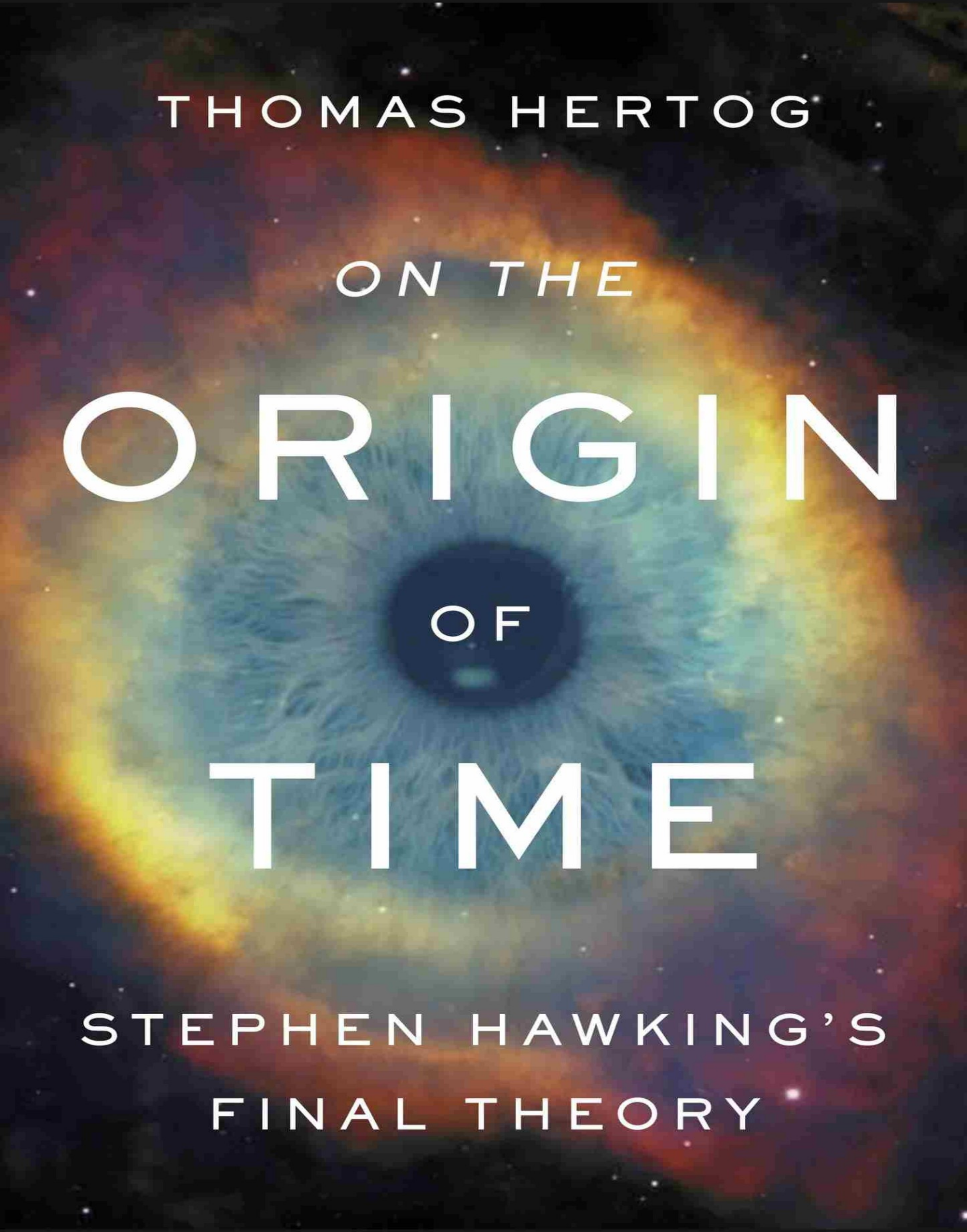
THOMAS HERTOG
ON THE
ORIGIN
OF
TIME
STEPHEN HAWKING'S
FINAL THEORY

ON THE ORIGIN OF TIME

THOMAS HERTOG

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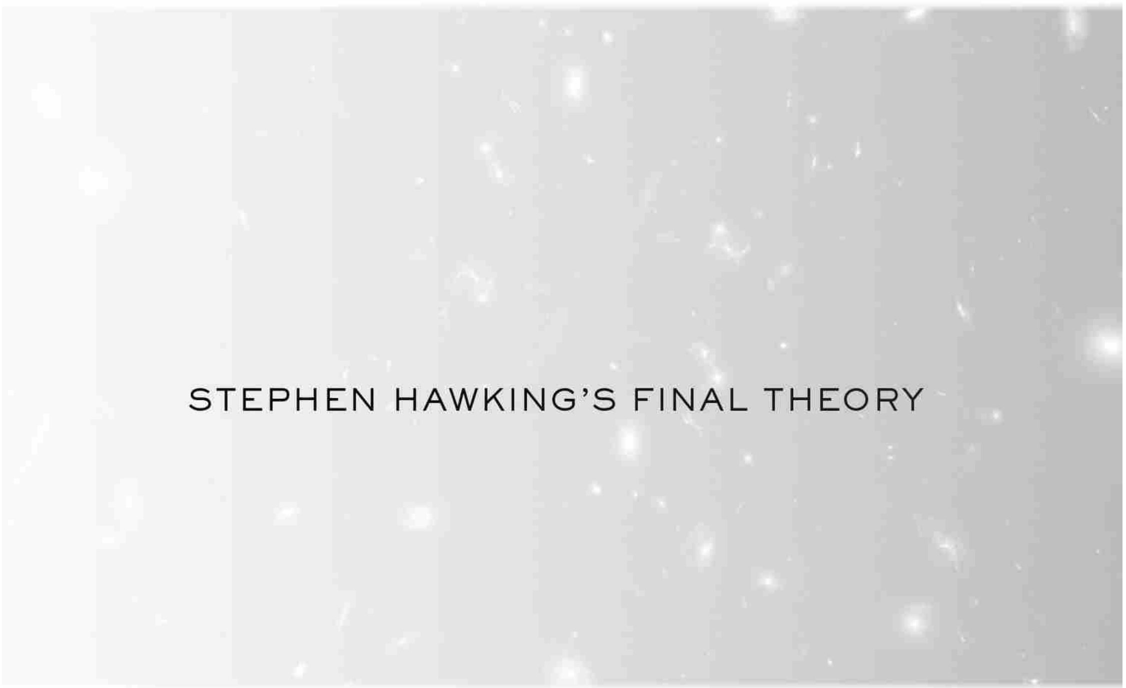

STEPHEN HAWKING'S FINAL THEORY

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Contents

La question de l'origine cache l'origine de la question.

The question of the origin hides the origin of the question.

—François Jacqmin

PREFACE

THE DOOR TO STEPHEN HAWKING'S office was olive green, and, though it was right off of the bustling common room, Stephen liked it to be slightly open. I knocked and entered, feeling as though I'd been transported into a timeless world of contemplation.

I found Stephen sitting quietly behind his desk, facing the entrance, with his head, too heavy to hold straight, leaning against a headrest on his wheelchair. He slowly raised his eyes and greeted me with a welcoming smile, as if he had been expecting me all along. His nurse offered me a seat next to him and I glanced at the computer on his desk. A screen saver scrolled perpetually across the screen: *To boldly go where Star Trek fears to tread*.

It was mid-June of 1998, and we were deep in the labyrinth of DAMTP, Cambridge's renowned Department of Applied Mathematics and Theoretical Physics. DAMTP was housed in a creaking Victorian building on the Old Press site on the banks of the river Cam, and for nearly three decades, this had been Stephen's base camp, the nexus of his scientific endeavors. It was here that he, wheelchair bound and unable to lift even a finger, had passionately strived to bend the cosmos to his will.

Stephen's colleague Neil Turok had told me the master wanted to see me. It was Turok's animated course, part of DAMTP's famous advanced math degree, that had recently kindled my interest in cosmology. Stephen had got wind, it seemed, that my exam results were excellent and wanted to see if I'd make a good doctoral candidate under his wing.

Stephen's dusty old office stuffed with books and scientific papers felt cozy to me. It had high ceilings and a large window that, I would later find out, he kept open even on freezing cold winter days. On the wall next to the doorway was a picture of Marilyn Monroe; below it a framed and signed photograph of Hawking playing poker with Einstein and Newton on the holodeck of the *Enterprise*. Two blackboards filled with mathematical symbols occupied the wall to our right. One featured a recent calculation to do with Neil and Stephen's latest theory of the origin of the universe but the drawings and formulas on the second one appeared to date from the early 1980s. Could they be his last handwritten scrawls?

FIGURE 1. *This blackboard hung in Stephen Hawking's office at the University of Cambridge as a memento from a conference on supergravity he convened in June 1980. Filled with doodles, drawings, and equations, it is as much a work of art as a glimpse into the abstract universe of theoretical physicists. Hawking is drawn in the center near the bottom, with his back toward us.*[1] *(See color version,* *plate 10* *in the insert.)*

A soft clicking broke the silence. Stephen had started talking. Having lost his natural voice in a tracheotomy following a bout of pneumonia more than a decade before, he now communicated through a disembodied computer voice. This was a slow, laborious process.

Mustering the last bit of force in his atrophied muscles, he exerted a feeble pressure on a clicking device, much like a computer mouse, which had been placed carefully in the palm of his right hand. The screen fitted to an arm of his wheelchair lit up, establishing a virtual lifeline between his mind and the outside world.

Stephen used a computer program called Equalizer that had a built-in database of words and a speech synthesizer. He appeared to navigate Equalizer's electronic dictionary instinctively, pressing the clicker rhythmically as if it were dancing to his brain waves. A menu on the screen displayed a number of frequently used words and the letters of the alphabet. The program's database included theoretical physics jargon, and the program anticipated his next word choice, displaying five options in the bottom row of the menu. Unfortunately, word selection was based on an elementary search algorithm, which failed to distinguish between general conversation and theoretical physics, with sometimes hilarious results, from cosmic microwave risotto to extra sex dimensions.

Andrei claims appeared on the screen below the menu. I waited, in hushed expectation, fervently hoping that I would understand whatever followed. A minute or two later Stephen directed the cursor to the icon "Speak" in the upper left corner of the screen and said, in his electronic voice, *Andrei claims there are infinitely many universes. This is outrageous.*

There we had it—Stephen's opening shot.

Andrei was the celebrated American-Russian cosmologist Andrei Linde, one of the founding fathers of the cosmological theory of inflation, proposed in the early 1980s. A refinement of the big bang theory, it postulates that the universe began with a brief burst of superfast expansion—inflation. Linde later concocted an extravagant extension of his theory, in which inflation produced not one but many universes.

I used to think of the universe as all there is. But how much is that? In Linde's scheme, what we have been calling "the universe" would be only a sliver of a vastly larger "multiverse." He envisaged the cosmos as an enormous swelling expanse of countless different universes lying far beyond one another's horizons, like islands in an ever-inflating ocean.

Cosmologists were in for a wild ride. Stephen, the most adventurous of them all, had taken note.

Why worry about other universes? I asked.

Stephen's answer was enigmatic. *Because the universe we observe appears designed,* he said. Then, as he continued clicking, *Why is the universe the way it is? Why are we here?*

None of my physics teachers had ever spoken about physics and cosmology in such metaphysical terms.

"Isn't that a philosophical matter?" I tried.

"Philosophy is dead," Stephen said, eyes twinkling, ready to engage. I wasn't quite ready, but I couldn't help thinking that for someone who had renounced philosophy, Stephen used it liberally—and creatively—in his work.

—

There was a touch of magic about Stephen. With barely a flicker of motion, he breathed so much life into our conversation. He conveyed a magnetism and charisma that I had rarely seen. His broad smile and expressive face, simultaneously warm and playful, made even his robotic voice sound rich with personality and drew me deeper into the cosmic mysteries he pondered.

Like the Oracle of Delphi, he had mastered the art of packing a lot into a few words. The result was a unique way of thinking and talking about physics and, as I shall describe, a new physics altogether. But that concision also meant that even a minor clicking glitch such as a single missing word—"not," for instance—could, and often did, lead to frustration and confusion. That afternoon, however, I didn't mind being immersed in confusion, and I was thankful that Stephen's browsing of Equalizer gave me time to consider my responses.

I knew that when Stephen said that the universe appears designed, he was referring to the extraordinary observation that it emerged from its violent birth spectacularly well configured to sustain life—if billions of years in the future. This convenient fact has, in one way or another, bedeviled thinkers for centuries because it feels like a major fix. It's almost as if the geneses of life and the cosmos are entwined with each other, that the cosmos knew all along that one day it would be our home. What are we to make of this mysterious appearance of intent? It is one of the central questions humans ask about the universe and Stephen felt deeply that cosmological theory had something to say about it. The prospect—or hope—of being able to crack the riddle of cosmic design drove much of his work indeed.

This itself was exceptional. Most physicists prefer to steer away from such difficult, seemingly philosophical matters. Or they believe that one day it will turn out that the universe's delicately crafted architecture follows from an elegant mathematical principle at the core of the theory of everything. If this were the case, the universe's apparent design would seem like a lucky accident, a serendipitous consequence of objective and impersonal laws of nature.

But neither Stephen nor Andrei was your usual physicist. Reluctant to bet on the beauty of abstract mathematics, they felt that the uncanny fine-tuning of the universe that engendered life tapped into a deep problem at the roots of physics. Not content to merely apply the laws of nature, they sought a more expansive view of physics that included questioning the very origin of the laws. This led them to ponder the big bang, for it was presumably at the universe's birth that its law-like design was laid out. And it was on its birth that Stephen and Andrei strongly disagreed.

Andrei envisaged the cosmos as a gigantic ballooning space in which many big bangs continually produce new universes, each with its own physical properties, as if the latter were little more than our local cosmic weather. We should not be surprised to find ourselves in a rare universe suited to life, he argued, for we obviously couldn't exist in one of the many universes where life is impossible. Any impression of a grand design behind it all would be an illusion in Linde's multiverse, stemming from our limited view of the cosmos.

Stephen argued that Linde's grand cosmic extension, from universe to multiverse, was a metaphysical fantasy that didn't explain anything, although I sensed that he couldn't quite prove it. Nonetheless, I found it intriguing and exciting that the world's most eminent cosmologists, while strongly disagreeing, were debating these foundational questions with such strong conviction.

Doesn't Linde invoke the anthropic principle, the condition that we exist, to pick out a biofriendly universe in the multiverse? I ventured.

Stephen turned his eyes, looked at me, and slightly moved his mouth, leaving me puzzled. Later I would learn that this meant he disagreed. When he realized I hadn't been introduced to the sort of nonverbal layer of communication practiced within his inner circle, he turned his eyes back to the screen and set out to construct a whole new sentence. Two sentences, in fact.

The anthropic principle is a counsel of despair, he wrote, my bemusement mounting in sync with his clicking. *It is a negation of our hopes of understanding the underlying order of the universe, on the basis of science.*

Well, this was surprising. Having read *A Brief History of Time,* I was well aware that the early Hawking had frequently flirted with the anthropic principle as part of the explanation for the universe. A cosmologist at heart, Stephen had appreciated early on the surprising resonances between the large-scale physical properties of the universe and the existence of life as such. As far back as the early 1970s he had advanced an anthropic argument —wrongly, it turned out—as an explanation for why the expansion of the universe proceeded at the same rate in all three directions of space.[2] Had he changed his mind on the merits of anthropic reasoning in cosmology?

While Stephen took a medical pit stop to clear his trachea, I looked around his office. Copies of *A Brief History of Time* translated into exotic languages were piled high on a shelf that stretched across the length of the wall on our left. I wondered what else was in there that he no longer subscribed to. Next to these brief histories I noticed a row of his former graduate students' PhD dissertations. Starting in the early 1970s Stephen had established a celebrated school of thought at Cambridge, which had always included a small circle of rotating graduate students and postdoctoral scholars.

The titles of their dissertations touched on some of the most profound questions physics had grappled with in the late twentieth century. From the 1980s I saw Brian Whitt's *Gravity: A Quantum Theory?* and also Raymond Laflamme's *Time and Quantum Cosmology*. Fay Dowker's *Spacetime Wormholes and the Constants of Nature* took me to the early 1990s when Stephen and his colleagues thought wormholes—geometric bridges across space—influenced the properties of elementary particles. (Stephen's friend Kip Thorne would later put wormholes to use in the movie *Interstellar,* to get Cooper back to the solar system.) To Fay's right stood *Problems in M Theory* by Marika Taylor, Stephen's most recent academic offspring. Marika had worked under Stephen in the midst of the second string theory revolution when the theory morphed into a much larger web known as M-theory, and Stephen finally began to warm up to the idea.

All the way to the left on the shelf stood two copies of an older book with a thick green cover, *Properties of Expanding Universes*. This was Stephen's own PhD dissertation, going back to the mid-1960s, to the time when the large Holmdel Horn Antenna at Bell Telephone Labs picked up the first echoes from the hot big bang in the form of faint microwave radiation. Stephen proved in his thesis that if Einstein's theory of gravity was right, then the mere existence of these echoes meant time must have had a beginning. Now how did that square with Andrei's multiverse we were just talking about?

Immediately to the right of Stephen's, I saw Gary Gibbons's *Gravitational Radiation and Gravitational Collapse*. Gibbons was Stephen's first PhD student, in the early 1970s, during a time when the American physicist Joe Weber claimed to hear frequent bursts of gravitational waves coming from the center of the Milky Way. The intensity of gravitational radiation he reported was so high that it seemed the galaxy was losing mass at a rate that could not be sustained for eons—if this were true, there would soon be no galaxy left. Captivated by this paradox, Stephen and Gary toyed with the idea of constructing their own gravitational-wave detector in the basement of DAMTP. This was a narrow escape; rumors of gravitational waves turned out to be false and it would be another forty years before LIGO, the Laser Interferometer Gravitational-Wave Observatory, would finally succeed in detecting these elusive rippling vibrations.

Stephen usually took on one new graduate student every year to work with him on one of his high-risk high-gain projects, to do with either black holes—collapsed stars hidden behind a horizon—or with the big bang. He tried to alternate, assigning one student to work on black holes and the next one to work on the big bang so that at any time his circle of graduate students covered both strands of his research. He did this because black holes and the big bang were like yin and yang in his thinking—many of Stephen's key insights into the big bang can be traced to ideas he first developed in the context of black holes.

Both inside black holes and at the big bang, the macroworld of gravity truly merges with the microworld of atoms and particles. Under these extreme conditions, Einstein's relativity theory of gravity and quantum theory had better work together. Except they don't, and this is widely viewed as one of the biggest unsolved problems in physics. For example, both theories embody a radically different view of causality and determinism. Whereas Einstein's theory adheres to the old determinism of Newton and Laplace, quantum theory contains a fundamental element of uncertainty and randomness and retains only a reduced notion of determinism, about half of what Laplace thought it was. Over the years, Stephen's gravity group and its diaspora had done more than any research group in the world to expose the deep conceptual questions that arise when one tries to marry the seemingly contradictory principles of these two physical theories into a single harmonious framework.

Meanwhile Stephen was "sorted out," as his nurse put it, and had started clicking again. (A second pause in our conversation that afternoon involved watching a preview of an episode of *The Simpsons* in which Stephen appeared and that he had been asked to vet.)

I want you to work with me on a quantum theory of the big bang…

I had apparently arrived in a big bang year.

…to sort out the multiverse. He looked up at me with a broad smile, eyes twinkling again. This was it. Not by philosophizing or by an appeal to the anthropic principle but by weaving quantum theory deeper into cosmology were we to get a grip on the multiverse. The way he had put it made it sound like an ordinary homework problem, and though I could discern from his face that we had already started working, I had no clue in which direction spaceship Hawking was heading.

*I am dying…*appeared on the screen.

I froze. I glanced at his nurse who was reading quietly in a corner of the office. I looked back at Stephen, who seemed fine, as far as I could tell, and continued clicking away.

…for…a…cup…of…tea.

This was Britain and it was four P.M.

—

UNIVERSE OR MULTIVERSE? *Design(er) or not?* This was the fateful question that would keep us occupied for twenty years. One homework problem led to another and soon Stephen and I found ourselves in the midst of what would become one of the most heated debates in theoretical physics in the first part of the twenty-first century. Nearly everyone had an opinion on the multiverse, though no one quite fathomed what to make of it. What started out as a doctoral project under his supervision evolved into a wonderfully intense collaboration ending only with Stephen's passing on March 14, 2018.

At stake in our work wasn't just the nature of the big bang, that enigma at the heart of existence, but also the deeper meaning of the laws of nature as such. What is it, ultimately, that cosmology finds out about the world? How do *we* fit into it? Such considerations take physics far out of its comfort zone. Yet this was exactly where Stephen liked to venture into and where his unmatched intuition, forged through decades of profound cosmological thinking, proved prophetic.

Like so many scholars before him, the early Hawking regarded the fundamental laws of physics as immutable, timeless truths. “If we do discover a complete theory…we would truly know the mind of God,” he wrote in *A Brief History of Time.* More than ten years on, however, during our first meeting—and with Linde’s multiverse breathing down our neck—I sensed he felt a crack in this position. Does physics really provide godlike foundations operating at the big bang origin of time? Do we need such foundations?

We were soon to discover that the Platonic pendulum in theoretical physics had swung too far indeed. When we trace the universe back to its earliest moments, we encounter a deeper level of evolution, at which the physical laws themselves change and evolve in a sort of meta-evolution. The rules of physics transmute in the primeval universe, in a process of random variation and selection akin to Darwinian evolution, with particle species, forces, and, we will argue, even time fading away into the big bang. Stronger still, Stephen and I came to see the big bang not only as the beginning of time but also as the origin of physical laws. At the heart of our cosmogony lies a new physical theory of the origin, which, we came to realize, at the same time encapsulates the origin of theory.

Working with Stephen was a voyage not only to the fringes of space and time but also deep into his mind—into what made Stephen Stephen. Our shared quest meant we grew close. He was a true seeker. Being around him, one could not fail to be influenced by his determination, and by his epistemic optimism that we could tackle these mystifying cosmic questions. Stephen made us feel like we were writing our own creation story, which, in a sense, we did.

And physics was fun! With Stephen you never quite knew when work ended and the party began. His insatiable passion to understand was matched only by his zest for life and his spirit for adventure. In April 2007, a few months after his sixty-fifth birthday, he took part in a zero-gravity flight aboard a specially equipped Boeing 727, which he saw as a prelude to a trip to space, all while his doctors panicked about him crossing the Channel on the Eurostar to come visit me in Belgium.

Meanwhile, with his natural voice permanently silenced and too weak now to move even a finger, he nevertheless became the biggest science communicator of our age. Inspired by a deep sense that we are part of a grand scheme that is written across the sky, waiting, as it were, for us to unravel, he shared his joy for discovery with a worldwide audience. Midway through our collaboration he wrote a book, *The Grand Design,* which reflects our confusion at the time. In it Stephen clings to the anthropic principle, the multiverse, and the idea of a final theory of everything, down to its rivalry with a God-created universe. But *The Grand Design* also contains the first traces of the new cosmological paradigm that would crystallize in our work a few years later. Shortly before his death, Stephen told me that it was time for a new book. This is that book. In the next few chapters I describe our journey back to and into the big bang, and how this journey ultimately led Hawking to discard the multiverse and replace it with a startling new perspective on the origin of time, profoundly Darwinian in spirit and nature and offering a radically revised understanding of the grand cosmic design.

We would often be joined in our endeavors by the American physicist Jim Hartle, Stephen's longtime collaborator with whom in the early 1980s he had pioneered the subject of quantum cosmology. Over the years the pair acquired a real knack for seeing the universe through a quantum lens. Even the language between them embodied their quantum thinking, as if they were wired differently. For example, by "the universe" cosmologists usually mean the stars and the galaxies and the vast space around us. When Jim or Stephen said "the universe," they meant the abstract quantum universe, awash in uncertainty, with all its possible histories living in some sort of superposition. But it was precisely their thoroughly quantum outlook that eventually made a genuine Darwinian revolution possible in cosmology. The later Hawking took quantum theory seriously—very seriously indeed—and decided to run with it, employing it to rethink the universe on the very largest scales. Quantum cosmology would be *the* field of research where Stephen remained at the forefront till the end of his life.

When a while into our collaboration he lost the remaining strength in his hand to press the clicker he used to converse, Stephen switched to an infrared sensor mounted on his glasses that he activated by slightly twitching his cheek. But eventually this too became difficult. Communication slowed, from a few words per minute to minutes per word, before basically grinding to a halt, even as demand for his voice skyrocketed.[3] Here was the world's most celebrated apostle of science, unable to talk. But Stephen wouldn't give up. With our intellectual connection deepened through years of close collaboration we moved increasingly beyond verbal communication. Bypassing Equalizer, sensors, and clickers, I would position myself in front of him, clearly in his field of vision, and probe his mind by firing questions. Stephen's eyes would light up brightly when my arguments resonated with his intuition. We would then build on this connection, navigating and exploiting the common language and mutual understanding we had forged over the years. It is out of these "conversations" that, slowly but steadily, Stephen's final theory of the universe was born.

There are critical junctures in science when metaphysical considerations come to the fore, whether we like it or not. At such forks in the road we learn something profound, not only about the workings of nature but also about the conditions that make our practice of science possible and worthy, and about the worldview our discoveries might nurture. Physics' quest to grasp what makes the universe just right for life has brought us to one such critical fork. For it is, at its core, a humanist question, much bigger than science. This is about *our* origins. Stephen's final theory of the universe contains the kernel of a uniquely powerful reflection on what it can mean to be human in this biofriendly cosmos, as stewards of planet Earth. For this reason alone it may ultimately prove to be his greatest scientific legacy.

AUTHOR'S NOTE

My numerous conversations with Stephen over a span of twenty years are faithfully and truly woven into the narrative. Quotes from Stephen that have also appeared in published form are cited in the endnotes.

CHAPTER 1

A PARADOX

Es könnte sich eine seltsame Analogie ergeben, daß das Okular auch des riesigsten Fernrohrs nicht größer sein darf, als unser Auge.

A curious correlation may emerge in that the eyepiece of even the biggest telescope cannot be larger than the human eye.

—LUDWIG WITTGENSTEIN, *Vermischte Bemerkungen*

THE LATE 1990S WERE THE culmination of a golden decade of discovery in cosmology. Long regarded as a realm of unrestrained speculation, cosmology—the science that dares to study the origin, evolution, and fate of the universe as a whole—was finally coming of age. Scientists all over the world were buzzing with excitement about spectacular observations from sophisticated satellites and Earth-based instruments that were transforming our picture of the universe beyond recognition. It was as if the universe was speaking to us. This posed quite a reality check for theoreticians, who were told to rein in their speculation and flesh out the predictions of their models.

In cosmology we discover the past. Cosmologists are time travelers, and telescopes their time machines. When we look into deep space we look back into deep time, because the light from distant stars and galaxies has traveled millions or even billions of years to reach us. Already in 1927 the

Belgian priest-astronomer Georges Lemaître predicted that space, when considered over such long periods of time, expands. But it wasn't until the 1990s that advanced telescope technology made it possible to trace the universe's history of expansion.

This history held some surprises. For example, in 1998 astronomers discovered that the stretching of space had begun to speed up around five billion years ago, even though all known forms of matter attract and should therefore slow down the expansion. Since then, physicists have wondered whether this weird cosmic acceleration is driven by Einstein's cosmological constant, an invisible ether-like dark energy that causes gravity to repel rather than to attract. One astronomer quipped that the universe looks like Los Angeles: one-third substance and two-thirds energy.

Obviously, if the universe is expanding now, it must have been more compressed in the past. If you run cosmic history backward—as a mathematical exercise, of course—you find that all matter would once have been very densely packed together and also very hot, since matter heats up and radiates when it is squeezed together. This primeval state is known as the *hot big bang*. Astronomical observations since the golden 1990s have pinned down the age of the universe—the time elapsed since the big bang—to 13.8 billion years, give or take 20 million.

—

CURIOUS TO LEARN more about the universe's birth, the European Space Agency (ESA) launched a satellite in May 2009 in a bid to complete the most detailed and ambitious scanning of the night sky ever undertaken. The target was an intriguing pattern of flickers in the heat radiation left over from the big bang. Having traveled through the expanding cosmos for 13.8 billion years, the heat from the universe's birth reaching us today is cold: 2.725 K, or about –270 degrees Celsius. Radiation at this temperature lies mainly in the microwave band of the electromagnetic spectrum, so the remnant heat is known as the *cosmic microwave background* radiation, or CMB radiation.

ESA's efforts to capture the ancient heat culminated in 2013 when a curious speckled image resembling a pointillist painting decorated the front pages of the world's newspapers. This image is reproduced in figure 2, which shows a projection of the entire sky, compiled in exquisite detail from millions of pixels representing the temperature of the relic CMB radiation in different directions in space. Such detailed observations of the CMB radiation provide a snapshot of what the universe was like a mere 380,000 years after the big bang, when it had cooled to a few thousand degrees. This was cold enough to liberate the primeval radiation, which has traveled unhindered through the cosmos ever since.

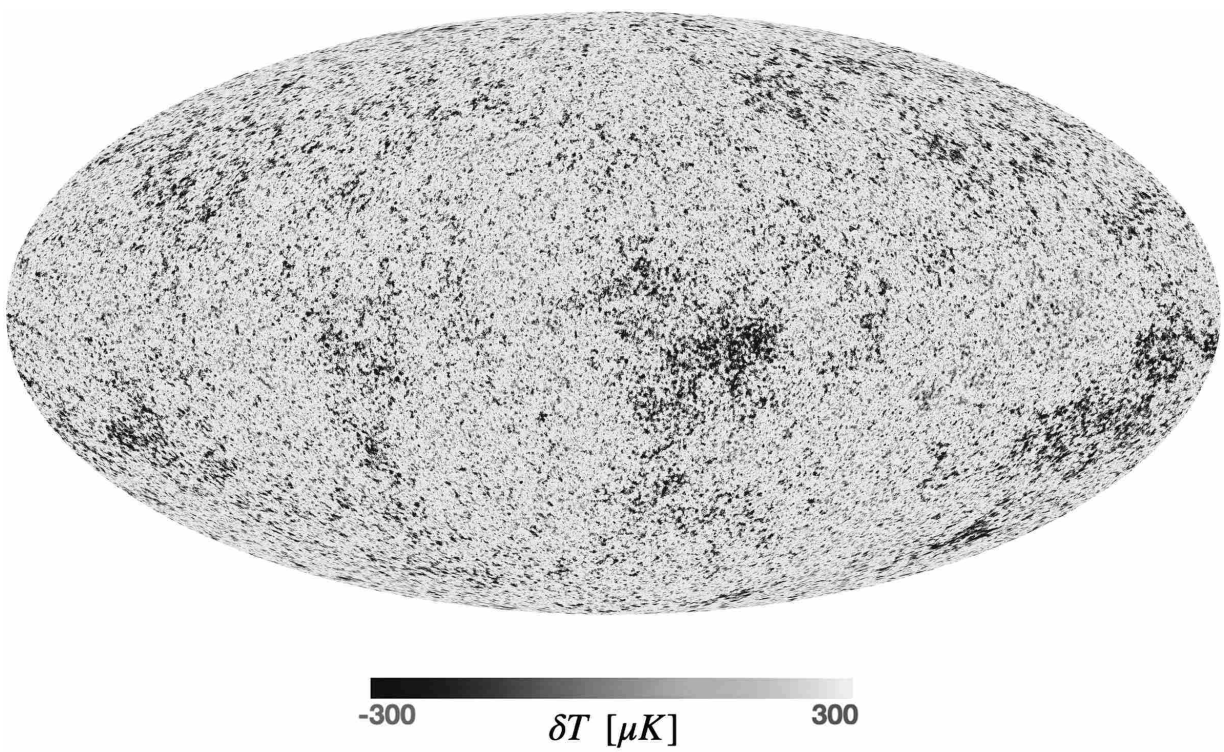

FIGURE 2. *A sky map of the afterglow of the hot big bang imaged by the European Space Agency's Planck satellite, named after quantum pioneer Max Planck. The speckles of different shades of gray represent slight temperature variations of the ancient cosmic microwave radiation as it reaches us from different directions in the sky. At first sight these fluctuations look random, but a close study has revealed that there are patterns interlinking different regions on the map. By studying these, cosmologists can reconstruct the universe's expansion history to model how galaxies formed and even predict its future.*

The CMB sky map confirms that the relic big bang heat is nearly uniformly distributed throughout space, although not quite perfectly. The speckles in the image represent minuscule temperature variations indeed, tiny flickers of no more than a hundred-thousandth of a degree. These slight variations, however small, are crucially important, because they trace the seeds around which galaxies would eventually form. Had the hot big bang been perfectly uniform everywhere, there would be no galaxies today.

The ancient CMB snapshot marks our cosmological horizon: We cannot look back any farther. But we can glean something about processes operating in yet earlier epochs from cosmological theory. Just as paleontologists learn from stone fossils what life on Earth used to be like, cosmologists can, by deciphering the patterns encoded in these fossil flickers, stitch together what might have happened before the relic heat map was imprinted on the sky. This turns the CMB into a cosmological Rosetta Stone that enables us to trace the universe's history even farther back, perhaps as far back as a fraction of a second after its birth.

And what we learn is intriguing. As we will see in chapter 4, the temperature variations of the CMB radiation indicate that the universe initially expanded fast, then slowed down, and, more recently (about five billion years ago), began accelerating again. Slowing down appears to be the exception rather than the rule on the scales of deep time and deep space. This is one of those seemingly fortuitous biofriendly properties of the universe, for only in a slowing universe does matter aggregate and cluster to form galaxies. If it hadn't been for the extended near-pause in expansion in our past, there would, again, be no galaxies and no stars, and thus no life.

In effect, the universe's expansion history was at the center of one of the very first moments in which the conditions for our existence slipped into modern cosmological thinking. This moment occurred in the early 1930s, when Lemaître made a remarkable sketch in one of his purple notebooks of what he called a "hesitating" universe, one with an expansion history much like the bumpy ride that would emerge from observations seventy years later[*1] (see insert, plate 3). Lemaître embraced the idea of a long pause in the expansion by considering the universe's habitability. He knew that astronomical observations of nearby galaxies pointed to a high expansion rate in recent times. But when he ran the evolution of the universe backward in time at this same rate, he found that the galaxies must all have been on top of one another no more than a billion years ago. This was impossible, of course, for Earth and the sun are much older than that. To avoid an obvious conflict between the history of the universe and that of our solar system, he imagined an intermediate era of very slow expansion, to give stars, planets, and life time to develop.

In the decades since Lemaître's pioneering work, physicists have continued to stumble across many more such "happy coincidences." Make but a small change in almost any of its basic physical properties, from the behavior of atoms and molecules to the structure of the cosmos on the largest scales, and the universe's habitability would hang in the balance.

Take gravity, the force that sculpts and governs the large-scale universe. Gravity is extremely weak; it requires the mass of Earth just to keep our feet on the ground. But if gravity were stronger, stars would shine more brightly and hence die far younger, leaving no time for complex life to evolve on any of the orbiting planets warmed by their heat.

Or consider the tiny variations, one part in a hundred thousand, in the temperature of the relic big bang radiation. Were these differences slightly larger—say one part in ten thousand—the seeds of cosmic structures would have mostly grown into giant black holes instead of hospitable galaxies with abundant stars. Conversely, even smaller variations—one millionth or less—would produce no galaxies at all. The hot big bang got it just right. One way or another it set off the universe on a supremely biofriendly trajectory, the fruits of which would not become evident until several billion years later. Why?

Other examples of such happy cosmic coincidences abound. We live in a universe with three large dimensions of space. Is there anything special about three? There is. Adding just a single space dimension renders atoms and planetary orbits unstable. Earth would spiral into the sun instead of tracing out a stable orbit around it. Universes with five or more large space dimensions have even bigger problems. Worlds with only two space