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INTRODUCTION: THE DARK MATTER PROBLEM

Suppose you became aware that there were specters, invisible beings, living in your house. You cannot see, hear, or feel them, but you know they are there, because they move things around your home, open and close doors, and change the room temperature. You begin to notice patterns for these changes, as if they are governed by rules.

After a time, knowing their patterns, you begin to learn the rules. You learn how to predict what changes they will make, and when they will make them. As more time passes, you come to suspect that there are many specters—maybe ten for each person in your house. The specters have always dominated your environment, and you and your family have always responded to them without knowing it.

Your curiosity about the specters grows, and you try to learn more about them—what are they made of? Where did they come from? What do they want? Still, you never sense them directly, but only learn about them through the changes they make in your (their?) home. The specters shape your environment, but you do not shape theirs. They are completely unresponsive to anything you do to communicate with or learn about them. You imagine that the specters have always been there. They are not intruders, but part of the natural order of things.

Most of us would find such a circumstance very strange, perhaps troubling, and certainly very frustrating. How could we have coexisted with so many specters for so long without knowing it? Why is it so difficult to learn about them? Where did they come from?

Over the twentieth century, **astronomers**[1] gradually became aware of "specters" in our universe in the form of a new substance first called "missing mass" and later "**dark matter**." This book uses the term dark matter. Dark matter created the shape and structure of galaxies, clusters of galaxies, and the universe itself.

The goal of this book is to make sense of the specters that represent dark matter: to explain how astronomers came to know about it; how theoreticians uncovered how dark matter shaped the largest structures in our universe through gravity; and how physicists and astronomers are navigating the complex, frustrating hunt to understand more about dark matter.

I will use the terms **visible matter** or **normal or luminous matter** to refer to **matter** that forms stars and generates the light that we observe through telescopes. Dark matter's "invisibility" means that it does not form stars or generate light (hence the term "dark" matter). More broadly, "dark" implies that dark matter does not significantly interact with visible or normal matter in any way *other* than through gravity.

Over the past 85 years, **particle physicists**, astronomers, and **astrophysicists** have shown through the process of elimination that no known substance can account for the

1. The glossary at the end of the book provides brief explanations of words in bold.

effects of dark matter. That includes planets, extra gas in the universe, and anything else that is made of particles that we know about. This also includes the black holes made from the collapse of stars at the end of their lives. However, there is the idea that as-yet unobserved **primordial black holes (PBHs)** that formed in the early universe from matter fluctuations in space-time could explain dark matter.

In the 1930s, a few astronomers began to understand that the amount of visible matter in clusters of galaxies could not explain the motion of the galaxies in their cluster. The total mass of the newly discovered invisible matter appeared to be tens or hundreds of times the visible mass of the stars. In the 1970s, measurements of how stars move inside galaxies led to the idea that some unseen gravitating matter causes the visible stars to orbit around the center of their galaxy faster than predicted from just the mass of the stars alone. To explain this concept, and set the stage for the rest of the book, Chapter 1 provides some physics background. Chapter 2 then lays out the evidence for dark matter from astronomical observations.

In Chapter 3, we turn to what we do know. Four **forces** describe almost all the dynamics of matter. The weak force causes radioactive decays, the strong force binds **quarks** into protons and neutrons and binds protons and neutrons into atomic nuclei, the electromagnetic force determines the structure of matter, and all matter and energy feel the force of gravity. The weak, strong, and electromagnetic forces are all variants of quantum field theory and collectively make up the **Standard Model** of particle physics. The three Standard Model forces act on quarks and leptons that make up normal matter.

The Standard Model explains almost all the observed interactions between particles made since Henri Becquerel first observed radioactive decay in 1896. Albert Einstein and his successors left us with an excellent classical theory of gravity, but theorists have been unable to find a quantum theory of gravity, leaving us with a patchwork of theories: the quantum mechanical Standard Model for quarks and leptons, and classical gravity that acts on all matter. Dark matter does not fit anywhere in our patchwork: None of the known particles from the Standard Model have the properties of dark matter; and classical gravity does not predict particles, as gravity acts on all matter.

Chapter 4 follows the experiments that led to the conclusion that dark matter does not fit into our current view of particle physics, leaving the problem of finding out what dark matter is.

Over the past 30 years, many ideas have emerged to explain the effects of dark matter. This book focuses mostly on two hypothesized new particles, called **Weakly Interacting Massive Particles (WIMPs)** and **axion**s, both of which could be dark matter particles. Chapters 5 and 6 explain some of the experiments searching for WIMPs on Earth and in space. Chapter 7 describes the idea behind axions, how axions could be dark matter, and how physicists search for axions.

This book does not end in Chapter 8 with a grand revelation of the properties of dark matter—these still elude my experimental colleagues and me. However, I hope that you will gain a deeper understanding of the dark matter problem and what a triumph it will be when we do learn something new about dark matter.

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