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The alignment of galaxies across all scales

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Chapter 1

Introduction

The topic of cosmology has been in the interest of humans for thousands of years. It is easy to understand why this is the case, since cosmology tries to tackle the largest and most mysterious questions we can impose: how is the Universe and everything in it created and what makes it evolve and appear as it is today. It is only reasonable to expect the curious nature of humans will lead to the study of the Universe, initially from a philosophical perspective, but later, especially during the last century, from a scientific point of view. In particular, during the last few decades, we have been able to construct a broad view of the different ingredients and physical processes taking place during the history of our Universe, and settled on a standard cosmological model which encompasses our understanding. We have been able to parametrise the Universe into a few cosmological parameters and, with improving technological and statistical techniques, measured them with great accuracy using many independent observations.

The success of the standard cosmological model in describing astronomical observations is perhaps overshadowed by the two main questions it raises: what is the nature of dark matter and dark energy. These two are components of the Universe that make up approximately 95% of the energy density of the present day Universe, and their existence is evidenced by many independent observations. In general, dark matter has the effect of increasing structure formation while dark energy halts it. However, there is very little we currently

understand about the fundamental physics that describe these components, and observations sensitive to them are crucial in increasing our understanding.

Several observational techniques can provide insight into dark matter and dark energy, but of particular interest in this thesis is weak gravitational lensing. This is the coherent distortion of light sources from the intervening matter as light traverses through the spacetime. The distortion can be extracted by statistically analysing shapes of a large ensemble of galaxies, and is related to the matter content as well as the geometry and expansion history of the Universe. This makes weak gravitational lensing sensitive to dark matter and dark energy, and with current and future astronomical surveys designed specifically to exploit this phenomenon, it has become a competitive cosmological probe with great statistical power in measuring cosmological parameters.

The statistical power and promise of future weak gravitational lensing surveys can only be realised if systematic contamination to the measured signal is controlled to very high accuracy. The most important astrophysical contaminant is intrinsic alignments, the correlation of galaxy shapes with the tidal gravitational field. Since lensing relies on measuring correlations of galaxy shapes, intrinsic alignments will cause shape correlations that are not due to gravitational lensing, and can bias the cosmological parameters extracted from lensing, if unaccounted for (see e.g. Kirk et al. 2015). The main focus of this thesis is the exploration of the galaxy intrinsic alignment signal, as measured from state of the art astronomical data, and the dependence of the signal on several galaxy properties, such as colour and galaxy scale.

1.1 Introduction to cosmology

Cosmology is a subject of astronomy that tries to answer two key questions. The first question is with regards to the Universe's origins, and understanding the physical laws and processes that took place at the beginning of the Universe with the goal of explaining its existence. The common approach to this question is the development and formulation of a quantum gravity theory, and the difficulty stems from the complexity of the problem as well as the lack of an observational testing ground for such models. The second question is about understanding the processes involved in evolving the Universe, from a small age and given initial conditions, to the way the Universe is observed today. This question is often approached with statistical studies of the Universe's properties and observational data.

It is now widely theorised that the Universe was created at the Big Bang,

a single point in time which marks the generation of spacetime and our Universe. This idea was mainly motivated by the observation of the expansion of our Universe and the postulate that, some finite time ago, the observable Universe had to be confined in a very small (if not infinitely small) space with extremely high energy density and temperatures. Particles at these conditions are strongly interacting with each other and, at later times, as the Universe expands and cools, atomic nuclei and atoms are formed, according to the Big Bang Nucleosynthesis.

With the Big Bang hypothesis, two important predictions can be made. The first is the existence of a radiation observed at every point in the sky, leftover from the epoch of recombination, when the Universe's energy density allows electrons to be captured by atoms and photons to traverse freely. This radiation, called the Cosmic Microwave Background (CMB), was predicted to have a temperature of $\sim 3 - 5$ Kelvin, and was first directly observed by Penzias and Wilson in 1964. The small inhomogeneities in the CMB, illustrated in Fig. 1.1, now serve as a highly important observable of the content and initial conditions of our Universe (e.g. Hinshaw et al. 2013; Planck Collaboration et al. 2018). The second prediction concerns the primordial creation of atoms in the Universe, and their relative abundances. Big Bang nucleosynthesis suggest that about 75% of the primordial baryonic matter in the Universe is hydrogen, 25% is helium and there is a very small amount of Deuterium, Helium-3 and Lithium. Observations of the CMB and abundance of elements have established the Big Bang hypothesis in the standard cosmological paradigm.

Another important era of the Universe's history is inflation, a short period of time right after the Big Bang and before the nucleosynthesis, during which the Universe is believed to grow exponentially in size. Inflation manages to provide explanation for key questions raised by the standard model of cosmology. These are the homogeneity and Gaussianity of the CMB temperature map, the lack of magnetic monopoles as well as the observation of a geometrically Euclidian universe, which would otherwise require a very precise fine tuning of the Universe's initial conditions.

1.1.1 The flat Λ CDM cosmology

In order to predict the evolution of the Universe given its initial conditions, a mathematical framework is provided by general relativity. However, the complexity of Einstein's field equations necessitate the use of several hypotheses. General relativity already assumes the universality of the physical laws, regardless of the point in spacetime. In addition, motivated by the homogeneity of the

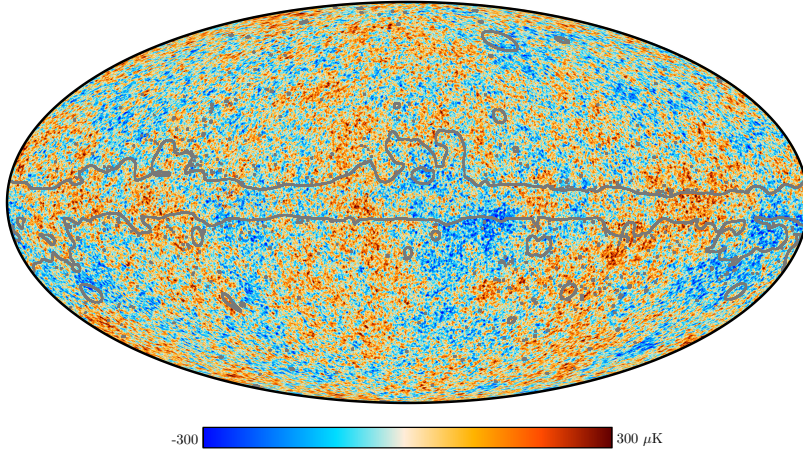


Figure 1.1: Temperature anisotropies from the Cosmic Microwave Background radiation, emitted at the early Universe at the time of recombination. The grey regions show masked areas due to our galaxy's and light from other bright objects. *Credit: ESA/NASA.*

CMB, it is assumed that the Universe is homogeneous and isotropic, leading us to spherical symmetry (also referred to as the *cosmological principle*). This assumption is also supported by the belief that the Universe as a whole should not appear different to two observers in different locations.

These assumptions result in what is called the Friedmann Universe, and allow the calculation of the evolution of the different components in the Universe. According to this model, the Universe started from a radiation dominated era, when radiation dominates the expansion history at the high energy densities of the Big Bang, and later went through a matter dominated era. This transition happens closely before the emission of the CMB, after which the Universe can be considered to be matter dominated.

Considering the amplitude of the anisotropies in the CMB, a universe dominated by baryonic matter does not have enough time to evolve and create structures such as galaxies and galaxy clusters, that we observe today. One way to solve this problem is to introduce another, non-baryonic matter component in the Universe, which is collisionless and interacts only gravitationally. Such a component will be unaffected during the radiation dominated era, and will be able to cluster and form gravitational wells in which baryonic matter will fall

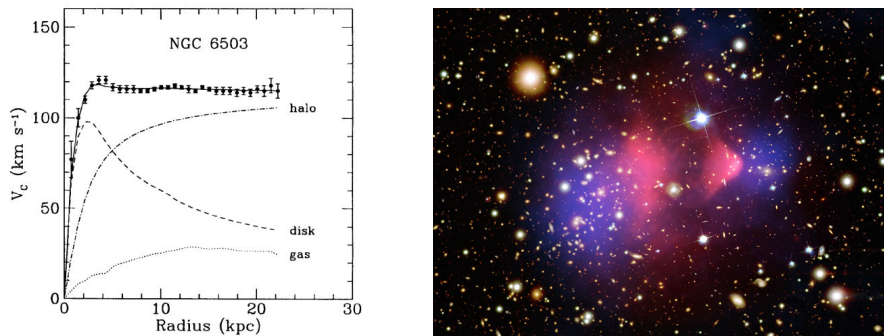


Figure 1.2: *Left*: Rotational curves as a function of distance from the galaxy’s centre for NGC6503, with the curve profile due to stars, gas and dark matter overplotted. *Right*: Colour image of the bullet cluster (merging of two clusters), with the x-ray gas emission in pink (which represents most of the luminous matter in the clusters) and the total mass obtained with gravitational lensing in blue (see Sec. 1.2). The displacement in mass suggests that the luminous matter does not correspond to the total observed matter in the clusters, providing evidence for the existence of dark matter. *Credit*: Freese (2017)

into and speed up structure formation. This component is called dark matter.

Evidence for the existence of dark matter has been found in many different, independent observations (Figure 1.2). For example, rotational velocity curves measured in spiral galaxies cannot be explained by the visible baryonic matter of the galaxies alone, but are understood if the galaxies are assumed to reside embedded in a large and smooth halo of dark matter particles. Moreover, observations of collisions between galaxy clusters show that the total mass of the clusters does not coincide with the visible mass (Clowe et al. 2004). Analysis of the power spectrum from the CMB anisotropies is also fit best by a Universe whose matter content is both baryonic and non-baryonic (Planck Collaboration et al. 2018). Dark matter is, therefore, accepted within the standard model of cosmology, with many observations hinting its existence.

Another important component observed in the Universe is dark energy, an unknown form of energy density which causes the expansion of the Universe to accelerate at late times, ending the matter dominated era. This acceleration was evidenced in distance measurements of type Ia supernovae via their luminosity curves (Riess et al. 1998), and many observations, such as the CMB power

spectrum, are consistent with the existence of dark energy. The impact of dark energy in the evolution of the Universe is encoded in the cosmological constant, Λ , which is considered to be constant in the standard model of cosmology.

The various components of the Universe are commonly parametrised with the energy density ratios, which are measurable quantities in many independent astronomical observations. The latest constraints of the density ratios at present day show a universe dominated by dark energy, with $\Omega_\Lambda \sim 69\%$. The ratio for dark matter is $\Omega_c \sim 26\%$, for baryonic matter and radiation is $\Omega_b \sim 5\%$ and $\Omega_r \sim 10^{-5}$, respectively, while the curvature of the Universe is measured to be consistent with zero.

1.1.2 Basics of galaxy formation and evolution

Given the standard cosmological model, solving for the evolution of the Universe beyond the linear regime is a very complicated problem. Moreover, as baryon density rises, interactions between baryons add an additional large complexity to this problem. For this reason, the most accurate qualitative and quantitative predictions come from numerical methods for solving the dynamics and interactions of matter contents in the Universe, also called cosmological simulations.

The first attempts at cosmological simulations involved numerically solving for a N-body system of dark matter “particles” (in a numerical sense, which doesn’t correspond to the actual fundamental dark matter particle but to a numerical quantity that describes a region of certain dark matter mass). The generally small gravitational forces involved during these calculations allow for the approximation of gravitational interactions with Newtonian dynamics, as well as using the Poisson equation. These simulations revealed that dark matter particles collapse into smooth, triaxial halos with a universal radial density profile, known as the Navarro-Frenk-White profile.

Baryonic gas generally follows the structure of dark matter, through gravitational interactions. However, gas is able to cool through baryonic interactions. The most important of these is bremsstrahlung radiation and photon emission from atomic and molecular excited states. This has the effect of allowing the gas to contract and increase its density even more, eventually being able to form stars and galaxies which are believed to be embedded in a halo of dark matter.

Galaxies and their host halos do not evolve in isolation but interact with other galaxies, and one way of interacting is called merging. During merging, the less massive galaxy will be stretched and stripped from its gas, and can end up orbiting the massive one. In this way, satellites and central galaxies are formed, in knots of high matter density, and a large number of gravitationally

bound galaxies will form galaxy groups and galaxy clusters. Merging can also result in a new more massive galaxy, formed from the coalition of the merged galaxies. In this way, more and more massive galaxies can form, in a “bottom-up” scenario, i.e. smaller galaxies merge to produce more massive ones. An elliptical galaxy is often the result of the merging of two approximately equal mass galaxies, with disk structures forming if angular momentum and cooling are high. For further information on galaxy evolution we refer the reader to Mo et al. (2010) and references therein.

In order to observe the matter content of the Universe, luminous tracers are often used, most commonly galaxies. However, given their formation and evolution mechanisms, galaxies are biased tracers of the matter density, with the bias depending on the galaxy properties. Moreover, since dark matter makes up for the majority of the matter content and interacts only gravitationally, observational techniques sensitive to gravity are optimal to study not only the matter content of the Universe, but the physics and behaviour of dark matter and its interplay with galaxies. A successful technique is gravitational lensing, which we introduce below.

1.2 Weak gravitational lensing

General relativity predicts that spacetime is curved due to the presence of mass. Moreover, light particles follow null geodesic curves, which minimize the distance between two points in space. If the space is curved, the geodesics will follow this curvature. Consequently, when light bundles travel near a massive object, their path is curved and the original shape and position of the source of these light bundles is distorted, a phenomenon called gravitational lensing (for an extensive review see Bartelmann & Schneider 2001).

The displacement due to gravitational lensing was first observed by Eddington in 1920 for stars deflected by the Sun, and was an important step towards establishing general relativity as the standard theory of gravity. For more massive and distant objects, there can be more than one null geodesic connecting the source and observer, passing near the lensing mass, which will result in the observer seeing multiple images of the source object. This was first discovered by Walsh et al. (1979). Moreover, light from extended sources can be distorted enough that the source appears as a ring, first observed by Hewitt et al. (1988).

The phenomena described above manifest only when the light source is very close to the lens object in the sky plane. However, massive objects can distort the shape of background sources (commonly galaxies) across the whole

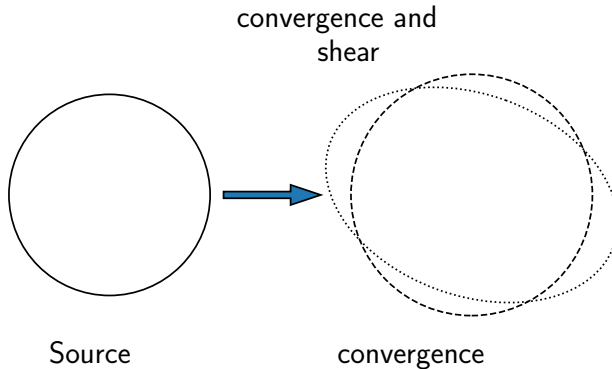


Figure 1.3: The effect of gravitational lensing on the shape of a circular source. The convergence alone has the effect of magnifying the radius of the circle (dashed line), while adding a non-zero shear will generally stretch the source and result in an apparent elliptical shape (dotted line).

sky plane, although weakly enough that they cannot be disentangled from the source galaxy’s intrinsic elliptical shape. The distortion pattern is coherent and tangential to the lens position, and can be extracted by statistically analysing a large number of background sources (in the case of massive galaxy clusters) or by stacking multiple lenses and their sources. This regime is referred to as weak gravitational lensing, and it follows three main assumptions; the validity of general relativity, the gravitational potential of the lens is weak and can be described in Newtonian fashion, i.e. $\Phi \ll c^2$, and the peculiar velocities of the lens object are small compared to the speed of light, which holds true for all astrophysical lenses except compact objects (which we do not analyse here).

1.2.1 Lensing by galaxies

Often the distance among the lensing object, the observer and the light source is much larger than the size of the lens, such as in the case of galaxies or galaxy clusters. This allows us to use the “gravitational lens theory”, where the lens is considered to be in a plane perpendicular to the line of sight.

The strength of the distortion caused by the lens is quantified by the convergence, κ , which is related to the lens 2-dimensional surface mass density. When

$\kappa \geq 1$ the observer will see multiple images of the source, which, however, is not a necessary condition. In the case of weak gravitational lensing, the convergence is typically very small, i.e. $\kappa \ll 1$. Another useful quantity is the gravitational shear, which describes specifically the shape distortion of a background source due to gravitational lensing. In the case of a circular source, the gravitational shear will stretch the observed image and make it appear elliptical (see Fig. 1.3). In addition to this, because the surface brightness of lensed background sources does not change (since photons are neither emitted nor absorbed due to gravitational lensing) the observed brightness of sources will be changed. This is quantified by the magnification μ , which depends on both shear and convergence. The magnification on weak lensing applications is generally small and biases arising from it can be neglected for state of the art measurements.

By measuring the shear of source galaxies, we can infer the surface mass of the lensing objects, which encodes valuable information on their baryonic and dark matter density. For massive galaxy clusters, a mass map can be directly reconstructed if deep observations are available, with high enough number density of background source galaxies. For less massive clusters or galaxy groups, or even individual galaxies, a stacking technique can be applied, where all lens-source pairs are considered and an average surface mass for the whole lens sample can be computed.

1.2.2 Lensing by the large scale structure

When light traverses through space to reach the observer, it encounters overdensities and underdensities along its path, which will distort its path through gravitational lensing. The thin-lens approximation that was discussed in the previous section is not applicable in this case, however, light can be considered to be propagating in a homogeneous and isotropic Friedmann Universe with local density perturbations described by the Newtonian potential $\Phi \ll c^2$. In this way an effective convergence of the light bundle, κ_{eff} , can be computed.

We are mainly interested in statistically analyzing a large ensemble of galaxies, and the quantity of interest is the power spectrum of the convergence, P_κ . Several estimators have been developed to connect the convergence power spectrum to observations. Some examples are Pseudo-Cl's (Hivon et al. 2002), 3D cosmic shear which analyzes weak lensing in three dimensions (e.g. Kitching et al. 2014) and the quadratic estimator (Hu & White 2001). A more common approach is to use two point correlation functions (Bartelmann & Schneider 2001).

The two point correlation functions can be estimated by measuring the el-

lipticity of galaxies and computing the functions in tomographic bins, which allows the measurement of lensing from the large scale structure (also called cosmic shear) in different redshift ranges. This allows us to map out the history of structure formation in the Universe, and provides competitive measurements on a combination of matter density and the amplitude of density perturbations, $S_8 = \sigma_8 \Omega_m^{0.5}$ (e.g. Abbott et al. 2018; Hikage et al. 2019; Hildebrandt et al. 2018).

Regardless of the choice of estimator, cosmic shear measurements face several important systematic errors. A large effort has been made in the last few decades in controlling and modelling these effects, increasing the precision with which cosmological parameters can be measured from cosmic shear. Upcoming surveys plan to increase the statistical power of cosmic shear measurements significantly, that these systematic errors need to be controlled to a precision of $\sim 0.1\%$ (e.g. Massey et al. 2013). Therefore, understanding and modelling weak lensing systematics is of crucial importance. The most important systematics include errors in the photometric redshift distributions, shear measurement bias and galaxy intrinsic alignments, the last of which we discuss below.

1.3 Galaxy intrinsic alignments

Under the assumptions that galaxies are randomly oriented in the sky, the average ellipticity of an ensemble of background source galaxies directly estimates the gravitational shear. However, galaxies are affected by the tidal gravitational field since their formation, and interact with it through their evolution. This causes them to be aligned with the tidal gravitational field, and consequently with the matter distribution and with each other (for extensive reviews, see Joachimi et al. 2015; Kirk et al. 2015; Kiessling et al. 2015).

Galaxy intrinsic alignments are believed to be generated according to the tidal alignment mechanism. For rotationally supported galaxies, alignments are imprinted at the time of formation, with their angular momentum correlated with the tidal gravitational field. The strength of this alignment is decreasing with redshift, with interactions and merging washing it out. Currently, observations have not conclusively detected this alignment, and tight constraints have been put on its amplitude.

For pressure supported galaxies, the most commonly used model is the linear alignment model (Hirata & Seljak 2004), which relates the intrinsic ellipticity linearly to the matter density contrast. The linear alignment model is successful in describing the intrinsic alignments of red central galaxies on large scales $\gtrsim 10$

Mpc/ h , and has been tested in observations, where a significant alignment signal has been observed for massive, intrinsically red galaxies. An empirical model called the non-linear linear alignment model (NLA, Bridle & King 2007) is successful in describing intrinsic alignments in smaller scales down to a few Mpc/ h , and relies on substituting the linear power spectrum with its non-linear counterpart.

On smaller scales, the non-linear evolution of galaxies becomes important and a general consensus for a model describing the intrinsic alignments has not yet been reached. A promising empirical approach is the halo model for intrinsic alignments, which describes how satellite and central galaxies populate dark matter halos, as well as how they are aligned, and is motivated by predictions from cosmological simulations. These simulations suggest satellite galaxies are radially aligned with their host halo, and the strength of the alignment drops at large radial separations.

Recent observations of intra-halo alignments have yielded conflicting results, with several studies suggesting a non-detection while others measured radial satellite alignment. Understanding and modelling the intrinsic alignment signal on small scales is important if we hope to exploit the weak lensing signal on small scales, where a lot of cosmological information is available.

1.4 This thesis

It is clear that weak gravitational lensing is a powerful tool with which cosmology and the nature of dark matter and its interplay with galaxies can be studied. In order to push the field further, with the next generation surveys, systematic contaminants to weak lensing measurements need to be further controlled, and the most important astrophysical contamination is intrinsic alignments. In this thesis, the galaxy intrinsic alignments are measured in state-of-the-art data which allow for studying the dependence of the alignment signal on various properties related to the way observations and measurements are made as well as the galaxy samples. With this, more informative priors can be used to mitigate the effect of intrinsic alignment on weak lensing measurements, as well as provide insight into more accurately modelling the phenomenon.

Chapter 2 studies the intrinsic alignment signal and its dependence on wavelength. To do this, the fact that outer regions of galaxies are more susceptible to the tidal interactions is considered. The resulting alignment signal may therefore depend on the passband if the colours of galaxies vary spatially. To quantify this, shapes of galaxies with spectroscopic redshifts from the Galaxy

And Mass Assembly (GAMA, Driver et al. 2011) survey are measured, using deep *gri* imaging data from the KiloDegree Survey (KiDS, de Jong et al. 2015). Shapes are obtained using the moment-based shape measurement algorithm DEIMOS (Melchior et al. 2011), and its performance is assessed using dedicated image simulations, which shows that the ellipticities can be determined with an accuracy better than 1% in all bands. Additional tests for potential systematic errors did not reveal any issues. A significant difference of the alignment signal between the *g*, *r* and *i*-band observations is measured. This difference exceeds the amplitude of the linear alignment model on scales below 2 Mpc/*h*. Separating the sample into central/satellite and red/blue galaxies, it is found that the difference is dominated by red satellite galaxies.

In **Chapter 3** the NLA model of intrinsic galaxy alignments is directly constrained, analysing the most representative and complete flux-limited sample of spectroscopic galaxies available for cosmic shear surveys. The projected galaxy position-intrinsic shear correlations and the projected galaxy clustering signal is measured using high-resolution imaging from the KiDS overlap with the GAMA spectroscopic survey, and data from the Sloan Digital Sky Survey (York et al. 2000). Separating samples by colour, no significant detection of blue galaxy alignments is made, constraining the blue galaxy NLA amplitude $A_{\text{IA}}^{\text{B}} = 0.21^{+0.37}_{-0.36}$ to be consistent with zero. Robust detections ($\sim 9\sigma$) for red galaxies are made, with $A_{\text{IA}}^{\text{R}} = 3.18^{+0.47}_{-0.46}$, corresponding to a net radial alignment with the galaxy density field, and no evidence for any scaling of alignments with galaxy luminosity is found. My contribution to this work, in particular, was the development of the highly accurate shape measurement catalogue, and its calibration. In addition, my input concerned the calculation of the data covariance, the understanding of the signal around random points as well as the interpretation of the results and the data splitting. As a result from this analysis, informative priors for current and future weak lensing surveys are provided, an improvement over de facto wide priors that allow for unrealistic levels of intrinsic alignment contamination. For a colour-split cosmic shear analysis of the final KiDS survey area, it is forecasted that these priors will improve the constraining power on S_8 and the dark energy equation of state w_0 , by up to 62% and 51%, respectively. The results indicate, however, that the modelling of red/blue-split galaxy alignments may be insufficient to describe samples with variable central/satellite galaxy fractions.

Following these results, **Chapter 4** looks into the alignment of shapes of satellite galaxies, in galaxy groups, with respect to the brightest group galaxy (BGG), as well as alignments of the BGG shape with the satellite positions,

using the GAMA and KiDS surveys. Systematic errors are controlled with dedicated image simulations and shapes obtained with the DEIMOS shape measurement method are used. A significant satellite radial alignment signal is detected, which vanishes at large separations from the BGG. No strong trends of the signal with galaxy absolute magnitude or group mass is found. The alignment signal is dominated by red satellites. In addition, it is found that the outer regions of galaxies are aligned more strongly than their inner regions, probed by varying the radial weight employed during the shape measurement process. This behaviour is evident for both red and blue satellites. BGGs are also found to be aligned with satellite positions, with this alignment being stronger when considering the innermost satellites, using red BGGs and the shape of the outer region of the BGG. Lastly, measurements of the global intrinsic alignment signal are made for two different radial weight functions and no significant difference is found.

Finally, in **Chapter 5**, the alignment between galaxies and their dark matter halos is studied. Cosmological simulations predict dark matter halos that are triaxial, in the standard cosmological paradigm, which makes the ellipticity of dark matter halos a useful quantity to test cosmology and structure formation. To study this, the ratio of halo-to-galaxy ellipticity, f_h , is measured, using weak gravitational lensing. Since satellite galaxies complicate the interpretation of the measurement, their contamination is minimised by developing an algorithm to construct a highly pure ($\sim 93.5\%$) sample of central galaxies from photometric data (KiDS) to be used as lenses, based on selecting the brightest galaxy in a galaxy-dense space. The purity of the sample is demonstrated using group catalogues from spectroscopic data (GAMA) as well as from numerical simulations (MICE, Crocce et al. 2015). A non-zero f_h is measured, with $1\text{-}\sigma$ and $2\text{-}\sigma$ statistical significance for the full and intrinsically red galaxy samples, respectively. The results are in agreement with previous studies, and indicate that lower mass halos are rounder and/or less aligned with their host galaxy than samples of more massive galaxies, studied in galaxy groups and clusters.

