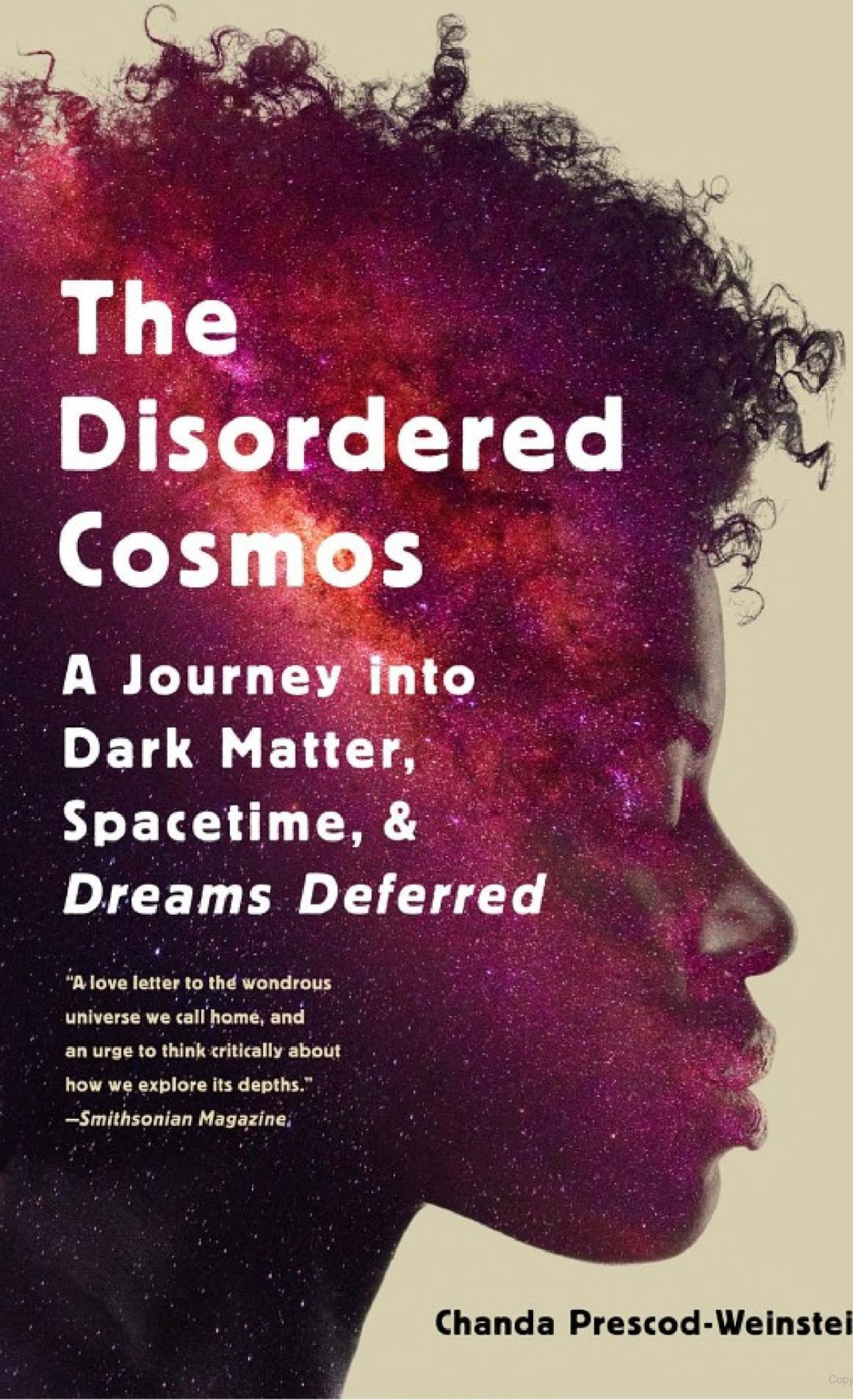

The Disordered Cosmos

A Journey into Dark Matter, Spacetime, & *Dreams Deferred*

"A love letter to the wondrous universe we call home, and an urge to think critically about how we explore its depths."
—*Smithsonian Magazine*

Chanda Prescod-Weinstein

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PHASE 4 ALL OUR GALACTIC RELATIONS

Sketch for *We Were Always Scientists* (2019) by Shanequa Gay

For Grandpa Norman z"l,
Grandma Elsa z"l, Grandpa Stanley z"l,
and Grandma Queens z"l.

For Uncle Cyril z"l.

For East LA and Brooklyn and Barbados and Hawai‘i.
For Repiblik d Ayiti, where this freedom began.

we the black bodies understand each other at visible frequencies without a dissection or death—which is to say witness us the black bodies rejoice to become mortals again because here is what is true:
a black body radiator be in thermodynamic equilibrium which is to say
a black body be at rest yes let the black bodies rest

—Lena Blackmon, from “quantum distributions for Sarah Baartman”

People need to know that we live in a universe that is bigger than the bad things that are happening to us.

—Margaret Prescod

IN THE BEGINNING

A Bedtime Story

ONCE UPON A TIME, THERE WAS A UNIVERSE. WE ARE NOT sure about how it started or whether there is a reason. We don't know, for example, if spacetime is ordered or disordered at the smallest scales, which are dominated by the weirdness of quantum mechanics. We are pretty sure that during the first sliver of a trillionth of a second it expanded very rapidly so that for the most part it looked the same in every direction and looked the same from every position. It was sameness everywhere. Except that particles started to blip out of nothing due to random fluctuations caused by quantum effects, maybe in spacetime, we are still not super sure about that. Then again, we are not super sure about this, either: for some reason those particles formed more matter than antimatter. That process, which formed a particle type called baryons, is called baryogenesis. From there those baryons started to form structures, and from those structures stars formed. Then the stars got old and some of them died in super epic, rather fabulous fashion. They exploded into supernovae, making heavy elements like carbon and oxygen in the process. Those elements went on to be the basis for all life on Earth. Earth is a planet, one of the structures that formed around stars from the leftovers of supernovae. Eventually, a smaller type of structure that we call life formed on Earth. Some of the life-forms that evolved were relatively hairless apes that use a variety of methods of communication. There are about 7 billion of these apes, with various levels of eumelanin and pheomelanin in their skin and hair, giving them a range of colors. The apes also have a lot of different hair textures. Some of the ones with less eumelanin have for a long time now been cruel to the ones with more, some of whom we know as "Black people.” We know why this is although we don’t fully understand the why, but it might be due to laziness or because they are jealous of our boogie. But despite this, Black lives come from the same baryogenesis, the same supernovae, and the same structure formation. No matter what the lowest-eumelanin people say, Black Lives Are Star Stuff and Black Lives Matter—all of them.

◆

Despite the facts of this story, there’s still a lot that we don’t know about the universe. In science, we tend not to think in these terms—imagining the subject (us) and object (universe) to be distinct. This way of thinking is something we inherit from European thought, specifically the ideas of René Descartes. When we study the Andromeda Galaxy, we record its details as Cartesian thinkers, seeing it as something apart from ourselves and our home in the Milky Way. But at the same time, we are in a very technical sense bound up with Andromeda. It has its own story: it is the Milky Way’s nearest major neighbor, and its existence does not trace back to a common origin with the Milky Way. Yet, in the future, these two galaxies will merge because they are bound together in a gravitational potential, which we can think of as a well in which they are both slowly spiraling downward, destined to eventually meet. Don’t worry—this collision isn’t set to be fully underway for another 4 billion years, and it won’t be the kind of violent chaos that we imagine when we think about the word “collision.” This isn’t two cars smashing into each other, quickly and violently. Rather, it is stars and gas and (maybe?) dark matter particles reorganizing themselves into a new formation, guided by their gravitational relationships with one another.

This story is maybe our story. I say maybe because around the time that this collision occurs, our sun will be dying and our solar system will be destroyed in its death throes. Before its life ends completely, the sun will expand the amount of space it takes up, changing what constitutes the habitable zone of this solar system before eventually destroying the earth entirely. By then, we may have self-immolated anyway, but perhaps we will have just relocated to another solar system in a galaxy far, far away, using technology that is completely unimaginable and even unbelievable to me now. Or perhaps we will be in a solar system closer by, still in the Milky Way, in which case we will be carried along with the collision. The observations that our progeny will use to watch this phenomenon slowly unfold over the course of millions of years will require careful calculations about their location relative to all of the action.

As it is, we already do this. We are always studying our location in the universe, even when we tell ourselves that we are simply looking outward, beyond ourselves. In our attempts to learn more about the structure of galaxies, we spend an enormous amount of time looking at our own and wondering if it is normal. We are still unsure whether the Milky Way is an average spiral galaxy or whether there is something special about it. Even though we are not the center of the universe, because indeed the universe has no center, we are the reason that we bother with the universe at all. Our location in all of it matters.

Some of us wonder about where we belong more than others. I am a descendant of Indigenous Africans whose connection to the land was forcibly severed through kidnapping and the colonization of their bodies. West Africa is enormous and full of so many different peoples. I do not know and will likely never know for sure which Indigenous communities my ancestors came from, so the question of location remains fraught for me. I am also by and for East LA (east of downtown Los Angeles), and forged from Black American, Black Caribbean, Eastern European Jewish, and Jewish American histories. Today I split my time between where I live on the Seacoast region of New Hampshire and where my spouse lives in Cambridge, Massachusetts. Los Angeles, Cambridge, and New Hampshire are colonial names for the homelands of the Tongva, Pennacook, Wabanaki Confederacy, Pentucket, Abenaki, and Massachuseuk Nations. These locations and the people rooted in them matter in this universe too.

I am also a scientist who as a child terrorized her single mother by persistently questioning everything. I am a born empiricist, someone who by nature (ask my mother!) takes seriously that information should be collected and then provided as a mechanism for explaining why the world is organized in the ways that it is. This commitment to rationalizing order often seemed to center on my household chores, but I also wanted to know why mathematics so accurately described the universe and how deep that relationship goes. That question, along with the need to have some kind of career because I knew that bills had to be paid somehow, is why I decided at age 10 to become a theoretical physicist. It is also a question that remains the subtext of my work as a theoretical physicist nearly 30 years later.

But I also wanted to know why my third-grade teacher had left all the Black children with two Black parents off the playbill for our class's forthcoming modernist production of *Strega Nona* (produced and directed by actress Conchata Ferrell z"l), where I was to play one of Macbeth's three witches. Mrs. M threw me out of class for asking the question, but at the time I didn't think of it as a challenge to her authority. I simply wanted to know if she was a racist. I was curious. I had watched my mom's grassroots organizing combating racism and sexism, I had experienced racism by her side trying to get motel rooms on road trips, and I just wanted to know if I had discovered an instance of it on my own.

When I was 10, I thought that I could keep my curiosity about the mathematics of the universe and the existence and function of racism separate. But it was not to be. A hard lesson I learned as I emerged from my mother's home into rarified academic settings (first stop: Harvard College) was that learning about the mathematics of the universe could never be an escape from the earthly phenomena of racism and sexism (and now that humanity is moving deeper into our solar system, racism and sexism are no longer earthbound). As I progressed through college, graduate school, and teaching, I learned quickly and painfully that physics and math classrooms are not only scenes of cosmology—the study of the origins and inner workings of the physical universe—but also scenes of society, complete with all of the problems that follow society wherever it goes. There is no escape.

In physics, matter comes in different phases. For example, water and ice are different phases of the same chemical—liquid and solid. A phase transition occurs when matter changes from one phase to another. We see such a phase transition occurring when water evaporates: the liquid becomes gas. When it freezes, the transition is from liquid to solid. Phase transitions also occur in environments that feel far less mundane to us, for example, when a massive star goes supernova and converts from plasma to a neutron star that is some combination of superfluids and solids quite unlike those we find on Earth. Similarly, I had to undergo incredible intellectual phase transitions to conceive of what it meant to go from being a Black girl who loved but did not understand particle physics to a queer agender Black woman who loves—and is one of the chosen few to understand how much we don't understand—particle physics. My new understanding that society would follow me into the world of physics was also something of a phase transition for me.

This book will reflect these different phases in order to provide a holistic picture of the ways of knowing that we call particle physics and cosmology. I used to think physics was just physics, separate from people. I thought we could talk about particles without talking about people. I was wrong. At different points I came to understand physics as something that involved people, and that particular understanding has gone through different phases of its own. Studying the physical world requires confronting the social world. I know personally that social barriers impact the practice of science, its results, and the people who comprise the community we call "science." In this book, I will reflect to readers both my love for science and the difficulties people like me face in holding on to that love. For this reason, what follows is broken into four phases: *Just Physics*, *Physics and the Chosen Few*, *The Trouble With Physicists*, and *All Our*

Galactic Relations.

This book is also part of a long tradition of scientists taking a moment to share with the wider world how they see science. Historically, scientists have aimed to give readers a sense of what communications researcher Alan G. Gross calls "the scientific sublime"—a feeling of awe at the universe and our place within it. This was a hallmark of Carl Sagan's science communication style, and I think it is why his documentary and book *Cosmos* captured the world's imagination and sustained me through difficult moments during college. Almost always, the scientists who have had the opportunity to share their views on science have been white men. Necessarily, as a Black agender woman, I see science differently than my science communication ancestors have because contrary to the usual lore, who you are matters in science. When you're looking at the world from the margins, a persistent feeling of "the sublime" can feel out of reach as you struggle against mundane and pervasive forces of oppression. It may, therefore, be tempting to cast this book as radically outside the popular science genre because I go beyond the sublime to acknowledge the big role that social phenomena play in science. Some will point to my own life as the central narrative of this text, but while you will learn some things about me along the way (and other scientists too), I am not the point. Much more interesting is the question of how we get free.

What does freedom look like? When I put this question to artist Shanequa Gay, she told me, "Freedom looks like choice making without having to consider so many others when I make those choices." I hear in Shanequa's response a deep cry for space to self-actualize, to not always be stuck in survival mode. A sketch of Shanequa's painting, *We Were Always Scientists*, appears at the beginning of this book; I commissioned that painting partly because I was trying to figure out my own answer to this question. I asked Shanequa to envision unnamed Black women scientists under slavery. I wanted to challenge the idea that "scientific thought" has been the exclusive purview of Euro-Americans and those of us who have been trained in their knowledge systems. I also wanted something to remind myself that I belonged in my physics department office, and to remind myself that even in the worst conditions, Black women have looked up at the night sky and wondered.

Those women whose names I do not know, who may or may not be part of my bloodline, are as much my intellectual ancestors as Isaac Newton is. In fact, it is through the lessons those women passed on that I have learned to manage living with the Isaac Newtons of the world: those who are good at physics, but who are not good to people. These ancestors also serve as a reminder that the universe is more than our attempts to manipulate it. I don't have to end up like Newton, who served as warden of The Royal Mint in the late 1600s and was said to enjoy his ability to burn at the stake, hang, and torture coin counterfeiters. I don't have to end up like J. Robert Oppenheimer, the brilliant and tragic theoretical physicist who oversaw the creation of the first nuclear weapons and spent the rest of his life trying to undo the damage. I believe we can keep what feels wondrous about the search for a mathematical description of the universe while disconnecting this work from its historical place in the hands of violently colonial nation-states. With this book, I hope to map out for myself and for others an understanding that creating room for Black children to freely love particle physics and cosmology means radically changing society and the role of physicists within it. In the end, I have two big dreams for Black children and others, besides clean water, good food, access to health care, and a world without mass incarceration:

1. To know and experience Blackness as beauty and power
2. To know and experience curiosity about the night sky, to know it belonged to their ancestors

That, too, is freedom.

בָּרוּךְ אַתָּה יי אֱלֹקֵינוּ מֶלֶךְ הָעוֹלָם אֲשֶׁר בִּדְבָרוֹ מַעֲרִיב עֲרָבִים. בְּחָכְמָה פּוֹתֵחַ שְׁעָרִים, וּבִתְבוּנָה מְשַׁנֶּה עִתִּים וּמַחֲלִיף אֶת הַזְּמַנִּים, וּמְסַדֵּר אֶת הַכּוֹכָבִים בְּמִשְׁמְרוֹתֵיהֶם בָּרָקִיעַ כִּרְצוֹנוֹ. בּוֹרֵא יוֹם וָלָיְלָה, גּוֹלֵל אוֹר מִפְּנֵי חֹשֶׁךְ וְחֹשֶׁךְ מִפְּנֵי אוֹר. וּמַעֲבִיר יוֹם וּמֵבִיא לָיְלָה, וּמַבְדִּיל בֵּין יוֹם וּבֵין לָיְלָה. יי צְבָאוֹת שְׁמוֹ: אֵל חַי וְקַיָּם תָּמִיד יִמְלוֹךְ עָלֵינוּ לְעוֹלָם וָעֶד. בָּרוּךְ אַתָּה יי, הַמַּעֲרִיב עֲרָבִים

Blessed are You, Universe, who brings in the evening with a word, in wisdom opening the gates and with understanding changing the times and seasons, ordering the stars along their paths in the sky. Creator of day and night, rolling back light from the dark and dark from the light, You make the day slowly fade and bring in the night, dividing between day and night, how great is Your Name. Living Universe, may we always feel your Presence in our lives. Blessed are You, Adonai, who brings in the evening.

PHASE 1

JUST PHYSICS

In which the universe is, for a time, human-free.

ONE

I ♥ QUARKS

THE STORY GOES LIKE THIS. ME: BLACK CHILD ON A SCHOOL bus that is slowly crawling along the 10 Freeway East, windows down, exhaust filling her nose and lungs, causing headaches that stop only years later when her dreams of particle physics carry her far away from the Los Angeles smog. I am reading and then taking breaks from reading to tell whoever is left on the bus—just a handful of children because between my school's grades six through twelve, only about four of us live this far away—about these things called quarks. I don't know what a quark is or where the name comes from. I don't particularly care about the name either. But I know that the world is made out of quarks. I know that my brain is a quark and electron collection.

These particles are not just a Black child dreaming. The Standard Model of particle physics is also all the things that a Black child is made out of. It is all of the things I am made out of as a scientist who has reached adulthood, still fascinated with what she still doesn't understand. The journey to know quarks in a more technical sense than *A Brief History of Time* could provide had an almost dizzying number of twists and turns because the math that describes them is some of the most complex in all of particle physics. There were many pieces I had to understand first. And instead of being put off by my descent into the world of particles, my attraction to them deepened with each step.

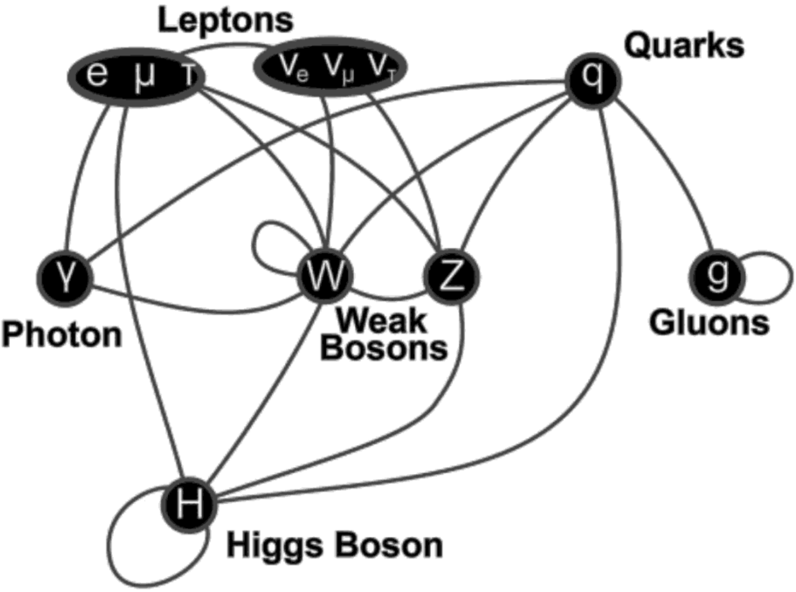

Figure 1. This diagram, made by a Wikipedia contributor, gives you a loose picture of the particles in the Standard Model and how they interact with each other. The top row of bubbles (leptons on the left and quarks on the right) are the matter particles. The middle row of bubbles (the photon, W and Z bosons, and gluons) are the force mediating particles. The bottom row is the Higgs boson. The lines between the bubbles show some of the possible interactions between these particles.

TriTertButoxy

During my intellectual adventure, I learned that I particularly enjoy a neatly ordered tale of an organized universe that can come off like a delicately constructed sum of its parts. This Standard Model is the framework that we use to describe and make predictions about elementary particles, the fundamental building blocks of matter, and three of the four known forces of the universe—electromagnetism, the weak force, and the strong force. Gravity, the one force we've been unable to fit into the Standard Model, has taught us that forces are felt—

completely surrounding us—but never seen. This is in part why gravity doesn't fit in, because it is embedded in spacetime, which literally completely surrounds us. By contrast, the other fundamental forces are in fact mediated—communicated—by a special class of particles called vector bosons.

Before we get to what I mean by "vector bosons," let me add that they are only one of the many strange new things that come up in particle physics. Every realm of intellectual work has its own vocabulary, and I may be biased, but I guarantee you that few if any are as strange, fantastical, and apparently true as in the world of particle physics. For example, there's spontaneous symmetry breaking, a phenomenon where the equation that governs a particle's behavior obeys certain rules, but then when you actually use the equation to calculate the particle's least energetic behavior, the particle doesn't appear to obey those rules. What? Particle physics is full of mathematical stuff like this that seems completely unreal, and yet, all of our experimental data matches these strange mathematical ideas. Though I work at the intersection of astrophysics and particle physics, it is particle physics that continues to teach me over and over again that the universe is always more bizarre, more wonderfully queer than we think.

Particle physics, for me, isn't just about organizing information, although I admit that I get a certain pleasure from that. It's also about the basic premise of what all physicists do. Whether we are studying particles or new ways to make powder stick to people's faces (yes, that's a job you can have!), we study systems as they change in time and look for patterns or make predictions about patterns in their behavior. We used to think that absolute predictions could be made if we had sufficient information. One of the toughest lessons of the twentieth century was that this is not the case—our world is at base quantum physical in nature.

For our purposes here, quantum physics (which physicists call "quantum mechanics") means that the fundamental properties of particles are such that we must now understand that each event in the universe is but one probability among others. Some events are more likely, but everything is possible. The probabilistic nature of quantum mechanics is particularly noticeable in the land of particle physics, where the fundamental objects are very small and more evidently governed by quantum rules. We can never really predict exactly what particles will do, but we can calculate the likelihood that something will happen and the timescale over which we expect it to occur. The quantum world of particles requires a kind of stretching of our scientific imagination into our scientific reality: things that do not seem intuitive are now what is real. The existence of any given object in our everyday life seems definitive, guaranteed. The table my feet are resting on is there—except there's an incredibly small, almost zero probability that in a moment it won't be.

That's not all of the strangeness of particle physics. Here is some more: all particles fall into one of two quantum mechanical categories, one of which is the boson (named after Indian physicist Satyendra Nath Bose). The other is a fermion (named after Italian American physicist Enrico Fermi). The difference between bosons and fermions comes down to a rule called the Pauli exclusion principle (named for Austrian physicist Wolfgang Pauli) and a quantum mechanical property that each particle has, which we call spin. The value of quantum spins are measured in multiples of a number we call Planck's constant. Bosons have the property that their quantum spins always occur in whole numbers (zero, one, two, etc.). The famed photon, the particle that mediates electromagnetic interactions and that we experience as light is a vector boson, a particle with a spin of one. Fermions, which include my beloved quarks, have the property that their spins always occur in multiples of a half (1/2, 3/2, etc.). The electron has a spin of a half and so do all of the quarks.

Importantly, this spin property is not like a spinning ball, but it gets its name because it is part of the quantum mechanical counterpart to our everyday notion of rotation. This quantum spin is additive: any object that contains particles has a spin, because the individual spins of those particles will combine in interesting ways dictated by the rules of quantum mechanics. Therefore atoms, which are made out of electrons and quarks, also have a quantum spin. This quantum spin has significant consequences for the structure of matter. This is a result of the fact that bosons and fermions obey different rules, which tell us how the particles can be distributed into different quantum energy levels. I tend to think of bosons as pep squad particles: they are happy to all share the same quantum energy state together. Fermions? Not so much. They're grubby and don't share well. More technically, they have to obey the Pauli exclusion principle, which says that no two fermions can share the same quantum state in the same quantum system at any given time. Students who take high school chemistry often struggle with figuring out orbitals, where electrons can only go into a few slots before the slots are full and new electrons have to move to higher orbitals. This is Fermi statistics and the Pauli exclusion principle in action.

As complicated as this sounds, the idea of spin is often taught to sophomore and junior physics majors in college. We are partly able to do this because we don't spend any time trying to make sense of why particles come in these two distinct formats. It is instead a definition that students are encouraged to accept as a fundamental axiom, and if they'd like to think deeply about that, there's maybe a philosophy class they can take in another department. The bizarre probabilistic math of quantum mechanics makes predictions that match our experiments, and for many physicists, that's enough since developing models that match data and testing theories using data are the two primary activities of physicists. Many of us accept quantum physics without ever trying to make sense of it, and we're not particularly encouraged to either. In other words, you're doing no worse than a future professional physicist if you just accept what I'm saying here without any substantive understanding of why things are this way. Of course, the question of "why" constantly lurks in the background, but research on what is called "foundations of quantum mechanics" has largely been relegated to the margins of physics research, in part because it's difficult and in part because it hasn't been profitable. There's still a lot that we don't know.

We do know that everything we have ever seen in the universe is made out of two categories of fermions: quarks, which like to combine to form other particles, and leptons, which like Bartleby the Scrivener, would prefer not to. Everything we have ever seen in the universe that is made out of quarks and leptons has a mass because of the Higgs, a scalar boson (which has a spin of zero). Every force that we know of in the universe, except gravity, is mediated by vector bosons, like the gluons that are responsible for the way quarks glue together into other particles. Some physicists think gravity may be mediated through spacetime by a spin 2 boson called a graviton, but for now that is a hypothetical idea that goes beyond the Standard Model of particle physics.

The Standard Model itself is largely understood to be experimentally complete as of 2012. Before then, we had detected elementary particles in three categories: quarks, leptons, and vector bosons. Many of these detections happened in particle colliders—literally experimental setups where particles are shot at each other and then the equipment picks up the signatures of the pieces of the smashed-up particles. But we still didn't know for sure how these particles got their mass. In 2012, scientists announced that this technique had yielded definitive experimental evidence for the hypothesized Higgs boson. The discovery of the Higgs (named for British physicist Peter Higgs), which gives *most* other Standard Model particles their mass, meant that for the first time, humanity had direct evidence for a fourth category in the Standard Model: scalar bosons. With this, the major predictions of the Standard Model were fully affirmed by experimental data. As I write, the Higgs is the singular scalar boson in the category of observed particles.

And recall, the Standard Model is everything we've ever seen. Maybe it is everything we will ever see. There's a kind of power in being able to name... everything. Here is how physicists use it: my faves, the quarks, get their name from a line in Irish modernist writer James Joyce's *Finnegans Wake*, "Three quarks for

Muster Mark!" Quarks come in six types: up, down, charm, strange, top, and bottom. The top and bottom are also sometimes called truth and beauty, respectively. According to historian Michael Riordan, these names were preferred by some physicists because they were looking for "truth" and "naked beauty." Ultimately the pairing of "top" and "bottom" prevailed. Quark is a departure from the standard particle nomenclature, many of which have an -on at the end, in reference to the electron (from the Greek word for amber, *ἤλεκτρον*, elektron), or diminutive -ino, used in Italian to mean "small."

The electron is part of the lepton family, which also includes the muon, the tau (sometimes tauon), and the known neutrino family[i]: an electron neutrino, a muon neutrino, and a tau neutrino. In the vector boson category, we have the photon, gluon, Z boson, and W boson. The lepton and quark families, along with the W boson, all have antimatter counterparts. The antielectron is better known as a positron, and every quark has an antiquark. These partner particles are completely similar except that they have the opposite charge sign, e.g., the electron is negatively charged and the positron is positively charged. These particle partners are also completely dissimilar in that leptons and quarks, not their antipartners, dominate matter. Why? We have no idea. Answering this question is a major area of research in particle physics.

As exciting as quarks and leptons are, you're more likely to hear about neutrons and protons. I'm completely aware that neutrons and protons (known collectively as nucleons because they appear in all atomic nuclei) have no feelings, and yet, I sometimes feel a little sad for them. They are not elementary particles at all, but rather composites made out of quarks. The neutron is a particle with no charge, and it is made out of an up quark and two down quarks. Protons by contrast are positively charged and are made out of two up quarks and one down quark. The difference in charge comes down to the difference in quark composition. If we use the charge of the electron as our standard for comparison, up quarks have a charge of two-thirds (of an electron charge), and down quarks have a charge of minus one-third. So a little arithmetic (2/3 + 2/3 - 1/3 = 1) shows that a proton, made of two ups and a down, will give us a total charge of +1. The neutron is literally neutral because its quark charge arithmetic is 2/3 - 1/3 - 1/3 = 0. While it's true that neutrons and protons sometimes feel like they are faking it—masquerading as fundamental particles while actually being composite particles—they do reflect the properties of their underlying building blocks. This means that just as there are antiquarks, there are antiprotons. There is even antihydrogen, which has been observed in the lab!

It's worth remembering that we didn't always know that protons and neutrons were made out of quarks. Before we knew about the possibility of quarks, one of the open questions in physics was why the proton and neutron had the charges they did. The quark family, particles first conceptualized by Murray Gell-Mann and George Zweig and then expanded by James Bjorken, Sheldon Glashow, James Iliopoulos, Makoto Kobayashi, Luciano Maiani, and Toshihide Maskawa, were eventually observed as a phenomenon in experimental physics, giving an answer to this question of why. Nucleons and other baryons—the class of particles made of three quarks—have the charge that they do because they are made of quarks that have specific charges.

Anyone who has dealt with a curious toddler or an obstinate teenager knows that the next question is still: why? One definition of a physicist is that a physicist is a person who gets really bugged about a question like this and then spends their life trying to solve it and problems that are related to it. Why do quarks have the charge that they do? We don't know—that's an open question. Want to know why something happens? That's cool, but the universe doesn't really care about our feelings. What's great about physics, and what made it intriguing to me as a child, is that physicists have come up with a really interesting way of gathering information about our universe that leads to a neatly self-contained story about how all of the pieces fit together—even though the universe isn't necessarily easy to understand. What we can say about quarks, therefore, is not *why* their properties are the way they are, but we have developed a complex and beautiful mathematical theory that accurately accounts for all of the properties of quarks.

How? Nuclear physicists had detected the existence of eight kinds of mesons—unstable, composite particles that we now know to be made of one quark and an antiquark—and were trying to understand the underlying structure that produced this phenomenon. An explanation was simultaneously realized by Yuval Ne'eman, who was born in Tel Aviv, Mandatory Palestine, and was a professor at Tel Aviv University in Israel; George Zweig, a Soviet-born, California Institute of Technology (Caltech) PhD who was working at the European Organization for Nuclear Research (CERN); and Murray Gell-Mann, a Manhattan-born physicist who was a professor at Caltech. What this international group realized was that mesons could be explained by organizing them into a model that had new particles in it—quarks. The recognition of quarks as a component of the model was motivated by the exploration of a sophisticated mathematical symmetry.

In physics, a system has a symmetry related to one of its properties if that property doesn't change even if the system is somehow altered. A very simple example of this is rotating a spherical ball: it looks the same even if you alter the ball's circumstances by turning it in your hands. This is rotational symmetry. Symmetries are valuable because they help us make approximations so that it's easier to solve the math problems that arise in physics. Physicists are taught from day one of frosh physics that if you can simplify a problem to something that has some symmetries, you should. In fact we have a running joke that all of physics boils down to "approximate this cow as a sphere." Cows don't have a shape that is easy to work with from the perspective of solving physics equations, but spheres? We know how to calculate with spheres because they are relatively simple geometric objects that display rotational symmetry—they look the same no matter how we turn them around. This symmetry effectively removes a level of complication, a dimension from the equations we might otherwise have to solve, whereas cows only have a left-right symmetry that doesn't simplify things much for us, and even that is an approximation because their left and right sides are probably somewhat different. So, we reduce the cow to a sphere for the purposes of doing physics.

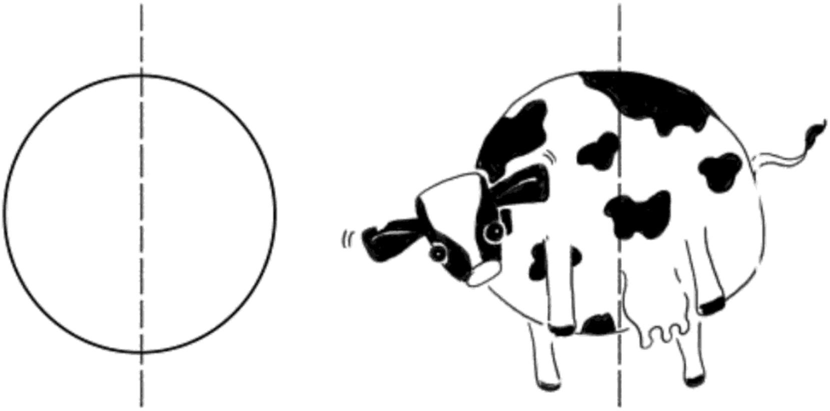

Figure 2. In this figure, you can see that the cow—though it is quite round—looks different if you look at the left half and the right half. By contrast, the sphere looks exactly the same no matter which side you choose.

S. Zainab Williams

In the twentieth century, symmetry was a deeply important guiding principle for particle physics, in part thanks to the work of German mathematician Emmy Noether. Her theorem teaches us that when a system has a symmetry, there is an associated conserved quantity, a property of the system that doesn't change with time even as the system evolves. This rule provided a road map for physicists: where there is a symmetry in the math, look for a conserved quantity. It also suggested that symmetries were mathematically foundational to descriptions in particle physics. Gell-Mann and others were following this rule when they developed what has come to be known as quantum chromodynamics, or QCD for short. Quantum chromodynamics is a colorful name for a theory that uses color as an analogy for physical properties that have nothing to do with color. Unfortunately, QCD came of age in a time when Black people were still using a moniker given to us by white people —“colored”—and to this day, textbooks still sometimes call it “colored physics.” A Black feminist physicist working in the 1960s would never have used this language, which—though it lacks the same social meaning—recalls for me the Third Reich–era phrase “Aryan physics.” But Black people were almost completely excluded from particle physics until after the Civil Rights era, and a Black woman wouldn’t even earn a PhD in any area of physics until the following decade (Willie Hobbs Moore, University of Michigan, 1972), nearly a century after the first Black man earned one (Edward Bouchet, Yale University, 1876).[ii] What I’m saying is, I love the idea of QCD, but the language is a hot mess.

Quantum chromodynamics, like other parts of the Standard Model that are for no good reason whatsoever less interesting to me, is an extraordinary artifice—my favorite in all of particle physics. I love QCD both because it is mathematically rich, like piecing together an elaborate three-dimensional puzzle, and because solving a little problem with it leads to the creation of the dark matter candidate that is at the center of my research. But before I get ahead of myself (you’ll have to wait until Chapter 2), there are non-dark-matter-related reasons to like QCD. For example, each quark and antiquark partner has not just an electrical charge, but also something called a color charge. It turns out that there are three colors: red, blue, and green. Yes, the antiparticles have anticolor properties—they are antired, antigreen, and antiblue. These labels have nothing to do with the colors we are used to seeing with our eyes and everything to do with physicists enjoying naming things for any number of random reasons. For example, the axion, which we will discuss momentarily, was named after a laundry detergent, which took its name from the Greek Orthodox Church liturgy, which has a prayer to the Mother Mary called Ἄξιον ἐστίν or “axion estin.” While the labels used to describe color charge are random, the phenomenon itself has a very specific importance: holding quarks together inside of mesons and baryons.

This property creates new rules that particles have to follow while they are exchanging the gluons that allow quarks to stick together in very particular configurations. It's almost like a game where the goal is to get a colorless particle at the end (and this is where the analogy suggests that not having color is apparently inherently good). There are two ways to achieve this colorlessness. In the case of the three quark baryons (like neutrons and protons), one quark of every color should be present to make the color charge white, or neutral. If you want to make a meson, you need two quarks—but not just any two quarks. One has to be a quark and the other an antiquark, and whatever color the quark is, the antiquark must be the anticolor of that color so that the two colors cancel out, leaving a neutral white charge.

For those reading between the lines for interesting analogies, there's actually nothing titillating to see in the language here. "Color" and "white as neutral" are here not as reflections of how the universe works, but rather how a homogeneous, white scientific community comes up with new names for stuff. Part of science, therefore, involves writing a dominant group's social politics into the building blocks of a universe that exists far beyond and with little reference to our small planet and the apes that are responsible for melting its polar ice caps. The color charge scheme makes about as much sense as naming the three charges chocolate, strawberry, and vanilla. A baryon could represent Neapolitan ice cream, and a meson would be ice cream–neutral. This maybe makes sense intuitively when you realize that mesons are extremely unstable, with lifetimes that are much shorter than a second. There are limits to this analogy at a technical level, I suppose. But what's important here is that color physics seems intuitive to physicists not because it's a great analogy for general audiences but because our educations socialize us into the "color + color + color = white" paradigm. It would be great if I never had to read the phrase "colored degrees of freedom" in a new the Standard Model that makes me stop in my tracks and think, "Wow." I get lost, in the best possible way, in the math—every single time. I will never get bored of picking up a particle physics textbook and starting from page one. At the same time, the history is replete with white men, few white women, few Asian people, few Black people, few Latinx[iii] people (and among those, almost uniformly men), and no Indigenous North American people. No past nonbinary folk are known to the historical record. To this day, the community is still essentially like that. For example, the University of Toronto string theorist A.W. Peet is the only significantly accomplished and well-known nonbinary high-energy physicist (a broad term that includes particle physicists and quantum gravity theorists). I have no love for how my professional community is structured. But it's also the case that when I think about quarks, I experience the kind of loving hope that is best set to Def Jef 's "Black to the Future": "We know where we're goin, because we know where we came from." Maybe, then, I'm not just a hack for colonial science, but more like Princess Shuri from *Black Panther*, giving particle physics a new spin and rhythm. This is not to say that the laws of the universe are not universal—but it may be that what we think we know is incomplete and will not be complete until we are able to think beyond how white men are trained to think in a Western educational setting.

Only time, and a community that does not have extensive barriers to the participation of people from a broad cross section of humanity, will be able to tell how our understanding of physics will change when our understanding of who can be a physicist changes. I am one of the first to confront and, to put it in quantum terms, tunnel through the barrier made out of the belief that it doesn't matter if Black women (people) are excluded or if parts of the universe are described by "colored physics," forever marking this work as "physics developed by and for white thinkers." It is unclear whether I am making it through because I have been assimilated or through the brute force of my own will and imagination.

Barad writes in their essay "No Small Matter: Mushroom

Clouds, Ecologies of Nothingness, and Strange Topologies of SpaceTimeMattering" about the ways that quantum field theory —the calculational tool that undergirds all of particle physics— and the atom bomb "inhabit and help constitute each other." If I see my intellectual life as inhabited and constituted by QFT, as we call it, does that mean I, too, am inhabited and constituted by the atom bomb? I know the answer to this question. My discipline received extensive funding because of the perception that, like the Manhattan Project, particle physics could continue to serve state interests, both technologically and psychologically. As this possibility has diminished, so has our funding. The way I have inhaled particle physics enmeshes me with this historical trajectory. But I am still also one natural conclusion of a Black child dreaming of quarks—not because quarks could serve state interests, but because quarks nourished the soul. The Standard Model? It is how I fell in love for the first time.

Footnotes

i Neutrinos, for some reason, don't get their mass through the Higgs mechanism in the same way that other particles do. More on them in the next chapter!

ii Bouchet was also the first African American to earn a PhD from a university in the United States.

iii To describe people who have origins in Central and South America, in this book, I have chosen to use the term "Latinx" rather than the conventional "Latino" in recognition of calls from nonbinary people and others for language that is non-gendered. I recognize that there is also an emergent term, "Latine," which some argue is a better replacement. My use of Latinx is not intended to actively stake a position on word choice as an outsider to this community discourse, but rather a decision to use a word that is more widely known at this point in time. This is a comprehension decision, rather than a political intervention. Importantly, Latinx people hold a variety of racial identities, including white. Here I use the term expansively, with the understanding that white Latinx people do not experience marginalization to the same extent that Latinx of color do.

TWO

DARK MATTER ISN'T DARK

Some particles are building blocks, and there are others, like the neutrino, that are mostly for the end days. No, no I don't actually mean the Christian apocalypse. I mean that they are literally a common product of decay in the universe. In fact, Wolfgang Pauli first hypothesized neutrinos in 1931 because the numbers for certain radioactive decays weren't adding up, and a good way to explain the missing energy was to propose that an as yet undetected particle was carrying it away. Soon after Pauli proposed this idea, Enrico Fermi developed a theory of radioactive decay that took these new particles into account, and he named them the "neutrino," which in Italian means "little neutral one." Nearly thirty years after neutrinos were initially proposed, they were first observed by Clyde L. Cowan and Frederick Reines in what is known as the Cowan-Reines neutrino experiment at Savannah River Nuclear Reactor in South Carolina. These experiments tested the theory that an antineutrino produced in a nuclear reactor, when interacting with a proton, would react and produce a neutron and positron. The positron, the antimatter of an electron, would then be destroyed through contact with an electron, giving off two high-energy particles of light, gamma rays. The Savannah River site experiments detected these gamma rays and the leftover neutron. The unique combination of two gamma rays and a neutron made clear that an antineutrino had been given off by the reactor, setting off the whole sequence of events.

In addition to being difficult to detect, neutrinos are kind of fabulous. They have no charge, but each type of neutrino has a charged leptonic partner. This means that they come in three flavors: the electron neutrino, the muon neutrino, and the tau neutrino. It took nearly 50 years to figure out that neutrinos have a mass. I was a senior in high school when that revelation first became public. Because their mass is so tiny, they are perpetually what we call "relativistic particles." They are able to move at speeds close to the universal speed limit, the speed of light. This makes them efficient carriers of energy away from, say, a site of nuclear decay. It's this feature that makes neutrinos extremely interesting from the point of view of not just particle physics but also astrophysics. One place neutrinos are made is in stars, and lots of them are made when stars explode—a phenomenon we call a supernova. Because of this, we use neutrinos, along with photons—particles of light—and the ripples in spacetime that we call gravitational waves to look at the universe. We are still unsure of what the neutrinos' masses are or how to explain why they have a mass that is extremely tiny but still bigger than zero. Everything we know about physics encourages us to expect the mass to either be zero or to be something notably bigger. And for a while, because we were unsure about their masses and whether they had any mass, we thought neutrinos were something called dark matter. It is only in the last decade or so that we have become certain that they aren't massive enough, leaving us with a problem. What the heck is dark matter?

Let me start here: dark matter isn't even necessarily real. "Dark matter" as a term was coined in French in 1906 by Henri Poincaré, who called it *matière obscure.* Twenty-two years before, English astronomer Lord Kelvin first proposed in 1884 that "many of our stars, perhaps a great majority of them, may be dark bodies." In the 1920s, Dutch astronomers Jacobus Kapteyn and Jan Oort similarly proposed the presence of something like the matière obscure based on observations of stars in the Milky Way and its galactic neighbors. In 1933, Swiss astrophysicist Fritz Zwicky proposed that there was evidence for what he called (in German) *dunkle Materie*, this time based on observations of clusters of galaxies. More evidence came from American[i] astronomer Horace Babcock in 1939, and by then the name "dark matter" had stuck even if it didn't really make sense because the problem wasn't that it was dark, but rather that it was unseeable, invisible.

This distinction is meaningful when we consider the first truly significant evidence for the existence of matière obscure, which came in the 1960s and 1970s, largely thanks to Vera Rubin's creative use of a new spectrograph developed by Kent Ford. This spectrograph breaks down light into different colors (more on this in Chapters 4 and 5), and Dr. Rubin was the first scientist to realize it could be used to measure galactic star speeds with unprecedented accuracy. The results showed that there was a significant mismatch between how fast stars were rotating around the center of the galaxy (if stars were the only matter in a galaxy) and how fast the stars were actually going. If all of the mass in a galaxy is contained in stars and dust, then we can measure how massive those galaxies are by looking at how much radiation we collect from the stars and dust. There's a nice physics equation that gives us a correlation between the luminosity—the brightness—and the mass. There's also another equation that gives us the relationship between the mass of the galaxy and how fast the stars are orbiting the galaxy's center. This is one of Newton's laws, and we teach it to high school students. But with galaxies, this is also where we run into a problem. The measured mass of all the stars together, based on the orbit speeds, does not match the measured mass of all the stars together based on the brightness measurements. The orbit speeds suggest there should be a lot more mass there.

This suggests, in turn, that there is a lot of missing, invisible matter. There are other possible solutions, like maybe our theory of gravity is wrong (and I'll touch on that later), but for now I will focus on the more popular idea that we need a solution to the missing matter problem because otherwise our two carefully collected types of data are not consistent with each other. Looking at star movements in galaxies was the first way that scientists understood that the missing matter problem was a real, big problem. But it is not the only way, and there are now management (for anyone younger than an early millennial, it's enough to say that "Crystal Pepsi," also marketed as "Pepsi Clear," had a massive marketing campaign—including a hyped Super Bowl ad—that ended in disaster for both Pepsi and one of Van Halen's beloved singles).

Of course, the first question was whether this could be explained using particles in the Standard Model, and for quite a long time, in fact until fairly recently, neutrinos were considered to be strong candidates. Neutrinos are not *entirely* invisible—they do have some kind of interaction with the electromagnetic force and therefore light—but the interaction is very small, making them largely invisible to us. But what we've learned in the last decade about neutrinos proves to us that they definitively cannot make up the majority of the invisible matter we need because they simply aren't massive enough. The neutrino would need to be hundreds or even thousands of times more massive than it is in order for it to be a good explanation for the missing matter problem.

Today, research into dark matter is considered to be "beyond the Standard Model" physics. The expectation is that this invisible matter is a particle we've never observed before. This kind of problem is again a defining one for a physicist: you can get so into it that you commit your life to it. That's not how I ended up becoming an expert on dark matter though. I fell into it because of the research opportunities I found available to me at a moment when I needed to be doing some kind of research and was a little bit lost. The orbit I ended up being captured in first was not what everyone was thinking about at the time, but rather something a little different: the axion.

The axion is still a hypothetical particle, but its conception as an idea is connected to yet another problem with the Standard Model. It turns out the Standard Model is not just missing a good candidate to explain the movements of stars in their galactic orbits; it has other problems too. One is called the strong CP problem, which is that the theoretical formulation of quantum chromodynamics does not break charge-parity (CP) symmetry. CP symmetry is the rule that the laws of physics are the same when a particle and its antiparticle are interchanged (this is charge symmetry) when it is viewed through a looking glass, as a mirror image (this is its parity symmetry). CP symmetry means that if you take a particle and replace it with its antiparticle and swap its left-right orientation, the physics works out the same. This symmetry is actually kind of fun to think about—consider swapping your hands for the antimatter version of your hands and then switching your left hand for your right hand. Under normal circumstances, this would pretty obviously change your life, but at the particle level, this symmetry is sometimes preserved.[ii] The problem with preserving it in quantum chromodynamics, however, is the neutron electric dipole moment. The preserved CP symmetry does things to the neutron that shift it into a particle with new properties, properties that, as far as we can tell, are completely absent. The equations must be shifted so that these tentacles are kept in check by breaking charge-parity symmetry.

Effectively, the magnificent Standard Model over-predicts things. The best patch for addressing this problem in the Standard Model is known as the Peccei-Quinn mechanism because it was developed by Roberto Peccei and Helen Quinn in the 1970s. Peccei and Quinn took a constant parameter in quantum chromodynamics and made it dynamical. Frank Wilczek and Steven Weinberg realized, independently, that this model had a new particle in it. This particle was called the Higglet by some scientists for a while, but now it is known by Wilczek's name for it, the axion.

Peccei and Quinn weren't thinking about dark matter when they developed their idea. But it turns out that the properties of the axion make it a good candidate for the dark matter particle. Unfortunately, we still don't know if the Peccei-Quinn theory is merely an elegant model or a good representation of how the universe actually works. One way to check is by looking for experimental consequences of the model that we can detect. And just a few years after physicists began to explore the properties of the axion, it was given new purpose when it was realized that it had the basic properties that we think dark matter has, based on astronomical observations: potential for lots of the particles to exist and slow moving (and therefore cold). Part of what I like about the axion is this feature: we need it to solve the strong CP problem and by total coincidence, it also satisfies the requirements for a good dark matter candidate. The axion is a good dark matter candidate because we need it anyway.

Axions are also exciting because they behave differently from how we might intuitively expect the missing matter to behave and can display some interesting quantum properties. This is because axions are scalar bosons like the Higgs that I discussed in Chapter 1. Because bosons are willing to hang out together, they can display fantastical behaviors. They are called bosons in honor of Indian mathematical physicist Satyendra Nath Bose, who was one of the earliest contributors to theories of quantum mechanics and collaborated with Albert Einstein on developing the equations that describe particles with whole-number spins. A consequence of these Bose-Einstein statistics, as they are known, is the Bose-Einstein condensate (BEC), where a large number of relatively cold particles or atoms all go into the same low-energy state and proceed to act like one single super atom. Bose-Einstein condensate formation uniquely reflects the quantum mechanical nature of matter, which sometimes behaves as if it is made of billiard ball-like particles and sometimes acts as if it is sloshing like watery waves. In the BEC state, the particles not only act like waves, but the waves add together coherently to create one super wave. This is a purely quantum mechanical phenomenon. In classical non-quantum physics, the particles would act like little unbreakable billiard balls and could never add up together the way they do when they are waves. The quantum BEC phenomenon is extremely difficult to produce in the lab and not expected to happen much in the universe, except maybe in neutron stars.

Well, it wasn't expected to happen much until physicists started thinking about what axions might do if they were the dark matter. In the last two decades, it has become clear that axions are an example of a special class of dark matter that now has a series of names: scalar dark matter, fuzzy dark matter, scalar field dark matter, and wave dark matter. These are all variations on a theme: “scalar” is another word for a boson with spin zero. The Higgs is a scalar, and the fact that we’ve observed it gives us confidence that perhaps other scalar particles exist too. The word “field” arises because when you merge quantum mechanics with Einstein’s special relativity, a mathematical structure called a field is needed to describe particles. A simple example of a scalar field is the temperature of a room: the temperature has a value at every place in the three-dimensional room. If you’re using central air, the temperature is probably about the same everywhere. In the open-concept living and dining room where I am writing, we only use a fireplace in winter, so the temperature changes significantly from the couch, which is near the fireplace, to the dining table, where my feet are currently very cold. A particle is described by a similar mathematical construct, but with a hefty dose of quantum mechanics. Sometimes the field description of a particle becomes particularly meaningful. Bose-Einstein condensate dark matter is one of those times.

The fact that the axion can behave like a BEC means that there may be macroscopic quantum waves floating around in space! How big they are depends on the mass of the axion, and theory doesn’t actually provide us much insight into what the mass should be. We have constraints from experiments that rule out certain values. There are also observational constraints that suggest a preferred value. In my research, I have found that at this preferred mass scale, axion BECs the size of an asteroid could have formed in the early universe. Do they survive into the present day? This is a problem that I am actively working on.

There are other axion mass scales that create very different astrophysical outcomes and tie into other areas of theoretical physics too. I’ve mentioned that we have been unable to fit gravity into the Standard Model. One possible way to address this is well known as string theory, which proposes to merge gravity and quantum field theory, the calculational structure behind particle physics. In exchange we have to accept that spacetime, which we traditionally think is made of three space dimensions plus one time dimension, may have at least ten spatial dimensions. String theory is incredibly elegant, and I like to joke with my friends that when you have so many dimensions to play in, anything can happen. It turns out that a lot does. For example, string theory has many by-products that include phenomena called moduli, and these moduli have very similar properties to the axion. In fact, the quantum chromodynamics (QCD) axion, as the Peccei-Quinn axion is known, is part of a larger class of particles with similar features that appear in models of quantum gravity—theories that unify gravity and quantum physics.

We are no longer dealing with just one kind of axion—QCD—but now dealing with a whole class, known as axion-like particles, or ALPs for short. With ALPs, the macroscopic quantum wave would be the size of a dark matter halo, which is the dark matter that envelopes a galaxy. The Milky Way has its own halo, and it's much bigger than the visible stars that we can see on the edge of our galaxy. If the halo is made of ALPs, the smaller structures, like the tens of galaxies that are satellites of the Milky Way, will have a distinct formation history compared to what may have happened in other dark matter models. Exactly *how* different is something I'm currently working to figure out.

And yes, there are other dark matter models. The axion-like particle is distinct from another class of proposed solutions to the missing-matter problem, weakly interacting massive particles, also known as WIMPs. Rather than being a specific particle candidate, WIMPs are a group that generally share the set of properties of interacting with each other via the weak force (one of the three forces described in the Standard Model) and being massive (often thought to be around 100 times the mass of the proton). Lots of candidates for WIMPs exist, and all of them require structure beyond the artifice of the Standard Model. Many of them fall under the umbrella of supersymmetry, an extension to the Standard Model that as yet has no experimental evidence for it, despite intense efforts by experimentalists at CERN's Large Hadron Collider.

When it comes to WIMP dark matter, we don't expect the evidence of phenomena that were similarly significant to finally proving the existence of something behaving like an invisible matter (the 2011 prize for dark energy). Another woman, Jocelyn Bell Burnell, watched as her male PhD adviser was awarded the prize for her observation of the first neutron star. Meanwhile, in my discussions about theory advances, Helen Quinn and Chien-Shiung Wu are the only women who make an appearance.

Today, much of my research focuses on dark matter and neutron stars, with a particular interest in axions as a dark matter candidate and neutron stars as axion laboratories. In general terms, the gendered history of these objects and my work on them is largely a coincidence. But maybe not entirely. As a graduate student who was struggling with self-confidence and her place in the theoretical physics community, I once spent a day with Dr. Rubin. When I met her, almost the first thing she did was ask me how I thought the dark matter problem could be solved. No one had ever asked my opinion about a major problem in physics before, not in grad school, and definitely not in college. Physicists are rarely interested in the opinions of undergraduates, who are often not deemed advanced enough to make a useful contribution to the conversation. In research, the convention is that one hands an undergraduate a problem to work on and hopes they will be creative in their efforts to apply known techniques to tiny fractions of difficult problems. In some sense, I understand this. And yet some of the most interesting research I have done as a scientist was a collaboration with undergraduates who dug in and went beyond their coursework, asking questions and finding interesting threads in the work. Importantly, physics is about precisely that, which means that we should probably be asking our undergraduates big-picture questions, not for the sake of getting solutions out of them, but to encourage them to take ownership over those questions.

But what if you never give yourself permission to think about a problem? This is what happened initially between me and dark matter. I understood it as a problem for observational astrophysics, not particle theory, and as a result, I wasn't particularly interested in it for myself. I thought it was an