Exploring the edge
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Chapter 1

Introduction

1.1 The modern Universe

Humanity's fascination with the cosmos is a pervasive theme of our shared history. The perfect illustration of this is religion, which aims to describe the origin of everything and its relation to our personal experience. In this context, creation myths are the first cosmogonies, i.e. models concerning the origin of the Universe, and most have humanity in a fundamentally privileged role, sometimes as the natural endpoint of cosmic history. In contrast, the development of cosmology, i.e. the scientific study of the origin and evolution of the Universe, has been a process of continuous abstraction from our personal experience and has proved to be a clear rejection of our unique position. What we have designed is an indifferent Universe, where we deliberately do not represent a privileged observer. For the most part, this undertaking has been a humbling and painful process. Consider, for example, Giordano Bruno, who was famously burned at the stake in the year 1600 for claiming that other stars might be other suns and that other worlds orbit around them. Nonetheless, modern cosmology is also a great example of our hubris. We are not concerned with making statements about *us*, *here and now*, but we aspire to explain *everything* that was and will ever be, to derive laws which we can genuinely call Universal.

This outward journey is not only conceptual but also profoundly empirical. Our depiction of the Universe started small, but over time has expanded towards scales that are now barely imaginable. One parsec, originally designed to study the motion of the furthest objects, is now a unit too small for most cosmologists, who are accustomed to units of the order of mega- or giga-parsecs, Mpc and Gpc, respectively. Similarly, it is remarkable that in only one century, we have gone from discussing if there are other galaxies, referred to as island universes (Shapley and Curtis, 1921), to debating if there is a string theory multiverse (Carr and Ellis, 2008). From a purely scientific perspective, what lead to these developments are two kinds of advancements. The first kind is technological advancements. For example, it is not by chance that Tycho Brahe, Johannes Kepler, and Galileo Galileo were the first to study the Solar System. These people first had the opportunity to look at the sky using large measuring instruments and powerful lenses, able to focus a large amount of light onto their small iris. Without telescopes and sextants to accurately measure the motion of the wandering stars, i.e. planets, we would never know of the Solar System's existence. The second kind is theoretical advancements, and their importance in this process of abstraction cannot be understated. The way we view the world is based on the way we model it. As an example of this, Isaac Newton's law of Universal gravitation, capable of explaining the motion of objects on Earth and in the Solar System alike, now almost sounds like a misnomer. Albert Einstein's theory of general relativity is what we see today as the Universe's law of gravitation because it can describe virtually every phenomenon in its purview. It has been successfully applied to atom interferometry (Rosi et al., 2014), the structure of black holes (Schwarzschild, 1916), and, most notably for this thesis, the evolution of the Universe itself (Friedmann, 1922).

Gravity is the most relevant force on the largest scales because it cannot be screened away, and its range is formally infinite. This fact is astonishing, given its relative weakness. For example, the typical strength of the gravitational pull on an electron, quantified by the gravitational coupling constant $\alpha_G \approx 10^{-45}$, is meager compared to its electromagnetic counterpart, the fine structure constant $\alpha \approx 1/137$. Because of the importance of gravity for cosmological applications, it is not surprising that the leading framework used in the field is based on general relativity. According to the current view, this theory represents the playground hosting a tug of war between two ingredients, dark matter and dark energy. These two components have opposite effects: one enhances structure through gravitational collapse, while the other pushes things apart and destroys structure. The first, dark matter, has dominated the evolution of the Universe for most of its existence thus far, but the second, dark energy, is now winning, and it is expected to eventually lead to the disintegration of all of the Universe's structure. In this process, "normal" matter, i.e. what forms everything we see and touch, is nothing more than a witness. In a humbling twist of fate, these baryons are only $1/6$th of the Universe's matter content according to the latest measurements (Planck Collaboration, 2020), and in our model of the largest scales, they represent a nuisance element with a relatively complex phenomenology. Despite being on the sidelines, the signals emitted by this form of matter act as tracers and provide the primary justification behind the model described above.

1.1.1 General relativity

First proposed in 1915, the theory of general relativity is what is called a metric theory of gravity (Einstein, 1916). It describes spacetime through a dynamical object, the metric $g_{\mu\nu}$, detailing its curvature. The evolution of this quantity is connected to the energy content of the system, specified by the energy-momentum tensor $T_{\mu\nu}$, and their relationship is formalized by Einstein's field equations:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}. \tag{1.1}$$

In this expression, $G_{\mu\nu}$ is called the Einstein tensor, a quantity derived from the metric itself. In addition to this, notice the presence of two constants: κ, needed to match the units of $G_{\mu\nu}$ and $T_{\mu\nu}$, and Λ. The latter is called the cosmological constant, and it has important implications for cosmology that will be discussed later.

Here, we want to highlight two predictions of general relativity that are particularly relevant. The first is the accurate prediction of the bending of light in the presence of a massive object along the line of sight. Thanks to the first observation of this phenomenon by Arthur Eddington in 1919 (Dyson et al., 1920), gravitational lensing was quickly established as an experimental fact, and, over the years, it became a robust observable that is still used to this day. In this theoretical framework, this unusual behavior has an obvious explanation: because photons are expected to follow the geodesics defined by the metric $g_{\mu\nu}$, the curvature induced by the presence of matter naturally results in a perturbed light path. The second relevant prediction to be highlighted is the existence of gravitational waves. Because the metric is dynamical, perturbations on top of a background profile can propagate after being generated by accelerating compact masses. The measurement of the decaying orbit of a binary pulsar due to the energy deposited in this fashion (Taylor and Weisberg, 1982) represented the first indirect observation of gravitational waves and, similarly to the lensing case, it quickly ushered in the birth of a new field. After a few decades, the interest in this science eventually resulted in the direct detection of these tiny spacetime ripples by the LIGO-Virgo consortium in 2015 (LIGO Scientific Collaboration and Virgo Collaboration, 2016).

When applied to the Universe as a whole, Einstein's field equations are solved under two simple assumptions: the system should have no preferred observer, and it should evolve over time. The first statement is known as the Copernican principle, and it is understood today as an axiom about symmetries. Over large scales, it implies spatial isotropy and homogeneity. In contrast, the second statement is an observational fact about the broken time-symmetry, and it is justified by the early discovery of the Universe's expansion by Edwin Hubble (Hubble, 1929). In practice, the combination of these two assumptions translates into a form for the metric $g_{\mu\nu}$. In terms of the line element ds, we write:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -dt^2 + a^2(t)\delta_{ij} dx^i dx^j. \tag{1.2}$$

This is known as the Friedmann–Lemaître–Robertson–Walker metric, and it describes spatially flat hypersurfaces parametrized by the coordinates x^i, $i = 1, 2, 3$. The distance between two comoving observers expands over time according to the scale parameter $a(t)$, usually defined such that $a = 1$ is the present-day $t = t_0$ and $a = 0$ represents the start of the Universe, $t = 0$. An important consequence of the Universe's expansion is the change in the frequency of a monochromatic wave. Its main application is that if the rest-frame wavelength of a light source or spectral feature is known, its shift towards redder frequencies due to cosmic expansion indicates when its light was emitted. This cosmological Doppler shift is a multiplicative factor in wavelength, and it is written in terms of the redshift z. Its connection to the scale factor can be expressed as

$$(1 + z) = \frac{1}{a}, \tag{1.3}$$

and represents the main way through which we can map cosmological distances using electromagnetic spectra. A second important consequence of the Universe's finite age and isotropic recession is the existence of a horizon for every observer. Because light travels a finite amount of space in the Universe's lifetime, this naturally determines the size of casually connected patches. In other words, there is a maximum distance that a ray of light could have originated from before reaching said observer. According to the leading model, the value of this horizon is about $14.4\ \mathrm{Gpc}$ and can be obtained by integrating the trajectory of a photon moving at the speed of light c in the metric of Equation (1.2):

$$\chi(t = 0) = \int_0^{t_0} \frac{c dt'}{a(t')}. \tag{1.4}$$

By changing the integration limits, the expression above can also define a measure of distance between two arbitrary instants in cosmic time. If evaluated between today and an arbitrary time t, it is called comoving distance, but in an expanding Universe, this definition of distance to the past is not unique. Two other definitions are commonly used in cosmology, the luminosity distance D_L and the angular diameter distance D_A. Historically, the first is defined based on the energy flux of photons, and the second is based on the angular size of objects in the sky. In the first case, the additional energy change due to cosmological redshift must be accounted for, resulting in $D_L(t) = \chi(t)/a(t)$. In the second case, the angular diameter distance is different from the comoving distance because of the evolution of the comoving grid defined by the metric in Equation (1.2). An object of fixed physical size is measured differently by comoving grids at different times and, because of this, the angular distance is defined as $D_A(t) = a(t)\chi(t)$.

1.1.2 Dark energy

In the late 1990s, the discovery of the Universe's accelerated expansion proved the existence of an additional component besides matter and radiation (Riess et al., 1998; Perlmutter et al., 1999). This discovery came initially as a surprise, as such acceleration is possible only in a Universe dominated by an exotic constituent with negative effective pressure. Over time, however, what we now call dark energy quickly became accepted as an observational fact thanks to numerous supporting observations. Broadly speaking, the evidence can be divided into two groups: one related to its role in shaping the expansion of the Universe, that led to its discovery, and the other pertaining to its part in shaping the distribution of structure in the Universe, that appeared only a few years later (Springel et al., 2005; Eisenstein et al., 2005). Despite the general belief in its existence, however, very little has been discovered about dark energy apart from the fact that it accounts for about 70 percent of the Universe's present-day energy content.

Cosmological constant

In the context of general relativity, the simplest explanation for dark energy is the cosmological constant appearing on the left-hand side of Equation (1.1). When moved to the right-hand side, Λ can be interpreted as a zero-point energy in addition to the energy-momentum content described by $T_{\mu\nu}$. If we assume that this constant is the sole cause of the accelerated expansion, then its value in terms of the Planck length l_P is measured to be

$$\Lambda = 2.89 \times 10^{-122}\ l_P^2, \tag{1.5}$$

with an uncertainty of a few percentage points. In general, an accelerated expansion causes the energy density of matter and radiation to quickly dilute over time and eventually results in a Universe completely dominated by the cosmological constant. Asymptotically, this leads to a de-Sitter Universe where the scale factor can be written as:

$$a(t) \propto \exp\left(\sqrt{\frac{\Lambda c^2}{3}} t\right). \tag{1.6}$$

Under such exponential expansion, all structures made of matter are eventually pulled apart until nothing remains. Despite this bleak outlook, it is important to stress that this explanation for dark energy appears at first glance to be perfectly satisfactory: it is a minimal solution, and it is consistent with data. Nevertheless, it would be deceiving not to mention that it is also associated with two main theoretical concerns. The first is due to its vacuum energy interpretation. In this case, the value of the cosmological constant is expected to be connected to micro-physics. However, the extremely low Λ needed to account for cosmic acceleration is so far removed from the scales associated with known forces that the fine-tuning required for such cancellations casts significant doubts on this interpretation. Currently, developments aimed at addressing this question and quantifying its discrepancy are limited by our inability to frame gravity within a quantum physics framework. The second issue linked to Λ is the suspicious timing of the emergence of dark energy. The exact value of this constant determines when this component becomes dominant in the history of time, and, in our Universe, it corresponds to the moment when dark matter begins to form complex structures through gravitational collapse. If the value of Λ is arbitrary and not connected to cosmology, it seems quite coincidental that dark energy is only now taking over the Universe, after the interplay of matter and radiation led to the variety of structures that we observe today.

Both of these points can be addressed if one posits the existence of a multiverse. According to the anthropic principle, if multiple realizations of the Universe with different fundamental constants are possible, only those where humanity can emerge should be considered valid since we are, in fact, observing the Universe. This is a relatively new and powerful idea, but it has not been thoroughly tested yet. From a practical perspective, it is unclear how such a theory could be falsifiable or, more simply, how to compute the likelihood of humanity's existence in the large parameter space of the Universe's constants. On a more fundamental level, what is troubling about this solution is that it might take us back to when our models assumed that the cosmos was explicitly designed to host humanity. This is a profoundly unsettling notion, especially for a science that has been fighting this urge for most of its history.

Dynamical dark energy and modified gravity

In light of these concerns, it is not surprising that the attempts to address the nature of dark energy as something beyond the cosmological constant have attracted great interest. These efforts can be divided into two camps. On one side, the introduction of a fluid with its energy density $T_{\mu\nu}^{DE}$ capable of mimicking the effects of Λ. This component is named *dynamical* dark energy, and its most straightforward realization is quintessence, a scalar field with negative pressure (Caldwell et al., 1998). Models of quintessence are noteworthy because they can address the coincidence problem in a general way through so-called tracker solutions, where a scalar field follows the formation of cosmic structure and its emergence today is guaranteed for a variety of initial conditions (Zlatev et al., 1999). On the other side, the second set of widespread attempts is based on modifying Einstein's field equations. Because general relativity is the only healthy metric theory of gravity describing a spin-2 massless field in four dimensions, there are only a handful of ways it can be generalized. Of these ways, a class of models that has been investigated extensively is the addition of an extra scalar force carrier. The archetypal example of this class of solution is Brans-Dicke gravity, where the inverse of the gravitational constant κ appearing in Equation (1.1) is upgraded to a dynamical degree of freedom (Brans and Dicke, 1961). This thesis discusses this and related generalizations and, for the purposes of this work, the main feature of these models is a non-zero derivative of the Planck mass M_P; usually a constant that is a function of κ.

The most generic version of such scalar-tensor theories was already written down by Gregory Horndeski in 1974 (Horndeski, 1974). This feat was possible thanks to the requirement that the equations of motion should not contain derivatives of order higher than second. Theories that do not respect this condition describe ghosts, i.e. fields with Hamiltonian unbounded from below and, in general, any field interacting with a ghost has an infinite decay rate as a consequence. Technically, this condition can be circumvented by exploiting some caveats, but the freedom is still limited (Gleyzes et al., 2015). From a practical point of view, the main constraints on scalar-field theories come from the prediction of an extra force associated with the new degree of freedom, a.k.a. a fifth force. Because no departure from general relativity has been detected at both laboratory and solar-system scales (Will, 1993), a method to avoid these constraints must be devised. These are called screening mechanisms and aim at reducing the impact of the fifth force in regions of high density while keeping the effects of the extra degree of freedom visible at cosmological scales. Screening in a dense environment is achieved dynamically either by limiting the range of propagation of the force in these regions (Vainshtein and chameleon mechanisms, Vainshtein, 1972; Khoury and Weltman, 2004), or by reducing the coupling of matter to this extra force carrier (symmetron mechanism, Hinterbichler et al., 2011).

1.1.3 Dark matter

The second puzzle of modern cosmology is the nature of dark matter. Similar to its dark energy counterpart, the presence of this component is necessary to explain a plethora of observations, but the details of its nature are still unknown. As opposed to dark energy, it should be noted that the existence of invisible material capable of interacting only gravitationally has never been a controversial statement. For most of the history of modern cosmology, however, it was assumed that this invisible material was simply extinguished stars, cool dim gas or microscopic bodies akin to asteroids. Only in the 1990s, with the advent of early Universe observations, it became apparent that the fraction of traditional matter formed in the primordial Universe was insufficient, and a new, unfamiliar kind was needed.

Before the era of precision gravitational lensing, the existence of dark matter could only be inferred through the motion of luminous matter in its gravitational potentials. Pioneering observations of these phenomena, performed by Fritz Zwicky (Zwicky, 1933), Vera Rubin (Rubin and Ford, 1970) and many others, eventually became the primary justification behind the present-day paradigm of dark matter. Its fundamental principles are simple: dark matter should be cold and non-interacting. These two properties are required to reproduce the observed distribution of structure in the Universe and match simulated data. In this context, cold represents the opposite of relativistic. Examples of relativistic species in the Universe are radiation and neutrinos, for which the majority of the energy is in the form of momentum instead of rest mass. This results in high velocities that help relativistic particles stream away from gravitational potentials and makes them unable to form small structures. In the case of dark matter, this suppression is not observed. The second property is connected to the fact that dark matter appears to interact only through gravitational forces. The argument behind this principle is also linked to the distribution of matter in the Universe. The existence of additional interactions would lead to more compact structures since kinetic energy would be dissipated into random motion more efficiently than through gravitational interactions alone. Once again, this phenomenon is not observed in the real Universe.

Finally, the non-interacting property of dark matter refers also to its inability to interact with baryons. Because the standard model of particle physics is equipped with weakly interacting particles, the idea that dark matter might actually be coupled to the standard model with low interaction cross-sections is now the leading hypothesis (Steigman and Turner, 1985). From a scientific point of view, models based on these standard model extensions have proved to be easily falsifiable thanks to their precise predictions. The methods used to test these predictions can be divided into three detection channels. The first channel is related to dark matter production. Particle colliders could produce dark matter by annihilating standard model particles and then detect the missing mass. The second channel is the reverse of this process, i.e. when dark matter particles annihilate with themselves and result in standard model particle-antiparticle pairs. Finally, the last channel is called direct detection. It is based on the ability of dark matter to scatter off of an extensive reservoir of baryons and deposit energy into the system. So far, multiple efforts to detect dark matter through all three of these methods have been attempted with no success (Schumann, 2019) and the region of parameter space allowed for these models has shrunk considerably. As a result, alternatives to this mainstream approach have now begun to attract the community's attention. Exotic theories such as primordial black holes or light bosonic fields such as axions appear promising. Still, the parameter spaces of these theories are also heavily constrained by observations, and the predictive power of the remaining freedom is still under scrutiny.

1.2 The large-scale structure of the Universe

1.2.1 Linear perturbations

In cosmology, the distribution of matter takes the form of what is called the large-scale structure of the Universe. Its emergence is a complex phenomenon, and it is studied in multiple separate regimes using different techniques.

At the linear level, the matter density ρ is treated as a dimensionless perturbation δ on top of a fluid of spatially constant density $\bar{\rho}(t)$, such that $\delta = \rho/\bar{\rho} - 1$. This treatment can also be extended to the other ingredients of our models: the background metric in Equation (1.2) is perturbed by the gravitational potentials induced by this matter distribution, and the dark energy fluid, if it exists, can also be described with its own perturbations. These perturbed quantities are Fourier transformed both to investigate the dynamics as a function of spatial scale and because, at linear level, different Fourier modes labeled by their Fourier vector $\boldsymbol{k}$ are independent. Furthermore, for an isotropic Gaussian field, the distribution of these perturbed quantities can be described by a single function, the power spectrum. For example, the Fourier transformed matter density contrast $\delta_{\boldsymbol{k}}$ is described by the matter power spectrum $P(k)$, defined as an average over Fourier space:

$$\langle \delta_{\boldsymbol{k}} \delta_{\boldsymbol{k'}} \rangle = (2\pi)^3 P(k) \delta^3(\boldsymbol{k} - \boldsymbol{k'}), \tag{1.7}$$

where $\delta^3(\boldsymbol{k})$ is the three-dimensional Dirac delta function. If we assume isotropy, it is common to drop the vector index and simply refer to these modes as δ_k.

A simple and instructive example of how these perturbations can be studied is the equation governing the evolution of cold dark matter perturbations in a Universe dominated by this component. If we consider scales below the size of the horizon, we are able to recover the Newtonian dynamics limit and write down the evolution of perturbations as:

$$\delta_k'' + \mathcal{H}\delta_k' = 4\pi G a^2 \bar{\rho} \delta_k, \tag{1.8}$$

where $\mathcal{H} = a'/a$ is named the Hubble parameter, and the prime symbol indicates a derivative with respect to conformal time τ such that $dt = a(\tau)d\tau$. In this equation, the right-hand side represents the mechanism through which gravity enhances overdensities. The second term on the left side, on the other hand, is a friction term and shows how the expansion of the Universe can affect the growth of structures. For example, a matter-dominated Universe implies $\delta \propto a$, while in a de-Sitter Universe, the growth is slowed to a halt. In a complete framework, the presence of nonlinearities and multiple interacting components, e.g. dark matter and baryonic matter, need, of course, to be considered. To make the importance of this first point clear, note that Equation (1.8) is valid only in the limit $\delta \ll 1$, where terms of the order δ^2 or higher are ignored. Outside of this linear regime, the growth of these massive perturbations cannot be tracked with this equation. In terms of the wavelength k, this breakdown roughly corresponds today to a scale of $0.1\ \mathrm{Mpc}^{-1}$, and it is said that such overdensities have decoupled from the so-called Hubble flow. This gravitational collapse can happen in three spatial directions and, depending on how many directions have been affected, the resulting structures are referred to as walls, filaments, or nodes. This process is still ongoing, and the combination of these formations creates the so-called cosmic web.

A crucial nonlinear aspect determining the Universe's large-scale structure is the fact that fully collapsed overdensities, known as halos, can also interact with each other. In fact, today's structures grow mainly through mergers, and smaller structures assemble into larger ones. This process of hierarchical structure formation was first investigated by William Press and Paul Schechter (Press and Schechter, 1974) and this research direction has led to a widely used semi-analytical formalism still in use today to study smaller scales. In simple terms, such halo models describe the Universe's structure as a superposition of collapsed spherical objects characterized only by their mass. This approach has been highly successful thus far and has allowed us to predict the average clustering of visible matter based on the statistical properties of dark matter. However, as we push to smaller scales and larger samples, its limited ability to model the connection to visible matter and the additional properties that might affect its spatial distribution have begun to show.

1.2.2 Spherical collapse and the edge of halos

Today, knowledge of physics below the 10 Mpc scale is predominantly extracted from numerical simulations, and the resulting computer-assisted studies can be used to describe the interaction of baryons with dark matter in a wide range of scales. Despite this, semi-analytical and purpose-built models to study these same scales are still relatively widespread. In this context, the objective is not to obtain accurate predictions but to quickly gain insight into the mechanism behind the observable.

In the case of gravitational collapse, the seminal work of James Gunn and Richard Gott, Gunn and Gott (1972), represents the first glimpse into the effects of self-gravity in an expanding Universe. Like many subsequent models, this one is based on the evolution of spherical shells of matter around a central overdensity. The setup is straightforward: the presence of an initial overdensity causes matter to move towards it and eventually decouple from the Universe's expansion, with the closest material collapsing first. After this moment, the individual shells are stuck in a periodic motion of constant expansion followed by re-collapse and, because multiple shells undergo this process at different times, bubbles with opposite velocities continuously intersect each other. In the real Universe, this simple picture is complicated by the existence of angular momentum. In this case, the virial theorem can account for the inherent instability of the spherical solutions and quantify the size of the collapsed region.

Contrary to the basic assumption of most halo models, non-fully virialized halos undergoing this process still exist today. Around such massive objects, we can identify a multi-stream region dominated by orbiting material surrounded by a single-stream region dominated by infalling material. The mass profile in the first zone is a collisionless equilibrium profile common to all collapsed structures, while the profile in the second zone can be quickly derived from first principles. If we assume a time-independent profile, the continuity equation of the collapsing material can be written in terms of the density ρ_s and velocity vector $\boldsymbol{v}$:

$$\nabla(\rho_s \boldsymbol{v}) = 0, \tag{1.9}$$

where the radial component of the velocity vector for an asymptotically unbound stream is fixed by conservation of energy:

$$v_r^2 = \frac{2GM(< r)}{r}, \tag{1.10}$$

where $M(< r)$ is the mass contained within each shell at radius r. In the proximity of the halo, this quantity is dominated by the mass of the collapsed object. Hence, we can consider it constant and neglect the self-gravity of the stream. Under this assumption, these two equations combined imply $\rho_s \propto r^{-3/2}$.

Even though numerical simulations corroborate this result, the simple derivation above has an evident shortcoming: it does not depend on nor predicts the amount of mass deposited on the halo since the incoming mass was neglected entirely. To extend this simple calculation, semi-analytical shell models can characterize this phenomenon and explore how the mass accretion rate shapes the transition between the single-stream and multi-stream regions. The sudden drop in density associated with the piling up of orbiting material leads to the formation of a constantly expanding, ever-present halo edge. This feature is a general prediction of spherical collapse, but its potential to study the physics of accretion has only been recently recognized (Diemer and Kravtsov, 2014).

The splashback feature, as it is now called (More et al., 2015), has been the subject of multiple theoretical studies in the last few years. Two factors can explain the popularity of this research line: its existence highlights a limitation of the halo model, and its phenomenology can be easily captured. This ability to truly describe nonlinear behavior instead of just reading it off of numerical simulations is particularly appealing in the context of the modeling complexities associated with small scales. Finally, what is perhaps more important is the fact that this interest has not been purely theoretical. This field thrived in the past few years thanks to wide galaxy surveys, capable of accessing a sizable fraction of the visible Universe, and the precision of present-day lensing measurements used to estimate the mass profile of halos.

1.3 Observations

1.3.1 Galaxies and baryons

Based on the conservation of entropy, we can retrace the expansion of the Universe to a denser and hotter infant state (Lemaître, 1931; Gamow, 1946). In this epoch, the baryonic matter was completely ionized and coupled to photons. Due to the resulting radiation pressure, the baryons could not collapse onto the primordial dark matter overdensities and moved instead in periodic motions called baryonic acoustic oscillations. As the Universe expanded, electrons and nuclei recombined, and baryons decoupled from radiation. At this point, these two components were free to evolve independently: baryons started collapsing onto the primordial dark matter overdensities, and light started streaming across the Universe, forming a cosmic relic we can still see today, the cosmic microwave background. Although they might appear related, gravitational collapse for baryons is not akin to its dark matter counterpart due to cooling, i.e. the ability to transform gravitational potential energy in forms of energy other than kinetic. For baryons, collapse assumes the form of a slow accretion process, and the end product is the collection of dense gas at the center of dark matter overdensities. Eventually, this gas fragments and stars are ignited, resulting in the birth of galaxies.

Because the dynamics of dark and baryonic matter are so intimately connected, the distribution of galaxies in the Universe acts as a probe of the total matter distribution. This is a powerful idea, but despite what might transpire from the initial description, the relationship between the two components is not purely one-directional. Feedback, i.e. the backreaction of baryonic dynamics on the distribution and motion of dark matter, is an important phenomenon, and nowadays, its effects are studied through hydrodynamical simulations capable of tracking both gravitational dynamics and baryonic microphysics. To provide an example of this relationship, consider the fact that luminous matter can release a large amount of energy through, e.g. supernovae explosions or the bright accretion disks of supermassive black holes. The energy deposited in this fashion can then reshape the host dark matter halos and impact the relationship between the luminosity of a galaxy and the mass of its host halo. When combined, cooling and feedback are perfect examples of how cosmology can connect micro and macro-scales: physics set by quantum mechanical interactions dictates the appearance of our Universe on the largest scales.

Naturally, galaxies also follow the process of hierarchical structure formation, and, in the case of the largest conglomerates, they assemble in so-called galaxy clusters or groups. These objects inhabit the heaviest dark matter halos and can be detected in the late Universe as overdensities of galaxies in the sky. The brightest one is usually associated with the heaviest halo and is commonly referred to as the central galaxy. Fainter galaxies, stuck in orbits surrounding it, are called satellite galaxies. For this thesis, it should be mentioned that a diffuse hot ionized gas is also present in galaxy clusters. This results in two main observables used to detect galaxy clusters: the X-ray signal emitted through cooling and the signal generated by the cosmic microwave background scattering off the ions, known as the Sunyaev-Zeldovich effect.

1.3.2 Gravitational lensing

The deflection of light paths in the presence of mass along the line of sight is the only observable capable of providing a direct snapshot of the dark matter distribution of cosmic structures. This thesis makes wide use of this technique and focuses exclusively on weak-lensing. In this regime, the shape of distant objects is distorted by the presence of matter, e.g. a cluster, and detecting this distortion corresponds to a direct measure of the mass profile. The linearized lensing equation governing this phenomenon is:

$$\delta\boldsymbol{\beta} = \mathcal{A}\delta\boldsymbol{\theta}, \tag{1.11}$$

where $\boldsymbol{\theta}+\delta\boldsymbol{\theta}$ is the perturbed location in the image plane of the point located at $\boldsymbol{\beta}+\delta\boldsymbol{\beta}$ in the source plane, i.e. the plane that would be observed in the absence of lensing. The Jacobian matrix $\mathcal{A}$ connects the two and it is derived from the so-called lensing potential, an integral of the gravitational potential along the light-path. If $\mathcal{A}$ is constant in the region surrounding $\boldsymbol{\theta}$, then it can be generically split into two constant quantities: a spin two-field $\boldsymbol{\gamma} = \gamma_1 + i\gamma_2$, called shear, and a scalar component κ. At first order, the scalar component quantifies magnification, i.e. the isotropic change in size of an infinitesimal area, while the shear quantifies deformations. These effects can be seen if we consider a circle centered on $\boldsymbol{\theta}$. This shape is deformed into an ellipse with imaginary ellipticity equal to

$$\epsilon = \frac{\gamma}{1-\kappa} \approx \gamma, \tag{1.12}$$

and its area is multiplied by a magnification factor

$$\mu = \frac{1}{\det \mathcal{A}} = \frac{1}{(1-\kappa)^2 - |\gamma|^2} \approx 1 + 2\kappa. \tag{1.13}$$

Because the absence of lensing corresponds to a value of 0 for both shear and convergence, we have Taylor expanded around this value to obtain the approximate equations. Notice that outside of this weak-lensing limit, e.g., if $|\gamma|, |\kappa| \sim 1$, the matrix $\mathcal{A}$ can be singular. Points where this happens are called critical points, and in their vicinity, we approach the strong lensing regime where multiple images are formed. The most famous example of this arises when a source, lens, and observer are collinear. In this case, distant sources deformed into arcs, called Einstein rings, surrounding the central mass.

In practice, galaxies are not simple circles, and shear in the weak lensing regime is obtained by measuring the shapes of a large number of distant galaxies. This is a sophisticated procedure since the image visible in the reduced data is a convolution of the intrinsic galaxy ellipticity, the lensing effect, and a point-spread function, i.e. the impact of the atmosphere and telescope optics. While the first represents an intrinsic source of scatter and can only be defeated by averaging multiple galaxies, instruments and observing conditions need to be optimized in order to minimize the unpredictability of the last. The best results, for example, are obtained using space telescopes, for which the effect of atmospheric diffraction is obviously not present.

1.4 This thesis

In studying the largest scales, the boundaries of collapsed structures offer a laboratory to examine the relationship between structure formation, cosmology, and galaxy formation. Theoretical and technological advancements have allowed us to test our hypotheses directly, but the field is still in its infancy, and additional knowledge is required before its true potential can be unleashed. In this thesis, we present four papers aimed at transforming this field into a mature probe and showcasing how the dynamical nature of the large-scale structure can be modeled and measured.

Chapter 2 presents the first constraints on the splashback feature around massive galaxy clusters. This result is unique because the targeted lensing measurements considered here explore a mass range otherwise inaccessible. Chapter 3 presents the first quantitative predictions of how the edge of halos is affected in the presence of modifications of gravity. A straightforward but not simplistic semi-analytical model is used to get a handle on the most critical parameters and connect this feature to the coincidence problem. Chapter 4 brings forward two new splashback observables. The first one is related to the correlation between a cluster splashback signal and the orientation of its central galaxy. The second is a mass-size relation for dark matter halos accessible thanks to the combination of lensing and galaxy profile measurements. By comparing hydrodynamical simulations to their dark-matter-only counterpart, this chapter also shows that the presence of baryons does not affect this feature. Chapter 5 is the culmination of the previous two and presents a concrete measurement of the mass-size relation used to constrain gravity models. Particularly noteworthy is the fact that this measurement is based only on photometric data. Finally, Chapter 6 presents three unrelated projects performed during the writing of this thesis. The focus is the intersection between gravitational-wave physics and the study of the large-scale structure of the Universe. We explore how this new class of signals is affected by gravitational lensing and cosmic expansion. Thanks to the direct connection to the metric, gravitational waves can be used to test a new sector of alternative theories of gravity that would be otherwise hard to constrain.

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