English summary

Many humans have been fascinated by questions like how our world came to be, and how it works. Since ancient times, people have looked for answers to these questions, which is reflected in many creation stories and philosophical writings that can be found around the planet. But we can also use science to try to answer these questions, by inventing new theories to explain what we see, using the theories to make predictions, and testing these predictions with measurements.

The world that we seek to understand is not just planet Earth, but the entire Universe. Astrophysics is one of the sciences that provide the answers to our questions. It is a branch of physics that seeks to explain the behaviour of astronomical objects, such as galaxies, using the laws of physics. This teaches us a lot about the physics of the Universe as a whole, which is the topic of the discipline known as cosmology.

Astronomy is a science that is rather different from the other natural sciences, because we have to rely on radiation such as light to convey information about our study subjects to us. While it is relatively easy to tell how bright a star, a galaxy, or a cluster of galaxies is, measuring how massive it is, is a lot more involved. About a century ago, when astronomers tried to make such measurements, they discovered something that changed cosmology forever. Galaxies and clusters of galaxies are much more massive than what their brightness suggests. The stars that we can see in them are just the tip of the iceberg: galaxies and galaxy clusters contain an enormous amount of dark matter. It turns out that this dark matter has properties very different from anything we know. It seems to not interact with anything, including light, except through gravity. So it is not just dark, rather it seems to be invisible.

One of the biggest questions of modern cosmology is: What is dark matter? As a working theory, cosmologists use cold dark matter (CDM), an idealized version that is made of relatively large particles that have zero interaction (besides through gravity). Cold dark matter is one of the ingredients of the ΛCDM paradigm, a model with which we can describe the behaviour of the Universe at the largest scales very well. But for some of the smallest galaxies, falling into the category named classical dwarf galaxies, predictions based on (Λ)CDM seemed to be wrong.

Computer simulations of Universes containing only CDM have predicted that dark matter forms structures, known as haloes, with a density that very rapidly increases as you get closer to the centre of the structure. However, observations of classical dwarf galaxies show that the density stops increasing and reaches a constant value at a certain point. Furthermore, many more small structures were visible in these simulations than there are small galaxies in the real Universe. Thirdly, galaxies in the real Universe seem to sit in smaller haloes than expected from these simulations.

At first sight, the above three problems suggest that CDM is not a good theory. But these first simulations neglected the effects of other matter, such as stars and gas. Though galaxies contain much more dark matter overall, in their centres the stars and gas can be very significant. Some of the classical dwarf galaxies turn out to have a particularly large amount of stars and gas compared to their dark-matter content. When large stars die, they produce a supernova: an enormous explosion that flings a part of the star's material into the surrounding space. These explosions heat the gas in the galaxy, and some of the gas will be blown out of the galaxy's centre. This changes the balance of gravity, and in response some of the dark matter will move away from the galaxy's centre. As a result, the dark-matter density in the centre decreases and can become constant, just as is observed for those classical dwarf galaxies. The lowered central density also explains why galaxies seem to be hosted in smaller haloes than expected. Finally, in the smallest haloes, the violently exploding stars could blow out the gas entirely, which means that no new stars can be formed and the galaxy will eventually go dark. This would explain why the tiniest simulated haloes have no counterpart galaxy in the real Universe.

Although this explanation seems reasonable, alternative explanations exist as well, which replace CDM with something else. If dark matter is not cold, but warm (WDM), it would be made of lighter and faster particles. These particles are not as easily contained by gravity. Instead of a sharp peak at the centre of a halo, the dark matter is more smeared out, thus explaining the flat cores of classical dwarf galaxies. On the other hand, the dark-matter particles cannot be too light and fast; this hot dark matter (HDM) would smear out the dark-matter peaks too much. Similar cores can be created with self-interacting dark matter (SIDM), wherein there is an additional interaction between dark-matter particles besides gravity. Finally, a theory that has recently received a lot of attention in the scientific literature, called fuzzy dark matter (FDM), states that dark-matter particles are so light that we start to see quantum-mechanical effects, normally only important at the scale of atoms, at the scale of a galaxy. One of these effects is that particles are not really a point, but more like a wave or a fuzzy cloud. The result is again a flat core in the dark-matter density.

It should be mentioned that there are also theories that try to explain the extra observed mass in galaxies and galaxy clusters by modifying the laws of gravity instead of adding dark matter. These theories may be able to explain the small-scale observations quite naturally, but have more trouble explaining the large-scale observations where CDM does very well.

In this thesis I focus on a few different dark-matter theories: CDM, SIDM, and FDM. In CDM, the dark-matter cores in the classical dwarf galaxies are explained with the effects of stars and gas. The smallest and faintest known galaxies, ultra-faint dwarf galaxies (UFDs), contain so few stars and gas that these should not noticeably influence the dark matter. Therefore, if CDM is correct, UFDs should not have a significant dark-matter core. On the other hand, in SIDM and FDM the core is caused by the nature of dark matter, therefore UFDs should have a core just like the classical dwarf galaxies. In this thesis, I therefore study the dark-matter contents of UFDs to learn more about the nature and properties of dark matter.

To determine the dark-matter contents of UFDs, I use the same principles used in the 1930s for the first mass measurements of galaxy clusters. On the one hand, there is the gravitational force, pulling inward, that is determined by the dark-matter content. On the other hand, the movement of stars along their orbit generates a centrifugal force, whose size is dependent on the velocity of the star. It can be helpful to visualize a bucket of water, swung hard overhead. Despite gravity pulling the water down, the water stays in the bucket because of the centrifugal force generated by the swinging motion. Assuming that a galaxy is long-lived, the forces on the stars must be balanced. By measuring the velocities of the stars, we can therefore determine the dark-matter content.

To measure these velocities, I use the Doppler effect, which makes approaching stars look bluer and receding stars redder. The same effect is responsible for the higher pitch of an approaching siren, and the lower pitch of a receding one. The changes in the colours of the stars are very small. We therefore need to use a spectrograph to split the starlight into the spectrum of its constituent colours. Chemical elements present in the atmospheres of stars absorb certain colours of the spectrum, producing dark absorption lines. These lines shift to different colours depending on the velocity, and these shifts can be measured with the spectrograph.

I use a spectrograph called MUSE, which is mounted on the Very Large Telescope (VLT) in Chile. The properties of MUSE are ideal for observing UFDs, because it is able to take images wherein for every pixel, it measures a spectrum. This allows us to measure spectra of many stars at the same time. An observational programme, called MUSE-Faint, is being carried out with MUSE to observe ten faint and ultra-faint dwarf galaxies. In this thesis I use data from five of these galaxies: Antlia B, Leo T, Eridanus 2, Hydra II, and Grus 1. Four of these, all except Antlia B, are UFDs and are satellites of our own galaxy, the Milky Way. Together with my collaborators, I have conducted four studies of these five faint galaxies, which are described in Chapters 2–5 of this thesis.

In Chapter 2, we study the centre of Eridanus 2 using data from MUSE-Faint. Eridanus 2 is special, because it is the only UFD that possibly contains a star cluster. If it does, the fact that the star cluster has survived allows us to constrain the properties of a particular kind of CDM: massive astrophysical compact halo objects (MACHOs). While dark matter is usually hypothesized to be made of elementary particles, MACHOs are very massive objects like black holes. Our observations of the velocities in the possible star cluster and in the rest of Eridanus 2 show that it is indeed likely that the star cluster is real. We then use our measurements to update the older theoretical constraints on MACHOs in Eridanus 2.

In Chapter 3, we add the rest of the MUSE-Faint data on Eridanus 2. Because we now have access to observations over a larger area, we can test how the density of the dark-matter halo of Eridanus 2 changes with the distance to the centre: Does the halo have a sharp peak or a flat core? We find that if there is a core, it cannot be very large, because we cannot detect one. This puts constraints on the properties of SIDM (the interaction rate) and FDM (the particle mass). The constraint on the FDM particle mass is very interesting, because it is inconsistent with the value that has been proposed to explain the cores of the some of the classical dwarf galaxies. On the other hand, we cannot rule out SIDM and FDM as a whole, nor CDM.

In Chapter 4, we move on to studying Antlia B, Leo T, Hydra II, and Grus 1. For each of these galaxies, we find that they cannot contain a large dark-matter core. We cannot, however, rule out cores in their entirety. We also find that these galaxies, as well as Eridanus 2, have not been significantly affected by the tidal forces of the Milky Way, which have the potential to strip away material from satellite galaxies. Finally, we compare the measured masses and brightnesses of all five galaxies against theoretical expectations, and find that we cannot yet reliably tell whether UFDs follow the expected relations.

In Chapter 5, we combine the data of the five previously studied faint galaxies with data from classical dwarf galaxies to determine joint constraints on the nature and properties of dark matter. Though we still cannot rule out CDM, SIDM, and FDM in their entirety, we obtain a significant improvement in our constraint on the FDM particle mass. It seems out of the question that FDM can be used to explain the dark-matter cores of classical dwarf galaxies, because the required particle masses are strongly ruled out by our UFDs. Our constraint on the FDM particle mass is one of the strongest obtained from UFDs, while we have made fewer assumptions in this chapter than others have made in previous studies.