The Elephant in the Universe

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OUR HUNDRED-YEAR SEARCH FOR DARK MATTER

Govert Schilling

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The Blind Men and the Elephant

A Hindoo Fable

It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind.

The First approached the Elephant,
And happening to fall
Against his broad and sturdy side,
At once began to bawl:
"God bless me!—but the Elephant
Is very like a wall!"

The Second, feeling of the tusk,
Cried: "Ho!—what have we here
So very round and smooth and sharp?
To me 't is mighty clear
This wonder of an Elephant
Is very like a spear!"

The Third approached the animal,
And happening to take
The squirming trunk within his hands,
Thus boldly up and spake:
"I see," quoth he, "the Elephant
Is very like a snake!"

The Fourth reached out his eager hand,
And felt about the knee.
"What most this wondrous beast is like
Is mighty plain," quoth he;
"'T is clear enough the Elephant
Is very like a tree!"

The Fifth, who chanced to touch the ear,
Said: “E’en the blindest man
Can tell what this resembles most;
Deny the fact who can,
This marvel of an Elephant
Is very like a fan!”

The Sixth no sooner had begun
About the beast to grope,
Then, seizing on the swinging tail
That fell within his scope,
“I see,” quoth he, “the Elephant
Is very like a rope!”

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right,
And all were in the wrong!

So, oft in theologic wars
The disputants, I ween,
Rail on in utter ignorance
Of what each other mean,
And prate about an Elephant
Not one of them has seen!

John Godfrey Saxe, 1872

Foreword

AVI LOEB

The term "dark matter" is used to represent most of the matter in the universe—five times more prevalent than ordinary matter, like the atoms that make up stars and planets. But, as the name suggests, we cannot see dark matter. We infer its existence only indirectly through its gravitational influence on visible matter. In this way, dark matter encapsulates our ignorance.

Like all good mysteries, the puzzle of dark matter is enduring. It has intrigued scientists for a hundred years. Observations and scientific theories suggest that dark matter could be made of any number of hypothetical building blocks: weakly interacting massive particles, so-called axions, even atoms that do not interact with ordinary matter or light. Today there is a scientific consensus that dark matter likely came out of the fiery soup during the origins of the universe, an ocean of invisible particles with initially small random motions. Although scientists have not detected any of these invisible particles yet, they have measured the imprint of the fluctuations. Today those dark matter fluctuations are evident in the slightly varied brightness of the cosmic microwave background, the relic radiation left over from the big bang.

Lord Kelvin was the first to offer a dynamical estimate of what we now think of as dark matter. In a talk given in 1884, Kelvin theorized that there might be dark bodies in the Milky Way. Almost fifty years and many ideas later, Swiss-American astronomer Fritz Zwicky estimated that there is more mass in galaxy clusters than is visually observable. In the 1970s evidence for invisible particles was revealed through the pathbreaking work of Vera Rubin, Kent Ford, and Kenneth Freeman. They showed that the dynamics of gas and stars in galaxies imply the existence of invisible mass in a halo that extends well outside the inner region, where ordinary matter concentrates. And in 1983 Moti Milgrom proposed a theory of modified Newtonian dynamics to explain the missing-mass problem. In this alternative hypothesis of gravity, Milgrom postulated that Newton's laws do not apply to galaxies.

Like most explorations in science, historical theories of dark matter found supporters and critics. Milgrom's simple prescription for modified dynamics at low accelerations accounts for the nearly flat rotation curves in many galaxy halos extremely well, even after four decades of scrutiny. But the theory does not adequately account for Zwicky's observed properties of galaxy clusters. Another possibility is that dark matter is strongly self-interacting and avoids galactic cores. And the hypotheses continue.

Throughout this book, Govert Schilling leads us on a captivating tour through the theories of dark matter and efforts to observe it, from early times to the present day. We'll travel with him to astronomical observatories on the ground and in space and to particle detectors in underground caves and tunnels. As we circle the globe, we meet the scientists, the protagonists of the story, who have spent their careers searching for a solution to the puzzle. It is a wide-ranging cast of characters. There are towering figures in the field of dark matter research, like Jim Peebles and Jerry Ostriker. There are younger scientists, true believers, skeptics, and heretics. Through their stories, we garner an extraordinary view into the past, present, and future of one of the deepest enigmas in science.

As *The Elephant in the Universe* shows, the search for dark matter is a work in progress. Hence the abundance of scientific interpretations. But one day all of the pieces of the puzzle will fall into place. It is with Schilling's stellar guidance that we join leading scientists in their crusade to understand this unknown gravitating matter, and, along the way, delight in the mysteries of our universe.

Introduction

In 1995 astronomers announced that they had developed sensitive spectrometers that made it possible to precisely measure the velocities of stars. Within a few years, I reckoned, these tools would be used to discover extrasolar planets: if the spectrometer picked up tiny, periodic perturbations in the velocity of a star, then there might be a massive planet nearby, the gravity of which was disrupting the parent star's movement through space. I decided to start researching a new book on the hunt for exoplanets, in the hope that the breakthrough find could be described in the closing chapter.

In October of that same year, when Michel Mayor and Didier Queloz announced their discovery of 51 Pegasi b—the first confirmed planet beyond our solar system orbiting a Sun-like star—I realized I had to hurry. For most of 1996, I worked on hardly anything else. My (Dutch) book, *Tweeling aarde (Twin Earth),* was published in early 1997. It was one of the first books to cover the initial round of extrasolar-planet discoveries.

Something similar happened about twenty years later. In early 2015 I began researching a book on gravitational waves—tiny undulations of the very fabric of the universe, caused by energetic events like colliding black holes. Albert Einstein's general theory of relativity predicted gravitational waves decades ago, and scientists have been hunting for them ever since. I knew as I started my research that advanced gravitational wave detectors would be going online in a matter of months—new versions of the Laser Interferometer Gravitational-Wave Observatory in the United States and the Virgo detector in Italy. It looked like a discovery couldn't be more than a few years away.

In fact, the first direct observation of gravitational waves came in September 2015 and was announced to the world in February of the following year. Again I put everything aside to complete the book as soon as possible. *Ripples in Spacetime* was published in the summer of 2017.

So when, in early 2018, I started seriously researching a new book on dark matter, I half-jokingly told the astrophysicists and particle physicists I was interviewing that I expected a revolutionary development in the field any day now. Wouldn't it be great if my book were the first to report on the long-awaited solution to the riddle of dark matter? The first to lay out what this mysterious stuff, said to constitute the balance of the cosmos, actually is?

Unfortunately, it didn't happen. So here's the spoiler: when you reach the last page of this book, you still won't know what most of the material universe is made of. But neither do scientists. Despite decades of speculation, searching, studies, and simulations, dark matter remains one of the biggest enigmas of modern science. Still, after reading this book, you *will* have learned a lot about the miraculous universe we live in, and about the ways in which astronomers and physicists have teased out its secrets.

Dark matter challenges our imagination. Like some invisible glue, it is what holds the universe together and what makes it tick. Without it, galaxies would fall apart, galaxy clusters would dissolve, and space would have expanded into oblivion long ago. Dark matter is the most important stuff out there, yet we've only found out about it in recent decades, and no one has a clue as to its true nature.

Well, at least we've learned what it's not, thanks to the work of hundreds of dedicated scientists. Dark matter is not an ocean of ultra-dim dwarf stars. It is not an all-pervading veil of murky gas in intergalactic space. Dark matter is not a population of black holes—at least not the "regular" kind that astronomers are slowly starting to explore. Dark matter isn't even composed of the atoms and molecules that we are familiar with. It's something weird and exotic altogether.

And it has shaped the universe we live in. Dark matter provided the scaffolding for the growth of cosmic structure. It enabled the formation of galaxy clusters, galaxies, stars, planets, and eventually people. However, despite the numerous disciplines and scientists that are involved in studying the problem, we don't seem to be able to really solve it. There have been hints and allegations. Circumstantial evidence and wishful thinking. But so far, not a single convincing detection. No hint of dark matter's true identity.

The story of the search for dark matter goes back to the 1930s, although the mystery wasn't generally acknowledged until some fifty years ago, when astronomers started to wonder about the high rotational velocities of the outer parts of spiral galaxies like our own Milky Way. Before long, particle physicists got involved, as it became evident that the puzzle couldn't be solved without invoking a completely new form of matter. And because of its pivotal role in the evolution of the universe, this new, dark matter also turned into a hot topic in cosmology, the study of the universe at the largest possible scales. Dark matter is a genuinely multidisciplinary area of research that has kept observers, theoreticians, experimentalists, and computer model builders busy for decades.

With so many people working on the problem over such a long time, it's outright impossible to do everyone justice in a book like this. After all, *The Elephant in the Universe* is not a technical book, nor does it pretend to be the definitive history of the field. Instead, this book provides a broad view of dark matter research in all its bewildering variety. Personal stories of many key players give a taste of the ingenuity, perseverance, and—sometimes—stubbornness of scientists who have devoted their professional lives to solving nature's biggest mysteries. I'll take you, the reader, along to remote astronomical observatories and underground laboratories. We'll attend scientific conferences and talk with Nobel laureates and postdoc researchers alike. Unfortunately, due to the COVID-19 pandemic, not all of my planned trips could be realized, and quite a number of interviews had to be conducted on the phone or via Zoom.

Our journey covers a wide range of dark matter–related topics. Although most of the twenty-five chapters could be read as standalone stories, I've arranged them in an order that presents the scope of the mystery and shows how that mystery has evolved. To set the stage, the first chapter introduces physicist James Peebles, who has been called the "father" of the popular cold dark matter (CDM) model and who was the corecipient of the 2019 Nobel Prize in Physics for his contributions to theoretical cosmology. Next, in chapter 2, a visit to the underground Gran Sasso laboratory in Italy gives a preliminary taste of the experimental approach to the dark matter riddle. Dark matter isn't the exclusive province of computer simulations and conference papers. At this very moment, dozens of scientists all over the world are putting theory to the test in hopes of solving this puzzle.

After whetting your appetite by means of this introductory brush with theory and experiment, we travel a century back in time in chapter 3, to learn about the first indications that something was amiss in our understanding of the material contents of the universe. Much later, in the 1970s, physicists realized that galaxies like our own Milky Way cannot be stable without huge, more-or-less spherical halos of dark matter (chapter 4). Pioneers like astronomer Vera Rubin started to realize that the high spin rates of galaxies can only be explained if they contain much more than meets the eye, as described in chapter 5.

Today Rubin's name adorns a brand-new telescope under construction. When completed, it will be one of the most powerful on Earth, an instrument central to scientists' attempts to map the three-dimensional distribution of galaxies in space. That project is an important dimension of dark matter research and the subject of chapter 6. Then, in chapter 7, we delve into the origin of the elements, only to discover why dark matter cannot consist of ordinary atoms and molecules. The decisive role of radio astronomy in proving that dark matter really exists is the topic of chapter 8. This concludes the first part of the book, which is largely focused on astronomical research.

Part II opens with two chapters discussing the growing conviction, in the second half of the 1970s, that the mysterious stuff must be composed of relatively slow-moving ("cold") elementary particles. Such particles fit remarkably well in the theory of supersymmetry—a promising candidate for the long-sought Theory of Everything. Thus dark matter started to play an important role in particle physics, too.

Chapter 11 details computer simulations of the evolution of the large-scale structure of the universe, which seemed to support a candidate for the contents of dark matter: weakly interacting massive particles, or WIMPs. But just as the WIMP hypothesis was emerging, some scientists began to doubt that dark matter is real. Their theory of modified Newtonian dynamics (MOND), discussed in chapter 12, claims that our understanding of gravity needs revision—dark matter hunters may be chasing a chimera after all.

In chapters 13 and 14, we encounter the powerful observational technique of gravitational lensing—the minute deflection of light by the gravity of massive objects. Gravitational lensing was recognized for its potential to rebut the MOND theory and to help scientists find an alternative dark matter candidate known as massive compact halo objects or MACHOs. Alas, the hunt for MACHOs came up all but empty. Instead, another mystery revealed itself in the late 1990s: dark energy. Scientists realized that empty space was expanding at an accelerating rate—a direct result of dark energy. That discovery, and what it might imply for the overall composition of the universe, are the topics of chapters 15 and 16.

Dark energy and the cold dark matter theory have been integrated into a single cosmological model known as lambda-CDM, where the Greek letter lambda (Λ) denotes dark energy. Studies of the cosmic microwave background (sometimes called "the afterglow of creation") provide strong supporting evidence for the model. Moreover, as described in chapter 17, the relic radiation can be compared to the current large-scale structure of the universe to provide a detailed view of cosmic evolution in which dark matter plays an unmistakable role. Even though we still don't know what dark matter is, we've come to realize that it is a key ingredient of cosmology.

Part III concerns current and future searches for dark matter, as well as some of the challenges facing today's cosmologists. In chapters 18 and 19, you'll read about high-tech experiments that seek to detect dark matter particles directly, using ultra-sensitive instruments installed in deep caves and tunnels, which shield the instruments from cosmic rays that would otherwise disturb the measurements. Surprisingly, cosmic rays themselves may carry telltale fingerprints of decaying dark matter particles—the topic of chapter 20.

Chapters 21 and 22 describe a number of worrisome issues that have lately arisen with respect to the lambda-CDM model. As yet, no one knows how serious these problems are, but theorists are already exploring a range of alternative ideas and hypotheses, some of which are presented in chapters 23 and 24. The closing chapter looks ahead, but it is impossible to predict which of the future experiments and observatories will finally solve the century-old mystery of dark matter. Let's just hope it doesn't take another hundred years.

As a science journalist specializing in everything beyond the Earth's atmosphere, I have probably focused a bit more strongly on astronomy than on particle physics, although I've tried to achieve a good balance between the two. I also put more emphasis on past developments, well-established ideas, and current experiments than on new, speculative theories; unconfirmed results; and possible future experiments. If these novelties are here to stay, you will undoubtedly read about them in a future book.

The dark matter hunt continues, but, though it is unfinished, it has already brought us a deeper understanding of a wide range of astronomical and physical phenomena, from fast-spinning galaxies, gravitational lensing, and the large-scale structure of the universe to the birth of atomic nuclei in the big bang and telltale patterns in the afterglow of creation. The search has also spawned other promising theories, fueling speculations about supersymmetry and as-yet-undiscovered denizens of the particle zoo. While searching for the true identity of the bulk of the universe, scientists have unlocked some of nature's most closely held secrets and revealed the stunning complexity of the world we are an integral part of.

PART I

Ear

I

Matter, but Not as We Know It

Phillip James Edwin Peebles, the Albert Einstein professor emeritus of science at Princeton University, fellow of the American Physical Society and the Royal Society, 2019 Nobel laureate in physics, and godfather of the theory of cold dark matter, slowly stands up from his desk and walks toward a bookshelf on the opposite wall, where he picks up two empty plastic bottles.[1]

He blows air over the opening of the larger one. A low, trembling sound fills the room. Next, he puts the smaller bottle to his lips. Another sound, at a much higher pitch. "It's the same principle," Peebles says, with a characteristically meek smile on his face. "Every size has its own favored frequency, and vice versa."

Now wait a minute. Something that simple doesn't earn you a Nobel Prize, right?

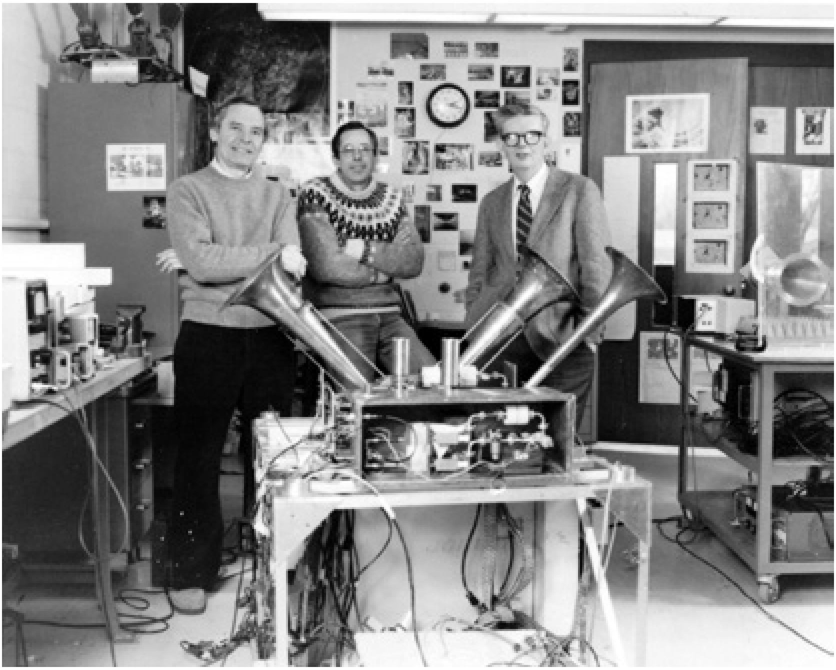
Well, it does if you successfully apply it to sound waves in the newborn universe. If you help prove that galaxies can't be stable without loads of mysterious dark matter. And if you then lay the basis for our current standard model of cosmology.

Thus, at 5 a.m. on Tuesday, October 8, 2019, Peebles got the magic phone call from the Swedish Academy of Sciences. He shared the prize with two others but received half of the prize money—totaling some $910,000—"for theoretical discoveries in physical cosmology." "Good God," his wife Alison said when she heard the news. Then Peebles made the daily one-mile walk from his home to his office on the second floor of Jadwin Hall, his eighty-four-year-old head full of jumbled thoughts.

You know, Jim Peebles had never imagined that he would become a cosmologist. Born in 1935 in the Canadian city of Saint Boniface, now part of metropolitan Winnipeg, little Jimmy was a tinkerer—a would-be Gyro Gearloose who studied the pages of *Mechanics Illustrated,* built electrical contraptions, experimented with gun powder, and fell in love with steam locomotives. Oh yes, he'd go out when the northern lights would perform their silent dance in the Manitoba winter sky, and sure, he knew how to find the Pole Star. But astronomy never really captured his tech-savvy mind. When he first learned about cosmology as a graduate student, he found it "exceedingly dull, and ad hoc, and unbelievable," as he once told astronomer Martin Harwit.[2]

That slowly changed after he arrived at Princeton in the fall of 1958. Peebles was a PhD student in the research group of the brilliant physicist Robert Dicke. On Friday evenings, Dicke organized seminars where students, postdocs, and professors freely discussed every scientific topic that piqued their interest. Intimidated at first by other people's grasp of quantum physics or general relativity, Peebles came to cherish these informal meetings, and not only for the occasional beer drinking afterwards. Dicke's preoccupation with cosmology turned out to be contagious.

In 1962 Peebles completed his thesis on the question of whether the strength of the electromagnetic force varies over time. He remained at Princeton as a postdoc, collaborating with Dicke and two other postdocs, David Wilkinson and Peter Roll. In a washed-out 1960s photograph that he showed during his Nobel lecture, Peebles looks tall and slim, with dark, straight hair, spectacles, and an Ice-



David Wilkinson (left), James Peebles (center), and Robert Dicke (right), in the early 1960s, with the receiver they built to study the cosmic microwave background.

landic sweater. There was a lot of distance between graduate school and the black-tie affair in Stockholm.

Peebles's career as a physical cosmologist was launched on a sweltering day in the summer of 1964. In the stuffy attic of the Palmer Physical Laboratory at Princeton, Dicke unfolded his ambitious plans to search for the radiation leftover from the newborn universe—a primordial conflagration millions of degrees hotter than any attic. Scientists expected that radiation from this long-ago event was out there, if only it could be found. Wilkinson and Roll were charged with building the equipment necessary to detect the radiation. "So Jim," Dicke said, "why don't you delve into the theory behind all this?"

Peebles worked out how the hot plasma of the early expanding universe—a mix of electrically charged particles—would have interacted with the energetic radiation to form a dense, viscous fluid, sloshing and vibrating with low-frequency sound waves like a primeval broth. Then, some 380,000 years after the big bang, when temperatures had dropped enough for neutral atoms to form, matter and radiation became "decoupled": no longer did the properties of one command the behavior of the other. And while the radiation could now freely propagate throughout the universe—cooling down to become the faint cosmic background glow that Dicke was after—the matter was left behind with a pattern of over- and underdensities: regions in which the density was just a tiny bit higher or lower than average, with dimensions determined by the frequencies of the original sound waves.

Size relates to frequency, and vice versa, as Peebles playfully demonstrated with his plastic bottles turned musical instruments. The same principle applies to the universe at large, producing that telltale pattern, which physicists call baryon acoustic oscillations. Over time, matter in overdense regions would further condense into galaxies. This is the reason that galaxies exhibit a nonrandom distribution in three-dimensional space: they tend to show up where the early acoustic waves left the densest deposits of matter. In other words, the current large-scale structure of the universe is set by events that took place shortly after the big bang.

It's complicated stuff, and you may forget it for now—we'll get back to baryon acoustic oscillations in chapter 17. Suffice it to say, around his thirtieth birthday, Jim Peebles developed a knack for thinking the grandest possible thoughts—maybe not about life, but certainly about the universe and everything. You don't need to be forty-two for that.

Peebles wasn't even distressed by the fact that radio engineers Arno Penzias and Robert Wilson beat the Princeton group in detecting the cosmic background radiation. From their perch at Bell Laboratories in nearby Holmdel, New Jersey, Penzias and Wilson made the discovery in 1964, just a few months after Dicke convened his team. "Well, boys, I think we've been scooped," a disappointed Dicke told them after he got the phone call about the discovery. But Peebles remembers having felt excited. The discovery meant that he and his colleagues were not engaged in mere speculation—there actually was something out there to be studied.

Peebles had caught the cosmology bug, and he has had it ever since. Soon enough he was lecturing on a topic that once had seemed exceedingly dull and unbelievable. His book *Physical Cosmology* was published in the fall of 1971, a year before he became a full professor.[3] The first edition sits prominently on the bookshelf next to his desk, close to an Albert Einstein action figure.

Physical cosmology. For centuries—no, for millennia—the origin and evolution of the universe as a whole had been treated as something metaphysical. A universe resting on the backs of elephants and giant turtles, a divine act of creation in the not-too-distant past. But finally, the mythological mists began to clear; the sacred stories made way for scientific scrutiny and physical investigation. Cosmology became something you could touch, take apart, understand, marvel at. Even fall in love with—like a steam locomotive.

Fast-forward half a century and Nobel Laureate Phillip James Edwin Peebles, his tall body casually clad in blue jeans and a moss-green sweater, bends over his computer monitor, takes off his glasses to discern the tiny characters on the screen, searches through archived scientific papers, loses himself in historical detail. So much has happened in the past five decades. So many breakthrough discoveries, so many dead-ends. So many riddles! But most of all, the gradual realization that our universe, our very existence, is governed by a mysterious substance. By enigmatic stuff that, for lack of a better understanding, goes by the name of dark matter. To paraphrase *Star Trek,* "It's matter, Jim, but not as we know it."

Yes, there had been early hints, back in the 1930s. But it wasn't until the 1970s and early 1980s that dark matter burst onto the scene, like a surprise protagonist who doesn't appear until the third act and then dramatically changes the plot of the play. There are more things in heaven and Earth, Horatio, than are dreamt of in your philosophy.

The details will have to wait (we still have many pages ahead of us), but there were numerous findings that only made sense in a universe filled with dark matter. Peebles's own research on the clustered distribution of galaxies in space, carried out before astronomers were able to create reliable three-dimensional maps, was suggestive. His theoretical work, together with Princeton colleague Jeremiah Ostriker, seemed to indicate that the stability of disk galaxies was impossible unless they are surrounded by massive halos of dark matter. Not much later, Vera Rubin and Kent Ford of the Carnegie Institution of Washington became the first to convincingly show (or were they?) that the outer parts of galaxies rotate much faster than they would in the absence of dark matter.

And there were ever-more-detailed observations of the cosmic microwave background radiation, the remnant radiation from the newborn universe, revealing that it was as smooth as a baby's skin. It was this unexpected result that led Peebles, in 1982, to propose his cold dark matter model. Here's the problem. Either the hot plasma of the early universe was too smoothly distributed, or the current large-scale structure of the cosmos is too lumpy. You can't have your cake and eat it, too: the feeble force of gravity, acting in an ever-expanding universe, never gets you from the smooth there and then to the lumpy here and now.

Unless.

Unless dark matter is something really weird. A new type of particle, responsive to gravity but not to other fundamental forces of nature like electromagnetism or the strong nuclear force. Not coupled to the early universe's hot radiation bath at all. Moving slowly enough—"cold" enough, in particle physics parlance—to start clustering into what would become an invisible scaffolding, well before the cosmic background radiation was released. A cosmic cobweb of unfamiliar stuff that subsequently pulled in old-fashioned ordinary atoms, which went on to form the luminous galaxies and clusters that we see today. Cold dark matter.

Theoretical discoveries in physical cosmology—that's what half of the 2019 Nobel Prize in Physics was awarded for. Sure enough, in the four decades since Peebles proposed cold dark matter, the theory became hot and illuminating, extremely productive, and an integral part of what is now known as the concordance model of cosmology. (Another key ingredient of this model is dark energy, which is no less mysterious than dark matter and will be discussed in chapter 16.) But Peebles is not the person to brag about it. He feels he has every reason to be modest.

First of all, he says, theoretical discoveries rank second after "real" discoveries. The other half of the 2019 physics Nobel went to astronomers Michel Mayor and Didier Queloz, the pair who in 1995 found the first planet beyond our solar system orbiting a Sun-like star. Now that's a discovery. Or what about the Higgs particle, found in 2012? Gravitational waves, 2015. Those were singular events in which scientists confirmed what was otherwise just (extremely well-informed) speculation. The theory of cold dark matter is nothing like that.

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