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## Weak gravitational lensing in the red-sequence cluster survey 2

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# 1

## Introduction

In this first chapter, we set the scene for the research projects presented in this thesis. We begin with a brief description of the standard model of cosmology,  $\Lambda$ CDM, and describe its main components. To study these observationally, a large variety of techniques has been developed. The one central to the studies in this thesis is weak gravitational lensing. We therefore provide a short description of how this method works, and give some examples of its applications. We also provide a short overview of the other chapters.

### 1.1 The $\Lambda$ CDM framework

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For millennia, people believed that the Earth was the centre of the Universe, with the Sun, the planets and all the stars revolving around it. Almost 500 years ago, this ancient world view started to change, and it has been subject to change ever since. Due to the work of, amongst others, Nicolaus Copernicus and Galileo Galilei, it became clear that our Sun did not revolve around the Earth, but that the Earth and the planets moved around the Sun. At the same time, Giordano Bruno proposed that the stars in our sky were actually very distant suns like our own, although it took more than two centuries before their distances from us could be determined. With the help of his telescope, Galileo Galilei found that the faint band of light that crossed our nocturnal sky actually consisted of many small stars our eyes could not discern. This large collection of stars was called our Galaxy, and at the beginning of the twentieth century it was a hot topic of debate whether or not other galaxies similar to ours existed outside our own. In the 1920s, Edwin Hubble measured the distances to some faint nebulae in the sky whose origin was uncertain. These distance measures conclusively showed that these objects had to reside far outside our Galaxy, and therefore had to be galaxies themselves. Subsequent observations showed that the Universe was filled with uncountable galaxies - currently, it is estimated that there are more than 100 billion of them.

Soon after the discovery of the existence of other galaxies, another important one followed. A few years earlier, in 1912, Slipher had already measured the spectra of these faint clouds that turned out to be nearby galaxies, and determined that almost all of them were receding from us at high speeds. Combining these velocity measurements with the distance measurements, Edwin Hubble and others soon discovered that the more distant a galaxy was located from our galaxy, the faster it was moving away from us. The interpretation was as simple

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as it was astonishing: it could only mean that all galaxies were moving away from each other, hence the Universe was expanding. Until then, the Universe had been thought to be static. If it was expanding, it meant that it had a beginning as well. This moment when everything was created has become famous as the Big Bang (the name was coined by Fred Hoyle in 1949, who believed in a static Universe and invented the term to sarcastically express his dislike in the theory - although according to his reading, the term only served to highlight the differences between the theories). The fact that people had great difficulties in believing in a Universe that was not static but expanding was demonstrated by one of the greatest minds of all times, Albert Einstein. In his work on General Relativity a few years earlier, he added a constant to one of his equations so that it would enforce a static Universe rather than an expanding one (the largest error of his career, he later confessed, as he could have predicted the expansion of the Universe before it was observed).

Another change of our world view was initiated in the 1930s by the work of Fritz Zwicky on groups of galaxies (galaxy clusters), but only became widely known after the work of Vera Rubin and her collaborators in the 1960s. Zwicky studied the orbital velocities of galaxies in the Coma cluster, and inferred from their large velocities that ‘missing’ mass had to be present to prevent these galaxies from flying off. Rubin studied rotation curves<sup>1</sup> of nearby spiral galaxies and deduced the total mass enclosed within a certain radius using standard Newtonian physics. The total mass exceeded the mass that could be accounted for by the sum of stars, gas and dust (the baryons). Hence another component had to be present, exerting gravity, but invisible to the eye: dark matter. Nowadays, the presence of dark matter has been confirmed by various observations, including the stellar dynamics in nearby galaxies, the kinematics of satellite galaxies in clusters, and by observations of hot X-ray emitting gas. These observations support the view that the galaxies and galaxy clusters we observe are embedded in giant dark matter structures. One of the most convincing observations supporting the existence of dark matter has been made by Clowe et al. (2006) in a system called the Bullet Cluster. In this work, two galaxy clusters are studied just after they crashed into each other. The hot gas from both galaxy clusters, which constitutes the major part of the ordinary baryonic matter, collided violently and slowed down, whilst emitting a huge amount of X-ray radiation. The dark matter, however, which only interacts through gravitation, did not collide and moved on after the collision, forming two separate clumps, clearly offset from the gas.

At about the same time of the first observations of galaxy rotation curves, Penzias and Wilson, two radio engineers working for Bell Labs, measured a source of radio noise at millimeter wavelengths coming from all directions in the sky. Radiation in this wavelength regime had already been predicted in 1948 by Gamow, Alpher and Herman as a relic of the Big Bang. Shortly after the Big Bang, the Universe consisted of one giant immensely dense and hot soup of elementary particles and radiation. After approximately 380 000 years of expansion and cooling, the conditions in the Universe allowed protons and electrons to recombine and form hydrogen atoms. During this process, photons were emitted with an energy of 13.6 eV, i.e. with a frequency peaking in the ultraviolet.

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<sup>1</sup>a rotation curve depicts the orbital velocity of stars as a function of distance from the galactic centre

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## 1.1. THE $\Lambda$ CDM FRAMEWORK

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Most of these photons traversed the Universe ever since, although the expansion of the Universe redshifted their frequency to the millimeter regime. This radiation, known as the Cosmic Microwave Background Radiation (CMBR), was exactly what Penzias and Wilson observed. The CMBR is found to be extremely homogeneous, and is very well described by a black-body spectrum with a temperature of 2.71 K, with fluctuations of the order  $10^{-5}$  K. The observation of the CMBR at exactly the expected wavelength regime is considered as one of the strongest proofs that the Big Bang actually happened. Detailed observations of the CMBR pattern across the sky with, amongst others, the Wilkinson Microwave Anisotropy Probe (WMAP) space telescope (Bennett et al. 2003; Jarosik et al. 2011) revealed a wealth of information about the structure of the Universe (e.g. that space appears flat rather than curved). It also provided constraints on the total amount of matter in the Universe, as well as strong evidence that a large fraction of the matter in the Universe has to be in a non-baryonic form (i.e. dark matter). The extreme homogeneity of the CMBR is commonly attributed to a period just after the Big Bang when the Universe expanded extremely rapid - exponentially - for a short timespan, which is called inflation. During inflation, the tiny quantum fluctuations in the Universe were blown up, and formed the seeds of the structure that formed afterwards.

In 1998, two independent research groups, called the *high- $z$  SN search*<sup>2</sup> and the *Supernova Cosmology Project*<sup>3</sup> determined the distance to very distant galaxies by studying the light of exploding stars (supernovae; Riess et al. 1998; Perlmutter et al. 1999). This led to the discovery that these distant galaxies are actually more distant than predicted for a Universe that expands at a constant rate. The only explanation again changed our world view radically - not only is the Universe expanding, but the expansion is actually accelerating! This conclusion has been disputed over the years, but the evidence supporting this view is increasing. For example, the CMBR observations show that the Universe is practically flat, which means that the average density in the Universe is close to a particular value (the critical density). Combining this with the constraints on the total amount of matter in the Universe, it follows that an additional form of energy has to be present. Also, studies of the growth of structure point in the same direction (e.g. Schrabback et al. 2010). What is causing this acceleration is not clear, but it is attributed to a hypothetical form of energy: dark energy. The nature of dark energy is not understood at all. Attempts have been made to relate it to the ground state energy of the quantum field that pervades space, but the discrepancy between the theoretical value and the value that follows from cosmological observations is an incredible factor of  $10^{-120}$ , which serves as a perfect illustration of our ignorance. These four components, i.e. the baryons, radiation, dark matter and dark energy, are currently believed to make up the Universe.

Parallel to all these observations, astronomers have developed countless models to describe our Universe and the way it evolves. Most of these models were discarded at some point as observations proved them wrong. One of them, however, has managed to stand the test of time so far, and is currently the most favoured model by the majority of the astronomical society. The model is called  $\Lambda$ CDM. The "CDM" stands for Cold Dark Matter, where the "Cold"

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<sup>2</sup><http://cfa-www.harvard.edu/cfa/oir/Research/supernova/home.html>

<sup>3</sup><http://supernova.lbl.gov/>

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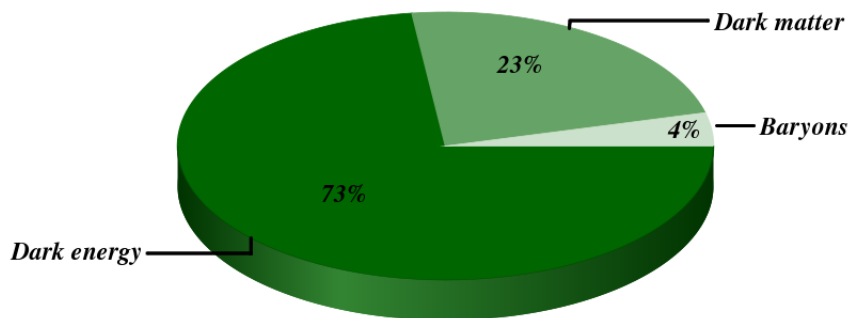


Figure 1.1: Contribution to the total energy density of the Universe by the three main components of  $\Lambda$ CDM.

indicates that the dark matter particles have relatively high masses and move at low speeds (as opposed to Hot Dark Matter, where the particles are assumed to move with relativistic speeds). The  $\Lambda$  refers to the constant Einstein added to his equations to enforce a static Universe, which he considered a mistake, but ironically has been reintroduced as the most natural description for dark energy. The  $\Lambda$ CDM model describes how the Universe, starting from a very hot and dense state, expanded, gradually cooled and eventually formed stars and galaxies. The strength and beauty of  $\Lambda$ CDM is that from a modest number of initial conditions and ingredients, it has the ability to predict with great precision a large variety of observations, ranging from the observations of density peaks in the cosmic microwave background radiation, to the cosmic abundances of the light elements (hydrogen, helium, deuterium and lithium), to the clustering of galaxies in the current day Universe. In  $\Lambda$ CDM, hot dark matter is also present in the form of neutrino's, but they only make up a small fraction of the total energy budget.

In our Universe, the baryons only make up a very modest part of the total content, as is depicted in Figure 1.1. The two dark components, dark matter and dark energy, dominate the energy density, but their nature is poorly understood at best. The majority of current research in cosmology is aimed at improving our understanding of these components: how are they distributed in the Universe, what are they made of, how do they interact, etc.

These efforts can be roughly divided into two main streams: numerical simulations and observations. In the first stream, the evolution and formation of structure in a certain volume of the Universe is simulated with computers. This field has rapidly expanded over the last two decades, propelled by the enormous growth of computational power. In recent simulations such as the Millennium Simulation (Springel et al. 2005), the movements of ten billion particles were traced from the moment of the formation of hydrogen (recombination) up to the current-day Universe, which is already an incredible achievement. The main difficulty with simulations is the correct incorporation of the baryons: baryonic physics is notoriously difficult, as many different processes such as supernova explosions and AGN<sup>4</sup> activity are important, but they are intertwined as well.

## 1.2. GRAVITATIONAL LENSING

These processes play, however, a very significant role in the formation of structure, and need to be incorporated accurately. If the implementation of these processes is not correct, neither will be the predictions from the simulations.

Although simulations improve our understanding of the evolution of our Universe, how it came to be as we observe it today, they need to be constrained by observations. For example, when we compare simulations with different implementations of supernova feedback to observations, we can learn which scenario is more likely than the other. But the opposite is true as well: for a given set of observations, we need simulations to help interpret what we see. Comparing observations with the results from simulations is generally complicated. Observations are distorted by all sorts of processes in the intergalactic medium, the atmosphere and the telescope, for which we have to correct. Simulations, however, offer a simplification of reality, as not all the processes that occur in the real Universe are accounted for. To match the observations to simulations and vice versa, we have to translate the one into the other, and herein lies the difficulty. Nonetheless, it is worth the effort as only through the combination of both we can improve our understanding of the Universe.

This thesis is part of the observational effort to study how dark matter is distributed in and around galaxies and galaxy clusters, and how it traces the baryons. The main technique we have used in our studies is gravitational lensing, which we introduce in the following section.

## 1.2 Gravitational lensing

As light emitted by distant galaxies (sources) travels through the Universe towards our telescopes, it is deflected by the gravitational pull of massive galaxies and galaxy clusters (lenses) that it passes on its way. Rather than in straight lines, each lightray follows a wiggly path through space. This effect is known as gravitational lensing. A sketch of a gravitational lens system is shown in Figure 1.2. A galaxy at a distance  $D_s$  from us that resides in the source plane emits light rays, that travel towards Earth (depicted by the thick solid line). After traveling the distance  $D_{ds}$ , the lightray is deflected by a massive structure in the lens plane, and travels the remaining  $D_d$  in a direction that is different from its original path towards the observer on Earth. This deflection of a lightray is described by the following geometrical relationship:

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(D_d\vec{\theta}) \frac{D_{ds}}{D_s}, \quad (1.1)$$

with  $\vec{\beta}$  the angular position of the source,  $\vec{\theta}$  the angular position of the image, and  $\vec{\alpha}(D_d\vec{\theta})$  the deflection angle. Introducing the angular coordinate  $\vec{\xi} = D_d\vec{\theta}$ , the deflection angle is given by

$$\vec{\alpha}(\vec{\xi}) = \frac{4G}{c^2} \int d^2\xi' \Sigma(\vec{\xi}') \frac{\vec{\xi} - \vec{\xi}'}{|\vec{\xi} - \vec{\xi}'|^2} \quad (1.2)$$

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<sup>4</sup>Active Galactic Nuclei refer to the centre of galaxies that harbour a massive black hole that actively accretes matter. An enormous amount of energy is released during this process through the expulsion of material in jets with speeds that near the speed of light.

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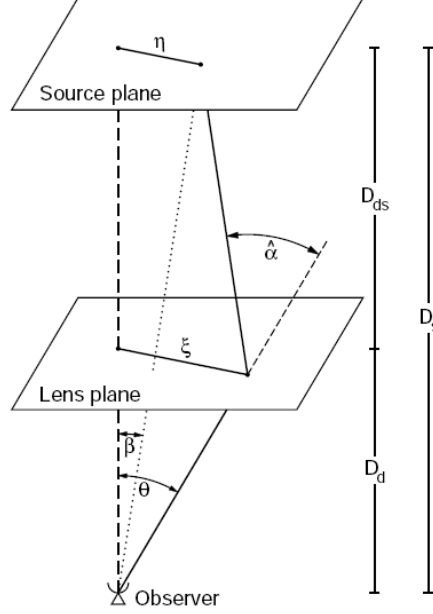


Figure 1.2: Sketch of a gravitational lens system (Bartelmann & Schneider 2001)

with  $\Sigma(\vec{\xi})$  the surface mass density and  $\vec{\xi}$  the impact parameter (Bartelmann & Schneider 2001).

Gravitational lensing affects our observations in several ways. Firstly, the observed location of source galaxies is different from their real positions on the sky. Since we do not know their positions beforehand, we cannot measure this effect. Secondly, if the lens is very massive, the light rays are bent around different sides of the lens towards Earth. As a result, we may observe more than one image of the same source galaxy. The length of the path that the light travels before it reaches us generally differs between the images. Therefore, when the light emitted by the source suddenly changes (for example due to a supernova explosion), this ‘news’ arrives at Earth for each image at a different moment. These so-called time delays can be used to study the rate of expansion of the Universe (Refsdal 1964), and constrain several cosmological parameters (Coe & Moustakas 2009).

From Equation (1.2) it can be observed that the deflection depends on the impact parameter; photons that pass the lens at different distances are deflected by different amounts. This differential deflection of the light rays leads to a remapping of the background sky. Consequently, the total amount of light of the sources is magnified, and their shapes are distorted. If the source galaxy image is small compared to the angular scale on which the lens properties change, the deflection of the light rays can locally be described by the deflection matrix. The deflection matrix relates the intrinsic (unlensed) surface-brightness of the source

## 1.2. GRAVITATIONAL LENSING

$I(x, y)$  to the observed one,  $I'(x', y')$ . It is given by:

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = (1 - \kappa) \begin{pmatrix} 1 - g_1 & -g_2 \\ -g_2 & 1 + g_1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \quad (1.3)$$

with  $(x, y)$  the observed coordinates and  $(x', y')$  the undistorted ones.  $\kappa$  is the convergence, defined as

$$\kappa = \frac{\Sigma(\vec{\xi})}{\Sigma_{\text{crit}}} ; \quad \Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_s}{D_d D_{\text{ds}}}, \quad (1.4)$$

with  $\Sigma_{\text{crit}}$  the critical surface mass density. The weak lensing regime is defined as the regime where  $\kappa \ll 1$  holds; if  $\kappa \geq 1$ , Equation (1.1) can have multiple solutions, resulting in multiple images of a single source for particular lens-source configurations.  $g_1, g_2 \equiv (\gamma_1, \gamma_2)/(1 - \kappa)$  is the reduced shear and  $(\gamma_1, \gamma_2)$  the shear. The shear describes the stretch of the image of the source due to the gravitational potential of the lens. Its effect on a round source is illustrated in Figure 1.3. The quantity we measure from the source ellipticities is the reduced shear, however. In weak lensing,  $\kappa \ll 1$ , and therefore  $g \approx \gamma$ , hence the reduced shear is approximately equal to the shear. If the distortion is small, it can be shown that the ellipticities of source galaxies change as follows:

$$e_i^{\text{obs}} = e_i^{\text{int}} + g_i, \quad (1.5)$$

with  $e_i^{\text{obs}}$  one of the two components of the observed ellipticity, and  $e_i^{\text{int}}$  the intrinsic ellipticity of the source. The shear can be retrieved in a certain part of the sky by averaging the ellipticities of a large number of sources:  $\langle g_i \rangle \approx \langle e_i^{\text{obs}} \rangle$ . The fundamental assumption made here is that the intrinsic ellipticities of galaxies have random orientations; the intrinsic part of the observed ellipticities averages out, leaving us with the average shear imprinted on those sources. This assumption is actually not correct as neighbouring galaxies that are or have been subject to the same large-scale gravitational field may have correlated ellipticities, an effect known as intrinsic alignments (e.g. Hirata et al. 2004, 2007). This affects studies that rely on the correlation of the ellipticities, but not the studies where the ellipticities are correlated with the *location* of the lenses as the lensing signal is generally averaged over large numbers of sources, and the effect averages out.

If a spherically symmetric lens lenses a source, the shape of the source is stretched tangentially, i.e. in the direction perpendicular to the vector that connects the lens with the source projected onto the plane of the sky. To understand this qualitatively, trace the light-rays back past the lens to the source. The light-rays that passed the lens at small impact radii (close to the lens) were deflected more than the light-rays that passed it at larger radii, hence the real image of the source is stretched radially compared to the image we observed. Vice versa, the observed image is stretched tangentially with respect to the real image. This process is illustrated in Figure 1.4.

A commonly used method to extract the shear from the shapes of the sources is therefore by measuring the source ellipticity components in the direction tangent to the line that connects the lens and the source, hence the direction in which they were distorted. The quantity we measure is the tangential shear (also known as the galaxy-mass cross-correlation function),

$$\gamma_t = -[\gamma_1 \cos(2\theta) + \gamma_2 \sin(2\theta)], \quad (1.6)$$

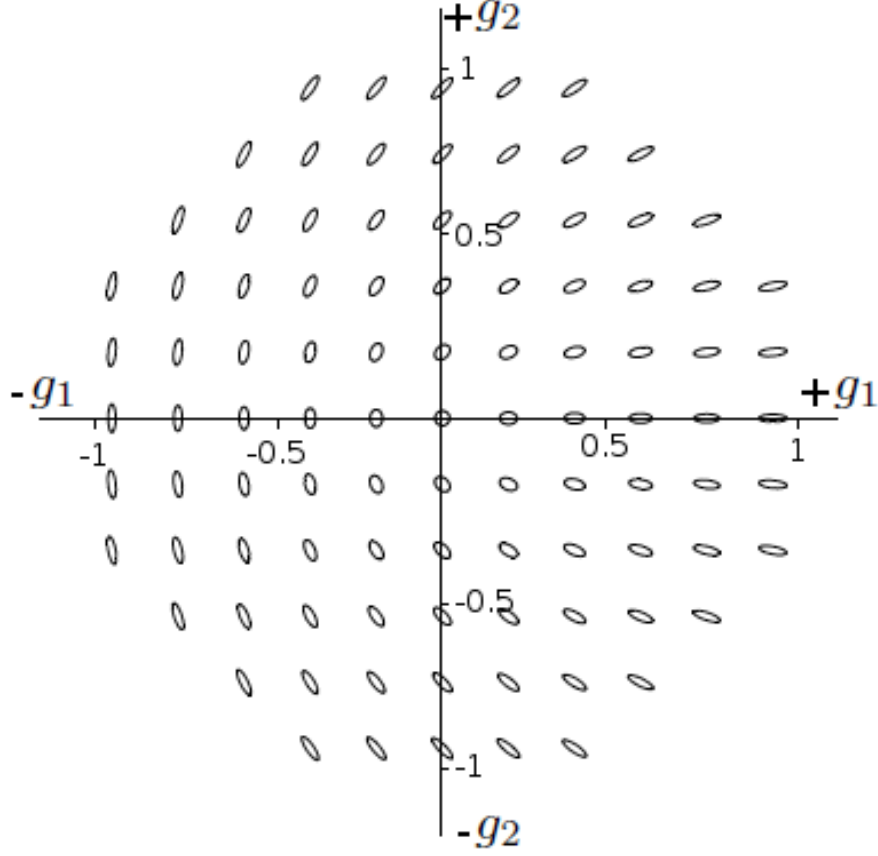


Figure 1.3: Gravitational shear applied on an intrinsically round source. If  $g_1$  is positive (negative), the source is stretched horizontally (vertically); if  $g_2$  is positive (negative), the source is stretched in the  $x = y$  ( $x = -y$ ) direction (source: D. Clowe).

with  $\theta$  the angle between the horizontal axis and the vector between the lens and the source. By measuring the tangential shear in concentric rings centred on the lens, the radial shear pattern of the lens can be studied.

To determine whether galaxy-galaxy lensing produces a tangential shear that is positive or negative, we imagine a round source galaxy that lies on the horizontal axis that passes through the centre of the lens, hence  $\cos(2\theta) = 1$ . The distortion of its shape is in the tangential direction: the source is stretched vertically. In Figure 1.3 we find that this corresponds to a negative  $\gamma_1$ . Therefore, the tangential shear is positive.

The tangential shear is a convenient way to quantify the lensing signal, because it can be directly related to the differential surface mass density:

$$\langle \gamma_t(\xi) \rangle = \frac{\Delta \Sigma(\xi)}{\Sigma_{\text{crit}}}, \quad (1.7)$$

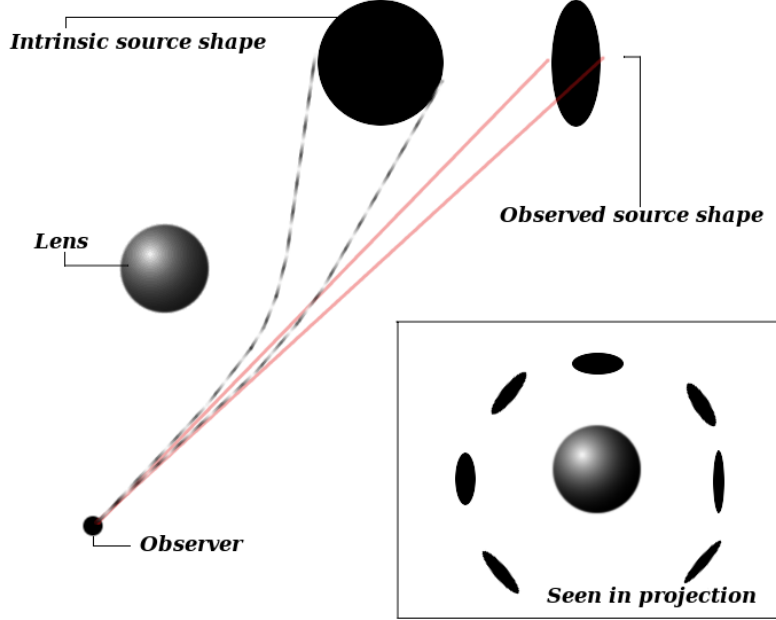


Figure 1.4: Cartoon of galaxy-galaxy lensing. Lightrays of a source passing the lens at different impact parameters are bent by different amounts. As a consequence, the shape of the source becomes elongated in the direction perpendicular to the lens-source separation. When seen in projection on the sky, a coherent shear pattern is formed around the lens when there are multiple sources at different positions behind the lens.

where  $\Delta\Sigma(\xi) = \bar{\Sigma}(< \xi) - \bar{\Sigma}(\xi)$  is the difference between the mean projected surface density enclosed by  $\xi$  and the mean projected surface density on a circle at  $\xi$ . Since we only measure the difference between projected densities, and not the projected density itself, we can in principle not determine the mass of the lenses, unless we know the value of the projected density at a certain position in the lens plane. In other words, if we were to increase the density uniformly across the lens plane, the tangential shear in the weak lensing regime ( $\kappa \ll 1$ ) would not change, but the mass obviously would – this problem is known as the mass-sheet degeneracy (Falco et al. 1985; Schneider & Seitz 1995). The most common solution to this problem is to assume a certain two-dimensional profile for the density (e.g. based on results from numerical simulations), and fit the corresponding lensing signal to the observed shear. Amongst the most popular models are the Singular Isothermal Sphere (SIS) profile, and the Navarro-Frenk-White (NFW) profile (Navarro et al. 1996). The total mass is then obtained by integrating the density in an area where the density is larger than a certain threshold value.

Another consequence of differential deflections is that the source galaxies are magnified, which leads to an increase of their flux. This cannot be measured for individual objects, as their brightnesses are not known a priori. However,

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if the luminosity function<sup>5</sup> of a certain sample of sources is accurately known, the effect is measurable (e.g. Hildebrandt et al. 2011). The systematic errors of shear and magnification are different, mainly because different quantities are measured: for shear, we measure the shapes of galaxies, whilst for magnification we measure their total flux. Particularly for high-redshift lenses magnification is expected to complement shear in constraining the dark matter distribution, because for magnification more faint and high-redshift sources can be used as the flux of a (faint) source is more easy to determine than its shape (van Waerbeke 2010).

The distortion of the background sky leads only by approximation to a stretch of the sources; the actual change of shape is more complex. The source galaxies are slightly bent as well, in such a way that the total deformation gives the sources the appearance of a banana. These higher-order distortions are called flexion, and they can be measured on small projected scales close to the lens (e.g. Goldberg & Natarajan 2002; Goldberg & Bacon 2005; Bacon et al. 2006; Velandier et al. 2011). Flexion is particularly sensitive to substructures in the lens, which makes it a useful complement to shear. If the distortion is very strong, for example close to a massive cluster of galaxies, the image of a source can be stretched into long arcs, and in exceptional cases even into rings (Einstein rings). This is the regime of strong lensing.

Shear, flexion and magnification are part of weak gravitational lensing. So far, most weak lensing studies have utilised the shape distortions by measuring the shear. The science chapters presented in this thesis are based on shear measurements too, and we discuss this further in the next section. Please note that in the forthcoming, when references are made to ‘weak lensing’, we generally mean the shear, unless explicitly stated otherwise.

### 1.2.1 Shear measurement

To measure the weak lensing signal, the ellipticities of a large number of source galaxies need to be accurately determined. In practice, this is a difficult task. When we observe galaxies from Earth, the images are distorted by the atmosphere, telescope and camera optics, changing the observed ellipticities of the galaxies and hence the shear we would infer from them. Since the gravitational lensing signal is very small, we have to correct for these distortions to a high level of accuracy. Any residual ellipticity pattern that is not due to gravitational lensing, but still present in the data, may be misinterpreted as real shear, which could bias the science results. Note that besides the technical difficulties, there are also physical complications (e.g. intrinsic alignments), which have to be properly accounted for when interpreting the observed lensing signal.

A large variety of methods has been developed since the 90s of last century, aimed at recovering the unconvolved shapes (i.e. the images before they entered Earth’s atmosphere) of the galaxies as precisely as possible. Their performance has been tested on artificial survey images that contain large numbers of galaxies whose morphologies mimic those of real galaxies (Heymans et al. 2006; Massey et al. 2007; Bridle et al. 2010). The best can measure the gravitational distortion with the precision of a few percent, which already enables

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<sup>5</sup>The luminosity function describes the number density of galaxies as a function of luminosity.

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### 1.3. APPLICATIONS OF WEAK GRAVITATIONAL LENSING

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a wealth of science projects. A lot of work is currently invested in developing methods that can reach an even higher precision, with subpercent errors on the measured shear values. This requires the understanding and control of ever smaller subtleties in the data, a difficult task but certainly worth the effort.

#### 1.2.2 Galaxy-galaxy/cluster lensing

In this thesis, we study the shear profile around (the positions of) lenses. If these lenses are other galaxies, this is called galaxy-galaxy lensing; if these lenses are clusters, this is called cluster lensing. As the shear of a lens is typically 10-100 times smaller than the intrinsic ellipticities of source galaxies, we generally cannot measure the tangential shear of a single lens. Only for massive low-redshift clusters the shear can be large enough to be detected for an individual system. For less massive clusters, and in the case of galaxy-galaxy lensing, the lensing signal has to be averaged over many lenses, as that reduces the noise caused by the intrinsic ellipticities of the sources. Even for small and low-mass lens galaxies, the lensing signal can be measured as long as we stack a sufficiently large number of lenses. The downside of stacking is that individual properties of galaxies cannot be studied; however, when we stack lenses of a certain type or brightness, we can still learn about the average properties, which is very interesting and useful.

It is clear from the definition of  $\Sigma_{\text{crit}}$  in Equation (1.4) that the magnitude of the lensing signal depends on the distances from us to the lens, to the source, and between the lens and the source. We measure a small signal at a given physical scale if either the lens is very close to us ( $D_d$  is small), or if the lens is very close to the source ( $D_{ds}$  is small). When the lens is roughly halfway between the source and the observer, the ratio of the distances, called the lensing efficiency, is optimal for lensing. To convert the tangential shear to  $\Delta\Sigma$ , we need to know either the individual redshifts of all galaxies involved, or the redshift distribution of the lenses and sources, and use the average distances. If no individual redshifts are available, the redshifts distributions can usually be obtained from public photometric redshift catalogues, to which identical selection criteria can be applied as was done for the lenses and sources.

In practice, there are various other issues that have to be accounted for: galaxies that were selected as sources may actually be physically associated to the lens; the ellipticity estimates of the sources may be inaccurate due to a variety of reasons; residual false shear patterns may still be present in the data. These complications have to be addressed and, when necessary, corrected. We will not go into detail here, as they are discussed when they come along in the following chapters.

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### 1.3 Applications of weak gravitational lensing

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Gravitational lensing is a unique tool in observational cosmology as it is the only method that directly probes the projected matter density distribution around lenses. Furthermore, since lensing does not depend on visible tracers, it can be used to measure the projected distribution of matter over a huge range of scales, from a few tens of kpc to a few Mpc. In contrast, other methods rely on

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the availability of visible tracers such as planetary nebulae or satellite galaxies that orbit the lenses, which limit their applicability to small scales (for planetary nebulae) or to particular types of lens galaxies (only central galaxies in satellite kinematic studies). Still other methods have to make assumptions on the physical state of the object (such as hydrostatical equilibrium of hot gas in X-ray measurements), which makes them less robust.

A broad variety of research topics can be studied with weak lensing. On large scales, weak lensing can be used to study the large-scale distribution of matter. Lensing by the large-scale distribution imprints coherent shear patterns on the ellipticities of galaxies, which can be studied by correlating the ellipticities of galaxies in a certain patch of the sky. These measures provide us with estimates of the statistical properties of the distribution of matter (e.g. Huff et al. 2011). When we have redshift information available for the galaxies, we can split the galaxies in redshift slices, and learn how these correlation functions – and hence the distribution of matter – change with time. These changes are on the one side due to gravity, which makes the distribution more clumpy as material is pulled towards each other. Acting in the opposite direction is dark energy, causing an accelerated expansion of the Universe, which pulls space – and therefore the matter that is embedded – apart. Hence by studying the variations of these correlation functions with time, we can measure how dark energy impacts the growth of structure, and therefore study properties of dark energy itself (Schraback et al. 2010).

When we measure the lensing signal around galaxies, we can compare the matter distribution to the light distribution. This reveals where the dark matter is residing, how much there is of it and how it is distributed (e.g. Gavazzi et al. 2007). By splitting the lenses as a function of type, environment, and redshift, we learn which types of galaxies host most of the dark matter, how this depends on the environment and how this has evolved over time (e.g. van Uitert et al. 2011; Leauthaud et al. 2012). This knowledge is crucial for understanding how galaxies form and evolve. Such studies also provide insights on the properties of dark matter (e.g. about its clumpiness), which may eventually lead to clues about the nature of dark matter.

Similarly to galaxies, we can also measure the lensing signal around groups of galaxies and galaxy clusters. This enables us to calibrate their masses without the need to make assumptions about the physical state of the cluster (e.g. hydrostatical equilibrium in X-ray measurements, or virial equilibrium in satellite kinematic studies). This is particularly useful for low-mass clusters, which have fewer tracers of the mass and are typically not in equilibrium. Measuring the mass as a function of the number of cluster members (e.g. Sheldon et al. 2009), and of redshift (e.g. see Chapter 6), leads to important insight into the formation and evolution of clusters, and hence into the physics that govern these processes.

In short, the observational constraints obtained from lensing provide crucial information on the relation between dark matter and baryons, the formation of structure and the evolution of the Universe. The expected arrival of high quality imaging data from upcoming surveys, in combination with the expected improvement of the methods used for lensing, leads to the belief that weak lensing is a particularly promising way to study dark energy in comparison to other methods (Albrecht et al. 2006).

## 1.4 This thesis

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In this thesis we study the distribution of matter around galaxies and galaxy clusters with weak gravitational lensing. Amongst the questions we attempt to answer are the following: how massive are the dark matter haloes of galaxies? Do some type of galaxies have more dark matter than others? What is the relation between the baryonic properties of galaxies (e.g. the total amount of light emitted, or the total mass in stars) and the total amount of dark matter of their haloes? Which of the baryonic tracers is most closely related to the halo mass of a galaxy? Are the dark matter haloes triaxial or not, and can we detect that with gravitational lensing? Does that depend on the type of galaxy? How massive are galaxy clusters, and how does the mass scale with their richness (total number of member galaxies)? Does the relation between mass and richness evolve with redshift?

We study these questions using the imaging data from the Red Sequence Cluster Survey 2 (RCS2), which is a 900 square degree imaging survey in the  $g'r'z'$ -bands. With a median seeing in the  $r'$ -band of  $0.7''$ , and a depth of  $\sim 24.3$  in  $m_{r'}$ , this survey enables many unique (lensing) studies that cannot be performed with any other currently available imaging data set. In **Chapter 2**, we discuss the details of the RCS2, and highlight the differences between the RCS2 and the other imaging surveys that have been used for lensing studies. We detail on the image reduction we have performed, and outline the steps that led to the creation of the galaxy shape catalogues. The shape catalogues, which contain the ellipticities of all the galaxies in the survey, are at the core of the science studies worked out in further chapters. We have performed various checks to ensure that the quality of the catalogues is at the desired level, and the results of these checks are presented.

The RCS2 overlaps with various other surveys, including  $\sim 300$  square degrees with the Sloan Digital Sky Survey (SDSS; York et al. 2000). The combination of spectroscopic coverage and photometry in five optical bands ( $u$ ,  $g$ ,  $r$ ,  $i$ ,  $z$ ) in the SDSS provides a wealth of information on galaxies that is not available for the RCS2 alone. We use this information, but also benefit from the improved lensing quality of the RCS2, by matching the shape catalogues from the RCS2 with various catalogues of the SDSS. This results in 17 000 matching galaxies with a spectroscopic redshift, and many other galaxy properties such as stellar mass, velocity dispersion and luminosity. These galaxies form the lens sample of **Chapter 3** and **Chapter 4**.

In **Chapter 3**, we study the relation between the baryonic properties of galaxies and their dark matter haloes. As this relation depends on galaxy type, we split the 17 000 matching galaxies in an elliptical (early-type) and spiral (late-type) sample. These samples are further divided in bins of either luminosity, stellar mass or dynamical mass, and the lensing signal of the lenses in each bin is measured. To model the lensing signal accurately, we have to account for the fact that a fraction of the lenses are satellite of a larger system. At large projected separations, these larger systems contribute significantly to the lensing signal, which has to be taken into account. For that purpose, we implement a halo model, which enables us to study both the mass and the clustering properties of the lenses. We study how the average luminosity and stellar mass relate to the total halo mass. Furthermore, we determine the satellite fraction of

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the lens samples, and study how it depends on luminosity and stellar mass. We derive mass-to-luminosity ratios and baryonic fractions of the lens galaxies, and study their dependence on luminosity and stellar mass, respectively. Finally, we divide the lens bins into redshift slices, in order to study potential evolutionary trends in the relation between baryons and dark matter.

In **Chapter 4** we use a subsample of the lenses from **Chapter 3** to address the question: which observable property of galaxies is most closely related to the lensing signal? We compare three properties: the stellar mass, the spectroscopic velocity dispersion and the model velocity dispersion, which is an alternative estimate of the spectroscopic velocity dispersion of galaxies. The calculation of the model velocity dispersion is based on the results of Taylor et al. (2010), who demonstrated that the dynamical mass and stellar mass are linearly related if one accounts for the structure of a galaxy. As the model velocity is calculated using quantities that are generally better determined than the spectroscopic velocity dispersion, it is believed that the former is a more robust velocity dispersion estimator. Comparing the model velocity dispersion to the spectroscopic velocity dispersion, we find that they correlate well for de Vaucouleur-type galaxies at redshifts  $z < 0.2$ , and these are the galaxies that form the lens sample. To determine which galaxy property is most closely related to the lensing signal, we measure how the lensing signal depends on each of them. We cannot directly interpret the measurements, however, because the three galaxy properties are correlated. To account for this, we remove the dependence of the lensing signal on either stellar mass or velocity dispersion, and study whether there is a residual dependence on the other property. Comparing these residuals enables us to determine which property of galaxies is most closely related to the lensing signal.

Weak gravitational lensing is not only a useful tool to determine the total masses of galaxies and their relative correlation with respect to the underlying dark matter distribution, but it can also be used to study the shapes of the dark matter haloes of galaxies. This is the subject of **Chapter 5**. Numerical simulations predict that matter collapses in triaxial haloes. If the orientation of galaxies and dark matter haloes are correlated (so either aligned or oriented at a  $90^\circ$  angle, i.e. anti-aligned), the lensing signal around galaxies becomes anisotropic. Hence by studying anisotropies in the weak lensing signal we can learn about the average projected dark matter halo ellipticity of galaxies. We use the imaging data from the RCS2 to select the lenses and sources, and perform the lensing analysis on the whole survey area. We select massive low-redshift galaxies as lenses to optimize the lensing signal-to-noise and to minimize potential systematic contributions. To study potential environmental dependencies, we divide the lens sample in an isolated and a clustered part, and analyse them separately. There are several complications that could change the anisotropy of the lensing signal. We address the impact of a few of them: PSF residual systematics in the galaxy shape catalogues, additional lensing by foreground structures, clustering and magnification. We set up a number of idealised simulations to estimate the impact of these complications on our measurements. To interpret the observed anisotropy of the shear in terms of the average halo ellipticity of galaxies, we need to account for the intrinsic scatter in the position angles between galaxies and their dark matter hosts. Recent studies suggest that the scatter is large, with a value in the range  $20^\circ$ - $40^\circ$ . We present estimates of the impact of this scatter on the observed anisotropy of the lensing

signal.

Finally, we move our attention to larger structures and study the largest gravitationally bound systems in the Universe, galaxy clusters, in **Chapter 6**. Cluster evolution has been one of the main science goals of the RCS2, and the survey design was chosen such as to optimize the detection of clusters up to a redshift  $z \sim 1$ . Nearly 30 000 galaxy clusters have been detected using the cluster red sequence method, a detection method that utilizes the property that the early-type galaxies in a cluster have very similar colours. These clusters are spread over a large range of optical richnesses (number of cluster members) and have redshifts in the range  $0.2 < z < 1.2$ . To learn about the growth and evolution of clusters, we can study how various properties of clusters are related as a function of redshift. One of the relations of interest is the one between the mass of a cluster and the richness. A careful calibration of the mass-richness relation is also crucial for studies aimed at constraining cosmological parameters using cluster number counts. To determine the evolution of the mass-richness relation, we divide the cluster sample into bins of richness and redshift, and measure the lensing signal in each bin to determine the average cluster mass. We end the chapter by measuring the excess galaxy number density around the clusters, and outline how we can use it to improve the modeling of the lensing signal.

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