Shaping massive galaxies: the structural evolution of galaxies across 0<1

Graaff, A.G. de

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1 | INTRODUCTION

1.1 The rich diversity of galaxies

A zoo of galaxies populates our Universe, of which the Milky Way provides just one, highly complex example. To understand the origins of our own galaxy and to be able to contextualise our place in the Universe, requires the study of nearby stars and distant galaxies.

The detailed mapping of the stars in the Milky Way has revealed that our galaxy alone already consists of multiple, intertwined structures. Whereas the central region comprises mainly old ($\sim 10\,\mathrm{Gyr}$) stars that together form a round bulge, the majority of stars (including the Sun) form a large disc, which is composed of prominent spiral arms and contains many gaseous star-forming regions. The disc can be decomposed into a thick and thin disc, with distinct differences in the ages and chemical compositions between the two groups of stars that make up these structures. Moreover, the bulge and disc are again encompassed by a stellar halo that is spherical in shape. These different observations all point toward a complex, multi-phase assembly history of the galaxy (for a review, see Bland-Hawthorn & Gerhard 2016), which still forms an active field of research.

Further from home, a new area of astronomy was opened up with the discovery of other galaxies in the nearby Universe. Over the past centuries, astronomers have catalogued thousands of objects in the night sky, perhaps one of the most famous of which being the Andromeda nebula. Although the nature of Andromeda and other nebulae had been subject to debate for longer, it was only one hundred years ago that Edwin Hubble discovered, based on the first accurate distance estimates, that Andromeda is in fact not a nebula, but an entirely different galaxy. Tremendous progress has since been made in the field of extragalactic astronomy. The few galaxies originally documented have been superseded by large imaging surveys with powerful telescopes that have by now catalogued millions of galaxies in the local Universe and much beyond.

Although the formation path of the Milky Way is unique, efforts to survey the night sky have revealed a large number of galaxies with similar properties to our own galaxy. Specifically, these galaxies are disc-like in shape and have ongoing star formation, and are therefore observed to have blue colours (Roberts & Haynes 1994). Despite their similarities, there is significant variation as well, as galaxies span a wide range in luminosity and size (Blanton et al. 2003). Moreover, the morphologies of some can be described as pure discs, whereas others also have red central bulges that can comprise nearly half of the total stellar mass. Nevertheless, these galaxies are commonly grouped into a single class of ‘spiral’ or ‘late-type’ galaxies, a classification that was proposed by Hubble (1926, 1936) based on morphology alone, or ‘star-forming’ galaxies when selected by colour.

On the other hand, many of the more luminous galaxies contain no discs at all, and instead are spheroidal in shape, reminiscent of the central bulge of the Milky Way. In addition to their different shapes, these galaxies typically have very red colours, indicating old stellar populations in which no new stars are formed, and have light distributions that are highly centrally concentrated (e.g., Kauffmann et al. 2003). These objects are often categorised as ‘elliptical’ or ‘early-type’ galaxies on the Hubble sequence, a misnomer given that the red galaxies must represent an evolutionary phase that follows after the ‘late-type’ epoch of star formation, or are labelled ‘quiescent’ galaxies.

How we have arrived at the present-day Universe with its great diversity of galaxy shapes, morphologies, and colours is a challenging question. To grasp not only the differences, but also the similarities between different types of galaxies requires observations of local galaxies and their distant counterparts to piece together the average evolution histories. Remarkably, the foundations for the formation of galaxies were already established shortly after the Big Bang. Vast progress has been made in the past century in our understanding of the subsequent 13 billion years of evolution.

1.2 Hierarchical formation of structure

Shortly after the Big Bang all matter in the Universe was extremely dense, hot and ionised, and therefore opaque to radiation. As the Universe expanded and cooled with time, electrons and protons were able to combine and form neutral atoms. The corresponding decrease in free electrons and the greatly expanded space allowed for photons to stream freely for the first time (Peebles 1968), approximately 380 000 years after the Big Bang. Radiation from this epoch permeates the entire Universe and is still observable today, although strongly cooled down, and known as the cosmic microwave background (CMB; Penzias & Wilson 1965; Dicke et al. 1965).

The CMB is highly homogeneous and isotropic, with a spectral shape that is a near-perfect black body of temperature $T = 2.73\,\mathrm{K}$ (Fixsen et al. 1996; Bennett et al. 2013; Planck Collaboration et al. 2020). Deviations from this temperature across different regions of the sky are of order $\Delta T/T \sim 10^{-5}$, and are caused by very small fluctuations in the underlying matter density that were already present in the early Universe.

Encoded in the details of these temperature fluctuations is critical information on the nature of the matter in the Universe (e.g., White et al. 1994; Scott et al. 1995). The magnitude of the fluctuations and the associated spatial scales indicate that the Universe is composed of not only ordinary baryonic matter, but also non-baryonic ‘dark’ matter. The nature of dark matter is still unknown, but its inferred properties are well-described by particles that are non-baryonic, weakly-interacting and had relatively low thermal velocities shortly after the Big Bang, and therefore referred to as cold dark matter (CDM).

The leading cosmological model for the last two decades has been the flat ΛCDM model, which describes the expansion history of the Universe and the time evolution of the energy densities of radiation, baryonic matter, cold dark matter, and the cosmological constant (Λ). This constant, a mysterious component that is also referred to as dark energy, is negligible in the early Universe, but comprises the majority of the energy density in the late-time Universe and governs the current accelerated expansion (Riess et al. 1998; Perlmutter et al. 1999).

Importantly, fits of the ΛCDM model to full-sky maps of the CMB have shown that there is approximately five times more dark matter than baryonic matter (Bennett et al. 2013; Planck Collaboration et al. 2020), which greatly affects the formation of structure. Whereas the baryons and photons were coupled in the early Universe, forming a fluid with complex oscillatory behaviour (Peebles & Yu 1970), the weakly-interacting dark matter was able to clump together by gravitational attraction. Very small primordial fluctuations in the matter density therefore grew into increasingly large density perturbations: this is the foundation for the hierarchical formation of structure.

Eventually, density perturbations became large enough that the local overdensities underwent gravitational collapse, forming dark matter haloes (e.g., Peacock 1999, Chapter 15, 17). These dark matter haloes formed the building blocks for galaxy formation, as the baryonic gas inside these haloes was able to cool and condense further. The first stars formed from this cooled gas, likely around ~ 100 million years after the Big Bang, giving rise to the very first galaxies.

At the present day, the initial density perturbations have grown into not only very large haloes, but also filamentary and sheet-like structures that span scales of $1 - 100\,\mathrm{Mpc}$. These structures are not distributed randomly, but form a cosmic web of dark and baryonic matter. Galaxies lie in the nodes of this web: rather than being islands of luminous stars, their evolution is strongly connected to the surrounding environment, as galaxies grow by accreting material from the cosmic web and through mergers with nearby haloes. Unlike dark matter, which can be described by the laws of gravity alone, the baryonic matter is subject to complex physical processes. How galaxies grew from small pockets of gas into the diverse stellar structures seen in the local Universe is a major question that is yet to be fully understood.

1.3 Assembly and evolution of massive galaxies

1.3.1 Probing galaxy evolution

Observations in the local Universe have provided great insight into the long evolutionary histories of galaxies. Different galaxy types have been found to correlate with not only morphology and colour, but also various spectral features, the galaxy dynamics and the local environment. From here a broad picture of the evolution of galaxies has emerged, in which star-forming galaxies gradually grow in both size and mass, forming new stars as gas from the cosmic web accretes onto the disc. On the other hand, massive elliptical galaxies are thought to have gone through a more brief, intense period of star formation, followed by a quiescent phase in which mass growth occurred through mergers with neighbouring galaxies.

However, the archaeological research of nearby galaxies struggles to capture the details of these processes, as the characteristics of some physical mechanisms may be washed out over time or be degenerate with those of other mechanisms (e.g., the spectrum of an old stellar population of solar metallicity is extremely similar to that of a younger, but high-metallicity population of stars). Observations of more distant galaxies, i.e. at higher redshifts, are more difficult to obtain, but offer a necessary complement to the local studies, as they probe the physical state of galaxies at earlier epochs in the history of the Universe. The average evolution between galaxies at different redshifts can then be inferred statistically.

Furthermore, theoretical models allow to directly trace the evolution histories of individual galaxies. Hydrodynamical simulations are of particular interest, as these model the non-linear formation of structure and the formation of galaxies from dark and baryonic matter within large volumes (up to $\sim 10^6\,\mathrm{Mpc}^3$), and thus have the ability to model multiple galaxies and their environments. These models help to assess our current theoretical understanding and provide critical insights into the intricate physical mechanisms that shape galaxies, assisting in the interpretation of our observations.

1.3.2 From light to mass

A major difficulty in the observations, regardless of redshift, stems from the fact that we are only able to measure the light emitted by galaxies. Measuring the mass distributions of galaxies from their light is critical to map the assembly histories of galaxies. The overall mass scale and its spatial distribution have to be inferred by exploiting measurements from imaging and spectroscopic data.

The sizes and shapes of galaxies are the easiest to estimate, as these are typically measured by fitting parametric models (Sérsic profiles; Sersic 1968) to single-band imaging at a rest-frame optical wavelength. These measurements, and their correlations with colour, reflect the stellar mass distributions within galaxies, and have been shown to quantify the dichotomy between the early- and late-type morphologies (e.g., Shen et al. 2003; Blanton et al. 2003; Kelvin et al. 2012): early-type galaxies typically have Sérsic indices of $n \approx 4$, whereas late-type galaxies have $n \approx 1$. In addition, at fixed luminosity, early-type galaxies are smaller in size than the late types. Moreover, the distributions of the projected axis ratios, quantifying the observed flattening, have been shown to correspond to different 3D shapes for the two populations. Early-type galaxies are typically rounder in shape, especially at high luminosity or stellar mass (e.g., Vincent & Ryden 2005; Padilla & Strauss 2008; van der Wel et al. 2009). In contrast, star-forming or late-type galaxies are well-described by a population of oblate (disc-like) shapes.

Adding in observations at other wavelengths, the colours of galaxies can be used to extract the stellar mass-to-light ratio (M_*/L). The total stellar mass of a galaxy is then obtained by scaling this ratio with the total measured luminosity. After composing a spectral energy distribution (SED) from multi-wavelength imaging and, if available, rest-frame optical spectroscopy, the M_*/L can be modelled by fitting template spectra of different types of stellar populations. These templates are constructed from stellar population models that follow different star formation histories, and thus have different present-day star formation rates, ages and metallicities (e.g., Bruzual & Charlot 2003; Maraston 2005). Including the effects of dust, and under the assumption of a constant initial mass function (IMF), these models are typically described by at least 4, but ranging up to ≈ 20 free parameters (for a review, see Conroy 2013). For a sufficiently flexible model and wide parameter space, as well as high-quality data (i.e., a SED that spans a broad wavelength range at high signal-to-noise ratio; SNR), the M_*/L and stellar mass can be estimated with high precision, although the systematic uncertainties in the models can be as large as a factor of 2 (Conroy et al. 2009).

However, the majority of the mass in the Universe is not luminous, such as dark matter or gas, and is therefore not directly observable. Nevertheless, measurements of the internal dynamics of the stars offer a way to estimate the *total* mass within a galaxy. By means of the virial theorem, the mass enclosed within a radius r for galaxies that are in virial equilibrium is proportional to the mean square speed (σ) of the stars (Binney & Tremaine 1987, Chapter 4):

$$M(< r) \ \propto \ r\sigma^2 \, . \tag{1.1}$$

Typically, σ is approximated by the velocity dispersion (line width) of the stellar absorption lines in galaxy spectra, which are spatially integrated and projected along the line of sight. The mass obtained in this way is referred to as the dynamical mass, and is sensitive to all (dark and baryonic) mass within the radius r, as σ traces the scale and shape of the total gravitational potential.

To obtain a total mass estimate, requires a constant of proportionality that takes into account the 3D structure of the galaxy and the effect of the line-of-sight projection on σ. In practice, however, this comparison between dynamical and total masses is very challenging, as independent measurements of the total mass are available for a only a few dozen strongly lensing galaxies (Bolton et al. 2008; Koopmans et al. 2009). Instead, other studies have used calibrations based on dynamical Jeans models or empirical trends with Sérsic index (e.g., Cappellari et al. 2006; Taylor et al. 2010).

1.3.3 Measuring mass assembly

Large galaxy surveys, such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) or the Cosmic Evolution Survey (COSMOS; Scoville et al. 2007), have obtained multi-wavelength photometry and spectroscopy for large numbers of galaxies. These data have provided stellar mass estimates, structural parameters, and velocity dispersions for $\sim 10^6$ galaxies, the majority of which are at $z \sim 0$, but with statistical samples ranging up to $z \sim 4$. Studies of the distributions of these galaxy properties and their evolution with redshift have attempted to reconstruct how galaxies built up their stellar mass.

The galaxy stellar mass function, describing the galaxy number density as a function of stellar mass, has been shown to evolve significantly between $0 < z < 4$, as the galaxy number density increases strongly toward lower redshift across the entire mass range (e.g., Marchesini et al. 2009; Ilbert et al. 2013; Muzzin et al. 2013a). However, when dividing the sample by colour, it becomes apparent that for star-forming galaxies only the less massive systems (i.e., below the 'knee' of the mass function, $\log(M_*/M_\odot) \lesssim 10.8$) grow significantly in mass with cosmic time. Quiescent galaxies, on the other hand, are extremely scarce at high redshifts, but their number density increases strongly with time, fully dominating the mass growth at the high mass end. At the present day, approximately 50% of all stellar mass is contained within quiescent galaxies (Bell et al. 2003). Crucially, these measurements demonstrate a correlation between the stellar mass and the galaxy type or star formation history.

Not only the mass functions, but also the distributions of the structural properties change with redshift. The number of galaxies with high Sérsic indices decreases strongly toward high redshift (Chevance et al. 2012), and high-redshift galaxies are therefore predominantly systems with exponential surface brightness profiles ($n \approx 1$). High-redshift galaxies, in particular the quiescent systems, are also significantly smaller in size (e.g., Trujillo et al. 2007; Franx et al. 2008). The shape distributions change as well: the high-redshift star-forming population contains a significant fraction of spheroidal and prolate shapes, in addition to a large fraction of oblate systems, particularly at lower masses (van der Wel et al. 2014b). Strikingly, the high-redshift population of quiescent galaxies contains a substantial fraction of oblate systems, which at the high mass end is a factor of three higher than observed in the local Universe (Chang et al. 2013).

To connect the multitude of observations into a coherent picture, requires a statistical framework. Galaxy scaling relations, and the redshift evolution thereof, can provide such a framework. A key relation is the strong correlation between the stellar masses and sizes of galaxies, which has been found to have a steeper slope and lower overall normalisation for quiescent galaxies, than the stellar mass-size relation of star-forming galaxies (e.g., Shen et al. 2003; Lange et al. 2015). The time evolution of this scaling relation also differs for the two populations, with the inferred average size growth of star-forming galaxies being broadly consistent with the gradual accretion of mass from the cosmic web, as described by the ΛCDM model. Quiescent galaxies, however, experience rapid evolution in their size at fixed mass, particularly at $z < 2$ (e.g., van der Wel et al. 2014a). This indicates a different growth mechanism for quiescent galaxies, likely caused by repeated merging with relatively small satellite galaxies (Bezanson et al. 2009; Naab et al. 2009), which may also explain the observed evolution in the Sérsic index and flattening.

Furthermore, stellar population properties have also been shown to correlate with stellar mass. More massive galaxies are typically older, have lower specific star formation rates, and higher stellar metallicities (e.g., Kauffmann et al. 2003; Brinchmann et al. 2004; Gallazzi et al. 2005). For some massive early-type galaxies, the central regions have been found to have relatively high α-element abundances (Thomas et al. 2005), indicative of a very rapid period of star formation. These observations led to the idea of 'down-sizing' in the mass assembly of galaxies (e.g., Cowie et al. 1996; Thomas et al. 2005; Graves et al. 2007), in which more massive galaxies accumulated the majority of their stellar mass earlier in the history of the Universe. This may appear counter-intuitive, given that the hierarchical formation of structure implies a bottom-up scenario in which the smallest structures formed earliest. The two mechanisms are mutually compatible, due to the fact that the haloes in which galaxies form need to be sufficiently large to allow for gas to cool and star formation to initiate, and that massive galaxies ceased forming stars relatively early as the result of complex feedback processes (Neistein et al. 2006).

1.3.4 The Fundamental Plane

The measurements of the evolution of galaxies have shown that, as galaxies grow in stellar mass with time, the stellar population properties and structural properties change accordingly. The coupling between these processes, however, is still not well understood. Importantly, by only mapping the evolution in the stellar mass, our picture is incomplete.

Simulations of galaxy formation and evolution predict that the manner by which mass is assembled impacts the galaxy structure, as mergers and in-situ star formation (and the efficiency thereof) can leave different signatures. As a result, not only the stellar mass, but also the dark matter distributions within galaxies are expected to differ for different types of galaxies (e.g., Hopkins et al. 2008).

Valuable insight may therefore come from the Fundamental Plane (FP), which provides a framework that incorporates the dynamical masses of galaxies, and thereby connects stellar population properties and galaxy structure in a simplistic way. The FP was originally found as the empirical, planar scaling relation between the galaxy size, velocity dispersion, and surface brightness of local early-type galaxies (Djorgovski & Davis 1987; Dressler et al. 1987):

$$\log r_{\mathrm{e}} = a \log \sigma + b \log I_{\mathrm{e}} + c \,, \tag{1.2}$$

where r_{e} is the effective radius and I_{e} the mean surface brightness within r_{e}. The coefficients a and b describe the tilt of the plane, and c the zero point.

Although initially used as a distance indicator for nearby elliptical galaxies, the FP is also of astrophysical interest, as it is rooted in the scalar virial theorem, but differs slightly from this simple prediction: from the virial theorem we might expect $a = 2$ and $b = -1$, whereas observational studies local galaxies find $a \approx 1.4$ and $b \approx -0.8$ (e.g., Jorgensen et al. 1996; La Barbera et al. 2008; Hyde & Bernardi 2009). This deviation has strong physical implications for the properties and evolution of early-type galaxies.

Crucially, the three coefficients of the FP can be interpreted in terms of the dynamical mass-to-light ratio, M/L (Faber et al. 1987). The fact that the tilt of the observed FP differs from the expected virial plane suggests a dependence of M/L on mass for early-type galaxies. Several physical mechanisms have been proposed to explain this observed variation in M/L.

Systematic variations in the stellar populations of early-type galaxies, and thus in M_{*}/L, as a function of mass have been shown to account for only half of the deviation of the observed FP from the virial plane (Hyde & Bernardi 2009; Graves & Faber 2010; La Barbera et al. 2010a). Therefore, the second half must be driven by variations in the galaxy structure as a function of mass: this can be either due to variation in the 3D stellar (kinematic) structure, also referred to as the non-homology of galaxies, or a systematic dependence of the dark matter mass fraction within galaxies on mass.

Non-homology is found by several studies to have a relatively small effect on the tilt (Cappellari et al. 2006; Bolton et al. 2007, 2008), although contrary results have also been reported (Bender et al. 1992; Graham & Colless 1997; Prugniel & Simien 1997; Trujillo et al. 2004; Desmond & Wechsler 2017). On the other hand, variations in the dark matter content are extremely difficult to measure observationally, but theoretical models have provided interesting insight. Simulations of galaxy mergers have shown that the mass dependence of M/L arises naturally among the descendants of major, dissipational galaxy mergers, as these types of mergers alter the baryonic and dark matter mass profiles (Boylan-Kolchin et al. 2006; Robertson et al. 2006; Hopkins et al. 2008). This possibly implies that all galaxies on the observed FP have a similar formation history. Within observational studies there is still debate regarding this interpretation, however, partially due to the large measurement uncertainty on the IMF, which is degenerate with variations in the dark matter fraction (e.g., Graves & Faber 2010; Bernardi et al. 2018).

Furthermore, not only the tilt, but also the zero point of the FP is directly related to M/L, as $c \propto -\log(M/L)$. The scatter about the zero point has been found to exceed the scatter expected due to measurement uncertainties, which implies that the FP is intrinsically not a true plane, but is better described by a dense cloud (Jorgensen et al. 1996). The offsets from the FP can therefore be interpreted as a variation in M/L, and have been shown to correlate with the stellar ages, metallicities, and α-element abundances of local early-type galaxies (Forbes et al. 1998; Gargiulo et al. 2009; Graves et al. 2009). Moreover, the scatter has been found to correlate with galaxy structure, specifically the Sérsic index and the dynamical-to-stellar mass ratio, which describes the amount of ‘dark mass’ within galaxies from either dark matter or missing stellar mass due to an incorrectly assumed IMF (Graves & Faber 2010; Bezanson et al. 2015).

By studying the details of the low-redshift FP, i.e. its tilt and scatter, we gain insight into the formation of local early-type galaxies. For instance, it has been shown that the combination of trends in the stellar population properties and structural properties throughout the FP can be explained by differences in the truncation times of the star formation in these galaxies, although dissipational mergers may likely also play a role (Gargiulo et al. 2009; Graves & Faber 2010).

Moving beyond the local Universe, the evolution of the FP provides an interesting metric of the time evolution of M/L for quiescent galaxies. If we assume that galaxies with old stellar populations evolve passively, which implies that they do not form or accrete new stars, M remains approximately constant. Measurements of the zero point of the FP at higher redshifts, and hence the change in M/L, then provide direct constraints on the formation epoch of the most massive quiescent galaxies (Franx 1993; van Dokkum & Franx 1996). Various results have been reported that suggest quiescent galaxies formed very early, at $z \sim 3$, before the peak of star formation in the rest of the Universe (e.g., Treu et al. 2005; van der Wel et al. 2005; van Dokkum & van der Marel 2007; van de Sande et al. 2014).

In addition, different studies have claimed to measure a change in not only the zero point, but also the tilt of the high-redshift FP with respect to $z \approx 0$ (e.g., di Serego Alighieri et al. 2005; Jørgensen & Chiboucas 2013), although these results have been subject to debate (Holden et al. 2010; Saglia et al. 2010, 2016). These studies suggest that galaxies at higher redshift may follow a different relation between M/L and mass, which can be due to evolution in the stellar populations or the structures of high-redshift galaxies. The limited availability of measurements at $z > 0$ prevents strong conclusions to be drawn, but indicate that improved high-redshift measurements of the FP can add significantly to our understanding of the evolution of galaxies.

1.3.5 Towards a holistic view of the FP

The FP has been demonstrated to provide a powerful probe of galaxy evolution. However, different studies have shown that the measurements of the FP, and thus the physics inferred from detailed studies of the relation, depend strongly on the selection of the galaxy sample and the measurements used (e.g., the chosen photometric band; Hyde & Bernardi 2009; La Barbera et al. 2010a). For instance, galaxies in clusters populate the FP differently than galaxies in the field (La Barbera et al. 2010b; Saglia et al. 2010). Similarly, a sample of galaxies selected by luminosity results in a different FP than a (stellar) mass-selected sample (e.g., van der Wel et al. 2005).

At low redshift these effects can be measured and taken into account, owing to the wealth of data available from large surveys such as the SDSS. However, selection biases become increasingly problematic toward higher redshift. The bottleneck is the measurement of the stellar velocity dispersion, which requires high SNR spectroscopy at rest-frame optical wavelengths in order to measure robust absorption line profiles. Due to the surface brightness dimming of distant galaxies, and the shifting of prominent absorption lines toward longer wavelengths, it is difficult to obtain the necessary high-quality data. Moreover, to measure the sizes of distant galaxies requires high-resolution imaging, which can currently only be achieved with the *Hubble Space Telescope* (HST) that is not affected by the turbulent atmosphere of the Earth.

Therefore, to make the expensive observations more efficient, high-redshift measurements have typically focused on luminous quiescent galaxies in dense environments, or very bright objects in the field. In this way, data for a few hundred quiescent galaxies has been collected over the past two decades (e.g., van der Wel et al. 2005; Treu et al. 2005; Saglia et al. 2010; Holden et al. 2010; Jørgensen & Chiboucas 2013; van de Sande et al. 2014). Although this has provided strong constraints on the evolution of the most massive systems, particularly those in cluster environments, these are not representative of the broader population of massive galaxies. An open question is therefore how the average quiescent galaxy evolves ($\sim L^*$ galaxies with stellar masses similar to the Milky Way by $z \approx 0$), and how this evolution compares with the measurements of the most massive galaxies.

Furthermore, so far nearly all studies of the FP have focused on early-type or quiescent galaxies alone. Samples are often specifically selected to include only galaxies that have high Sérsic indices, are round in shape, and red in colour with no significant Balmer emission lines. Star-forming galaxies are usually considered separately, and have been shown to obey their own dynamical scaling relation: there is a tight correlation between the rotation speed and luminosity or stellar mass of star-forming discs (Tully & Fisher 1977). Unlike the FP, this Tully-Fisher relation is a linear relation and independent of the galaxy size (Zwaan et al. 1995; Courteau & Rix 1999).

Few studies have shown, however, that both galaxy populations may be reconciled within one planar relation (Zaritsky et al. 2006, 2008). Two conditions need to be met in order to place star-forming and quiescent galaxies onto a single dynamical scaling relation: (i) in addition to the dispersion due to random motions of stars, the measure of σ has to explicitly include the line broadening due to rotation, and (ii) the differences in M_*/L need to be modelled and taken into account. These modifications result in the stellar mass FP, which differs from the luminosity FP by the replacement of the surface brightness with the stellar mass surface density (Hyde & Bernardi 2009). At low redshift, this has resulted in the finding of common stellar mass FP for all galaxies (Bezanson et al. 2015). There is also evidence that suggests this common relation may hold beyond $z \sim 0$, but a larger sample of star-forming and quiescent galaxies is needed to assess the statistical significance and physical implications of this finding.

These results are potentially very promising, as they allow to study the galaxy population as a whole. Instead of focusing solely on the differences between galaxy types, a unified scaling relation may also highlight their similarities, and thereby shed light on the coupling between different physical properties of galaxies. However, the interpretation of the stellar mass FP is challenging, due to the more complex range of structures and star formation histories that the star-forming galaxies introduce, and the difficulty in measuring the dark matter content in galaxies. Therefore, in addition to observations across a wide redshift range, theoretical models are needed to map the details of the FP and evaluate possible roles of different physical mechanisms.

1.4 Thesis summary

In this Thesis we explore the evolution in the M/L of massive galaxies in the context of the Fundamental Plane. By disentangling the effects of varying stellar population properties and structural properties, we evaluate what drives the observed variation in the M/L and assess how this evolves with time. This work is built on a combination of observational data and theoretical models, to form a holistic picture of the FP. Deep spectroscopic surveys are used to construct a representative sample of massive quiescent *and* star-forming galaxies across $0 < z < 1$. Cosmological simulations are used to assess the physical properties that may underlie the observed FP.

Chapter 2 presents a comprehensive analysis of the FP at $z \approx 0.8$, using a large sample of quiescent and star-forming galaxies. We base our sample on the LEGA-C Survey, a large spectroscopic survey of ~ 3000 K_s-band selected galaxies at $0.6 < z < 1.0$ that provides very deep, rest-frame optical spectra. Further complemented by multi-wavelength photometry that covers ultra-violet to mid-infrared wavelengths, as well as high-resolution HST imaging, we obtain rest-frame colours and structural parameters. We perform SED modelling to estimate stellar masses and stellar population properties for the LEGA-C galaxies.

The constructed sample of 1419 galaxies is selected by the estimated stellar mass ($M_* > 10^{10.5}\,\mathrm{M}_\odot$), and covers a wide range in morphology, star formation activity and environment. We measure the rest-frame g-band FP spanned by this sample, and show that there is evidence for a slight evolution in the tilt of the FP with respect to $z \approx 0$, after accounting for selection effects. Examining the differences between the star-forming and quiescent population, we find that the two populations are distributed differently in the parameter space of the FP, as the star-forming population is offset from the quiescent population and shows much larger scatter. This reflects significant differences in the M/L, and we demonstrate that this is primarily due to differences in the stellar age and star formation activity, and to a lesser extent the dust attenuation.

However, by explicitly accounting for the differences in M_*/L among the sample, we find that both star-forming and quiescent galaxies follow the same stellar mass FP at $z \approx 0.8$. We show that the scatter about the stellar mass FP is approximately equal for both populations, forming an intrinsically tighter relation than the luminosity FP. Nevertheless, the scatter is still greater than the measurement uncertainties alone, which suggests there are systematic variations in M/M_* within the scatter. We examine whether the remaining scatter correlates with physical properties, but find no correlations with stellar population properties and the local overdensity, and only a weak dependence on the morphology, despite the strong non-homology of the sample. Overall, we show that, at fixed size and velocity dispersion, differences in M_*/L (for an assumed, universal IMF) across the sample account for approximately 54% of the variation in M/L, which implies that remainder must be caused by systematic fluctuations in the dark matter content or variations in the IMF between galaxies.

In **Chapter 3** we combine the LEGA-C data with a low-redshift sample from the SDSS to measure the redshift evolution in M/L and M/M_* across $0 < z < 1$. We find rapid evolution in the zero point of the g-band FP, and thus in M/L, which is stronger for quiescent galaxies than for star-forming galaxies. In comparison with previous studies, the evolution in M/L of quiescent galaxies is significantly stronger, which we show is largely due to the inclusion of less massive galaxies ($M_* < 10^{11}\,\mathrm{M}_\odot$) in the LEGA-C sample, with an additional weak effect from the large fraction of field galaxies rather than cluster galaxies.

On the other hand, the stellar mass FP is remarkably stable across cosmic time, as we measure no significant evolution in the zero point. At fixed size and velocity dispersion, the structural evolution in M/M_* is therefore negligible, and implies that the observed evolution in M/L must be caused by a combination of evolution in the stellar populations and the effects of progenitor bias. The fact that star-forming and quiescent galaxies lie on the same, stable scaling relation across $0 < z < 1$, also suggests that any evolution in the size or velocity dispersion has to occur along the stellar mass FP: as galaxies grow in size or undergo a morphological transformation, there must be a corresponding change in the dynamical structure, such as to remain on the stellar mass FP.

In **Chapter 4** we evaluate how a fair comparison can be made between observations and cosmological simulations. As simulations model mass in the form of particles, which distinguish between gas, stars, dark matter and black holes, they cannot be directly compared with measurements based on the observed light from galaxies. Moreover, measurements extracted from simulations typically differ fundamentally from the methods used to analyse telescope data. We therefore use the stellar mass-size relation in the EAGLE cosmological simulations to examine the magnitude of these effects.

We create mock SDSS images of the projected stellar mass distributions and optical light distributions of $z = 0.1$ galaxies in the $100^3\,\mathrm{Mpc}^3$ simulation, and apply standard observational methods to measure the sizes, Sérsic indices and projected axis ratios. The use of a measurement method that is consistent with observational rather than other theoretical works, leads to a 0.06 dex difference in the inferred sizes of galaxies. Most importantly, we find a strong difference between the measured half-light radii and the half-mass radii, which is on average 0.1 dex, but can be as large as 0.5 dex, depending on the star formation activity, mean stellar age, and dust attenuation.

The stellar mass-size relation obtained with these mock observations is in significantly better agreement with the observed scaling relation than is the case for the size measurements that are conventional in theoretical studies. On the other hand, we find that the mock observations also reveal strong differences between simulated and real galaxies, as the distributions of the Sérsic indices and projected axis ratios differ substantially. This discrepancy is contrary to previous studies that used different measurement methods and found good agreement between the morphologies of simulated and real galaxies. Our work therefore highlights the importance of constructing mock observations and applying common observational analysis methods to fairly evaluate cosmological simulations.

Chapter 5 builds on these results, and investigates the physical drivers of a common stellar mass FP for quiescent and star-forming galaxies using the EAGLE simulations. First, we use the total mass enclosed within the effective radius and the stellar velocity dispersion to show that the simulated galaxies obey a tight total mass FP that is very close to the virial theorem. Despite a large diversity in the kinematic structures of the galaxy population, the effects of non-homology on the simulated FP are therefore small ($\lesssim 10\%$). This implies that the dynamical mass is a close approximation of the total mass within the effective radius.

Second, we demonstrate that when we use the stellar mass rather than the total mass, we obtain a stellar mass FP that deviates strongly from the virial plane. We show that this deviation is driven by the dark matter content of galaxies, as the dark matter fraction within the effective radius ($f_{\mathrm{DM}}(< r_{\mathrm{e}})$) is a smooth, power-law function of the galaxy size and stellar mass. Moreover, because it is this smooth variation in the dark matter fraction that sets the coefficients of the stellar mass

FP, both star-forming and quiescent galaxies lie on the same FP, with equally low scatter. We show that the variations in $f_{\rm DM}(< r_{\rm e})$ reflect more than just a dependence of M/M_* on mass, which may have been expected based on previous studies, but instead arise primarily from the large variation in $r_{\rm e}$ (and hence $f_{\rm DM}$) at fixed stellar mass. In turn, the fluctuations in $r_{\rm e}$ are likely the product of multiple, complex physical processes.

Third, using luminosity-weighted mock observations of the size, stellar mass surface density, and the velocity dispersion, we demonstrate that observational biases have a significant influence on the measured coefficients of the stellar mass FP. Moreover, the luminosity weighting strongly increases the scatter in the relation, which we discuss is likely caused by the fact that the most luminous stars lie in dynamically-cold discs, and the resulting velocity dispersion is therefore strongly dependent on the inclination angle. Accounting for these effects, we show that the stellar mass FP in the EAGLE simulation broadly agrees with the observed scaling relation. However, when examined in detail, we find significant discrepancies. This likely reflects a fundamental difference between the 3D mass profiles of simulated galaxies and galaxies in the local Universe, which may arise from inaccuracies in the EAGLE subgrid model and its implementation in the simulation. Therefore, we suggest that the stellar mass FP may offer a new, straightforward measure of success for future cosmological simulations.