

THE END OF EVERYTHING

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 obviously 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

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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

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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

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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.