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At the Edge of Time

Nature shows us only the tail of the lion. But there is no doubt in my mind that the lion belongs with it even if he cannot reveal himself to the eye all at once.

—ALBERT EINSTEIN

SOME 13.8 BILLION YEARS AGO, our universe experienced its first moments. Almost everything about this earliest period of time remains a mystery to us. We don't know what forms of matter existed, or what physical laws they obeyed. All we know for sure is that our newborn universe had little in common with anything that exists in our world today.

Only a fraction of an instant later—10^{-43} seconds or so—gravity may have started to behave a lot like the force that we know and love. In contrast, the other known forces of nature—electromagnetism and the strong and weak nuclear forces—likely appeared very different from the way they do today.

Then things got really weird. Sometime in the first 10^{-32} seconds or so, our universe began to expand even more rapidly—wildly more rapidly—than it had been before. This expansion was so fast as to appear virtually instantaneous, and it left our universe utterly transformed. During this era, known as cosmic inflation, our universe grew in volume by an incredible factor of about 10^{75} within a span of only 10^{-32} seconds. This expansion carried every piece of matter away from every other at speeds far greater than the speed of light. By the time that inflation was over, every particle was left in isolation, surrounded by a vast expanse of empty space extending in every direction. And then—only a fraction of a fraction of an instant later—space was once again filled with matter and energy. Our universe got a new start and a second beginning.

After a trillionth of a second, all four of the known forces were in place, and behaving much as they do in our world today. And although the temperature and density of our universe were both dropping rapidly during this era, they remained mind-bogglingly high—all of space was at a temperature of 10^{15} degrees. Exotic particles like Higgs bosons and top quarks were as common as electrons and photons. Every last corner of space teemed with a dense plasma of quarks and gluons, alongside many other forms of matter and energy.

After expanding for another millionth of a second, our universe had cooled down enough to enable quarks and gluons to bind together, forming the first protons and neutrons. Within a few minutes, many of those protons and neutrons had fused together into the first atomic nuclei. During this era, our entire universe resembled the core of a modern star. But things did not remain that way for long. As space further expanded, the temperature continued to fall, leading to dramatic changes from minute to minute, and then from hour to hour and day to day. After a few hundred thousand years, our universe had cooled to a mere few thousand degrees. It was around this time that electrons began to bind to nuclei, forming the first complete atoms.

Slowly but steadily, clumps of matter began to collapse under the influence of gravity, which in turn led to the formation of stars and galaxies. We estimate that the first stars appeared in our universe about 200 million years after the Big Bang. These early stars were much larger and shorter lived than those found today. Only now are telescopes powerful enough to produce images of these stars about to come into use. Our Sun and its Solar System are relative latecomers to our universe, forming about 9.2 billion years after the Big Bang. Today, at the age of 13.8 billion years, our universe continues to expand, cool, and evolve. Its past contained a vast and diverse range of eras and transformations. Its far future is sure to usher in new epochs, both expected and otherwise.

If you've ever watched a documentary, listened to a lecture, or read a book about the Big Bang, there is a good chance that you've been presented with a timeline similar to the one described over the past few pages. Over most of this cosmic history, we have good reasons to be confident that the events and eras it describes actually took place. We have directly observed the formation of stars and galaxies, and we have measured the light released during the formation of the first atoms with remarkable detail and precision. We have determined the rate at which our universe has expanded over the past several billion years and identified the abundances of the various nuclear elements that were forged in the heat of the Big Bang. Taken together, this body of empirical evidence makes it clear that our universe has, in fact, evolved very much as our calculations had predicted—at least over the majority of its history.

But as it turns out, cosmic timelines are ordered not only by the progress of events, but also in terms of our direct knowledge. The events that lie in the most distant past, and closest to the Big Bang, are also generally those that we know the least about.

For the period of time ranging from a few hundred thousand years after the Big Bang to the present, we have a rich array of observations and measurements on which to rely, and this collection of data leaves us confident that we understand this portion of our universe's history quite well. Along with the vast majority of other cosmologists, I would be shocked if this part of the chronology turned out to be substantively wrong—there are just too many different and powerful lines of evidence that support our current understanding of this series of events. Finding out that we got this very wrong would be like finding out that there had never been an American Civil War, or that Christopher Columbus actually landed in Wales in the twelfth century and not in the West Indies in 1492. While it's good to keep an open mind about what you might have gotten wrong, in some cases the evidence is just too strong to reasonably contemplate being entirely mistaken.

As we go back farther in cosmic history, however, our confidence begins to decline. Between the first few seconds and a few hundred thousand years after the Big Bang, we have fairly strong support for what's described in the standard timeline. Observations and measurements tell us that the rate of expansion and the quantities of matter and energy in our universe cannot have been very different from those our calculations predicted. That said, it is still plausible that important and unknown cosmological events may have taken place during this period. The information we have about our universe's first hundreds of thousands of years is significant, but it is not exhaustive.

But reaching even farther back in time—into the first seconds and fractions of a second after the Big Bang—we transition from having incomplete information to having essentially no direct observations on which we can confidently rely. This era remains hidden from our view, buried beneath as-yet-impenetrable layers of energy, distance, and time. Our understanding of this period of cosmic history is, in many respects, little more than an informed guess, based on inference and extrapolation. Yet it is clear that these first moments are the key to many of our most urgent and enduring cosmic mysteries. Understanding this era is essential to understanding our universe.

With this book, I offer you a glimpse of the Big Bang—our universe's first seconds and fractions of a second. During this earliest of epochs, matter and energy took on very different forms from those found in our universe today and may have been subject to forces that we are yet to discover. Key events or transitions that we don't yet know about may very well have taken place. Matter likely interacted in ways that it no longer does, and space and time themselves may have behaved differently than they do in the world that we know. Almost everything that we know about physics could have been different during this first instant of time.

By any reasonable standard, the science of cosmology has had a spectacular century. One hundred years ago, we knew nothing about our universe's distant past and certainly nothing about its origin. But building upon Einstein's vision of space and time, astronomers discovered that our universe is expanding, and by the late 1960s it was clear that it had emerged over billions of years from the hot, dense state we call the Big Bang. For the first time, human beings had begun to understand how their universe began.

Since then, cosmologists have steadily pieced together the history of our universe, from these first moments to the present.

The past several decades have witnessed a diverse array of high-precision measurements that have enabled us to reconstruct our universe's past in new ways and with unprecedented detail. By measuring the expansion rate of our universe, the patterns of light released in the formation of the first atoms, the distributions in space of galaxies and galaxy clusters, and the abundances of various chemical species, we were able to confirm that our universe had expanded and evolved in just the way that the Big Bang theory had long predicted. Our universe looked more comprehensible than ever before.

And yet, not all is understood. Despite our considerable efforts, there remain essential facets of our universe that we simply do not know how to explain—especially pertaining to the first seconds and fractions of a second that followed the Big Bang. When it comes to the origin and youth of our universe, mysteries continue to abound.

The most famous, perhaps, is that of dark matter. Astronomers and cosmologists have determined how much matter there is in our universe to a very high degree of precision, and it is much more than exists in the form of atoms. After decades of measurement and debate, we are now confident that most of the matter in our universe does not consist of atoms or of any other known substances, but of something else that does not appreciably radiate, reflect, or absorb light. Over the past few decades, physicists have been engaged in an ambitious experimental program seeking to reveal what this substance is and how it was formed in the Big Bang. But despite initial optimism, we remain ignorant of dark matter and its nature. The experiments have performed just as designed, but have seen nothing. Dark matter has turned out to be far more elusive than we had once imagined.

Even the origin of "ordinary" matter harbors stubborn secrets of its own. Although protons, neutrons, and electrons, and the atoms they constitute, can be easily created through well-understood processes, such processes also create an equal quantity of more exotic particles, known as antimatter. Whenever particles of matter and antimatter are brought into contact with one another, both are annihilated. So why, then, does our universe contain so much matter and so little antimatter? In fact, why is there any matter at all? If matter and antimatter had been created in equal amounts in the heat of the Big Bang—as our current understanding of physics would lead us to expect—then almost all of it would have been destroyed long ago, leaving our universe essentially devoid of atoms. Yet there are atoms all around us. Somehow, more matter than antimatter must have been created in the first fraction of a second of our universe's history. We don't know how or when this came to pass, or what mechanism was responsible. But somehow, something about the conditions of the early universe made it possible for the seeds of atoms—and all of chemistry, including life—to survive the heat of the Big Bang.

Going back even farther in time, we come to what is perhaps the single most intriguing of our cosmic mysteries. In order to make sense of our universe as we observe it, cosmologists have been forced to conclude that space, during its earliest moments, must have undergone a brief period of hyperfast expansion. Although this epoch of inflation lasted only a little longer than a millionth of a billionth of a billionth of a billionth of a second, it left our universe utterly transformed. In many ways, one can think of the end of inflation as the true beginning of the universe that we live in. Despite identifying many compelling reasons to think that inflation really took place, cosmologists still know and understand very little about this early, key era of our cosmic history.

In the 1990s, cosmologists set out on an ambitious program to measure the more recent expansion history of our universe, allowing us to determine the geometry and ultimate fate of our world. For the first time, it was thought, we would be able to learn whether our universe will continue to expand forever, or instead eventually reverse and collapse in upon itself. These measurements were ultimately successful, but they revealed to us something that very few scientists expected: our universe is not only expanding, but is expanding at an accelerating rate. To explain this fact, we have been forced to conclude that our universe contains vast amounts of what is known as dark energy, filling all of space and driving it apart. But our best efforts to understand this phenomenon have come up almost entirely empty-handed. We simply do not understand what dark energy is, or why it exists in our universe.

Each of these puzzles and problems is deeply connected to the first moments that followed the Big Bang. Whatever the dark matter consists of, it was almost certainly formed in the first fraction of a second after the Big Bang. Similarly, the simple fact that atoms exist in our world reveals that the earliest moments of our universe's history must have included events and interactions that we still know nothing about. Cosmic inflation also took place during these earliest of times, and its possible connection to the existence of dark energy raises many questions of its own. In these and other ways, our universe's greatest mysteries are firmly tied to its first moments.

In recent years, scientists have constructed new observatories and carried out new experiments in the hope of pulling back the shroud that has up until now hidden our universe's first moments from our view. But despite having conducted a range of impressive observations and measurements, we are in many ways only more perplexed than we were two decades ago. Instead of neatly resolving what had once seemed like a few loose ends, our increasingly precise cosmological measurements have only intensified the aforementioned puzzles, and even brought some new ones to light. As of late, it seems that the more we study our universe, the less we understand it.

Perhaps more than any other experimental or observational program, particle physicists and cosmologists alike had put a great deal of hope and confidence in particle accelerators such as the famed Large Hadron Collider in Geneva (LHC for short). These incredible machines accelerate beams of particles—typically protons or electrons—to the highest speeds possible, then collide these beams into one another. When protons collide at the LHC, many different kinds of matter can be created, including all of the known particle species, from electrons and photons to Higgs bosons and top quarks. In the early universe, interactions of these kinds filled all of space with a zoo of subatomic particles, all of which were constantly interacting with each other and being repeatedly created and destroyed. By studying these processes at the LHC, we have learned not only how matter and energy behave in our world today, but also how it behaved a minute, a second, a millionth of a second, and even a trillionth of a second after the Big Bang.

Many of us imagined that the new and spectacular LHC would lead us to a qualitatively superior understanding of our universe and its origin, enabling us to resolve many of our most puzzling questions. But since the start of its operations in 2010, the results from the LHC have in many ways left us only more confused. With the exception of the Higgs boson, this machine has not yet discovered any of the new particles or other phenomena that we anticipated. The problems cosmologists faced prior to the LHC remain firmly in place. Many of the solutions we had once imagined would resolve these problems are, in fact, not solutions at all.

For example, by remaining stubbornly elusive, dark matter has become only more perplexing as the experiments carried out over the past years and decades have ruled out many of our most promising hypotheses for what this substance—or substances—might consist of. In light of these results, cosmologists have been forced to give up their favorite theories and to consider radically new ideas about what the dark matter might be and how it might have formed in the first instants after the Big Bang.

It is from this perspective that I sometimes find myself contemplating the state of cosmology. We have in our possession a beautiful and remarkably successful theory. But it is also the case that we have recently struggled, if not outright failed, to explain many of our universe's most striking features. From the origin of atoms and the mystery of cosmic inflation, to the natures of dark matter and dark energy, it is clear that we are missing key elements in the way we understand our universe and its beginning.

We are at a time of reckoning. When it comes to understanding our universe and its origin, incredible progress has been made—there is no question about that. But despite this progress, it is undeniable that we are facing many formidable questions and vexing problems. Perhaps these issues are just a series of loose ends, which we will nicely tie up in the years ahead with new experiments and observations. But more and more often these days, I find myself wondering whether these problems might represent more than loose ends. Perhaps they are the symptoms of a deeper problem with the lens through which we see our world.

With this book, I will bring you on a tour of our universe's first moments. We will begin with Einstein's revolutionary insights into the nature of space and time and see how these ideas led to the discovery that our universe had a beginning in the hot, dense state we now call the Big Bang. I will do my best to explain how we learned what we know about our universe's early history, using tools ranging from telescopes to particle accelerators. From there, we will turn our attention to the puzzles, mysteries, and open questions that litter our universe's first fractions of a second. How did our universe come to contain so much matter and so little antimatter? How did the dark matter come to be formed? Our universe seems to have undergone a brief period of hyperfast expansion, but how and why? And is this connected to the fact that our universe is now once again expanding at an accelerating rate?

If you are looking for a story with an ending that wraps up nicely, you may have chosen the wrong book. This book is as much about open and unanswered questions as it is about anything we currently understand. But today's mystery is tomorrow's discovery. Powered by new data, observations, and ideas, we are poised to shed light on many of our most perplexing questions. With these new advances, we will see deeper and more clearly into the past than ever before—closer to the edge of time.

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