English summary

We are just an advanced breed of monkeys on a minor planet of a very average star. But we can understand the Universe. That makes us something very special.

– Stephen Hawking

The Universe at large

Looking at the sky in a dark night, we can note that stars are not distributed randomly but, in their majority, are located in a thin stripe across the sky. This stripe corresponds to the *Milky Way*, the spiral galaxy in which the Sun resides. With the Sun, it is estimated that the Milky Way contains some 100 million stars. The left panel of Figure 1 shows a typical spiral galaxy, known as Messier 81, located roughly 12 million light years away. Its blue color, characteristic of spiral galaxies, corresponds to the colour of light emitted by young stars, formed about 100 million years ago or less. Our Galaxy is part of the *Local Group*, corresponding to an aggregate of about 50 galaxies, dominated by the Milky Way and the Andromeda galaxy, located some 2.5 million light years from the Milky Way.

Most galaxies in the Universe reside in aggregates, and the Local Group is but one example. As a convention, we call galaxy *groups* those aggregates containing roughly 50 galaxies or less, and galaxy *clusters* those that contain more. These clusters of galaxies are the largest objects formed so far in the Universe. A cluster of galaxies may contain more than a thousand visible galaxies, and a mass equivalent to $\mathbf{10^{15}}$ (that is, 1,000,000,000,000,000) times the mass of the Sun. The right panel of Figure 1 shows the cluster of galaxies Abell 2218 (discovered by U.S. astronomer George Abell). Dozens of (mostly elliptical) reddish galaxies can be identified in the image, most of them belonging to the cluster. This cluster is located some 2 billion light years from us.

Galaxies in a cluster look reddish and not blue like spiral galaxies, which are usually rather isolated. The reason is that the cluster's gravity, together with its pervading gas and the other hundreds of galaxies in the cluster, remove all the gas from the galaxy, which would have been used to form new stars. Not being able to form new stars, the galaxy adopts the reddish color of its older stars.

Dark matter

The galaxies we can see, including their stars, gas and dust, and all the atoms in the Universe, only make up approximately 20 per cent of the mass of the Universe. Most of the matter corresponds to a mysterious component we call *dark matter*. Although we cannot see

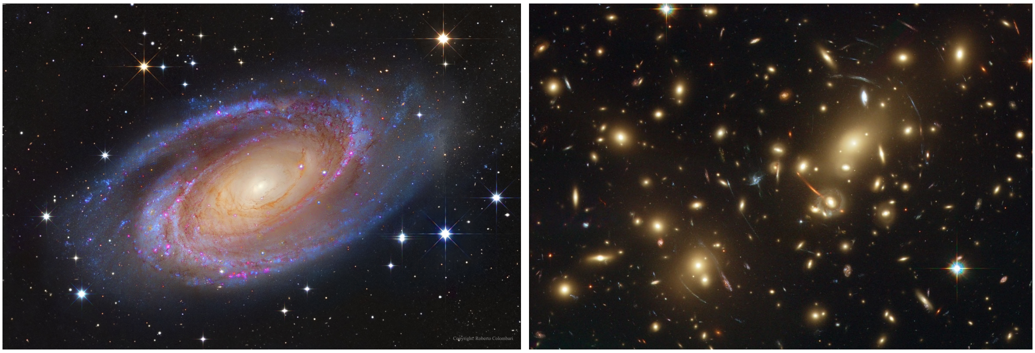

Figure 1: Left: spiral galaxy Messier 81. The image is a combination of observations undertaken with the Subaru Telescope in Hawaii and the Hubble Space Telescope. The blue colour shows the light emitted by young stars, while the red color shows dust in the galaxy. **Right:** galaxy cluster Abell 2218, observed with the Hubble Space Telescope. Most of the reddish objects are galaxies belonging to the cluster. The image also shows a number of arcs surrounding the main galaxies; these correspond to galaxies distorted by strong gravitational lensing.

dark matter directly, we can infer its presence by its gravitational influence on the matter we do see.

The discovery of dark matter dates back to the year 1933, when Swiss astronomer Fritz Zwicky showed that galaxy clusters must contain a vast amount of unseen matter to keep galaxies together, because the latter move too fast, and would otherwise escape the cluster. In 1980, a study led by U.S. astronomer Vera Rubin showed that stars in spiral galaxies also move faster than expected, and that large quantities of dark matter are required to keep the stars within the galaxies. Since then, evidence in favour of the existence of dark matter has accumulated and, although its existence has not yet been confirmed, most astronomers accept the hypothesis of the existence of dark matter.

Therefore, to be able to understand the formation and evolution of galaxies, we must also study the dark matter surrounding them. There exist two techniques to directly probe dark matter through its gravitational influence: the motions of stars and galaxies, and gravitational lensing.

The motions of stars and galaxies

The relation between the motion of stars in galaxies and the mass of the latter is relatively simple in theory. Just like a rocket needs a particular speed to escape the Earth's atmosphere (known as the *escape velocity*), there is a maximum speed which stars can have before they escape their host galaxy. This speed is directly connected to the total mass of the system. Therefore measurements of the maximum velocity of stars in a galaxy provide a direct measure of the mass of said galaxy.

In the case of spiral galaxies, we can use the *rotational velocity* of stars (that is, the speed at which they orbit the galaxy) to measure the galaxy's *rotation curve*: the rotational velocity of stars as a function of distance to the galaxy's centre. Under the no dark matter hypothesis, stars further out should have lower rotational velocities than stars at a given "pivot" radius. However, as first shown by Vera Rubin and collaborators in 1980, the rotational velocity of stars is constant until the edge of the galaxy. This can be explained because of the much larger extent of dark matter, which can hold stars further out from the galaxy.

In the case of elliptical galaxies, and similarly of galaxy groups and clusters, there is no coherent rotation. Instead, galaxies inside a cluster move randomly, and their *velocity dispersion*—that is, the typical velocity of galaxies in a given cluster—is directly related to mass through the *Virial Theorem*. This was the method used by Fritz Zwicky in 1933, which led him to propose the existence of dark matter for the first time.

Gravitational lensing

The gravitational lensing effect is the apparent distortion of distant objects, due to intervening matter. This effect is a consequence of the intimate connection between the geometry of space and its matter content, described in the famous General Theory of Relativity published by Albert Einstein exactly 100 years ago. According to this theory, mass curves space, such that light travels in curved, instead of straight, trajectories, and therefore distant galaxies, especially if they are behind another galaxy or a cluster of galaxies, look distorted. Therefore, by observing a gravitationally lensed galaxy we can directly infer the matter distribution of the lensing object.

The right panel of Figure 1 shows a number of thin arcs surrounding the largest galaxies. These arcs correspond to galaxies in the background of the cluster whose images are distorted by gravitational lensing by the cluster. When the effect is so obvious, it is known as *strong* gravitational lensing, and can only be observed in the inner regions of galaxy clusters or very massive galaxies. Further from the centre, we can only observe the *weak* gravitational lensing effect, in which light from each galaxy in the background suffers only a small distortion. In this case, the distribution of mass in the cluster is revealed by the average distortion of thousands of background galaxies.

Both effects allow us to directly measure the matter content of the galaxy or galaxy cluster producing the gravitational lensing effect. Ideally, these effects must be combined to fully determine the total mass content of a galaxy or galaxy cluster in a detailed way. In practice, this requires very detailed obsservations over large regions of the sky, and has only been possible so far for a few galaxy clusters.

The connection between mass and light in galaxies and galaxy clusters

As a first step to study the connection between dark and luminous matter (or simply between "mass" and "light"), it is important to distinguish to classes of galaxies: *central* galaxies and *satellite* galaxies. In general, galaxy clusters (or groups) contain one dominant galaxy in the centre, brighter than all other galaxies, which we call the central galaxy. All other galaxies are referred to as satellite galaxies. In Abell 2218, shown in the right panel of Figure 1, the central dominant galaxy can be clearly identified towards the top right of the image, surrounded by arcs produced by gravitational lensing.

This distinction is important because both classes of galaxies are affected very differently by their environment. The reason is that satellite galaxies orbit and fall towards central galaxies, and central galaxies grow by the successive accretion of satellite galaxies. In practice, it is difficult to differentiate both kinds of galaxies, since this requires accurate measurements of the distances of galaxies. Central galaxies are easier to identify, since they are generally the brightest galaxy in their vicinity, and most studies of the connection between mass and

Figure 2: Mass and light in the galaxy cluster El Gordo, a very massive system composed of at least two clusters colliding with each other. The background image was taken with the Hubble Space Telescope. The blue tone shows the distribution of dark matter, determined with weak gravitational lensing, while the red tone shows the gas distribution, determined with X-ray observations. Given the enormous distance to this cluster, of about 7 billion light years, it is difficult to see its galaxies in this image, but the central galaxy can be seen to the left of the red peak of the gas distribution. Due to the massive collision, dark and luminous matter in El Gordo are clearly dissociated.

light so far have focused on central galaxies. The main conclusion is that, as expected, more luminous galaxies are also more massive, and that both the least massive and the most massive galaxies have the highest fraction of dark matter, with galaxies in between having a lower fraction. Galaxy clusters, in turn, tend to have a fixed fraction of dark matter (of 80–85%) independent of their masses. Nevertheless, the connection between mass and light has not been explored in much detail. Given the radical transformation of galaxies once they become satellites (compare the left and right panels of Figure 1), a similar transformation might be expected to affect their dark matter. The second half of this thesis is dedicated to the connection between mass and light in satellite galaxies in galaxy groups and clusters.

Galaxies in galaxy clusters make up only about 20% of the luminous matter in a cluster (that is, approximately 4% of the total mass). The remaining 80% is in the form of a hot gas, with temperatures of 10^7 degrees or more, that permeates the cluster. Given its temperature, this gas can be observed in X-ray wavelengths. Figure 2 shows the distribution of mass in the galaxy cluster "El Gordo", located about 7 billion light years away. In this cluster, we can identify two distinct regions with large quantities of matter (mostly dark matter, shown in blue), that does not coincide with the distribution of gas (shown in red). This image shows that this cluster is composed of two very massive sub-clusters that are colliding and merging with each other. Since most of the luminous matter corresponds to the gas halo, this separation between total and luminous matter provides direct evidence for the existence of dark matter. In the first half of this thesis we study the relation between total and luminous mass in a number of galaxy clusters.

This thesis

This thesis starts by exploring the global connection between the amount of mass and light in galaxy clusters combining observations of the gas content with determinations of the cluster's total mass. Then, we study this connection directly on the galaxies residing in groups and clusters.

In **Chapter 2**, we study the galaxy cluster PLCK G004.5−19.5 (thus called due to its coordinates on the sky). We use strong gravitational lensing to measure the total mass of this cluster, and find that it is lower than expected from measurements of the properties of its gas halo. The reason of this difference is not clear from the available data. We also use radio wavelength data to tentatively conclude that the cluster is undergoing a collision with a smaller system. This collision could explain the above difference in mass measurements, because both estimated masses assume that the cluster is isolated. In the future, we will use new observations to obtain more information about this cluster.

In **Chapter 3**, we take a more statistical approach and compare the amount of mass in 44 galaxy clusters estimated using the cluster gas properties and measurements of the velocity dispersions of their member galaxies. An important part of this chapter is a detailed discussion of the strengths and weaknesses inherent to the use of galaxy velocities to determine galaxy cluster masses. We find that masses inferred with galaxy velocities are, on average, consistent with those determined from the gas properties. Nevertheless, there are too many factors affecting these results. These factors limit the applicability of galaxy velocities for accurate determinations of cluster masses.

In **Chapter 4**, we turn our attention to satellite galaxies residing in clusters, and explore a different aspect of the connection between mass and light: the orientation of each component. A cluster exerts a strong tidal force over its satellite galaxies, and in this chapter we explore whether this tidal force is able to align satellite galaxies towards the cluster centre. This effect is observed clearly in dark matter simulations but direct constraints have been scarce. Using some 14,000 galaxies in 90 different clusters, we observe no signs of alignments of galaxies towards their cluster centres, nor towards each other.

An important aspect of the results of **Chapter 4** is the link between the alignment of galaxies and measurements of gravitational lensing, because this latter effect is observed by measuring the apparent alignment of galaxies behind other galaxies or galaxy clusters. Our measurements suggest that any alignments of galaxies within clusters must be very weak, and does not affect measurements of gravitational lensing with current experiments significantly. We will need more precise measurements of galaxy alignments in order to know whether this will be the case for future experiments with increased precision.

In **Chapter 5**, we measure the weak gravitational lensing effect produced by satellite galaxies in galaxy groups. This is only the second time this effect has been measured. We find that these galaxies have a total mass approximately 20 times larger than their mass in stars, similar to central galaxies. We also showed, as a proof of concept, how more precise measurements of this effect may in the future be used to test different cosmological models.

Finally, in **Chapter 6** we extend the study of **Chapter 5** to more massive galaxy clusters—those used in **Chapter 4**. We use the same technique of weak gravitational lensing to measure the amount of dark matter in these cluster galaxies. Taking advantage of the better quality of the data compared to **Chapter 5**, we contrast our results with theoretical predictions. For now, our results are consistent with these predictions: all cluster galaxies have more or less the same fraction of dark matter of about 95%. To investigate the physical mechanisms that give rise to these results, in the future we will explore similar measurements in computer simulations, which we will be able to contrast with our observations.