Chapter 1

Introduction

Galaxies come in different shapes and sizes. Some have impressive spiral arms and dustlanes and are classified as spiral or *late-type* galaxies. Others have a simpler appearance, looking very smooth without any apparent structure. These systems are the elliptical and lenticular galaxies, or *early-type* galaxies (see Figure 1.1). How did these galaxies form, and how have they developed into such different shapes and sizes? These are some of the big questions that astronomers are attempting to solve.

1.1 Dark matter

In 1933 Swiss astronomer Fritz Zwicky made an important discovery. While studying galaxies in the Coma cluster, he found that the dynamical mass, mea-

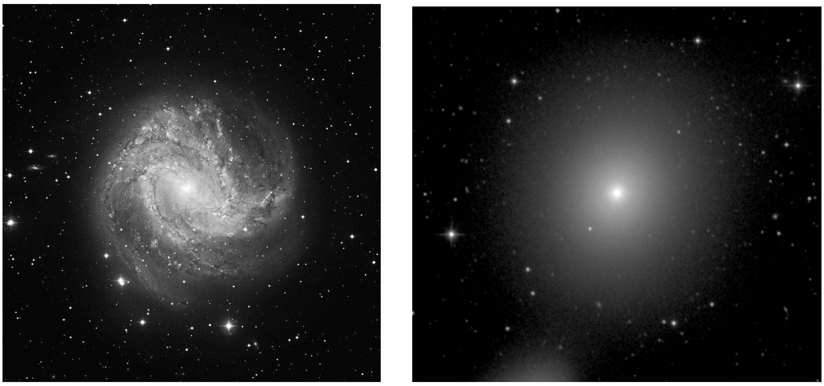

Figure 1.1 — Two images of different types of galaxies. Left: spiral galaxy M83, captured by the Wide Field Imager of La Silla Observatory, Chile (Credit: ESO). Right: elliptical galaxy NGC 3379, imaged by the 1.3m McGraw-Hill Telescope of MDM Observatory, Kitt Peak, US.

sured by means of kinematics of the galaxies, far exceeded the luminous mass, formed by stars and gas in the cluster (Zwicky 1933). The implication of this discovery was that there had to be some kind of invisible mass, dark matter, to keep the galaxies in the cluster gravitationally bound. Later, more evidence was found for dark matter in the Universe. Rotation curves of neutral gas (H I) around spiral galaxies obtained with radio telescopes revealed that these systems are embedded in haloes of dark matter (e.g. Rubin et al. 1985; van Albada et al. 1985). Large clusters of galaxies acting as gravitational lenses also point to the existence of large amounts of dark matter (e.g. Soucail et al. 1988), and from observations of the cosmological background radiation, we know that the amount of dark matter in the Universe exceeds the amount of normal, baryonic matter by a factor five (Komatsu et al. 2009).

Dark matter is ubiquitous, and plays an important role in the formation and evolution of galaxies. In the current galaxy formation paradigm (e.g. Springel et al. 2005), the early Universe had a much smoother dark matter distribution than it has today. Through gravitational instabilities, dark matter started to form clumps and provided a framework for structure formation. Within these structures, gas cooled and formed stars. In order to understand galaxy formation and evolution, we therefore also need to study the structure and evolution of the dark matter haloes that surround them. That is the main topic of this thesis.

1.2 Dark matter in early-type galaxies

Dark haloes around late-type spiral galaxies have been observationally confirmed, using rotation curves of cold neutral gas. For early-type galaxies, observational proof of dark matter haloes is however much more difficult to obtain. Because the dark matter halo only starts to dominate over the luminous matter in the outskirts of the galaxy (beyond $\sim$3 effective radii R_e[1]) we need to trace the gravitational potential at large radii to map the dark halo. Large cold neutral gas discs (or rings), that extend far beyond the stellar disc, are ideal tracers of the gravitational potential, as the cold gas moves on circular orbits. But since these gas discs are only rarely found around early-type galaxies (though see Morganti et al. 2006 for recent discoveries of H I gas in these systems), we need to resort to other tracers of the gravitational potential in order to study dark haloes in these galaxies.

Instead of gas kinematics, stellar kinematics can in principle also be used to infer the dark matter distribution. However, galaxies fade relatively quickly with

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[1] An effective radius or R_e is defined as the radius within which half the total light of the galaxy is contained, and is therefore also sometimes called a half-light radius.

radius, so that with traditional long-slit spectrography it is almost impossible to obtain spectra with sufficient signal-to-noise (S/N) outside $\sim$2 R_e. Mass models based on spectra out to this radius are not always conclusive, though many studies with long-slit spectra hint at the existence of dark matter haloes around early-type galaxies (e.g. Carollo et al. 1995; Rix et al. 1997).

X-ray observations of the hot interstellar medium can also be used to constrain the dark matter content of galaxies. Assuming hydrostatic equilibrium, the total mass profile can be recovered from density and temperature measurements (e.g. Humphrey et al. 2006; Pellegrini & Ciotti 2006). However, not all early-type galaxies contain a large enough amount of hot gas to be detected in X-ray, and the assumption of hydrostatical equilibrium has to be validated.

Weak gravitational lensing (e.g. Gavazzi et al. 2007) is another technique to study the mass and shapes of dark haloes around galaxies that are lensed by massive clusters. This technique is however not applicable to galaxies in the nearby Universe, as there are no nearby massive galaxy clusters that could act as gravitational lenses for these nearby systems. Strong gravitational lensing in combination with stellar dynamics has been used to determine the dark matter content of early-type galaxies that act as lenses themselves (e.g. van de Ven et al. 2008b; Barnabe et al. 2009).

Another approach to probe the gravitational potential in galaxies at large radii is by measuring the radial velocities of discrete tracers, such as globular clusters (e.g. Côté et al. 2003; Pierce et al. 2006) and planetary nebulae (e.g. Douglas et al. 2006; Napolitano et al. 2009). Both these tracers are visible in nearby (within $\sim$ 50 Mpc) galaxies: globular clusters because of their concentration of starlight emitted by hunderd thousands of stars, and planetary nebulae because of their strong emission of the [O III] line.

With the Planetary Nebulae Spectrograph (Douglas et al. 2002) over one hundred planetary nebulae can be observed in a galaxy, allowing the construction of smoothed velocity and velocity dispersion maps (Coccato et al. 2009). However, obtaining higher order moments of the line-of-sight velocity distribution (LOSVD), such as the Gauss-Hermite moments h_3 and h_4, requires an even larger number of measurements. These higher order moments, most importantly h_4, are needed to constrain the orbital structure of the galaxy, in order to break the mass-anisotropy relation (e.g. Gerhard 1993). Briefly, by replacing tangential orbits by radial ones (i.e. increasing the radial anisotropy over the tangential anisotropy) it is possible to increase the total mass of a spherical or axisymmetric system, for a decreasing or constant velocity dispersion profile (e.g. Richstone & Tremaine 1984; Dekel et al. 2005; de Lorenzi et al. 2009). However, h_4 provides constraints for the anisotropy, with positive h_4 corresponding to more tangential anisoptry, while negative h_4 indicates more radially anisotropic systems.

We therefore developed in this thesis a new technique to use integral-field spectrography to measure the LOSVD of the integrated stellar light at large radii. This way, we can measure also the higher order moments of the LOSVD and by not limiting ourselves to a discrete representation of the stellar population we are confident that indeed we are tracing the gravitational potential (e.g. Sambhus, Gerhard & Méndez 2006).

1.3 Integral-field spectrography

With integral-field spectrography we can simultaneously obtain spectra at each position in the field-of-view, resulting in a three dimensional datacube (x, y, λ). From the spectra not only the kinematics of stars and gas, but also absorption line strengths of the stars can be obtained, providing means to determine metallicity and age of the system. All these quantities can be displayed in two dimensional maps. This is an enormous advantage over traditional long-slit spectrography, where in order to get the same spatial coverage, multiple slits need to be observed.

In this thesis we use the integral-field spectrograph SAURON (Spectrographic Aerial Unit for Research on Optical Nebulae, see also Bacon et al. 2001). This spectrograph has an optical system of lenslets to map the galaxy (see Figure 1.2), and is a visitor instrument at the William Herschel Telescope of the Isaac Newton Group at La Palma, Canary Islands, Spain. We develop a new observing technique to obtain stellar kinematics in early-type galaxies out to large radii, using SAURON as a 'photon-collector'. Even though the light collected by one lenslet is too faint to yield a spectrum with sufficient S/N to measure the LOSVD in the faint outskirts of galaxies, by combining the light of all 1400 lenslets we obtain a spectrum from which we can reliably extract the kinematics.

In one chapter we also use the integral-field spectrograph PPAK (Kelz et al. 2006), which is mounted at the 3.5m Telescope at Calar Alto, Spain. This spectrograph works with fibers instead of lenslets, and has a lower spatial resolution than SAURON: the diameter of one fiber is 2.7 arcsec, while SAURON has lenslets that measure 0.94 × 0.94 arcsec. However, the field-of-view of PPAK is four times as large as that of SAURON and its spectral range is also longer, allowing us to measure a larger number of line strength indices.

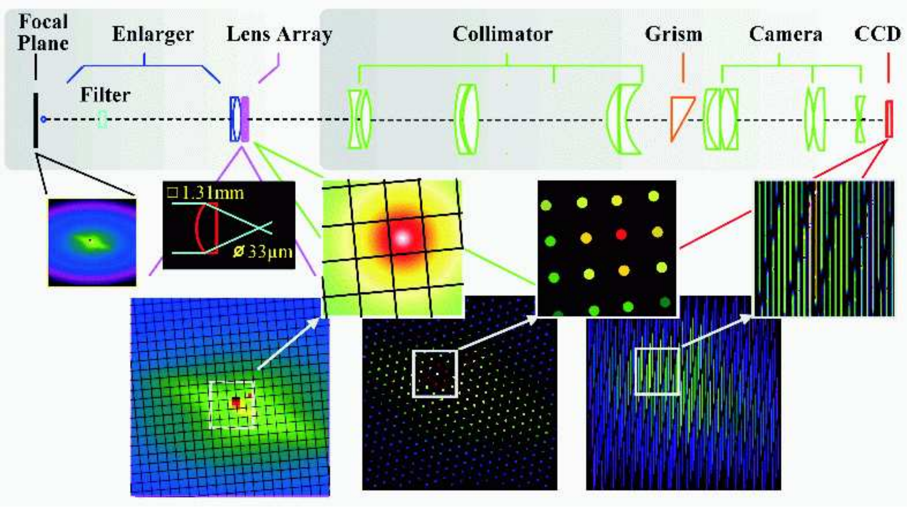

Figure 1.2 — Optical lay-out of the integral-field spectrograph SAURON. Light within the desired wavelength interval (4810 - 5350 Å) is selected by a filter, after which it hits the central part of the instrument, which consists of a matrix of lenslets. Each lenslet maps its infalling light beam on a pinhole, after which a grism breaks up the light in a spectrum. The spectra are imaged on a CCD under a small angle (about 6°) to prevent overlap between adjacent spectra. See Bacon et al. (2001) for a detailed description of the instrument and data processing.

1.4 Dynamical models

In this thesis we mostly make use of Schwarzschild orbital superposition models (Schwarzschild 1979), to find the properties of the dark haloes around our observed galaxies. In an a priori specified potential we calculate stellar orbits, which are stored in a library. From this library a superposition of orbits is calculated, that best fits the observed LOSVD (including higher order Gauss-Hermite moments), as well as the observed surface brightness. These models are fully general, and yield best-fit parameters such as viewing angles, mass-to-light ratio and halo mass. They also allow a study of the intrinsic orbital structure, to identify different orbit families and the presence of separate components.

1.5 Stellar halo populations

Stellar absorption line strengths trace the properties of the stellar population. Based on these measurements, stellar population models (e.g. Bruzual & Charlot 2003; Thomas, Maraston & Bender 2003; Schiavon et al. 2007) can provide several quantities, such as age, metallicity and stellar mass-to-light ratios. With integral-field spectrography we can now for the first time measure these line strengths outside 2 R_e, to study the stellar halo population. In this thesis we study line strength gradients and investigate the connection between stellar populations and halo mass at large radii.

The behaviour of line strengths as a function of radius provides strong constraints for the starformation and merging history of a galaxy. Briefly, if galaxies form in a monolithic collapse, the line strengths are expected to follow a steep gradient (Carlberg 1984). Mergers however can dilute these gradients (White 1980), but subsequent starformation triggered by the merger can steepen the gradients again in the central part of the galaxy (Hopkins et al. 2009b).

There exists a tight relation between local line strength index (most notably the magnesium absorption line Mg *b*) and the local escape velocity $V_{\rm esc}$ (e.g. Davies, Sadler & Peletier 1993; Scott et al. 2009). This relation was also observed for colours and $V_{\rm esc}$ (Franx & Illingworth 1990), reflecting the fact that colours trace metallicity in a galaxy. By including a dark halo into the gravitational potential of the galaxy, $V_{\rm esc}$ becomes larger. This effect is relatively larger at large radii: a test-particle at larger radii would perhaps have escaped relatively easy from the potential well of the luminous matter in the galaxy, but now also has to overcome the halo potential. The result is that at large radii the shift in $V_{\rm esc}$ is larger than at smaller radii, close to the centre of the galaxy. This introduces a change in slope of the Mg *b* - $V_{\rm esc}$ relation, when taking the halo into account (see also Franx & Illingworth 1990).

1.6 This thesis

In this thesis we explore new techniques to study the dark and luminous matter in the outskirts of galaxies.

In **Chapter 2** we use the Very Large Array (VLA) to map the H I ring around the early-type NGC 2974. This gas ring extends out to 5 R_e (24 kpc) and displays regular rotation. We compare the kinematics of the H I with the ionised gas and stellar kinematics in the central R_e of the galaxy, as observed by SAURON. Both neutral and ionised gas share the same kinematics, which supports the view that they form one coherent gas structure. To combine the kinematics of the cold and warm gas, we apply an asymmetric drift correction (see e.g. Binney & Tremaine 2008, section 4.8.2) to the observed rotation curve of the latter. This is needed because the ionised gas has a high velocity dispersion, which is a measure of random motions. The cold gas does not have this high dispersion and is on circular

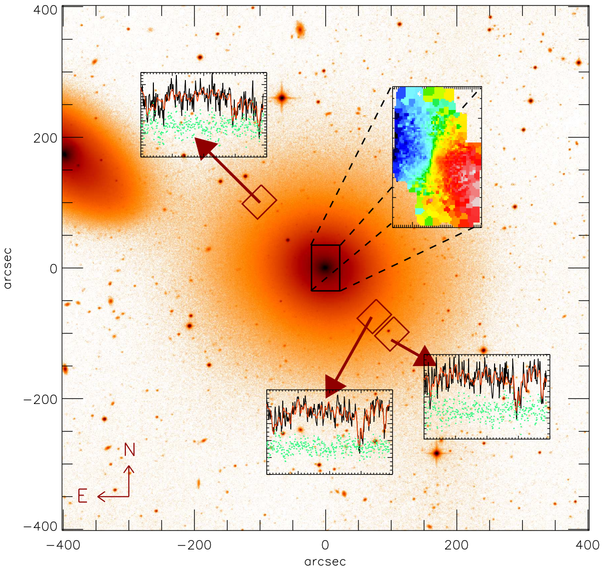

Figure 1.3 — Illustration of the usage of SAURON as a 'photon-collector'. The underlying image is a V-band image of early-typa galaxy NGC 3379. In the central part of the galaxy, S/N in individual spectra is high, and we can construct kinematic maps, where binning of spectra is only needed along the edges of the field-of-view (FoV), where the galaxy is fainter. At large radii (3 and 4 R_e) we bin the light of all spectra within the SAURON FoV together, in order to obtain a spectrum with sufficient S/N to measure the stellar kinematics. See colour supplement for a colour version of this figure.

orbits, and therefore its observed rotation curve agrees with its ciruclar velocity, which traces the gravitational potential. After this correction is done, we combine the rotation curves of the central warm gas with the cold gas in the outskirts, and construct mass models of this galaxy. We find that NGC 2974 is surrounded by an axisymmetric dark halo, and that within 5 R_e at least 55% of the total mass is dark.

Chapter 3 deals with two other early-type galaxies: NGC 3379 and NGC 821. These galaxies are not detected in H I and therefore we need to obtain stellar kinematics in order to model the haloes of these systems. We use SAURON as a 'photon-colllector' to measure the LOSVD at 3 and 4 R_e. Combining these measurements at large radii with the SAURON kinematics maps covering the inner R_e of these galaxies (see Figure 1.3), we construct triaxial Schwarzschild models and add a dark halo to the potential. We find that both galaxies contain dark matter haloes: for NGC 3379, at least 34% of the total mass within 4 R_e is dark, while for NGC 821 this percentage is even higher, at least 49%. We also find that the orbital structure of our best-fitting models becomes radially anisotropic at larger radii, but that an increase of halo mass does not translate into an increase of radial anisotropy, as observed in spherical models (e.g. Richstone & Tremaine 1984). More studies of the orbital structure in triaxial models are needed to understand this trend. We also obtained line strengths from the spectra at large radii, and for the first time confirm that line strength gradients observed within 1 R_e extend out to at least 4 R_e. Constructing the Mg b - $V_{\rm esc}$ relation, we find that the slope of this relation steepens by including the dark halo in our model, as was previously found by Franx & Illingworth (1990) using colours instead of line strength indices.

In **Chapter 4** we observe the early-type galaxy NGC 2549 with the integral-field spectrograph PPAK. We compose a mosaic of four pointings, mapping the galaxy out to almost 5 R_e. The stellar kinematic maps show that this galaxy has a disc-like rotation out to the edge of the observed field. Also there are indications of a disc component, embedded in a larger disc or bulge. From the line strengths we construct age and metallicity maps, and these also provide some evidence for a younger, metal-enriched central component. The line strength gradients remain stable from 0.1 to at least 4 R_e.

The line strength maps allow us to construct a map of the stellar mass-to-light ratio, and we find only small variations over the observed galaxy field. While constructing a mass model based on the PPAK spectra, complemented with higher spatial resolution SAURON kinematics for the inner R_e, we find that dark matter is necessary to explain the observations, and that therefore like the galaxies studied in Chapters 2 and 3, NGC 2549 is embedded in a dark matter halo, with at least 63 per cent of the total mass being dark within 5 R_e. We find however that our models cannot reproduce the observed rise in velocity dispersion at larger radii. Most likely this is caused by the limitations on the shape of the dark halo in our models, which we have kept fixed to spherical. This could imply that kinematics over the full field-of-view (in contrast to discrete measurepoints as we obtained in Chapter 3) can be used to constrain the shape of the dark halo. This is currently under investigation.

Finally, we turn our attention in **Chapter 5** to the high-redshift Universe. With SAURON we study the structure and kinematics of a Lyα emitting gas cloud at $z = 3.1$. This object, Lyman Alpha Blob 1 (LAB1), is situated in a dense proto-cluster environment, and is the largest LAB discovered to date, with diameter > 100 kpc. LABs are still mysterious objects, as it is not clear what powers the ionisation of these gas clouds. Proposed scenarios include photo-ionisation (possibly by massive starbursts and/or AGN, obscured along our line-of-sight), cooling flows, and superwinds caused by overlapping supernova remants. With our deep (23.5 hrs) SAURON observations we find that LAB1 is not one large coherent structure, but instead consists of five separate blobs. Two of these blobs are identified with Lyman Break Galaxies and a third is most likely associated with a dust-obscured submillimeter galaxy. The remaining two blobs cannot be connected with any source in the optical or infra-red, and could be genuine gas clouds trapped in the proto-cluster potential.

1.7 Conclusions and outlook

By using integral-field spectrography it has now become possible to measure the LOSVD and absorption line strengths of integrated stellar light out to large radii in early-type galaxies. We explore the behaviour of line strength gradients and subsequently investigate differences in age, metallicity and stellar mass-to-light ratio (M_*/L). These studies provide important constraints for the starformation and merger histories of early-type galaxies. By constructing dynamical models based on the observed LOSVD we can map the dark haloes around early-type galaxies, similar to what was done for spiral galaxies with H I kinematics, and build statistical sample of halo properties, as a function of galaxy type and environment.

Our dynamical models however have still room for improvement. One of the main uncertainties in our models is M_*/L. Most models in this thesis have used a maximal spheroid (or equivalently: minimal halo) assumption, with M_*/L fixed to its maximal value, as allowed by the observed kinematics. Therefore the dark matter fractions we found for these galaxies are lower limits: the actual halo could very well be heavier. In Chapter 4 we explored the determination of M_*/L from stellar population models. This requires accurate measurements of multiple line strength indices. With spectra over long wavelength ranges, possibly complemented with colour measurements (e.g. Zibetti, Charlot & Rix 2009), we can start to remove this uncertainty from our dynamical models.

Another assumption in our models concerns the shape and profile of the dark halo. Most galaxy formation theories predict triaxial haloes (e.g. Frenk et al. 1988; Hayashi, Navarro & Springel 2007), while we so far modeled our galaxies with spherical haloes. Also, although structure formation simulations find cuspy haloes (such as the NFW profile that we utilized in this thesis, see Navarro, Frenk & White 1996), observations of nearby low-surface brightness and dwarf galaxies point to haloes with central cores (e.g. de Blok et al. 2008). We need to investigate whether with kinematics over a large field-of-view (Chapter 4) we can distinguish between different halo shapes and profiles.

In order to understand the evolution of dark haloes, we should also explore the dynamics of galaxies at higher redshift. Obtaining kinematic maps of galaxies at high redshift is not straightforward: these systems are faint and small, so that we need long integrations times and high spatial resolution (Chapter 5). Still, integral-field spectrographs with high spatial resolution have already been employed to obtain the gas kinematics of disc galaxies at $z \sim 2$ (e.g. Shapiro et al. 2008; van Starkenburg et al. 2008). Also, by using gravitational lenses, some lensed galaxies residing at $z = 1$ have been mapped with a resolution comparable to $z = 0.1$ galaxies (e.g. Swinbank et al. 2006). Observationally there has been a lot of progress in the study of high-redshift kinematics, and now modeling techniques should be developed to analyse these systems in more detail.

Our ultimate goal is to understand the formation and evolution of galaxies. Observations of galaxies nearby and at high redshift show us how galaxies change in time, due to starformation and interactions with other galaxies. If we want to understand these observations, we need to develop a theoretical framework to explain them. Simulations of galaxy formation are not always in agreement with observations, predicting haloes that are too massive or too concentrated (e.g. Napolitano et al. 2009). We therefore need to bring theory and observations together, to solve the mysteries that still surround the formation and evolution of galaxies.