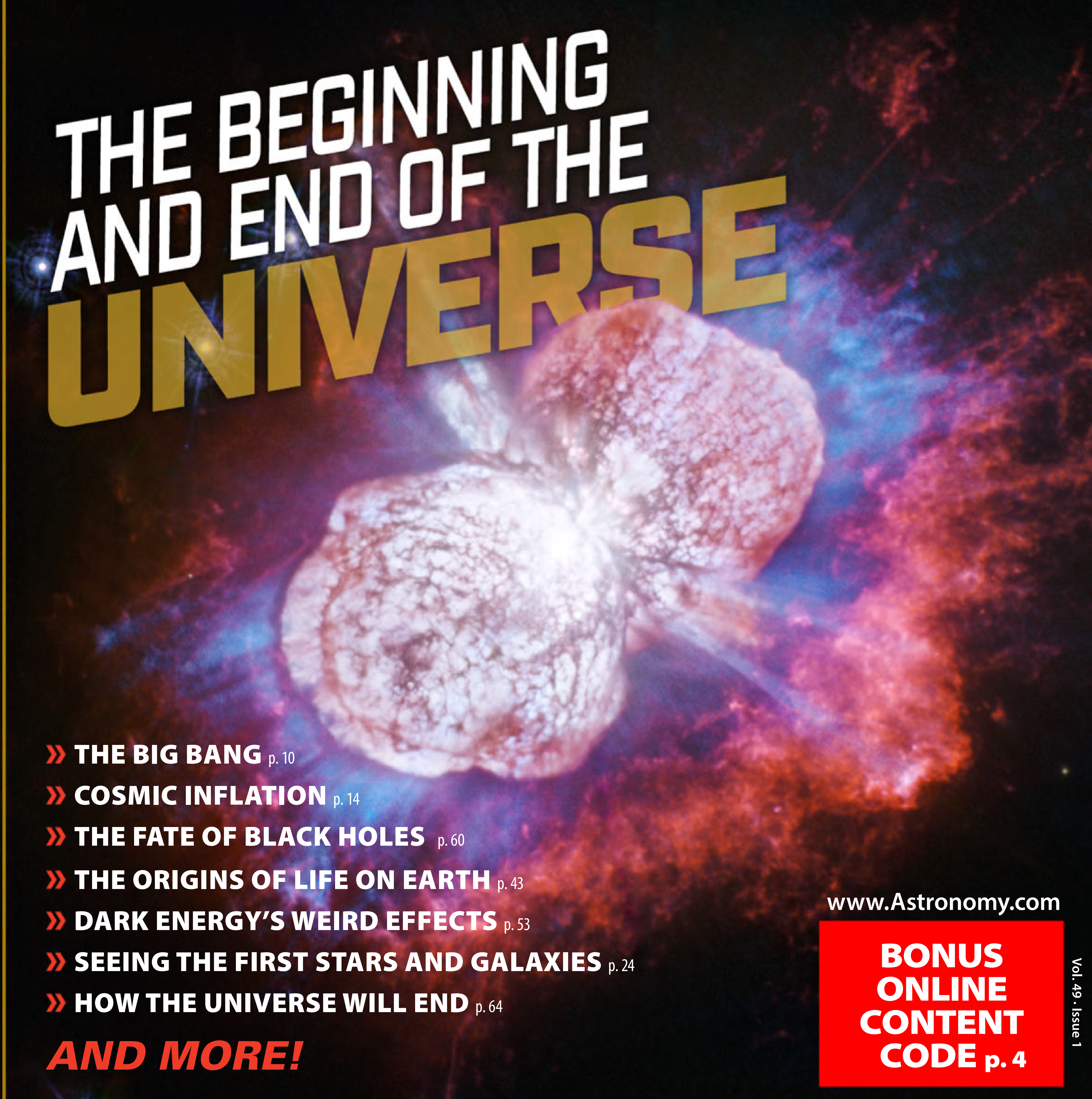
SPECIAL ISSUE

Astronomy®

JANUARY 2021

The world's best-selling astronomy magazine

THE BEGINNING AND END OF THE UNIVERSE



AND MORE!

www.Astronomy.com

BONUS ONLINE CONTENT CODE p. 4

Vol. 49 • Issue 1

A COLD, LONELY DEATH

Everything — from creatures to stars to black holes — will eventually decay into nothingness. BY DOUG ADLER

The universe, like everything else, was born, matures, and will eventually die. But exactly how and when that death will occur remains one of the greatest mysteries in the field of cosmology.

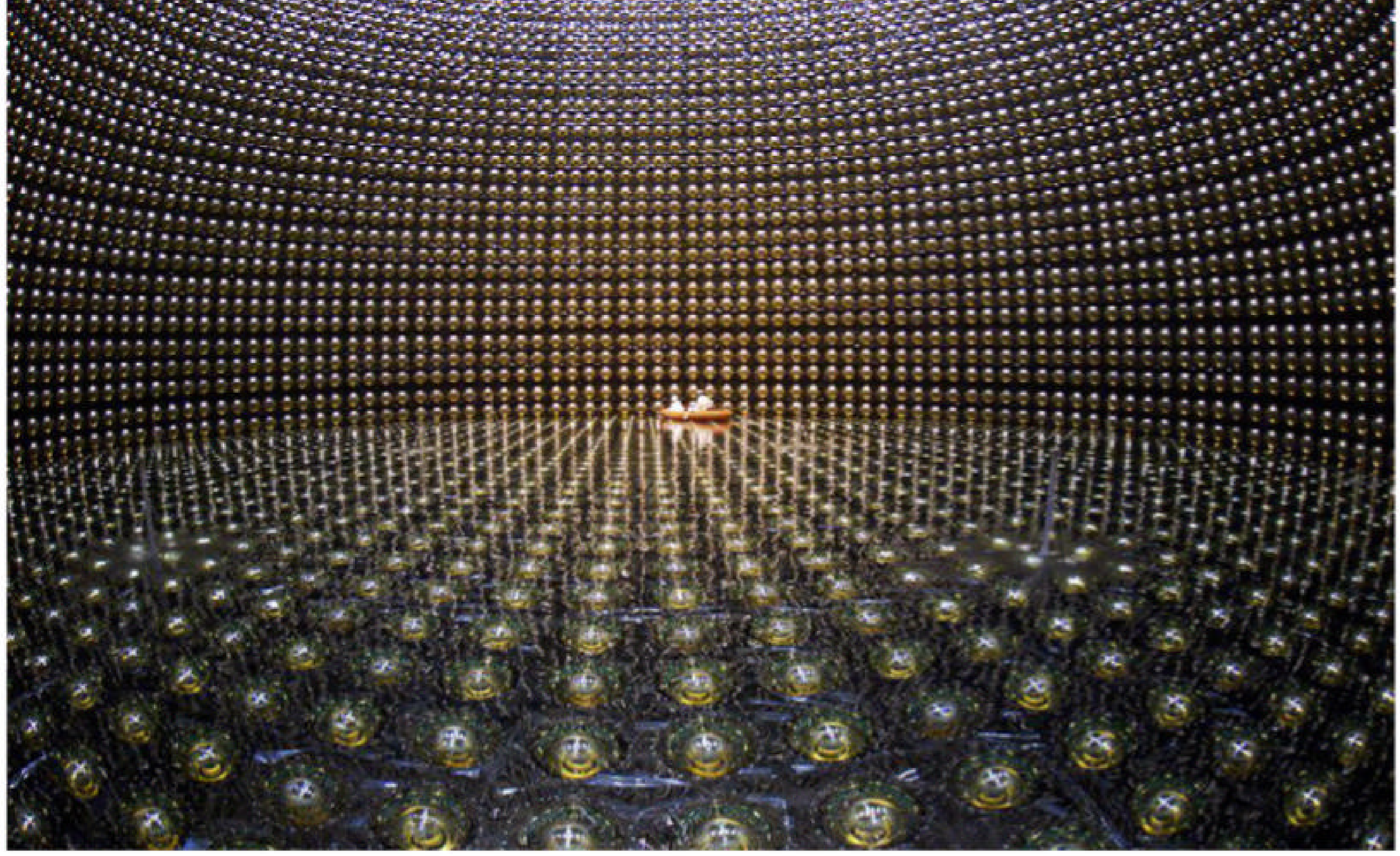
Many scientists have previously categorized cosmic time into different eras. Fred Adams and Greg Laughlin, for example, wrote a popular science book called *The Five Ages of the Universe* (Free Press, 2000). According to the pair, the first era was the **Primordial Era**, during which the Big Bang occurred, kicking off the cosmos' ongoing expansion.

The next era, which we're currently in, is known as the **Stelliferous Era**, in which matter is organized into stars, planets, nebulae, and larger constructs, such as galaxies and galaxy clusters. This era is hypothesized to run from about 10^6 to 10^{14} (1 million to 100 trillion) years after the Big Bang. Once all stars exhaust their hydrogen fuel and go dark, we will have entered the **Degenerate Era**. This period is hypothesized to take place between 10^{15} and 10^{39} (1 quadrillion to 1 duodecillion) years after the Big Bang. It will be dominated by stellar remnants such as black holes, white dwarfs, brown dwarfs, and neutron stars. As time unceasingly marches on, the universe will continue to cool and darken; eventually, life and matter as we understand it will likely come to an end.

The universe fades to black (holes)

But what happens after that? White dwarfs, brown dwarfs, and neutron stars are expected to eventually die through a process known as proton decay, when the subatomic particles

ABOVE: As the cosmos ages over an unbelievably long timescale, the stars will fade before matter itself decays. JONATHAN SAUTTER



Kamioka Observatory, seen here, is located some 3,300 feet (1,000 m) below ground in a mine outside of Kamioka, Japan. The Super-Kamiokande experiment uses a tank filled with about 50,000 tons of pure water surrounded by detectors to seek flashes of Cherenkov light produced by incoming neutrinos — or perhaps, by proton decay. KAMIOKA OBSERVATORY, ICRR (INSTITUTE FOR COSMIC RAY RESEARCH), THE UNIVERSITY OF TOKYO

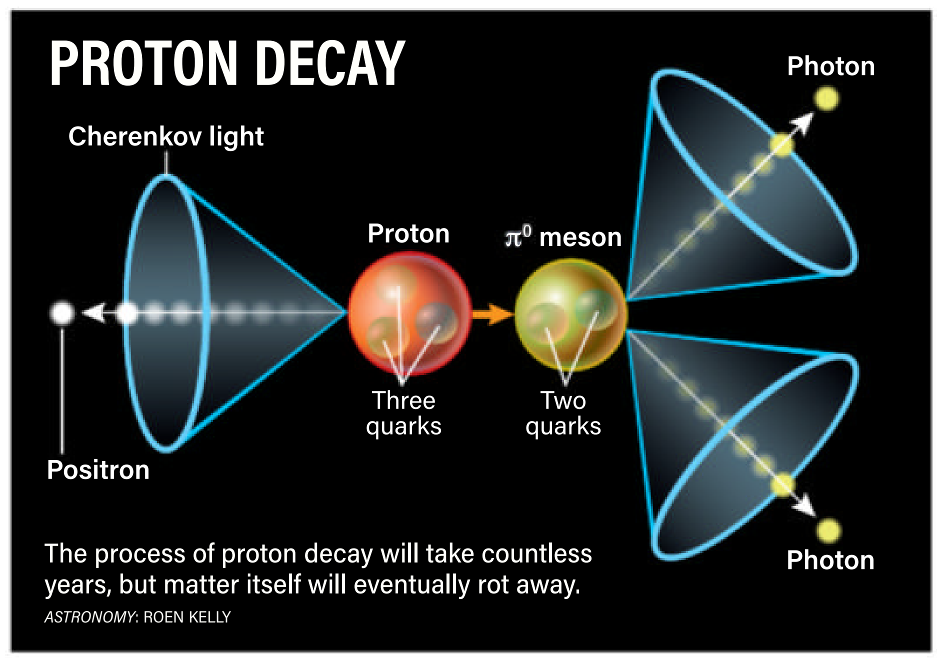
they are made of literally fall apart. Cosmologists predict this will occur late in the Degenerate Era, as the half-life (the time it takes for half of a substance to decay) of a proton is thought to be about 10^{34} years. And when the last remnants of stars rot away at the particle scale, only black holes will remain, dominating what is left of the universe.

The **Black Hole Era**, which is predicted to last from about 10^{40} to 10^{100} (10 duodecillion to 1 googol) years after the Big Bang, spans an unimaginably long stretch of time, even for astronomical timescales. Imagine a universe with no bright stars, no planets, and no life whatsoever — that's the Black Hole Era. Very little heat and light will linger in the universe at this point.

Black holes are so dense and massive that they produce tremendous distortions in the fabric of space-time, forever capturing anything that gets too close. And during the Black Hole Era, these dark beasts' gravitational influence will only increase as they gobble up lingering remnants of ordinary matter.

Still, even these monsters will not last forever. (See "How black holes die," page 60.) Although the popular conception is that "nothing can escape a black hole, not even light," scientists aren't entirely sure that's true. Astronomers believe black holes do emit radiation — in particular, Hawking radiation, named after famed physicist Stephen Hawking, who first proposed the idea. Although Hawking radiation has yet to be detected, if black holes do leak the radiation, it would provide a mechanism by which they could die off — literally evaporating into the cosmos.

However, even for tiny black holes, this process would still take an absurd amount of time. For a stellar-mass black hole, it could take up to 10^{64} years, and for the largest supermassive black holes, it might take as long as a couple googol years — again, that's a 1 followed by 100 zeros — or possibly even longer. Astronomers simply don't have the observational evidence to know for sure.



The process of proton decay will take countless years, but matter itself will eventually rot away. *ASTRONOMY*: ROEN KELLY

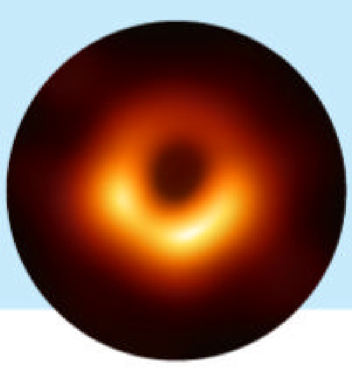
Everlasting darkness

After the last black hole has faded away, it's hard to even comprehend what the universe will be like. The concepts of space and time barely have any real meaning once the last structures have disappeared. The period following the demise of black holes is known as the **Dark Era**, which is expected to begin sometime around 10^{101} years after the Big Bang, though its start depends on how long black holes last. So when — and if — this era ends is anybody's guess.

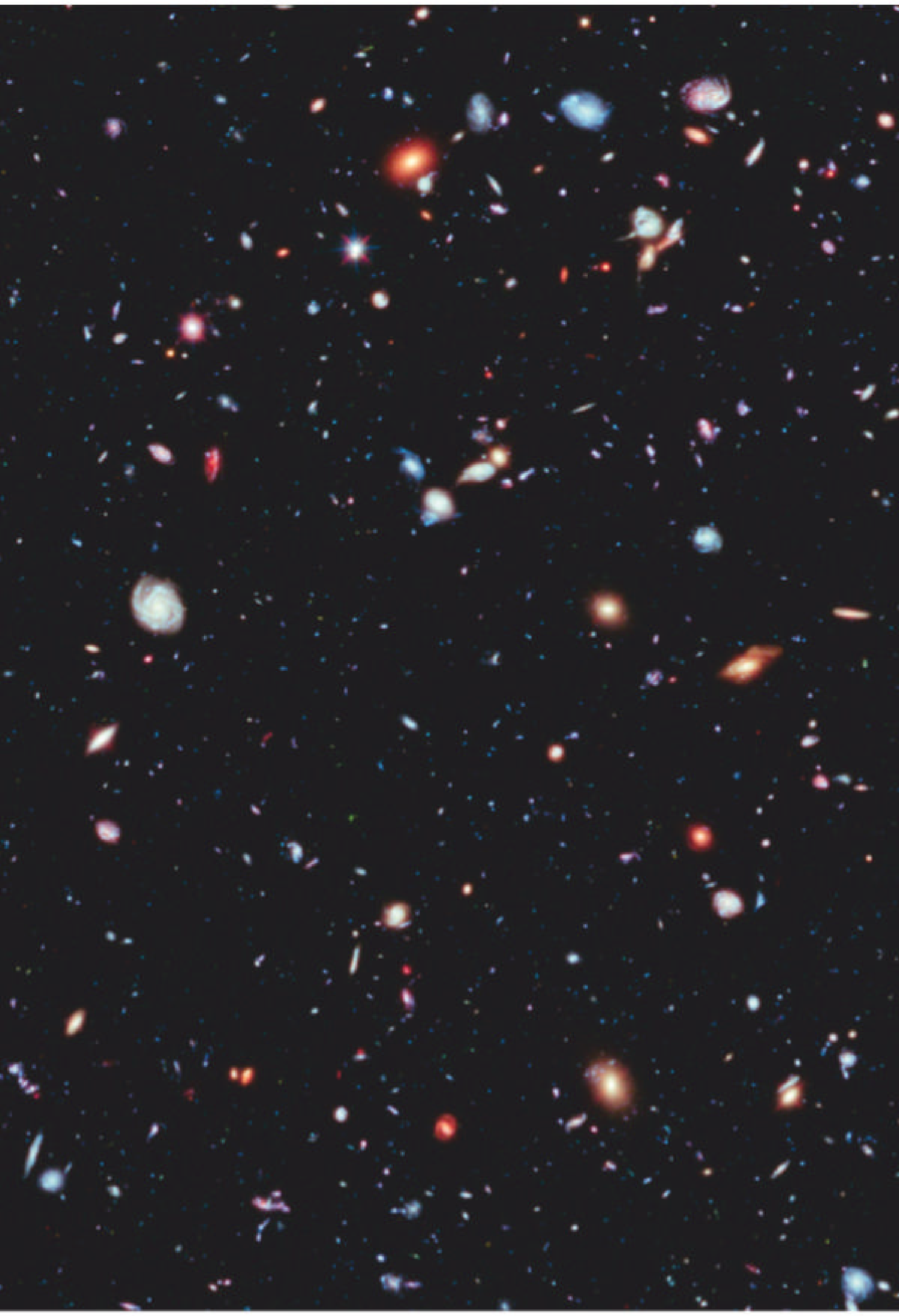
During the Dark Era, the universe will consist of only a few subatomic particles and potentially dark matter, which is an little understood substance that does not absorb, emit, or reflect electromagnetic radiation and may not decay at all. Whatever remains, however, will be very spread out. That's because as the universe cools, it will likely continue to expand. Scientists still debate how much the universe can balloon up, but by the time of the Dark Era, even a volume of

BLACK HOLE FLAVORS

Black holes come in a variety of sizes. The LIGO/Virgo gravitational-wave detectors, for example, have already picked up many mergers between **stellar-mass black holes**, which form when massive stars collapse. But in September 2019, the collaboration announced the first direct detection of gravitational waves from a black hole merger that created a never-before-confirmed **intermediate-mass black hole**, weighing in at about 142 solar masses. Meanwhile, our galaxy's **supermassive black hole**, Sagittarius A*, tips the scales at about 4 million solar masses; H1821+643, in the constellation Draco, is a giant supermassive black hole that weighs in at an astounding 30 billion solar masses. *—Jake Parks*



This first image of the shadow of a black hole was released by the Event Horizon Telescope in April 2019. The bright ring is from the black hole's accretion disk heating matter, which radiates light. In the distant future, black holes will run out of fuel and fade away. EVENT HORIZON COLLABORATION



The famed Hubble Ultra Deep Field, part of which is seen here, reveals how even a relatively empty patch of sky is still filled with countless galaxies. But in the distant future, space will expand and matter will decay to the point where a region of space the size of the current observable universe will only contain a few subatomic particles, if that. NASA/ESA

Our understanding of the cosmos is far from complete. There's a chance our best educated guesses about how the universe will end are missing something major — something that will allow life to survive and thrive forever. NASA

space larger than our current observable universe might only contain a single, solitary subatomic particle.

But despite interactions between subatomic particles being incredibly rare, the occasional collision should still occur. In the absence of protons and neutrons, an electron will sometimes slam into a positron — the positively charged, antimatter counterpart of an electron. This may briefly form an atom of the bizarre element positronium, which is unstable and will quickly destroy itself when the matter and antimatter annihilate each other.

Many cosmologists think the universe will continue to cool, eventually playing out the so-called Big Freeze, when there is no heat remaining anywhere. (See "The Big Crunch vs. the Big Freeze," page 50.) The cosmos will eventually reach a point of total disorder, or maximum entropy. The Second Law of Thermodynamics, which states that the entropy of a closed system (like the entire universe) can only increase, will have finally reached its logical conclusion.

Maybe, just maybe, the universe will end with neither a death nor a rebirth.

Is this cosmic fate guaranteed?

No. Much of the above is theoretical or based on ideas that are difficult or impossible to empirically test.

For example, the Big Crunch offers an alternate vision for how the universe ends — not by simply cooling and expanding to nothingness, but rather by halting its current expansion and bringing everything crashing back in on itself. Essentially, the death of the universe in this scenario would play out like the Big Bang in reverse.

Such a catastrophic collapse would kill any lingering life in the universe — though it's tough to imagine life surviving to this point anyway. Perhaps the Big Crunch would even be followed by another Big Bang, birthing a fresh universe from the ashes of our own.

However, most scientists think the Big Crunch is an unlikely fate. Instead of being guided by gravity, the universe appears to be under the influence of dark energy (see "The mystery of dark energy," page 53), causing space itself to expand at an accelerating rate and making the Big Freeze a more likely end.

These are difficult — and even upsetting — scenarios to ponder. But keep in mind, history has taught us that these theories may someday be superseded by others, markedly changing our predictions about the distant future. Perhaps our cosmological conjectures are still missing a major consideration or two.

Maybe, just maybe, the universe will end with neither death nor rebirth. Indeed, there could be a plot our imaginations have yet to envision, one where the physical laws of the universe allow matter, and life, to press on indefinitely.

Doug Adler *is a frequent* Astronomy *contributor and co-author of* From the Earth to the Moon: The Miniseries Companion *(2020).*