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Could dark energy be changing over time?

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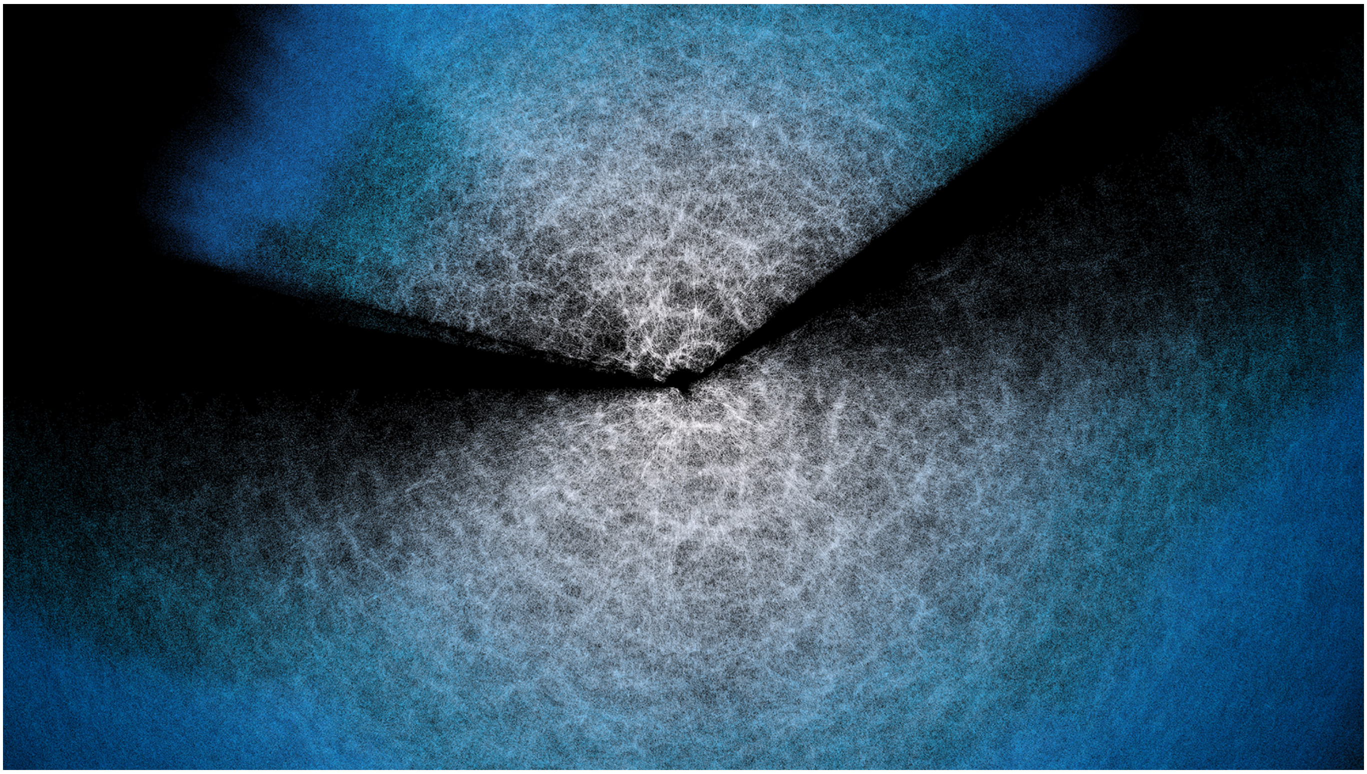

DESI has made a large 3D map of our universe to study dark energy. These two "fans"—with Earth at the center—correspond to the primary areas DESI has observed, above and below the plane of our Milky Way. Bluer points indicate more distant objects. Image credit: DESI Collaboration/ Department of Energy (DOE)/Kitt Peak National Observatory (KPNO)/National Optical-Infrared Astronomy Research Laboratory (NOIRLab)/National Science Foundation (NSF)/Association of Universities for Research in Astronomy (AURA)/R. Proctor.

Dark energy has been a profound puzzle since its discovery 25 years ago. Cosmologists had known since the 1920s that the universe was expanding, and models predicted that the gravitational pull of matter would slow this expansion over time. But in the late 1990s, two separate teams of astronomers noticed that bright supernovae in the distant universe were dimmer than expected (1, 2). This implied that some unknown effect was acting in opposition to gravity, causing the expansion of space to accelerate. This unknown thing was named "dark energy." Theorists are still at a loss to explain what it is. That's a pretty big gap in our knowledge, given that the stuff makes up most of the total energy of the universe.

Some physicists are now wondering if they may have gotten a new clue to dark energy's true nature. Using the Dark Energy Spectroscopic Instrument (DESI), researchers have drawn new maps of the universe throughout cosmic history. These suggest that the unknown entity's antigravitational strength has changed over time (3), weakening in the current cosmic era. The unexpected finding could open new channels for explaining just what dark energy is and perhaps help researchers predict the distant future of the cosmos. The results have injected a sense of renewed possibility into the field. "It's an exciting time to do cosmology," says Kevork Abazajian, an astrophysicist at the University of California, Irvine.

Origin of Darkness

Dark energy's story begins with Albert Einstein. In 1917, he used the equations of his newly derived theory of relativity to study the universe as a whole (4). He tried to make a mathematical model of a universe that was static, as was assumed to be the case. But matter pulls gravitationally on itself, so an initially static universe will collapse inward. Einstein introduced a fudge factor, a new constant in the equations denoted by the Greek letter lambda, which resulted in a sort of antigravitational force to balance the gravity of matter and prevent his model cosmos from shrinking away.

Published September 24, 2025.

DESI is attached to the Mayall Telescope atop Kitt Peak in Arizona's Sonoran Desert and contains 5,000 tiny robotic arms that each position a fiber-optic cable to capture light from a single galaxy or quasar in the night sky. Image credit: Marilyn Sargent/Berkeley Lab.

Within a few years, astronomer Edwin Hubble began observing distant galaxies moving away from us. It turned out that the universe was not static at all, but rather, expanding. Einstein would then delete lambda, calling it his greatest blunder. But when dark energy arrived on the scene in the 1990s, physicists realized that Einstein's supposed blunder was serendipitous; not only was the universe expanding, but there was indeed some antigravitational force accelerating its expansion.

Einstein's version of dark energy is known as the cosmological constant. It implies a fixed amount of dark energy in each cubic meter of space; as the universe expands, more dark energy appears. So far, this strange possibility has aligned with observations of the cosmos. But it remains a fudge factor—just a constant number added to the equations.

Hoping to study dark energy in more detail, researchers built DESI, an instrument attached to the Mayall Telescope atop Kitt Peak in Arizona's Sonoran Desert. DESI contains 5,000 tiny robotic arms that each position a fiber-optic cable to capture light from a single galaxy or quasar in the night sky. Every 20 minutes, the robots reconfigure the cables and take snapshots of 5,000 more cosmic objects. The light is sent to spectrometers that look for characteristic wavelength signatures corresponding to different elements. The expanding universe has stretched the wavelengths of the light that these cosmic objects emitted, thus shifting these signatures toward the redder end of the electromagnetic spectrum. Measuring that redshift allows DESI scientists to determine how much the universe has expanded since light left the galaxy or quasar of interest. This is the first piece of information that researchers need to delve deeper into dark energy.

The second one is distance. To figure out the exact distance to those objects, the DESI team uses cosmic features known as baryon acoustic oscillations (BAOs). These arose shortly after the big bang, when sound waves propagated through the hot, thick plasma suffusing space. Once the universe expanded enough for that plasma to thin out, these waves became frozen into the matter located throughout the cosmos, like ripples on a pond that iced over. These BAOs make an imprint in the clustering of galaxies, forming giant rings about a billion light years in diameter. BAOs thus provide a standard ruler in the universe. The farther away one is, the smaller that ring will appear, allowing researchers to infer distances with great precision. "From that, we create the biggest 3D map of the universe," explains Kushal Lodha, a DESI team member at the Korea Astronomy and Space Science Institute in Daejeon, South Korea.

Combining these distances with the redshifts measured by DESI's spectrometers, cosmologists can plot how the universe has expanded over the course of its history and see what influence dark energy has had at various epochs.

DESI began taking data in 2021 and has already determined the positions of more than 40 million objects across 11 billion years of cosmic history. DESI's first data release last year suggested that dark energy's strength has weakened slightly over cosmic history (5). Physicists talk in terms of a value known as sigma, which indicates how likely some result is to be a statistical accident. A two-sigma result should happen by accident about 1 in 20 times, while a three-sigma result is about 1 in 300. DESI's first-year findings were around the three-sigma level, piquing the community's interest. "Two-sigma things happen all the time," says Dragan Huterer, a cosmologist at the University of Michigan in Ann Arbor. "But three sigma—I'm listening now."

Varying Levels of Confidence

Scientists wondered whether such results would hold up when DESI delivered its second data release last March at a meeting of the American Physical Society in Anaheim, California. There, the team announced that their maps were still pointing to a time-varying dark energy, with a confidence level now between 2.8 and 4.2 sigma; the exact number depends on which other datasets were included with the DESI observations. This led to international headlines and scientific discussions about whether something revolutionary was occurring. "I think people are really taking this seriously," says Seshadri Nadathur, a cosmologist at the University of Portsmouth in the United Kingdom who worked on the DESI analysis.

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>
> **—Dragan Huterer**

This tantalizing possibility of time-varying dark energy has led theorists to revisit alternative notions about dark energy's true nature. Until now, the default idea had been that its density is constant, suggesting that dark energy is an inherent feature of empty space. Some models have posited that it could be tied to quantum fluctuations in empty space, which cause particles and antiparticles to pop into existence and almost immediately annihilate one another. In the brief moments they exist, such particles can interact with other existing particles, generating a low-level but overall repulsive force. But there's a problem: When researchers try to calculate the value of this vacuum energy, they find it to be 120 orders of magnitude larger than the observed value of dark energy.

However, if DESI's results are correct, then the density of dark energy is not constant after all. Instead, it rose to a peak around four and a half billion years ago and steadily declined since then. That would imply that it's not a property of empty space. Theorists have come up with several possible explanations. One theory, known as quintessence, posits that dark energy is essentially a new fundamental force that can change over time (6). A set of more recent theories involves a connection between dark energy and dark matter, another unknown gravitational influence on the universe. Known as interacting dark sector models, they suggest that the two mysterious phenomena can transfer energy between one another, allowing dark energy's density and therefore its influence to shift with time (7).

Dark energy is integral to the overall evolution of the universe. If its density remains constant, the current expansion of the universe will keep accelerating, and eventually, most of today's visible universe will be beyond our sight, a scenario sometimes dubbed the Big Freeze. If DESI's results are right and its density continues to fall, then the outcome could be subtly different. It could just mean weaker acceleration, a less rapid kind of Big Freeze, or if the density falls far enough, gravity's influence could eventually become stronger than dark energy's, potentially leading the universe to expand at an increasingly slower pace. In that case, galaxies currently moving out of view from us would become visible again.

Reality Check

Physicists are certainly not ready to declare this a done deal. For one thing, DESI's findings are still shy of the five-sigma threshold that physicists consider to be a firmer line for new discoveries—where a result will happen by accident only 1 in 3.5 million times. "I think it's a little bit premature to talk about four sigma and hints," says Hiranya Peiris, an astrophysicist at the University of Cambridge in the United Kingdom.

The time-varying models are only favored when physicists add other datasets into the analysis. The different datasets involve measurements from distant supernovae and from the cosmic microwave background (CMB), a remnant light released 380,000 years after the big bang. Including them both can boost the DESI results up to a highly intriguing 4.2 sigma. But while the CMB observations are well understood, the supernova datasets are still being developed and could contain systematic errors, Peiris says. Depending on which supernova dataset is included, the results can also be a more humdrum 2.8 sigma.

Other objections stem from theoretical physics. If the DESI findings are correct, they might violate what's been labeled the null energy condition, which states that the energy density of a region of space can't be negative. Plus, DESI's observations could potentially imply that the sum of the masses of the three known neutrinos would be negative. Neither negative energy nor negative mass makes physical sense, although the exact interpretation of all these criticisms is still being debated within the community.

Further insights will likely come from the Vera C. Rubin observatory, a ground-based, all-sky survey currently under construction in Chile, which will not only expand the supernova dataset, but provide a flood of new data on BAOs and the evolution of large-scale structure over cosmic history. The first images from the observatory were released in June 2025. The space-based Nancy Grace Roman telescope is also expected to capture additional supernovae once it launches in May 2027. Together, they will help researchers understand which dark energy models are best explained by the data.

Another set of informative data could come from the European Space Agency's Euclid satellite, which launched in 2023 and has been making high-quality galaxy cluster maps spanning 10 billion years of cosmic history. Its first cosmological results will appear in October of next year. The DESI team meanwhile anticipates that their project will have mapped 50 million objects by the time it wraps up its initial five-year survey next year—measurements that could either strengthen or challenge its current observations.

Before DESI began, many thought the project was going to measure dark energy's constant influence with greater and greater precision, a valuable, if mundane, task. The fact that it has cast doubt on that constancy has led to delight from some corners of cosmology. "I can't wait to see how this unfolds," Huterer says.

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