very early on in the history of the universe. This correlation is further demonstrated in Fig. 3.5, where we have coadded the galaxy spectra based on their stellar mass. The bin sizes of these stellar mass bins are represented here in vertical red dashed lines at stellar masses.

spectra, along with their associated SFH, are shown in Fig. 3.5. As the S/N is much higher for the coadded spectrum of the galaxies, we adopt the standard $\Delta\chi^2 = \sqrt{2 \times N_{\text{DoF}}}$ criterion for regularization (for further information, please refer to Section 3.4.2).

Also, the significantly high S/N allows us to confidently fit the coadded spectra using the entire metallicity range of the MILES models, $[M/H] = -1.7$ to 0.22 . We should point out that the $[M/H]$ is not equivalent to $[Fe/H]$ for the low metallicity models, however Vazdekis et al. (2010) state that this doesn't effect the galaxy age and metallicity estimates significantly. The same trend that we could see in the individual spectra appears cleaner in the stacked ones: (i) the most massive galaxies require a maximally old and nearly solar population to reproduce the observations, with little room for recent star formation. (ii) The galaxies with intermediate masses still peak at the oldest ages, but allow for a more extended star formation history. (iii) The lowest mass galaxies do not peak at the oldest ages any more and additionally show clear evidence for ongoing star formation.

The well known age-metallicity degeneracy of stellar population models implies that the effect on a galaxy spectrum due to a decrease in its mean age can be negated by an increase of its metallicity (Worthey, 1994; Renzini, 2006). This degeneracy is reduced by the use of full-spectrum fitting, which tries to reproduce a large number of spectral features (Conroy, 2013), but the general trend is still present in our recovered age and metallicity distributions. An example of this can be seen in the bottom right panel of Fig. 3.5: The ridge of equally-large weights going from an age of 2 Gyr with nearly solar metallicity, to an age of 7 Gyr with the lowest metallicity is likely due to the degeneracy, combined to our relatively narrow wavelength range. In Table. 1, we present the relevant stellar modelling quantities of the full galaxy sample of the study. The complete version of this table is available online with the published article.

In this study, we calculate the mean age of the galaxies from the SFH as follows:

$$\langle \log(\text{Age}) \rangle = \frac{\sum_j w_j \log(\text{Age}_j)}{\sum_j w_j}, \quad (3.2)$$

DEEP2 ID	Redshift	R_e	R_e^{Maj}	M_B	$(M_*/L)_B^{\text{Sal}}$ (Regul.)	Mass- weighted Age	Luminosity- weighted Age	$\log(M_*^{\text{Sal}})$
(1)	(2)	(kpc)	(kpc)	(Mag.)	$(M_\odot/L_\odot)$	(Gyrs)	(Gyrs)	$(M_\odot)$
11044628	0.824	9.7	10.0	-22.06	0.5	1.65	0.28	10.686
11050845	0.840	4.4	5.2	-21.76	3.5	4.85	4.57	11.429
11051246	0.777	4.4	4.6	-21.18	0.9	2.47	0.71	10.592
12003915	0.749	3.2	5.1	-20.89	0.7	2.52	0.34	10.391
12004067	0.748	9.4	10.2	-21.76	0.8	2.26	0.54	10.784

Column (1) : DEEP2 galaxy identifier. Column (2) : DEEP2 estimated redshift. Column (3) : Effective radii of the galaxies derived analytically from the circularised MGE model. This R_e has been corrected for the underestimation that was shown in Shetty & Cappellari (2014). Column (4) : Major axis of the isophote containing half of the observed light of the galaxy. Similar to the R_e , this value has also been corrected for the underestimation. Column (5) : Absolute B (Vega) band magnitude of the galaxies derived analytically through MGE models of the F814W photometry. Column (6) : The mass-weighted M_*/L_B derived through the regularised full-spectrum fit using the entire template grid. In this study, we adopt the intrinsic scatter between the (M_*/L) derived through the different methods and template grids as their error, i.e. 0.08 dex. Column (7) : Mass-weighted age of the galaxies calculated from the regularised full-spectra fit using the entire template grid. Column (8) : Luminosity-weighted age of the galaxies calculated from a regularised full-spectra fit using the entire template grid. Column (9): The log of the stellar mass, in units of $M_\odot$, derived using the values in Column (7) and Column (5). Adopting the intrinsic scatter between our value and that of Bundy et al. (2006), 0.16 dex is a good approximation to the error in this value.

Table 3.1 Results of Stellar Population Modelling. The table below is a partial representation of the complete set, which is presented in Appendix. D.

where w_j is the weight associated to the j th template during the regularised luminosity-weighted full-spectrum fit and Age_j is the corresponding age. To obtain luminosity-weighted quantities one can simply normalize all the SSPs to the same mean flux within the fitted wavelength range, before the pPXF fit. Of course the luminosity weighting refer to the fitted wavelength, which in our case lies between the U and B band. When the SSP spectra used in the pPXF fit have the flux as given by the models, namely corresponding to a unitary stellar mass, this equation provides mass-weighted quantities.

In Fig. 3.6, we present the luminosity-weighted ages of the galaxies against their respective stellar masses. The black points represent the full sample of 154 galaxies of this study, while the red triangles represent the luminosity-weighted ages of the entire sample of ~ 70 galaxies of G14, at similar redshift. On the bottom right of the figure, we plot a representative error bar for the 154 galaxies in this study. The error on the stellar mass is based on the scatter in Fig. 3.2, ie 0.16 dex. To estimate the error on the ages we bootstrap the galaxy spectra to derive their age multiple times. From this distribution of ages for each galaxy, we calculate robust standard deviations and take the median of these as the representative error. This bootstrapping is done using only the templates with solar metallicities and without the regularisation of the template weights.

The two sample appear to largely overlap, however our sample includes a larger number of low-mass and correspondingly younger galaxies. The solid black line is the resulting best-fit to our galaxy sample using a similar formula as G14:

$$\frac{\text{Age}_b}{\text{Age}(M_*)} = 1 + \left(\frac{M_b}{M_*} \right)^\gamma, \quad (3.3)$$

which describes an age trend as a function of stellar mass M_* following a power-law $\text{Age} \propto M_*^\gamma$ at small masses and reaching the asymptotically constant value Age_b above the characteristic mass M_b , with a smooth transition in between. The best-fitting coefficients for the luminosity-weighted and mass-weighted (not shown) ages of our 154 galaxies are presented in Table. 2.

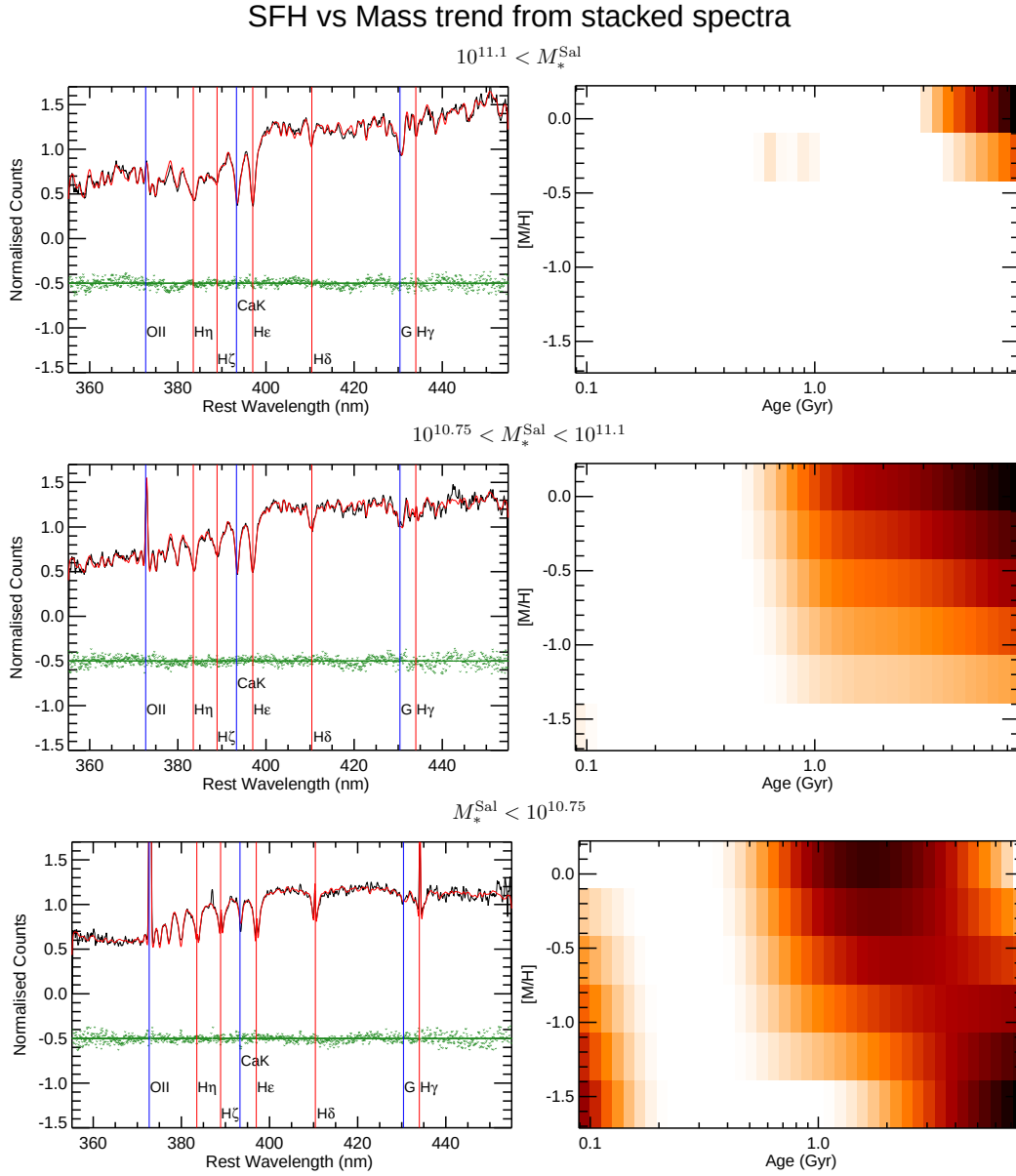


Fig. 3.5 The plots above present the spectral fits and star formation history derived for the coadded spectra for the three stellar mass bins: $10^{11.1} < M_*^{\text{Sal}}$, $10^{10.75} < M_*^{\text{Sal}} < 10^{11.1}$ and $M_*^{\text{Sal}} < 10^{10.75}$. The plots on the left hand side illustrate each coadded spectra (Black line) along with the best fit from pPXF (Red line) plotted on top. The green points below are the residuals of the fit vertically shifted to -0.5. For reference, we have also plotted the location of stellar absorption and gas emission lines within the observed wavelength. By eye it is clear that the quality of the coadded spectrum is far superior to that observed for each individual spectrum. In this case, the pPXF fit includes both stellar SSP models and gas emission line templates. For the latter, we included in the fits the Balmer emissions and the [OII] λ 3727 doublet, for which we adopted the same kinematics. This allows us to use the full spectral range without the need for masking the emission lines. Along the right hand side, we have plotted the mass fraction of the fitted stellar population models of various ages and metallicities. We clearly see a trend between the star formation history of the galaxies along with the stellar mass of the galaxies. The coadded spectra of the highest masses indicate that these galaxies are likely to form the bulk of their stars in the early epochs of the universe and undergo a passive evolution thereafter. In the case of the intermediate masses, the galaxies appear to have an extended SFH while the lowest mass spectra require recent star formation, along with a very old population, to match the observed spectra.

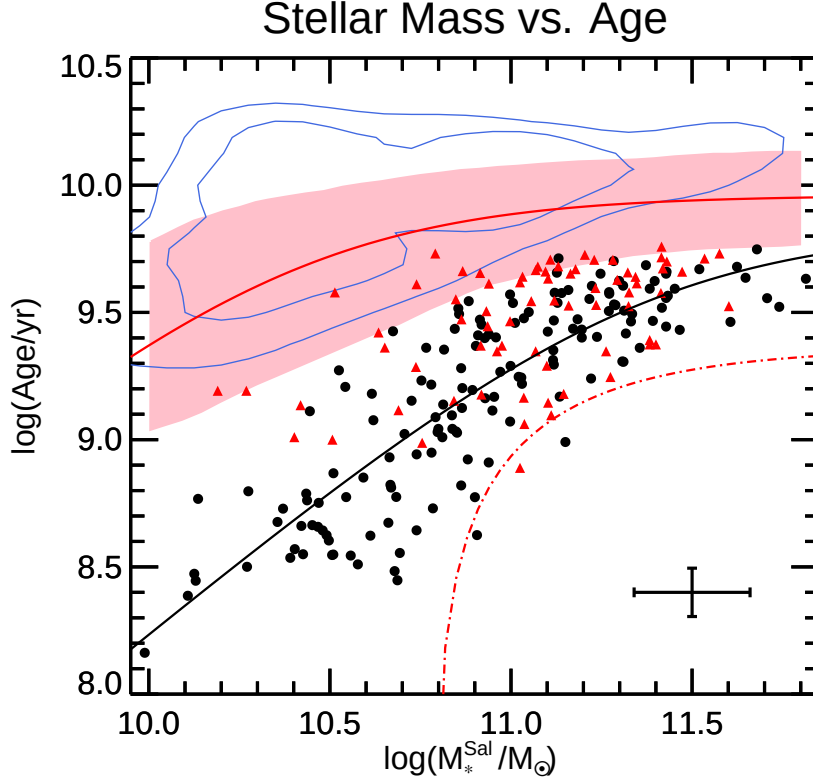


Fig. 3.6 Above we present the observed trend between the regularised luminosity-weighted stellar ages of galaxies and their stellar masses. The black points represent our sample of 154 galaxies at redshift $0.7 < z < 0.9$ with the solid black line representing the best fit to the trend using Eq. 3.3. A representative error bar for the galaxies is presented in the bottom right of the plot. The red triangles in the plot are the luminosity-weighted ages of Gallazzi et al. (2014). The plot demonstrates the trend between our luminosity-weighted ages and the stellar mass of the galaxies. In this plot we also present two samples of the local universe for reference. The solid red line represents the best fitting relations for the galaxies of Gallazzi et al. (2006) with the red band enclosing the 16th and 84th percentiles of the distribution. The blue contours represent the probability density of the ATLAS^{3D} sample. The dash-dotted red line represents the trend expected from the local galaxies of Gallazzi et al. (2006) at $z \sim 0.8$ if these galaxy have evolved passively since then.

In Fig. 3.6, we also present two local samples. The median luminosity-weighted age trend of the sample of both spirals and ETGs from Gallazzi et al. (2005) is represented by the red solid line, with the red band enclosing the 16th and 84th percentiles of the age distribution. The blue contour lines represents the probability density distribution of the single stellar population ages (similar to luminosity-weighted ages) of the volume-limited 260 ETGs of the ATLAS^{3D} survey (Cappellari et al., 2011a), as determined by McDermid et al. (2015, Hereafter MD15). This was calculated using the Epanechnikov kernel, with a smoothing template that was optimised for each dimension, based on Silverman (1986). The dot-dashed red line in the plot represents for reference the passive back evolution of the trend observed in Gallazzi et al. (2005). These two samples provide a local universe reference for our results, and given the differences in the two samples selection give a sense of the possible ranges in the local trends. Our most massive galaxies are *not* consistent with passively evolving into the corresponding sample of spirals and ETGs of the Gallazzi et al. (2005) sample, but they *are* consistent with evolving passively into the massive ETGs of MD15. This is not only true according to their mean ages but, most importantly, it is also true also for the actual SFH, which in both cases shows the galaxies essentially consists of a maximally old stellar population.

The results presented in Fig.3.4 and Fig.3.5 are in line with the results of G14, where the authors predict that the SFH of galaxies has to be a function of their stellar mass. We note that since our analysis is based on the spectra of galaxies taken within the central $1''$ of the galaxies, these results are relevant only to that region. Our analysis is unable to give any direct insight into the evolution of the outer regions of these galaxies.

By directly studying the SFH of galaxies at half the age of the universe, our study serves as a stringent test to the scenario of galaxy formation and evolution that was presented in the Introduction of this paper. Work by Onodera et al. (2012), where the authors use stacked spectrum of 17 passively evolving galaxies at redshifts of $z \gtrsim 1.4$, demonstrated that those

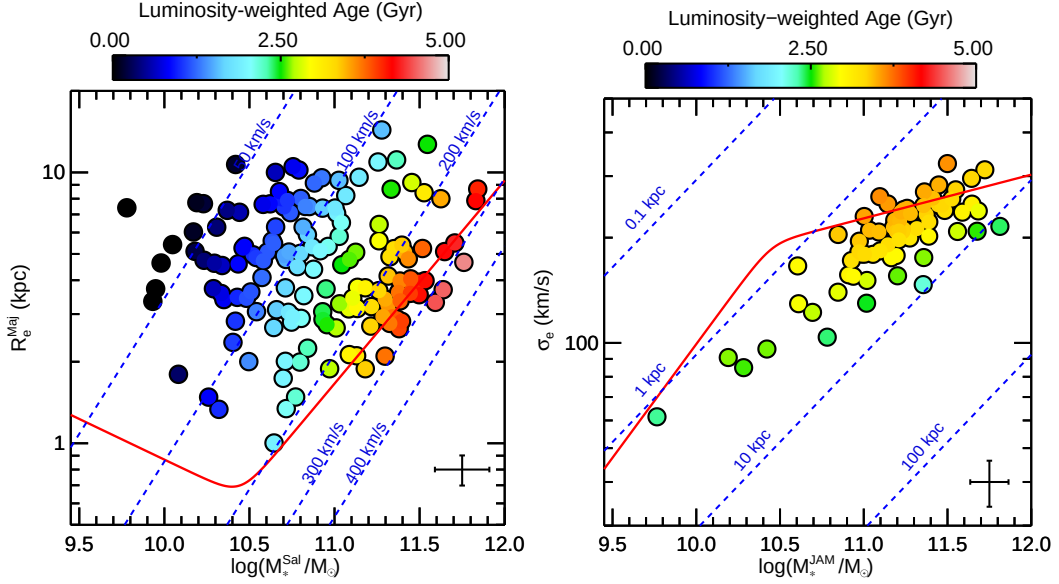


Fig. 3.7 The two panels above illustrate the mass size plot for the 154 galaxies in our full galaxy sample and dynamical stellar mass against the velocity dispersion for our secondary galaxy sample. In the left panel, the mass is derived from the mass weighted regularised stellar population modelling while the galaxy size is represented by R_e^{Maj} . The solid red line of the plot defines the Zone of Exclusion (ZOE) determined by the ATLAS^{3D} group (C13a), beyond which the probability distribution of galaxies is negligible. The dashed blue lines are lines of constant velocity dispersion. The colour trend observed in the plot is the LOESS smoothed (C13b) luminosity weighted age. This plot looks similar to its dynamical variant in the local universe (See fig. 6 and fig. 7 of MD15), where the authors find that the age of the stellar population within a galaxy is correlated to the its velocity dispersion. The left panel also demonstrates that some quiescent galaxies are on the other side of the ZOE and would require to grow by a factor of ~ 1.5 to be consistent with local observations. The right panel is equivalent to the Faber-Jackson relationship for the galaxies. In this plot, the dashed blue lines depict lines of constant size. Since the quantities of this plot is derived in a manner independent of those in the left panel, this plot illustrates the robustness of the results discussed. In the lower right corner of both panels, we present a representative error bar for the quantities.

Technique	$\log \text{Age}_b$	$\log M_b/M_\odot$	γ
Mass-weighted Ages	9.70	10.66	1.15
Luminosity-weighted Ages	9.83	11.35	1.18

Table 3.2 Best fitting parameters for equation 3.3

massive galaxies had been quenched since $z \sim 2.5$. This is consistent with work by Juneau et al. (2005) and Behroozi, Wechsler & Conroy (2013), where the authors use observational data covering a large redshift range, to show that the star formation rate peaks at redshift of ~ 3 for the most massive galaxies and that this peak evolves to lower redshifts for lower mass galaxies.

This trend in the star formation rate of the galaxies has been known for about two decade from observations of the fossil record in the local Universe (e.g. Cowie et al., 1996; Heavens et al., 2004; Thomas et al., 2005; Panter et al., 2007, MD15). However the local studies require a significant extrapolation to describe the SFH over the full evolution of the Universe. While our study directly recovers the SFH at an epoch when the Universe was half its current age, it is reassuring to find that the extrapolated local SFH trends are consistent with what we observe. Our result further strengthens these results and the picture of galaxy evolution that they support, by demonstrating that the bulk of stars of the massive galaxies had formed in the early epochs of the Universe and have been evolving passively, while low mass galaxies were/are still forming significant mass fractions of their stellar populations till $z \sim 0.8$.

3.5.2 Mass-Size Distribution

In C13b, the authors demonstrate that by replacing the luminosity with mass, and the circularised R_e with R_e^{maj} , the Fundamental Plane evolves into a Mass Plane, which follows the virial equation. This shows that the Fundamental Plane is due to virial equilibrium,

combined with a smooth M/L variation with the galaxy velocity dispersion σ . Most of the information on galaxy evolution is contained in the non edge-on views of the plane, e.g. the Mass-size and Mass- σ distribution. Cappellari et al. (2013a, Hereafter C13a) shows that galaxy properties, namely the stellar age, colour, M/L , IMF and gas content, all best follow lines of constant σ , which they demonstrate traces the bulge mass fraction. MD15 additionally showed that metallicity and non-solar abundance are also driven by σ . Below we present the trend of the stellar population in the mass plane of galaxies at $z \sim 1$ and compare it with that observed in the local universe.

Using the physical parameters derived in this study we are able to study the mass plane of our galaxies which are presented in Fig.3.7. In the left panel of Fig. 3.7, we plot the stellar mass, derived through stellar population modelling, and the galaxy size for the 154 galaxies in our full sample. In the lower right corner, we plot a representative error bar for the derived quantities. The error on the stellar mass derived using stellar populations modelling is based on the scatter observed in Fig. 3.2, ie 0.16 dex. The error on the galaxy size is based on our comparisons with Fernández Lorenzo et al. (2011), where the authors fit a de Vaucouleurs stellar profile to I-band photometry of 40 galaxies present in our sample. We compare the effective radii calculated by these authors with that calculated using the MGE models of this study and derive an error of 0.05 dex on the galaxy size. The colour of the symbols in the two plots represents the luminosity-weighted age (Gyrs) of the stellar population in the galaxy. This was LOESS smoothed (Cleveland, 1979) using implementation (see footnote 1) of C13b. This plot can be directly compared to fig. 1 and fig. 3 of C13a and to fig. 7 of MD15, where the authors respectively show that for the ATLAS^{3D} volume limited sample of ETGs the observed stellar population indicators and stellar age of the galaxies correlate with their velocity dispersion. Our plot suggests that this trend is in place by $z \sim 1$.

The solid red line in the left panel of Fig. 3.7 is the Zone of Exclusion (ZOE) for the nearby galaxies as prescribed by C13a, beyond which the probability of finding galaxies

within a volume-limited sample is $\sim 1\%$. The left panel demonstrates that some galaxies in the full sample would lie a factor of ~ 1.5 below the ZOE in the local universe. The robustness of this result is demonstrated in the right panel of Fig. 3.7, where we have plotted the dynamical stellar mass against the stellar velocity dispersion for the secondary galaxy sample. This plot is equivalent to the Faber-Jackson relationship with the galaxy luminosity substituted for the dynamical stellar mass derived by the multiplication of $(M_*/L)_{\text{JAM}}$ with the total luminosity of the galaxies. The solid red line in this plot is the ZOE translated into this Faber-Jackson plot via the Virial equation. Despite the stark contrast between the methodology used to derive the physical parameters in the two plots, both plots present a consistent picture. Considering that the ATLAS^{3D} sample is volume-limited and thus provides a representative reference for the local population, while our $z \sim 1$ sample is biased towards the most dense objects (Sec. 3.3.2), this implies that the factor of 1.5 provides a stringent upper limit to the growth of galaxies since $z \sim 1$. To aid the reader in accurately interpreting this plot, a representative error is presented. This error bar is based on the median error of the velocity dispersion, derived via bootstrapping (see section 3.1 of Shetty & Cappellari (2014)), and the propagation of this error onto the derived dynamical mass via eq. 8 of Cappellari (2008).

Our upper limit to the size growth of the most compact galaxies since $z \sim 1$ is consistent with previous works such as Newman et al. (2012), where the authors fit the observed mass-size relation for galaxies in bins of redshift. Their fits suggest that a galaxy of mass $M_* = 10^{11} M_\odot$ within their redshift bin of 0.4 to 1 grow by a factor of 1.2 by redshift of 0.06. In the work presented by van der Wel et al. (2014), the authors use 3D-HST and CANDELS data to study the evolution of the mass-size distribution of 30,958 galaxies with stellar masses $> 10^9 M_\odot$ and $0 < z < 3$. Their comparison of the size evolution of the median sizes of galaxies from $z = 0.75$ to $z \sim 0$ demonstrates a size growth of ~ 1.4 , consistent with our findings. There have been recent suggestions that part of the observed size growth

in quiescent galaxies may be due a progenitor bias, i.e. the increase in the average size of the quiescent galaxy population with cosmic time is due to the inclusion of larger recently quenched galaxies into the quiescent galaxy population (e.g. Poggianti et al., 2013; Carollo et al., 2013). However, the results of recent work (e.g. Krogager et al., 2014; Belli, Newman & Ellis, 2015) have shown that the progenitor bias isn't sufficient to accommodate the size growth that has been observed since $z \sim 2.5$.

3.5.3 Dark Matter Fraction and IMF

In Shetty & Cappellari (2014), we had modelled the stellar kinematics of the galaxies assuming that mass-follows-light and using the total M/L to account for the dark matter contribution. When making our inferences on the IMF of those galaxies we made the empirically-motivated assumption that the dark matter fractions within their central regions were negligible. The basis for our assumption were mainly the results of C13b and Hilz, Naab & Ostriker (2013). In C13b, the authors were able to derive the dark matter fraction of their 260 local ETGs using integral-field data and dynamical modelling, and accounting for the dark matter via multiple dark matter profiles. Their results robustly proved that the dark matter fraction of the central regions of massive ETGs is <30 per cent. Furthermore, galaxy merger simulations of Hilz, Naab & Ostriker (2013) find that the dark matter fraction of galaxies would increase with time, i.e. with decreasing redshift.

A robust test of the assumption would be a direct measurement of the dark matter fractions in these galaxies, however this is not feasible from the stellar dynamics without spatially-resolved information, which is still difficult to obtain with current instruments. Therefore, to test this assumption, we place our galaxies within dark matter haloes predicted by abundance matching techniques. Furthermore, to get robust results on the dark matter fractions of the galaxies, we have derived the dark matter fractions for our galaxies using two independent SHMRs (Sec. 3.4.4).

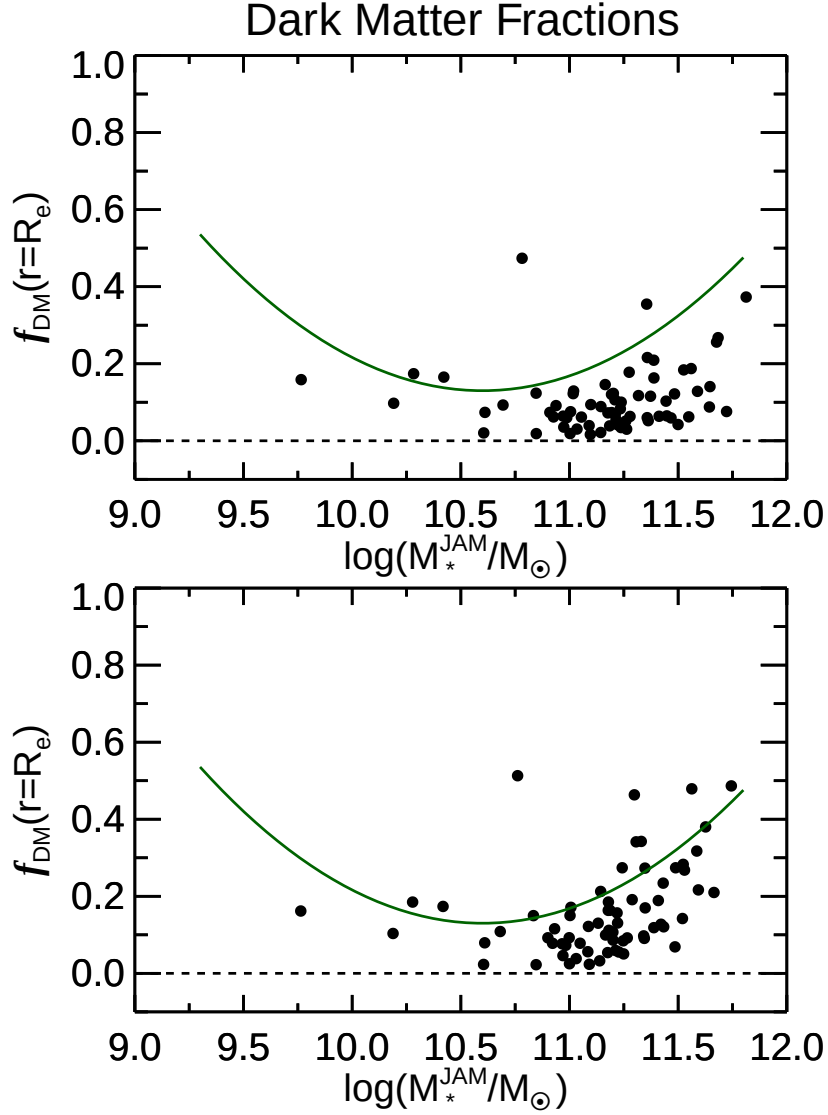


Fig. 3.8 The plot above represents the dark matter fraction within $1R_e$ for the 68 galaxies for whom we have created dynamical models. The dark matter fraction is the dark matter enclosed within a radius of $1R_e$ divided by the total mass (i.e. stellar + dark matter) enclosed by that radius. In the top panel, the dark matter haloes are assigned based on the SMHR derived by Leauthaud et al. (2012) while the SMHR by Moster et al (2013) is used to derive the dark matter haloes for the bottom panel. Despite the difference in the absolute value of the dark matter fraction, both results demonstrate a low dark matter fraction for the inner regions of massive galaxies.

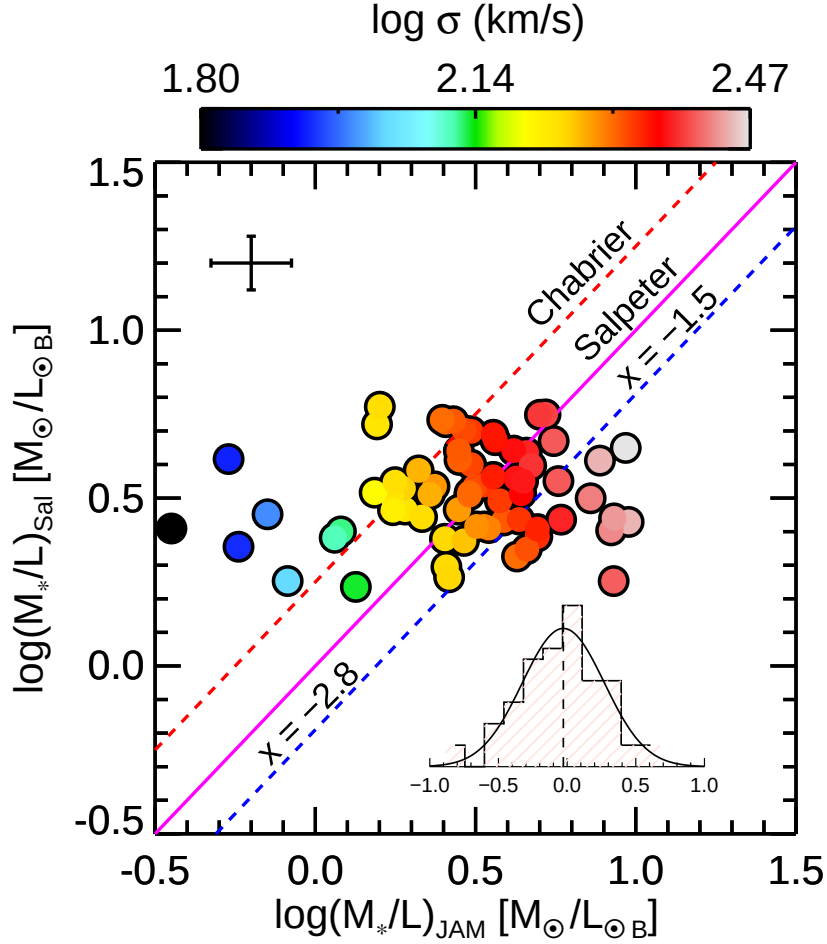


Fig. 3.9 Presented is the IMF normalisation for the 68 galaxies with dynamical models. This is an updated version of the fig. 4 in Shetty & Cappellari (2014) the difference being that here we use the $(M_*/L)_{\text{JAM}}$ derived from dynamical models, instead of the total one. Along the x-axis, we have plotted the (M_*/L) derived via dynamical modelling while the y-axis represents the stellar (M_*/L) derived via stellar population modelling, assuming a Salpeter IMF. The colour trend shown here is the LOESS smoothed (C13b) central velocity dispersion of the galaxies. Representative errors on the (M_*/L) is presented in the top left corner of the plot, based on Fig. 3.2 and eq. 8 of Cappellari (2008).

The results of the dynamical modelling are presented in Table. 3 and illustrated by Fig. 3.8. The plots demonstrate that, to be consistent with the observed surface brightness and velocity dispersion, as well as with the halo matching results, massive galaxies at this redshift must contain low dark matter fraction $f_{\text{DM}}(R_e)$ within a sphere of radius $1R_e$. The inferred median value for our sample of 68 galaxies is $f_{\text{DM}}(R_e) = 9$ and 13 per cent, while the 90th percentile is $f_{\text{DM}}(R_e) = 21$ and 34 per cent, using the SHMR of Leauthaud et al. (2012) and Moster, Naab & White (2013) respectively.

In the two panels of Fig. 3.8, the green line represents the robust parabolic fit to the dark matter fractions of the 260 galaxies (C13b) derived using SHMR relation of Moster et al. (2010), while additionally requiring the models to best fit the integral-field kinematics and photometry. This is similar to our dark matter fraction results derived using Moster, Naab & White (2013). Comparing our results to that of ATLAS^{3D}, the dark matter fraction appears to have increased in the last ~ 7 Gyrs. The lower dark matter fraction derived at higher redshifts is consistent with the numerical simulation prediction of Hilz, Naab & Ostriker (2013) and is also consistent with recent results by Beifiori et al. (2014), which found that the ratio of the dynamical mass (dark matter + stellar mass) to the stellar mass of the galaxies reduces with increasing redshift. However, we do note that this trend may be in part influenced by the differences in the sample selection.

In the work presented in Shetty & Cappellari (2014), the IMF normalisation of the 68 dynamically modelled galaxies was shown in fig. 4. The plot illustrated that the IMF normalisation for massive ETGs at $z \sim 1$ was Salpeter-like, however a caveat of the work was the assumption that the dark matter fractions in the central regions of high redshift galaxies was not significant. In this study we include dark matter explicitly and in Fig. 3.9 present an updated version of the plot, with the dark matter contribution explicitly removed. This confirms the assumption that dark matter fraction has a negligible effect on the IMF

DEEP2 ID	σ	$\delta\sigma$	$(M_*/L)_{JAM}$	$\log(M_*^{\text{IAM}})$	f_{DM}
	(km s ⁻¹)	(km s ⁻¹)	($M_\odot/L_\odot$)	($M_\odot$)	
(1)	(2)	(3)	(4)	(5)	(6)
11050845	298.2	28.7	5.74	11.644	0.088
12004136	202.4	21.7	2.80	11.275	0.178
12004516	176.4	28.6	2.56	11.164	0.146
12008254	250.7	33.3	4.56	11.444	0.103
12008360	185.2	31.1	2.54	10.974	0.035
12008441	257.7	64.3	8.53	11.646	0.141
12011900	318.5	57.1	9.30	11.499	0.042

Column (1) : DEEP2 galaxy identifier. Column (2) : Velocity dispersion as measured by full-spectrum fitting of the galaxy spectra. Column (3) : Error on the derived velocity dispersion of the galaxy through a bootstrapping technique. Column (4) : B-band (M_*/L) derived through dynamical modelling, where the dark matter halo was assigned using the SHMR of Leauthaud et al. (2012). Column (5) : The log of the stellar mass, in units of $M_\odot$, of the galaxy derived using the absolute luminosity (Column (5) of Table. 1) and the M/L of Column (4). Column (6) : Fraction of dark matter within $1R_e$ of the galaxy. This was derived by using the SHMR of Leauthaud et al. (2012).

Table 3.3 Results of Dynamical Modelling. The table below is a partial representation of the complete set, which is presented in Appendix. E.

normalisation of the galaxies, i.e. the *average* IMF normalisation of massive ETGs at redshift of ~ 1 is still consistent with a Salpeter IMF. This result is independent of the SHMR used.

This confirmation of our Shetty & Cappellari (2014) result is also in agreement with recent work by Sonnenfeld et al. (2015), where the authors have used a joint lensing and stellar dynamics modelling of massive galaxies out to $z \approx 0.8$, including about ten galaxies within our redshift range. The authors found that the stellar IMF normalisation was close to Salpeter IMF for $M_* = 11.5$. Also, work by Martín-Navarro et al. (2015a), using IMF sensitive spectral features, determined that more massive galaxies have a bottom heavier IMF at redshifts between 0.9 and 1.5. The Salpeter normalization of the IMF is also consistent with the non-universality of the IMF reported in the nearby Universe (e.g. van Dokkum & Conroy, 2010; Cappellari et al., 2012). In fact, if the centres of massive galaxies at $z \sim 1$ passively evolve into the massive ETGs population, their IMF is expected to have a Salpeter normalization as observed locally (Auger et al., 2010; Conroy & van Dokkum, 2012; Cappellari et al., 2013a).

3.6 Summary

In this study, we have determined the SFH of the galaxies at redshift $0.7 < z < 0.9$ in a non-parametric manner, using full-spectrum fitting. From a parent sample of 2,896 galaxies from the DEEP2 survey, we apply strict quality selection criteria to extract 154 galaxies with $10^{10} \lesssim M_* \lesssim 10^{12} M_\odot$ for which we derive our SFHs. For a subsample of 68 galaxies, with $M_* \gtrsim 10^{11} M_\odot$, we additionally construct dynamical models. Due to these selection criteria, our galaxy samples have a higher magnitude cut-off than the DEEP2 survey and preferentially selects galaxies with high surface brightness. However, we show that the full galaxy sample is representative of the red sequence and all but the bluest galaxies of the blue cloud, while the secondary sample mainly consists of galaxies from the red sequence.

The derived SFH for the full galaxy sample indicates that the most massive galaxies formed the bulk of their stars in the early epoch of the universe unlike low mass galaxies which are forming stars at a significant rate even at redshift of ~ 1 . This is qualitatively consistent with previous fossil record studies in the local universe, where authors have found that the star formation rate of the most massive galaxies peaked early in the age of the universe, and hence provides a robust and independent test of these results and the narrative of the formation and evolution of galaxies that these results have produced. Our results based on Fig. 3.4 and Fig. 3.5 demonstrate that the difference between the SFH of galaxies evolves gradually and is a function of stellar mass.

We study the distribution of galaxy ages on the mass-size diagram. This demonstrates that the velocity-dispersion dependence in the age of the stellar populations of the central regions of the galaxies was already in place by $z \sim 1$. We also place an upper limit of a factor of ≈ 1.5 to the size growth of individual galaxies since $z \sim 1$, in agreement with other studies.

Finally, using the dynamical models of the 68 galaxies in our secondary sample, which account for the dark matter in the galaxies using results from abundance matching techniques, we measure a median dark matter fraction $f_{\text{DM}}(R_e) \approx 10$ per cent per cent, within a sphere of radius R_e , for the most massive galaxies, with small variations depending on the adopted Stellar-Halo mass relation. Comparing this to the dark matter fraction determined locally, we find that the dark matter fraction of galaxies has marginally increased in the last 8 Gyrs, but is otherwise insignificant. This result confirm the study of Shetty & Cappellari (2014) stating that the average IMF normalisation of the most massive galaxies is on average consistent with a Salpeter IMF.

Chapter 4

A Stellar and Dynamical Analysis of Galaxies in the Coma Cluster

In this chapter, I present the analysis and results of the dynamical modelling and stellar population synthesis of galaxies in the Coma cluster. This work aims to probe the luminous and dark matter of these galaxies. Utilising the SAURON Integral-Field Spectrograph data for 53 galaxies in the cluster and their corresponding photometric data obtained from SDSS, I created detailed dynamical models for their observed kinematics and consequently deriving accurate mass-to-light ratios and robust Dark Matter fractions. Motivated by the results of their dark matter fractions, I extend the study to a large sample of 148 galaxies in the cluster. Taking advantage of the spectral and photometric data made available by SDSS, I derive the dynamical and stellar properties of this larger sample using techniques employed in the previous two chapters. Taken together, these results provide insights into the properties of the luminous and dark matter content of the galaxies in the cluster.

4.1 Galaxy Samples

The galaxy sample for this study was taken from that used in Cappellari (2013), where the authors selected galaxies within one square degree of the Coma cluster with total K-band absolute magnitude limit of $M_K < -21.5$ ($M_* \gtrsim 6 \times 10^9 M_\odot$). This sample was designed to be identical to the ATLAS^{3D} *parent* sample, from which the ETGs of the ATLAS^{3D} were extracted. This Coma cluster sample contained a total of 161 galaxies.

Of this sample of 161 galaxies, I construct a sample of 148 galaxies based on the availability of spectral data in SDSS catalogue (York et al., 2000). These 148 galaxies constitute the full Coma sample analysed and discussed in this chapter. For a subset of 53 galaxies, data was taken using the SAURON Integral-Field Spectrograph (IFS) mounted on the William Herschel Telescope. These galaxies were to be observed by the SAURON Integral-Field Spectrograph (IFS), with an observational strategy that began at the cluster centre and observe galaxies at progressively larger radii. This strategy ensured that the observed sample was mass-complete within the observed projected radii. Of these 53 galaxies, due to issues regarding the Signal-to-Noise (S/N), leftover artefacts from the data reduction process and others, dynamical models for only 42 galaxies could be made. Of these 42 galaxies, two galaxies did not have SDSS spectral observations. For simplicity of exposition, we ignore this fact in what follows and we still refer to the galaxies with SAURON data as a subset of the main sample.

In Fig. 4.1, I present the M_k distribution of the full sample and the SAURON subset, and compare them to the original sample of 161 galaxies. Making the common assumption of a constant K-band M/L within the cluster, the histogram demonstrates that the full sample, and the SAURON subset, present the entire mass range of the original sample. To quantify this, I conducted the two sample Kolmogorov-Smirnov test (Please see chapter. 7 of Pratt & Gibbons, 1981) which calculated that the null hypothesis, i.e. two samples are derived from the same parent sample, is accepted with p-values of 1 and 0.99 for the full sample

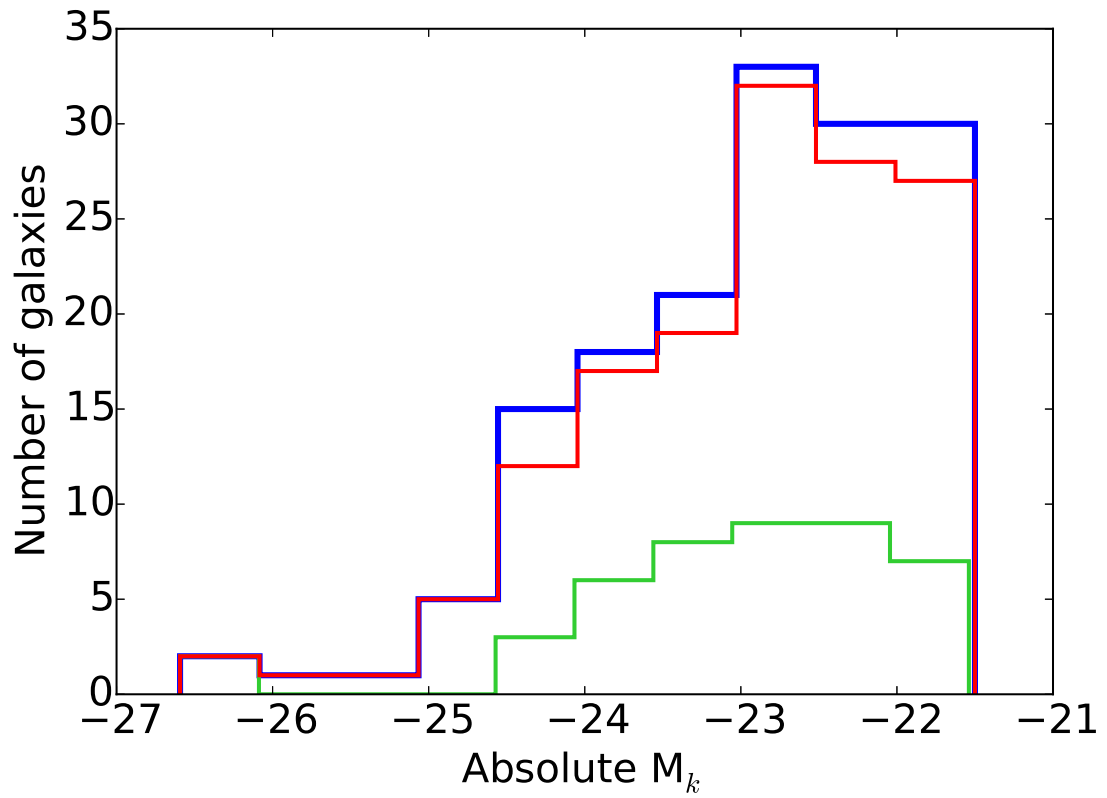


Fig. 4.1 Here I present the histogram distribution of the original sample of 161 galaxies in blue, and compare it to the two sample sets used in this study; the full sample represented in red and the SAURON subset represented by green. The histogram demonstrates that both samples represent the original in an unbiased manner, allowing the results of this study to be applicable to the cluster in general.

and SAURON subset respectively. The unusually high p-values for these tests are due to the fact that p-values are random variables that are biased to lower values when the null hypothesis is false and hence, the high value of p-value is only indicative of the acceptance of the hypothesis and not a measure of the goodness of fit (Bland, 2013).

4.2 Data

4.2.1 SDSS Data

To make a prediction for the stellar kinematics, which is compared to the observed one, the dynamical models require one to specify (i) the distribution of the total mass, from which the gravitational potential is generated and (ii) the distribution of the “tracer” population, for which one wants to predict the kinematics with the models. The latter is typically obtained by deprojecting the parametrised surface brightness of the galaxies. In this study, we use the *r*-band mosaic images observed by SDSS (York et al., 2000) to do this. This band was selected for its high S/N relative to the other bands in SDSS, and to keep the photometric data close to the wavelength range used to derive the stellar kinematics. The second reason for this is to ensure when modelling, the deprojected luminosity density correspond to the stellar populations whose kinematics have been observed. The median *r*-band Point Spread Function (PSF) width of the survey is $1.43''$, and the images used in this study have a resolution of $0.396''/\text{pixel}$.

In addition to the photometric data, I also obtained SDSS spectral data for the 148 galaxies in the full sample. While most galaxies were observed as part of the SDSS-I/II survey (York et al., 2000), two galaxies were observed in the BOSS survey in SDSS-III (Dawson et al., 2013). Consequently, the data were observed either using the original SDSS spectrographs, or the BOSS spectrograph. The instruments observe using different aperture diameters, i.e. $3''$ and $2''$ respectively, which is vital to note when modelling the dynamics

of the galaxies. Furthermore, both these instruments observe in similar wavelength ranges, around $3,800 - 9,200\text{\AA}$, though the BOSS instrument does observe out to slightly higher and lower wavelengths. For a detailed comparison of the two instruments, I would refer the interested reader to Ahn et al. (2012).

4.2.2 SAURON data

Additionally, I have 42 galaxies with IFS data obtained using the SAURON instrument on the William Herschel Telescope in the La Palma Observatory. Of these 42 galaxies, 40 galaxies are common to the full sample while 2 galaxies are found only within the sample Cappellari et al. (2015). The SAURON instrument is a lenslet-based IFS, consisting of $\sim 1,400$ spaxels, capable of observing between the wavelength range $4,810 - 5,350\text{\AA}$ (Bacon et al., 2001a). We observed our galaxies in the low resolution mode of SAURON, which observes $41'' \times 33''$ of the sky at a spatial resolution of $0.94''/\text{spaxel}$. The spectral resolution of the instrument is $3.9\text{\AA}$ FWHM which corresponds to an instrumental velocity dispersion of 98 km s^{-1} .

The data was reduced using the *XSAURON* software (Bacon et al., 2001b; Emsellem et al., 2004) which implements bias subtraction, flat-fielding, wavelength calibration and sky-subtraction on the observed data to produce the final “data cubes”, where each (x, y) coordinate in the file has a corresponding spectrum. Though this software is intended to produce the final reduced data cubes, in some instances the data requires manual tweaking to guarantee the data quality. This optimisation is currently being undertaken by a member of the collaboration, however it is unlikely that the optimisation will significantly effect the results presented in this study.

4.3 Analysis

4.3.1 Parametrisation of Surface Brightness

As mentioned previously, the dynamical modelling of galaxies requires a parametrisation of the galaxy surface brightness. I do this using the MGE parametrisation, described in Section. 1.3.3 of this thesis, and have discussed it in the previous chapters (Emsellem, Monnet & Bacon, 1994; Cappellari, 2002). Briefly, the MGE algorithm fits a series of 2-dimensional Gaussians to the observed galaxy surface brightness. These Gaussians permit the convolution and deprojection of galaxies in a simple and efficient manner, while demonstrating to be robust to the light profiles of multi-component galaxies.

For the galaxies in the Coma cluster, I modelled the surface brightness of the galaxies using their r-band mosaic images obtained from SDSS DR12 (Alam et al., 2015). The images were downloaded as thumbnails of size $75'' \times 75''$ for most galaxies, however for smaller galaxies these thumbnails were reduced to $40'' \times 40''$. Visual observations of these thumbnails verified the complete coverage of the galaxy light with additional sky coverage so as to estimate the sky and noise levels. In the case of the two massive central galaxies, NGC4889 and NGC4874, thumbnails of size $252'' \times 252''$ were obtained.

When fitting for the surface brightness of galaxies, it is critical to ensure that the pixels used for the procedure contain information of the intrinsic light profile of the galaxies. During the parametrisation process, I realised that light halos, caused by the internal reflection of the galaxy light within the telescope's optical components (Slater, Harding & Mihos, 2009), had a significant effect on the final result. Though these faint effects are not visually observable in the SDSS images, due to their low surface brightness, they do bias the parametrisation algorithm towards more extended profiles. To avoid this artificial extension, I visually fine-tune the minimum counts for the pixels that were eventually used in the algorithm.

I model the surface brightness of the galaxies using the *MGE_FIT_SECTORS* package¹ (Cappellari, 2002). Before fitting the galaxy photometry, the code is processed by the *find_galaxy* code in the package to derive the global parameters of the galaxies, such as position angle, ellipticity etc. To minimise the effect that bars in galaxies would have on these properties, it is good practice to derive these quantities by fitting the outermost regions of the galaxies. However, given the high density environment of the cluster, these quantities are occasionally affected by the presence of nearby galaxies. In such scenarios, the derivation of these global quantities were based on the observations of the inner region of the galaxies, and where possible the photometric position angle of the galaxies is manually changed to match the observed kinematic position angle of the galaxy.

Furthermore, the presence of non-axisymmetric features, such as bars, can affect the results of the fit and force the fit away from the underlying stellar distribution. I reduce this effect by adapting the prescription described in Scott et al. (2013). As per this, following an initial fit to the galaxies I iteratively constrain the allowed axial ratios of the Gaussians being fitted to the galaxies until the subsequent change in the mean absolute deviation of the fits grows by $> 10\%$. By doing so, the MGE model is pushed away from modelling these perturbations and instead models the underlying stellar distribution. In Scott et al. (2009), the authors state that doing so significantly improves the dynamical models, providing improved predictions of the galaxy kinematics and better predictions of the galaxy inclination when compared to that inferred from the shape of the galaxy disk.

4.3.2 Gravitational Potential

Knowledge of the underlying gravitational potential is crucial to predict the kinematics of particles in them, and when realistic models for the potential of the galaxies are used, the dynamical models provide insight into the structure of the galaxies. In galaxies, these

¹<http://purl.org/cappellari/software>

gravitational potentials are generally dominated by their stars and dark matter. Hence, to understand the galaxies being modelled it is vital that realistic models for the distribution of their luminous and dark matter be used when modelling their kinematics. Currently, much about the distribution of matter in galaxies is unknown and it is not possible to confidently model “realistic” gravitational potential for galaxies.

In this study, I model the dynamics of the full sample using two distinct assumptions for their gravitational potential. For the SAURON subset, I model the observed two dimensional stellar kinematics with these assumptions and an additional third to robustly constrain the dark matter fraction of the galaxies.

It is important to note here that though the stars and dark matter dominate the gravitational potential of galaxies, this is not true in their innermost regions. In the innermost parsecs of galaxies, the gravitational potential of galaxies are dominated by their Supermassive Black Holes (SMBHs). The *JAM* models used in this study incorporate the effect of SMBHs and I model them using the $M_{\text{BH}} - \sigma_e$ relation (Ferrarese & Merritt, 2000; Gebhardt et al., 2000) with the parameters given by Kormendy & Ho (2013, eq. (7)). However to further ensure that these SMBHs do not affect the results presented in this study, I have masked the spaxels within the inner $1''$ of the galaxies which at its assumed distance of 100 Mpc (Carter et al., 2008) effectively masks the inner ~ 0.8 kpc.

Self-Consistent Model

The first model that I use for dynamical modelling is the Self-Consistent model, which assumes that the total mass distribution of a galaxy follows the distribution of its light. Assuming such a model, the dynamical model of the galaxies can be described by just three free parameters: (i) the inclination of the galaxy, (ii) the velocity anisotropy, defined as $\beta_z = 1 - (\frac{\sigma_z}{\sigma_R})^2$, and (iii) the mass-to-light ratio, $(M/L)_{\text{JAM}}$. Optimising the first two

parameters predicts the shape of the stellar kinematics, while the $(M/L)_{\text{JAM}}$ scales the stellar kinematics to match that observed using the IFS data.

The deprojection of the observed surface brightness into a corresponding three dimensional density distribution, needed to model and predict kinematics, is a mathematically degenerate problem (Rybicki, 1987). This problem is generally solved by ad hoc assumptions on the intrinsic shape of the galaxies. The MGE method provides a unique solution for the deprojection of the observed surface brightness of galaxies, for a given inclination, by enforcing roundness of the models. This solution does not break the intrinsic degeneracy of the problem, however it has been known to usually provide luminosity densities that resemble realistic surface brightness when viewed at any angle. Concurrently, the MGE parametrisation places limits to the possible values of inclination of the galaxies, to permit realistic density distributions. Given an MGE parametrisation of an axisymmetric galaxy, one can constrain the possible range of inclinations by requiring that the minimum axial ratio of every Gaussian be positive and larger than a small value, like 0.05 used in this study. This is done using eq. (10) of Cappellari (2002):

$$q^2 = \frac{q'^2 - \cos^2 i}{\sin^2 i} \quad (4.1)$$

Here, q' is the minimum axial ratios of the Gaussians to the galaxy photometry, i is its inclination ($i = 90^\circ$ is edge-on) and q is the intrinsic axial ratio of the galaxy.

The velocity anisotropy, defined as $\beta_z = 1 - (\frac{\sigma_z}{\sigma_R})^2$, describes the shape of the velocity ellipsoid. In this study, I fix the β_z of a galaxy to be constant at all radii. The effect of this assumption was tested by Cappellari (2008) and Lablanche et al. (2012), where the authors concluded that this assumption had a minor effect on the derived (M/L) and inclinations of the galaxies. More recently, Li et al. (2016) assessed the ability of the JAM models to accurately model the kinematics of 1,413 realistic galaxies in the ILLUSTRIS simulation (Vogelsberger et al., 2014). They conclude that the models recovered the “total” density

profiles of the galaxies with good accuracy and negligible bias. Furthermore, I limit the values of β_z to between 0 and 1 as previous studies, using the more general Schwarzschild's models (Schwarzschild, 1979), demonstrate that the β_z is well within this range (Cappellari et al., 2007; Thomas et al., 2009).

As mentioned earlier, the inclination and velocity anisotropy of the galaxies constrain the shape of the stellar kinematics, which can then be matched to the observed stellar kinematics of the galaxies to calculate the dynamical (M/L) of the galaxies. However, for the full sample, no information on the shape of the stellar kinematics is available. Hence, to model these galaxies, I assign $i = 60^\circ$ and $\beta_z = 0.2$. If an inclination of 60° is inconsistent with Eq. 4.1, then the lowest permitted inclination for the galaxies is used as its inclination.

Abundance-Matched Model

For this model, the total mass profile is described as the sum of the stellar and dark matter distribution. The shape of the stellar distribution is defined by surface brightness of the galaxies, while the dark matter is modelled based on Abundance matching. For each value of stellar $(M_*/L)_{dyn}^{AM}$, the total luminosity of the galaxy constrains the stellar mass of the galaxy. Using the relation between the Stellar-to-Halo Mass relation (SHMR) of Moster, Naab & White (2013) and $c_{200} - M_{200}$ relation by Klypin, Trujillo-Gomez & Primack (2011) then constrains the parameters of the halo. For this study, I describe the dark matter halo of galaxies as a spherical NW profile (Navarro, Frenk & White, 1996). Hence, the stellar $(M_*/L)_{dyn}^{AM}$ of a galaxy constrains the total density profile, and the gravitational potential, of the galaxy. This technique is similar to the one used in Chapter. 3. Since both relations used to constrain the dark matter profile of the galaxies are based on cosmological simulations, this model is heavily reliant on the theoretical assumptions of Abundance Matching.

As with the previous model, I solve for the best-fitting dynamical models of the galaxies by optimising for the three parameters of the galaxies: (i) the inclination of the galaxy,

(ii) the velocity anisotropy, and (iii) $(M_*/L)_{dyn}^{AM}$. The solution for the full sample is also derived similarly to the previous model, i.e. by fixing the values of the inclination and β_z and optimising for $(M_*/L)_{dyn}^{AM}$.

Power-Law Model

The third dynamical model is motivated by the empirical results of lensing studies (See review by Treu, 2010) and dynamical modelling (Cappellari et al., 2015). These results suggest that the total density profile of galaxies, within the region that this study samples, is well reproduced by a single nearly-isothermal profile, $\rho_{tot} \propto r^{-\gamma}$. In this study, I model a galaxy's gravitational potential using the generalised NFW profile, i.e.:

$$\rho_{tot} = \rho_s \left(\frac{r}{r_s} \right)^\gamma \left(\frac{1}{2} + \frac{1}{2} \frac{r}{r_s} \right)^{-\gamma-3} \quad (4.2)$$

Where ρ_s is the density of the galaxy profile at scale radius, r_s . The break in the profile takes place at large radii, well outside the region sampled in the study and hence, this profile is indistinguishable from that of a pure power-law and its shape is affected only by γ . Concurrently, the kinematics analysed in this study cannot reliably constrain the r_s of the profile, and hence I fix its value to 20 kpc. Therefore, the predicted stellar kinematics of this model is defined by only 4 free parameters: (i) galaxy inclination, (ii) velocity anisotropy, (iii) ρ_s , and (iv) γ .

This assumption on the total density profile is only used to model the two dimensional stellar kinematics of the galaxy subset with SAURON data, as it has degrees of freedom that are not yet understood and hence cannot be constrained using just one dimensional kinematic data.

4.3.3 Stellar Kinematics

Similar to previous chapters, the kinematics of galaxies is derived using the *pPXF* code² (Cappellari & Emsellem, 2004). This code models the observed galaxy spectrum with an input set of template spectra in pixel space. To model the observed spectra in this study, we use the Indo-US Library of Coudé Feed Stellar Spectra Library (Valdes et al., 2004). This library consists of 1,273 stellar spectra covering the wavelength range of 3,460 – 9,464Å at a resolution of ~ 1.35 FWHM (Beifiori et al., 2011). The Indo-US stellar library was selected for this study for two reasons:

- Extensive coverage of stellar parameters: To minimise the effect of template mismatch, it is critical that the template set used to model the galaxy spectrum is representative of the stars within the galaxy. In an effort to test this, Winge, Riffel & Storchi-Bergmann (2009) derive the stellar kinematics for a two dimensional dataset using different template sets. Depending on the template set used, the authors report varying kinematics offset and false detections of kinematic structures. Hence, to derive accurate kinematics it is crucial that one uses a diverse set of template spectra.
- High resolution: To make full use of the spectral resolution of the galaxy spectra to derive the kinematics of the galaxies, one should use template stellar spectrum that have a higher resolution than that of the galaxy spectrum. In this study, the SDSS spectra is shown to have a resolution of ~ 2.3 Å FWHM at the wavelength range within which I derive the stellar kinematics. Despite the MILES stellar spectral library (Sánchez-Blázquez et al., 2006) having a more extensive coverage of stellar parameters, it has a resolution of ~ 2.54 Å FWHM (Beifiori et al., 2011) compared to that of 1.35Å of the Indo-US library. Hence in this study, I use the latter of the two to derive the stellar kinematics of the galaxies.

²<http://purl.org/cappellari/software>

SAURON Kinematics

Due to the light profile of galaxies, the S/N in each spaxel of any IFS data cube commonly span a large range of values. Hence, when working with IFS data it is common practice to spatially bin the results over the plane of the IFS so as to recover information within spaxels with low S/N. For the SAURON data, I bin such spaxels using the *voronoi_2d_binning* code³ (Cappellari & Copin, 2003) which bins the spaxels according to Voronoi tessellations. The Voronoi tessellation allocates the pixels on a plane to the point, called a generator, closest to it. By inputting the signal and noise for each spaxel and the minimum desired S/N in the field of IFS data, the *voronoi_2d_binning* solves for a set of generators that minimises the scatter of S/N around the desired S/N. The code does not force the solution to ensure all bins are above the desired S/N as this may result in the loss of spatial information, and additionally binning too many spaxels with drastically low S/N could lead the bins into becoming dominated by systematics and hence produce artificial features in the kinematics of galaxies.

As mentioned above, the binning of the spaxels via Voronoi tessellation requires that the signal and noise within each spaxel is known. Though the signal and noise are theoretically well understood quantities, their accurate determination is non-trivial and only estimates of their true values (or formal values) are used in practice. The data reduction software, *XSAURON*, does include within the data cube the formal error for each spectral pixel. Hence, a straightforward estimate of the signal and noise of each spaxel is possible. This is, however a formal estimate and hence, to test its robustness, I compared this estimate with the S/N derived by spectral fitting for a few galaxies. I did this by coadding the spectrum within the central 3'' spaxels of a galaxy to generate a spectrum with very high S/N. I then fit this spectrum using *pPXF* with the entire Indo-US stellar library. I used the results of this fit to generate an optimal template, which is the sum of the templates used multiplied by its corresponding weight. Utilising this optimal template, I fit each spaxel in the data cube and

³<http://purl.org/cappellari/software>

measure the S/N of each spaxel as the median of the best fit spectrum divided by the standard deviation of its residuals.

Fig. 4.2 presents an example of the relation between the S/N derived from the formal errors of the *XSAURON* against the S/N derived from the spectral fitting of each spaxel. In the plot I compare the two quantities using the *LTS_LINEFIT* method⁴ (Cappellari et al., 2013b) which robustly fits a linear relation to the data and intrinsic scatter. This method is used throughout this study, when comparing or fitting linear relations to quantities. Fig. 4.2 demonstrates a tight correlation between the two estimates with a slight offset. The practical nature of the S/N through the spectral fitting technique gives confidence in the reliability of the formal errors produces by *XSAURON*. Interestingly the S/N estimated by the spectral fitting of the spaxel spectra suggests that the formal error by *XSAURON* overestimates the noise. The value of this offset varies for the galaxies and hence to normalise the quality of the data of the galaxies, I calibrate the error estimate by *XSAURON* for each galaxy based on the spectral fitting of the central spaxels of the galaxy data cubes.

Based on these calibrated noise estimates, I clip spaxels with S/N less than 1, as these spaxels are noise-dominated, and then use *voronoi_2d_binning* to bin the spaxels to a target S/N of 25. The value of 25 was selected to ensure the highest resolution in the kinematics maps while reproducing the observed maps at higher target S/Ns.

As mentioned earlier, template mismatch can have serious consequences on the derived kinematics of galaxies and hence, it is crucial to take steps to minimise the effect that this may have on the derived stellar kinematics of galaxies. To make our results robust to this effect, for each galaxy I derive an optimal template by fitting the high quality spectrum derived by coadding the spaxels within the effective radii of the galaxy. This optimal template is then used to fit for the kinematics of all the bins within the data cube.

Furthermore, I realised that bins with S/N less than 15 exhibited a dramatic increase in the kinematic errors and unrealistic velocity dispersion values. These issues were likely

⁴<http://purl.org/cappellari/software>

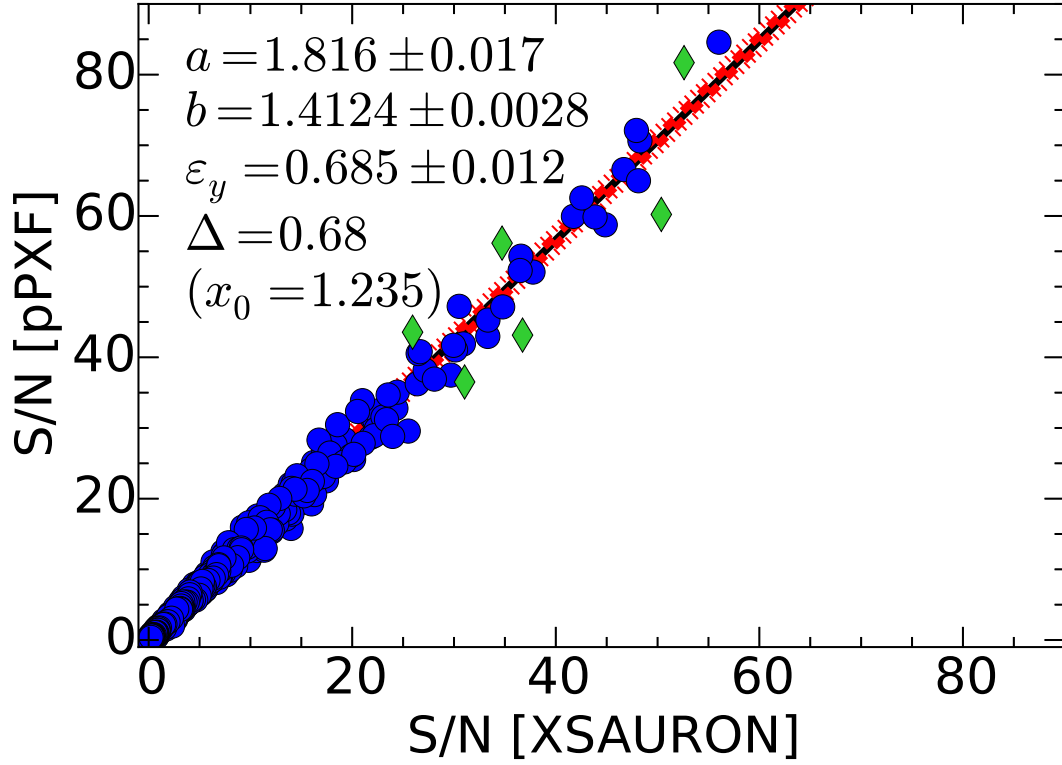


Fig. 4.2 This plot compares the formal S/N estimated by the *XSAURON* reduction pipeline, represented along the x-axis, to the S/N estimated by the spectral fitting of spaxels using the Optimal template of the galaxy, represented along the y-axis. The solid black line represents the best fit result using the *LTS_LINEFIT* code (Cappellari et al., 2013b), while the dashed and dotted red lines enclose the 1σ and 2.6σ error of the fit. The parameters of the best fit are shown on the top-left corner of the plot. The plot demonstrate that the S/N derived by *XSAURON* is a good estimate of the true S/N.

systematic issues and hence, I clipped these bins from the dynamical modelling process. In addition to this, I manually clip bins that appear spurious and bi-symmetrise the observed V_{rms} field (e.g: Cappellari & Emsellem, 2004). Following this, I smooth the V_{rms} map using the LOESS smoothing techniques described by Cappellari et al. (2013a). This approach is similar to that used by Cappellari et al. (2015) where the authors successfully removed outliers and reproduced the smooth velocity fields consistent with the smooth galaxy images.

SDSS Kinematics

The kinematics of the full sample was derived using the SDSS spectra of the galaxies. The technique used to derive the stellar kinematics was similar to that used for the SAURON subset. To permit the direct comparison of the results between the two distinct datasets, I derive the stellar kinematics of the full sample within the wavelength range of the SAURON, i.e. 4,810 – 5,350Å.

4.3.4 Stellar Population Modelling

The modelling of the stellar populations of these galaxies was done via the full-spectrum fitting technique used in the previous chapter. Briefly, this technique involves the fitting of the observed galaxy spectrum with a template grid of single stellar population spectra with a range of ages and metallicities. The *pPXF* code, which is used for the fitting process, then solves for the best fitting linear combination of the population that best represents the galaxy spectrum and hence providing the maximum-likelihood solution for the problem. However, the solution for the star formation history of galaxies is degenerate and hence, to break this degeneracy I regularise the weights associated with population models along the template grid until the χ^2 of the galaxy spectrum fit increases with respect to an unregularised fit by $\sqrt{2 \times N_{DoF}}$ (Press, 2007, section 19.5).

For these galaxies, I model the stellar populations using the MILES stellar population models which are based on the MILES empirical stellar spectrum library (Vazdekis et al., 2015). The template grid covers an age range of 0.08 – 14.1 Gyrs, which is sampled logarithmically, and samples six metallicities within the range $[Z/H]=-1.71-0.22$. The stellar population models span a wavelength of 3,540 – 7,410Å. I model the stellar population of the galaxies using their SDSS spectrum, however due to limit in the wavelength range of the model spectrum only 3,900 – 7,500Å of the SDSS spectra is used. These models assume a Salpeter IMF (Salpeter, 1955) and use $0.1 M_{\odot}$ and $100 M_{\odot}$ lower and upper stellar mass cut-offs respectively.

Since the MILES population models are based on the MILES empirical stellar spectra library, the models have a resolution limit of 2.54Å as well. However, the instrumental resolution of the SDSS spectra is lower in a significant region of its wavelength range, and hence I lower resolution of the SDSS spectrum to match the resolution of MILES. It must be noted that doing so does not affect the results of the stellar population modelling.

Based on the resulting weights of the regularised spectral fitting, I derive the stellar $(M_*/L)_{pop}^{Salp}$ and age of the models using Eq. 3.1 and Eq. 3.2.

4.4 Consistency tests and Error Analysis

Before interpreting the results of an analysis, it is critical that one is confident of the values derived and has a good estimate of the errors in the derived quantities. In this section, I present the tests and further analysis conducted to assess the accuracy of the quantities and to estimate their error.

4.4.1 Surface Brightness Parametrisation

In order to ensure the accurate parametrisation of the photometry of galaxies, it is crucial to inspect the quality of the fits visually. This was done using contour plots, such as those presented in Fig. 4.3, which demonstrate the quality of the fits for the SAURON subset. These plots demonstrate that the models can reproduce the observed surface brightness of galaxies within the region where reliable kinematics can be extracted, typically $10'' \times 10''$. To quantify the reproducibility of galaxy global parameters, I compare the derived magnitudes and sizes of the galaxies with that published by SDSS and 2MASS, respectively. The comparison of the quantities to the same derived independently, via different techniques, provides a robust test of the quality of the fits and provides an estimate to the error in the measured values.

In Fig. 4.4 I compare the apparent magnitudes derived from the MGE parametrisation of the galaxies with that published by SDSS which used a simultaneous fit of a de Vaucouleurs profile and exponential disk to the galaxy photometry. The plot illustrates a strong one-to-one relation between the two apparent magnitudes, with a few outliers. Upon visual verification, it was found that these outliers have nearby light sources, such as other galaxies or stars, that could have contaminated the measured photometry. It is consistent with the results of Scott et al. (2013), where the authors compare the magnitudes derived using MGE from r -band SDSS images with the magnitudes published by SDSS DR8 to find the results consistent with an observed rms scatter of $\Delta = 0.17$ mag. This scatter is expected to reduce for this study, as the published magnitudes of SDSS DR8 were based on an earlier version of the SDSS photometric data which was later updated utilising an improved sky subtraction technique described by Blanton et al. (2011).

Fig. 4.5 compares the circularised effective radii of the galaxies derived by the MGE parametrisation of this study and that from 2MASS (Skrutskie et al., 2006). For the MGE models, I first circularise the MGE Gaussians by replacing $(\sigma_j, q'_j) \rightarrow (\sigma_j \sqrt{q'_j}, 1)$, where σ_j and q'_j are the dispersion and observed axial ratio of the j^{th} gaussian. I then use eq. (11)

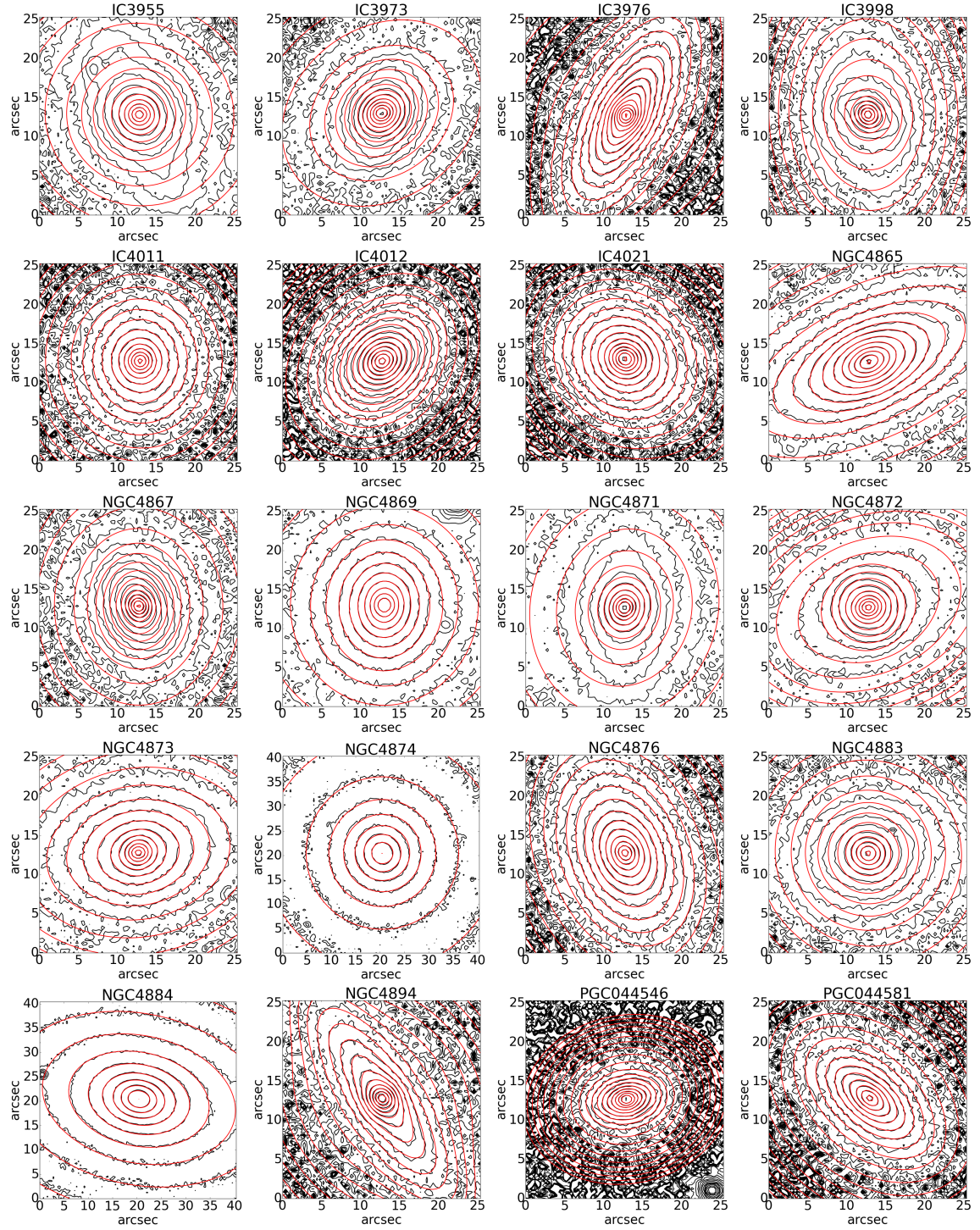


Fig. 4.3 – continued

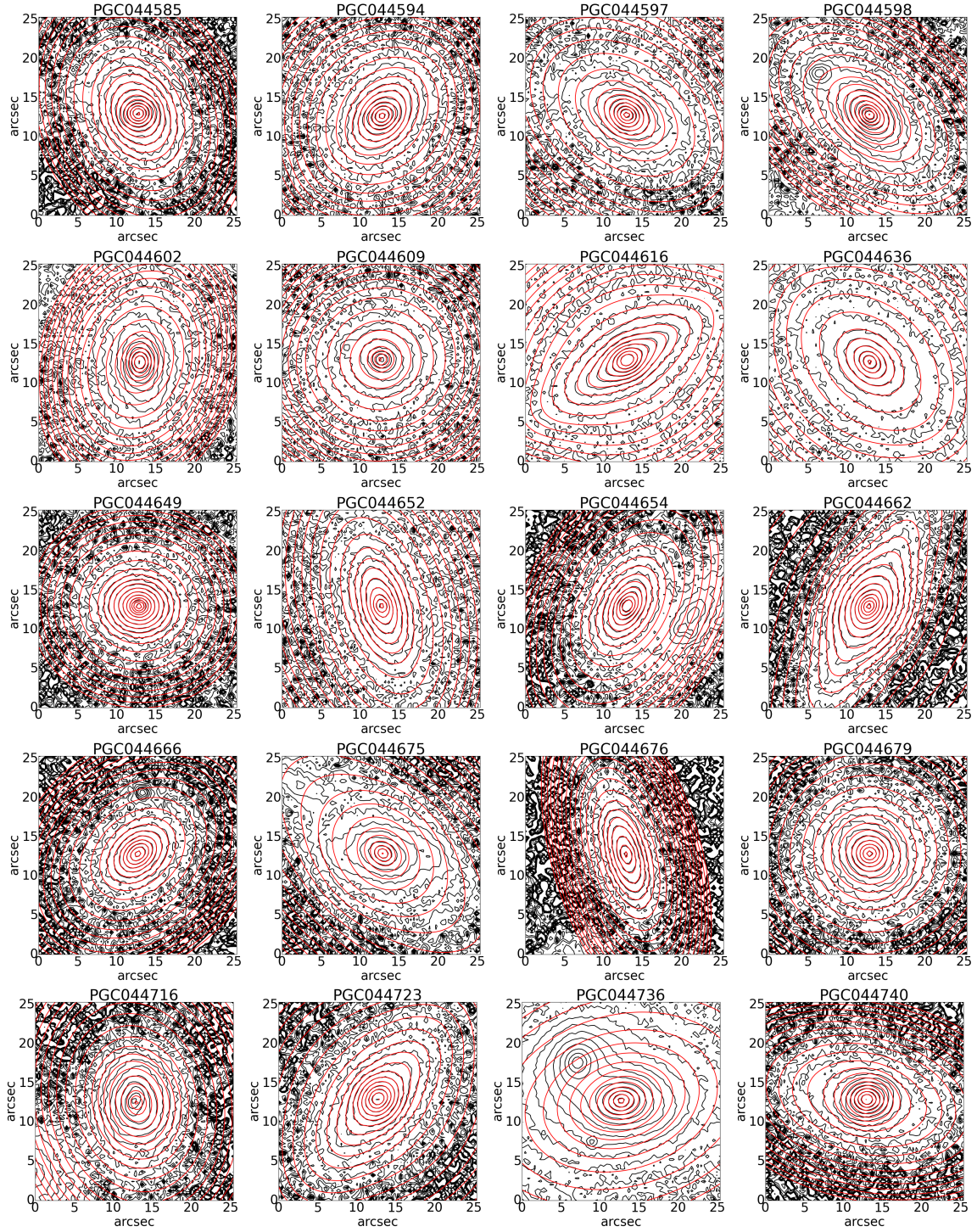


Fig. 4.3 – continued

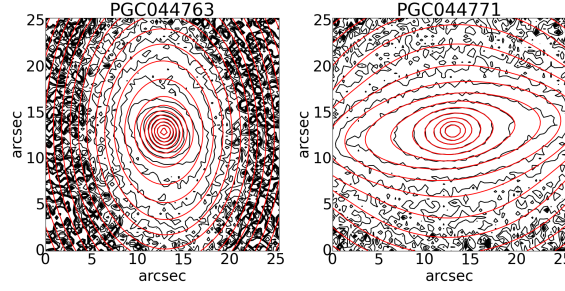


Fig. 4.3 Here, I present the contour plots of the SAURON subset for the Coma cluster. The black lines represent the observed galaxy surface brightness while the red lines represent the best fit MGE models to it. So as to inspect the quality of the MGE fits, these images depict the inner $25'' \times 25''$ thumbnails of the galaxies, while for the two massive central galaxies I present the inner $40'' \times 40''$ thumbnails. These plots depict the ability of the MGE models to represent the observed surface brightness of the galaxies, particularly in the inner regions of the galaxies where the stellar kinematics is observed. The contour plots for the full sample is available in Appendix. F.

of Cappellari et al. (2013b) to derive the radius which contains half of the total light of the MGE model. The effective radii of 2MASS was calculated using the eq. (6) of Cappellari et al. (2011a), i.e. median of semi-major axes of the half-light ellipse of the galaxy in the J, H and K_s band (j_{eff}, h_{eff} and k_{eff} of the 2MASS catalogue) times its axial ratio (k_{ba}).

The near unity slope and small scatter ($\Delta = 0.077$ dex) is indicative of the robustness of the two quantities as both measurements were taken from distinct datasets and techniques. In Cappellari et al. (2013b), the authors find that the effective radii they derived using the MGE method underestimated the sizes derived by 2MASS, when 2MASS was calibrated to the RC3 catalogue (de Vaucouleurs et al., 1991). Since this study uses the same photometric data (SDSS r band photometry) and technique, I calibrate the MGE R_e estimates using the offset observed by ATLAS^{3D}, i.e. factor of 1.35.

4.4.2 Stellar Kinematics

To test the accuracy of the stellar kinematics of the full sample, I compare the velocity dispersion derived in this study, within the limited wavelength range of SAURON (4,810 –

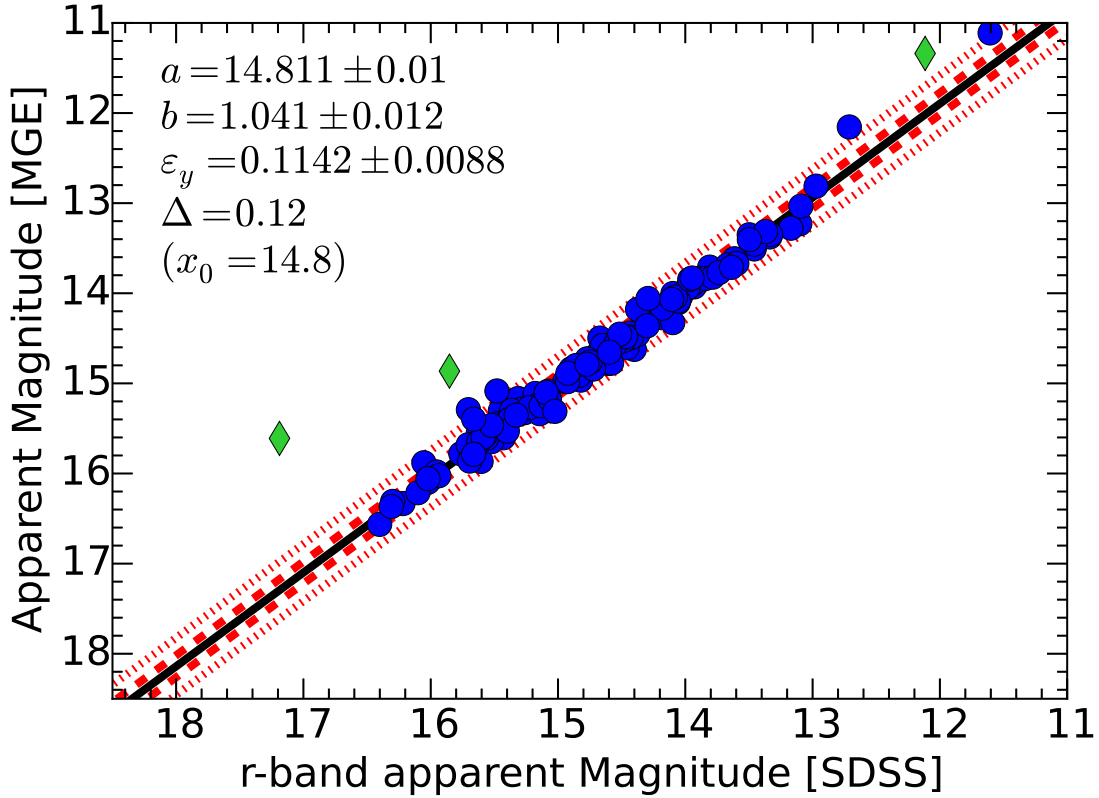


Fig. 4.4 This plot contrasts the apparent magnitude of the full sample published by the SDSS, shown along the x-axis, and the same quantity derived using their MGE models, plotted along the y-axis. The SDSS magnitudes used in this plot are those based on their cModel profile fits, i.e. those derived by fitting a de Vaucouleurs profile and exponential disk profile to the observed surface brightness of the galaxies. The comparison demonstrates a tight one-to-one relation between the two quantities as would be expected given that they are both measured from the same data. Some galaxies in the sample are significantly offset from this relation, however they are due to contamination by nearby galaxies and/or stars.

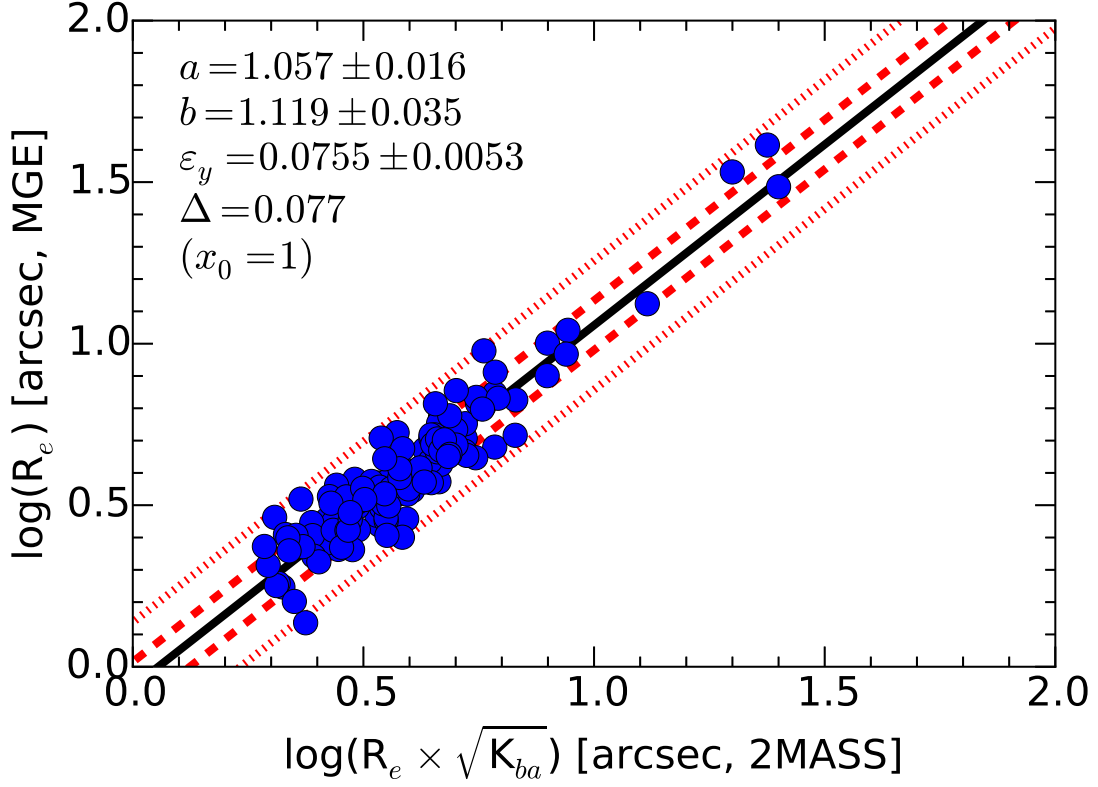


Fig. 4.5 Here I compare the circularised effective radii derived using the MGE fits of galaxies to that published by 2MASS. The plot above presents the effective radii of the galaxies derived using the MGE models along the y-axis, and compares it to the effective radii of the galaxies derived by the 2MASS collaboration along the x-axis. The effective radii by 2MASS is calculated using eq. (6) of Cappellari et al. (2011a), i.e. the median of semi-major axes of the half-light ellipse of the galaxy in the J, H and K_s band (j_r_eff , h_r_eff and k_r_eff of the 2MASS catalog) times its axial ratio (k_{ba}). This radii has been corrected for its PSF effects using eq. (1) of Cappellari (2013), which is relevant for radii $> 2''$, however the result is robust when only galaxies with sizes $> 5''$ are considered. The plot presents a strong correlation between the two quantities with a slope near unity. The observed rms scatter in the plot (0.077 dex) is comparable to that in fig. 7 of Cappellari et al. (2013b), where the authors compare MGE derived effective radii with that of 2MASS, recalibrated to the RC3 catalogue (de Vaucouleurs et al., 1991).

5,350Å), with that derived by Bolton et al. (2012). These catalogued kinematics are derived using the ELODIE stellar spectral library and are available within the spectral files of SDSS. In Fig. 4.6, the comparison suggests that the two quantities are consistent with a near one-to-one relation for values greater than 100 km s^{-1} . The plot does report a slight offset between the two quantities (0.022 dex or $\sim 5\%$), the relation is excellent given the differences in the techniques, wavelength range and the templates used in the derivation of the two quantities. At values lower than the 100 km s^{-1} , a systematic bias arises in the comparison of the two quantities. This bias is likely caused by the instrumental resolution limit of the SDSS spectra. In this study, I use the “OverSample” keyword in *pPXF* during the derivation of the stellar kinematics, which over samples the template spectra so as to improve the reliability of the derived stellar kinematics when the velocity dispersion is lower than the instrumental resolution. Based on the observed rms scatter in the plot, which would correspond to $\Delta/\sqrt{2} = 0.019$ dex error on each quantity.

To test the consistency of the kinematics derived for the SAURON data, I compare the kinematics derived using the SAURON data with that derived with the SDSS spectra. To reduce the effect due to other sources, velocity dispersion for the SAURON subset is derived from the coadded spectrum approximately within the aperture size of the corresponding SDSS spectra. The comparison of the two quantities is presented in Fig. 4.7, which demonstrates a strong linear relation with slope unity for galaxies with velocity dispersion greater than 60 km s^{-1} , when derived using the SDSS spectra. The discrepancy between the two quantities is likely due to the effect of low S/N, combined with a velocity dispersion lower than the instrumental resolution of SDSS. In this scenario, the derived velocity dispersions are quite unreliable and essentially only upper limits can be derived, but the derived velocity dispersion can scatter down to quite low values as observed. As the plot demonstrates, though the “OverSample” keyword does improve the reliability of the stellar kinematics below the resolution limit, at velocity dispersion below 60 km s^{-1} the derived quantities become

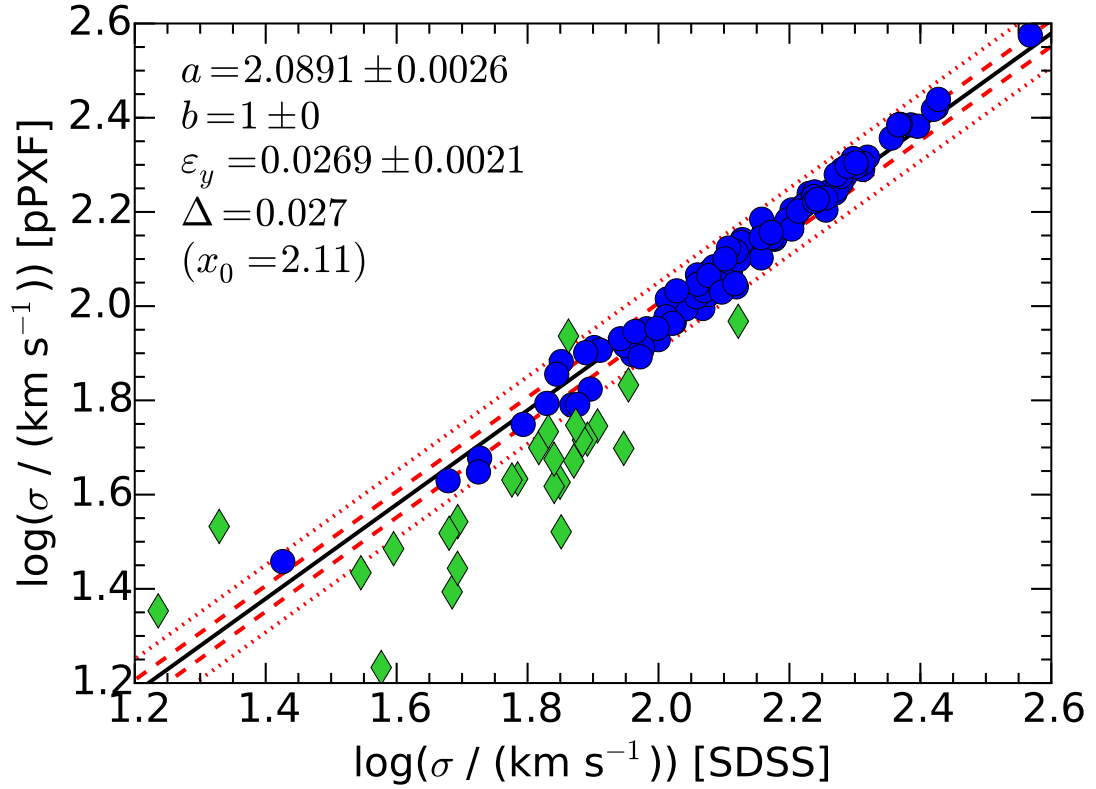


Fig. 4.6 In this plot, I compare the velocity dispersion derived for the full sample using pPXF, presented along the y-axis, with that published by SDSS (Bolton et al., 2012), plotted along the x-axis. The error bars along the x-axis are the errors on the individual values provided by SDSS. The plot demonstrates the consistency of the derived stellar dispersion for galaxies with $\sigma > 100 \text{ km s}^{-1}$. The large scatter between the two quantities at lower dispersion values can be attributed to the resolution limit of the galaxies.

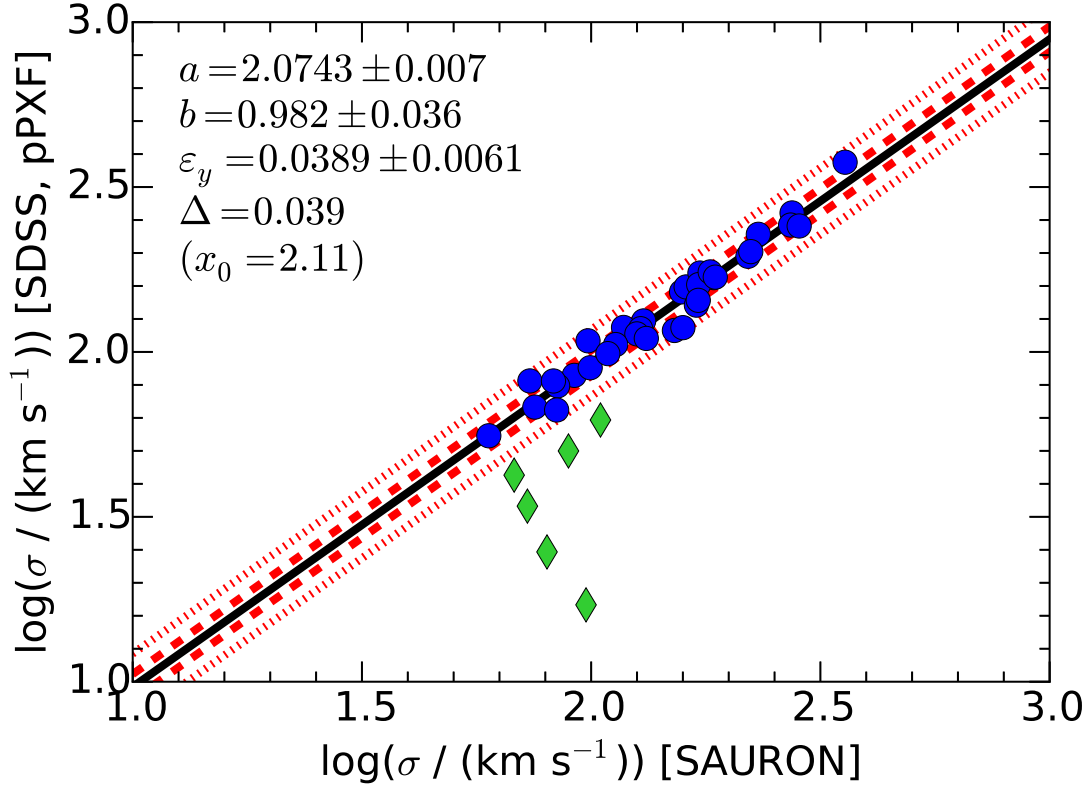


Fig. 4.7 This plot illustrates the consistency between the velocity dispersion derived using the SDSS spectra and the SAURON IFS data within a similarly sized aperture. The x-axis represents the kinematics derived using the SDSS spectra while the y-axis represents the same derived using the SAURON IFS data. The strong correlation between the two quantities is encouraging, as it demonstrates that the derived stellar kinematics in this study are robust.

extremely unreliable. Hence in this study, SDSS galaxies with derived velocity dispersions below 60 km s^{-1} are not used in the interpretation of the results.

The observed rms scatter in Fig. 4.7 is the quadratic sum of the errors on each of the two quantities of velocity dispersion. Given that from Fig. 4.6 we estimated that the error in the kinematics derived from the SDSS dataset is 0.029 dex. Taken together, the rms scatter in Fig. 4.7 indicates that the kinematics derived using the SAURON data have a error of 0.026 dex. These error estimates is similar to those in literature such as Emsellem et al. (2004); Cappellari et al. (2013b).

4.4.3 Dynamical Modelling

In order to test to the dynamical modelling code for the SAURON subset, I have used my code to model the dynamics of the ATLAS^{3D} galaxies. I did this using the stellar kinematics (Cappellari et al., 2011a) and MGE parameters (Scott et al., 2013) of the ATLAS^{3D} galaxies⁵ and inputting them to my code. The dynamical modelling was done using the Self-consistent model and though the quality of a few galaxies were visually verified, a complete verification and manual tweaking (e.g. removing bad spaxels) for any individual galaxies was not done. In Fig. 4.8, the plot compares the dynamical $(M/L)_{JAM}$ derived by my code against that published by Cappellari et al. (2013b). The one-to-one relation between the two quantities, with an observed scatter of just 2%, suggests that the dynamical modelling code can accurately model the dynamics of most galaxies.

In addition to testing the dynamical modelling code, I visually verified the quality of the dynamical models created for the SAURON subset of the Coma cluster. This was done by comparing the observed V_{rms} maps, after being bi-symmetrized and LOESS smoothed, and the $\langle v_{los}^2 \rangle^{1/2}$ for the best fit dynamical model. Examples of these plots are presented in Fig. 4.9. Based on these plots I visually classify galaxies into three groups using similar classification as Cappellari et al. (2013b): galaxies with good dynamical models that reproduce the observed kinematic structures ($Qual = 2$ in Table. 4.1), galaxies acceptable dynamical models that reproduce some of the observed kinematic structures ($Qual = 1$), and galaxies for reliable kinematics couldn't be derived ($Qual = 0$). The results of the classification, along with a brief reasoning behind them, can be found in Appendix. J. During the visual verification, it was realised that the observed V_{rms} in the innermost regions of the galaxies are larger than that predicted by models for a significant number of galaxies. The cause of this is yet to be determined, though preliminary results that allowed the models to fit for the mass of the SMBH did resolve the issue. This is a potentially interesting result suggesting

⁵<http://www-astro.physics.ox.ac.uk/atlas3d/>

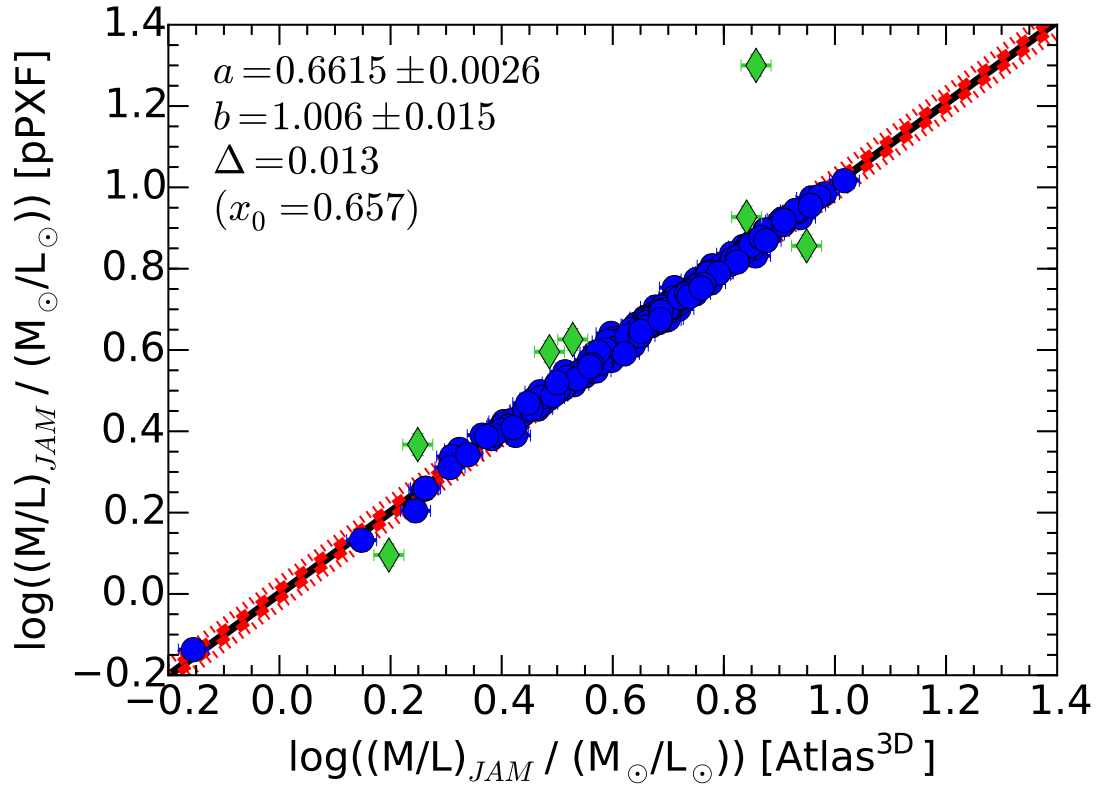


Fig. 4.8 This plot compares the dynamical $(M/L)_{JAM}$ derived by my code and that by ATLAS^{3D} . The plot above demonstrates the consistency between the dynamical $(M/L)_{JAM}$ derived by the ATLAS^{3D} collaboration (presented along the x-axis) and the same derived using my code (presented along the y-axis). The plot indicates that the dynamical modelling in this study is unlikely to be effected by any errors in the modelling technique or code.

that these galaxies have SMBHs more massive than those predicted by the $M_{\text{BH}} - \sigma_e$ relation. However, further tests are needed to eliminate other sources of the discrepancy. For the purpose of the visual classification, I have focused solely on the reproduction of kinematic features that are sufficiently far from the centre that they are not affected by an inaccurate estimate of the SMBH.

To optimise for the free parameters of the dynamical models, I adopt a Bayesian inference technique. In particular, I compute the posterior distribution of the free parameters of each model using the *emcee*⁶ (Foreman-Mackey et al., 2013) implementation of the affine-invariant Markov-Chain Monte Carlo (MCMC) proposed by Goodman & Weare (2010). The prior distribution of the free parameters is a constant within given reasonable limits and falls sharply beyond them. The distribution is centred on the results of an initial fit for the dynamical models using the *Python* implementation of the *mpfit*⁷ code, a global optimisation code. I model the probability of a model for a set of parameters as :

$$P(\text{data}|\text{model}) \propto \exp\left(\frac{-\chi^2}{2}\right) \quad (4.3)$$

Where the χ^2 is defined as

$$\chi^2 = \sum_j \left(\frac{\langle v_{\text{los}}^2 \rangle_j^{1/2} - V_{\text{rms},j}}{\Delta V_{\text{rms},j}} \right)^2 \quad (4.4)$$

Here $\langle v_{\text{los}}^2 \rangle_j^{1/2}$ is the predicted second moment of velocity for the dynamical model being evaluated, while $V_{\text{rms},j}$ and $\Delta V_{\text{rms},j}$ are the observed stellar kinematic and its error, in the j^{th} bin of the galaxy's two dimensional kinematic map. The best fit values of the free parameters, and their associated uncertainties, are derived from their respective posterior distributions.

Having tested the reliability of the models used in the SAURON subset, I test the dynamical modelling of the full sample by comparing its $(M/L)_{\text{JAM}}$ with that derived for

⁶<http://dan.iel.fm/emcee/current/>

⁷<http://cars.uchicago.edu/software/python/mpfit.html>

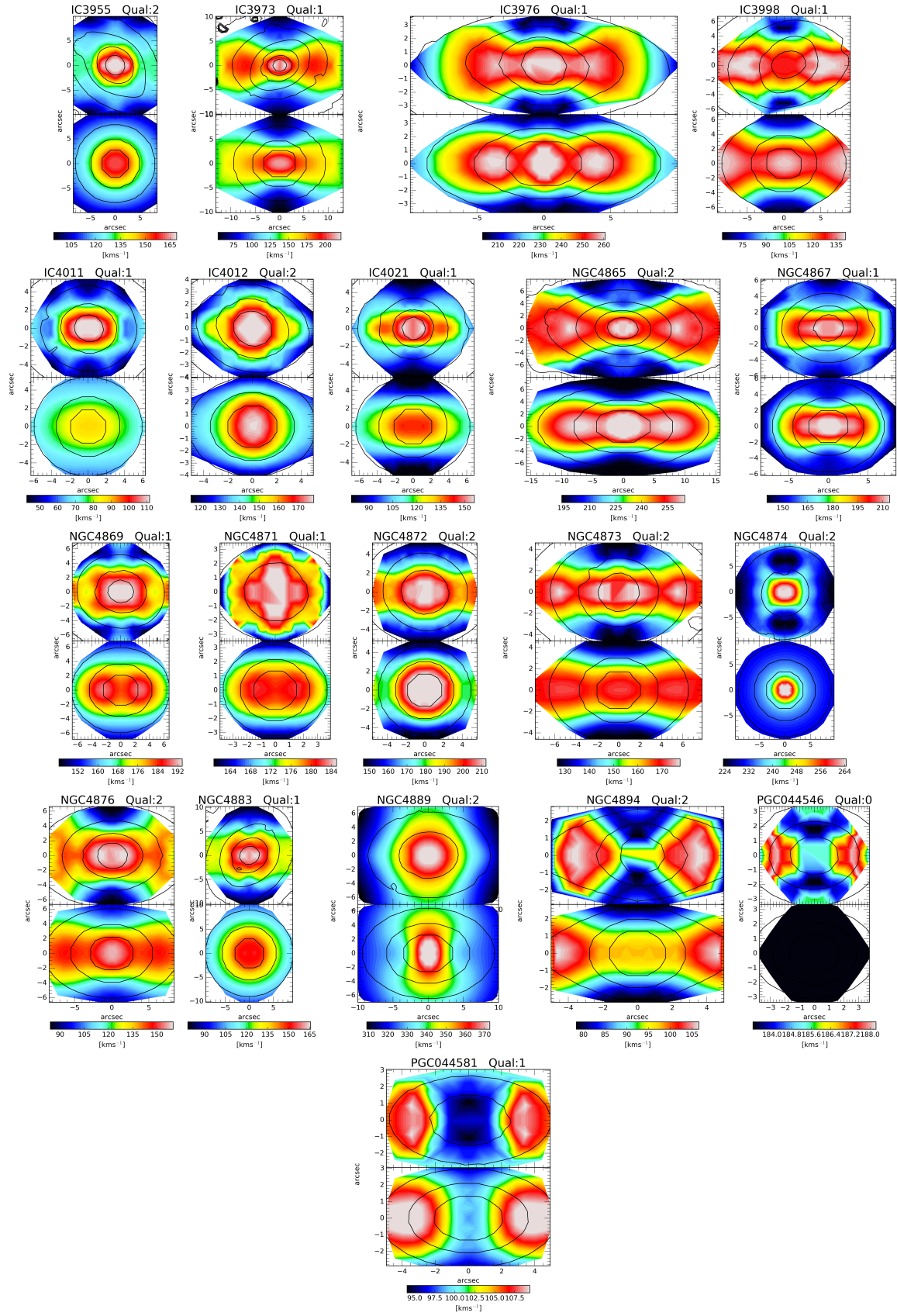


Fig. 4.9 – continued

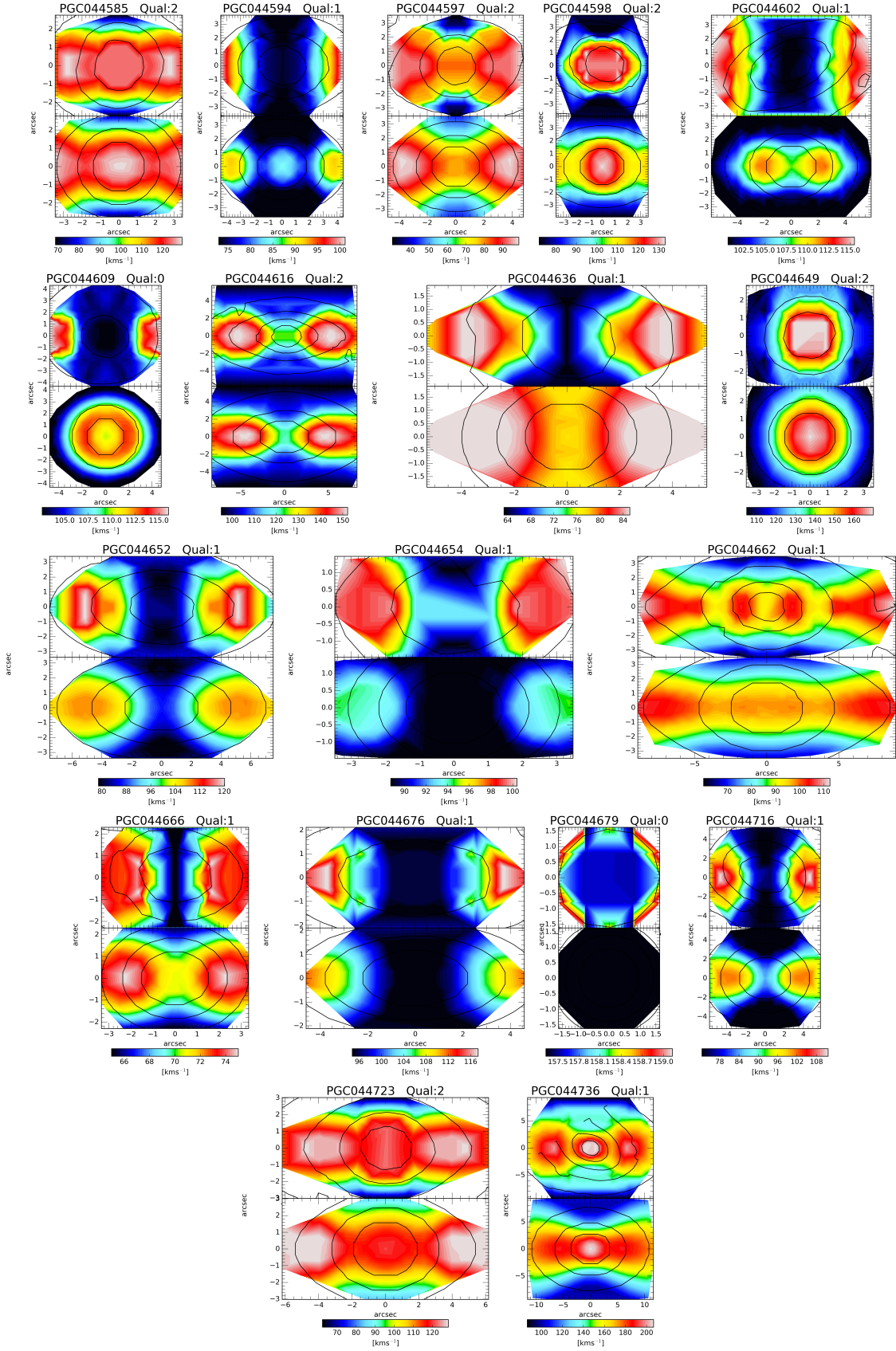


Fig. 4.9 – continued

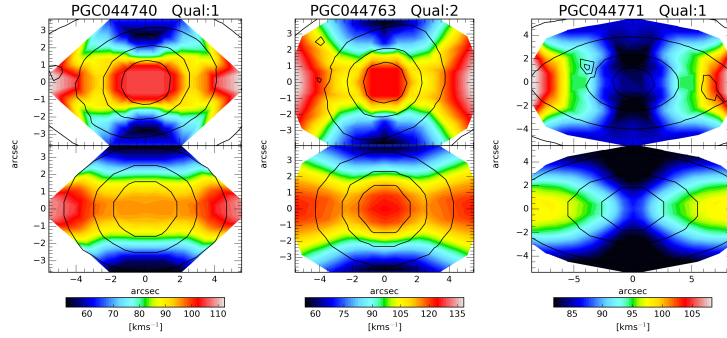


Fig. 4.9 In the panels above, I present the bi-symmetrised and LOESS smoothed observed V_{rms} of the galaxies (top panel) with the best fitting Self-Consistent model (bottom panel) for the SAURON subset. In the top panels, the black contours represent the observed surface brightness of the galaxies, while the contours in the bottom panel represent the contours of the MGE model fits to the galaxy.

the common galaxies in the SAURON subset. This comparison is presented in Fig. 4.10, which demonstrates that a linear relation with a slope of unity is a good fit between the two quantities. This comparison is done within a small range of M/L values and suffers from a small number of galaxies, hence one should be cautious of over-interpreting its results.

4.4.4 Stellar Population Models

Similar to Fig. 4.8, to test the code used to model the stellar populations of the galaxies I model the stellar populations of the ATLAS^{3D} galaxies. I do this using the SAURON data cubes for the galaxies obtained from the ATLAS^{3D} website⁸. I model the stellar populations of the galaxies with the spectrum obtained by coadding the spaxels within the effective radii of the galaxies and do so using my code. In Fig. 4.11, I compare the stellar $(M_*/L)_{pop}^{Salp}$ derived by my code with the same quantity published (referred to as $(M/L)_{Salp}$) in Cappellari et al. (2013a). The plot indicates a near unity slope and a small offset, however this offset is within the typical zero-point uncertainties.

In Appendix. G, I exhibit the summary plots of the stellar population models for the galaxies. These plots present the results of the full-spectrum fit to the observed galaxy spectra

⁸<http://www-astro.physics.ox.ac.uk/atlas3d/>

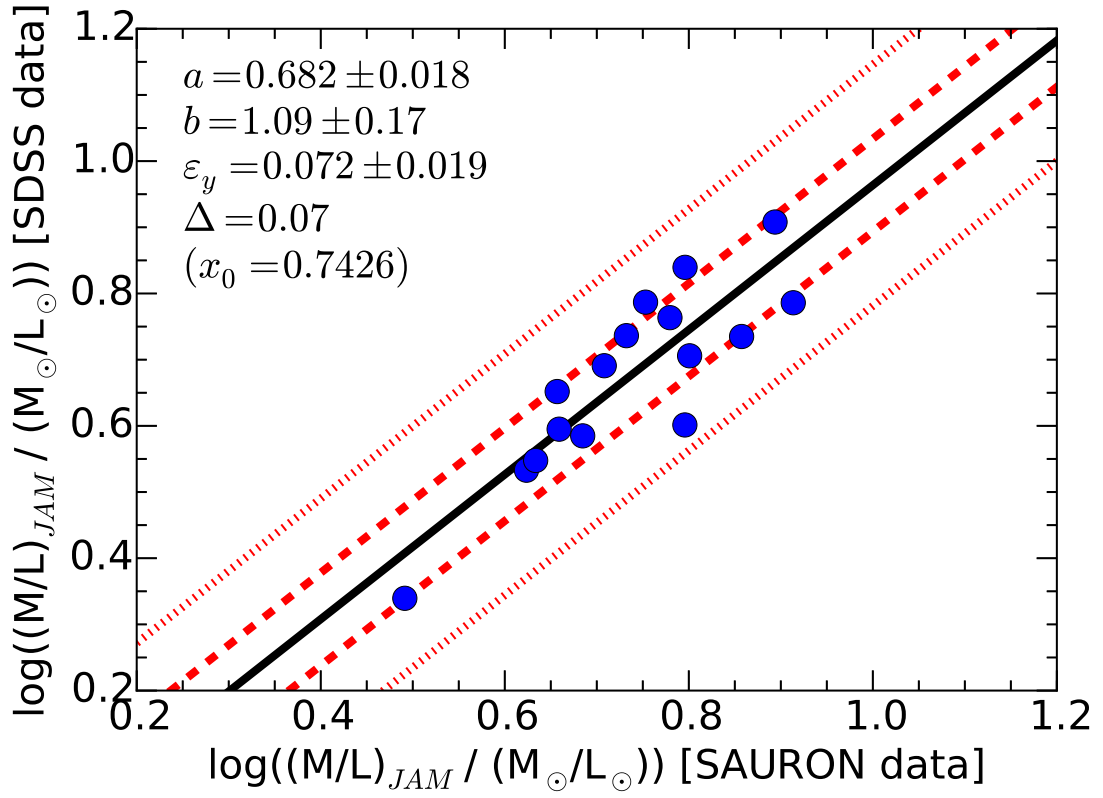


Fig. 4.10 This plot presents the dynamical $(M/L)_{JAM}$ for the 15 galaxies in the full sample whose two dimensional stellar kinematics (SAURON kinematics) are well reproduced by the models ($Qual = 2$ in Table. 4.1). Comparing the these values, modelled using identical assumptions, demonstrates the consistency between the two techniques and gives confidence on the values derived in the study.

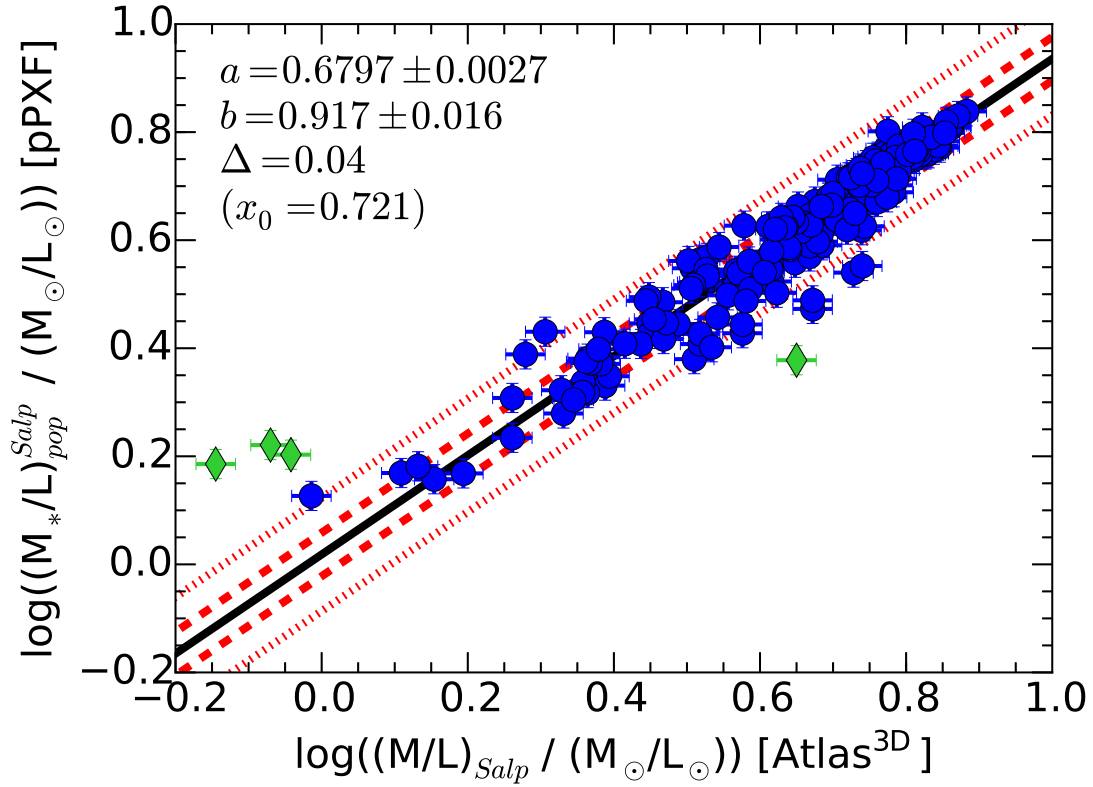


Fig. 4.11 This plot compares the $(M_*/L)_{pop}^{Salp}$ derived for the ATLAS^{3D} sample using my code against those published by the ATLAS^{3D} group (See quantity $(M/L)_{Salp}$ in Cappellari et al., 2013a). The comparison illustrates a near unity slope between the two quantities and a negligible observed rms scatter of 0.04 dex (10%). The plot also demonstrates an offset of 0.04 dex (10%) which is typical of the uncertainties associated with the model zero-points.

and the weight distribution of the templates used along a grid of model age and metallicity. These plots demonstrate the quality of the models and their results in a clear manner.

4.5 Results

Based on the above mentioned analysis, Table. 4.1 and Table. 4.2 present the physical quantities derived for the SAURON subset and full sample respectively. In the following subsections, I use these quantities to study the properties of the galaxies and the dark matter halo that they reside in. To do this, I first present the $(M/L)_{JAM}$ - σ_e relation of the galaxies and compare this to the previous results. This exercise serves as a test for the quantities derived in the study and as a test of the robustness of the relationship. Next, I use the dynamical models of the SAURON subset of galaxies to study the density profiles of the galaxies, and separate the stellar component and dark matter halo. This provides an excellent opportunity to study the dark matter halo of the galaxies. Next I study the IMF normalisation of the galaxies and compare this to previous results. In addition to these results, I study the scaling relations of these galaxies to infer trends in the properties of galaxies and contrast that with the same found for galaxies in lower density environments.

Galaxy	RA ($^{\circ}$) (1)	Dec ($^{\circ}$) (2)	$\log(R_e)$ (arcsec) (3)	$\log(R_e^{\text{Maj}})$ (arcsec) (4)	$\log(\sigma_e)$ (km s^{-1}) (5)	M_r (mag) (6)	$\log(M/L)_{JAM}$ ($M_{\odot}/L_{\odot}$) (7)	$\log(M_*/L_*)_{dyn}^{AM}$ ($M_{\odot}/L_{\odot}$) (8)	$f_{DM,AM}$ (10)	$\log(\rho_{tot})$ ($M_{\odot} \text{ pc}^{-3}$) (11)	γ (12)	$\log(M_*/L_*)_{dyn}^{PL}$ ($M_{\odot}/L_{\odot}$) (13)	$f_{DM,PL}$ (14)	$\log(M_*)$ ($M_{\odot}$) (15)	JAM Quality (16)	Hubble Morph. (17)
IC3955	194.775146	27.996647	6.633	6.683	2.18	-20.704	0.763	0.767	0.15	-2.917	-2.134	0.707	0.16	10.905	2	S0
IC3973	194.878326	27.884117	5.135	5.511	2.29	-20.972	0.778	0.748	0.09	-2.680	-2.123	0.645	0.24	10.992	1	S0
IC3976	194.872345	27.850227	3.464	5.200	2.42	-20.534	1.075	1.038	0.05	-2.790	-2.276	0.907	0.10	11.108	1	E
IC3998	194.945053	27.973686	6.790	7.383	2.08	-20.478	0.735	0.683	0.17	-2.664	-1.782	0.544	0.46	10.730	1	S0
IC4011	195.026825	28.003969	5.026	5.256	1.95	-20.111	0.383	0.303	0.20	-4.150	-2.601	0.121	0.00	10.204	1	E

Table 4.1 Results of analysis of the SAURON subset of Coma cluster galaxies. Only a small snippet of the table is presented here, and I would like to refer the interested reader to Appendix. H to view it in its entirety. Notes:- Column (1) : Galaxy name. Column (2) : Right Ascension in degrees (J2000). Column (3) : Declination in degrees (J2000). Column(4) : Effective radii of the galaxies in arcsec. These quantities are derived from the MGE parametrisation of the galaxy photometry and have been multiplied by 1.35 as per the offset observed in ATLAS^{3D}. For more details, please refer to Section. 4.4.1. Column (5) : Major axis of the half-light isopleth in arcsec. This is derived as per the prescription in Cappellari et al. (2013b) and has been multiplied by 1.35, as done for the effective radius. Column (6) : Log of the velocity dispersion measured within an aperture of $1R_e$ in units of km s^{-1} . The error in the derived velocity dispersion is 0.042 dex or 10%. Column (7) : Absolute magnitude of the galaxy derived from its r -band SDSS photometry. Column (8) : Log of the dynamical (M/L) of the galaxies derived using the Self-Consistent model. It is measured in units of ($M_{\odot}/L_{\odot}$), and has an error of 0.04 dex or 10%. Column (9) : Log of the stellar (M/L) of the galaxies derived dynamically using the Abundance-Matching model. It is measured in units of ($M_{\odot}/L_{\odot}$) and similar errors as the dynamical (M/L)_{JAM}. Column (10) : Dark matter fraction within $1R_e$ of the galaxies based on the Abundance Matched model. Column (11) : Log of the total density at the scale radius (20 kpc) of the best fitting power law density profile, as derived using the Power Law model. This value is measured in units of ($M_{\odot} \text{ pc}^{-3}$). Column (12) : The slope, γ , of the best fitting power law density profile, as derived using the Power Law model. Column (13) : Log of the stellar (M/L) for the galaxies derived from the best fitting power law density profile, as derived using the Power Law model. Column (14) : Dark matter fraction within $1R_e$ of the galaxies based on the Power Law model. Column (15) : Log of the stellar mass of the galaxies in units of $M_{\odot}$, calculated using the galaxies absolute magnitude and stellar ($M_*/L_*)_{dyn}^{AM}$. Column (16) : Quantity indicating the quality of the dynamical models based on the results of the Self-Consistent model. Column (17) : Hubble morphological classification of the galaxies taken from HyperLEDA (Makarov et al., 2014).

Galaxy	RA	Dec	$\log(R_e)$	$\log(R_e^{\text{Maj}})$	$\log(\sigma)$	M_r	$\log(M/L)_{IAM}$	$\log(M_*/L)_{dyn}^{AM}$	$\log(M_*/L)_{pop}^{Salp}$	Age	$\log(M_*)$	SAURON	Hubble
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
IC3943	194.651505	28.113808	5.019	7.580	2.23	-20.809	0.756	0.754	0.768	11.42	10.934	0	S0
IC3946	194.702881	27.810249	5.013	6.300	2.31	-21.036	0.749	0.761	0.774	12.05	11.031	0	S0
IC3947	194.717026	27.784977	4.311	5.495	2.15	-20.410	0.668	0.656	0.731	11.39	10.676	0	S0
IC3955	194.775146	27.996647	6.633	6.683	2.14	-20.704	0.601	0.568	0.704	9.95	10.706	1	S0
IC3957	194.781067	27.767759	4.810	4.934	2.21	-20.395	0.729	0.723	0.786	12.35	10.737	0	E

Table 4.2 Results of analysis of the Full sample of Coma cluster galaxies. Only a small snippet of the table is presented here, and I would like to refer the interested reader to Appendix. I to view it in its entirety. Column (1) : Galaxy name. Column (2) : Right Ascension in degrees (J2000). Column (3) : Declination in degrees (J2000). Column(4) : Effective radii of the galaxies in arcsec. These quantities are derived from the MGE parametrisation of the galaxy photometry and have been multiplied by 1.35 as per the offset observed in ATLAS^{3D}. For more details, please refer to Section. 4.4.1. Column (5) : Major axis of the half-light isophote in arcsec. This is derived as per the prescription in Cappellari et al. (2013b) and has been multiplied by 1.35, as done for the effective radius. Column (6) : Log of the velocity dispersion measured in km s^{-1} . The error in the derived velocity dispersion is 0.042 dex or 10%. Column (7) : Absolute magnitude of the galaxy derived from its r-band SDSS photometry. Column (8) : Log of the dynamical (M/L) of the galaxies derived using the Self-Consistent model. It is measured in units of ($M_\odot/L_\odot$), and has an error of 0.04 dex or 10%. Column (9) : Log of the stellar (M/L) of the galaxies derived dynamically using the Abundance-Matching model. It is measured in units of ($M_\odot/L_\odot$) and similar errors as the dynamical (M/L)_{IAM}. Column (10) : Stellar mass-to-light ratio in units of ($M_\odot/L_\odot$). These are derived by the regularised mass-weighted fitting of the galaxy spectra with stellar population models, assuming a Salpeter IMF. Column (11) : Mass-weighted stellar age of the galaxies in Gyrs. Column (12) : Log of the stellar mass of the galaxies in units of $M_\odot$, calculated using the galaxies absolute magnitude and stellar (M_*/L)_{dyn}^{AM}. Column (13) : Quantity stating if the galaxy has SAURON observations (=1) or not (=0). . Column (14) : Hubble morphological classification of the galaxies taken from HyperLEDA (Makarov et al., 2014).

4.5.1 (M/L) – σ Relation

In Fig. 4.12, I present the $(M/L)_{JAM} - \sigma_e$ relation for the full sample and the SAURON subset of this study. The $(M/L)_{JAM}$ for these relations are derived using the Self-Consistent dynamical models of the two samples. The σ_e for the SAURON subset is derived from the spectral fitting of the spectra integrated within an R_e . For the full sample, for which spectral data within fixed apertures are available, I use eq. (1) of Cappellari et al. (2006) which presents an aperture correction for the σ_e of ETGS based on IFS observations of local ETGs. Previous studies have indicated these quantities are tightly correlated and that exhibited minimal variations within intermediate redshifts and different environment (e.g: Cappellari et al., 2006; van der Marel & van Dokkum, 2007). This makes the relation an ideal test for the accuracy of the dynamical analysis conducted in this study, and the consistency of the results between the two datasets.

Fig. 4.12 presents the $(M/L)_{JAM} - \sigma$ relation for the SAURON subset and the full sample of the study, and compares the relation to that seen in the ATLAS^{3D} galaxies Cappellari et al. (2013b). The relation derived for the full sample and the galaxies with $Qual = 2$ of the SAURON subset, are consistent within their 1σ errors, establishing the reliability of the analysis of the full sample to accurately model the galaxies in the cluster. In the plot, the solid green line represents the $(M/L)_{JAM} - \sigma_e$ relation observed in the global ATLAS^{3D} sample. The consistency of the slopes between the Coma galaxies and ATLAS^{3D} is encouraging and is as expected given that both samples should be dominated by fast rotators (Cappellari et al., 2013b; Cappellari, 2013). However, the plots exhibit an offset of 0.06 dex (15%) between the ATLAS^{3D} and Coma cluster galaxies, which is persistent in both datasets of this study. A possible reason for this is the uncertainty in the distance to the Coma cluster, in fact $M/L \propto D^{-1}$, where D is the adopted cluster distance. This issue is further discussed in Section. 4.5.3.

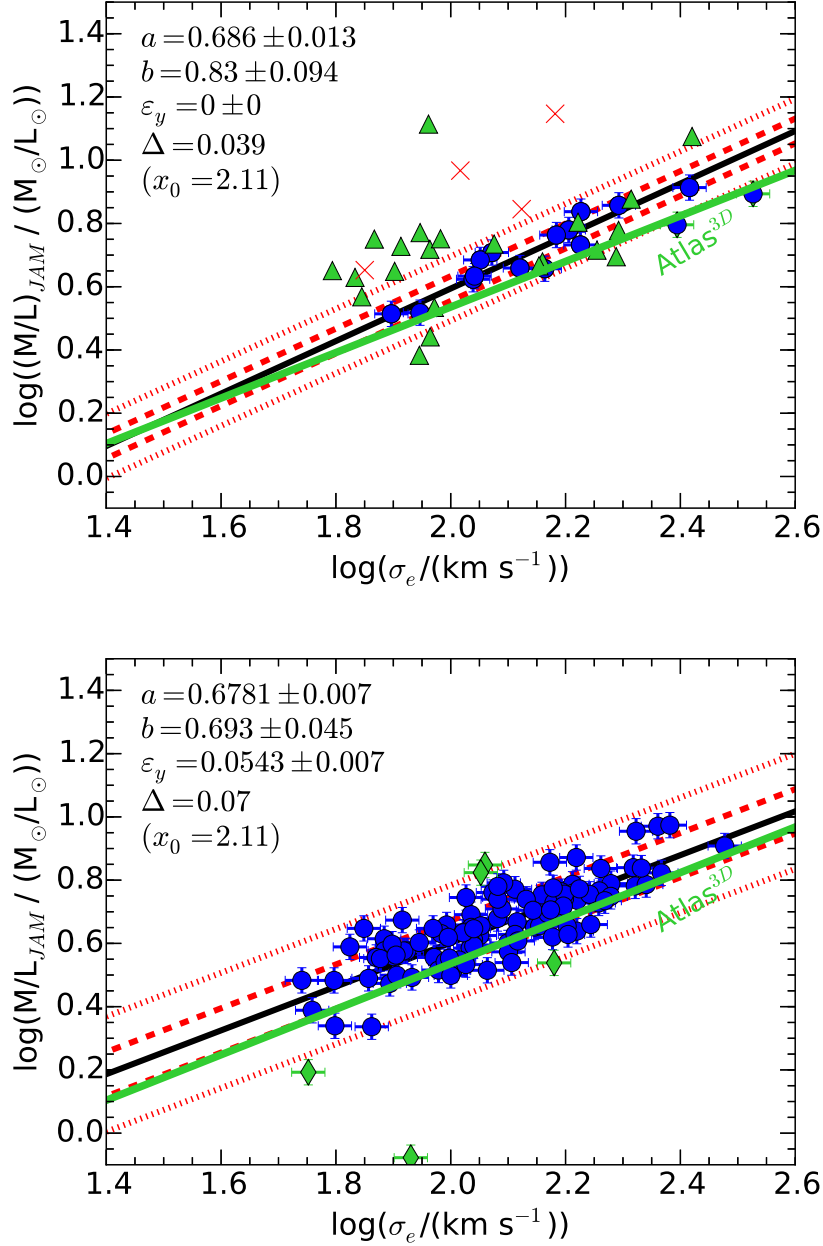


Fig. 4.12 These plots depict the dynamical (M/L) – σ_e relation for the SAURON subset (top) and the full sample (bottom). The blue points in the top panel represent the galaxies with $Qual = 2$, with the green triangles and red crosses depict galaxies with acceptable and bad dynamical models respectively. The plots show that the best fit relation to both datasets, SAURON ($Qual = 2$) and SDSS, of this study are consistent within their 1σ error, and demonstrates the reliability of the quantities derived in the full sample and hence probe the overall cluster properties. The solid green line represents the relation observed for the ATLAS^{3D} sample (Cappellari et al., 2013b). It is also reassuring to see that slope of the relation observed in Coma cluster is consistent to that observed in ATLAS^{3D}, which is to be expected given the tested robustness of the relation. There is an observed offset of 0.06 dex (15%) between cluster results and that of ATLAS^{3D}, however this is discussed in Section. 4.5.3.

4.5.2 Dark Matter in Galaxies

To probe the dark matter content in the galaxies, I model the SAURON subset using two assumptions for the gravitational potential of the galaxies. The Abundance Matching model (AM model) is based on the Stellar-to-Halo Mass relation derived from matching the dark halos in the Millennium simulation (Springel et al., 2005) with the observed stellar mass functions of galaxies. On the other hand, the Power Law model (PL model) is motivated by the empirical results, from gravitational lensing and dynamical modelling Sand et al. (2008); Auger et al. (2010); Newman et al. (2013b); ?; Cappellari et al. (2015), that demonstrate that the total mass distribution of galaxies can be well approximated by an isothermal profile, i.e. $\rho_{tot} \propto r^{-\gamma}$. These model assumptions are sufficiently distinct to provide a sense of the expected systematic uncertainties in our dark matter determinations.

In Fig. 4.13, I present the distribution of the best fit γ , slope of the power law density distribution in Eq. 4.2, for galaxies with good dynamical models, $Qual > 1$, depicted by the green distribution, and for galaxies with good or acceptable fits, $Qual > 0$, depicted by the blue distribution. Galaxies with $Qual > 1$ appear to have $\langle \gamma \rangle = -2.14$, consistent with previous works using lensing and dynamical modelling of galaxies (Auger et al., 2010; Cappellari et al., 2015). Since galaxies with $Qual = 1$ have a significant spread in the derived $\langle \gamma \rangle$, I only refer to the galaxies $Qual = 2$ to infer the dark matter fraction of galaxies in the Coma cluster.

To quantify the dark matter content in galaxies, I measure their dark matter fractions within a sphere of radius $1R_e$. For the Abundance-Matched model, I use the best fit $(M_*/L)_{dyn}^{AM}$ to define the dark matter halo of the galaxy, as described in Section. 4.3.2. Using *mge_fit_1d* (which is part of the *mge_fit_sectors* package) to parametrise this halo profile, I use the following equation to determine the mass of each component within an effective radii:

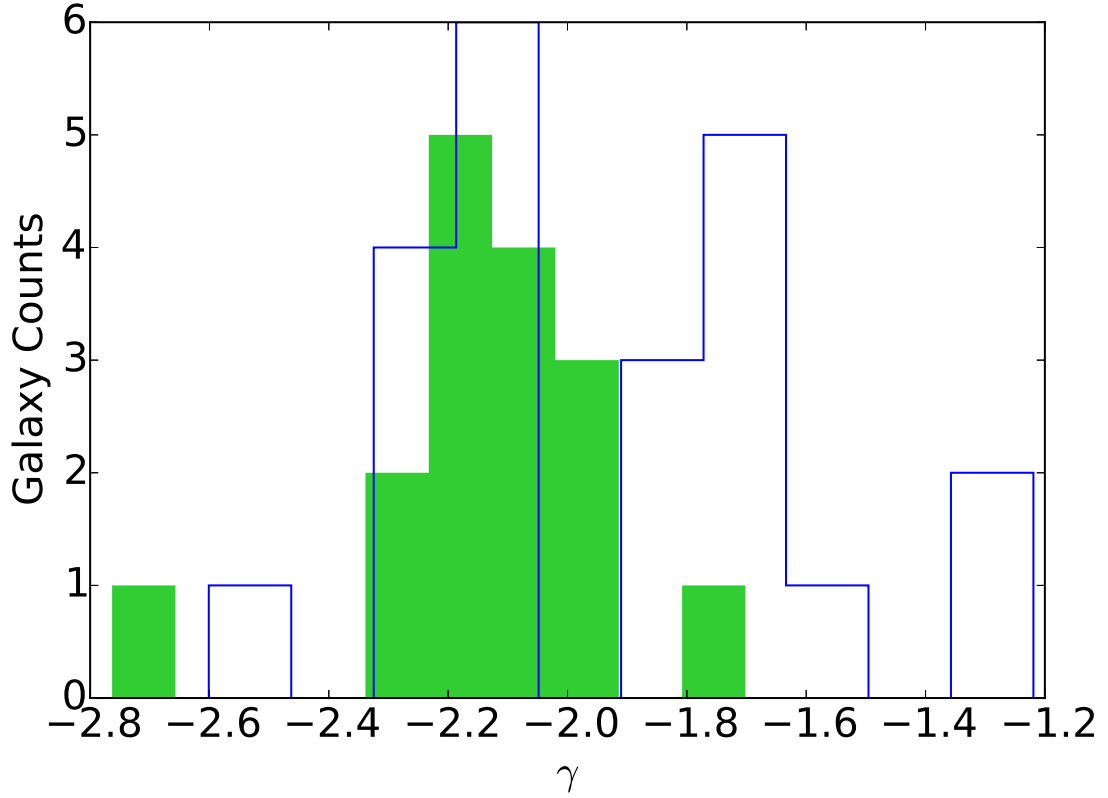


Fig. 4.13 This histogram illustrates the distribution of the best fitting slope to the power law density distribution of the Power Law model, i.e. γ of Eq. 4.2. The blue distribution represents galaxies with unreliable dynamical models, i.e with $Qual = 1$, while the green distribution represents galaxies with good dynamical models i.e. $Qual = 2$. The plot demonstrates that most galaxies with $Qual = 2$ have a slope around -2.2, consistent with the inner slopes measured by Auger et al. (2010) and Cappellari et al. (2015). Hence in this study I refer only to these galaxies when inferring the dark matter fraction of galaxies.

$$M(r) = \sum_{j=1}^N M_j \left\{ \operatorname{erf}[h(r)] - \frac{\exp[-(h(r) q_j)^2] \operatorname{erf}\left[\sqrt{1-q_j^2} h(r)\right]}{\sqrt{1-q_j^2}} \right\} \quad (4.5)$$

$$h(r) = \frac{r}{\sqrt{2}\sigma_j q_j} \quad (4.6)$$

Here, M_j is the mass of each gaussian of the MGE fit, while σ_j and q_j are their dispersion and intrinsic scatter respectively. Within this framework, the dark matter fraction is simply $M_{DM}(R_e)/[M_*(R_e) + M_{DM}(R_e)]$.

To calculate dark matter fraction for the Power Law model, one needs to disentangle the stellar and dark matter component of the galaxy. The dynamical modelling of the galaxy kinematics using the Power Law model provides the best fitting total density profile for each galaxy. In this study, I define the total density profile of the galaxy as the sum of the stellar and dark matter profile, i.e.:

$$\rho_{tot}(r) = (M_*/L)_{dyn}^{PL} \times \rho_*(r) + \rho_{DM,s} \times \left(\frac{r}{r_s}\right)^{-1} \left(\frac{1}{2} + \frac{1}{2} \frac{r}{r_s}\right)^{-2} \quad (4.7)$$

Where the total matter density of the galaxy at radius r , $\rho_{tot}(r)$, is described as the sum of the stellar component, $(M_*/L)_{dyn}^{PL} \times \rho_*(r)$, and dark matter component, defined in the later half of the equation. In this equation, the stellar mass density profile of the galaxy is defined as the product of the stellar M/L, $(M_*/L)_{dyn}^{PL}$, and the stellar density profile, $\rho_*(r)$. The stellar density profile is derived from the deprojection of the observed surface brightness profile using the MGE models for each galaxy and the best fitting inclination for the Power Law dynamical model. The dark matter component of the galaxy is described using a NFW profile and is normalised by the density at the scale radius, i.e. $\rho_{DM,s}$.

Based on the above model, the shape and normalisation of the best fitting Power Law model is described by the sum of the shape and normalisation of the stellar and dark matter components of the galaxies. The shape of the two components are fixed using the

observed surface brightness profile, best fitting inclination to the galaxy kinematics and the assumption of a spherical NFW profile for the dark halo. Hence the normalising factors for the two components, i.e. $(M_*/L)_{dyn}^{PL}$ and $\rho_{DM,s}$, are the only remaining parameters needed to disentangle the contributions of the stellar and dark matter to the total density profile of galaxies.

These free parameters are derived by solving for the best fitting combinations for the parameters such that the residuals between the linear sum of the two components and that of the best fitting Power Law model are minimised. This minimisation was done using a least-square fitting algorithm. The minimisation of the residuals was done within the radius range of the kinematic data used in the dynamical modelling, i.e. between the radius of $2''$ and the maximum radius within which the kinematics of the galaxies were derived.

In Fig. 4.14, I present a couple of examples of the decomposition of galaxy profiles. In the figure, the blue line represents the best fitting Power Law density profile based on the dynamical modelling of the galaxy, while the dashed red and dashed black lines represent the disentangled contributions of its stellar and dark matter components. The yellow line indicates the sum of the contributions of the two components. The figure demonstrates a good fit of the best-fitting density profile from the dynamical model of the galaxies with the sum of the stellar and dark matter components. Both plots demonstrate that the best-fitting power law is steeper than the sum of the two components in the inner region, which may be due to the fact that the SMBH may influence the stellar kinematics in this region.

In Fig. 4.15, the dark matter fractions for the SAURON subset is presented for both models. Given the results of Fig. 4.13, I refer only to galaxies with $Qual = 2$ for the derived dark matter fractions. Hence in Fig. 4.15, galaxies with $Qual < 2$ are represented by red crosses, while galaxies with $Qual = 2$ are presented with blue points. As depicted by the plots, the dark matter fraction for both galaxies under both models are low. Quantifying this result for the Abundance Matched model, 90th percentile of galaxies classified as having

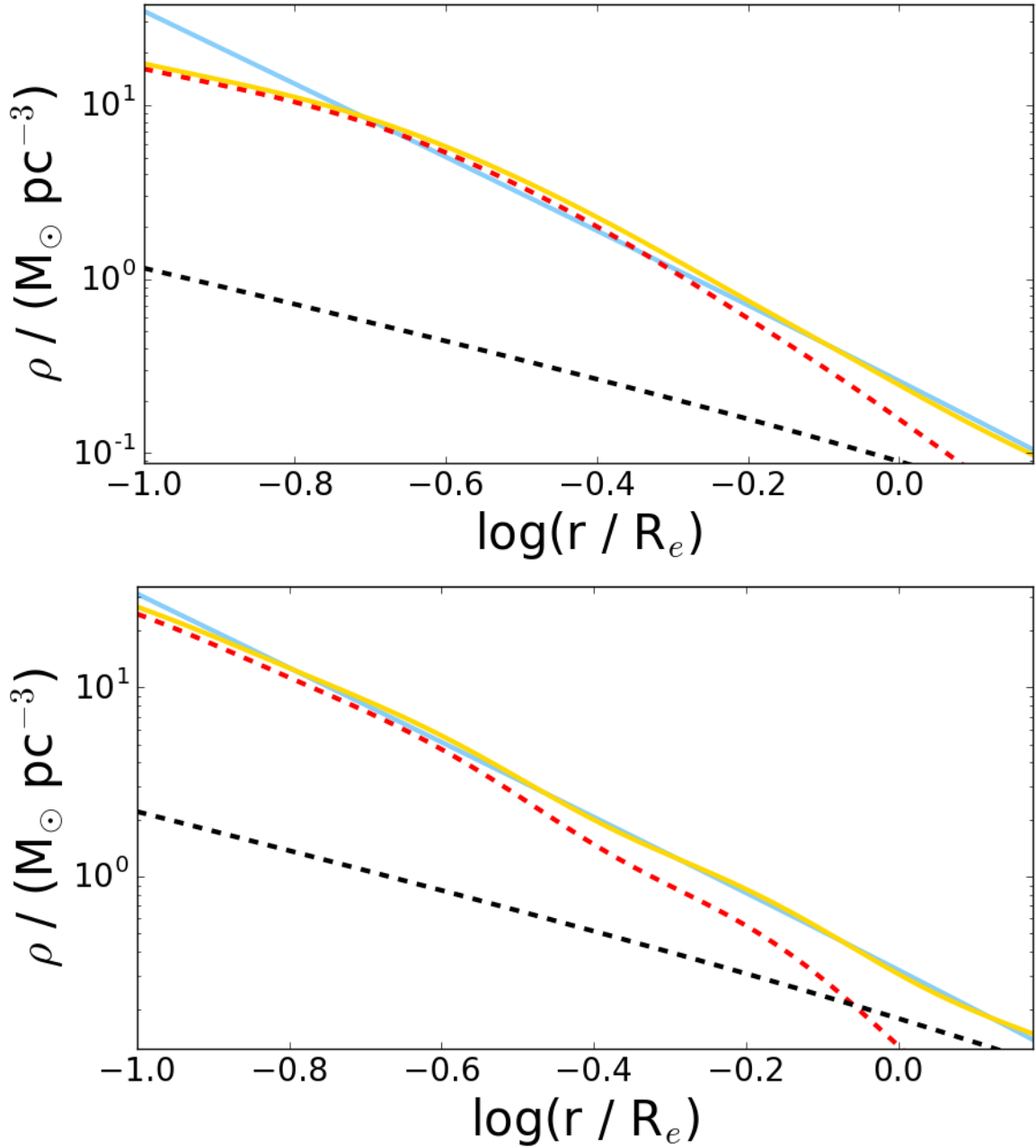


Fig. 4.14 The above two panels demonstrate the decomposition of the best fitting Power Law total matter density into stellar and dark halo components. The x-axis presents the log of the radius in the units of effective radii, while the y-axis represents the density at that radii. The solid light blue line represents the best fitting power law derived from the dynamical modelling, while the dashed red and dashed black lines depict the best fitting stellar profile $((M_*/L)_{dyn}^{PL} \times \rho_*(r))$ and dark matter profile $(\rho_{DM,s} \times \left(\frac{r}{r_s}\right)^{-1} \left(\frac{1}{2} + \frac{1}{2} \frac{r}{r_s}\right))$ respectively. The solid yellow line displays the sum of the best fit stellar and dark matter profiles (ρ_{tot}). The panels represent the region within which the kinematics of galaxies are modelled. The plot demonstrates that the sum of the stellar and dark matter profiles are a good fit to the best fit power law profile.

good models and excluding the two massive central galaxies, have a dark matter fraction of 20% and a median of 10%. For the Power Law model, these quantities are 30% and 17% respectively. Taken together, the models robustly constrain low dark matter fractions for the galaxies in the Coma cluster.

Having shown that the two models consistently predict low dark matter fractions for the galaxies in SAURON subset, the two massive central galaxies are significant outliers to that claim. The assessment of the quality of the JAM models for the two galaxies in Fig. 4.16 conclusively indicates that the AM model does not reproduce the observed kinematics for either BCG. These plots suggest that the Abundance Matching technique used in this study may over-predict the halo concentrations for the two massive BCGs of the cluster. Similar results have been found by authors such as Newman et al. (2013a), where the authors used lensing and stellar kinematics of 7 cluster BCGs to discover that, within a radius comparable to the effective radius of the BCGs, the dark matter distribution are shallower than that predicted by the canonical NFW profile. Furthermore, in ? the authors further developed on their results by demonstrating a correlation between the halo profile and mass. The detailed dynamical modelling of the two BCGs in this study provides a strong evidence for inadequacy of the Abundance Matching techniques in predicting the properties of the haloes in which these massive galaxies formed. It is suggested that this difference between the measure inner dark matter profile of massive galaxies and the results of dark matter only simulations could be due to the dynamical heating of the dark matter by infalling satellites and/or feedback effects (Newman et al., 2013a; Dutton et al., 2015b; ?; Remus et al., 2016). The results of this study, and those mentioned above, demonstrate that the baryons in the universe have a significant effect on its dark matter distribution, hence would have serious consequences on our understanding of the formation of galaxies and the large scale structure of the universe.

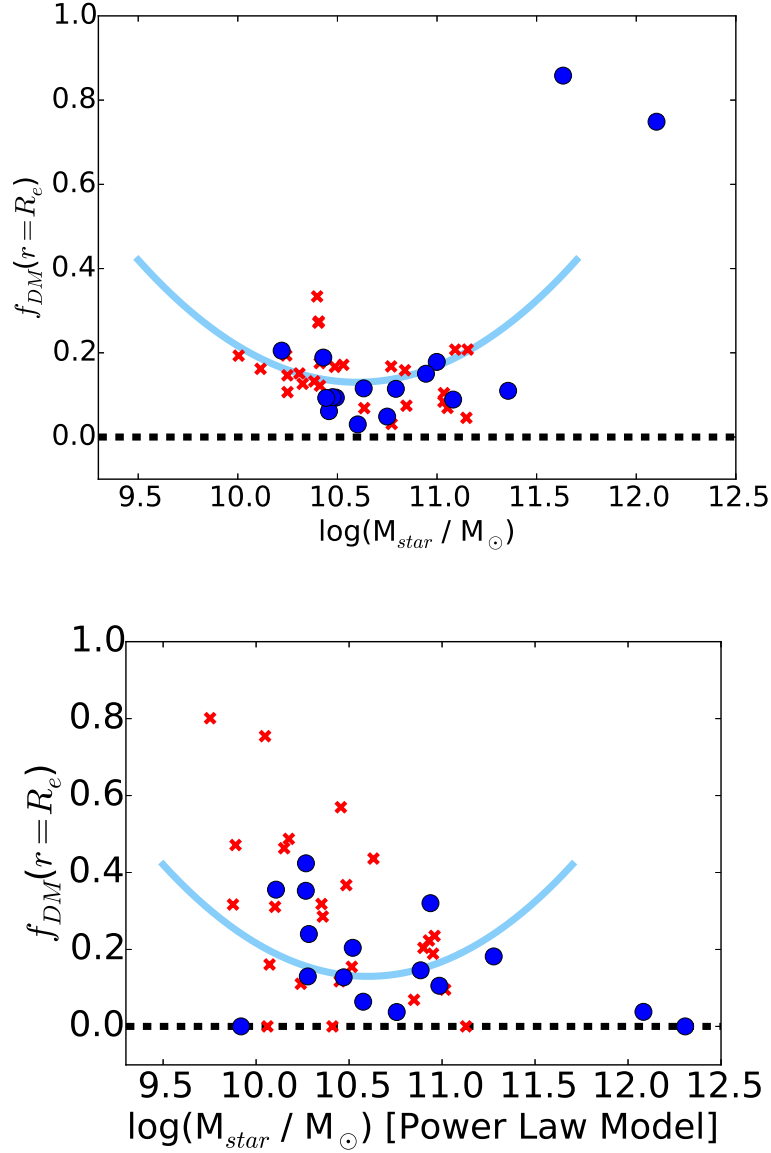


Fig. 4.15 The plots above present the dark matter fractions within a sphere of radius $1R_e$ for the SAURON subset, calculated from the best fit dynamical models using the Abundance Matching model (top) and the Power Law model (bottom). The blue circles represent the galaxies with $Qual = 2$, while the red crosses represent the rest. The solid blue line represents the curve fit to the dark matter fraction derived for the ATLAS^{3D} galaxies using a model similar to that of the Abundance Matching model in this study. A comparison between the dark matter fractions derived from the two distinct models, robustly indicates that the dark matter fraction of these galaxies are low. However, the plot represents a discrepancy between the dark matter fractions of the two massive central galaxies. Upon further investigation, it was discovered that the Abundance Matching model failed to accurately reproduce their observe stellar kinematics and hence, is likely an unrealistic model for their potential.

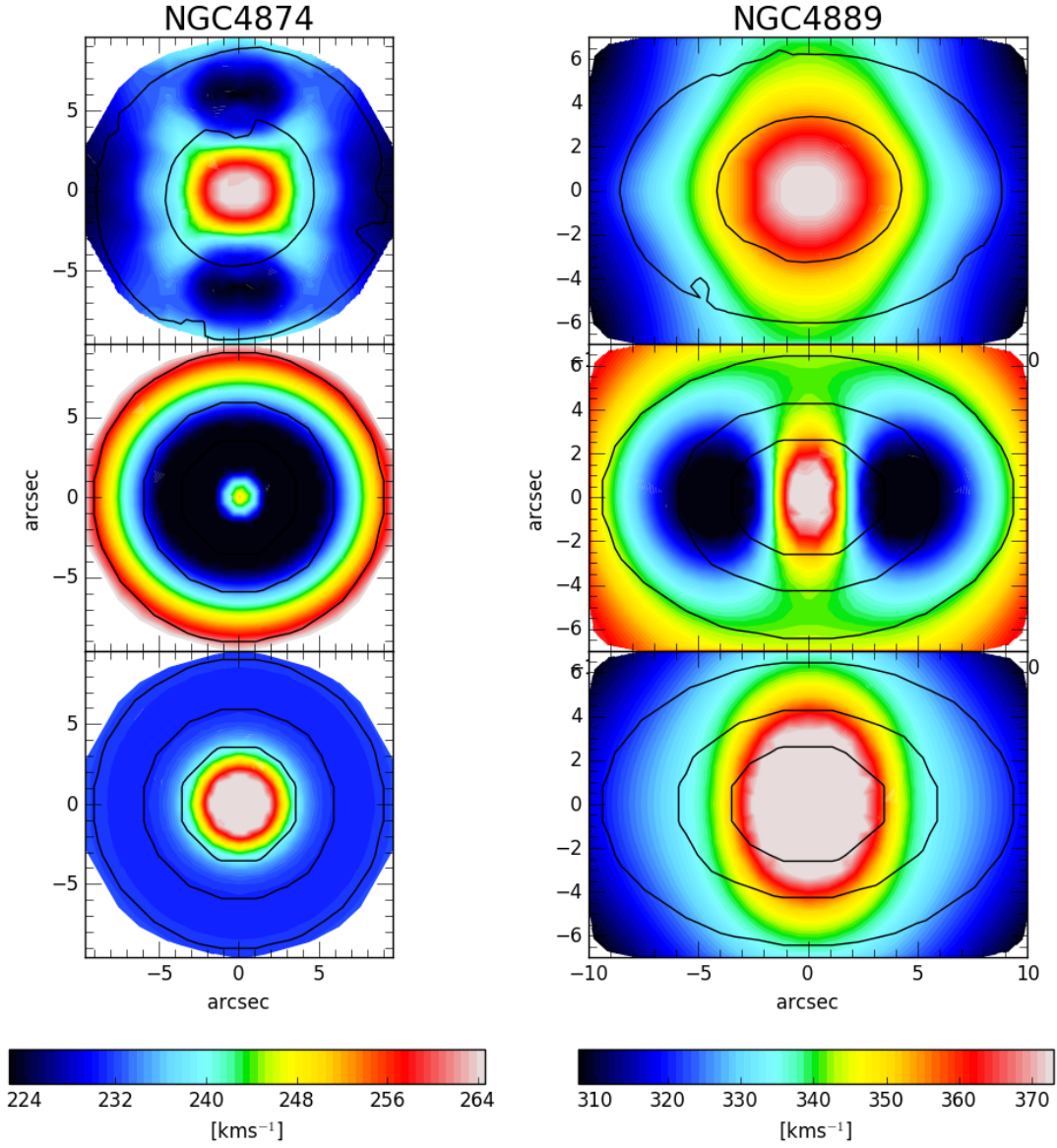


Fig. 4.16 These panels represent the observed V_{rms} and the kinematic prediction of dynamical models, based on the Abundance matched and Power Law model, for the two central massive galaxies of the Coma cluster; NGC4874 and NGC4889. The top panel depicts the observations, while the middle and bottom panels represent the best fitting predictions for the Abundance Matched and Power Law model, respectively. The plots indicate that the Abundance Matched models are not a good representation of the underlying gravitational potential for these galaxies, with the model over predicting the total mass along the outer edge of the plots.

4.5.3 IMF Normalisation

In recent years, a flurry of studies have indicated a systematic variation in the IMF of external galaxies using lensing/dynamical techniques (e.g: Cappellari et al., 2012; Dutton et al., 2013) and stellar population techniques (Conroy & van Dokkum, 2012; Spiniello et al., 2012). These studies have indicated that the IMF normalisation of galaxies is correlated to its observed stellar velocity dispersion (Cappellari et al., 2012; Dutton et al., 2013; Posacki et al., 2015) and its metallicity (Conroy & van Dokkum, 2012; Martín-Navarro et al., 2015b).

In Fig. 4.17 I present the IMF normalisation– σ_e relation for the galaxies in the Coma galaxies. In the plot, I have presented the results of the SAURON subset (red triangles) and the full sample (blue circles and green diamonds, the latter are points that were clipped by *LTS_LINEFIT*), with the solid black line representing the best fit relation to the full sample. The dashed and dotted red lines are the 1σ and 2.6σ error to the fit. The plot also presents the relation derived by Posacki et al. (2015), where the authors extend the dynamical determinations for the ATLAS^{3D} sample (Cappellari et al., 2013a) with 55 massive ETGs of the SLAC survey (Bolton et al., 2006b). The extended sample of Posacki et al. (2015) derives the trend for an extended velocity dispersion range and further strengthens the result of ATLAS^{3D}.

The plot demonstrates a low observed rms scatter in the relationship between the two quantities. The best fit results of the relation depicts an observed rms scatter of just 0.088 dex (23%), compared to the relation found in Cappellari et al. (2013a) and Posacki et al. (2015) where both authors calculate an scatter of 0.12 dex (32%). The lower scatter in study verifies the analysis of Cappellari et al. (2013b), where the authors concluded that the relative uncertainty in the distance to galaxies is a significant source of the error observed, and hence the results of this study present the most accurate IMF normalisation of galaxies to date. The slope of this relation is steeper than that seen in the previous studies. The reason for this may be due to the assumptions in the dark matter content of the galaxies. To test the authenticity

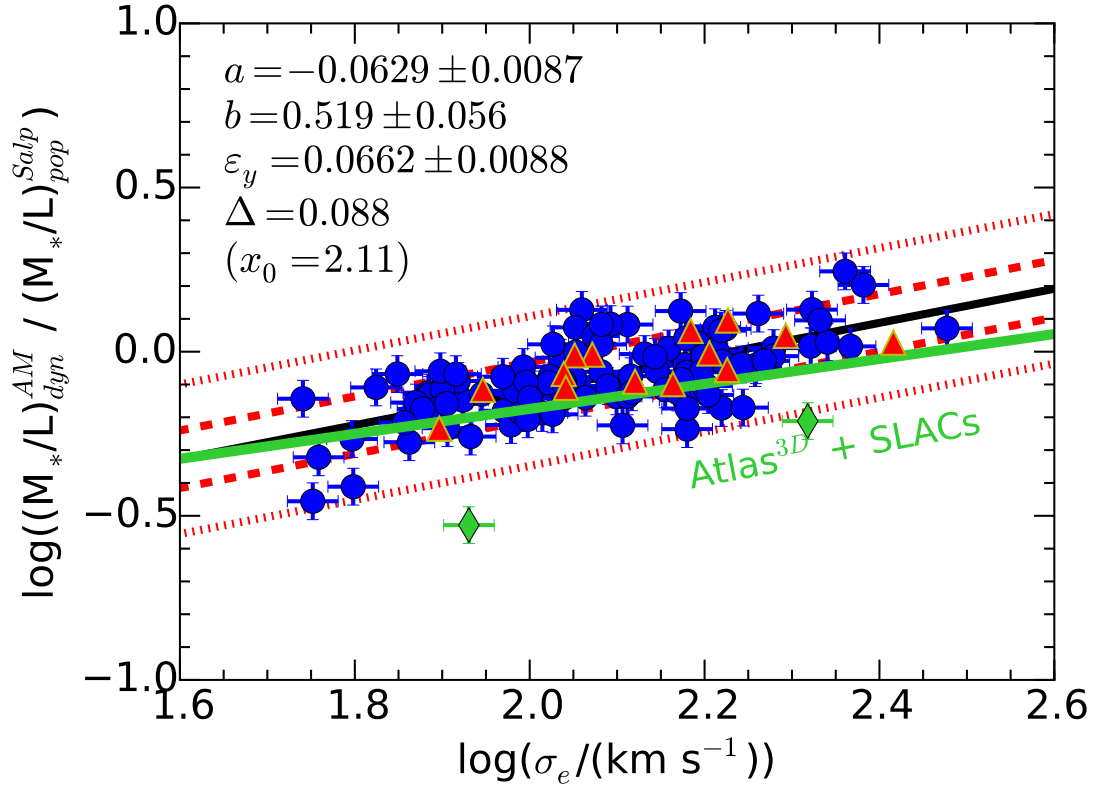


Fig. 4.17 In this plot, I present the IMF normalisation– σ_e relation for the galaxies in the Coma cluster. The IMF normalisation is derived using the stellar $(M/L)_{star}^{JAM}$ from the Abundance Matching model and the stellar $(M/L)_{star}^{Salp}$ calculated from the regularised mass-weighted fit to the galaxy spectra. The black line represents the best fit to the full sample, depicted in blue circles, and the dashed and the dotted red lines are the 1σ and 2.6σ lines respectively. The solid green line is the IMF normalisation– σ_e relation for the extended sample of the ATLAS^{3D} + SLACS galaxies. As expected, due to the low relative uncertainty in distances, the galaxies in the Coma cluster illustrate a tighter IMF normalisation – σ_e relation than previous studies. This relation appears to have a steep slope, and a significant offset.

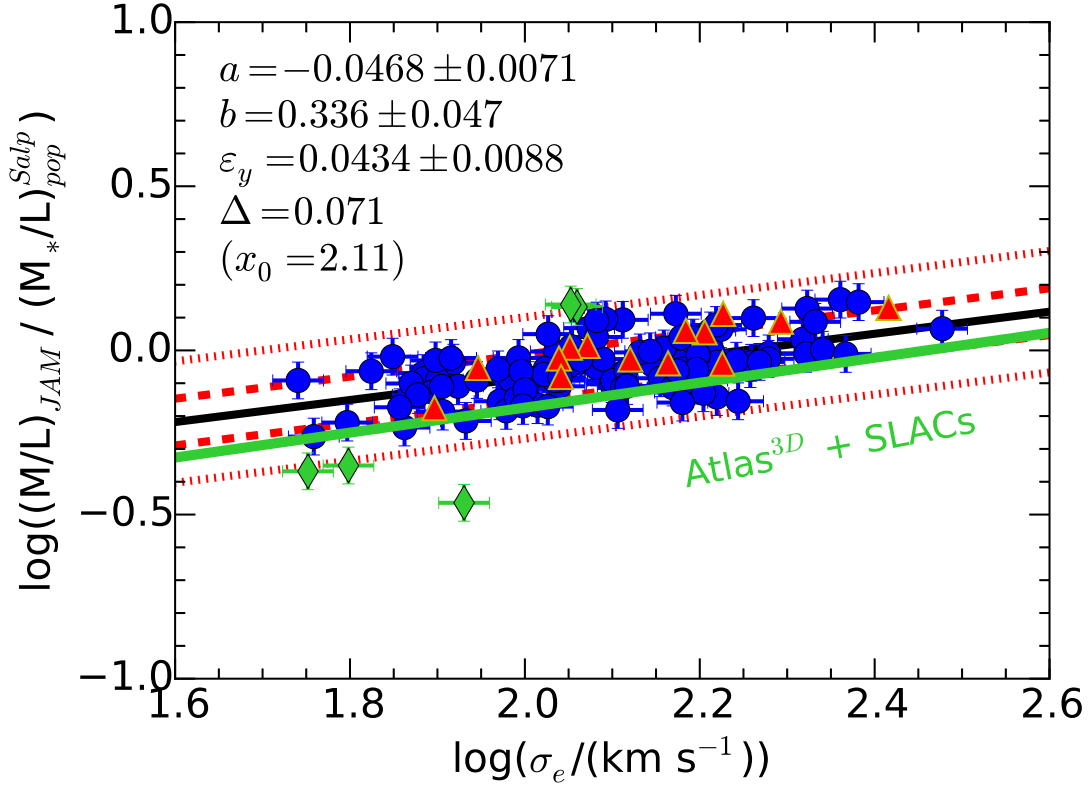


Fig. 4.18 This plot is identical to that in Fig. 4.17, with the difference that here I derive the IMF normalisation using the dynamical $(M/L)_{JAM}$ derived using the Self Consistent model.

of this trend, in Fig. 4.18 I reproduce the IMF normalisation – σ_e relation using the results of the Self-Consistent model for the galaxies. The slope of this relation is consistent with the preferred relation of Cappellari et al. (2013a) within the 1σ errors. Taken together, Fig. 4.17 and Fig. 4.18 demonstrate the range of systematic uncertainties present in the study. Crucially, by eliminating a key source of systematic bias and scatter, this study confirms the robustness of this relation for galaxies in different samples and environments.

When comparing the relation found in the Coma cluster with that seen for the global ATLAS^{3D} + SLACS galaxies, represented by the solid green line in the plots, an offset of ~ 0.01 dex is observed. This offset is present in the full sample and the SAURON subset, as would be expected given the results of the previous section indicating low dark matter

fractions for the galaxies. It is likely that this offset is caused by the uncertainty in the distance to the Coma cluster. In this study, we assumed the distance to the Coma cluster to be 100 Mpc, however independent studies have measured its distance to be 85 ± 6 Mpc to 108 ± 12 Mpc. If the observed offset in the full sample is entirely due to the uncertainty in the distance, then the upper limit of the distance to the Coma cluster must be 115 Mpc. This distance measurement is strongly dependent on any offset in the velocity dispersion estimation of the galaxy kinematics and hence, based on the error of the slope and the typical offset in velocity dispersion measurements (please refer to Fig. 4.6 and Fig. 4.7) and the error in the calculated offset, I estimate the uncertainty on the measurement to be ± 9 Mpc.

In addition to the contribution of distance, a systematic offset in the derived $(M_*/L)_{pop}^{Salp}$ can also cause the observed offset which can, as demonstrated in Fig. 4.11, account for the entire offset observed in the plot. Since the contribution of the uncertainty in the distance to the offset observed cannot be accurately determined given the uncertainties from various other sources, I do not recalibrate the derived quantities with the proposed distance in the rest of the study.

4.5.4 Scaling Relations

Several publications in recent years have indicated that the stellar populations and (M/L) s of galaxies correlate well with its physical parameters (Kauffmann et al., 2003; Cappellari et al., 2006; Franx et al., 2008; Graves, Faber & Schiavon, 2009; Graves & Faber, 2010). Taking advantage of the detailed dynamical modelling of galaxies, Cappellari et al. (2006); Bolton et al. (2007); Auger et al. (2010); Cappellari et al. (2013b) demonstrate that the tilt in the Fundamental plane (e.g: Djorgovski & Davis, 1987; Dressler et al., 1987) was caused by the smooth variation of the (M/L) of the galaxies, correcting for which the edge-on view of the Fundamental Plane only exhibited the Virial equilibrium condition. Following this, the authors proposed that the non-edge on projection of the Mass Plane (M_{JAM} , R_e^{Maj} , σ_e)

contained the information on the evolution of the galaxies, and utilises these projections to conclude that the most galaxy properties are strongly correlated to its velocity dispersion.

In Fig. 4.19, I present two projections of the Mass Plane of the Coma galaxies, the Mass-Size and Mass- σ_e relations, to study their stellar populations. The size of the galaxy in the Mass-Size plot is represented by major axis of the isophote containing half of the galaxy. This quantity is preferred over the more standard effective radii due to its robustness against the inclination (Hopkins et al., 2010). The coloured points in the plots represent the LOESS-smoothed (as implemented in Cleveland, 1979; Cappellari et al., 2013b) trends in the regularised mass-weighted ages of the galaxies. The solid red line in both plots cuts out the Zone of Exclusion (ZoE) of the plane, beyond which the probability of finding a galaxy drops significantly in the ATLAS^{3D} sample (Cappellari et al., 2013a).

From the figure, it can be seen that the galaxies in the Coma cluster occupy the same regions in the two scaling relations, and the mass-weighted ages of the galaxies follow a similar trend, as the ATLAS^{3D} sample (Cappellari et al., 2013a; McDermid et al., 2015). Since the galaxies in the SAURON subset with masses $M_{\text{JAM}} < 10^{11.5} M_{\odot}$ and good dynamical models exhibit significant rotation in their observed stellar kinematics, they are likely the fast rotator population of the cluster. Furthermore, as the regions populated by these fast rotators are the same as those populated by the galaxies of the full sample with $M_{\text{JAM}} < 10^{11.5} M_{\odot}$, it is likely that they represent the fast rotator population of the cluster. When contrasting these fast rotators with those in the ATLAS^{3D} sample, it would appear that the cluster galaxies are significantly older than their field counter-part, and in general these cluster galaxies exhibit a smaller range in stellar ages than ATLAS^{3D}. Taken together this would suggest that despite a considerable influence of the environment (Boselli & Gavazzi, 2006; Haines et al., 2007), the evolutionary processes of the fast rotators are likely similar to that of their field counter-part, i.e. driven by the growth of their bulges (Cappellari et al., 2013a). This result is consistent with the paradigm of galaxy evolution as described by Cappellari (2013).

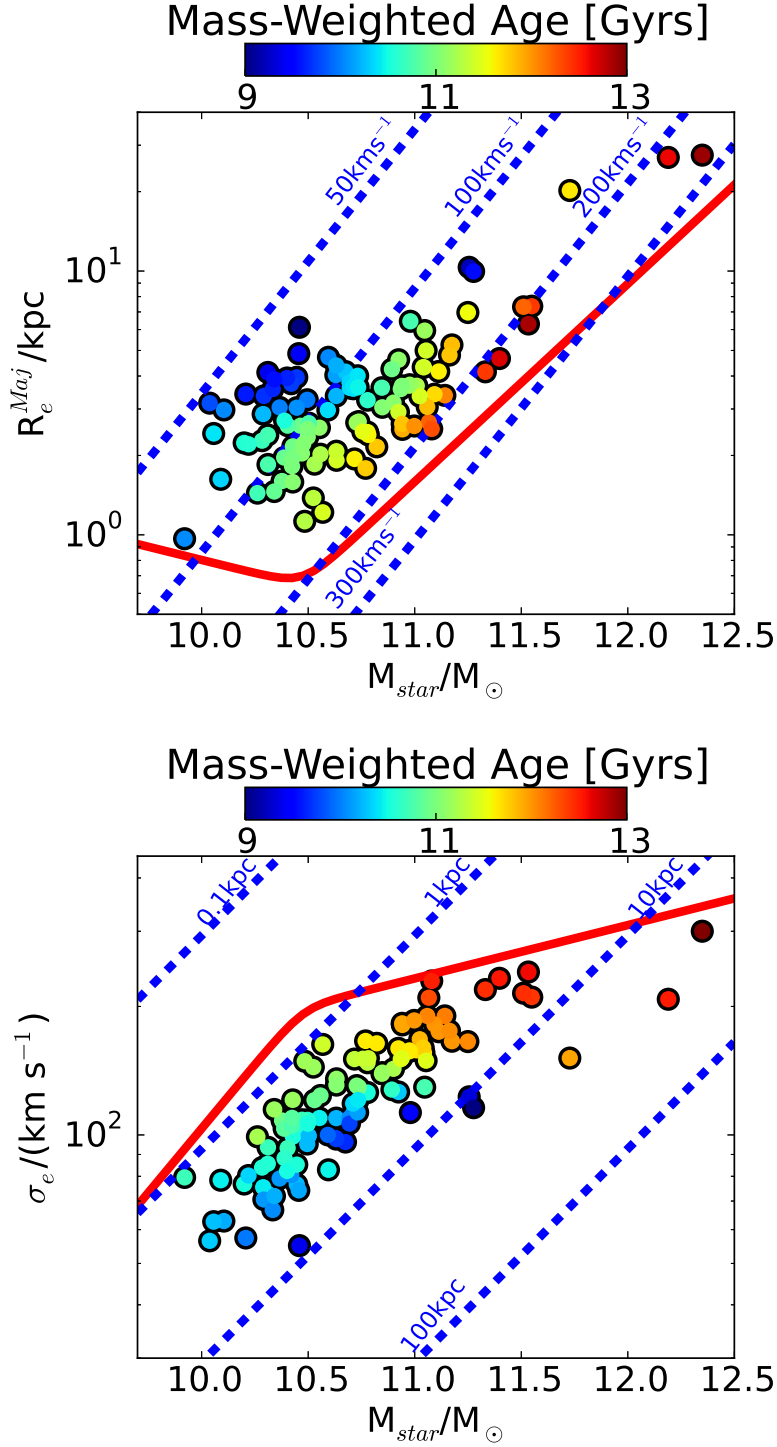


Fig. 4.19 The two plots here represent two projections of the Mass Plane (M_{JAM} , σ_e , R_e^{Maj}); The Mass-Size relation (top), and the Mass- σ relation (bottom) of the galaxies (Cappellari et al., 2013b). The circles in these plots denote the galaxies of the full sample, while their colour represents the LOESS smoothed mass-weighted age of the galaxies. The dashed blue lines represent lines of constant σ and size in the Mass-Size and Faber-Jackson relation respectively. The galaxies in the Coma cluster appear to occupy similar regions of the Mass Plane as the ATLAS^{3D} sample. However, the range of ages in the cluster sample is significantly lower than that of the observed in their field counterpart, providing evidence of the environmental quenching of the cluster galaxies.

Chapter 5

Conclusions

With the aim of understanding the structure and evolution of galaxies, this thesis examines two samples of galaxies; one at redshift $z \sim 1$, and another in an high density environment, as that found in the Coma cluster. I do this using the dynamical models of Cappellari (2008) which, under the assumption of flattened velocity ellipsoids, reproduces the observed stellar kinematics of galaxies in a simple and efficient manner. These dynamical models probe the underlying gravitational potential of galaxies, and using empirically or theoretically motivated models, can disentangle the stellar and dark matter components in galaxies. In addition, these results are complemented by the stellar population synthesis of the galaxies, conducted in this study using a full-spectrum fitting technique that can model for the star formation histories of galaxies in a non-parametric manner. Taken individually and collectively, these results place strong constraints on the evolutionary history of galaxies.

In Chapter. 2, I present the results of using dynamical models to study the IMF normalisation for 68 massive ($M_* > 10^{11} M_\odot$) ETGs at high redshift, i.e. $z \sim 1$. These dynamical models were demonstrated to be robust to the techniques used to derive the global galaxy parameters used for the Virial estimators, which is generally the popular method to derive galaxy masses dynamically. The results of this analysis indicated that the IMF normalisation of the galaxies in at these redshifts are, *on average*, Salpeter-like. This is consistent with

what is found locally where dynamical and lensing studies of dynamical galaxies suggest that massive ETGs have Salpeter-like IMF (e.g: Cappellari et al., 2012; Auger et al., 2010; Cappellari et al., 2013a; Dutton et al., 2013; Tortora, Romanowsky & Napolitano, 2013), while stellar population studies suggest that these galaxies tend to have a bottom-heavy IMF (e.g: van Dokkum & Conroy, 2010, 2011; Spiniello et al., 2012; van Dokkum & Conroy, 2012; Ferreras et al., 2013). Furthermore, consistent results with our study were found using joint dynamical and lensing study of 81 strong lens (Sonnenfeld et al., 2015) and a stellar population study by Martín-Navarro et al. (2015a) for a sample of massive quiescent galaxies at $0.9 < z < 1.5$.

In the following Chapter. 3, I expand upon the analysis of the high redshift sample of galaxies by modelling the star formation history for an expanded sample of 154 galaxies. These galaxies cover a wider mass range, $M_* \gtrsim 10^{10} M_\odot$, and include some galaxies within the blue cloud of my parent sample. The results indicate that the star formation histories of galaxies follow a systematic trend with their final stellar mass, such that while galaxies with the lowest stellar mass in my sample are actively undergoing significant star formation, galaxies with higher stellar mass have had no significant star formation for over 1 Gyr. This systematic trend was also observed in (Heavens et al., 2004; Thomas et al., 2005; Panter et al., 2007; McDermid et al., 2015) and this result indicates that this trend has been established by redshift of $z \sim 1$. This scenario of star formation is consistent with the results of Schiavon et al. (2006) and Gallazzi et al. (2014) who demonstrate that the passive evolution of galaxies from $z \sim 1$ to present day cannot explain the stellar ages of galaxies observed at these epochs. This result is also consistent with the result of Choi et al. (2014), where the authors found a lack of chemical evolution for massive quiescent galaxies since redshift of 0.7.

In addition to the stellar population synthesis of high redshift galaxies, in Chapter. 3 I also present the updated results of dynamical modelling of the 68 galaxies in Chapter. 2. In the previous models of Chapter 2, the dynamical models of the galaxies were made using

a self-consistent model, which assumed that the mass distribution of galaxies follows the distribution of the observed light, hence effectively assuming negligible dark matter for the galaxies. In Chapter. 3 I improve upon this result by accounting for the dark matter, using the results of Abundance Matching. These models demonstrated that the dark matter fraction within $1R_e$ for 68 massive galaxies in the sample are low, and hence the assumption of negligible dark matter in the galaxies is valid. This result gives weight to the theoretical results of Hilz, Naab & Ostriker (2013) where the authors use merger simulations to predict that galaxies at higher redshifts had dark matter fractions lower than that observed today. Also, in this chapter I present the Mass Plane of galaxies at high redshifts. Comparison of these scaling relations with that observed in the local Universe (Cappellari et al., 2013a) suggest that the most massive quiescent galaxies in this sample require some size growth so as to be consistent with observations of the local Universe.

In Chapter. 4, I present the results of an ongoing study of galaxies in the Coma cluster. Here, I study a sample of 148 galaxies selected using identical selection criteria as the ATLAS^{3D} Project (Cappellari et al., 2011a), and based on the availability of SDSS spectral data. For these galaxies, I create one dimensional dynamical models and stellar population models based on the techniques used in the previous Chapters. In addition, I create detailed dynamical models for a subset of 40 galaxies of this sample, and an additional two that did not have SDSS spectral data available but that had SAURON IFS observations available. This study virtually eliminates the error introduced by the relative uncertainty in galaxy distances to the derived dynamical Mass-to-Light ratios (M/L). Based on this, the study presents the most accurate relation between the IMF normalisation of galaxies and their velocity dispersion, which were found to be consistent with that found by ATLAS^{3D}, within the systematic uncertainties. The persistence of this trend, even when distance errors and possible distance biases are removed, and in such a dense environment, is a demonstration of its robustness.

Furthermore, Chapter. 4 also presents the dark matter fraction of galaxies for the SAURON subset of galaxies. These detailed dynamical models indicate a low dark matter fraction within a sphere of radius $1R_e$ of the galaxies. The robustness of this result is tested by the use of two models for the gravitational potential of the galaxies; (i) a model based on the Abundance Matching of the observed stellar mass and the simulated dark matter halo, and (ii) a model based on the empirical results of dynamical modelling and lensing which conclude that the total density distribution of galaxies can be well reproduced by a single isothermal power law, $\rho_{tot} \propto r^{-2}$. Also in this Chapter, I present the age distribution on the (M_{JAM}, R_e^{Maj}) plane of the full sample of galaxies in this study. This relation is consistent with the age distribution presented in McDermid et al. (2015), however the mass-weighted age of low mass galaxies in the Coma cluster are lower than that seen in the ATLAS^{3D}. This is likely evidence of the environmental quenching taking place in these galaxies.

Final Remarks

The two results taken together provide an intriguing picture of galaxy evolution, and both galaxy samples promise more insights if followed up with future work. The results of the high redshift sample demonstrates the average IMF normalisation of the galaxies, however fails to provide evidence towards the presence of its systematic variation observed in the local universe. In this study, the lack of low mass galaxies needed to test for the IMF normalisation is a consequence of the selection criteria of the galaxies and hence, a study aimed at studying the IMF normalisation relation of galaxies at high redshift would require better data. In addition to the IMF normalisation, this thesis also suggests a possible evolution of the Mass Plane of the galaxies, however due to the errors in the quantities derived, a conclusive result is not possible and hence, these results stand to be tested with better data.

The analysis of the Coma cluster galaxies has provided some interesting results, however further research is yet to be conducted on the data. One such topic of interest is the

Morphology-Density relation of the galaxies. The results of the Coma cluster provide an extension of the relation observed in Cappellari et al. (2011b), where the results indicated a potential rise in the fraction of fast rotators, compared to spirals, at high density. Also, as mentioned in Chapter. 4, some galaxies in the SAURON subset had peaks in the central regions of their observed V_{rms} maps that could not be reproduced without a SMBH with mass greater than that predicted by the $M_{BH}-\sigma_e$ relation. Further tests to eliminate other sources of this effect, and an improvement in the dynamical models of the galaxies, using photometric data from the Hubble Space Telescope, will be needed to resolve this issue.

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Appendix A

Results for massive galaxies at $z \sim 1$

Table A.1 Results of dynamical models and multiple population fitting. Column (1): DEEP2 galaxy identifier. Column (2): DEEP2 estimated redshift. Column (3): Absolute B (Vega) band magnitude. Column (4): Effective radius as derived from MGE (without re-scaling). Column (5): Aperture velocity dispersion. Column (6): Error on aperture velocity dispersion. Column (7): Dynamical mass-to-light ratio with a median error of 0.11dex.

DEEP2 ID No.	Redshift	M_B	R_e (")	σ (km/s)	$\Delta\sigma$ (km/s)	$(M/L)_{\text{JAM}}$ ($M_\odot/L_\odot$)	$(M/L)_{\text{Sal}}$ ($M_\odot/L_\odot$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
11050845	0.840	-21.76	0.40	298	28	6.10	3.55
12004136	0.812	-21.62	0.50	202	21	3.09	2.92
12004516	0.820	-21.44	0.44	176	28	2.85	1.97
12008254	0.745	-21.51	0.41	250	33	4.92	4.32
12008360	0.828	-20.97	0.18	185	31	2.63	2.39
12008441	0.832	-21.34	0.53	257	64	9.26	1.79
12011900	0.719	-20.88	0.23	318	57	9.75	4.46
12011905	0.718	-22.03	0.68	253	44	6.20	2.43
12012829	0.744	-22.14	0.42	213	14	2.07	2.92
12012898	0.835	-22.33	0.44	241	19	2.60	3.43
12015451	0.713	-21.85	0.40	180	15	2.05	3.38
12015693	0.836	-20.86	0.11	154	26	1.24	2.52
12015735	0.714	-20.48	0.21	123	20	1.86	3.21
12015909	0.722	-21.28	0.29	209	22	3.24	3.98

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Table A.1 – *Continued from previous page*

12016736	0.747	-22.17	0.81	221	57	5.14	2.12
12019617	0.820	-21.30	0.31	249	36	6.27	2.73
12019681	0.819	-21.03	0.24	166	27	2.27	2.78
12019978	0.734	-21.20	0.22	222	20	3.46	3.46
12020055	0.719	-21.28	0.28	93	14	0.62	4.13
12020404	0.809	-21.43	0.35	209	26	3.29	5.00
12021111	0.716	-21.38	0.26	177	17	2.20	3.82
12021121	0.744	-21.07	0.31	205	53	4.11	2.71
12021129	0.717	-21.96	0.39	234	17	2.76	5.32
12023514	0.833	-21.45	0.25	235	26	3.29	3.42
12023935	0.842	-21.27	0.32	275	40	7.57	3.16
12024057	0.736	-20.98	0.18	203	22	3.01	5.04
12024136	0.729	-21.72	0.86	109	30	1.03	1.79
12024878	0.782	-21.74	0.33	207	23	2.41	3.24
12025292	0.813	-20.97	0.16	237	27	3.86	3.10
12025294	0.732	-20.93	0.38	134	34	3.34	2.36
12028330	0.820	-21.41	0.39	316	47	10.12	2.69
12028349	0.758	-21.22	0.31	255	43	5.87	4.67
12028846	0.761	-21.95	0.34	189	29	1.65	3.28
13003868	0.781	-21.94	0.50	224	41	2.98	5.36
13010426	0.821	-20.63	0.16	85	20	0.64	2.27
13011780	0.810	-20.91	0.20	233	32	5.49	5.61
13011785	0.808	-21.04	0.26	216	32	4.39	4.38
13011809	0.882	-21.31	0.26	261	43	4.80	2.23
13012297	0.806	-21.13	0.26	119	20	1.26	2.41
13018001	0.740	-21.73	0.84	157	30	4.01	3.28
13019278	0.707	-21.41	0.25	175	18	1.83	2.91
13019286	0.737	-21.20	0.22	229	23	3.80	4.70
13019294	0.851	-21.35	0.12	188	18	1.37	1.72
13019820	0.850	-21.82	0.58	206	34	3.49	3.23
13025397	0.736	-22.13	0.54	218	19	3.86	2.60
13025469	0.761	-20.09	0.14	57	26	0.43	2.57
13025494	0.739	-21.14	0.50	261	31	8.81	4.09
13025532	0.745	-21.05	0.40	151	35	2.86	1.86
13027442	0.768	-21.92	0.51	246	42	4.85	3.26
13033202	0.710	-21.77	0.80	233	58	11.76	2.53
13033906	0.744	-20.47	0.27	153	27	3.70	2.58
13033944	0.763	-20.67	0.14	217	40	3.67	3.66
13033965	0.750	-20.96	0.21	236	21	4.91	3.95
13034882	0.744	-20.63	0.25	82	19	0.83	2.83
13035168	0.782	-21.35	0.63	183	35	4.98	2.73
13035209	0.740	-21.59	0.30	207	15	2.62	5.41

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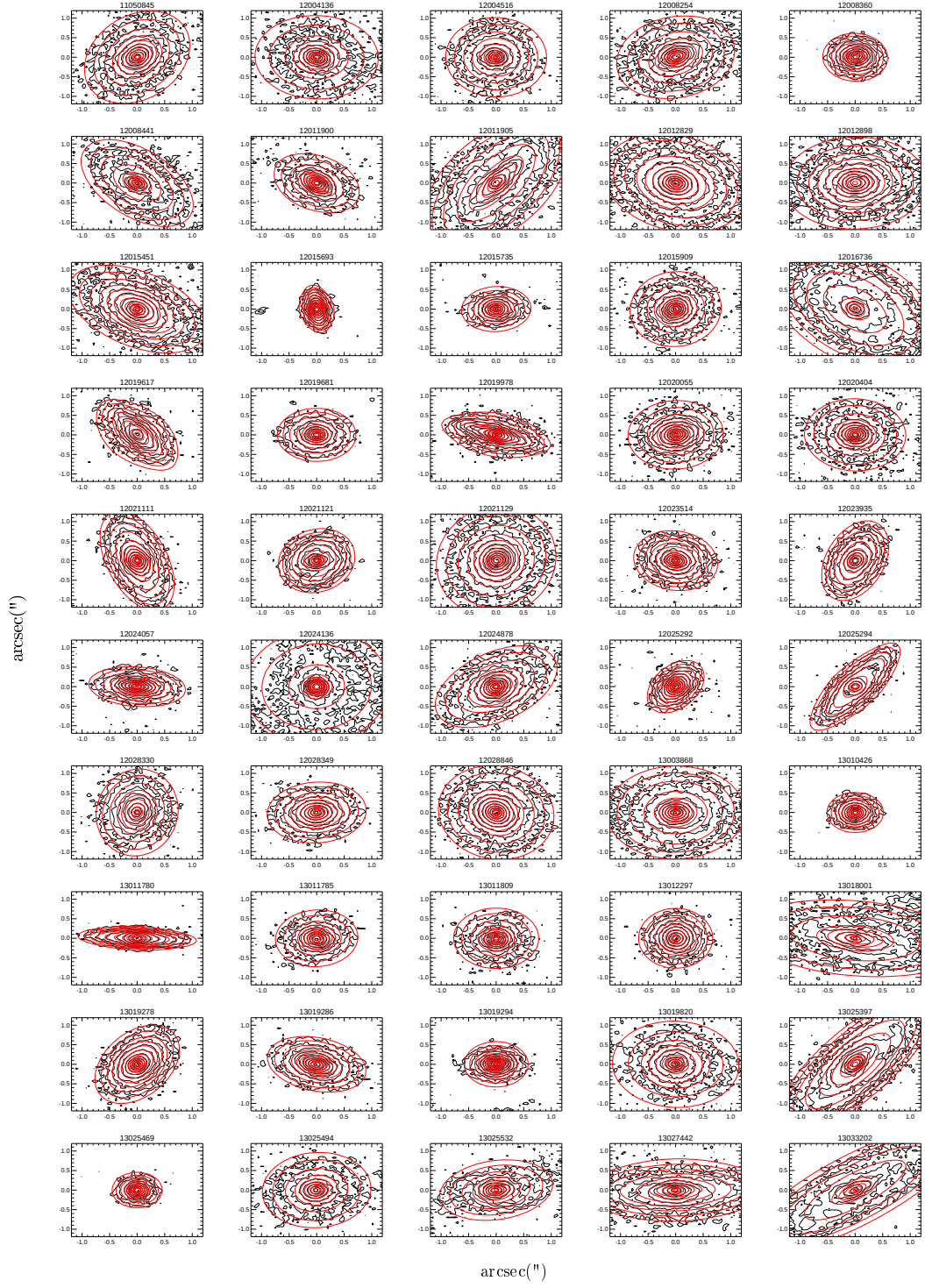
Table A.1 – *Continued from previous page*

13035326	0.744	-21.41	0.31	153	16	1.67	5.24
13040619	0.711	-20.85	0.25	176	20	2.97	4.11
13040632	0.743	-20.71	0.22	201	20	4.40	3.62
13042352	0.737	-21.63	0.28	230	23	2.96	4.37
13043049	0.780	-21.04	0.33	137	17	1.94	3.53
13049668	0.715	-20.61	0.28	244	50	9.05	2.75
13049901	0.887	-21.19	0.36	195	26	3.89	4.88
13050512	0.808	-20.82	0.42	159	45	5.39	2.56
13050545	0.807	-21.55	0.31	278	20	4.68	3.55
13050602	0.736	-21.79	0.32	181	20	1.71	5.92
13057979	0.742	-20.54	0.14	247	35	5.13	5.60
13058235	0.714	-20.80	0.28	174	34	3.40	2.60

Appendix B

MGE Summary of Secondary Sample at

$z \sim 1$



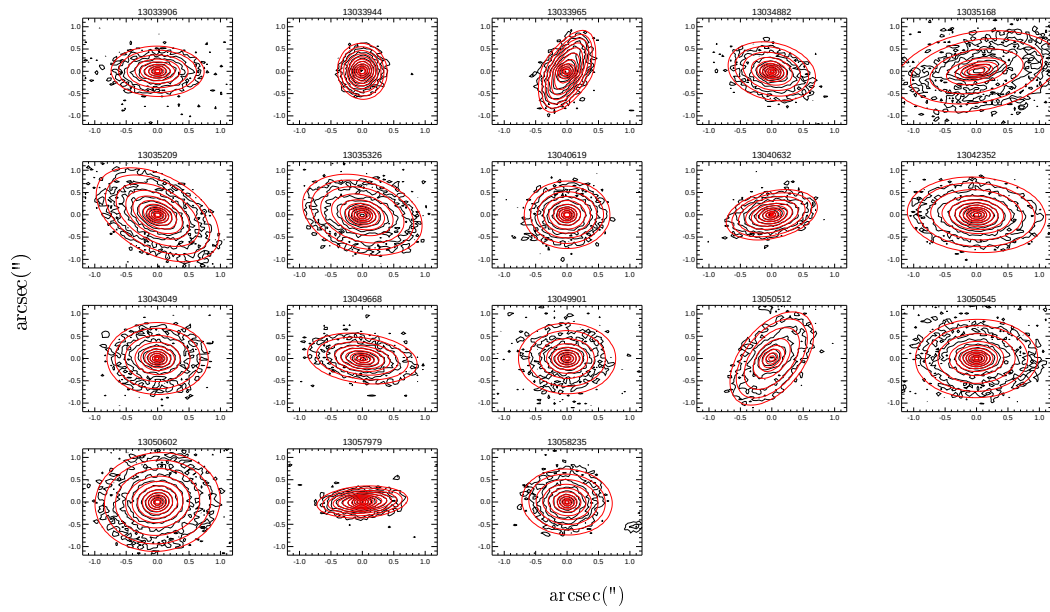
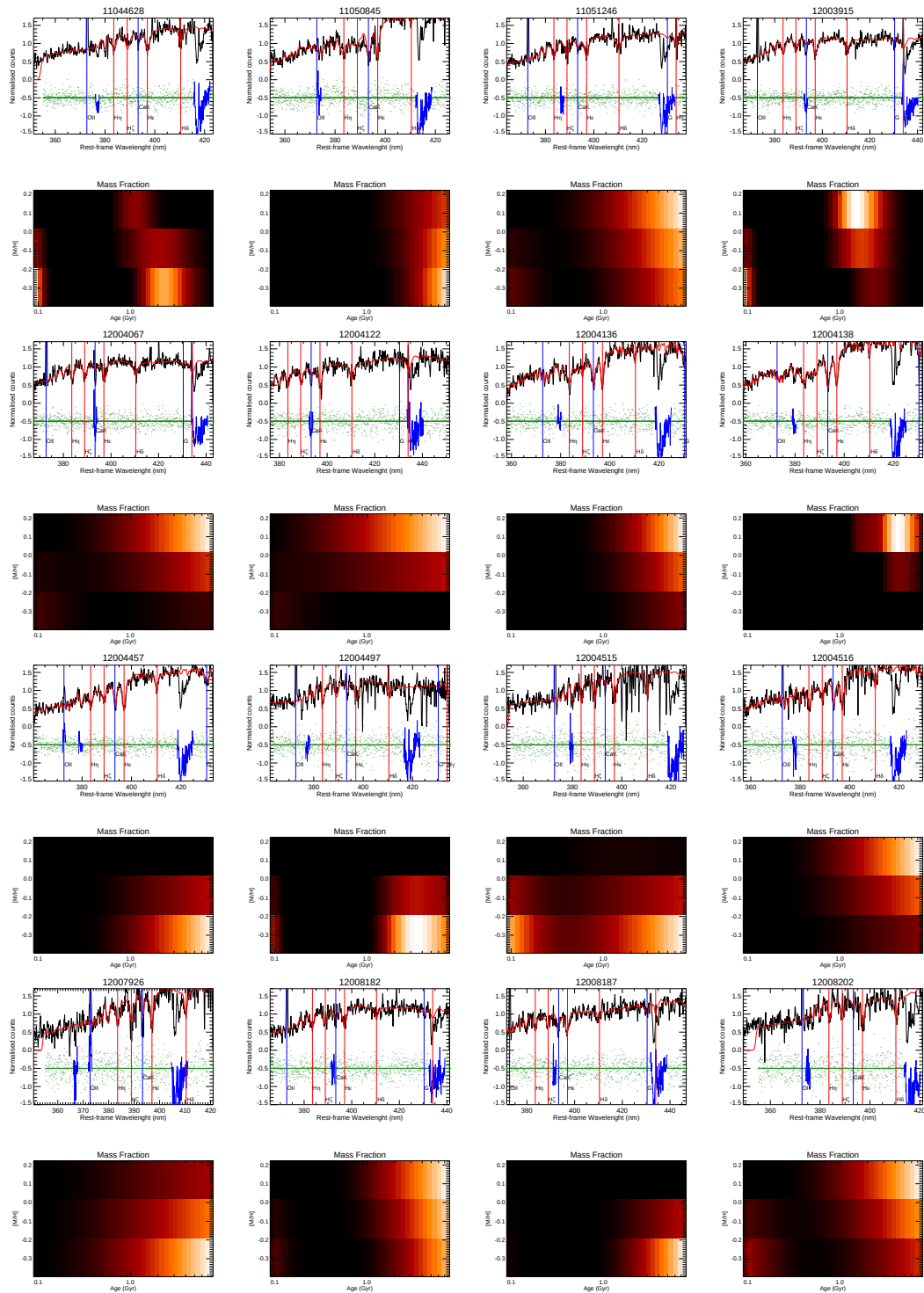
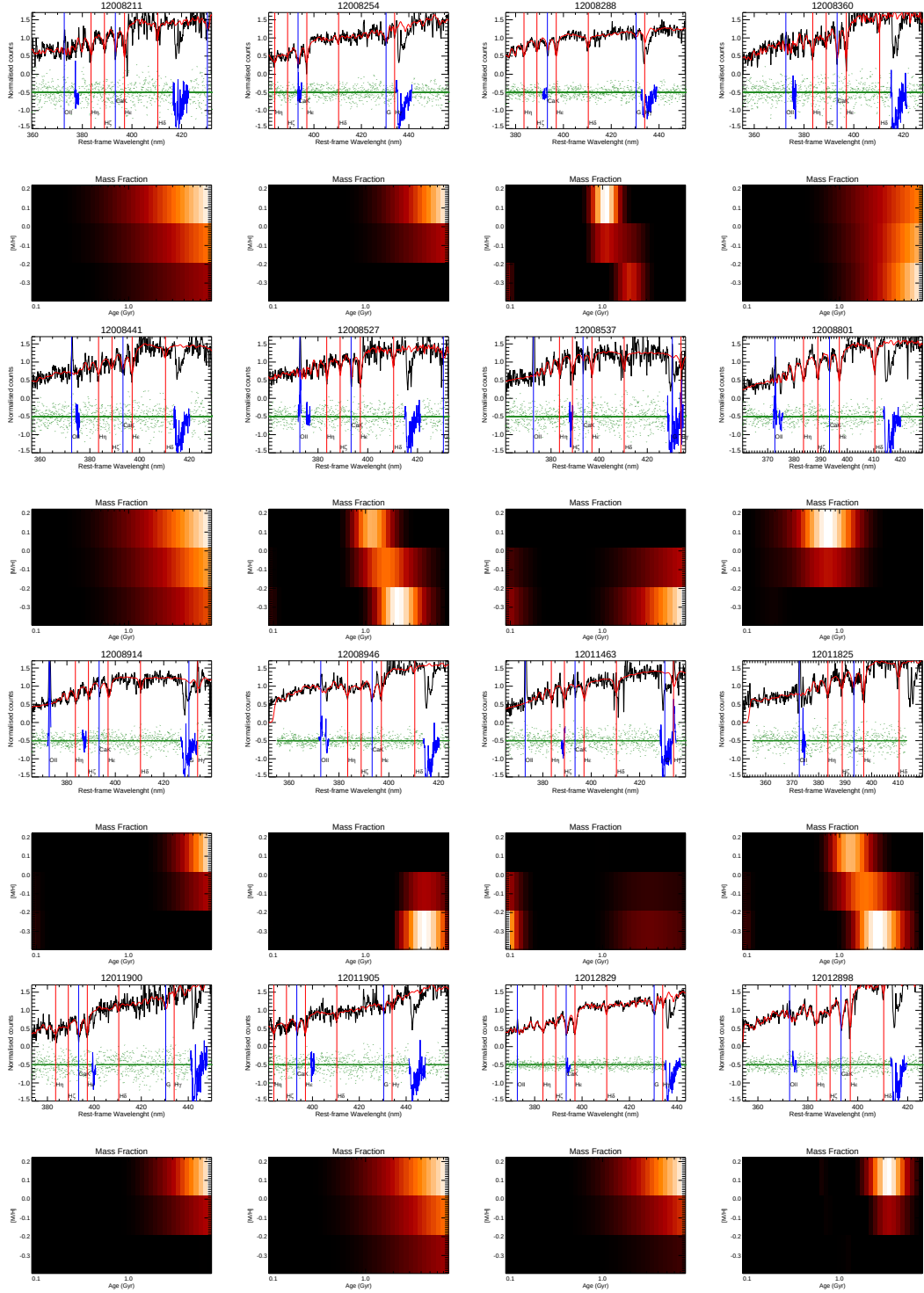


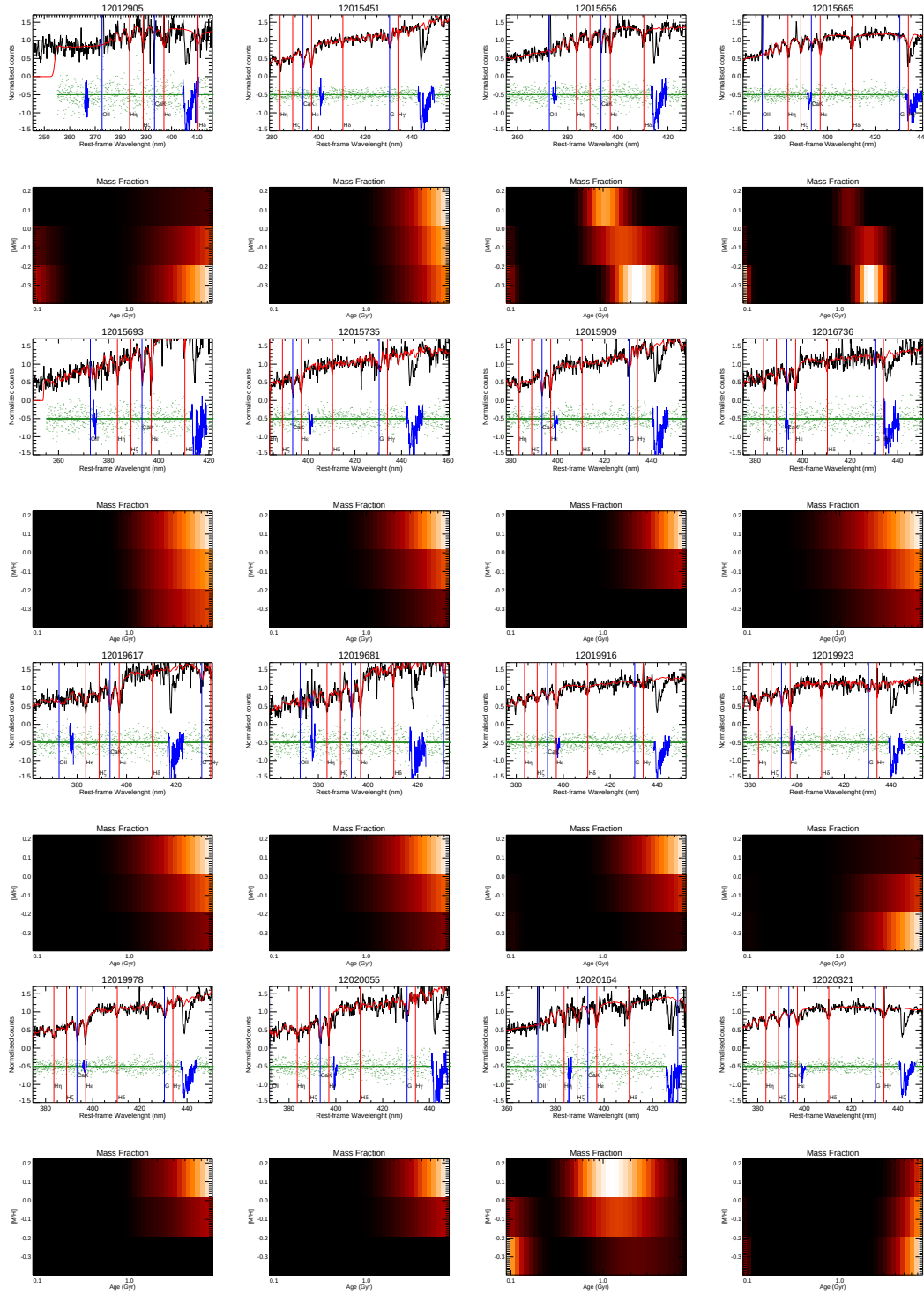
Fig. B.1 Here I present the quality of photometry parametrization through contour plots for the 68 galaxies in my secondary sample of galaxies at $z \sim 1$, for whom we create dynamical models. In the plots, the black contours are the contours of constant surface brightness as observed for our galaxies, while the red contours are the contours of the best fitting models. The numbers on top of each plot is the DEEP2 ID number for each galaxy.

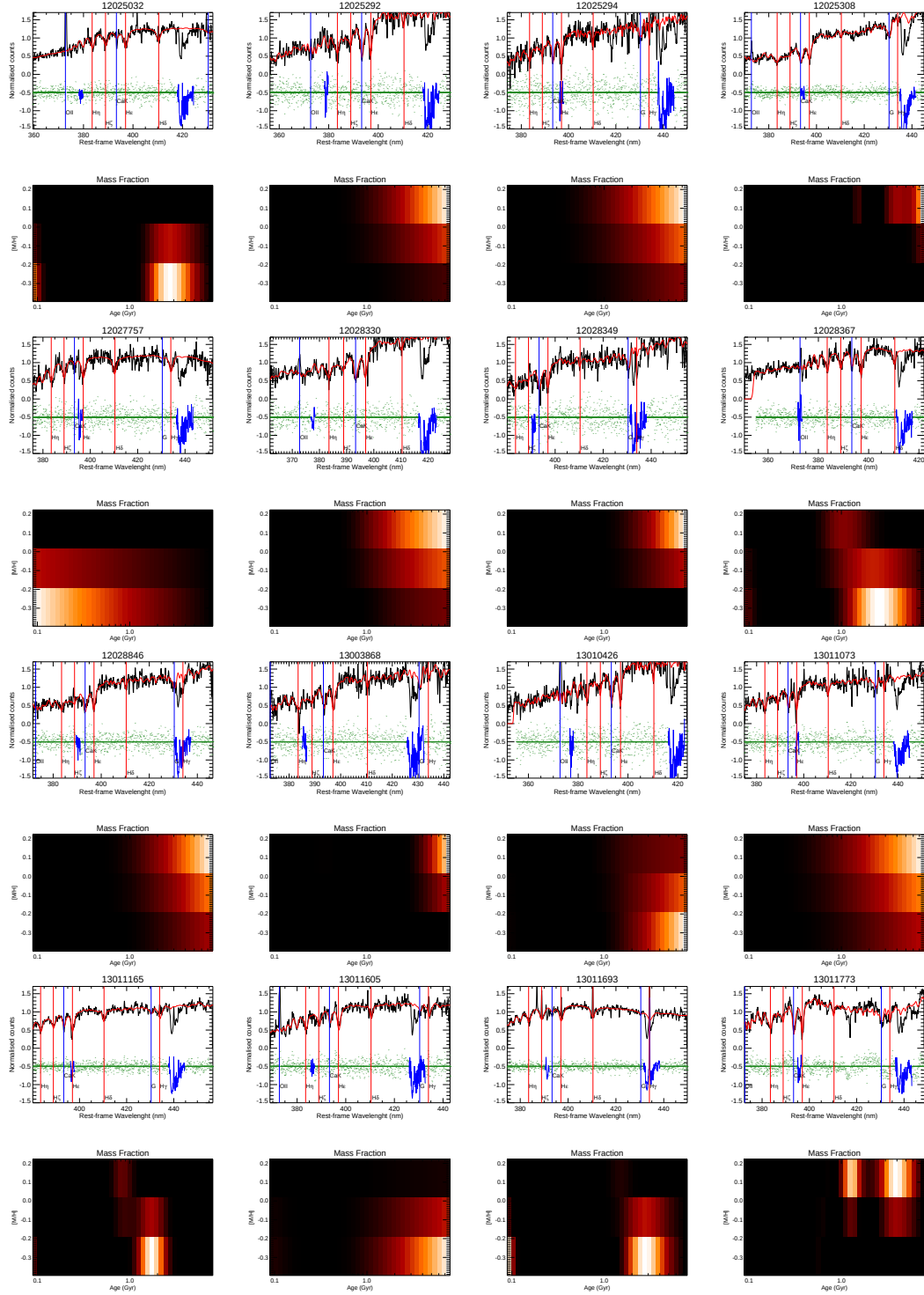
Appendix C

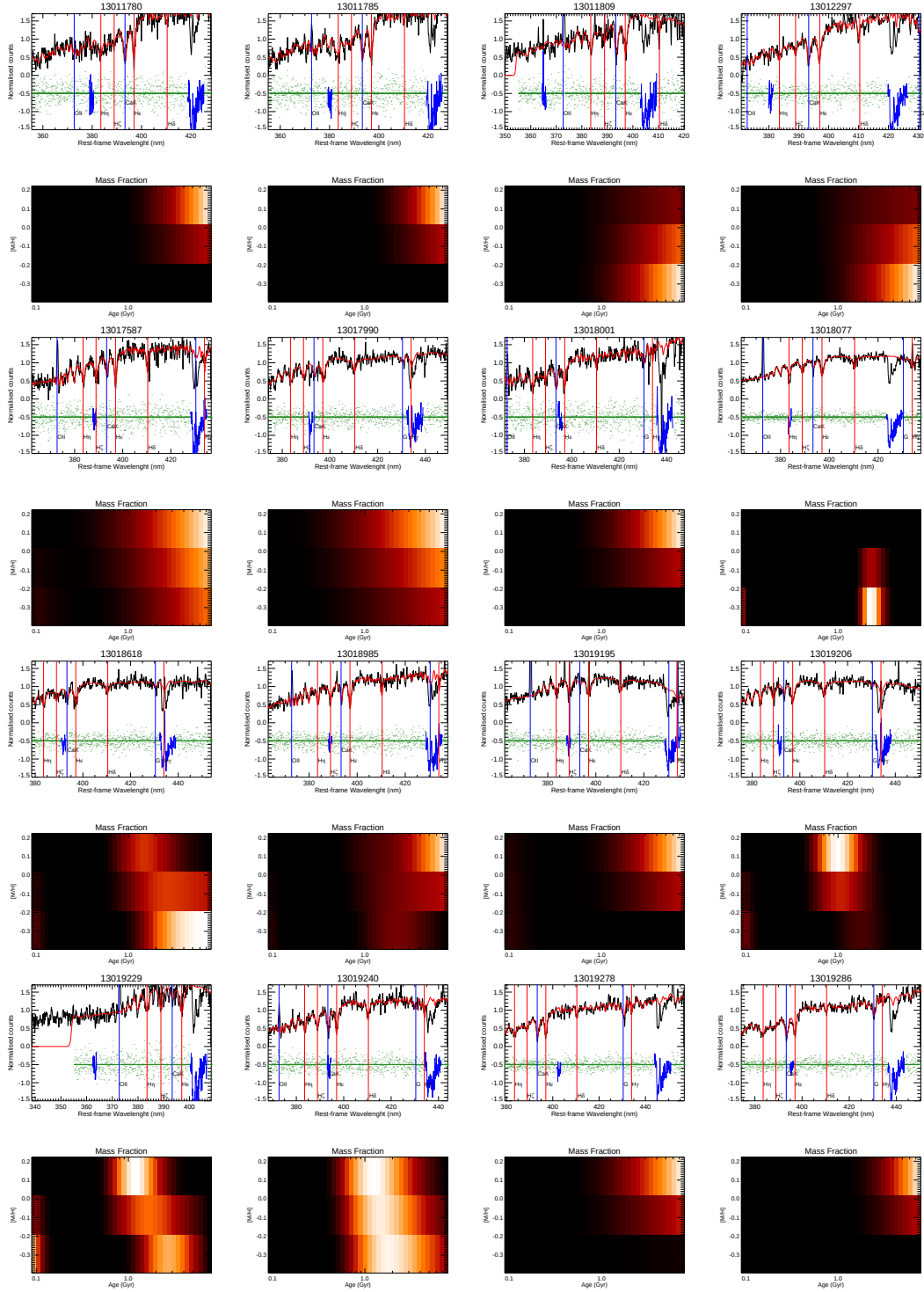
SPS Summary of Galaxies at $z \sim 1$

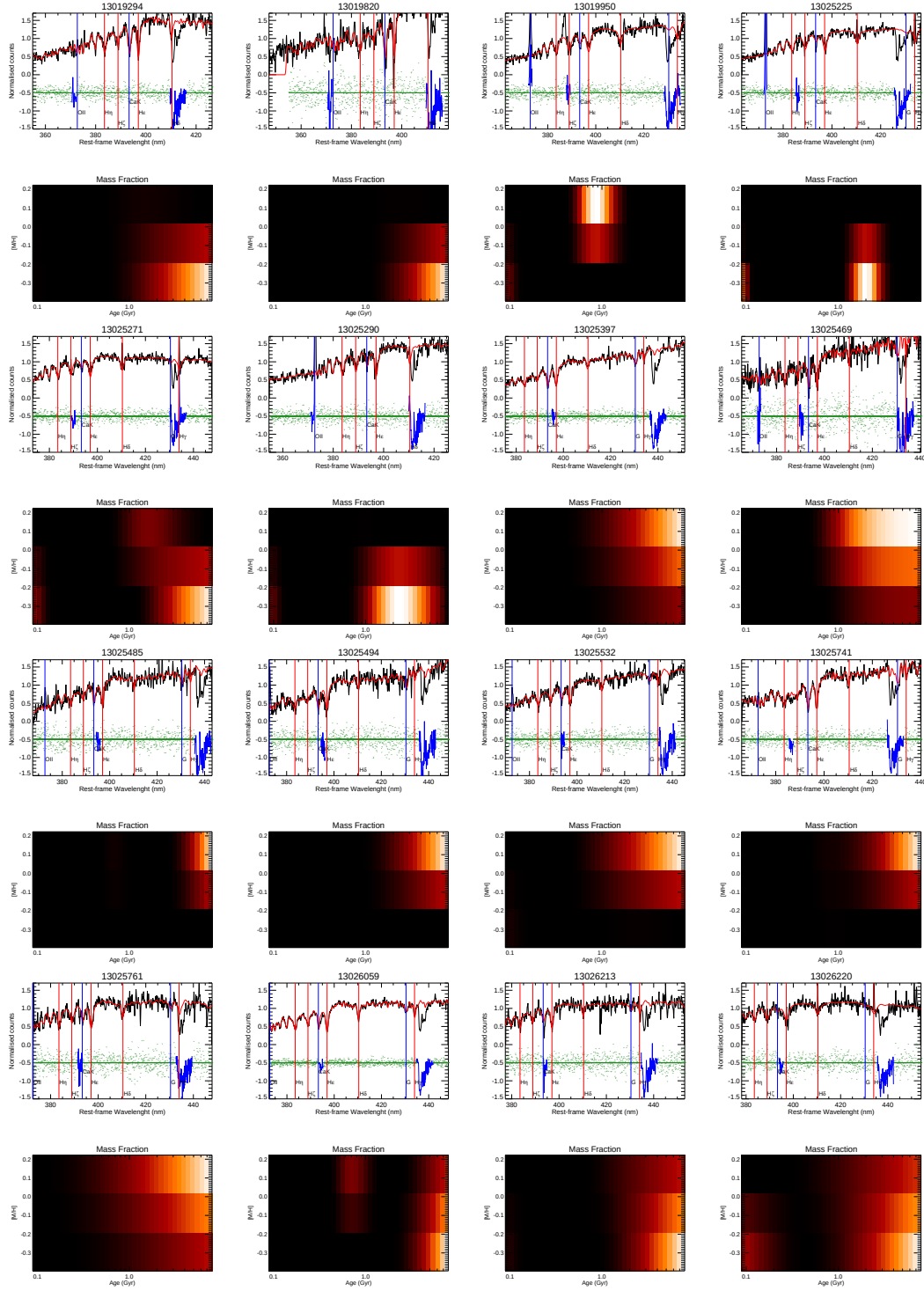


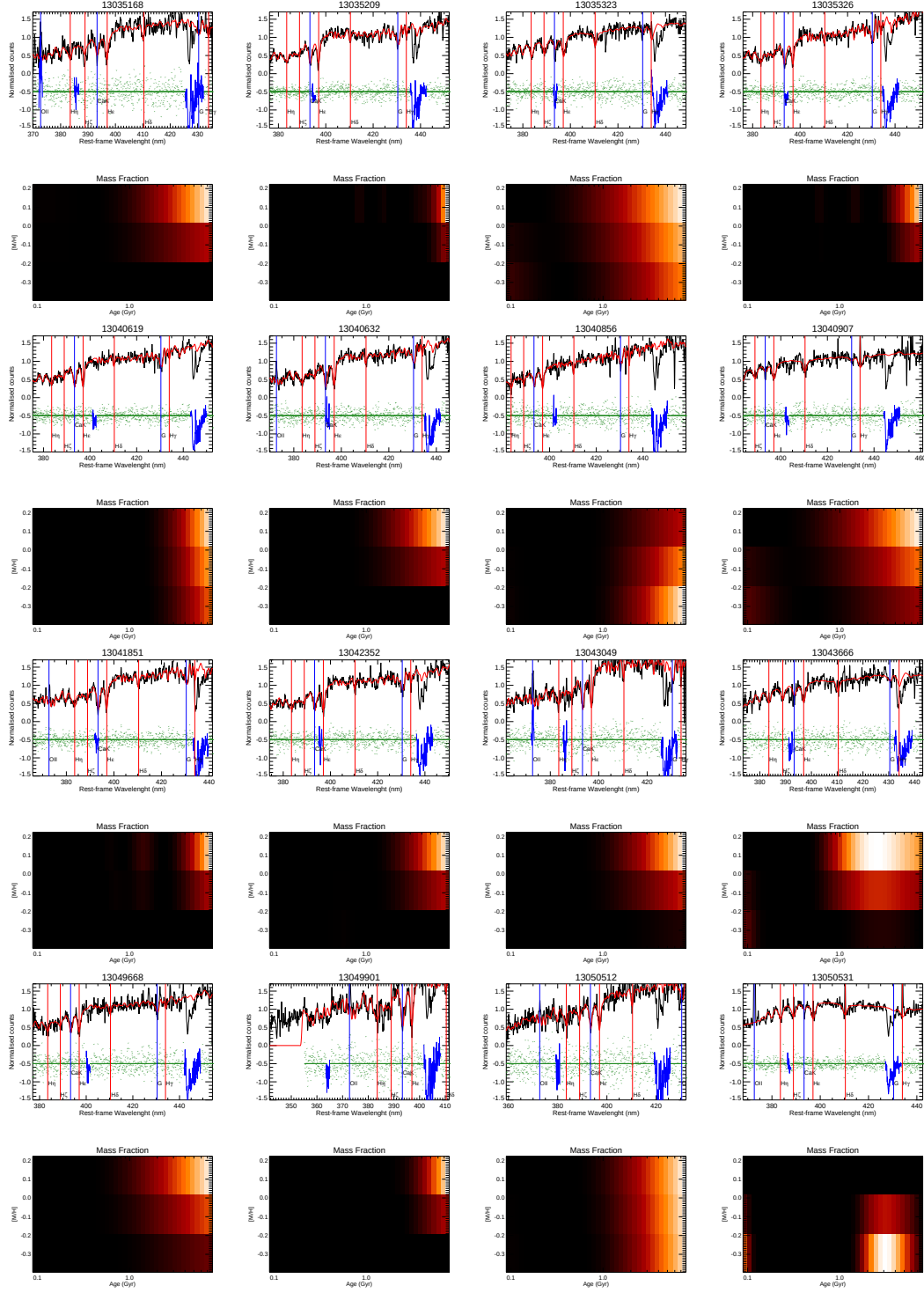












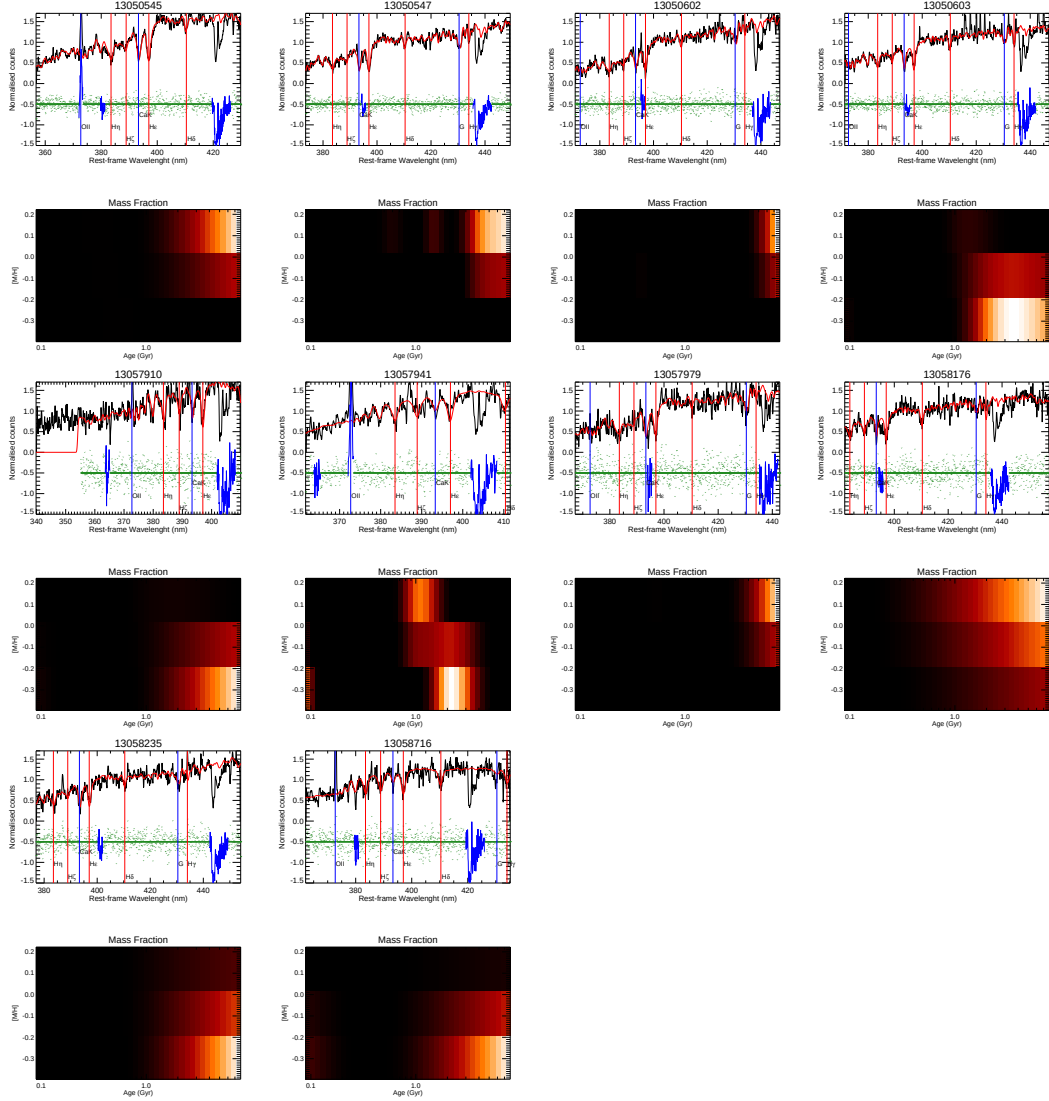


Fig. C.1 Here we present the stellar population modelling of our full galaxy sample at redshift $z \sim 1$. We present the observed galaxy spectra, reproduced by the solid black line, along with the best fit spectra in the solid red line. The green points are the residuals of the fits normalised at -0.5 with the blue points representing the penalised pixels. The blue line represent the masked pixels of the galaxy spectra. The best fit to the galaxy spectra were calculated using the keyword *REGUL* of pPXF, so that the χ^2 increases by $\sqrt{2 \times N_{\text{pixels}}}$ from the unregularised fits. The panel below the galaxy spectra represents the regularised weight distribution along the galaxy template. Please note that compared to Fig.3.5, the colour map in these panels have been inverted. The x-axis of the panel represents the logarithmic age distribution of the stellar population templates, while the y-axis represents distribution in metallicity.

Appendix D

Results of Stellar Population Modelling of galaxies at $z \sim 1$

Table D.1 Results of Stellar Population Modelling. Column (1): DEEP2 galaxy identifier. Column (2): DEEP2 estimated redshift. Column (3): Absolute B (Vega) band magnitude. Column (4): Effective radius as derived from MGE (without re-scaling). Column (5): Aperture velocity dispersion. Column (6): Error on aperture velocity dispersion. Column (7): Dynamical mass-to-light ratio with a median error of 0.11dex.

DEEP2 ID	Redshift	R_e (kpc)	R_e^{Maj} (kpc)	M_B (Mag.)	$(M_*/L)_B^{\text{Sal}}$ (Regul.) $(M_\odot/L_\odot)$	Mass- weighted Age (Gyrs)	Luminosity weighted Age (Gyrs)	$\log(M_*^{\text{Sal}})$ $(M_\odot)$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
11044628	0.824	9.7	10.0	-22.06	0.5	1.65	0.28	10.686
11050845	0.840	4.4	5.2	-21.76	3.5	4.85	4.57	11.429
11051246	0.777	4.4	4.6	-21.18	0.9	2.47	0.71	10.592
12003915	0.749	3.2	5.1	-20.89	0.7	2.52	0.34	10.391
12004067	0.748	9.4	10.2	-21.76	0.8	2.26	0.54	10.784
12004122	0.748	7.7	7.7	-21.20	0.6	1.65	0.45	10.467
12004136	0.812	5.5	5.6	-21.62	2.9	3.93	3.38	11.288
12004138	0.811	7.3	8.7	-22.50	3.6	3.85	3.33	11.741
12004457	0.811	3.2	4.4	-21.65	1.5	3.06	1.75	11.028
12004497	0.821	3.0	3.4	-20.90	0.9	3.22	0.42	10.491
12004515	0.811	3.3	3.3	-20.93	0.4	1.31	0.24	10.108
12004516	0.820	4.8	5.0	-21.44	1.9	3.05	1.66	11.030
12007926	0.873	2.4	3.1	-21.50	1.1	2.42	1.10	10.800
12008182	0.753	3.7	6.3	-20.61	1.2	3.16	0.74	10.510
12008187	0.755	7.4	10.5	-21.26	1.8	3.93	1.46	10.929
12008202	0.832	4.2	6.0	-20.56	0.5	1.83	0.59	10.136
12008211	0.820	2.8	3.1	-20.83	1.7	2.95	1.71	10.753
12008254	0.745	4.3	5.1	-21.51	3.4	4.09	3.21	11.312
12008288	0.753	5.5	5.6	-21.52	0.8	1.30	0.65	10.669

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Table D.1 – Continued from previous page

12008360	0.828	2.0	2.0	-20.97	2.3	3.58	2.51	10.928
12008441	0.832	5.8	7.5	-21.34	1.8	3.09	1.85	10.970
12008527	0.828	7.8	8.0	-21.59	1.1	1.76	1.08	10.848
12008537	0.770	3.7	4.6	-20.63	0.5	2.13	0.30	10.126
12008801	0.833	1.3	1.3	-21.29	0.5	0.65	0.47	10.355
12008914	0.775	4.6	4.6	-21.39	1.5	4.46	0.59	10.900
12008946	0.832	7.4	8.0	-22.69	2.8	4.55	3.60	11.707
12011463	0.770	3.7	3.7	-21.11	0.2	0.94	0.15	9.989
12011825	0.836	8.4	9.6	-22.33	1.1	2.00	0.98	11.150
12011900	0.719	2.4	3.1	-20.88	3.9	4.47	3.78	11.121
12011905	0.718	7.1	11.1	-22.03	2.1	3.30	2.02	11.311
12012829	0.744	4.4	4.8	-22.14	2.7	3.68	2.70	11.466
12012898	0.835	4.9	5.1	-22.33	3.1	3.29	2.90	11.606
12012905	0.875	10.4	10.7	-21.49	0.5	2.33	0.35	10.506
12015451	0.713	4.1	5.2	-21.85	3.3	4.55	3.68	11.433
12015656	0.834	3.2	3.6	-20.91	0.8	1.73	0.58	10.437
12015665	0.752	2.9	3.7	-20.96	0.5	1.47	0.32	10.271
12015693	0.836	1.2	1.5	-20.86	2.4	3.57	2.34	10.903
12015735	0.714	2.2	2.2	-20.48	3.0	4.03	3.28	10.855
12015909	0.722	3.0	3.2	-21.28	3.8	4.41	3.74	11.271
12016736	0.747	8.6	10.9	-22.17	2.0	3.24	2.30	11.355
12019617	0.820	3.4	5.1	-21.30	2.6	3.72	2.94	11.118
12019681	0.819	2.6	2.7	-21.03	2.6	3.70	2.88	11.011
12019916	0.729	3.8	4.8	-20.95	1.7	3.70	1.07	10.797
12019923	0.727	4.9	4.9	-20.88	1.8	3.76	1.65	10.780
12019978	0.734	2.3	3.8	-21.20	3.4	4.11	2.97	11.184
12020055	0.719	2.9	2.9	-21.28	3.8	4.39	3.80	11.271
12020164	0.781	5.3	5.4	-20.86	0.4	0.92	0.28	10.130

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Table D.1 – Continued from previous page

12020321	0.721	7.1	9.4	-21.65	1.2	4.78	0.42	10.906
12020367	0.832	7.2	7.4	-21.30	0.1	0.17	0.17	9.820
12020387	0.760	3.3	3.5	-21.34	0.5	0.99	0.35	10.426
12020404	0.809	3.8	3.9	-21.43	4.7	5.67	4.49	11.428
12020429	0.719	7.3	7.4	-21.44	1.3	3.11	1.33	10.865
12020679	0.761	2.3	2.4	-20.74	1.4	2.82	1.52	10.616
12021111	0.716	2.7	3.8	-21.38	3.6	5.36	5.03	11.284
12021121	0.744	3.2	3.5	-21.07	2.6	4.68	1.77	11.021
12021129	0.717	4.1	4.7	-21.96	5.2	6.12	5.60	11.679
12023514	0.833	2.7	2.9	-21.45	3.3	4.09	3.40	11.285
12023935	0.842	3.5	4.9	-21.27	3.0	3.96	2.73	11.171
12024039	0.838	6.1	6.3	-21.06	1.7	4.16	1.25	10.837
12024057	0.736	1.9	2.6	-20.98	4.7	5.13	4.49	11.247
12024136	0.729	9.1	9.6	-21.72	1.8	4.05	1.48	11.134
12024742	0.826	2.3	2.8	-21.73	0.8	1.04	0.89	10.781
12024794	0.733	4.2	5.3	-20.52	1.4	2.83	1.61	10.542
12024878	0.782	3.6	4.1	-21.74	3.3	4.12	2.93	11.392
12025032	0.814	4.6	5.0	-21.45	0.7	2.36	0.32	10.577
12025292	0.813	1.7	2.1	-20.97	3.0	3.93	3.17	11.049
12025294	0.732	4.0	7.1	-20.93	2.3	3.41	2.57	10.909
12025308	0.744	6.9	7.9	-22.44	4.5	4.84	4.29	11.814
12027757	0.737	1.6	1.8	-20.65	0.7	1.85	0.63	10.275
12028330	0.820	4.2	5.3	-21.41	2.4	3.29	2.25	11.117
12028349	0.758	3.3	3.5	-21.22	4.3	4.75	4.20	11.299
12028367	0.845	1.9	2.0	-21.80	1.1	2.60	0.81	10.939
12028846	0.761	3.6	4.0	-21.95	2.9	4.12	3.60	11.428
13003868	0.781	5.4	5.5	-21.94	4.9	6.03	4.33	11.648
13010426	0.821	1.7	1.7	-20.63	2.4	4.10	2.26	10.815

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Table D.1 – *Continued from previous page*

13011073	0.731	3.8	5.9	-20.97	2.0	3.20	1.91	10.862
13011165	0.732	6.9	7.5	-21.97	0.8	1.48	0.84	10.881
13011605	0.779	7.3	7.5	-21.36	1.3	3.35	1.07	10.851
13011693	0.757	2.5	3.1	-21.73	0.6	2.40	0.30	10.679
13011773	0.737	3.9	4.0	-21.99	2.1	2.64	2.03	11.307
13011780	0.810	2.2	3.4	-20.91	3.9	4.50	3.77	11.140
13011785	0.808	2.8	2.8	-21.04	4.2	4.81	4.02	11.223
13011809	0.882	2.9	2.9	-21.31	2.2	3.71	3.00	11.036
13012297	0.806	2.8	3.0	-21.13	2.1	3.57	2.52	10.958
13017587	0.770	6.5	8.0	-21.32	1.2	2.79	1.23	10.792
13017990	0.754	4.6	7.1	-21.15	1.5	2.75	1.37	10.813
13018001	0.740	8.9	12.7	-21.73	2.8	3.70	2.61	11.317
13018077	0.791	5.0	5.1	-21.70	0.8	2.19	0.44	10.739
13018618	0.754	4.8	5.1	-21.17	1.2	2.78	0.88	10.739
13018985	0.768	7.2	7.4	-21.59	1.5	3.10	1.18	10.998
13019195	0.769	6.9	8.5	-20.92	0.7	2.56	0.46	10.421
13019206	0.756	6.6	7.1	-21.39	0.6	0.98	0.44	10.480
13019229	0.893	4.1	4.5	-21.08	0.6	1.68	0.37	10.403
13019240	0.745	3.4	4.5	-21.04	1.1	1.65	1.19	10.620
13019278	0.707	2.6	3.1	-21.41	2.8	3.69	2.52	11.195
13019286	0.737	2.3	2.8	-21.20	4.5	4.98	4.03	11.310
13019294	0.851	1.3	1.3	-21.35	1.9	3.61	1.95	10.999
13019820	0.850	6.4	6.4	-21.82	3.1	4.86	4.20	11.397
13019950	0.769	1.8	2.0	-21.60	0.5	0.73	0.40	10.497
13025225	0.781	7.8	7.9	-21.91	0.6	1.60	0.36	10.693
13025271	0.762	3.3	3.4	-21.20	0.9	2.84	0.42	10.612
13025290	0.849	2.7	2.8	-21.17	1.0	2.90	0.66	10.667
13025397	0.736	5.7	9.2	-22.13	2.5	3.62	2.78	11.428

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Table D.1 – Continued from previous page

13025469	0.761	1.5	1.5	-20.09	2.0	2.79	1.87	10.525
13025485	0.739	4.0	4.8	-20.91	3.6	5.66	2.66	11.102
13025494	0.739	5.3	5.4	-21.14	3.8	4.62	3.57	11.216
13025532	0.745	4.2	4.9	-21.05	1.7	3.34	1.10	10.838
13025741	0.779	2.6	3.2	-21.29	3.1	4.06	2.71	11.195
13025761	0.752	7.4	8.2	-21.31	1.5	2.73	1.59	10.866
13026059	0.743	2.1	2.1	-21.92	1.9	3.94	1.74	11.221
13026213	0.744	2.9	3.7	-20.72	1.8	3.88	1.42	10.726
13026220	0.741	6.9	7.2	-21.31	0.6	1.96	0.46	10.451
13026812	0.716	6.6	7.7	-20.84	0.7	2.13	0.54	10.371
13027442	0.768	5.4	8.4	-21.92	3.0	5.03	3.30	11.417
13027526	0.710	7.5	9.1	-21.35	1.2	3.32	1.02	10.810
13033202	0.710	8.3	14.3	-21.77	2.2	3.76	2.54	11.237
13033203	0.710	3.7	4.7	-20.56	1.1	2.94	0.61	10.435
13033872	0.710	5.2	5.3	-21.20	1.0	4.02	0.47	10.661
13033890	0.718	1.0	1.0	-20.43	1.2	2.51	1.29	10.445
13033906	0.744	2.9	3.3	-20.47	2.5	3.49	2.30	10.766
13033927	0.735	3.0	3.1	-20.78	2.7	4.11	2.83	10.919
13033939	0.749	3.2	3.2	-21.51	1.5	2.11	1.30	10.949
13033944	0.763	1.5	1.9	-20.67	3.5	4.25	3.72	10.997
13033965	0.750	2.2	3.4	-20.96	3.9	4.49	3.88	11.158
13034447	0.748	1.9	2.7	-21.59	0.7	1.52	0.85	10.665
13034551	0.749	3.4	3.6	-21.40	0.6	1.72	0.35	10.509
13034882	0.744	2.6	2.9	-20.63	2.7	3.79	3.12	10.857
13035160	0.716	4.9	5.5	-20.39	2.2	4.01	2.67	10.674
13035168	0.782	6.8	8.7	-21.35	2.5	3.81	1.97	11.118
13035209	0.740	3.2	4.0	-21.59	5.1	6.06	4.68	11.520
13035323	0.746	4.5	4.7	-21.19	1.1	2.72	1.05	10.706

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Table D.1 – *Continued from previous page*

13035326	0.744	3.2	3.6	-21.41	4.3	5.22	3.92	11.383
13040619	0.711	2.6	2.7	-20.85	4.0	5.36	4.53	11.127
13040632	0.743	2.3	2.7	-20.71	3.5	4.16	3.44	11.005
13040856	0.709	3.8	5.8	-20.98	2.3	4.24	2.59	10.939
13040907	0.707	4.6	4.6	-21.08	0.9	2.44	0.59	10.545
13041851	0.750	2.6	2.9	-21.31	3.7	5.00	3.20	11.270
13042352	0.737	2.9	3.3	-21.63	4.2	4.99	3.92	11.452
13043049	0.780	3.6	3.7	-21.04	3.4	4.15	3.45	11.128
13043666	0.754	7.1	7.7	-21.49	1.2	2.62	0.66	10.862
13049668	0.715	2.9	3.7	-20.61	2.6	3.82	2.73	10.845
13049901	0.887	4.0	4.0	-21.19	5.2	5.70	4.85	11.373
13050512	0.808	4.5	6.5	-20.82	2.5	4.05	2.96	10.914
13050531	0.776	3.6	4.1	-21.25	0.8	2.80	0.35	10.558
13050545	0.807	3.3	3.6	-21.55	3.4	4.39	2.91	11.331
13050547	0.741	3.0	3.4	-21.52	3.5	4.23	3.12	11.334
13050602	0.736	3.4	3.7	-21.79	5.3	6.75	4.78	11.624
13050603	0.742	1.9	2.1	-21.64	1.9	3.32	2.06	11.116
13057910	0.887	6.1	6.3	-21.25	1.9	3.91	1.47	10.953
13057941	0.886	3.7	5.3	-21.05	0.7	1.62	0.56	10.469
13057979	0.742	1.5	1.9	-20.54	5.5	6.13	5.16	11.131
13058176	0.740	4.4	5.1	-21.23	1.7	2.90	1.57	10.894
13058235	0.714	2.9	2.9	-20.80	2.4	4.06	3.50	10.883
13058716	0.808	7.4	7.6	-21.42	0.9	2.86	0.60	10.683

Appendix E

Results of Dynamical modelling of galaxies at $z \sim 1$

Table E.1 Results of Dynamical Modelling. Column (1) : DEEP2 galaxy identifier. Column (2) : Velocity dispersion as measured by full-spectrum fitting of the galaxy spectra. Column (3) : Error on the derived velocity dispersion of the galaxy through a bootstrapping technique. Column (4) : B-band (M_*/L) derived through dynamical modelling, where the dark matter halo was assigned using the SHMR of Leauthaud et al. (2012). Column (5) : The log of the stellar mass, in units of $M_\odot$, of the galaxy derived using the absolute luminosity (Column (5) of Table. 1) and the M/L of Column (4). Column (6) : Fraction of dark matter within $1R_e$ of the galaxy. This was derived by using the SHMR of Leauthaud et al. (2012).

DEEP2 ID	σ (km s ⁻¹)	$\delta\sigma$ (km s ⁻¹)	$(M_*/L)_{JAM}$ ($M_\odot/L_\odot$)	$\log(M_*^{JAM})$ ($M_\odot$)	f_{DM}
(1)	(2)	(3)	(4)	(5)	(6)
11050845	298.2	28.7	5.74	11.644	0.088
12004136	202.4	21.7	2.80	11.275	0.178
12004516	176.4	28.6	2.56	11.164	0.146
12008254	250.7	33.3	4.56	11.444	0.103
12008360	185.2	31.1	2.54	10.974	0.035
12008441	257.7	64.3	8.53	11.646	0.141
12011900	318.5	57.1	9.30	11.499	0.042
12011905	253.8	44.4	4.93	11.684	0.268
12012829	213.5	14.1	1.91	11.317	0.117

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Table E.1 – *Continued from previous page*

12012898	241.0	19.2	2.35	11.483	0.122
12015451	180.1	15.7	1.88	11.193	0.120
12015693	154.1	26.4	1.20	10.605	0.020
12015735	124.0	20.8	1.73	10.611	0.074
12015909	209.9	22.8	3.07	11.177	0.072
12016736	221.6	57.2	4.26	11.677	0.256
12019617	249.4	37.0	5.85	11.467	0.059
12019681	166.1	27.8	2.15	10.926	0.062
12019978	222.2	20.8	3.36	11.185	0.039
12020055	93.6	14.4	0.54	10.422	0.165
12020404	209.7	26.2	3.06	11.238	0.100
12021111	177.5	17.9	2.10	11.055	0.062
12021121	205.3	54.0	3.87	11.194	0.073
12021129	234.1	17.6	2.55	11.373	0.116
12023514	235.4	26.1	3.15	11.259	0.051
12023935	275.3	40.0	7.23	11.549	0.062
12024057	203.2	22.7	2.91	11.034	0.030
12024136	109.4	30.7	0.82	10.782	0.474
12024878	207.0	23.9	2.28	11.234	0.083
12025292	237.4	27.3	3.77	11.144	0.022
12025294	134.1	34.0	2.91	11.017	0.122
12028330	316.1	47.9	9.50	11.723	0.076
12028349	255.6	44.0	5.54	11.412	0.064
12028846	189.4	29.8	1.53	11.144	0.089
13003868	224.9	41.5	2.70	11.388	0.163
13010426	85.2	20.3	0.58	10.191	0.097
13011780	233.2	32.1	5.23	11.263	0.030
13011785	216.8	32.6	4.16	11.214	0.055
13011809	261.9	43.5	4.57	11.362	0.052
13012297	119.1	20.8	1.15	10.694	0.093
13018001	157.5	30.7	3.03	11.355	0.355
13019278	175.7	19.0	1.75	10.987	0.060
13019286	229.8	23.3	3.64	11.221	0.042
13019294	188.3	19.0	1.34	10.847	0.019
13019820	206.5	34.6	3.02	11.388	0.209
13025397	218.8	19.6	3.37	11.560	0.187
13025469	57.2	26.4	0.36	9.765	0.159
13025494	261.5	31.2	7.73	11.525	0.184
13025532	151.9	35.6	2.62	11.019	0.129
13027442	246.8	42.7	4.39	11.589	0.128
13033202	233.2	58.9	8.38	11.813	0.373
13033906	153.6	27.3	3.48	10.910	0.074

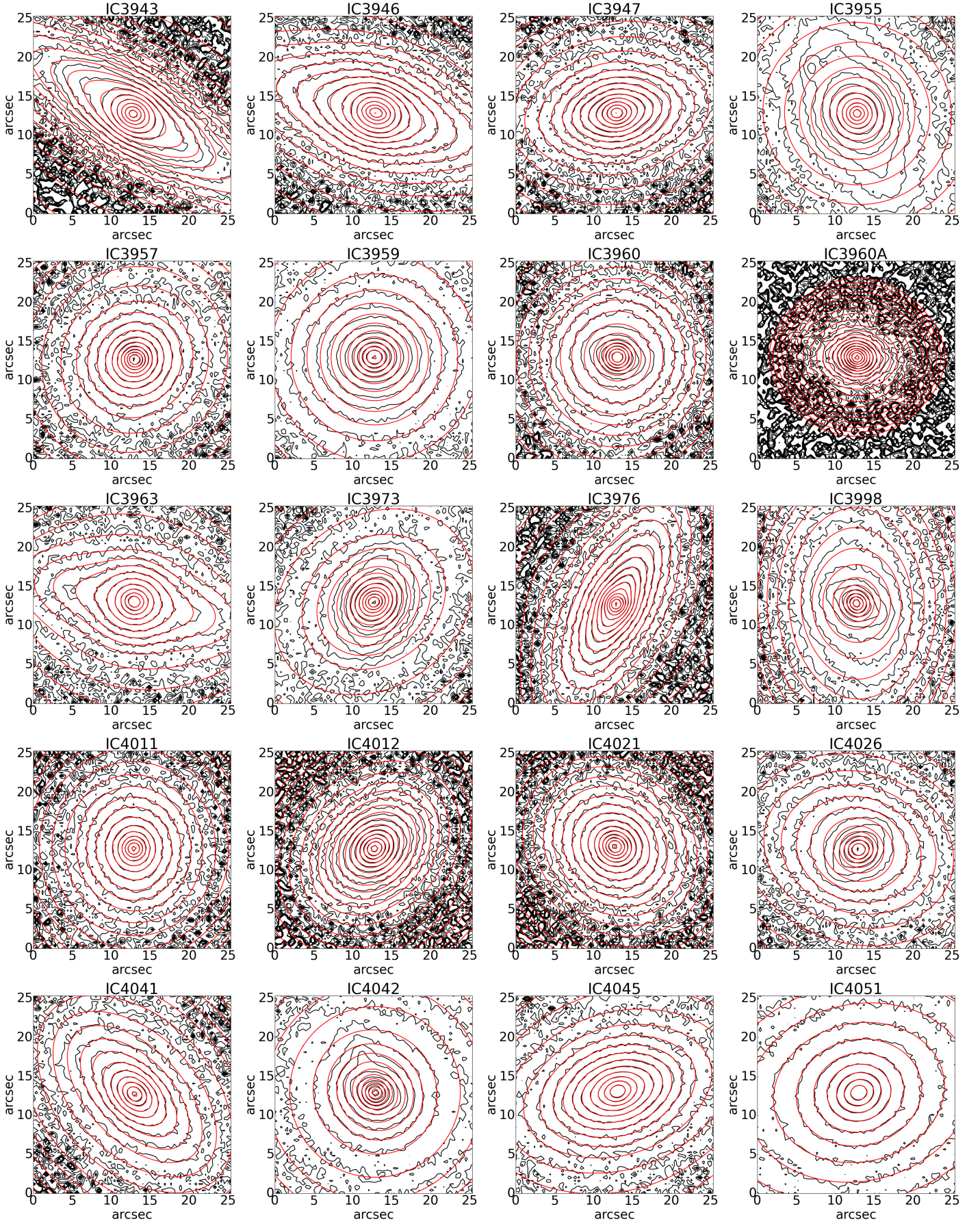
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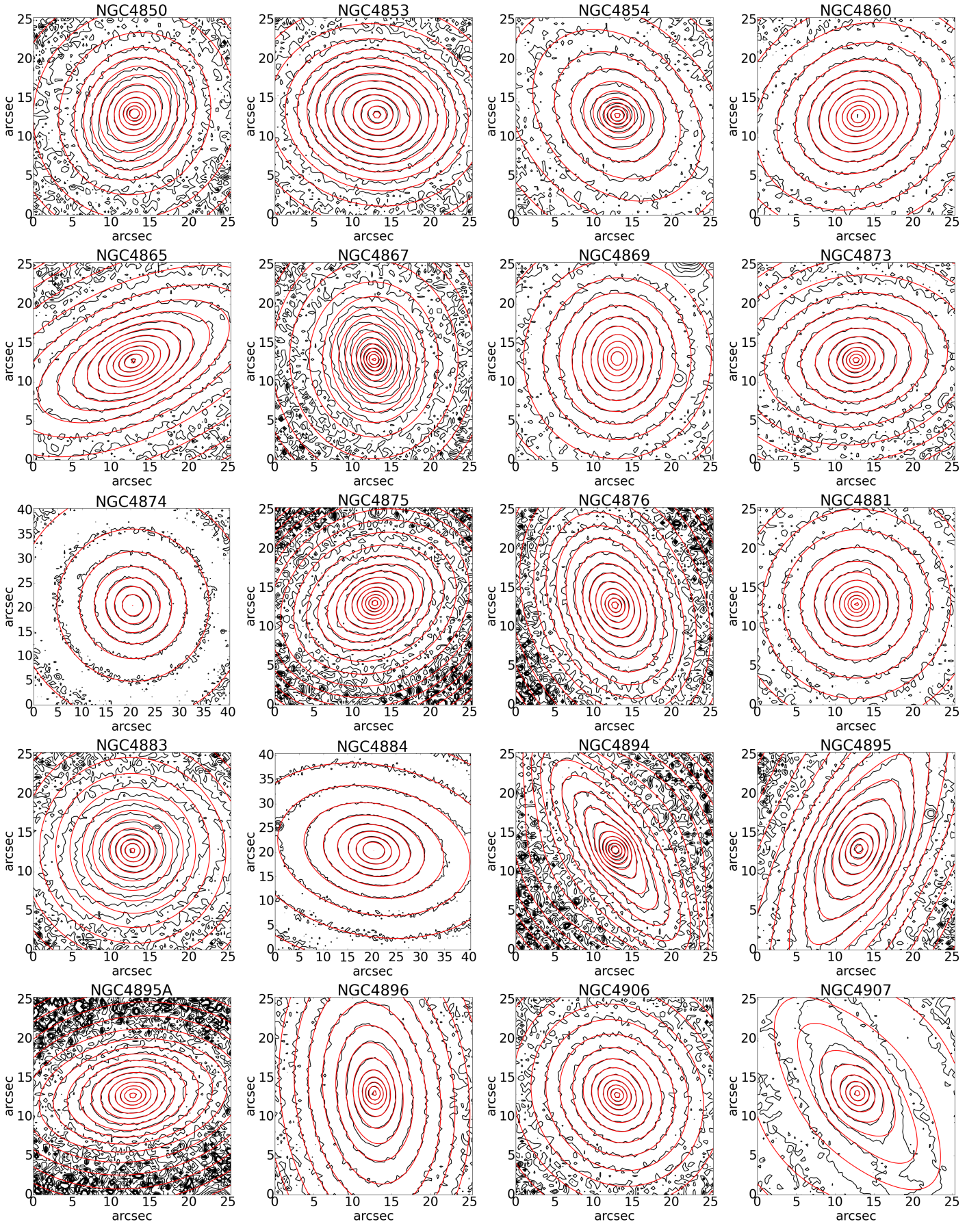
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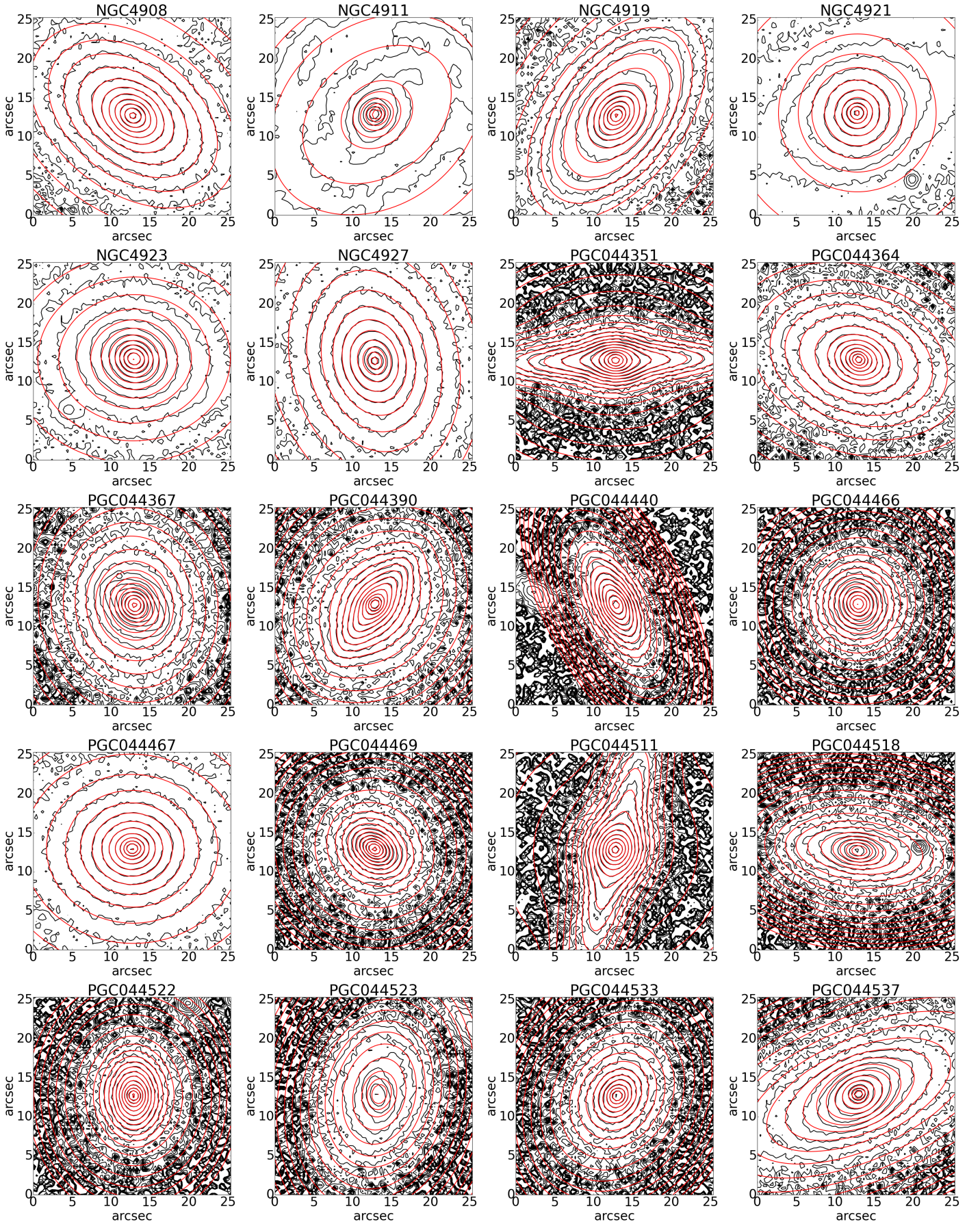
13033944	217.3	41.0	3.59	11.003	0.019
13033965	236.5	21.9	4.72	11.237	0.034
13034882	82.6	19.3	0.71	10.283	0.174
13035168	183.3	35.2	4.33	11.358	0.216
13035209	207.7	15.7	2.49	11.211	0.069
13035326	153.1	16.5	1.56	10.938	0.091
13040619	176.8	20.9	2.82	10.971	0.064
13040632	201.2	20.5	4.22	11.090	0.039
13042352	230.2	23.9	2.80	11.278	0.063
13043049	137.8	17.1	1.77	10.846	0.124
13049668	244.6	50.6	8.55	11.358	0.060
13049901	195.4	26.9	3.59	11.209	0.106
13050512	159.4	45.5	4.93	11.202	0.123
13050545	278.7	20.8	4.45	11.448	0.065
13050602	181.3	20.5	1.59	11.098	0.094
13057979	247.8	35.5	5.02	11.096	0.016
13058235	174.9	34.9	3.19	11.005	0.075

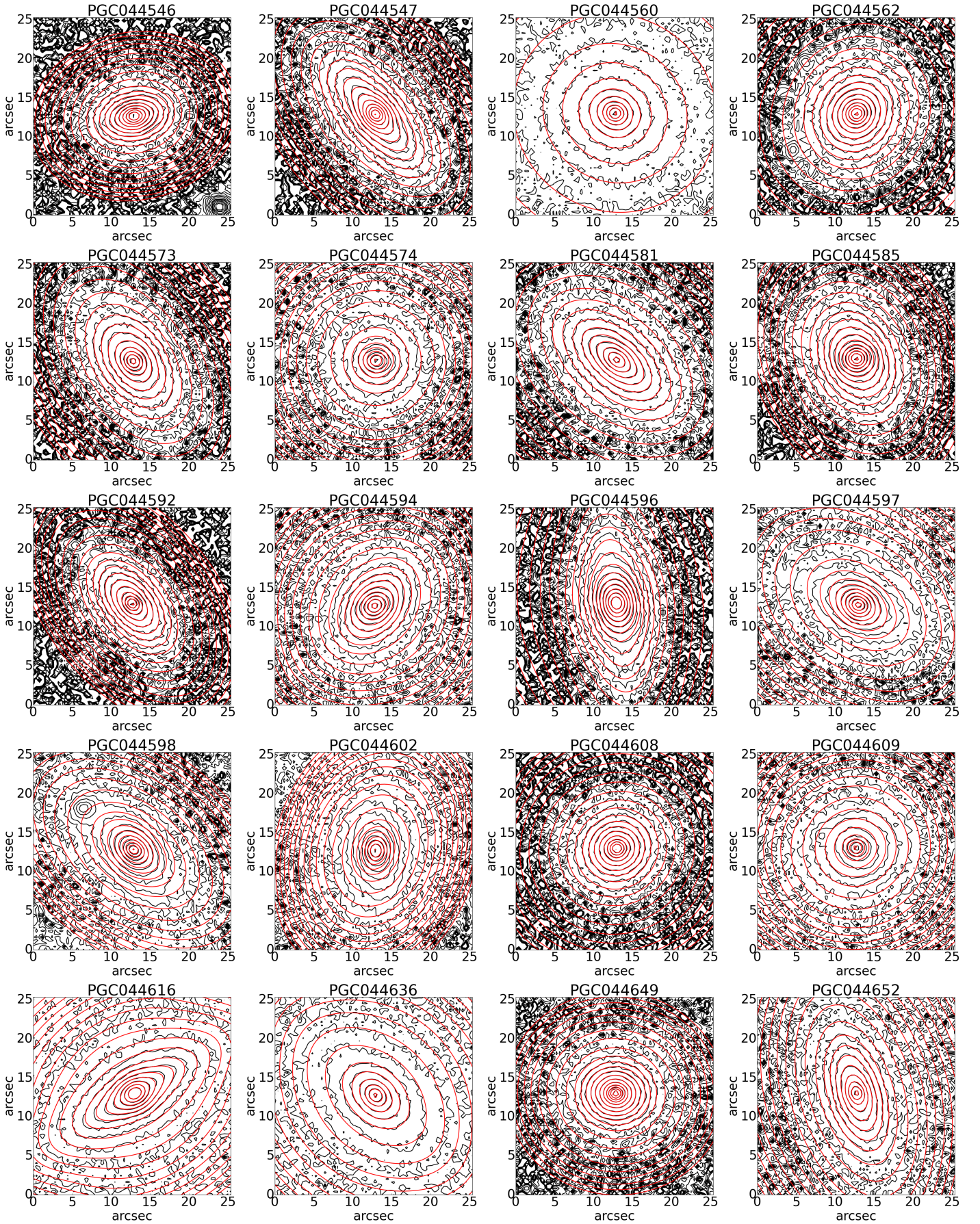
Appendix F

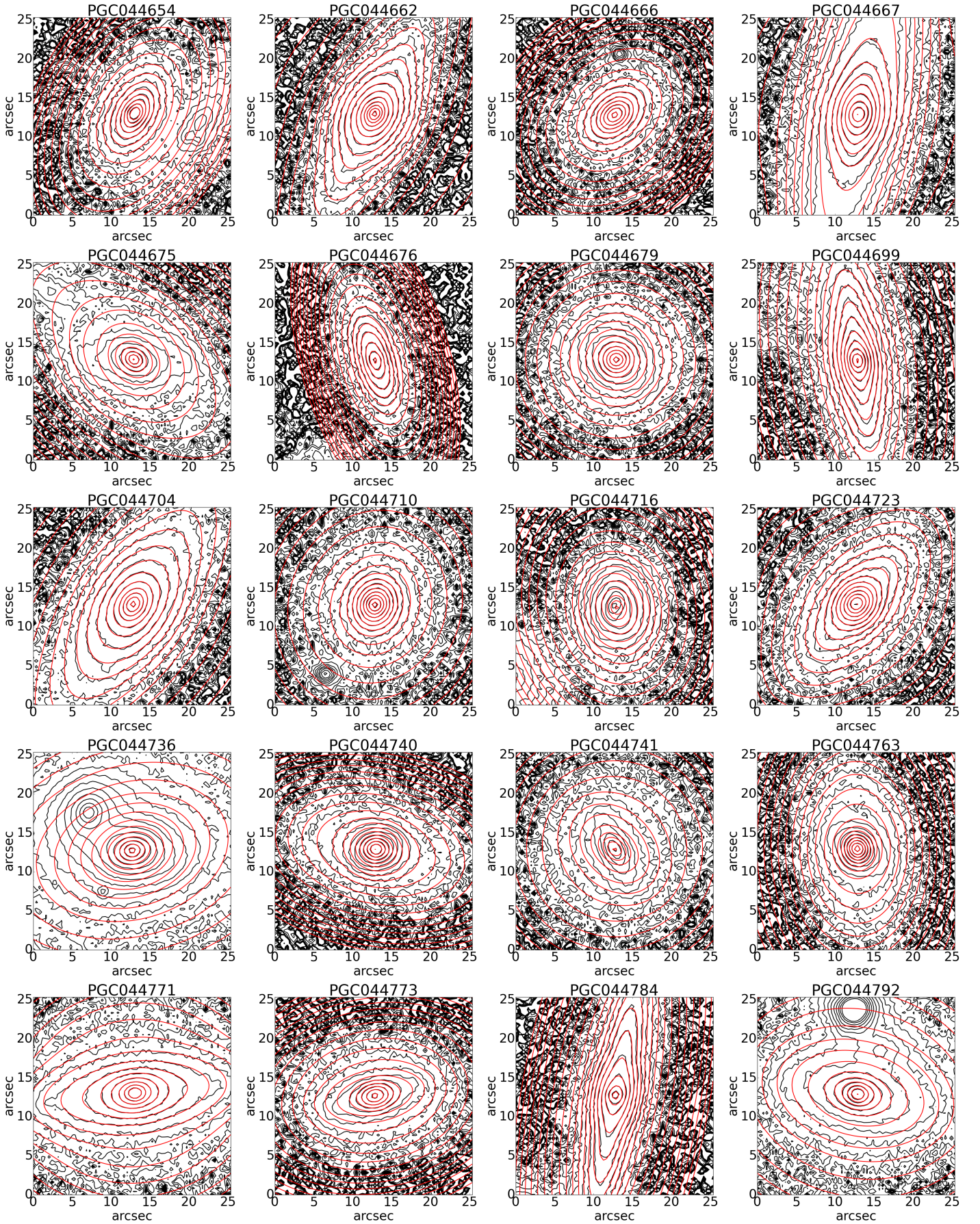
MGE Summary plots for Coma Cluster

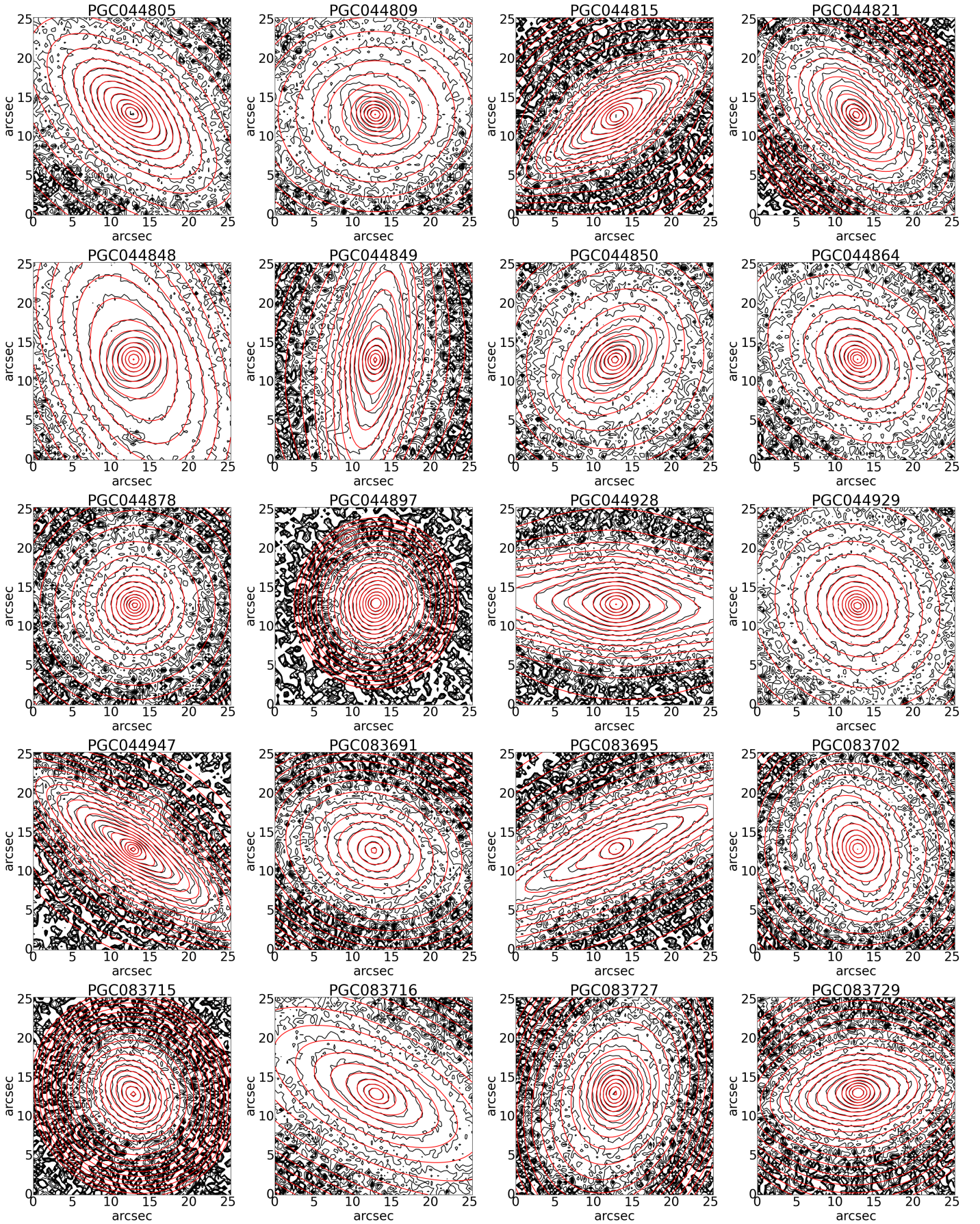












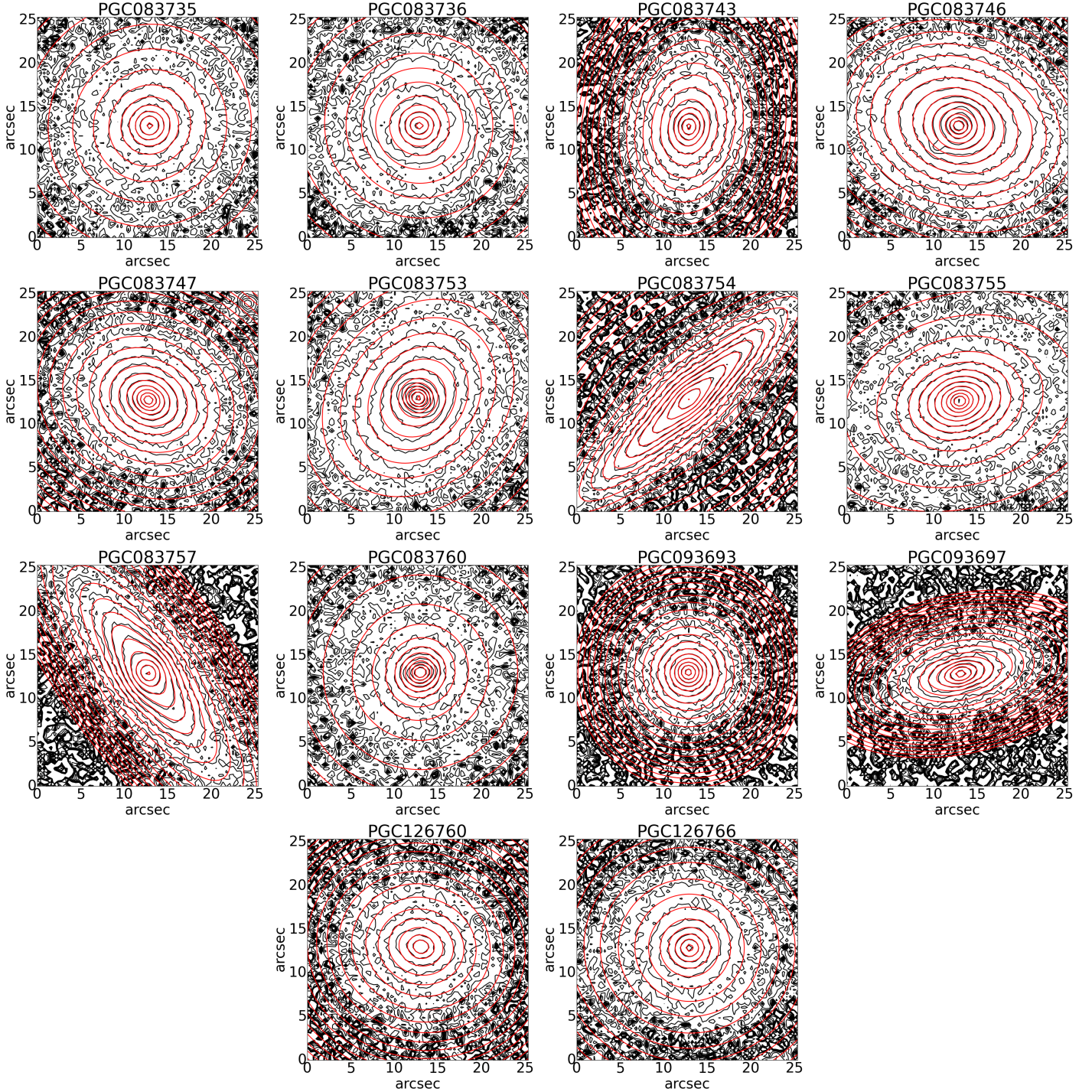
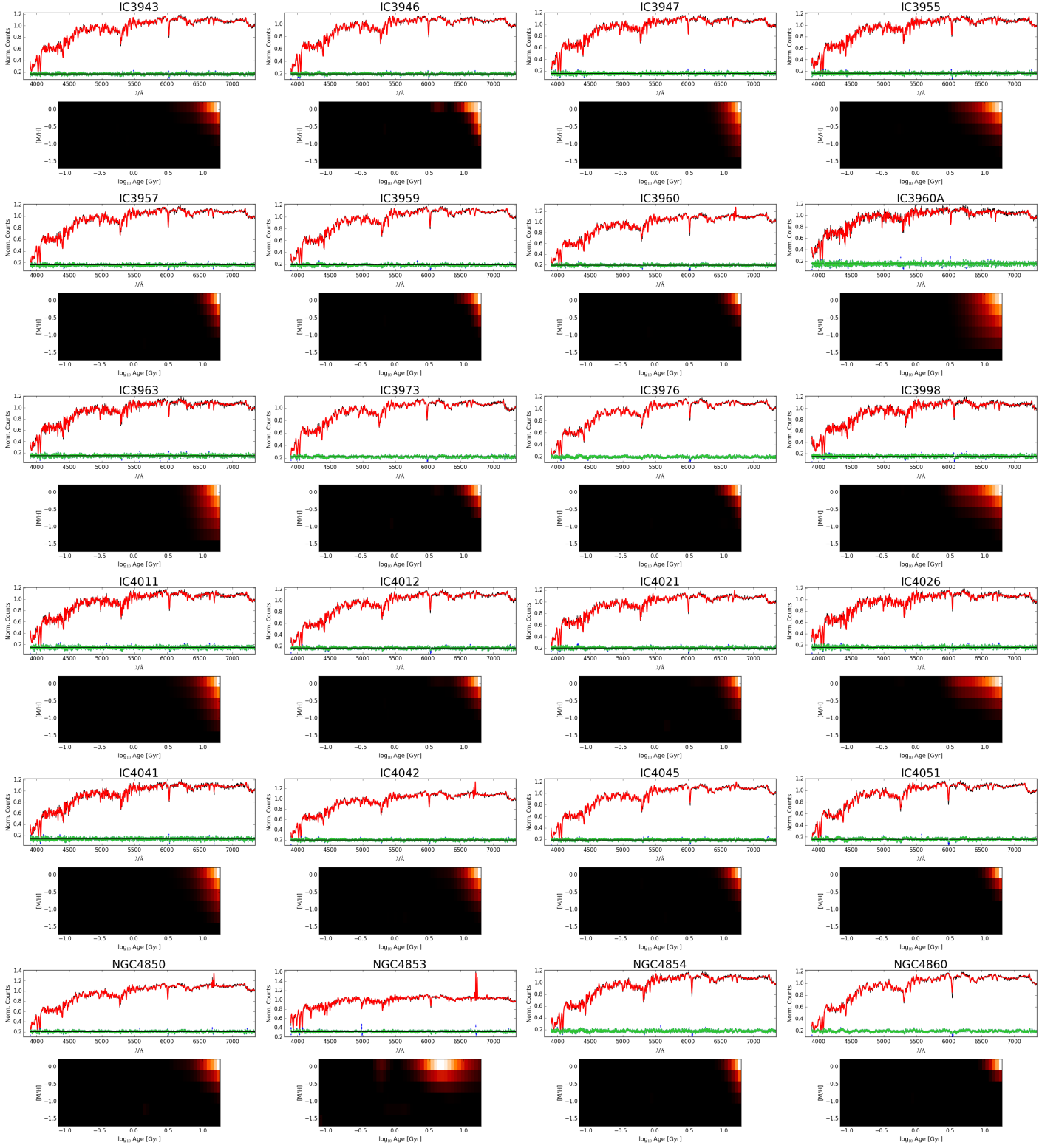
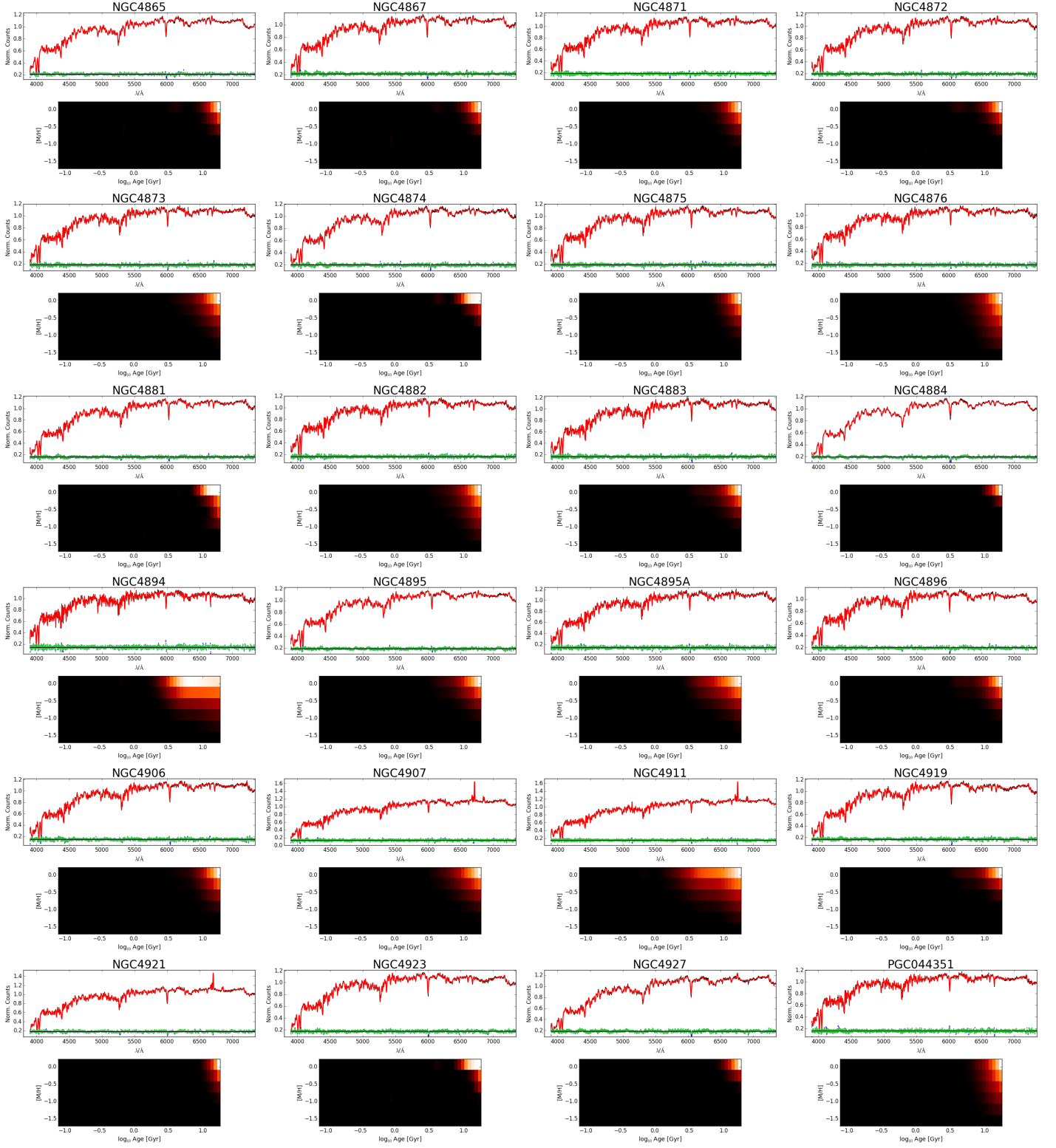


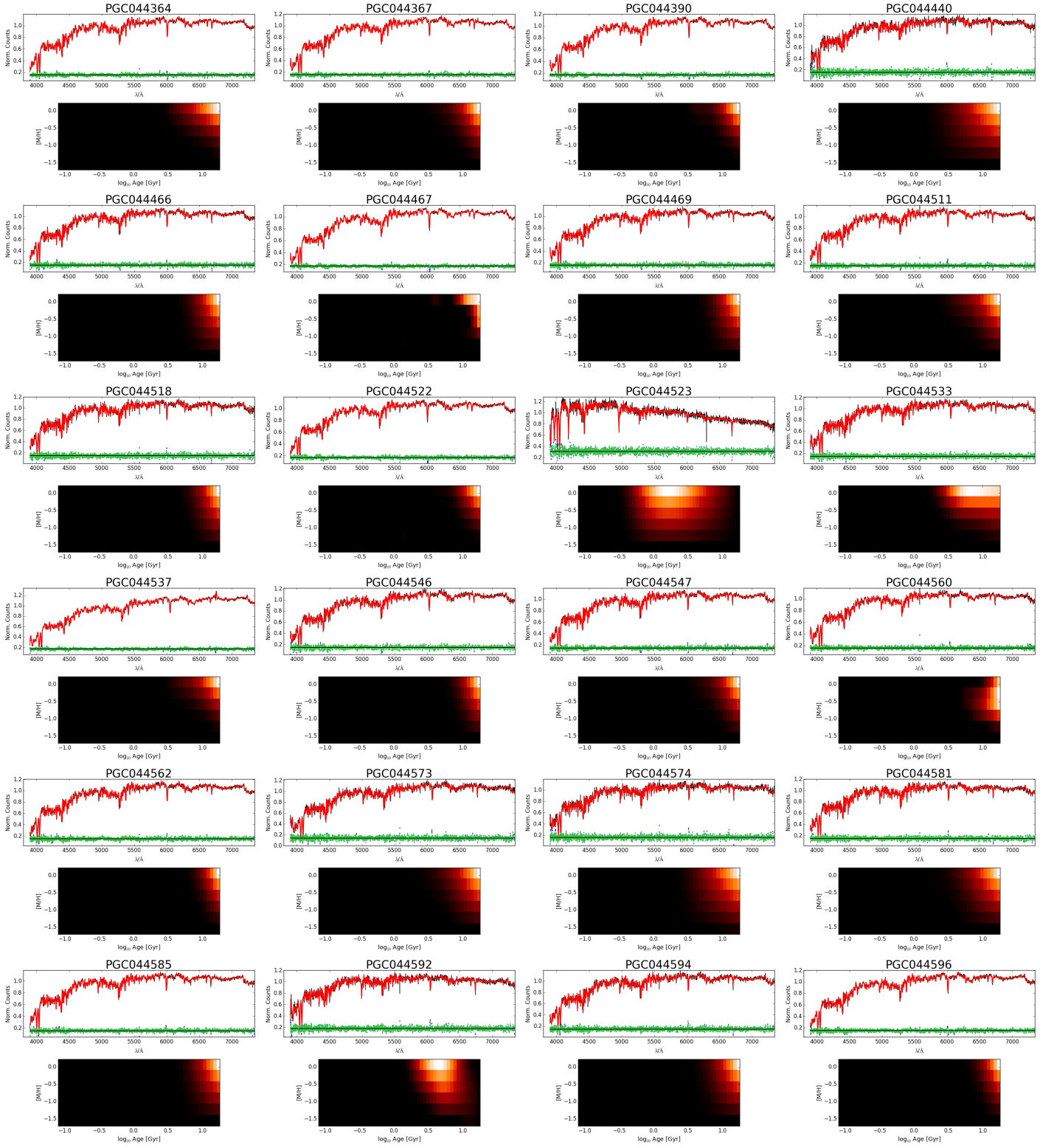
Fig. F.1 Here, I present the contour plots of the full sample for the Coma cluster. The black lines represent the observed galaxy surface brightness while the red lines represent the best fit MGE models to it. So as to inspect the quality of the MGE fits, these images depict the inner $25'' \times 25''$ thumbnails of the galaxies, while for the two massive central galaxies I present the inner $40'' \times 40''$ thumbnails. These contours plots demonstrate how well the MGE model represent the observed surface brightness of the galaxies.

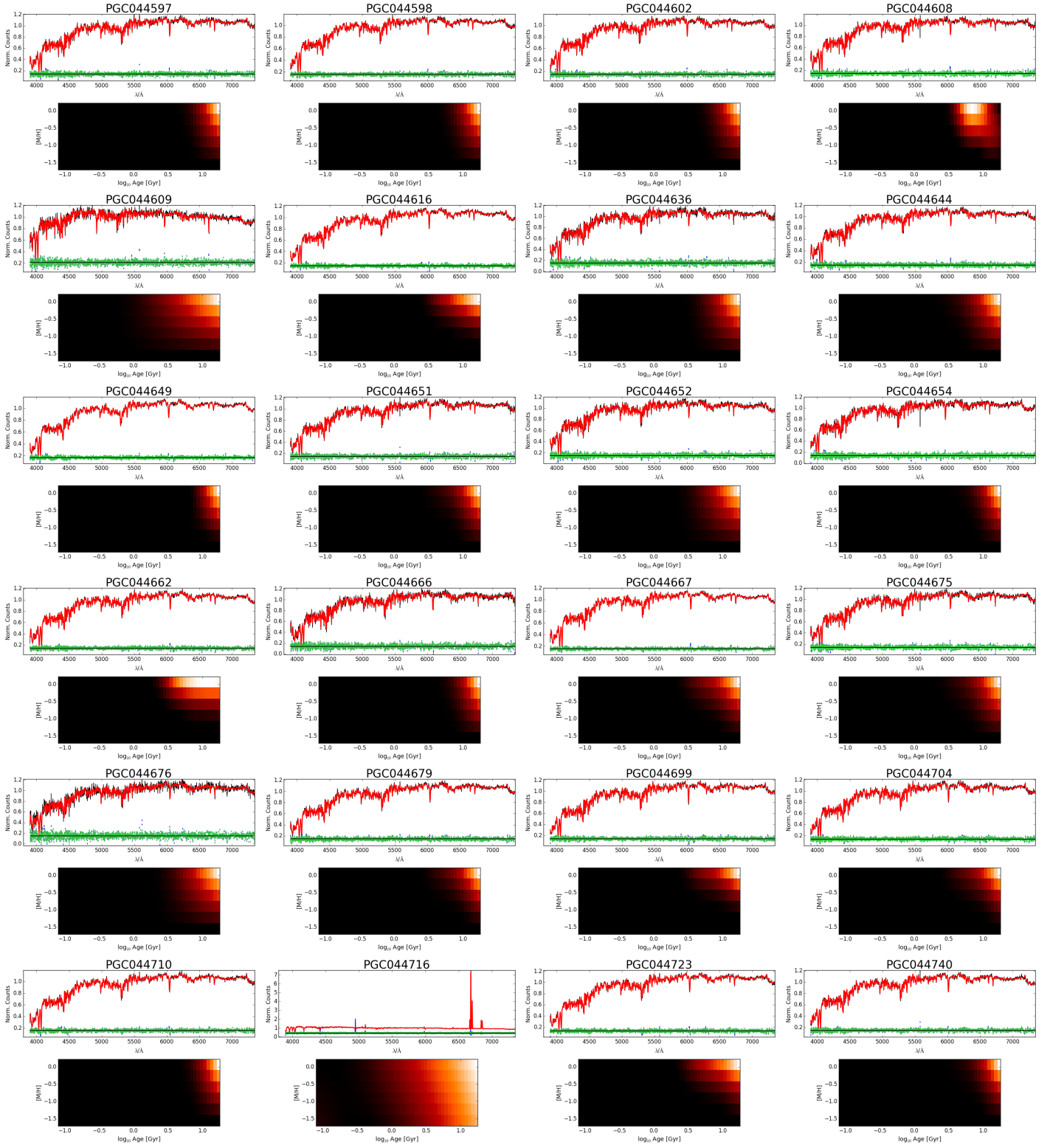
Appendix G

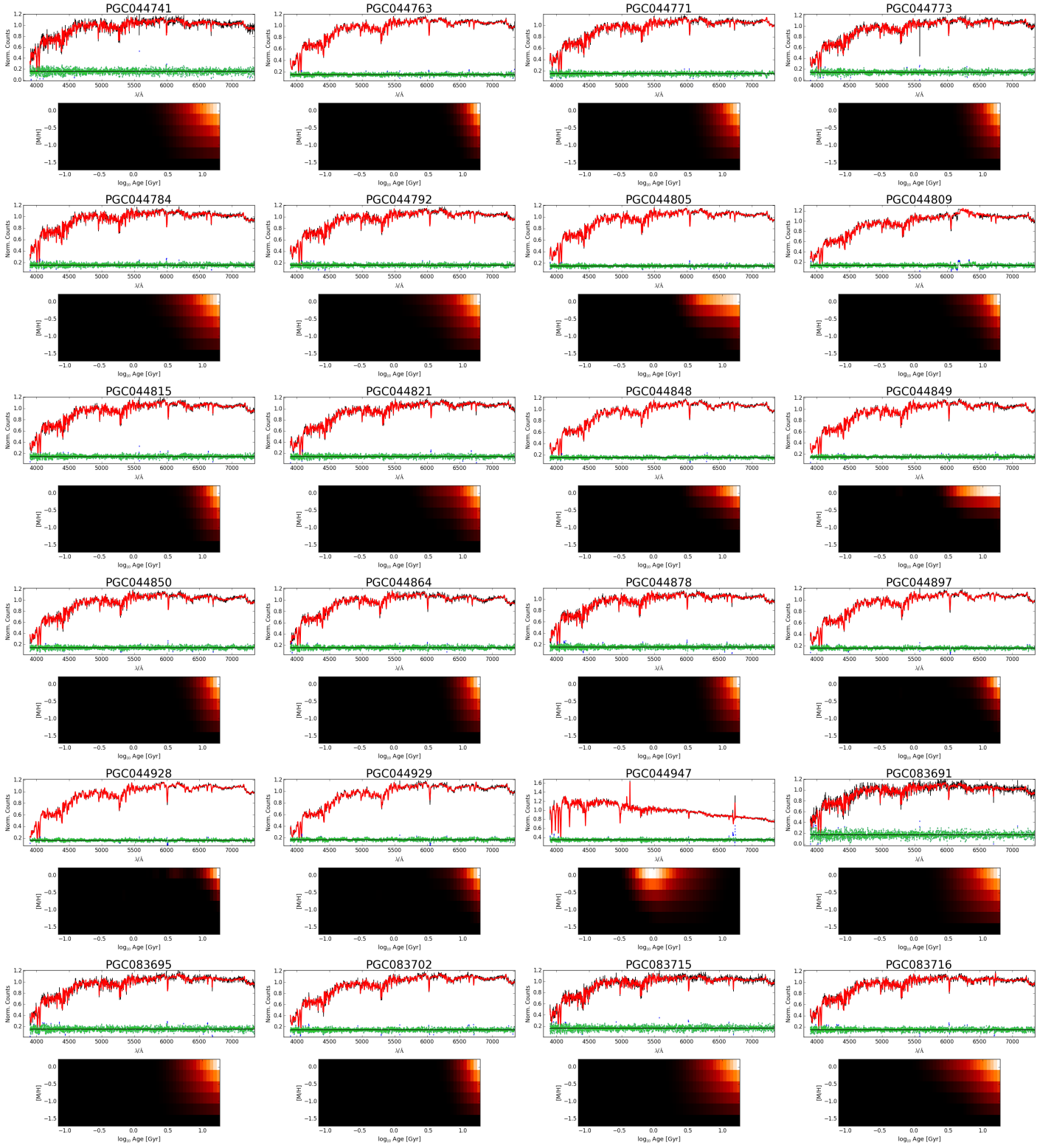
SPS Summary plots for Coma Cluster











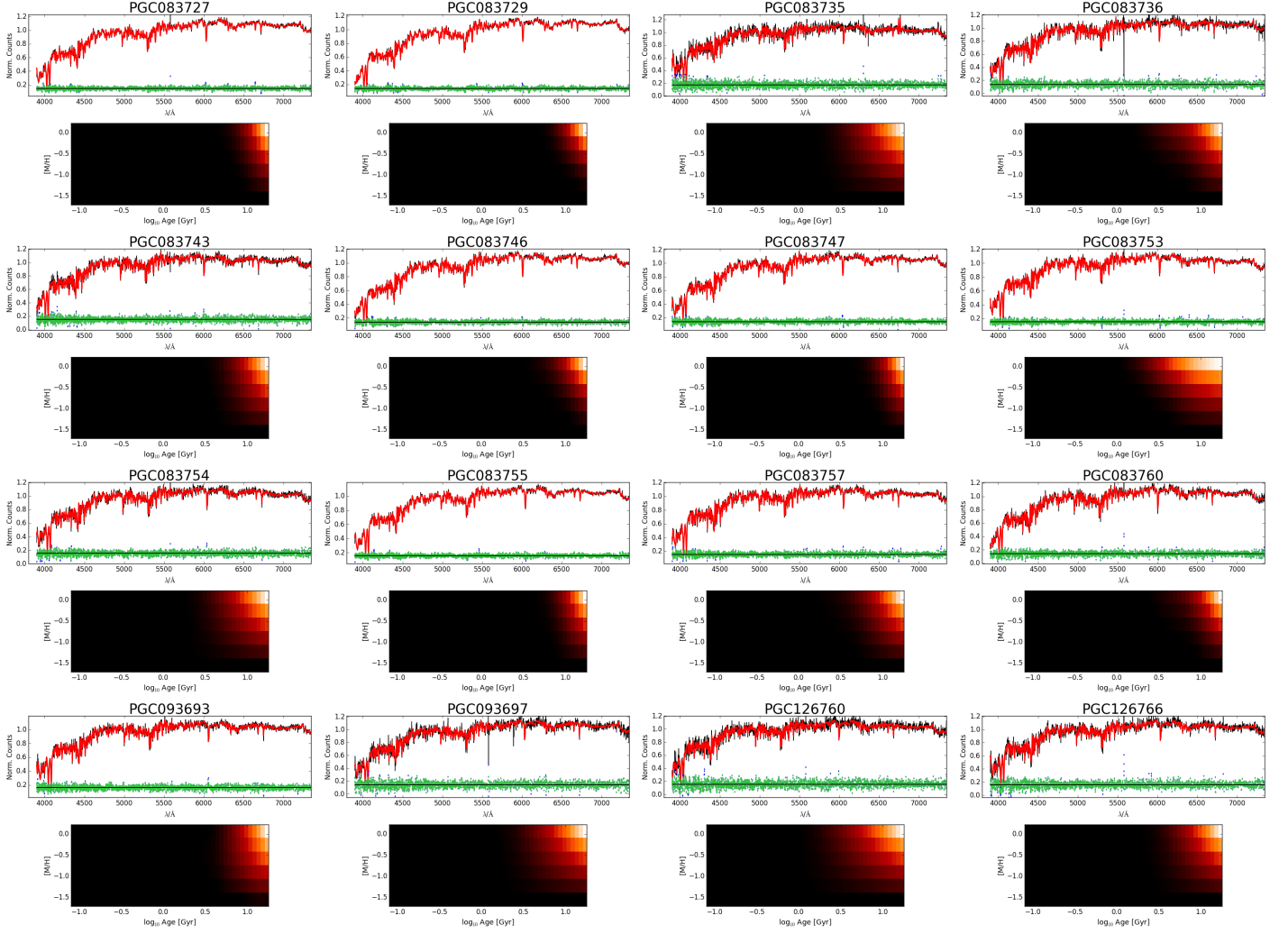


Fig. G.1 Here I present the stellar population models for the observed galaxy spectra. In the top panels, the observed galaxy spectra (black line) is presented with the best fit spectra (red line) overlaid. The green diamonds underneath the spectra and its best fit are the residuals of the fit, with the clipped residuals represented by blue diamonds. These residuals are offset to allow visual clarity. The bottom panels represent the distribution of weights along the template grid, with the age represented along the x-axis and the metallicities along the y-axis. These galaxy spectra were modelled in a mass-weighted manner and the template weights have been regularised.

Appendix H

Results of Coma cluster: SAURON

Subset

Table H.1 Results of analysis of the SAURON subset of Coma cluster galaxies. Notes:- Column (1) : Galaxy name. Column (2) : Right Ascension in degrees (J2000). Column (3) : Declination in degrees (J2000). Column(4) : Effective radii of the galaxies in arcsec. These quantities are derived from the MGE parametrisation of the galaxy photometry and have been multiplied by 1.35 as per the offset observed in ATLAS^{3D}. For more details, please refer to Section. 4.4.1. Column (5) : Major axis of the half-light isopleth in arcsec. This is derived as per the prescription in Cappellari et al. (2013b) and has been multiplied by 1.35, as done for the effective radius. Column (6) : Log of the velocity dispersion measured within an aperture of $1R_e$ in units of km s^{-1} . The error in the derived velocity dispersion is 0.042 dex or 10%. Column (7) : Absolute magnitude of the galaxy derived from its r -band SDSS photometry. Column (8) : Log of the dynamical (M/L) of the galaxies derived using the Self-Consistent model. It is measured in units of $(M_\odot/L_\odot)$, and has an error of 0.04 dex or 10%. Column (9) : Log of the stellar (M/L)_{JAM}. Column (10) : Dark matter fraction within $1R_e$ of the galaxies based on the Abundance Matched model. Column (11) : Log of the total density at the scale radius (20 kpc) of the best fitting power law density profile, as derived using the Power Law model. This value is measured in units of $(M_\odot \text{pc}^{-3})$. Column (12) : The slope, γ , of the best fitting power law density profile, as derived using the Power Law model. Column (13) : Log of the stellar (M/L) for the galaxies derived from the best fitting power law density profile, as derived using the Power Law model. Column (14) : Dark matter fraction within $1R_e$ of the galaxies based on the Power Law model. Column (15) : Log of the stellar mass of the galaxies in units of $M_\odot$, calculated using the galaxies absolute magnitude and stellar $(M_*/L)_{dyn}^{AM}$. Column (16) : Quantity indicating the quality of the dynamical models based on the results of the Self-Consistent model. Column (17) : Hubble morphological classification of the galaxies taken from HyperLEDA (Makarov et al., 2014).

Galaxy	RA ($^\circ$)	Dec ($^\circ$)	$\log(R_e)$ (arcsec)	$\log(R_e^{\text{Maj}})$ (arcsec)	$\log(\sigma_e)$ (km s^{-1})	M_r (mag)	$\log(M/L)_{JAM}$ ($M_\odot/L_\odot$)	$\log(M_*/L)_{dyn}^{AM}$ ($M_\odot/L_\odot$)	$f_{DM,AM}$	$\log(\rho_{tot})$ ($M_\odot \text{pc}^{-3}$)	γ	$\log(M_*/L)_{dyn}^{PL}$ ($M_\odot/L_\odot$)	$f_{DM,PL}$	$\log(M_*)$ ($M_\odot$)	JAM Quality	Hubble Morph.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
IC3955	194.775146	27.996647	6.633	6.683	2.18	-20.704	0.763	0.767	0.15	-2.917	-2.134	0.707	0.16	10.905	2	S0
IC3973	194.878326	27.884117	5.135	5.511	2.29	-20.972	0.778	0.748	0.09	-2.680	-2.123	0.645	0.24	10.992	1	S0
IC3976	194.872345	27.850227	3.464	5.200	2.42	-20.534	1.075	1.038	0.05	-2.790	-2.276	0.907	0.10	11.108	1	E
IC3998	194.945053	27.973686	6.790	7.383	2.08	-20.478	0.735	0.683	0.17	-2.664	-1.782	0.544	0.46	10.730	1	S0
IC4011	195.026825	28.003969	5.026	5.256	1.95	-20.111	0.383	0.303	0.20	-4.150	-2.601	0.121	0.00	10.204	1	E
IC4012	195.033463	28.078413	3.280	3.687	2.23	-20.344	0.732	0.716	0.05	-3.128	-2.240	0.543	0.07	10.710	2	E
IC4021	195.061462	28.041180	3.783	4.001	2.15	-20.248	0.666	0.640	0.07	-3.074	-2.172	0.520	0.17	10.595	1	E
IC4026	195.092331	28.047106	—	—	—	—	—	—	—	—	—	—	—	—	—	S0
NGC4865	194.832718	28.084393	6.355	8.559	2.42	-21.624	0.914	0.811	0.11	-2.491	-2.074	0.732	0.20	11.317	2	E
NGC4867	194.813553	27.970776	4.635	5.179	2.31	-20.796	0.877	0.838	0.07	-2.710	-2.106	0.686	0.22	11.013	1	E
NGC4869	194.847214	27.911615	8.634	9.305	2.25	-21.467	0.716	0.609	0.21	-2.802	-2.096	0.646	0.00	11.051	1	E
NGC4871	194.874848	27.956432	9.492	10.306	2.22	-21.129	0.804	0.806	0.21	-2.996	-2.176	0.612	0.25	11.114	1	S0
NGC4872	194.891833	27.946944	5.261	5.334	2.29	-20.917	0.857	0.818	0.09	-2.492	-1.938	0.675	0.34	11.041	2	E/S0
NGC4873	194.886520	27.983559	7.646	8.905	2.21	-20.960	0.780	0.719	0.18	-2.856	-2.084	0.705	0.11	10.959	2	S0
NGC4874	194.898788	27.959389	55.611	55.609	2.39	-23.637	0.796	0.282	0.86	-2.282	-1.702	0.732	0.04	11.593	2	E
NGC4876	194.934921	27.912430	5.281	6.280	2.16	-20.751	0.657	0.597	0.12	-3.131	-2.218	0.560	0.04	10.754	2	E
NGC4882	195.018500	27.987583	—	—	—	—	—	—	—	—	—	—	—	—	—	E
NGC4883	194.983414	28.034805	6.537	6.542	2.16	-20.872	0.679	0.594	0.16	-3.005	-2.142	0.605	0.08	10.799	1	E/S0
NGC4889	195.033737	27.977024	45.906	56.733	2.53	-23.864	0.894	0.660	0.75	-2.242	-2.113	0.866	0.00	12.062	2	E
NGC4894	195.068970	27.967564	5.045	8.512	1.95	-20.196	0.518	0.455	0.20	-3.180	-1.958	0.294	0.45	10.389	2	S0
PGC044546	194.767273	27.959148	2.447	3.011	2.18	-18.992	1.147	1.280	0.03	-2.367	-1.767	0.992	0.39	10.733	0	E
PGC044574	194.834290	28.074392	—	—	—	—	—	—	—	—	—	—	—	—	—	—
PGC044581	194.834015	27.886061	5.077	7.048	1.98	-19.807	0.752	0.669	0.18	-2.877	-1.695	0.540	0.30	10.448	1	E/S0
PGC044585	194.844391	27.896894	3.115	3.299	2.05	-19.742	0.685	0.665	0.07	-3.058	-2.065	0.491	0.26	10.418	2	E/S0
PGC044594	194.860733	27.998562	3.857	4.602	1.85	-19.317	0.568	0.492	0.17	-2.975	-1.632	0.267	0.49	10.074	1	E/S0
PGC044597	194.855377	27.968006	5.000	6.137	1.90	-19.673	0.514	0.455	0.22	-3.360	-2.032	0.342	0.38	10.180	2	E/S0
PGC044598	194.856018	27.973284	3.916	4.847	2.07	-19.778	0.708	0.685	0.10	-4.450	-2.763	0.112	0.00	10.452	2	E/S0
PGC044602	194.869537	28.040504	4.064	4.693	1.95	-19.529	0.771	0.705	0.13	-2.834	-1.710	0.443	0.49	10.372	1	S0

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Table H.1 – Continued from previous page

PGC044609	194.868607	28.085505	5.644	5.789	2.02	-19.365	0.967	0.888	0.18	-1.461	-0.959	-5.000	1.00	10.490	0	S0
PGC044616	194.880875	28.046616	4.450	6.931	2.12	-20.353	0.659	0.595	0.12	-3.004	-1.997	0.483	0.22	10.592	2	E/S0
PGC044636	194.909485	27.987164	8.016	9.914	1.87	-19.670	0.751	0.634	0.35	-3.283	-1.900	0.685	0.13	10.358	1	S0
PGC044649	194.926437	27.924656	2.383	2.511	2.23	-19.714	0.837	0.821	0.03	-3.151	-2.311	0.689	0.14	10.562	2	E
PGC044652	194.934326	27.958540	4.872	7.113	1.96	-19.683	0.718	0.642	0.19	-2.790	-1.564	0.407	0.51	10.371	1	S0
PGC044654	194.916962	27.854939	3.870	4.995	1.91	-19.195	0.728	0.675	0.16	-3.107	-1.824	0.528	0.33	10.209	1	S0
PGC044662	194.942093	27.857149	4.204	5.345	1.96	-20.130	0.441	0.361	0.16	-3.562	-2.234	0.293	0.12	10.269	1	E/S0
PGC044666	194.958908	27.924801	3.705	4.418	1.83	-18.924	0.630	0.539	0.21	-3.251	-1.790	0.410	0.34	9.965	1	S0
PGC044675	194.986252	27.930084	7.159	8.157	1.85	-19.840	0.653	0.572	0.28	-2.607	-1.347	0.216	0.77	10.364	0	S0
PGC044676	194.962692	27.833138	3.815	5.990	1.96	-18.642	1.114	1.031	0.14	-2.832	-1.636	1.058	0.00	10.344	1	–
PGC044679	194.979630	28.128416	4.197	4.198	2.12	-19.810	0.845	1.027	0.08	-2.264	-1.548	0.636	0.59	10.807	0	E/S0
PGC044699	195.022995	27.807583	–	–	–	–	–	–	–	–	–	–	–	–	–	S0
PGC044716	195.038101	27.866467	4.212	4.812	1.79	-19.581	0.651	0.597	0.13	-2.269	-1.219	0.024	0.82	10.286	1	SBab
PGC044723	195.053619	28.075626	3.768	4.466	2.04	-19.998	0.624	0.580	0.10	-3.530	-2.323	0.383	0.14	10.436	2	E/S0
PGC044736	195.073669	27.955339	5.714	6.686	2.29	-21.265	0.695	0.633	0.11	-2.708	-2.061	0.550	0.20	10.995	1	E
PGC044740	195.070923	28.063951	3.458	3.812	1.97	-19.650	0.535	0.494	0.11	-3.576	-2.245	0.317	0.17	10.210	1	S0
PGC044741	195.078247	27.937098	–	–	–	–	–	–	–	–	–	–	–	–	–	E
PGC044763	195.116592	27.956005	3.772	4.050	2.04	-19.859	0.634	0.604	0.10	-3.021	-2.002	0.428	0.37	10.404	2	S0
PGC044771	195.118164	27.972395	6.460	10.030	1.90	-20.011	0.649	0.507	0.29	-3.111	-1.800	0.452	0.34	10.367	1	S0

Appendix I

Results of Coma cluster: Full Sample

Table I.1 Results of analysis of the Full sample of Coma cluster galaxies. Column (1) : Galaxy name. Column (2) : Right Ascension in degrees (J2000). Column (3) : Declination in degrees (J2000). Column(4) : Effective radii of the galaxies in arcsec. These quantities are derived from the MGE parametrisation of the galaxy photometry and have been multiplied by 1.35 as per the offset observed in ATLAS^{3D}. For more details, please refer to Section. 4.4.1. Column (5) : Major axis of the half-light isophote in arcsec. This is derived as per the prescription in Cappellari et al. (2013b) and has been multiplied by 1.35, as done for the effective radius. Column (6) : Log of the velocity dispersion measured in km s^{-1} . The error in the derived velocity dispersion is 0.042dex or 10%. Column (7) : Absolute magnitude of the galaxy derived from its r-band SDSS photometry. Column (8) : Log of the dynamical (M/L) of the galaxies derived using the Self-Consistent model. It is measured in units of ($M_{\odot}/L_{\odot}$), and has an error of 0.04dex or 10%. Column (9) : Log of the stellar (M/L) of the galaxies derived dynamically using the Abundance-Matching model. It is measured in units of ($M_{\odot}/L_{\odot}$), and similar errors as the dynamical (M/L)_{AM}. Column (10) : Stellar Mass-to-Light ratio in units of ($M_{\odot}/L_{\odot}$). These are derived by the regularised mass-weighted fitting of the galaxy spectra with stellar population models, assuming a Salpeter IMF. Column (11) : Mass-weighted stellar age of the galaxies in Gyr. Column (12) : Log of the stellar mass of the galaxies in units of $M_{\odot}$, calculated using the galaxies absolute magnitude and stellar (M_{*}/L)_{dyn}. Column (13) : Quantity stating if the galaxy has SAURON observations (=1) or not (=0). Column (14) : Hubble morphological classification of the galaxies taken from HyperLEDA (Makarov et al., 2014).

Galaxy	RA ($^{\circ}$) (2)	Dec ($^{\circ}$) (3)	$\log(R_e)$ (arcsec) (4)	$\log(R_{e}^{\text{Maj}})$ (arcsec) (5)	$\log(\sigma)$ (km s^{-1}) (6)	M_r (mag) (7)	$\log(M/L)_{AM}$ ($M_{\odot}/L_{\odot}$) (8)	$\log(M_{*}/L)_{dyn}^{AM}$ ($M_{\odot}/L_{\odot}$) (9)	$\log(M_{*}/L)_{prop}^{Salp}$ ($M_{\odot}/L_{\odot}$) (10)	Age (Gyr) (11)	$\log(M_{*})$ ($M_{\odot}$) (12)	SAURON (13)	Hubble Morph. (14)
IC3943	194.651505	28.113808	5.019	7.580	2.23	-20.809	0.756	0.754	0.768	11.42	10.934	0	S0
IC3946	194.702881	27.810249	5.013	6.300	2.31	-21.036	0.749	0.761	0.774	12.05	11.031	0	S0
IC3947	194.717026	27.784977	4.311	5.495	2.15	-20.410	0.668	0.656	0.731	11.39	10.676	0	S0
IC3955	194.775146	27.996647	6.633	6.683	2.14	-20.704	0.601	0.568	0.704	9.95	10.706	1	S0
IC3957	194.781067	27.767759	4.810	4.934	2.21	-20.395	0.729	0.723	0.786	12.35	10.737	0	E
IC3959	194.784210	27.784147	7.042	7.040	2.30	-21.078	0.766	0.762	0.804	12.68	11.050	0	E
IC3960	194.782974	27.854980	5.057	5.058	2.20	-20.472	0.694	0.683	0.807	12.53	10.727	0	S0
IC3960A	194.790207	27.867201	1.847	1.994	1.91	-18.665	0.558	0.530	0.647	9.89	9.852	0	-
IC3963	194.806183	27.774698	6.660	9.051	2.03	-20.485	0.542	0.501	0.688	10.76	10.551	0	S0
IC3973	194.878326	27.884117	5.135	5.511	2.36	-20.972	0.782	0.809	0.792	12.35	11.053	1	S0
IC3976	194.872345	27.850227	3.464	5.200	2.38	-20.534	0.970	1.060	0.816	12.89	11.130	1	E
IC3998	194.945053	27.973686	6.790	7.383	2.09	-20.478	0.625	0.593	0.671	9.00	10.640	1	S0
IC4011	195.026825	28.003969	5.026	5.256	2.07	-20.111	0.613	0.581	0.722	10.93	10.481	1	E
IC4012	195.033463	28.078413	3.280	3.687	2.24	-20.344	0.736	0.742	0.772	11.69	10.736	1	E
IC4021	195.061462	28.041180	3.783	4.001	2.20	-20.248	0.722	0.719	0.758	11.93	10.674	1	E
IC4026	195.092331	28.047106	6.883	7.438	2.08	-20.518	0.592	0.555	0.649	8.39	10.618	1	S0
IC4041	195.170059	27.996567	6.270	8.574	2.02	-20.371	0.631	0.601	0.720	10.84	10.605	0	E
IC4042	195.178238	27.971289	7.028	7.360	2.22	-21.046	0.620	0.601	0.748	11.58	10.875	0	S0
IC4045	195.202820	28.090727	5.527	6.967	2.32	-21.142	0.789	0.809	0.798	12.49	11.122	0	E
IC4051	195.226898	28.007555	13.551	15.177	2.39	-21.747	0.955	0.955	0.827	12.72	11.510	0	E
NGC4850	194.591064	27.967701	5.570	6.028	2.24	-20.932	0.655	0.642	0.746	11.39	10.871	0	S0
NGC4853	194.646606	27.956310	5.537	6.257	1.97	-21.570	-0.078	-0.142	0.387	4.63	10.342	0	E/S0
NGC4854	194.697617	27.674692	12.533	14.367	2.28	-21.205	0.872	0.858	0.794	12.67	11.196	0	S0
NGC4860	194.766342	28.123594	8.811	9.611	2.42	-21.697	0.823	0.850	0.834	12.77	11.384	0	E
NGC4865	194.832718	28.084393	6.355	8.559	2.38	-21.624	0.786	0.813	0.784	12.20	11.319	1	E
NGC4867	194.813553	27.970776	4.635	5.179	2.29	-20.796	0.728	0.735	0.785	12.22	10.909	1	E
NGC4871	194.874848	27.956432	9.492	10.306	2.23	-21.129	0.706	0.683	0.768	11.77	10.991	1	S0
NGC4872	194.891833	27.946944	5.261	5.334	2.30	-20.917	0.735	0.742	0.770	11.56	10.965	1	E/S0
NGC4873	194.886520	27.983559	7.646	8.905	2.24	-20.960	0.763	0.750	0.724	10.85	10.990	1	S0
NGC4874	194.898788	27.959389	55.611	55.609	2.42	-23.637	0.840	0.594	0.806	12.09	11.905	1	E
NGC4875	194.907883	27.907442	3.975	4.447	2.24	-20.414	0.760	0.764	0.764	11.94	10.786	0	S0
NGC4876	194.934921	27.912430	5.281	6.280	2.18	-20.751	0.652	0.636	0.696	10.82	10.792	1	E

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NGC4881	194.990631	28.246473	10.748	10.826	2.28	-21.600	0.639	0.609	0.781	12.37	11.105	0	E
NGC4882	195.018500	27.987583	8.659	8.759	2.16	-21.144	0.539	0.496	0.721	11.09	10.810	1	E
NGC4883	194.983414	28.034805	6.537	6.542	2.20	-20.872	0.656	0.626	0.741	10.72	10.830	1	E/S0
NGC4889	195.033737	27.977024	45.906	56.733	2.58	-23.864	0.908	0.913	0.842	12.91	12.315	1	E
NGC4894	195.068970	27.967564	5.045	8.512	1.90	-20.196	0.336	0.295	0.571	7.19	10.230	1	S0
NGC4895	195.074799	28.202284	9.472	15.096	2.38	-21.942	0.838	0.846	0.751	11.06	11.479	0	S0
NGC4895A	195.037903	28.170355	4.620	5.543	2.14	-20.175	0.771	0.761	0.678	9.21	10.687	0	E
NGC4896	195.128113	28.346287	9.151	12.268	2.16	-21.306	0.628	0.606	0.743	11.04	10.985	0	E/S0
NGC4906	195.165649	27.923790	7.049	7.578	2.24	-20.933	0.741	0.724	0.757	11.44	10.953	0	E
NGC4907	195.203156	28.158228	14.852	21.309	2.16	-21.627	0.709	0.631	0.735	10.66	11.138	0	Sb
NGC4908	195.214920	28.042830	–	–	–	–	–	–	–	–	–	–	E
NGC4911	195.233734	27.790779	17.943	20.558	2.13	-22.164	0.515	0.402	0.543	6.83	11.124	0	SABb
NGC4919	195.323395	27.808941	6.846	8.915	2.25	-21.289	0.628	0.627	0.759	10.90	10.998	0	S0
NGC4921	195.358887	27.885981	41.310	41.666	2.28	-22.821	0.704	0.569	0.805	12.87	11.554	0	Sab
NGC4923	195.382355	27.847424	9.205	9.909	2.30	-21.520	0.660	0.644	0.815	12.86	11.108	0	E/S0
NGC4927	195.489853	28.005817	11.019	12.994	2.44	-21.660	0.974	1.030	0.827	12.65	11.550	0	E/S0
PGC044351	194.447021	27.833176	3.182	5.193	2.05	-20.173	0.533	0.513	0.704	11.08	10.438	0	S0
PGC044364	194.450134	27.882900	6.313	7.450	2.18	-20.614	0.705	0.691	0.707	10.18	10.793	0	E
PGC044367	194.452759	28.180401	4.049	4.280	2.15	-20.322	0.608	0.592	0.716	10.96	10.577	0	E
PGC044390	194.514557	27.814863	3.383	5.077	2.20	-20.213	0.775	0.777	0.736	11.16	10.718	0	S0
PGC044440	194.580109	27.762142	2.782	4.058	1.67	-18.918	0.309	0.247	0.551	7.93	9.671	0	E
PGC044466	194.632919	28.049644	2.970	2.969	2.02	-19.367	0.619	0.590	0.683	10.69	10.192	0	E/S0
PGC044467	194.625977	28.014647	8.075	8.584	2.29	-21.154	0.755	0.747	0.787	12.69	11.065	0	E
PGC044469	194.631577	27.673532	2.851	3.271	2.10	-19.378	0.780	0.773	0.690	10.84	10.380	0	E
PGC044511	194.711563	28.083862	3.570	4.557	2.05	-19.863	0.636	0.616	0.691	10.50	10.417	0	S0
PGC044518	194.721100	27.813311	4.341	6.460	1.75	-19.294	0.412	0.339	0.688	10.73	9.913	0	S0
PGC044522	194.730164	27.964701	2.408	2.846	2.17	-19.687	0.753	0.757	0.748	11.64	10.488	0	E/S0
PGC044523	194.733810	28.463591	6.044	7.181	1.63	-19.445	0.172	-0.069	0.051	2.02	9.565	0	Sab
PGC044533	194.750290	27.967482	3.905	4.364	1.72	-19.273	0.181	0.070	0.575	7.30	9.635	0	E
PGC044537	194.757523	28.225260	5.925	6.920	2.26	-20.889	0.771	0.777	0.708	10.26	10.989	0	S0/a
PGC044546	194.767273	27.959148	2.447	3.011	2.07	-18.992	0.848	0.843	0.716	11.17	10.296	1	E
PGC044547	194.769165	27.910814	3.583	5.349	1.99	-19.651	0.647	0.629	0.705	10.82	10.345	0	S0
PGC044560	194.807892	28.076363	12.827	13.303	2.11	-20.650	0.824	0.758	0.684	11.65	10.874	0	E/S0
PGC044562	194.792953	27.619978	3.573	3.755	2.06	-19.705	0.646	0.624	0.728	11.43	10.362	0	E
PGC044573	194.834244	28.198004	4.539	5.652	1.70	-19.329	0.230	0.130	0.675	10.44	9.718	0	S0
PGC044574	194.834290	28.074392	5.462	5.461	1.39	-19.094	-0.306	-1.294	0.581	8.47	8.199	1	–
PGC044581	194.834015	27.886061	5.077	7.048	1.79	-19.807	0.389	0.329	0.651	9.94	10.108	1	E/S0
PGC044585	194.844391	27.896894	3.115	3.299	2.05	-19.742	0.585	0.566	0.676	10.56	10.319	1	E/S0
PGC044592	194.858826	28.287451	3.445	4.580	1.44	-18.950	-0.206	-0.424	0.422	5.20	9.013	0	S0
PGC044594	194.860733	27.998562	3.857	4.602	1.91	-19.317	0.577	0.531	0.663	10.24	10.114	1	E/S0
PGC044596	194.853821	27.738840	3.110	3.823	2.10	-19.888	0.679	0.669	0.731	11.35	10.481	0	E/S0
PGC044597	194.855377	27.968006	5.000	6.137	1.83	-19.673	0.339	0.279	0.690	10.75	10.004	1	E/S0
PGC044598	194.856018	27.973284	3.916	4.847	2.06	-19.778	0.691	0.676	0.694	10.88	10.443	1	E/S0
PGC044602	194.869537	28.040504	4.064	4.693	1.95	-19.529	0.576	0.538	0.685	10.72	10.205	1	S0
PGC044608	194.877686	27.791338	3.266	3.350	1.92	-19.301	0.473	0.426	0.600	8.05	10.002	0	E
PGC044609	194.868607	28.085505	5.644	5.789	1.23	-19.365	-0.704	-3.427	0.412	5.94	6.175	1	S0
PGC044616	194.880875	28.046616	4.450	6.931	2.07	-20.353	0.595	0.576	0.687	9.37	10.573	1	E/S0
PGC044636	194.909485	27.987164	8.016	9.914	1.75	-19.670	0.401	0.244	0.641	9.74	9.968	1	S0
PGC044644	194.915241	27.953909	5.192	8.011	1.89	-19.891	0.489	0.446	0.663	10.11	10.259	0	S0
PGC044649	194.926437	27.924656	2.383	2.511	2.23	-19.714	0.787	0.800	0.726	11.43	10.542	1	E
PGC044651	194.917801	27.968237	5.476	8.109	1.95	-19.579	0.674	0.628	0.697	10.61	10.316	0	S0
PGC044652	194.934326	27.958540	4.872	7.113	1.70	-19.683	0.238	0.164	0.613	9.13	9.893	1	S0
PGC044654	194.916962	27.854939	3.870	4.995	1.82	-19.195	0.483	0.437	0.703	10.84	9.970	1	S0
PGC044662	194.942093	27.857149	4.204	5.345	2.03	-20.130	0.516	0.491	0.606	7.54	10.399	1	E/S0
PGC044666	194.958908	27.924801	3.705	4.418	1.63	-18.924	0.150	0.004	0.688	10.68	9.430	1	–

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PGC044667	194.946411	27.710354	6.194	9.511	2.14	-21.138	0.573	0.548	0.665	9.53	10.860	0	S0
PGC044675	194.986252	27.930084	7.159	8.157	1.93	-19.840	0.615	0.559	0.684	10.51	10.351	1	S0
PGC044676	194.962692	27.833138	3.815	5.990	1.53	-18.642	0.339	0.191	0.589	8.63	9.504	1	–
PGC044679	194.979630	28.128416	4.197	4.198	2.07	-19.810	0.651	0.621	0.706	10.53	10.401	1	E/S0
PGC044699	195.022995	27.807583	4.462	8.316	2.02	-20.189	0.658	0.635	0.681	9.10	10.566	1	S0
PGC044704	195.026123	27.775915	5.987	7.822	2.07	-20.132	0.745	0.718	0.695	10.03	10.627	0	E/S0
PGC044710	195.026108	27.685360	3.845	4.169	2.12	-19.676	0.791	0.781	0.697	10.95	10.507	0	E
PGC044716	195.038101	27.866467	4.212	4.812	1.62	-19.581	-0.082	-0.296	0.140	4.16	9.393	1	SBab
PGC044723	195.053619	28.075626	3.768	4.466	2.02	-19.998	0.533	0.510	0.648	8.85	10.366	1	E/S0
PGC044740	195.070923	28.063951	3.458	3.812	1.99	-19.650	0.556	0.530	0.710	10.84	10.246	1	S0
PGC044741	195.078247	27.937098	6.888	7.961	1.43	-19.439	-0.206	-1.041	0.594	8.70	8.590	1	E
PGC044763	195.116592	27.956005	3.772	4.050	2.04	-19.859	0.548	0.528	0.714	11.04	10.327	1	S0
PGC044771	195.118164	27.972395	6.460	10.030	1.91	-20.011	0.556	0.501	0.656	10.08	10.362	1	S0
PGC044773	195.135498	27.766010	4.856	6.935	1.88	-19.372	0.647	0.598	0.666	10.29	10.203	0	S0/a
PGC044784	195.148026	28.146290	4.918	11.332	1.72	-20.165	0.244	0.147	0.622	9.09	10.069	0	S0
PGC044792	195.161575	28.014345	7.632	9.716	1.96	-20.308	0.576	0.524	0.614	8.85	10.503	0	S0/a
PGC044805	195.184296	28.337400	4.247	6.129	2.03	-20.494	0.499	0.478	0.619	8.15	10.532	0	S0
PGC044809	195.178558	27.963232	6.246	6.706	2.02	-20.210	0.516	0.476	0.700	10.56	10.416	0	S0
PGC044815	195.185822	28.100731	3.437	5.921	1.90	-19.602	0.552	0.513	0.688	10.67	10.210	0	S0
PGC044821	195.197403	27.922117	4.739	6.271	1.93	-19.681	0.598	0.568	0.628	8.72	10.297	0	S0/a
PGC044848	195.216965	28.366161	6.556	7.571	2.22	-21.263	0.538	0.524	0.697	9.51	10.885	0	E/S0
PGC044849	195.246735	27.899782	4.924	8.268	2.10	-20.452	0.656	0.643	0.644	7.99	10.679	0	S0/a
PGC044850	195.294510	27.802837	6.089	7.715	1.95	-20.064	0.499	0.453	0.686	10.65	10.334	0	E/S0
PGC044864	195.288544	27.818117	6.588	7.530	2.12	-20.136	0.761	0.741	0.693	10.89	10.651	0	E/S0
PGC044878	195.306778	27.914225	4.531	4.548	1.94	-19.403	0.563	0.515	0.673	10.49	10.132	0	–
PGC044897	195.363083	27.999083	2.150	2.321	2.18	-19.329	0.856	0.868	0.745	11.31	10.456	0	E
PGC044928	195.445847	28.094929	4.816	7.648	2.23	-20.907	0.718	0.713	0.776	11.63	10.932	0	E/S0
PGC044929	195.459320	27.893538	5.202	5.435	2.30	-20.521	0.837	0.854	0.738	11.14	10.919	0	E
PGC044947	195.500641	27.782766	3.083	5.859	1.68	-20.088	-0.116	-0.194	-0.012	1.40	9.697	0	S0
PGC083691	194.401749	28.076902	6.135	7.080	1.46	-19.188	-0.078	-0.786	0.577	8.40	8.745	0	S0
PGC083695	194.442368	27.757063	6.803	16.336	1.54	-20.187	0.126	-0.095	0.603	8.91	9.836	0	S0
PGC083702	194.460815	27.879295	4.631	5.588	1.98	-19.726	0.603	0.564	0.693	10.84	10.310	0	E/S0
PGC083715	194.540588	27.549587	3.444	3.933	1.65	-18.608	0.278	0.106	0.566	8.19	9.405	0	E
PGC083716	194.557617	28.182692	8.470	12.626	1.79	-20.200	0.483	0.431	0.575	7.89	10.367	0	S0
PGC083727	194.722565	28.126089	3.566	3.994	2.05	-19.736	0.633	0.612	0.707	10.94	10.362	0	E
PGC083729	194.742172	27.594704	3.177	3.954	2.15	-19.995	0.739	0.738	0.746	11.22	10.592	0	S0
PGC083735	194.922058	28.507158	9.664	9.852	1.52	-19.665	-0.046	-0.731	0.558	8.11	8.991	0	S0
PGC083736	194.922195	27.659658	9.044	9.078	1.63	-19.639	0.177	-0.199	0.630	8.94	9.512	0	Sab
PGC083743	195.043320	27.595076	4.794	5.646	1.75	-19.113	0.419	0.310	0.656	10.05	9.812	0	S0
PGC083746	195.079773	27.553766	5.035	5.467	2.03	-20.134	0.553	0.516	0.722	10.81	10.426	0	E/S0
PGC083747	195.112061	27.515448	4.445	4.932	1.96	-19.806	0.492	0.449	0.707	10.93	10.227	0	E
PGC083753	195.287674	28.359783	5.943	6.511	1.79	-19.873	0.193	0.105	0.561	7.60	9.911	0	E/S0
PGC083754	195.301041	27.604506	4.331	10.045	1.68	-19.577	0.420	0.310	0.586	8.57	9.997	0	S0
PGC083755	195.345001	28.196018	6.384	7.481	2.12	-20.247	0.740	0.721	0.699	10.94	10.676	0	E/S0
PGC083757	195.451721	27.604094	4.460	7.360	1.86	-19.623	0.589	0.543	0.652	9.86	10.248	0	S0
PGC083760	195.542709	28.191938	8.797	8.945	1.73	-19.510	0.314	0.171	0.697	10.51	9.831	0	E/S0
PGC093693	194.547562	27.939863	3.164	3.163	1.63	-18.762	0.112	-0.062	0.635	10.10	9.298	0	E
PGC093697	194.789307	28.041090	3.398	5.009	1.52	-18.411	0.250	0.105	0.563	8.13	9.325	0	–
PGC126760	195.077377	27.815432	5.841	6.279	1.35	-18.877	-0.224	-1.922	0.496	7.04	7.485	0	–
PGC126766	195.036331	28.159800	6.879	6.926	1.49	-19.110	-0.016	-0.774	0.610	9.07	8.726	0	–

Appendix J

JAM model Summary of Coma Cluster

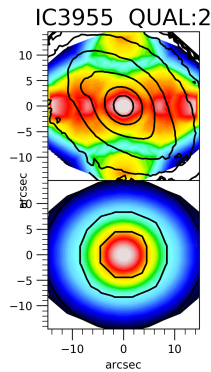
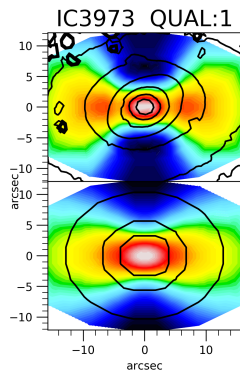
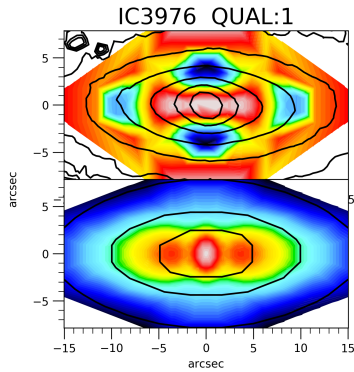


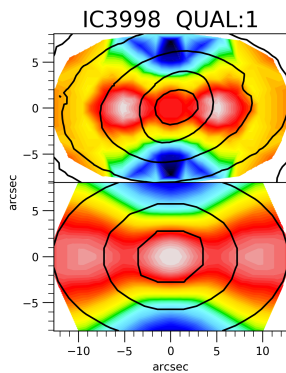
Fig. J.1 Visual inspection of the velocity dispersion field of the galaxy suggests that the observed extension of the bulge along the major axis is likely due to noise and is not a real feature. Given the well modelled shape and normalisation of the stellar kinematics, I assign this model a *QUAL* of 2.



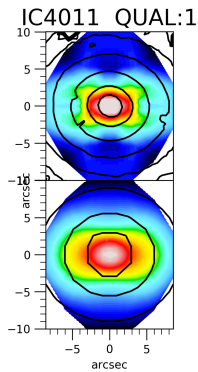
For this galaxy, I assign a *QUAL* of 1 since the observed symmetric peaks in the stellar kinematics aren't reproduced by the model but general normalisation of the kinematics is well matched.



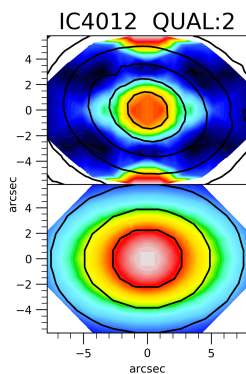
Similar to the IC3973 (above), the *QUAL* value of this galaxy is set to 1 due to the contrast in the shape but well matched normalisation between the observed and model kinematics.



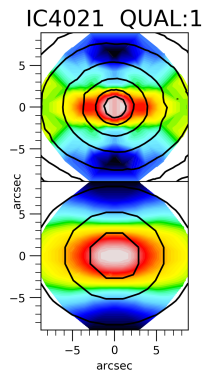
In this galaxy, due to offset of the position of the peaks along the major axis between the observation and the model, I selected a value of 1 for the *QUAL* keyword.



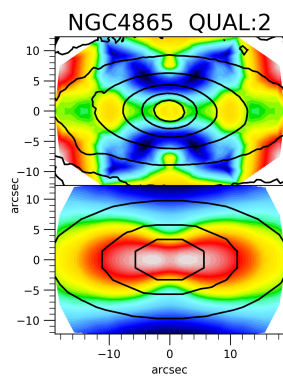
Here I set *QUAL* to 1 due to difference in the shape of the the kinematics despite the well modelled normalisation.



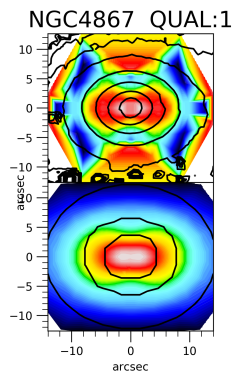
For IC4012, I set the *QUAL* to 2 despite the contrast in the shape of the kinematics. This was because the visual inspection of the velocity dispersion of the galaxy suggests that this extension is likely due to noise in the data.



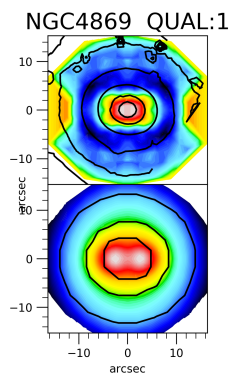
In this plot, it is clear that the model has not been successful in modelling the shape of the galaxy kinematics, however the normalisation of the kinematics does look reliable. Hence for this galaxy I have set the *QUAL* to 1.



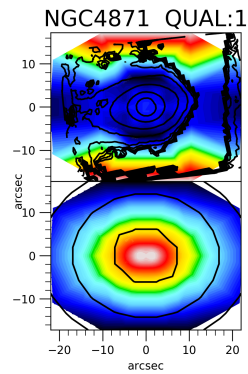
Here we see that the model for the galaxy has reproduced the features of the stellar kinematics of the galaxies while having a reliable normalisation and hence I assign this model a *QUAL* if 2.



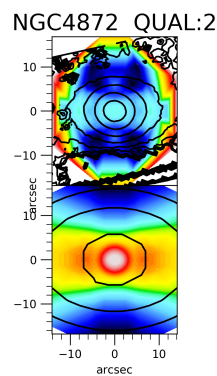
The two plots for NGC4867 demonstrate that the model is unable to reproduce the extended shape of the central bulge of the galaxy and hence for this galaxy, I assigned *QUAL* as 1.



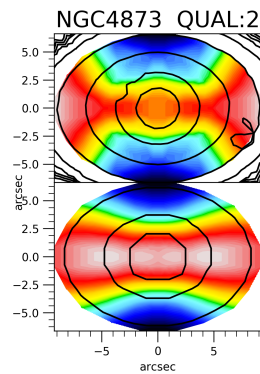
For the model fo NGC4869, I assign *QUAL* as 1 due to difference in the shape of the kinematics but well reproduced normalisation.



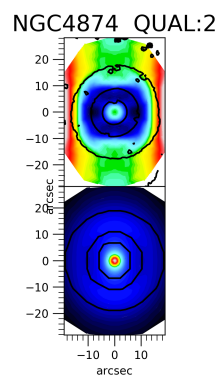
Similar to previous galaxy (NGC4869), the model for NGC4871 doesn't reproduce the features of the observed stellar kinematics and hence *QUAL* was set to 1.



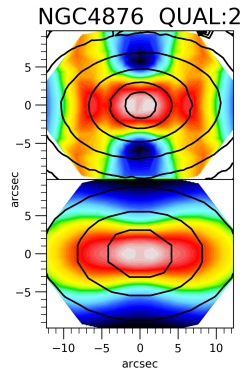
These plots illustrate the well reproduced shape of the stellar kinematics of the galaxies. Hence, this model was assigned a *QUAL* of 1.



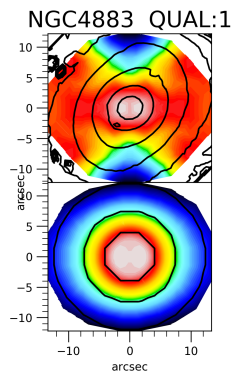
Despite the slight difference in the two plots, the dynamical model of NGC4873 reproduces all the observed kinematics features and hence is assigned a *QUAL* of 2.



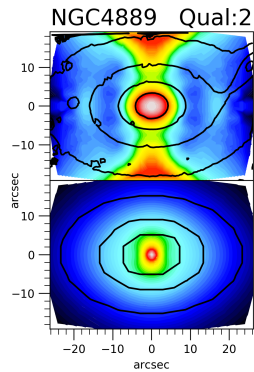
In these plots, the model accurately reproduces the lack of significant rotation of the observed, while not modelling the light blue feature which is likely to be the result of noise. Hence for this model, I assign the quality keyword, *QUAL*, to be 2.



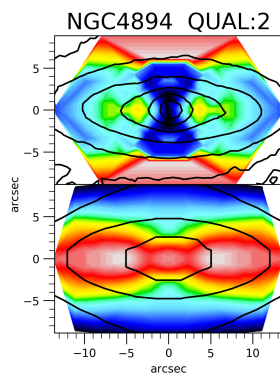
Here, I assign the keyword *QUAL* to 2, despite the contrast in the shape of the kinematics in the central region of the galaxy. This is because the central 2'' of the galaxy is masked during the dynamical modelling process because of the significant effect of the SMBH on the galaxy kinematics. Neglecting the central region, the model reproduces the twin peaks in kinematics along the major axis (though the X-shape present in the observed kinematics is unrealistic and likely due to some spurious points).



In the case of NGC4883, the dynamical modelling process is unable to reproduce the observed shape of the stellar kinematics and hence for this galaxy I set the *QUAL* to 1.

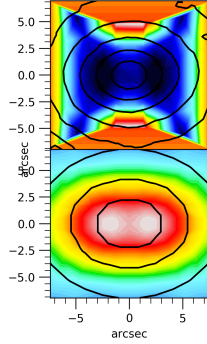


In the case of NGC4889, the JAM models reproduce the kinematic structure of the galaxy (the high kinematics along the y-axis of the plot are likely driven by noise and hence ignored) and hence for this galaxy I set the *QUAL* to 2.



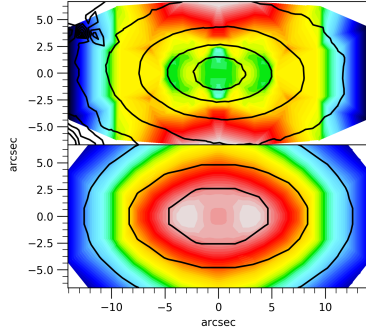
Similar to NGC4874, here we see that model accurately models the lack of significant rotation within the galaxy kinematics. Hence, I assign these galaxies with a quality keyword, *QUAL*, of 2.

PGC044546 QUAL:0



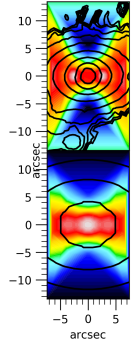
For PGC044546, due to the low S/N of the observations, the derived kinematics is unreliable and consequently the dynamical modelling process is unable to reproduce the shape of the kinematics. Hence for this model, I set *QUAL* to 0.

PGC044581 QUAL:1



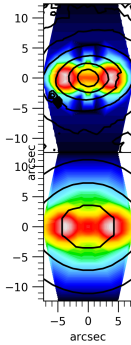
For PGC044581, the velocity dispersion field couldn't be reliably derived due to low S/N and hence a constant velocity dispersion field of value, equal to velocity dispersion derived in the central spaxel, is used to calculate the second kinematic moment of the galaxy. Hence, despite the fact that the dynamical modelling process reproduces the observed kinematic field, I assign *QUAL*=1.

PGC044585 QUAL:2

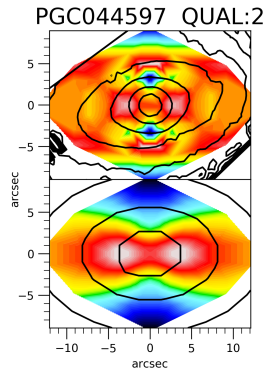


Here the plots demonstrate how well the dynamical model of the galaxy reproduces the observed kinematics. Hence for this galaxy, I assign *QUAL* to 2.

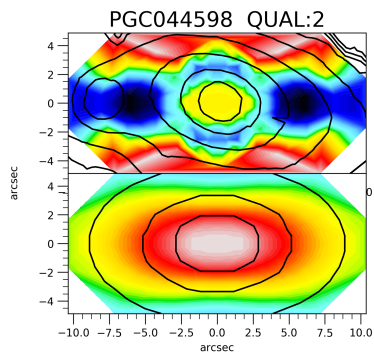
PGC044594 QUAL:1



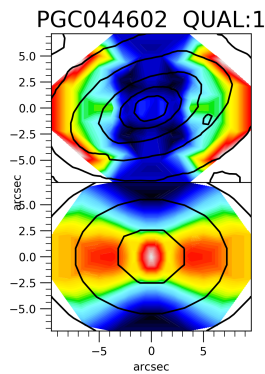
Similar to PGC044581, the low S/N of the data prevents the derivation of reliable stellar dispersion field and hence I use a constant velocity dispersion field. Due to this reason, I set *QUAL* to 1 for this model.



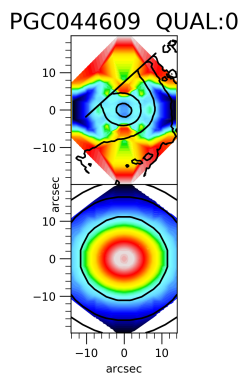
Since the dynamical model of the galaxy reproduces the observed stellar kinematics, I fixed *QUAL* to 2.



Similar to PGC044581, the low S/N of the data prevents the derivation of a reliable velocity dispersion. Due to this reason, I set *QUAL* to 1 for this model.

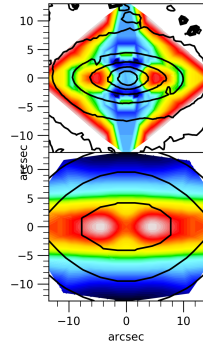


For this galaxy, the dynamical model do reproduce the features of the observed stellar kinematics, however these features aren't accurately reproduced. Hence for this galaxy I set the quality of the dynamical model, *QUAL*, to 1.



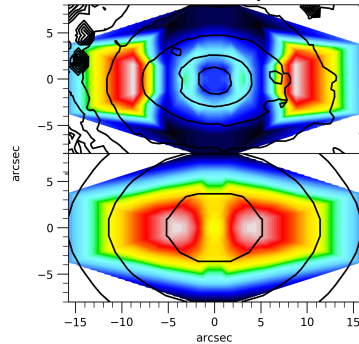
As the plots demonstrate, the dynamical model of the galaxy is unable to reproduce the observed feature and hence *QUAL* is set to 0.

PGC044616 QUAL:2



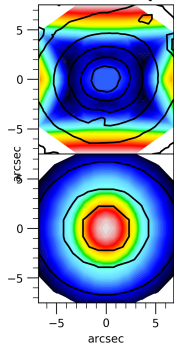
Given the good representation of the observed kinematics of the galaxy by the model, *QUAL* for this galaxy is set to 2.

PGC044636 QUAL:1



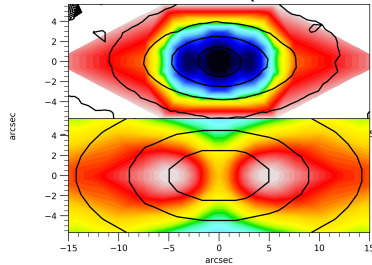
Similar to PGC044581, the derived velocity dispersion of this galaxy is unreliable and hence *QUAL* is set to 1.

PGC044649 QUAL:2

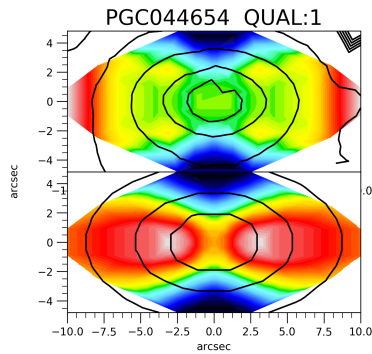


The two panels here illustrate the good match between observed and the model of the stellar kinematic of PGC044649 and hence I set *QUAL* to 2 for this galaxy.

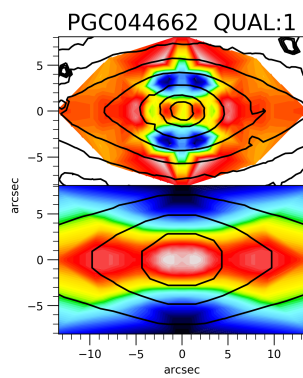
PGC044652 QUAL:1



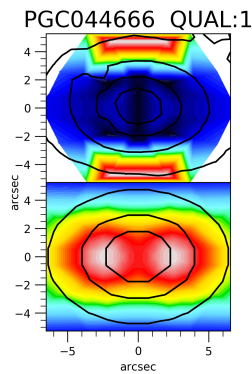
Due to the low S/N observation of the galaxy, the velocity dispersion of the galaxy was not derived accurately and hence *QUAL* for this galaxy was set to 1.



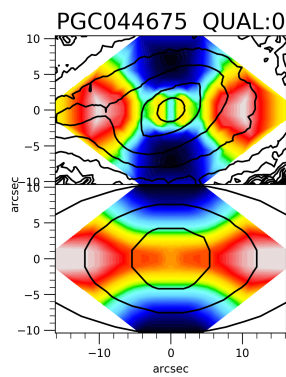
In this galaxy, I find that the low S/N of the galaxy doesn't permit the accurate derivation of velocity dispersion of the galaxies and hence $QUAL$ is set to 1 for this model.



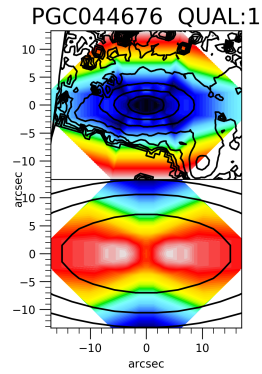
Despite the reproduction of most aspects of the observed kinematics by the model, the noisy nature of the unsmoothed kinematics maps make the observed kinematics unreliable and hence I set $QUAL$ to 1.



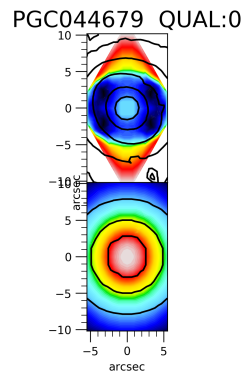
Here, the stark contrast between the observations and the model, and the fact that low S/N of the data lead to unreliable velocity dispersion estimation, I assign $QUAL=1$ for this galaxy.



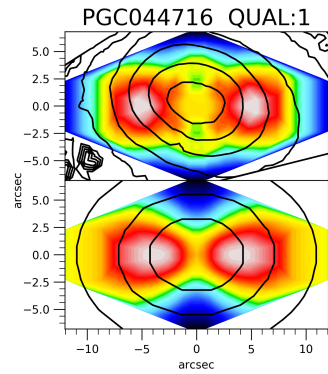
Due to the significant disparity between the observation and model, I characterise the quality of the model, $QUAL$, as 0.



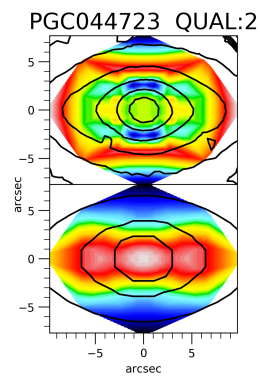
For this galaxy, I set *QUAL* to 1 due to the low S/N of the galaxy observations leading to the use of a constant velocity dispersion map for the galaxy.



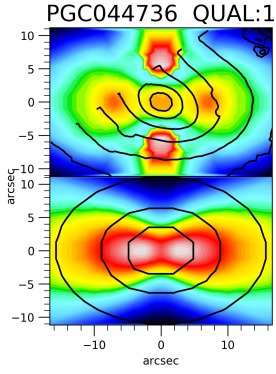
Due to the large disparity between the observed and model kinematic maps of the galaxy, I assign the model's quality keyword, *QUAL*, to 0.



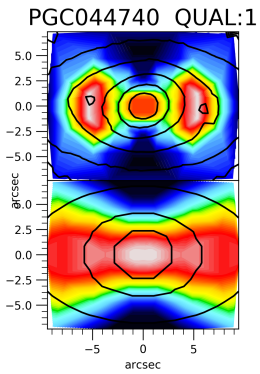
Similar to PGC044581, the unreliable estimation of the velocity dispersion map of the galaxy, I assign the model a quality keyword, *QUAL*, value of 1.



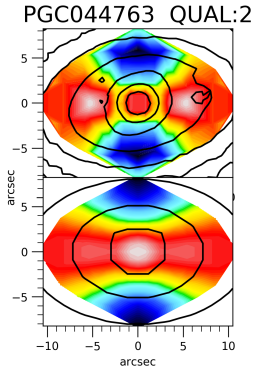
Though the central region of the galaxy is not well reproduced by the model, the outer kinematic features are well reproduced and hence I assign the model a quality value of 2.



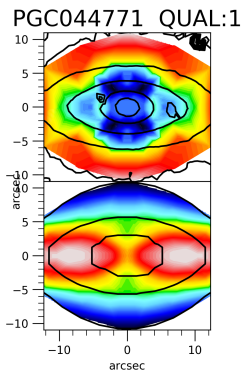
Due to the close proximity of this galaxy to another in the sky, it makes the derived kinematics of the galaxy unreliable and hence the *QUAL* keyword of the model is set to 1.



Despite the apparent good reproduction of the observed galaxy kinematics by the model, the observed twin peak in the kinematics along the major axis of the galaxy is driven by two low S/N spaxels and hence may be unrealistic and hence this model quality, *QUAL*, is assigned 1.



Since the model reproduces the different aspects of the kinematic field, I set the quality keyword *QUAL*, to 2.



Due insufficient S/N in the galaxy observations, reliable velocity dispersion maps couldn't be derived and hence the model quality is set to 1.