Dark Matter in the Universe

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Marc S Seigar

Department of Physics and Astronomy,
University of Minnesota Duluth, USA

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For my wife, Colleen, and my children, David and Andrew

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Preface

The study of dark matter encompasses three main areas in fundamental physics: astrophysics, cosmology, and particle physics. As such, it is difficult to cover every aspect of dark matter in a concise book, such as this, and so this book is intended as an introduction for beginning physics majors, or those interested in a short course in dark matter.

This book starts by giving a brief historical overview of why dark matter is a necessary concept in modern physics, at least from an astrophysical perspective. The first three chapters focus on the astrophysical necessity for dark matter, and why it is necessary if we want to be able to describe the structures that we see in the Universe, particularly on the largest scales. The next three chapters focus on the particle physics necessary to understand dark matter. I have chosen to focus on just a few possible forms of proposed dark matter: Weakly Interacting Massive Particles or WIMPs (whether predicted by supersymmetric or non-supersymmetric models), Super Weakly Interacting Massive Particles or SuperWIMPs, sterile neutrinos, and axions. A brief overview of the Standard Model of particle physics is given along with the need for extensions to it. All of these extensions predict the existence of new particles, some of which have predicted characteristics that would be necessary for dark matter. The final chapter summarizes our modern cosmological model and how dark matter fits in. The final chapter also includes some possible scenarios that may play out within the next decade or so.

I hope that the readers of this book are inspired to learn more about the subject of dark matter.

Marc S Seigar
Department of Physics and Astronomy
University of Minnesota Duluth
Duluth, MN, USA
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Author biography

Marc S Seigar

Marc S Seigar is a Professor of Physics and Astronomy and the Head of the Department of Physics and Astronomy at the University of Minnesota Duluth (UMD). He is also the Director of the Marshal W Alworth Planetarium at UMD. Prior to his arrival at UMD, he worked as a Professor of Astrophysics at the University of Arkansas at Little Rock, a Project Scientist at the University of California, Irvine, and a Staff Astronomer at the United Kingdom Infrared Telescope (UKIRT). Professor Seigar has published numerous papers and conference proceedings articles in the field of galaxy dynamics, spiral structure, and dark matter.

Chapter 1

The need for dark matter

Figure 1.1. Fritz Zwicky. Image courtesy of scienceblogs.com.

Fritz Zwicky (a photo of whom can be seen in figure 1.1) was born in Bulgaria, a citizen of Switzerland, and did most of his best work at the California Institute of Technology in Pasadena, California. He was in the very tough spot of having a number of great and correct ideas that, by and large, people did not take seriously. One of them was the discovery of 'missing mass' in the Universe.

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While examining the Coma cluster of galaxies in 1933, Fritz Zwicky was the first to infer the existence of unseen matter. He coined the phrase *dunkle materie* or dark matter. Using the Newtonian law of gravity, Zwicky calculated the gravitational mass of the galaxies within the Coma cluster and obtained a value that was considerably higher (at least 400 times higher) than that expected from the starlight being emitted by all of the galaxies in the cluster. This meant that most of the matter in the cluster was unseen or dark, thus the term dark matter. While Zwicky had overestimated the amount of dark matter in the Coma cluster, the same calculation based on better, more recent data, still indicates that the majority of matter in galaxy clusters appears to be dark.

The Coma Cluster, as shown in figure 1.2 in an image from NASA's Hubble Space Telescope, is a collection of thousands of galaxies that are gravitationally bound into a single, spherical volume more than 20 million light-years in diameter. This Hubble Space Telescope image captures the magnificent starry population of the Coma Cluster of galaxies, one of the densest known galaxy collections in the Universe. However, the visible galaxies are just a small part of the picture as most of the space in this cluster is filled with invisible, dark matter. The need for dark matter, while originally discovered by Fritz Zwicky, was never really taken seriously until Vera Rubin confirmed the result by looking at individual galaxies four decades later.

Figure 1.2. The Coma Cluster. Image credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA). Acknowledgement: D Carter (Liverpool John Moores University) and the Coma Hubble Space Telecope Treasury Team.

Figure 1.3. Vera Rubin. Image courtesy of the American Museum of Natural History.

In the 1970s, Rubin (pictured in figure 1.3) began research on the rotation curves of galaxies, starting with the Andromeda Galaxy. A rotation curve is a plot of orbital velocity versus distance from the galactic center, and this is what Rubin studied for several galaxies from the early 1970s through to the mid-1980s. She pioneered this field by showing that material in galaxies (the stars and gas) was moving too fast. Galaxies would fly apart if the material holding them together gravitationally was just made up of their constituent stars. However, galaxies do not fly apart, and therefore a huge amount of unseen mass (or dark matter) must be holding them together. Rubin's calculations showed that galaxies must contain at least ten times as much dark mass as can be accounted for by the visible stars and gas. Attempts to explain this discrepancy led to the theory of dark matter being much more widely accepted, but this may have been partly due to research that was happening in parallel, within a different field of physics.

In the 1970s and 1980s, in particle physics, it was realized that the Standard Model of particle physics had some gaps and some aspects that simply could not be explained. For instance, it does not include gravity, but it does include the other three fundamental forces of nature (electromagnetism, the weak nuclear force, and the strong nuclear force). Also, gravity is an incredibly weak force, and there can be huge differences in mass between different fundamental particles, which is not adequately explained by the Higgs mechanism. This leads to new theories, all of which are essentially extensions to the Standard Model of particle physics. The most popular of these extensions is known as supersymmetry. In theories of supersymmetry, every Standard Model particle has a supersymmetric partner. This predicts that more fundamental particles should exist, and this can explain the discrepancies between the strengths of fundamental forces and the differences between the masses of the fundamental particles. Some of these 'new' particles have some intriguing properties. Supersymmetry (as well as some other models) predicts a class of particle known as weakly interacting massive particles or WIMPs. These particles have high masses, but they have a very small chance of ever interacting electromagnetically or interacting through the strong nuclear force. Due to their large masses, however, they can have a strong gravitational influence. Suddenly, there was a theory that had a prediction of what dark matter could be.

Our particle physics models now predict a host of particles that could potentially be candidates for dark matter (see chapter 4 for more details). They all have little or no electromagnetic interaction or strong nuclear interaction. One could imagine that the gauge bosons that carry these forces (photons and W and Z bosons) essentially pass right by these particles without being affected. In other words, these dark matter candidates act as if they are transparent to photons. If we were naming this type of matter today, we might call it transparent matter rather than dark matter. Indeed, transparent matter is a much better description of the underlying physical processes than dark matter.

In a nutshell, this introductory chapter has outlined the dark matter problem. In this book you will be able to read all about it. We will start by discussing how dark matter is detected through its gravitational effect in galaxies and clusters of galaxies, and how our theories explain this. We will talk about the different types of proposed dark matter particles. We will learn about how dark matter can potentially be detected, and about the experiments scientists are building to detect dark matter. We will even discuss what it means if we never detect dark matter, other than through its gravitational interaction with normal matter. This book is written for the undergraduate student with an interest in frontier physics. It is aimed as an introduction to the topic of dark matter cosmology. I think it is an intriguing story, and I hope you do too.

Suggested further reading

Rubin V C and Ford W K Jr 1970 *Astrophys. J.* **159** 379–403

Rubin V C, Thonnard N and Ford W K Jr 1978 *Astrophys. J.* **225** L107–10

Rubin V C, Ford W K Jr and Thonnard N 1980 *Astrophys. J.* **238** 471–87

Rubin V C, Ford W K Jr, Thonnard N and Burstein D 1982 *Astrophys. J.* **261** 439–56

Rubin V C, Burstein D, Ford W K Jr and Thonnard N 1985 *Astrophys. J.* **289** 81–98, 101–4

Zwicky F 1933 *Helv. Phys. Acta* **6** 110–27

Chapter 2

The formation of structure and dark matter in Galaxies

In this chapter, we will discuss the need for dark matter from an astrophysical point of view. We will see that dark matter is needed not only to explain the dynamics of galaxies, but also so that we can explain the observed large-scale structure in the Universe. This will unveil why dark matter is a cornerstone in the study of modern cosmology.

The motion of stars and gas in spiral galaxies provides a means of measuring the mass of such galaxies simply using the ideas of Newtonian gravity. From Newtonian gravity, we know that the velocities of stars around a galaxy follow a simple relation given by,

$$v_{\mathrm{rot}} = \sqrt{\frac{GM}{r}} \tag{2.1}$$

where r is the distance from the center of the galaxy, M is the mass contained within the distance r, and $G = 6.67 \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$ is Newton's gravitational constant. This tells us that the rotational velocity, v_{rot}, falls off inversely as the square root of the distance from the center of the galaxy.

In the late 1960s, Vera Rubin started to take observations of the rotation velocities of spiral (or disk) galaxies (otherwise known as rotation curves). One of the most famous rotation curves she obtained was that of M31, the Andromeda Galaxy (see figure 2.1). The main result of this study was that the rotation velocities of material in the Andromeda Galaxy remain high at very large galactocentric radii. However, according to the equation for the rotational velocities above, this was unexpected. From the visible mass in the galaxy (i.e., the stars), we would expect the velocities to fall off as the inverse of the square root of the distance. The only way we can reconcile this observational result with our theories of gravity is if the enclosed mass, M, is higher than observed (about 4–5 times higher), and also if the dark

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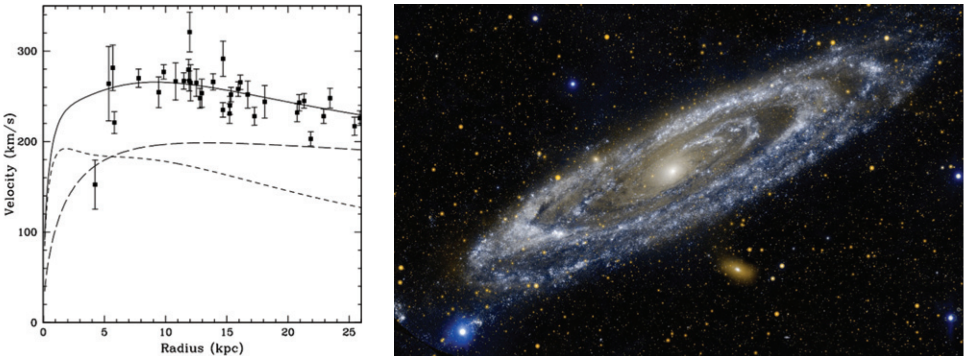

Figure 2.1. The rotation curve of the Andromeda galaxy (left) and an ultraviolet image of the Andromeda galaxy (right). Rotation curve credit (left): from Seigar *et al* (2008, Monthly Notices of the Royal Astronomical Society, Vol. 208, pp 1911–23). Image credit (right): NASA Galaxy Evolution Explorer Team.

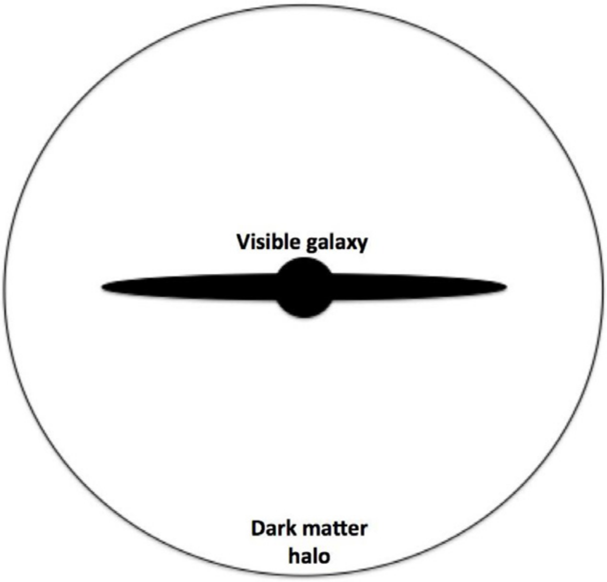

Figure 2.2. A schematic diagram of a visible galaxy in a dark matter halo (not to scale). The dark matter halo is typically 5–6 times the radius of the visible galaxy at its center.

matter extends well beyond the visible part of the galaxy. Therefore, the conclusion from these rotation curve data is that galaxies must contain much more mass than the visible light would otherwise indicate. Indeed, our modern picture of galaxies has a visible galaxy sitting at the center of a sphere of dark matter with a radius that is 5–6 times larger than that of the visible galaxy. A schematic diagram of this is shown in figure 2.2.

These so-called ‘flat’ rotation curves were confirmed in a series of investigations in the late 1970s and early 1980s. These rotation curves have now been extended to larger radii with sensitive measurements of neutral hydrogen gas, demonstrating that the rotation velocities remain high far beyond the visible disk in galaxies. This suggests that the visible light (and thus stellar mass) accounts for only a small fraction (typically 15% or smaller) of the mass in spiral galaxies. This still remains one of the best pieces of evidence in favor of dark matter cosmology. In order to get the flat rotation curves we observe, the simplest model is such that the dark matter exists in a large extended (almost) spherical halo surrounding the visible galaxy (see figure 2.2).

It has now been more than 40 years since the discovery that galaxies are surrounded by extended massive halos of dark matter. In this time, a variety of observational probes have made it possible to map dark matter halo mass distributions in some detail. These distributions are intimately linked to the nature of the dark matter, the way dark halos formed, and the cosmological context of dark halo formation.

The basic assumptions of modern cosmology are that the Universe is homogeneous and isotropic (the so-called cosmological principle). Homogeneous means that the Universe looks the same from every point within it. Isotropic means that the Universe looks the same in every direction. Both of these taken together means that there is no special place in the Universe, and the Universe has no center. On the largest scales, this assumption works extremely well. For instance, if we take a sphere of radius 4000 mega-parsecs and place it in random locations within the Universe, the variation in the average mass density measured within the sphere will be about 1 part in 10 000. However, on cosmologically small scales (i.e., galaxy-sized scales), just the fact that galaxies (and clusters of galaxies) exist, suggests that there are inhomogeneities (or overdensities), which cannot be explained by the cosmological principle alone. The structure of the Universe becomes much more complicated at these scales, with the growth of structure dominated by gravity. The standard model for the cosmology of the Universe (which includes dark matter and dark energy) has proven to be an invaluable tool as this cosmology reproduces the large-scale structures observed in the Universe extremely well.

In the tiniest fraction of a second after the Big Bang (up to about 10^{-32} s), the Universe was dominated by quantum perturbations or fluctuations. Particles were essentially created out of energy in this so-called hot Big Bang model. This is one of the results of Einstein's famous equation that showed that energy and mass are related to each other, i.e.,

$$E = mc^2 \tag{2.2}$$

where E is energy, m is rest mass, and $c = 2.998 \times 10^8$ m s^{-1} is the speed of light. Equation (2.2) is often referred to as mass-energy equivalence. In other words, mass is simply another form of energy. Particles (or quantum fluctuations) being created in the hot Big Bang model are also a result of the Heisenberg uncertainty principle, which can be written as

$$\sigma_x \sigma_p \geqslant \frac{h}{4\pi} \tag{2.3}$$

where σ_x is the uncertainty in a particle's measured position, σ_p is the uncertainty in its momentum, and $h = 6.626 \times 10^{-34}$ J s is Planck's constant. Equation (2.3) means that pairs of particles can be created and destroyed all the time, if the two uncertainties in equation (2.3), taken together, violate the condition of the equation. If the condition is violated, it is as if the particles do not exist, and they are referred to as virtual particles.

Under some conditions, however, it is possible to transform virtual particles into real particles. For this, we go back to equation (2.2), where even a tiny amount of mass can be equivalent (or can be converted to) a lot of energy. Furthermore, if there is enough energy available, particles can be created with the equivalent amount of mass. As mentioned above, mass is simply another form of energy. The particles are always created in pairs, a particle and an antiparticle. Under most circumstances, they would annihilate each other and their mass would be converted back into energy. However, at these early times, the Universe underwent an inflationary expansion, which took place between 10^{-36} s and 10^{-32} s after the Big Bang (the Big Bang being defined as the very beginning when time $t = 0$). During this brief amount of time, the Universe expanded extremely rapidly, at an exponentially increasing rate. Why do we believe this happened?

An expanding Universe generally has a cosmological horizon, which, by analogy with the more familiar horizon caused by the curvature of the Earth's surface, marks the boundary of the part of the Universe that an observer can see. Light (or other radiation) emitted by objects beyond the cosmological horizon never reaches the observer, because the space in between the observer and the object is expanding too rapidly. The observable Universe is one causal patch of a much larger unobservable Universe; there are parts of the Universe that cannot communicate with us yet. These parts of the Universe are outside our current cosmological horizon. In the standard hot Big Bang model, without inflation, the cosmological horizon moves out, bringing new regions into view. Yet as a local observer sees these regions for the first time, they look no different from any other region of space the local observer has already seen: they have a background radiation that is at nearly exactly the same temperature as the background radiation of other regions, and their space–time curvature is evolving lock-step with ours. This presents a mystery: how did these new regions know what temperature and curvature they were supposed to have? They couldn't have learned it by getting signals, because they were not in communication with our past light cone before.

Inflation answers this question by postulating that all the regions come from an earlier era with a big vacuum energy, or cosmological constant. A space with a cosmological constant is qualitatively different: instead of moving outward, the cosmological horizon stays put. For any one observer, the distance to the cosmological horizon is constant. With exponentially expanding space, two nearby observers are separated very quickly; so much so, that the distance between them quickly exceeds the limits of communications. The spatial slices are expanding very fast to cover huge volumes. Things are constantly moving beyond the cosmological horizon, which is a fixed distance away, and everything becomes homogeneous very quickly. As the inflationary field slowly relaxes to the vacuum, the cosmological constant goes to zero, and space begins to expand normally. The new regions that come into view during the normal expansion phase are exactly the same regions that were pushed out of the horizon during inflation, and so they are necessarily at nearly the same temperature and curvature, because they come from the same little patch of space.

The inflationary model of the Universe thus explains why the temperatures and curvatures of different regions are so nearly equal. It also predicts that the total curvature of a space-slice at constant global time is zero; in other words, the Universe is flat, and the density parameter $\Omega_{\text{total}} = 1.0$.

Following the inflationary period, the Universe continues to expand, but at a much slower rate. The inflationary model helps to explain the large-scale structure of the Universe, because at this early stage, during the inflationary period, the Universe is expanding extremely rapidly, so this expansion essentially prevents the particle pairs from annihilating. In fact, the particle pairs are virtual, but the expansion of the Universe causes the particles to move apart from each other very rapidly. As a result, they cannot annihilate, and they are transformed into real particles. The Universe is hot and energetic enough at this time, and so this is where equation (2.2) comes into play. The energy here can give the particles their mass, and hence the Universe if now filled with real particles. This is the source of quantum fluctuations, which grew very rapidly to become overdense regions that provided the seeds for gravitational collapse. These collapsing overdensities were composed mainly of dark matter, and they provided the mechanisms necessary for visible (or normal) matter to condense to begin the process of galaxy formation. The idea is that these initial perturbations grew to become the galaxies and clusters of galaxies that we see in the current Universe. The inflationary model of the Universe was first developed in the late 1970s and early 1980s by physicists Alan Guth and Andrei Linde.

There is a slight problem with this somewhat over simplistic description of the early Universe. In this model, for every particle that is created, there should be an antiparticle. In that case, where is all the antimatter, and why do we live in a Universe dominated by matter? There are some symmetry violations that have been observed in particle physics experiments, and as a result there is slightly more matter created than antimatter in the early Universe. This idea will be described in more detail in chapter 4.

The overdensities created by quantum fluctuations in the inflationary model are the seeds for structures (or galaxies and clusters) to grow through gravitational collapse. Observations provide abundant evidence that the structure in the Universe formed hierarchically. In other words, the first structures (or galaxies) in the Universe were small. In an overdense region, the gravitational attraction between these small galaxies would result in them eventually merging. As a result, small structures evolve into larger galaxies over time.

The first dark matter halos begin to form as a result of quantum fluctuations and, in the present-day Universe, visible galaxies live at the centers of these massive halos. Dark matter dominates the total matter density of the Universe, and, as it does not interact with radiation, it is the first matter to undergo collapse due to gravity. Early halos of dark matter will grow through two processes. The first of these is smooth accretion of additional material. The second growth mechanism is mergers with other dark matter halos. In the standard cosmological models the merger rate of distinct dark matter halos is robustly predicted.

Figure 2.3. An image of the Antennae Galaxies, the closest example of a merger between two galaxies in the Universe. Image credit: NASA/STScI Hubble Space Telescope Legacy Team.

We expect that galaxies formed inside larger dark matter halos. The early galaxies begin to form as the dark matter halos draw baryonic matter gravitationally into the halos, allowing galaxies to form earlier than would otherwise be possible. These galaxies grow through mass accretion as additional material is drawn into the dark matter halo. Galaxy mergers allow the growth of more massive galaxies as the Universe continues to age. These merger events are key in altering galaxy morphologies by growing bulges in spiral galaxies, transforming spiral galaxies into elliptical galaxies and inducing star formation. In fact, from observations from the Hubble Space Telescope, we know that mergers between galaxies are common in the Universe (see for example, figure 2.3), and they were even more common when the Universe was young and galaxies were closer together.

Comparisons between predictions from models and simulations of a cold dark matter Universe and observations show remarkable agreement on the largest scales. Computer simulations of large volumes of the Universe in this cosmological model reproduce the clustering and distribution of galaxies on the largest scales, and they look incredibly homogeneous and isotropic. One of the most famous simulations of this kind is the Millennium Simulation[1], which was led by a group of astrophysicists at the *Max-Planck-Institut für Astrophysik* in Garching, Germany. Part of this simulation is shown in figure 3.1 at the beginning of chapter 3.

Despite the successes of the cold dark matter cosmology at describing the large-scale structure of the Universe, the model remains far from perfect. Observations show significant differences on small-scales from the theoretically predicted structures.

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[1] http://www.mpa-garching.mpg.de/galform/virgo/millennium/

A detail of significant difference comes from how dark matter is distributed in galaxies, or within a dark matter halo. The density of dark matter will decline as we move out from the center of a halo. The exact formula, which describes how the dark matter density falls off as a function of radius (the density profile), is predicted by theoretical simulations of large-scale structure in the Universe (such as the Millennium Simulation). These simulations of structure growth have shown that galaxy-sized dark matter halos all have cuspy central densities, and computer simulations have shown that the dark matter density profiles, $\rho(r)$, within a halo all follow the same form (regardless of their mass or size), which is given by

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2} \tag{2.4}$$

where r is the distance from the galactic center, and ρ_0 and R_s (the scale radius) are parameters which vary from halo to halo. Equation (2.4) is known as the Navarro, Frenk, and White (or NFW) dark matter density profile. From equation (2.4), it can be seen that the density is maximum in the very central regions of a galaxy, and it falls off very rapidly as you move out of the center (this is called a density cusp). However, observations of real galaxies, particularly the small, dwarf galaxies, show that the densities remain constant in the central regions, and the density only declines after a significant distance has been traversed (figure 2.4 demonstrates these differences), which is best given by the following, pseudo-isothermal density profile

$$\rho(r) = \frac{\rho_0 r_0^3}{(r + r_0)\left(r^2 + r_0^2\right)} \tag{2.5}$$

where r_0 is the core radius and ρ_0 is the central density. This discrepancy between dark matter simulations and observations of galaxies is still something that is difficult for cold dark matter cosmology to predict.

A potential solution for this conflict could be that the observational results are affected by a significant amount of non-circular motion in the central regions of a galaxy. In the determination of the observed density distribution of dark matter in galaxies, it is assumed that orbits of visible material (stars or gas) are circular (see equation (2.1), which is based upon circular motions). However, this is not necessarily the case, and orbits could actually be elliptical in nature. This would result in non-circular motions in the central regions of galaxies. There are other reasons why orbits could be non-circular in central regions. Some galaxies have bars, which would also induce non-circular motions. Most galaxies will almost certainly live in triaxial halos, in which the halo coordinates are given by

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \tag{2.6}$$

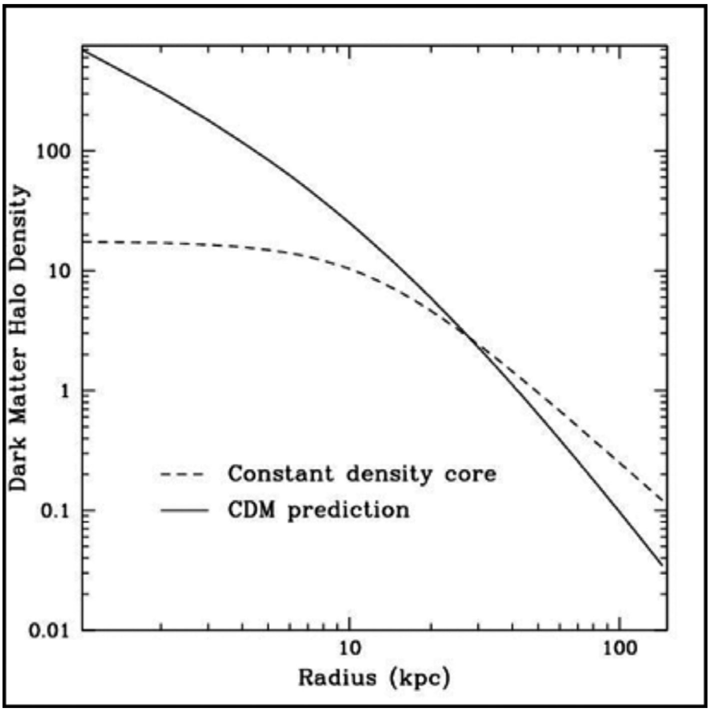

Figure 2.4. The difference between a density profile with a central cusp (the solid line or cold dark matter, CDM, prediction, also known as the NFW profile) and a density profile that remains constant in the central regions (the dashed line or constant density core).

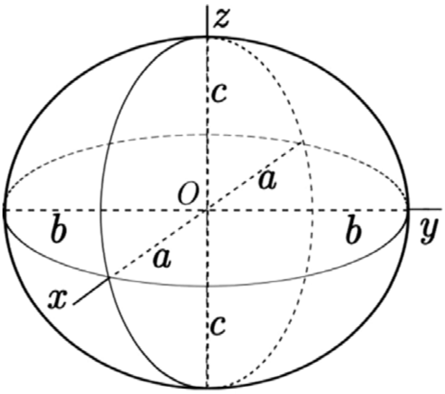

Figure 2.5. A triaxial halo or ellipsoid.

where x, y, z are Cartesian coordinates and a, b, c are the semi-principal axes in the x-, y-, and z-directions, respectively. An example of a triaxial halo (or ellipsoid) is shown in figure 2.5.

All of these possibilities result in non-circular motion, which means that a star will change its speed as it moves along its orbit (unlike circular motion, where its speed remains constant). The velocity of a star in its orbit is described by Kepler's second law, which states that an imaginary line joining that star to the gravitational center of the Galaxy sweeps out an equal area of space in equal amounts of time (Kepler's original laws were initially applied to planets, but Newton showed they could be applied to orbits in any gravitationally bound system). For elliptical orbits, Kepler's second law implies that stars move fastest when they are at their closest approach to the center of the galaxy. As the distance of a star from the galactic center changes constantly if orbits are elliptical, the stellar velocities are also constantly changing.

The density we calculate depends upon the speed of the objects we are using to trace the mass. This is fine for circular motions, but if non-circular motions are present, and speeds are changing depending on where a star is in its orbit, then our density calculations would be incorrect. Instead of using equation (2.1) to determine the central mass and therefore density profile, we need to know the exact shape of the elliptical orbits, and we need to use an equation that relates orbital velocities to the shapes of the elliptical orbits rather than assuming circular motions (see equation (2.7)), such that

$$v_{\mathrm{rot}} = \sqrt{GM\left(\frac{2}{r} - \frac{1}{a}\right)} \tag{2.7}$$

where M is the enclosed mass at radius r and a is the semi-major axis of the elliptical orbit. To determine if orbits are elliptical, and the eccentricity of the orbits, we need instrumentation that can map the velocity fields of galaxies, and this can be done with integral field unit (IFU) spectroscopy. These types of instruments, however, typically can only do this for the very smallest (i.e., dwarf) galaxies or for the very central regions of large galaxies.

These non-circular (or elliptical) motions may result in observations of lower than expected velocities in the central regions of galaxies. Despite these differences in how orbital shape affects velocities of stars, several studies (particularly for dwarf galaxies) have shown that, even when taking into account these non-circular motions, it is difficult to reproduce the dark halo densities expected by cold dark matter cosmology.

Dwarf galaxies are dominated by their dark matter content at all locations. In other words, the visible material is such a small amount of matter in these galaxies that estimating the distribution of the visible mass incorrectly does not strongly affect our estimates of the dark matter density distributions. Their velocity fields can also be mapped with IFU spectrographs. Dwarf galaxies are, therefore, great laboratories with which to study dark matter halos. Most studies of dwarf galaxies conclude that dark matter models are in clear conflict with the density distribution of dwarf galaxies. One of the exceptions is the Triangulum Galaxy, M33, a small satellite galaxy in orbit around the Andromeda Galaxy. The Triangulum Galaxy may be the only small galaxy which has a cuspy central density (and therefore appears to be consistent with the cold dark matter paradigm) that we know of (see figure 2.6). It is a very late-type galaxy, and we therefore might expect it to have a constant density core, just like the dwarf galaxies described above. Nevertheless, two

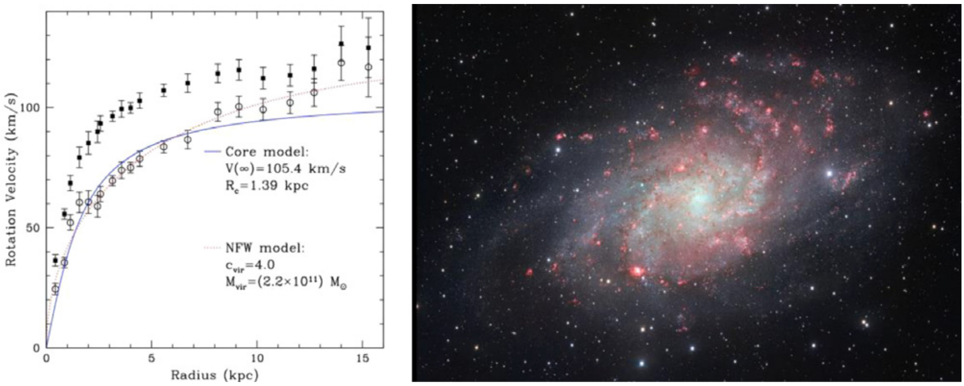

Figure 2.6. The rotation curve of the Triangulum Galaxy (left) modeled using a pseudo-isothermal model (solid blue line) and the dark matter simulation model (or NFW model, dotted red line). The squares are the total rotation velocities of the neutral hydrogen gas in the Triangulum Galaxy. The circles are the dark matter contribution to the rotation velocities after subtraction of the stellar and gas mass. The rotation curve is taken from Seigar (2011, ISRN: Astronomy and Astrophysics, Vol. 2011, Article ID 275697, 8 pages). Image of the Triangulum Galaxy (right). Image credits (right): European Southern Observatory's VLT Survey Telescope.

studies of M33 from the last decade both show that it seems to conform to the expectations of cold dark matter cosmology.

Despite the work on the Triangulum Galaxy pointing towards a dark matter distribution that is consistent with cold dark matter cosmology, there are many other studies (already mentioned above) that clearly indicate that there is a problem. Several possible solutions to resolving this conflict have been suggested. One possibility is that these observations are pointing to a real problem with cold dark matter cosmology, perhaps indicating that dark matter is not cold, but rather warm (see chapter 3 for a clearer explanation of cold versus hot dark matter), or possibly even a form of self-interacting dark matter, in which case it is easier to produce constant density cores at the centers of dark matter halos. In the last few years, however, it has been shown that these scenarios are unlikely. This is because of discrepancies in the sizes of the cores created in the warm dark matter models, which are much smaller than the observed sizes. The conclusion is that there is no motivation to prefer warm dark matter halos over cold dark matter halos, at least from an astrophysical perspective.

Another possible explanation for the prevalence of constant density cores in these dwarf galaxies is because they formed late in the history of the Universe, unlike large elliptical and spiral galaxies, which formed at earlier times and therefore conform to the standard expectations cold dark matter cosmology. This is because the central mass densities of galaxies tend to reflect the density of the Universe at their formation time. Galaxies that formed when the Universe was younger will have higher central densities simply because the Universe was smaller, and therefore the overall density of the Universe was higher. Nevertheless, while this explanation may be appropriate for the lower central densities typically found in dwarf galaxies, it does not explain the shape of the inner density profiles, as the dark matter simulations presented for dwarf galaxies still result in central cuspy densities for all mass scales, albeit with a lower central density when compared to massive galaxies.

The last possible explanation for this discrepancy between theory and observations is that the simulations are based on pure dark matter and do not contain any physics relating to normal, visible matter, or the interaction (if any) between dark and visible matter. If one were to include these effects in the simulations, the visible matter may interact (at least gravitationally) with the dark matter in some way that might resolve this cusp/core problem. However, the effect of visible matter on the dark matter may act to make the problem even worse. As early as the mid-1980s it was shown that as visible matter cools and falls into the center of a dark matter halo to form a visible galaxy, the dark matter halo contracts. This makes the central density profile even more cuspy and also sets up other problems (for instance, in this scenario, galaxies of a given mass—or size—rotate faster in these simulations than our observations suggest). More recently, however, mechanisms for preventing this contraction have been suggested, and they may appear to work. These mechanisms are referred to as feedback, and there are two types of feedback.

The first type of feedback is feedback from star formation. Observations have made it clear that in many galaxies, stars form at a much lower rate than expected. A second observational puzzle is the presence of high velocity outflows of cold gas in galaxies that form stars at the highest rates. These outflows may be a result of winds from massive stars or supernova explosions. In some cases, the rate at which gas is outflowing is similar to the rates at which stars are forming. Two things can now happen. First of all, these observations suggest that, at least in some systems, the star formation provides a feedback mechanism that removes the neighboring gas that would otherwise be available for further star formation. This limits the size of the visible galaxy for a given halo mass. Secondly, this also means that the efficiency at which material (i.e., gas) falls to the center of a halo is decreased due to these winds or outflows. This changes the interaction between the normal matter and the dark matter, and as a result the above halo contraction no longer occurs.

The second form of feedback is called AGN feedback. Almost every galaxy in the Universe harbors a supermassive black hole in its nucleus. These black holes have masses of between 100 000 and a few billion times the mass of the Sun. At some point in the life of a galaxy, these supermassive black holes would have been actively swallowing (or accreting) material. Material falling into a black hole first forms a hot accretion disk around it. For supermassive black holes, these disks become so hot that they can outshine their host galaxies. This is an active galactic nucleus or AGN. Some of these AGN have jets of material that blast material away from the central regions at speeds close to the speed of light (typically the minimum velocities observed are about $0.9c$). These jets are another feedback mechanism that can both expel gas from a halo (and thus inhibit further star formation) and a mechanism that can stop halo contraction.

So, while theoretical results from the mid-1980s suggested that the interaction between visible and dark matter would lead to an even cuspier central profile, our understanding of feedback physics (which is supported by observations) has shown that this contraction probably does not take place. This alone does not resolve the cusp/core problem, but it also does not make it any worse than it has to be.

If feedback from star formation can affect the early stages of halo formation, steep cuspy density profiles may be transformed into the observed flat cores. In one particular set of simulations that included star formation feedback, strong outflows from supernova explosions remove gas, which inhibits the formation of central visible bulges in galaxies and decreases the dark-matter density in the central regions. Galaxies that are bulgeless and have shallow central dark-matter profiles arise from these simulations. These are the analogues of the late-type and dwarf galaxies that are observed to have constant density core profiles in their central regions. These simulations seem to provide a working solution to the cusp/core problem. From this work, it appears that supernova feedback provides a mechanism for transforming cuspy density profiles into shallower central density profiles. However, even in the case of these simulations, all of the observational studies that have dealt with the cusp/core problem have focused on the properties of late-type dwarf and low-surface brightness galaxies. Galaxies with dominant bulges have yet to be explored in detail. In the few cases where such galaxies have been explored, a cuspy profile seems to result from the observational data. Also, in the case of elliptical galaxies (which could be thought of as pure-bulge galaxies) and clusters of galaxies the cupsy cold dark matter model provides a remarkable fit to the density profile. This highlights the need to extend these studies to include galaxies with significant bulges. Such studies are difficult, because the central regions of these galaxies are dominated by visible matter (unlike dwarf galaxies which are dark matter dominated at all locations). Determining the central visible mass depends on several factors such as how accurate the light distribution can be converted into a mass distribution, which is definitely not simple as it depends on the types of stars that make up the light that we see. There are theoretical models that can help us calculate this transformation from light to stellar mass, but they are all approximations. In a region where the dark matter content is small, even the smallest inaccuracies or approximations will lead to very misleading results.

So, to bring this chapter to a conclusion, cold dark matter cosmology reproduces the large-scale structure of the Universe extremely accurately. However, on galaxy-sized scales there are several known issues with the theory. Here, we have highlighted one particular problem, namely the cusp/core problem, which highlights the fact that cold dark matter simulations of structure formation predict central cusps in the density profiles of dark matter halos. However, observations, particularly of dwarf and late-type galaxies, suggest that the central densities are flat over the inner 3000 light-years (about 1 kilo-parsec). This is a serious issue with cold dark matter cosmology. A solution involving supernova feedback may be the answer, but this model needs to be applied to large spiral and elliptical galaxies to see how widely applicable it is.

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