Exploring the edge
Contigiani, O.

Summary

6.11 Modern cosmology

Humanity's fascination with the cosmos is a pervasive theme of our shared history. The first creation myths represent the simplest 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, in which we deliberately do not represent a privileged observer. Nonetheless, modern cosmology is also a display 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. A perfect example of this is Albert Einstein's theory of general relativity, which we see today as the Universe's law of gravitation. It is able to describe virtually every phenomenon in its purview and can accurately predict a plethora of observations: the gravitational attraction between atoms, the structure of the densest objects in the Universe (black holes), and the evolution of the Universe itself.

Despite its relative weakness, gravity is the most relevant force at large scales because it cannot be screened away and its range is formally infinite. Therefore, it is not surprising that the leading framework used in cosmology is based on general relativity. According to the current leading 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, the first forms structures held together by gravitational forces, while the other pulls things apart and destroys structure. Despite their essential role, very little is known about the dark sector apart from these very basic properties and the fact that both components do not emit light. Hence the "dark" adjective. In contrast, the "normal" matter, which forms everything we see and touch, is a subdominant component that does not play an important role in shaping the history of the Universe.

6.12 The edge and dark energy

The Milky Way is a spiral galaxy hosting the Solar System and Earth. Because of our position, the stars that comprise it appear as a streak spilled of milk visible in the night skies of remote areas. These large cosmic structures are familiar to most, but in reality, the Universe contains even larger objects. In particular, the main focus of this thesis is dark matter halos, dense clumps of dark matter that are $1,000$ times larger than our galaxy. These objects are surrounded by a web-like distribution commonly referred to as the large-scale structure of the Universe. In the past few decades, it became possible to study the emergence of this complex network through numerical simulations. Simulated universes are created and analyzed to estimate the effects of the dark sector on structure formation. This understanding, however, is complicated by the fact that dark matter structures cannot be photographed in the real Universe, since they do not emit light. Fortunately, the galaxies that form and evolve inside the halos can be used to probe the structures they live in. When looking at them from far away, galaxies appear as bright points embedded in the dark matter scaffolding that is the large-scale structure of the Universe.

The early Universe consisted of a homogeneous distribution of matter, but over time gravitational forces led to the formation of dense clumps that attract even more matter thanks to their gravitational pull. These are the dark matter halos at the center of this thesis. When looking at their simulated version in detail, one can recognize a dense inner core surrounded by an outer region made of material slowly flowing towards the inner region. The transition area between these two zones is relatively small and it is associated with an abrupt change of density: because the inner region has been growing over cosmic time it is significantly denser than the outer region. This sharp drop in mass density is known as the splashback feature and it represents the titular edge of this thesis.

To understand how dark energy affects structure formation and splashback, let us consider a simple model for it. The minimal explanation for dark energy is the so-called cosmological constant, a numerical parameter appearing in the equations of general relativity that results in a pressure force opposing the attractive pull of gravity. This effectively slows down the growth described above and hinders the formation of cosmic structures. However, doubts are cast on this explanation because, if true, the numerical value of this constant would be significantly smaller than other constants of Nature. To address this discrepancy, alternative models of dark energy describe it as a quintessence: a form of energy that can evolve over time. In particular, due to its exclusive connection to gravitational phenomena, models of quintessence can also be interpreted as an extended version of general relativity instead of a new generic component. Because they evolve, the pressure exerted by these modified gravity models is different from the cosmological constant case and their impact on the Universe's structure can be used to study them.

6.13 This thesis

The boundaries of the largest structures offer a laboratory to examine the relationship between dark matter halos and cosmology. The feature that defines these edges is a straightforward prediction, but its potential to study the physics of structure formation has only been being recently recognized. In particular, this field thrived in the past half-decade thanks to recent wide surveys of the sky, capable of observing millions of galaxies distributed in a sizable portion of the observable Universe. Despite a surge in interest, the field is still in its infancy, and additional knowledge is required before its true potential can be realized. This thesis presents four chapters aimed at transforming this science into a mature field and showcasing how the dynamical nature of the large-scale structure of the Universe can be modeled and measured.

Chapter 2 of this thesis presents the first measurement of the splashback feature around massive halos. This measurement makes use of gravitational lensing, a particularly sophisticated way to observe the distribution of dark matter in the Universe. In general relativity, the gravitational pull of massive objects is understood as a deformation of the fabric of space-time. Therefore light rays emitted by distant objects are affected by the curvature of dark matter structures along the line of sight. The deformation of images resulting from this effect can then be used to measure the mass distributions in the Universe.

Chapter 3 presents the first quantitative predictions of how the edge of halos is affected in the presence of quintessence. The chapter focuses on a specific model, the symmetron, and makes use of a straightforward semi-analytical model to get a handle on the most critical parameters of this theory. The result is a consistent view of this feature as a function of these parameters in the context of the known paradigm of structure formation.

Chapter 4 brings forward two new observable quantities. The first one is the relationship between the shape of a halo's edge and its connection to the cosmic web surrounding it. The second one is the existence of a clear relationship between the size of a halo, defined by its boundary, and its mass. Measuring this relation is informative because extended models of gravity are found to affect the first but not the second.

Chapter 5 is the culmination of the previous two. Its main results are the measurement of the mass-size relation in the data obtained by the Kilo-Degree Survey, and the study of its implication for the symmetron model.

Chapter 6 is a summary of three additional projects that were performed during the writing of this thesis. Their focus is the study of the large-scale structure of the Universe through a new probe, gravitational waves. Due to the large curvature associated with black holes, the mergers of two such objects create space-time ripples that can be observed from across the cosmos. This chapter explores this new class of signals in alternative theories of gravity and in the presence of gravitational lensing.