Cover Page

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Introduction

1.1 A brief history of the Universe

The questions concerning the origin, evolution, and fate of the Universe are probably as old as conscious mankind. For millennia the attempts to answer these questions were fundamentally connected to the religious narratives emerging throughout all human cultures. Just a few centuries ago with the rise of modern natural sciences based on observations and experiments, with which predictive mathematical theories can be falsified, the task of answering these cosmological questions moved beyond religious belief and physical cosmology started to emerge.

Just about a century ago Albert Einstein presented his field equations of gravity, the key equations of his theory of general relativity, to the Prussian Academy of Science in Berlin (Einstein 1915b). Within two years, in 1917, Einstein applied these field equations to the whole Universe and established the field of relativistic cosmology (Einstein 1917), which until today is at the very roots of our view on the cosmos.

Nowadays the theory of general relativity is regarded as a triumph of human mind, but at the time there was really no observational evidence supporting such a major revision of the prevalent gravity theory of Newtonian mechanics. Only the tiny precession of Mercury's perihelion hinted already in 1859 at an inconsistency in Newtonian mechanics (Le Verrier 1859), although astronomical zeitgeist favoured explaining the discrepancy rather with a never-to-be-detected planet 'Volcano'.

General relativity could naturally explain the precession of Mercury's perihelion (Einstein 1915a) and further observational evidence for it became available in 1919. During a solar eclipse Arthur S. Eddington observed the deflection angles of stars in close projected vicinity on the sky to the Sun (Eddington 1920). The observations employed the gravitational lensing effect, the phenomenon that light from a background source is deflected due to the mass of a foreground lens. In this particular case, the mass of the Sun deflects the light of stars in close projected vicinity to it on the sky. The observations convincingly showed that the stars visible during the eclipse did not appear at positions deflected by an angle predicted by Newtonian gravity. These results made Einstein world famous over night and contributed to the general acceptance of his new theory of gravity in the scientific community. This triggered rich theoretical research in this new field by Willem de Sitter (e.g. de Sitter 1917), Alexander Friedmann (e.g. Friedmann 1922), and Georges Lemaître (e.g. Lemaître 1927), and many others.

Around the same time, in 1920, the 'Great Debate' between astronomers Harlow Shapley and Heber Curtis was in full progress about what the actual size of the Universe is (Shapley & Curtis 1921). Shapley argued that the Milky Way represents the entirety of the Universe. Thus, he was convinced that the peculiar 'spiral nebulae', of which more and more were being observed as bigger and bigger telescopes became available, were contained in the Milky Way. Curtis, however, believed the nebulae to be 'island universes' arguing that they are

extragalactic and galaxies just like the Milky Way. Eventually, the debate was settled by the work of Edwin Hubble (Hubble 1925) and others who showed that the 'spiral nebulae' were indeed galaxies of their own. Spectral data of these nebulae taken by Slipher and interpreted by Lemaître and Hubble showed that almost all galaxies also seemed to be moving away from us (Slipher 1917; Lemaître 1927; Hubble 1929). This cosmic recession, however, was already interpreted by Lemaître in a cosmological sense as actually being the effect of an expanding Universe rather than the Doppler shifted peculiar motions of galaxies. The discovery of the expansion of the Universe made Einstein admit his 'greatest blunder' by which he referred to the introduction of the cosmological constant in his field equations in order to make the Universe eternal and static.

Tracing the evolution of an expanding Universe backwards in time leads to the conclusion that there must have been a point in space-time from which the Universe started its expansion, the 'Big Bang', estimated to have happened about 13.8 billion years ago. The Big Bang cosmology also predicts that the Universe was very dense and hot in its beginning and became cooler and less dense while expanding. When the Universe cooled down to a temperature that allowed for creating the first neutral hydrogen atoms out of the hot particle and radiation plasma, the Universe became transparent to radiation (around $380\,000$ years after the Big Bang). Even today we are able to observe the relics of this thermal radiation, the afterglow released right after the formation of the first neutral atoms, redshifted to very long (radio) wavelengths. In 1964, Arno Penzias and Robert Wilson discovered this cosmic microwave background (CMB) radiation by chance (Penzias & Wilson 1965). Today ever more precise and accurate measurements of the tiny temperature fluctuations in the CMB, for example by the *Wilkinson Microwave Anisotropy Probe (WMAP*; Hinshaw et al. 2013) or the *Planck* satellite (Planck Collaboration XIII 2015a), led to a detailed view on the Universe and its constituents expressed in terms of just a handful of cosmological parameters. The tiny temperature fluctuations, the seeds for all subsequent cosmic large-scale structure, are interpreted to be due to quantum fluctuations in the primordial plasma present directly after the Big Bang. These fluctuations are believed to be magnified to cosmic size during inflation, the extremely short period of exponential expansion of the Universe just 10^{-36} seconds after the Big Bang. Moreover, inflation theories whose development started in the early 1980s (Guth 1981; Linde 1982; Steinhardt 1982) also address and solve major problems of Big Bang cosmology:

(i) the horizon problem – the distribution of the tiny temperature fluctuations in CMB maps are extremely isotropic and homogeneous even for regions of space that must have been causally disconnected, i.e. behind an observational horizon, due to expansion and the finiteness of the speed of light by the time the CMB radiation was released.

(ii) the flatness problem – the observed flatness of space today presents a fine-tuning problem because in the past space must have been even 'flatter' in the sense that today's measured tiny curvature parameter must have been orders of magnitude tinier in the past.

(iii) the magnetic-monopole problem – in the extreme temperature and density conditions just after the Big Bang the weak, strong, and electromagnetic forces are believed to be unified, which is commonly referred to as the grand unification theory (GUT). However, as soon as the conditions become less extreme the GUT force is expected to undergo a spontaneous symmetry breaking into the three forces we know today during which magnetic monopoles are predicted to have been produced in large abundances. However, these have not been observed yet.

An extremely short inflationary period right after the Big Bang for about 10^{-35} to 10^{-34} seconds solves all three problems: a flat region of space sufficiently small to be isotropic and homogeneous is magnified to cosmic size which solves the horizon and flatness problems. If inflation also happened before the density and temperature conditions allowed for the
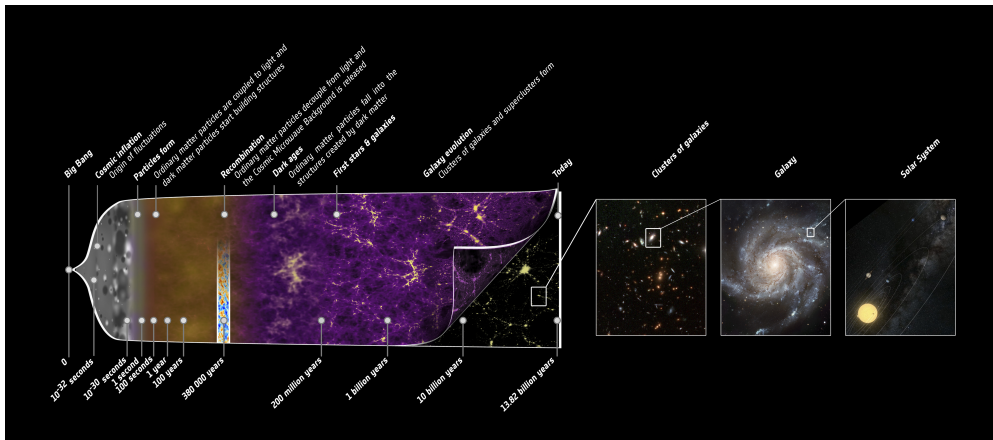
Figure 1.1: A brief history of the Universe from the Big Bang to today (Credit: ESA, C. Carreau).

production of magnetic monopoles, then these would form later already separated by cosmic distances while the Universe continues to expand. Hence, their observable density would be reduced by many orders of magnitude. Although inflation solves the problems of Big Bang cosmology, its physical nature is not at all understood yet. Moreover, no direct evidence for inflation, such as primordial gravitational waves, has been detected yet either (BICEP2 Collaboration 2014), but instruments becoming increasingly more sensitive might change this already in the very near future.

A major revelation of the modern cosmological concordance model is that all atoms and particles, which we and all the matter interacting with us in daily-life consist of, contribute only about 20 per cent to the total matter in the Universe. The remaining 80 per cent consists of something that we refer to as 'dark matter' (so that at least we have a name for it). However, the total matter of the Universe represents only about 30 per cent of its total energy density. The remaining 70 per cent of the energy density is usually attributed to the even more mysterious 'dark energy'. This cosmological ingredient is required to explain the accelerated expansion of the Universe as indicated by the observations of supernovae in the late 1990s (Riess et al. 1998; Perlmutter et al. 1999). The source of the accelerated expansion is counteracting the tendency of matter to cluster on cosmologically large scales due to gravity. An attempt of connecting the accelerated expansion of space to the standard model of particle physics interprets Einstein's 'greatest blunder', the cosmological constant, as the energy density of the vacuum. The standard model of particle physics predicts that the vacuum possesses energy due to the constant production and annihilation of particles and antiparticles within the limits of Heisenberg's uncertainty principle. Unfortunately, quantitative predictions for this vacuum energy are off by about 100 orders of magnitude. In principle, this discrepancy can be explained by postulating an additional symmetry which cancels the effect of vacuum energy up to the small amount we measure today and attribute to the cosmological constant. Therefore, alternative explanations for the accelerated expansion are explored (for example it might be time-dependent) and in order to combine them into a common framework, we call the physical cause just 'dark energy' (a term that is also liked better by funding agencies). However, any dark energy theory must still explain why the cosmological constant can be set to zero. Lovelock (1972) showed that the cosmological constant is a fundamental ingredient to Einstein's field equations under general mathematical assumptions: Einstein's field equations explicitly including the cosmological constant are the only unique formulation of tensor

equations depending only on the metric up to its second-order derivatives in four dimensional space-time.

In that regard, explaining the physical nature of dark matter is considered to be a slightly easier task: although no particle of the standard model possesses the properties of dark matter one can think of extensions, such as super-symmetry, that predict a stable Weakly Interacting Massive Particle (WIMP), whose properties match the ones of dark matter. However, even at the currently most powerful particle collider experiment, the Large Hadron Collider (LHC), super-symmetric particles have not been detected yet. This is either a sign that super-symmetry is not the correct extension or that the energies reached by the LHC are still just too low.

Neutrinos, particles that interact only via gravity and the weak force, were once a candidate for hot dark matter. Measurements and simulations of the cosmic large-scale structure formation have shown though, that dark matter must be cold in the sense that their velocity dispersion is small. Hence, their free streaming length, the distance indicating how far dark matter particles could move in the early Universe before being affected by gravitational collapse, sets the minimum length scale for subsequent structure formation. Density fluctuations within this minimum length scale are washed out due to the free streaming of dark matter particles. In order to explain the observationally established bottom-up scenario of cosmic structure formation then, potential dark matter particles must be cold. The bottom-up scenario of structure formation implies that large structures such as galaxy clusters build up from smaller structures like galaxies and hence they formed later. Despite not being a viable dark matter candidate anymore, neutrinos are still required as an ingredient for our cosmological model since they affect the growth of cosmic large-scale structure (cf. Lesgourgues & Pastor 2006 for a review). Large ground experiments such as *Super-Kamiokande* and the Sudbury Neutrino Observatory (SNO) measured neutrino oscillations, i.e. the mixture of neutrino flavour eigenstates (electron, muon, and tau neutrino) with their mass eigenstates (m_1, m_2, and m_3), for the first time around the year 2000 (Super-Kamiokande Collaboration 1998; SNO Collaboration 2001, 2002). These flavour oscillations imply that neutrinos possess a (tiny) mass, which is in contradiction with fiducial standard model predictions implying massless neutrinos. However, with this kind of experiments it is only possible to measure (squared) mass differences. The absolute mass scale of neutrinos, however, determines the mass-hierarchy between the three neutrinos: in the normal hierarchy scenario one mass eigenstate is the lowest and the other two are increasingly more massive. In contrast to that, the inverted hierarchy predicts three degenerate mass eigenstates. The lower mass bound is set at $\Sigma m_\nu \geq 0.06\,\text{eV}$ by the lowest measured mass difference. The most stringent upper mass bounds come, however, from cosmological probes. For example, CMB constraints from *Planck* set an upper bound of $\Sigma m_\nu < 0.72\,\text{eV}$ (Planck Collaboration XIII 2015a), whereas a combination of Lyα power spectrum measurements with constraints from baryon acoustic oscillations (BAO) yields an upper bound of $\Sigma m_\nu < 0.14\,\text{eV}$ (Palanque-Delabrouille et al. 2015). Pushing this boundary to values lower than ~0.1 eV in combination with the measured (squared) mass differences will enable us to determine the absolute values of the three mass eigenstates. Hence, neutrino masses are yet another current research topic linking once more the cosmological concordance model and the standard model of particle physics.

In summary, a host of observations can be reconciled within a cosmological concordance model. It is based on general relativity, and we have very precise and accurate measurements of the energy densities for the constituents of the Universe. However, we do not at all understand what the physical nature of the two dominant species, dark matter and dark energy, is. Revealing that is the major motivation behind current cosmological research. An advance in that direction is also naturally linked to new insights regarding the standard model of particle

physics and its inevitable extension.

1.2   Gravitational lensing

Already Newtonian gravity predicts the perpendicular deflection of light from a source behind a mass distribution, a lens, along the line-of-sight towards an observer (assuming a corpuscular theory of light though). However, general relativity predicts the effect to be twice as large, which was confirmed by the larger deflection angles observed by Eddington (1920).

Treating the propagation of light in the full framework of general relativity employing arbitrarily curved space-times is challenging. Employing the space-time of the cosmological concordance model, which encodes the observationally established isotropy and homogeneity of the Universe when averaged over sufficiently large scales, reduces the complexity of the equations substantially. Furthermore, we can assume for a typical configuration of observer, lens, and source that the diameter of the lens is negligible compared to the distances from source to lens, from source to observer, and from lens to observer. Moreover, the peculiar motion of the lens is usually also negligible compared to the speed of light. Then the complexity of the equations simplifies to the level of geometrical optics: the deflection of light rays from a background source due to a mass in its foreground can be described by an effective refraction index, altering the propagation speed of the emitted light in the vicinity of the lens.

The geometrical configuration of the observer-lens-source system and the mass distribution of the lens determine whether we observe strong image distortions and/or multiple image systems or only weak but coherent deflections in the lensed image(s) of the background source. We refer to these two regimes as strong and weak lensing, respectively. Mathematically the image distortions due to gravitational lensing can be described in terms of a mapping from the plane of each background source to the plane of the lens (or image plane). Curves in the lens plane along which this mapping becomes singular (and hence where it is locally not invertible) are called 'critical curves'. Mapping these critical curves back into the source plane yields 'caustic curves' (following the nomenclature of mathematical singularity theory). When a source crosses a caustic curve towards the lens a pair of strongly magnified images is created in the lens plane, which can be observed as a pair of multiple images of the same source. In general, caustic curves are not smooth and hence more than two images of the same source can occur in the lens plane. Critical curves and correspondingly strong lensing phenomena only occur in close vicinity to the lens, whereas weak lensing can still be observed at large distances from the lens. Fig. 1.2a shows an example of a strongly lensed and highly distorted multiple image system forming a 'horseshoe' of one and the same background galaxy. When the mass distribution of the lens is axis-symmetric and the source, observer, and lens are aligned along the line-of-sight a perfectly circular 'Einstein ring' of multiple images can be observed.

Already in the 1930s when dark matter entered the scientific discussion, Fritz Zwicky pointed out that clusters of galaxies must contain much more mass than estimated from their light alone. He reached this conclusion by applying the virial theorem to the Coma and Virgo clusters of galaxies assuming that the systems are in hydrostatic equilibrium (Zwicky 1937b). Back of the envelope calculations further show that galaxies or entire clusters of galaxies are due to their high masses ideal objects to target for observing strong lensing phenomena (e.g. Zwicky 1937a). It still took until 1979, however, before the first strong lensing object, a doubly lensed quasar, was discovered (Walsh et al. 1979). The first luminous arcs, i.e. highly distorted images of background galaxies, were found in galaxy clusters and also attributed to strong gravitational lensing in 1987 (Lynds & Petrosian 1986; Soucail et al. 1987; Paczynski 1987). Today strong lensing has developed into a major tool for estimating the mass of a

(a)   (b)

Figure 1.2: (a) Horseshoe 'Einstein ring' observed with the *Hubble Space Telescope*. The 'horseshoe' is actually the strongly lensed image of a galaxy in the background of the lens, the massive elliptical galaxy in the centre of the horseshoe (Credit: ESA/Hubble & NASA). (b) Composite image of the merging Bullet cluster. The hot intra-cluster gas observed through its thermal Bremsstrahlung in X-rays (red contours) lags behind the dark matter dominated mass component (blue contours) as inferred from weak lensing (Credit: NASA/CXC/M. Weiss).

lens (e.g. Johnson et al. 2014; Zitrin et al. 2015), which is possible if one can model very accurately and precisely the lensing geometry including, for example, the positions of where multiple images or luminous arcs are expected to occur. Moreover, the most massive lenses, i.e. galaxy clusters, are used as dedicated 'natural telescopes' in the search for the light of the oldest galaxies in the Universe (e.g. Coe et al. 2013; Bouwens et al. 2014). Just like in regular optics, lensed images are also magnified and thus allow for detailed spectral studies of objects that are too far away to be resolved even with our current best telescopes.

The effects due to weak lensing are not visible by eye and can only be studied statistically. Images of objects in the outskirts of lenses, for example, are only very weakly distorted by the gradient of the lens' gravitational potential. Assuming that the intrinsic shapes of galaxies are randomly distributed in the Universe, averaging the shapes of a statistically large sample of background galaxies around a lens yields the gravitational shear contribution, i.e. the coherent image distortions due to the lens, since the signal of the randomly distributed intrinsic shapes averages out. Again this technique can be used to study the mass scale and distribution within objects such as galaxy clusters very accurately and precisely. However, instead of looking at single lenses, we can also look at the weak-lensing effect due to the entire cosmic large-scale structure along the line-of-sight and study its mass distribution, in that sense we use the entire Universe as a lens. This approach is referred to as 'cosmic shear'. Cosmic shear signals were detected for the first time in 2000 (Bacon et al. 2000; Van Waerbeke et al. 2000; Wittman et al. 2000; Kaiser et al. 2000). Studying it also as a function of redshift, for example in tomographic redshift slices, allows us to infer the growth rate of structures in and the geometry of the Universe (cf. Kilbinger 2015 for a recent review). Apart from measuring shapes for millions of galaxies very accurately and precisely this also requires to estimate their redshifts. In order to measure shapes and (photometric) redshifts at the same time, large dedicated optical multi-band imaging surveys such as the Kilo-Degree Survey (KiDS; Jong et al. 2012; de Jong et al. 2015; Kuijken et al. 2015), the Subaru Hyper SuprimeCam survey (HSC), and the Dark Energy Survey (DES; Flaugher 2005; Jarvis et al. 2015) are carried out right now. They are expected to cover several 1000 square degrees in the next few years, which presents an improvement by an order of magnitude compared to weak-lensing surveys that are currently

available. Within the next decade this development will culminate in nearly all-sky surveys carried out by spaceborne observatories such as the *Euclid* satellite (Laureijs et al. 2011).

1.3 Cosmic large-scale structure

The largest gravitationally bound objects in the Universe are clusters of galaxies. The time it takes for a member galaxy to cross a cluster once is an order of magnitude shorter than a Hubble time. Therefore, cluster member galaxies had enough time to cross low-redshift galaxy clusters several times and hence virialized galaxy clusters can be observed in the local Universe. The application of equilibrium physics to such virialized clusters by Fritz Zwicky in 1937 showed already that the stellar, i.e. light emitting mass, was not enough to explain why clusters are gravitationally bound (Zwicky 1937b). Today it is an observationally well-established fact that indeed galaxy clusters are dominated by dark matter, and intra-cluster gas together with the stellar mass of the constituent member galaxies make up only a small fraction of the total mass in a cluster. This makes galaxy clusters ideal objects to study properties of dark matter, as for example the famous merging 'Bullet cluster' in Fig. 1.2b shows: whereas the baryons of the smaller 'Bullet cluster', i.e. mainly the intra-cluster gas as observed in X-rays (red contours), lag behind due to colliding with the baryons of the bigger cluster, the dominant dark matter of both clusters (blue contours) passed right through (Markevitch et al. 2002; Clowe et al. 2006), also implying that the cross-section of potential dark matter particles must be tiny (e.g. Markevitch et al. 2004).

The cosmological concordance model also predicts a universal density profile for an ensemble of galaxy clusters (Navarro et al. 1997). Although the physical principles behind such a profile are not fully understood yet, studying the mass distribution of galaxy clusters is an important cosmological test and strong lensing, for example, can be used to produce very accurate and precise measurements of the mass distribution in the core region of a cluster. Moreover, the number of clusters per cosmic volume of a given mass at a given redshift is strongly dependent on parameters of the cosmological model influencing the growth of structure. Hence, with the detection of hundreds of massive clusters over recent years mainly due to applying new observation techniques such as the Sunyaev–Zel'dovich (SZ) effect (Sunyaev & Zeldovich 1972), cluster counts have become an important independent cosmological probe (e.g. Planck Collaboration XXIV 2015b). The SZ effect describes the average energy boost a low-energy CMB photon gains due to inverse Compton scattering with high-energy electrons of the hot intra-cluster gas when passing through a galaxy cluster. This effect is independent of the redshift of the cluster and although many massive clusters have already been discovered employing the SZ effect, it has one shortcoming: in order to estimate the actual mass of the cluster, which is an essential ingredient for the cluster counts, from the measured strength of the SZ effect, one has to rely on scaling relations calibrated with other mass measurement techniques such as weak lensing. The level of uncertainty of the mass estimates for clusters is fundamentally limited by the accuracy and precision of these scaling relations. Investigating the statistical uncertainties and systematic errors of different mass calibration methods is hence an important topic of current research in order to improve the precision and accuracy of cluster counts as a competitive cosmological probe.

In the big picture of cosmic large-scale structure galaxy clusters are the nodes of the 'cosmic web': filaments of dark matter, gas, and galaxies extend through space-time in a web-like structure and the 'empty', i.e. extremely under-dense, regions in between are referred to as 'cosmic voids'. The evolution of the large-scale structure over cosmic time is very sensitive to the clustering properties of dark and luminous matter. Hence, studying its evolution, for example by means of measuring the cosmic shear signal as a function of redshift, is a very
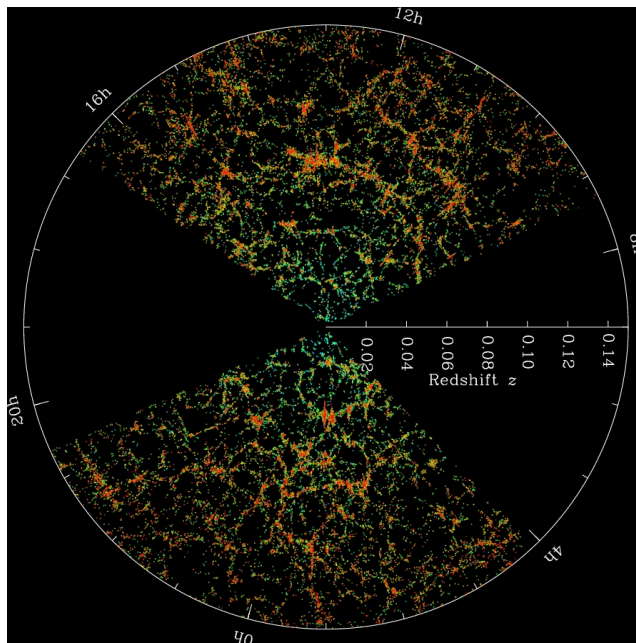
Figure 1.3: A map of the cosmic large-scale structure as seen in the Sloan Digital Sky Survey. Every dot in this picture represents an entire galaxy (Credit: M. Blanton and the Sloan Digital Sky Survey).

promising cosmological probe, especially in the current era of dedicated large-area imaging surveys serving as pathfinder missions in anticipation of the close to all-sky surveys of the next decade.

1.4   This thesis

In the following chapters we present applications of strong and weak gravitational lensing in a cosmological context.

We start in **Chapter 2** with the very detailed study of the strong lens model required to explain the occurrences of giant luminous arcs and multiple image systems based on high-quality data from the Cluster Lensing And Supernova survey with Hubble (CLASH; Postman et al. 2012) in the massive and very X-ray luminous merging cluster RX J1347.5–1145. In addition to presenting a consistent lens model derived with two independent modelling approaches, we finally measure the mass profile of and the mass distribution in the cluster core.

In **Chapter 3** we look at ensembles of galaxy clusters and address the limitations of weak lensing in deriving mass estimates for ensembles of clusters. We study this with a focus on the future *Euclid* mission (Laureijs et al. 2011) and derive the level of statistical uncertainties on the mass estimates for this mission and study the impact of various sources of bias. In particular, we investigate the bias due to cluster member galaxies that due to erroneously assigned photometric redshifts are scattered into the galaxy source sample. For stacks of galaxy clusters this effect is severe and must be properly accounted for. Finally, we investigate the bias due to miscentring, the displacement between the true position of the minimum of the gravitational potential of the galaxy cluster and any observationally defined cluster centre. With respect to the expected low level of statistical uncertainties this bias is significant. However, complementary future missions such as the X-ray survey *eROSITA* (Merloni et al. 2012) will allow us

to put very informative priors on miscentring parameters, making it possible to mitigate this bias.

In the final two chapters we take the leap from studying galaxy clusters to studying the entire cosmic large-scale structure using cosmic shear. Significant advances in computer technology allow us also to employ a computationally demanding maximum-likelihood algorithm to extract the power spectrum of cosmic shear in terms of band powers instead of following the standard approach in the literature of using shear-shear correlation-functions to measure the cosmic shear signal in real-space. A major advantage of the power-spectrum estimator is that scale-dependent features such as those caused by massive neutrinos or baryon feedback can be studied much more cleanly in the cosmic shear power spectrum. In order to improve cosmological parameter constraints, in **Chapter 4** we extend the technique to include redshift bins and test it extensively on mock data before applying it to shear catalogues from the lensing analysis of the Canada–France–Hawaii Telescope Legacy Survey (CFHTLenS; Erben et al. 2013; Heymans et al. 2012).

Finally, in **Chapter 5** we use state-of-the-art shear data based on 450 square degrees of imaging data from an intermediate data release from KiDS. Again, we apply the cosmic shear power spectrum estimator to it and derive cosmological parameter constraints. The se results are in tension with latest CMB results from Planck Collaboration XIII (2015a) but agree well with other low-redshift probes.

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