# Contents

CHAPTER 1:

# Introduction to the Cosmos

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

Robert Frost, 1920

The question of how the world will end has been the subject of speculation and debate among poets and philosophers throughout history. Of course, now, thanks to science, we know the answer: it's fire. Definitely, fire. In about five billion years, the Sun will swell to its red giant phase, engulf the orbit of Mercury and perhaps Venus, and leave the Earth a charred, lifeless, magma-covered rock. Even this sterile smoldering remnant is likely fated to eventually spiral into the Sun's outer layers and disperse its atoms in the churning atmosphere of the dying star.

So: fire. That's settled. Frost was right the first time.

But he wasn't thinking big enough. I'm a cosmologist. I study the universe, as a whole, on the largest scales. From that perspective, the world is a small sentimental speck of dust lost in a vast and varied universe. What matters to me, professionally and personally, is a bigger question: how will the *universe* end?

We know it had a beginning. About 13.8 billion years ago, the universe went from a state of unimaginable density, to an all-encompassing cosmic fireball, to a cooling, humming fluid of matter and energy, which laid down the seeds for the stars and galaxies we see around us today. Planets formed, galaxies collided, light filled the cosmos. A rocky planet orbiting an ordinary star near the edge of a spiral galaxy developed life, computers, political science, and spindly bipedal mammals who read physics books for fun.

But what's next? What happens at the end of the story? The death of a planet, or even a star, might in principle be survivable. In billions of years, humanity could still conceivably exist, in some perhaps unrecognizable form, venturing out to distant reaches of space, finding new homes and building new civilizations. The death of the universe, though, is final. What does it mean for us, for everything, if it will all eventually come to an end?

## WELCOME TO THE END TIMES

Despite the existence of some classic (and highly entertaining) papers in the scientific literature, I first encountered the term "eschatology," the study of the end of everything, by reading about religion.

Eschatology—or more specifically, the end of the world—provides a way for many of the world's religions to contextualize the lessons of theology and to drive home their meaning with overwhelming force. For all the theological differences between Christianity, Judaism, and Islam, they have in common a vision of the End Times that brings about a final restructuring of the world in which good triumphs over evil and those favored by God are rewarded.* Perhaps the promise of a final judgment serves to somehow make up for the unfortunate fact that our imperfect, unfair, arbitrary physical world cannot be relied upon to make existence good and worthwhile for those who live right. In the same way a novel can be redeemed or retroactively ruined by its concluding chapter, many religious philosophies seem to need the world to end, and to end "justly," for it to have had meaning in the first place.

Of course, not all eschatologies are redemptive, and not all religions predict an end time at all. Despite the hype around late December 2012, the Mayan view of the universe was a cyclic one, as it is in Hindu tradition, with no particular "end" designated. The cycles in these traditions aren't mere repetitions, but are imbued with the possibility that things will be better the next time around: all your suffering in this world is bad, but don't worry, a new world is coming, and it will be unscarred, or perhaps improved, by the iniquities of the present. Secular stories of the end, on the other hand, run the gamut from a nihilist view that nothing matters at all (and that nothingness ultimately prevails) to the heady notion of eternal recurrence, where everything that has happened will happen again, in exactly the same way, forever.† In fact, both these seemingly opposing theories are commonly associated with Friedrich Nietzsche, who, after proclaiming the death of any god that might bring order and meaning to the universe, grappled with the implications of living in a cosmos lacking a final redemption arc.

Nietzsche isn't the only one to have contemplated the meaning of existence, of course. Everyone from Aristotle to

* Exactly how those rewards are doled out, and to whom, is not the part they have in common.

† This view is also espoused, though not explored in philosophical detail, in the classic early-2000s TV series *Battlestar Galactica.*

Lao-Tzu to de Beauvoir to Captain Kirk to Buffy the Vampire Slayer has at one point asked, "What does it all mean?" As of this writing, we have yet to reach a consensus.

Whether or not we subscribe to any particular religion or philosophy, it would be hard to deny that knowing our cosmic destiny must have some impact on how we think about our existence, or even how we live our lives. If we want to know whether what we do here ultimately matters, the first thing we ask is: how will it come out in the end? If we find the answer to that question, it leads immediately to the next: what does this mean for us now? Do we still have to take the trash out next Tuesday if the universe is going to die someday?

I've done my own scouring of theological and philosophical texts, and while I learned many fascinating things from my studies, unfortunately the meaning of existence wasn't one of them. I may just not have been cut out for it. The questions and answers that have always drawn me in most strongly are the ones that can be answered with scientific observation, mathematics, and physical evidence. As appealing as it sometimes seemed to have the whole story and meaning of life written down for me once and for all in a book, I knew I would only ever really be able to accept the kind of truth I could rederive mathematically.

## LOOKING UP

Over the millennia since humanity's first ponderings of its mortality, the philosophical implications of the question haven't changed, but the tools we have to answer it have. Today, the question of the future and ultimate fate of all reality is a solidly scientific one, with the answer tantalizingly within reach. It hasn't always been so. In Robert Frost's time, debates still raged in astronomy about whether the universe might be in a steady state, existing unchanging forever. It was an appealing idea, that our cosmic home might be a stable, hospitable one: a safe place in which to grow old. The discovery of the Big Bang and the expansion of the universe, however, ruled that out. Our universe is changing, and we've only just begun to develop the theories and observations to understand exactly how. The developments of the last few years, and even months, are finally allowing us to paint a picture of the far future of the cosmos.

I want to share that picture with you. The best measurements we have are only consistent with a handful of final apocalyptic scenarios, some of which may be confirmed or ruled out by observations we're making right now. Exploring these possibilities gives us a glimpse of the workings of science at the cutting edge, and allows us to see humanity in a new context. One which, in my opinion, can bring a kind of joy even in the face of total destruction. We are a species poised between an awareness of our ultimate insignificance and an ability to reach far beyond our mundane lives, into the void, to solve the most fundamental mysteries of the cosmos.

To adapt a line from Tolstoy, every happy universe is the same; every unhappy universe is unhappy in its own way. In this book, I describe how small tweaks to our current, incomplete knowledge of the cosmos can result in vastly different paths into the future, from a universe that collapses on itself, to one that rips itself apart, to one that succumbs by degrees to an inescapable expanding bubble of doom. While we explore the evolution of our modern understanding of the universe and its ultimate end, and grapple with what that means *for us*, we'll encounter some of the most important concepts in physics and see how these connect not just to cosmic apocalypses,* but also to the physics of our everyday lives.

* apocalypsi?

## QUANTIFYING COSMIC DOOM

Of course, for some of us, cosmic apocalypses are already a daily concern.

I remember vividly the moment I found out that the universe might end at any second. I was sitting on Professor Phinney's living room floor with the rest of my undergraduate astronomy class for our weekly dessert night, while the professor sat on a chair with his three-year-old daughter on his lap. He explained that the sudden space-stretching expansion of the early universe, cosmic inflation, was still such a mystery that we don't have any idea why it started or why it ended, and we have no way of saying that it won't happen again, right now. No assurance existed to tell us that a rapid, un-survivable rending of space couldn't start right then, in that living room, while we innocently ate our cookies and drank our tea.

I felt completely blindsided, as if I could no longer trust the solidity of the floor beneath me. Forever etched into my brain is the image of that little child sitting there, fidgeting obliviously in a suddenly unstable cosmos, while the professor gave a little smirk and moved on to another topic.

Now that I'm an established scientist, I understand that smirk. It can be morbidly fascinating to ponder processes so powerful and unstoppable yet precisely mathematically describable. The possible futures of our cosmos have been delineated, calculated, and weighted by likelihood based on the best available data. We may not know for certain if a violent new cosmic inflation could occur right now, but if it does, we have the equations ready. In a way, this is a deeply affirming thought: even though we puny helpless humans have no chance of being able to affect (or effect) an end of the cosmos, we can begin to at least understand it.

Many other physicists get a little blasé about the vastness of the cosmos and forces too powerful to comprehend. You can reduce it all to mathematics, tweak some equations, and get on with your day. But the shock and vertigo of the recognition of the fragility of everything, and my own powerlessness in it, has left its mark on me. There's something about taking the opportunity to wade into that cosmic perspective that is both terrifying and hopeful, like holding a newborn infant and feeling the delicate balance of the tenuousness of life and the potential for not-yet-imagined greatness. It is said that astronauts returning from space carry with them a changed perspective on the world, the "overview effect," in which, having seen the Earth from above, they can fully perceive how fragile our little oasis is and how unified we ought to be as a species, as perhaps the only thinking beings in the cosmos.

For me, thinking about the ultimate destruction of the universe is just such an experience. There's an intellectual luxury in being able to ponder the farthest reaches of deep time, and in having the tools to speak about it coherently. When we ask the question, "Can this all really go on forever?," we are implicitly validating our own existence, extending it indefinitely into the future, taking stock, and examining our legacy. Acknowledging an ultimate end gives us context, meaning, even hope, and allows us, paradoxically, to step back from our petty day-to-day concerns and simultaneously live more fully in the moment. Maybe this can be the meaning we seek.

We're definitely getting closer to an answer. Whether or not the world is at any given moment falling apart from a political perspective, scientifically we are living in a golden age. In physics, recent discoveries and new technological and theoretical tools are allowing us to make leaps that were previously impossible. We've been refining our understanding of the beginning of the universe for decades, but the scientific exploration of how the universe might end is just now undergoing its renaissance. Hot-off-the-presses results from powerful telescopes and particle colliders have suggested exciting (if terrifying) new possibilities and changed our perspective on what is likely, or not, in the far future evolution of the cosmos. This is a field in which incredible progress is being made, giving us the opportunity to stand at the very edge of the abyss and peer into the ultimate darkness. Except, you know, quantifiably.

As a discipline within physics, the study of cosmology isn't really about finding meaning per se, but it is about uncovering fundamental truths. By precisely measuring the shape of the universe, the distribution of matter and energy within it, and the forces that govern its evolution, we find hints about the deeper structure of reality. We might tend to associate leaps forward in physics with experiments in laboratories, but much of what we know about the fundamental laws governing the natural world comes not from the experiments themselves, but from understanding their relationship to observations of the heavens. Determining the structure of the atom, for example, required physicists to connect the results of radioactivity experiments with the patterns of spectral lines in the light from the Sun. The Law of Universal Gravitation, developed by Newton, posited that the same force that makes a block slide down an inclined plane keeps the Moon and planets in their orbits. This led, ultimately, to Einstein's General Theory of Relativity, a spectacular reworking of gravity, whose validity was confirmed not by measurements on Earth, but by observations of Mercury's orbital quirks and the apparent positions of stars during a total solar eclipse.

Today, we are finding that the particle physics models we've developed through decades of rigorous testing in the best Earthly laboratories are incomplete, and we're getting these clues from the sky. Studying the motions and distributions of other galaxies—cosmic conglomerations like our own Milky Way that contain billions or trillions of stars—has pointed us to major gaps in our theories of particle physics. We don't know yet what the solution will be, but it's a safe bet that our explorations of the cosmos will play a role in sorting it out. Uniting cosmology and particle physics has already allowed us to measure the basic shape of spacetime, take an inventory of the components of reality, and peer back through time to an era before the existence of stars and galaxies in order to trace our origins, not just as living beings, but as matter itself.

Of course, it goes both ways. As much as modern cosmology informs our understanding of the very, very small, particle theories and experiments can give us insight into the workings of the universe on the largest scales. This combination of a top-down and bottom-up approach ties into the essence of physics. As much as pop culture would have you believe that science is all about eureka moments and spectacular conceptual reversals, advances in our understanding come more often from taking existing theories, pushing them to the extremes, and watching where they break. When Newton was rolling balls down hills or watching the planets inch across the sky, he couldn't possibly have guessed that we'd need a theory of gravity that could also cope with the warping of spacetime near the Sun, or the unimaginable gravitational forces inside black holes. He would never have dreamed that we'd someday hope to measure the effect of gravity on a single neutron.* Fortunately, the universe, being really very big, gives us a lot of extreme environments to observe. Even better, it gives us the ability to study the early universe, a time when the entire cosmos was an extreme environment.

• • •

* We do this by bouncing it. Really. First we cool the neutrons to almost absolute zero, then we slow them to jogging speed, then we bounce them up and down like a Ping-Pong ball on a paddle. And this also tells us something about dark energy, the mysterious something that makes our whole universe expand faster. Physics is wild.

A quick note about terminology. As a general scientific term, *cosmology* refers to the study of the universe as a whole, from beginning to end, including its components, its evolution over time, and the fundamental physics governing it. In *astrophysics*, a cosmologist is anyone who studies really distant things, because (1) that means looking at quite a lot of universe and (2) in astronomy, faraway things are also far in the past, since the light that reaches us from them has been traveling for a long time—sometimes billions of years. Some astrophysicists explicitly study the evolution or early history of the universe, while some specialize in distant objects (galaxies, clusters of galaxies, and so forth) and their properties. In *physics*, cosmology can veer in a direction that is much more theoretical. For instance, some cosmologists in physics departments (as opposed to astronomy departments) study alternative formulations of particle physics that might have applied to the first billionth of a billionth of a second of the universe's existence. Others study modifications of Einstein's theory of gravity that could pertain to objects as hypothetical as black holes that can only exist in higher dimensions of space. Some cosmologists even study whole hypothetical universes that are very explicitly not our own—universes in which the cosmos has a totally different shape, number of dimensions, and history—in order to gain insight into the mathematical structure of theories that *might* someday be found to have relevance to us.*

The upshot of all this is that cosmology means a lot of dif-

* String theorists produce a lot of these theories. (String theory is a blanket term for theories that try to bring together gravity and particle physics in new ways, but most of the work done to develop it now relies on mathematical analogs rather than anything pertaining to the "real" world.) Sometimes when I'm in string theory talks, I have to resist the urge to raise my hand and clarify that none of these calculations pertain to *our* universe, just in case anyone in the room is as confused as I first was when I started attending string theory talks.

ferent things to a lot of different people. A cosmologist who studies the evolution of galaxies might be utterly lost talking with a cosmologist who studies the way quantum field theory can make black holes evaporate, and vice versa.

As for me, I love it all. I first learned cosmology was a thing when I was about ten years old, through encounters with books and lectures by Stephen Hawking. He was talking about black holes and warped spacetime and the Big Bang and all sorts of stuff that made me feel like my brain was doing backflips. I *could not get enough*. When I found out that Hawking described himself as a cosmologist, I knew that was what I wanted to be. Through the years, I've done research across the whole range, bouncing back and forth between physics and astronomy departments, studying black holes, galaxies, intergalactic gas, intricacies of the Big Bang, dark matter, and the possibility that the universe might suddenly blink out of existence.* I even dabbled in experimental particle physics for a while, in my misspent youth, playing with lasers in a nuclear physics lab (despite what the records might say, the fire was not my fault) and paddling an inflatable boat around a 40-meter-tall water-filled underground neutrino detector (that explosion was not my fault either).

These days, I'm pretty solidly a theorist, which is probably better for everyone. This means I don't carry out observations or experiments or analyze data, though I do frequently make predictions for what future observations or experiments might see. I work mainly in an area physicists call phenomenology—the space between the development of new theories and the part where they're actually tested. That is to say, I find creative new ways to connect the things the fundamental-theory people hypothesize about the structure of the universe with

* This is, of course, one of the most fun things I've ever worked on, hence this book. I'm not sure why I like it so much. It may be a bad sign.

what the observational astronomers and experimental physicists hope to see in their data. It means I have to learn a lot about everything,* and it's a heck of a lot of fun.

## SPOILER ALERT

This book is an excuse for me to dig deep into the question of where it's all going, what that all means, and what we can learn about the universe we live in by asking these questions. There isn't just one accepted answer to any of this—the question of the fate of all existence is still an open one, and an area of active research in which the conclusions we draw can change drastically in response to very small tweaks in our interpretations of the data. In this book, we'll explore five possibilities, chosen based on their prominence in ongoing discussions among professional cosmologists, and dig into the best current evidence for or against each of them.

Each scenario presents a very different style of apocalypse, with a different physical process governing it, but they all agree on one thing: there will be an end. In all my readings, I have not yet found a serious suggestion in the current cosmological literature that the universe could persist, unchanged, forever. At the very least, there will be a transition that for all intents and purposes destroys *everything*, rendering at least the observable parts of the cosmos uninhabitable to any organized structure. For this purpose, I will call that an ending (with apologies to any temporarily sentient bursts of random quantum fluctuation† that may be reading this). A few of the scenarios carry with them a hint of possibility that the cosmos might renew

* And we're talking about the universe here, so I really do mean EVERYTHING.

† Please stick around until Chapter 4, when the Boltzmann Brain community will get their proper due.

itself, or even repeat, in one way or another, but whether some tenuous memory of previous iterations can persist in any way is a matter of rather intense ongoing debate, as is whether or not anything like an escape from a cosmic apocalypse could in principle be possible. What seems most likely is that the end for our little island of existence known as the observable universe is, truly, the end. I'm here to tell you, among other things, how that might happen.

Just to get everyone on the same page, we'll start with a quick catch-up on the universe from the beginning until now. Then we'll get on with the destruction. In each of five chapters, we'll explore a different possibility for the end, how it might come about, what it would look like, and how our changing knowledge of the physics of reality leads us from one hypothesis to another. We'll start with the Big Crunch, the spectacular collapse of the universe that would occur if our current cosmic expansion were to reverse course. Then come two chapters of dark-energy-driven apocalypses, one in which the universe expands forever, slowly emptying and darkening, and one in which the universe literally rips itself apart. Next is vacuum decay, the spontaneous production of a *quantum bubble of death** that devours the cosmos. Finally, we'll venture into the speculative territory of cyclic cosmology, including theories with extra dimensions of space, in which our cosmos might be obliterated by a collision with a parallel universe . . . over and over again. The closing chapter will bring it all together with an update from several experts currently working on the cutting edge on which scenario looks most plausible now, and what we can expect to learn from new telescopes and experiments to settle the question once and for all.

What that means for us as human beings, living our lit-

* Technically it is called a "bubble of true vacuum," which, to be fair, also sounds pretty darn ominous.

tle lives in all this inconsiderate vastness, is another question entirely. We'll present a range of perspectives in the epilogue, and address whether or not sentience itself could have any kind of legacy that endures beyond our destruction.*

We don't know yet whether the universe will end in fire, ice, or something altogether more outlandish. What we do know is that it's an immense, beautiful, truly awesome place, and it's well worth our time to go out of our way to explore it. While we still can.

*Another spoiler: it's not looking great.