A dark, star-filled night sky with the text "What is" in a white serif font. The sky is filled with numerous stars of varying sizes and colors, including bright yellow and white stars, and some faint, distant galaxies. The text is positioned in the upper right quadrant of the image.

What is

dark energy?

A mysterious force accelerates cosmic expansion and pervades all of space.

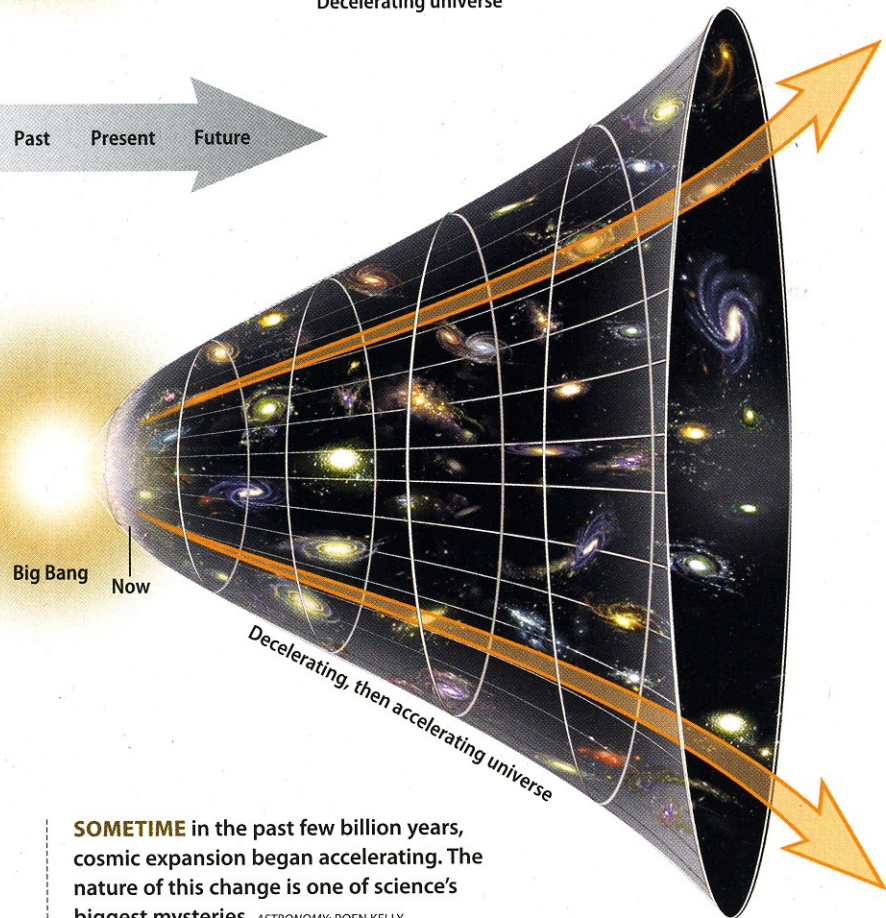
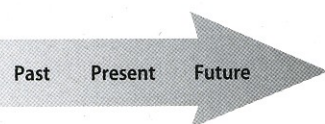
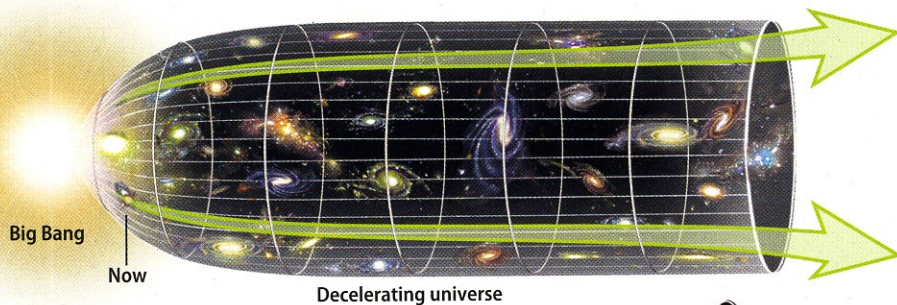
/// BY STEVE NADIS

Most astronomers now subscribe to a startling proposition: Nearly three-quarters of the universe comprises a strange entity that's spread evenly throughout space — it may even be a part of space itself. This mysterious entity, which astronomers call “dark energy,” causes our universe's expansion to speed up. If dark energy remains as persistent as it appears, it will disperse everything in the cosmos into a cold, ever-expanding void.

This strange scenario has gained credence since 1998, when studies of distant type Ia supernovae suggested these stellar explosions, which are

THE COMA GALAXY CLUSTER is a dense collection of galaxies, with thousands of them spanning some 20 million light-years. The strong gravitational interactions between the galaxies and the as-yet-unidentified material called dark matter holds the cluster together. Dark energy, the strange force that's pushing the universe apart, can't pull apart such clusters. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

A cosmological turning point



SOMETIME in the past few billion years, cosmic expansion began accelerating. The nature of this change is one of science's biggest mysteries. ASTRONOMY: ROEN KELLY

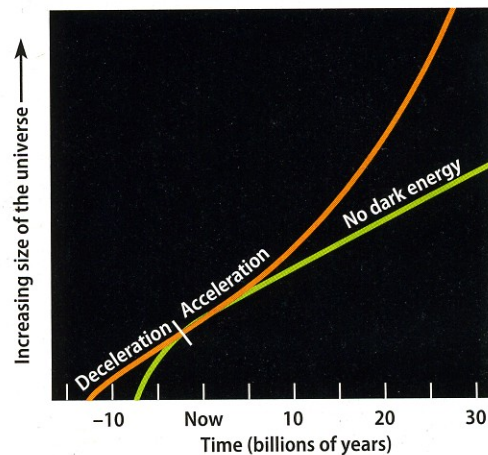
known for uniform energy output, were dimmer — and thus farther away — than expected for their redshifts. Astronomers proposed that an unseen force was causing the universe to expand at an accelerated rate. Cosmic microwave background (CMB) measurements from the Wilkinson Microwave Anisotropy Probe (WMAP) and other experiments supported this notion.

“There was a moment of disbelief,” acknowledges Saul Perlmutter of the Lawrence Berkeley National Laboratory, who leads one of the supernova-study teams. But as data filtered in from multiple fronts, astronomers moved from denial to grudging acceptance. Dark energy, which many consider to be the deepest, most important mystery in all of science, was here to stay.

“Dark energy is not predicted by the physics we understand,” says Adam Riess of the Space Telescope Science Institute in Baltimore. “So, learning about it will almost certainly lead us to something new and exotic.”

Groping in the dark

Astronomers have three leading explanations for dark energy, and deciding among them will be a major focus of cosmologists for years. The first is the cosmological constant, proposed (and later recanted) by Albert Einstein. In this view, dark energy is an intrinsic, uniform property of space. The second idea, called quintessence, involves an unidentified energy field of varying strength that fills space like a fog. Scientists envision this unidentified energy



UNTIL 1998, cosmologists thought the universe was slowly decelerating as the gravity of all matter within it slowed expansion. Since then, astronomers have accumulated evidence that the expansion began accelerating as dark energy counters gravity's tug. The most recent data indicate cosmic acceleration will continue forever. ASTRONOMY: ROEN KELLY

as similar to that which drove inflation, the rapid burst of expansion in the instant following the Big Bang.

The third alternative? Dark energy is an illusion. Instead, the effects we see result from a breakdown in Einstein's theory of gravity over the largest distance scales. Most scientists have focused on the existence of dark energy. But this “modified gravity” alternative deserves serious consideration, as well, says Princeton University's David Spergel. The right explanation may turn out to be “none of the above.”

While these competing ideas differ dramatically, says Daniel Eisenstein of the University of Arizona, “From an observational standpoint, the differences could be extremely subtle. You can construct all kinds of models that give you answers that are close to the cosmological constant. The only way to tell the difference is by doing the measurements extremely accurately.”

It won't be easy, Perlmutter admits. “It took us 10 years to realize the universe is accelerating, and it will take at least as long to figure out what's behind it,” he says. “The good news is that we have ways of attacking the problem.”

“We need to throw everything we can at this problem,” insists Robert Nichol of the University of Portsmouth, England. “We

Steve Nadis, a frequent Astronomy contributor, often writes about cosmic conundrums.

need to throw the kitchen sink at it.” All told, astronomers are pursuing roughly a dozen different approaches. So far, the big payoff has come from supernovae, which provided the first direct measure of cosmic acceleration and are scientist’s favorite tools.

Standard candles

To chart the universe’s expansion history, astronomers measure a supernova’s luminosity and redshift. Because each type Ia supernova releases about the same energy, each blast’s brightness reflects its distance from Earth. The redshift tells us how much the light has stretched (how much the universe has expanded) during its travel. By looking at supernovae over a broad redshift range, astronomers discovered that the universe’s expansion rate has varied.

The focus now, says Riess, is to push back to higher redshifts in order to measure the acceleration’s onset. The Hubble Space Telescope is the best tool for finding distant supernovae. But a dedicated space instrument, such as the proposed Supernova/Acceleration Probe (SNAP), would hasten the process. As now envisioned, SNAP would best Hubble with both a larger field of view (0.7°) and a billion-pixel imager.

When did dark energy’s push overtake gravity’s pull? Based on Hubble observa-

“IT TOOK US 10 YEARS to realize the universe is accelerating, and it will take at least as long to figure out what’s behind it.” — Saul Perlmutter

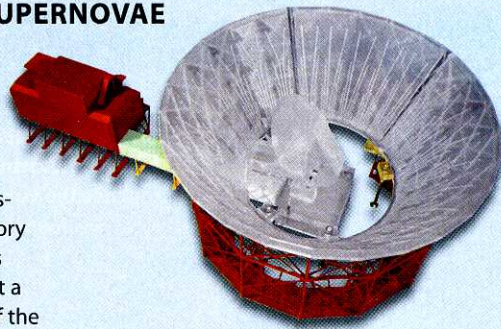
tions, Riess believes the balance tipped about 5 billion years ago, but he’d like to know exactly when the changeover occurred because predictions differ among theories. The transition occurs earlier in quintessence models, for instance, than in cosmological-constant ones.

Surveys now in progress will amass bigger and more homogeneous data sets. The ESSENCE program at the Cerro Tololo Inter-American Observatory in Chile has almost completed a 5-year project to mea-

DESPERATELY SEEKING SUPERNOVAE

The most far-flung supernovae are extremely faint and detectable only in wavelengths blocked by Earth’s atmosphere. NASA and the U.S. Department of Energy are sponsoring the Joint Dark Energy Mission (JDEM), a space-borne observatory dedicated to unlocking dark energy’s secrets. JDEM, to be launched at least a decade from now, will employ one of the following designs:

- **Dark Energy Space Telescope (DESTINY).** This project, headed by Tod Lauer of the National Optical Astronomy Observatory, is a 1.8-meter near-infrared space telescope dedicated to surveying high-redshift supernovae.
- **Advanced Dark Energy Physics Telescope (ADEPT).** This 1.3-meter space telescope would monitor 1,000 type Ia supernovae, capture redshifts for more than 100 million galaxies, and study baryonic acoustic oscillations. Charles Bennett of Johns Hopkins University heads up ADEPT.
- **Supernova/Acceleration Probe (SNAP).** This 2-meter optical and near-



THE SOUTH POLE TELESCOPE (SPT) observes the sky at millimeter and longer wavelengths, a region between radio and the infrared. Its first key project, a wide-area survey of galaxy clusters using the Sunyaev-Zeldovich effect, complements supernova studies. UNIVERSITY OF CHICAGO

infrared scope would discover and measure the spectra of 6,000 distant supernovae during its 3-year mission. It would also perform a weak-lensing survey. Saul Perlmutter of the Lawrence Berkeley Laboratory is the principal investigator. — S. N.

sure 200 supernovae at intermediate redshifts. Another 5-year effort, the Supernova Legacy Survey at the Canada-France-Hawaii Telescope on Mauna Kea in Hawaii, is designed to detect and monitor several hundred high-redshift supernovae. “It’s hard to say how big a sample we need,” notes Riess. “It depends on what nature has in store for us.”

Meanwhile, astronomers need to understand type Ia supernovae better to make them truly reliable dark-energy probes. “There weren’t as many heavy metals in the early universe, which could lead to a difference in explosion physics — and, hence, brightness — that might fool us,” explains Harvard University physicist Christopher Stubbs. Astronomers are trying to address this concern through close scrutiny of supernova spectra.

Wiggling baryons

One method for exploring dark energy potentially has the highest precision, according to University of Oklahoma cosmologist Yun Wang. It involves “baryonic acoustic oscillations” — fluctuations in the distribution of photons and particles of ordinary matter (baryons) caused by sound waves sloshing around in the early uni-

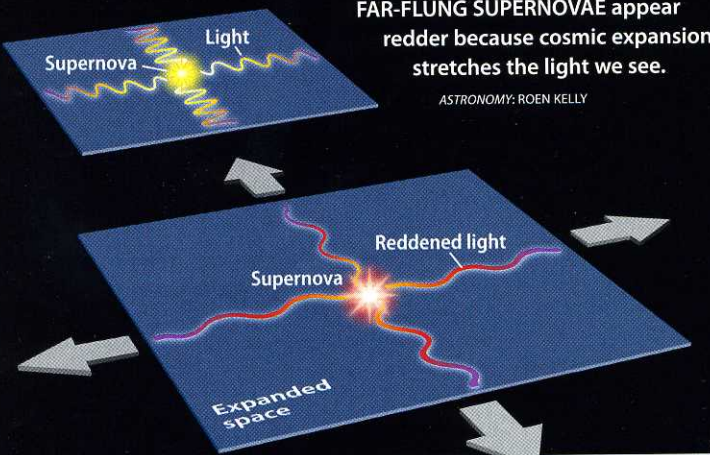
verse. Think of these fluctuations as the ripples made by tossing a pebble in a glass-smooth pond. The waves left a faint imprint in the distribution of galaxies. The galaxies, in other words, tend to space themselves on a distinct physical scale. They constitute a “standard ruler,” just as type Ia supernovae serve as standard candles.

The basic approach is to find a large number of galaxies with the same redshift. Knowing that the ruler’s length correlates with redshift, observers then determine the scale of peak clumpiness. By measuring the angle this “preferred length” subtends, scientists say they can determine the distance to the galaxy. The distance-redshift relation, as with supernovae, tells researchers how dark energy has influenced the universe’s expansion.

Daniel Eisenstein and colleagues first measured these baryon wiggles in 2005 in Sloan Digital Sky Survey data. The result validates the supernova findings through different means, but it will take a more precise redshift survey, drawing on more galaxies in a larger volume of space, to probe dark energy further. “With Sloan, we detected the effect with 4 percent precision, but we’d like to get to 1 percent precision,” Eisenstein says.

Four ways to target dark energy

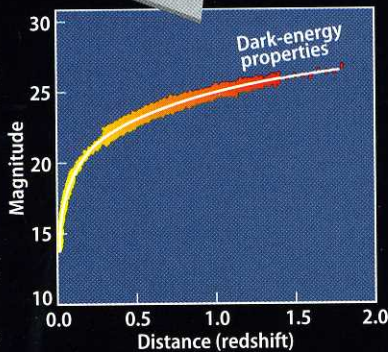
High-redshift supernovae



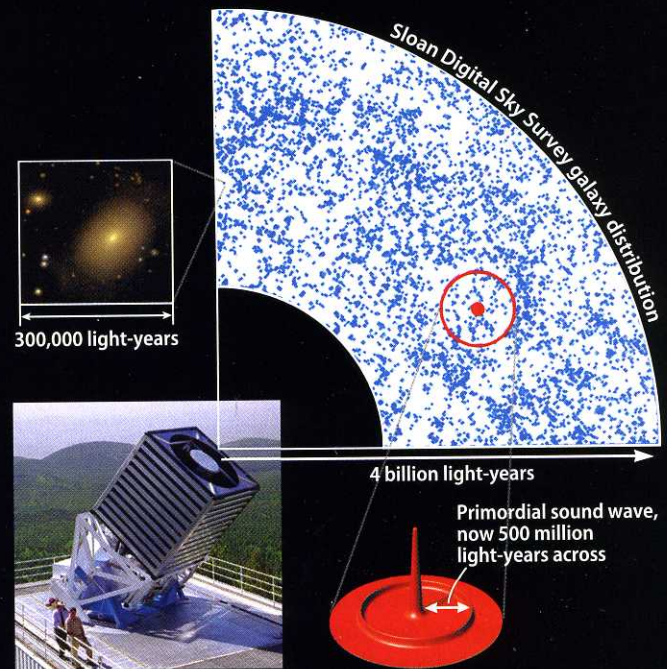
FAR-FLUNG SUPERNOVAE appear redder because cosmic expansion stretches the light we see.

ASTRONOMY: ROEN KELLY

THE MOST DISTANT type Ia supernovae look dimmer than they should, which indicates they're located farther from us than expected from the standard energy of these blasts. SN 1997ff, which lies at redshift 1.7, is the farthest such supernova known, but most of the type Ia variety have redshifts less than 1. In a single year, a space telescope dedicated to finding supernovae could identify thousands at redshift 1.5 and beyond. This would reveal much about dark energy's properties. *ASTRONOMY: ROEN KELLY*

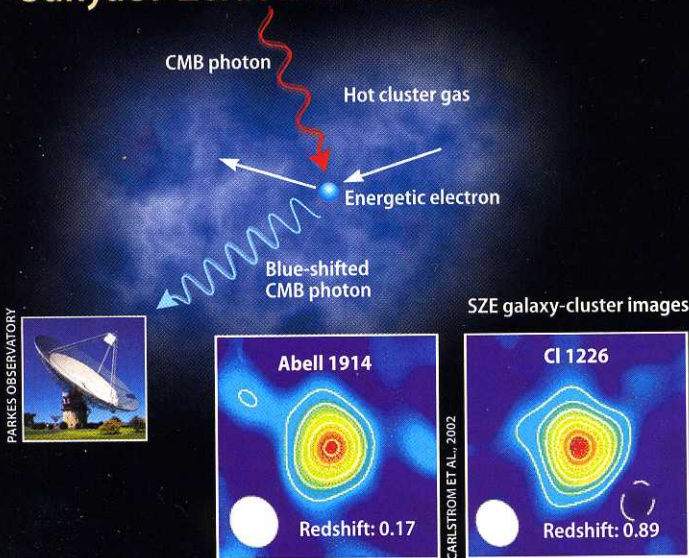


Baryonic acoustic oscillations



SOUND WAVES in the early universe left their imprint in the cosmic microwave background (CMB). In 2005, Daniel Eisenstein and colleagues announced the discovery of corresponding ripples in the distribution of galaxies mapped as part of the Sloan Digital Sky Survey (SDSS). Because the ripples appear both in relatively nearby galaxy groups and the high-redshift CMB, they offer a geometric measure of the relative distance between these widely separated redshifts — and more clues to cosmic acceleration. *SDSS*

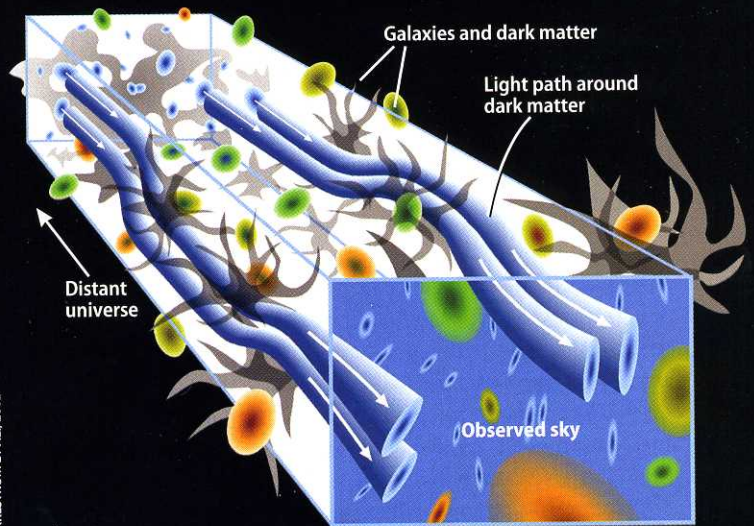
Sunyaev-Zeldovich effect



HOT GAS in massive galaxy clusters distorts the CMB. The gas' fast-moving electrons can give a CMB photon an energy boost. This distortion of the CMB is called the Sunyaev-Zeldovich effect (SZE).

ASTRONOMY: ROEN KELLY

Weak lensing



LIGHT FROM the distant universe wends its way through gravitational distortions caused by regions of dark matter. This creates a slight shear in individual galaxy images — so slight, it's apparent only when astronomers compare large numbers of galaxies. *LSST CORPORATION*

Two experiments are planned to achieve this goal. The Hobby-Eberly Telescope Dark Energy Experiment will survey a million galaxies out to redshift 3, starting in 2010. For comparison, this is almost double the 1.7 redshift of SN 1997ff, the most distant supernova known. Eisenstein is working with a competing group that hopes to install a Wide-Field Multi-Object Spectrograph (WFMO) on Hawaii's Subaru or Gemini North telescope. First light for the new instrument is scheduled for 2013.

Clusters count

Galaxy clusters offer insights into the problem, too. One method exploits the fact that the CMB spectrum is distorted in characteristic ways when its microwave photons interact with the hot gas inside clusters. The phenomenon, which cools long-wavelength photons and energizes short-wavelength photons, is called the Sunyaev-Zeldovich effect (SZE).

The South Pole Telescope (SPT) is a millimeter- and submillimeter-wavelength instrument in Antarctica searching for this effect. SPT designers expect to discover up to 30,000 new clusters with masses greater than 100 trillion Suns.

Once the survey identifies targets, optical observers will measure the clusters' redshifts so astronomers can determine how the number of clusters changes as a function of redshift. This, in turn, will show how dark energy evolved as the universe aged: The number of clusters is sensitive to whether gravity or dark energy is the dominant cosmic force.

High-energy astronomers are doing something similar using facilities like NASA's Chandra X-ray Observatory. "We see the cluster gas directly with X rays, whereas the SZE approach sees how the gas affects the CMB," explains Stanford University's Steven Allen.

In December 2008, Chandra scientists announced that they independently determined dark energy's existence. They looked for dark energy's effects on the growth of galaxy clusters. Over time, dark energy's repulsive effect should put the brakes on the growth of such clusters by counteracting gravity's pull. The astronomers found that structure growth has slowed in the past 5 billion years, which is roughly when many scientists think dark energy kicked in.

Through a lens weakly

Any concentration of mass bends the light of galaxies behind it. Sometimes this occurs in spectacular fashion, producing rings or double images in the sky. So-called weak gravitational lensing is more common, causing subtle effects that can be observed only statistically. In regions where matter is clustered, galaxy shapes become stretched a tiny bit, say 1 percent. This modest shearing of galaxy images is detectable because it generally occurs in a single direction. But you have to look at millions or, preferably, billions of galaxies to see a pattern.

Because dark energy affects the universe's expansion rate, it affects the distances between the source, lensing galaxy, and us. By changing these distances, dark energy alters the distortion pattern's strength, which is something scientists can measure.

Astronomers first documented the phenomenon of cosmic shearing in 2000, so the technique is still new. The best effort, according to University of Pennsylvania physicist Gary Bernstein, involved a survey of about 2 million galaxies over 75 square degrees. "We're just starting to measure dark energy, but the more galaxies we get, the better we'll do," he says. "The goal is to see as much sky as possible."

The Canada-France-Hawaii Telescope Legacy Survey at Mauna Kea — a 5-year effort begun in 2003 — measured millions

**"WE'RE JUST STARTING
to measure dark energy,
but the more galaxies we
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— Gary Bernstein

of galaxies over roughly 170 square degrees of sky. The 8.4-meter Large Synoptic Survey Telescope (LSST), scheduled to see first light in 2014 and begin science operations in 2015 at Cerro Pachón in northern Chile, is even more ambitious. This scope will survey a billion or so galaxies covering 30,000 square degrees. With this unparalleled combination of aperture and field of view, weak lensing — despite its name — could become powerful indeed.



THE LARGE SYNOPTIC SURVEY TELESCOPE is a ground-based, wide-field, 8.4-meter instrument designed to image the entire available sky every 3 nights. Its superb images will help astronomers trace the shapes of remote galaxies — and see distortions produced by dark matter. This will provide an important and independent measure of dark energy. LSST CORPORATION

Grand synthesis

A proposal called the Dark Energy Survey would gather data on 300 million galaxies and merge all of these techniques into a coherent overview. "These techniques complement each other well," says Joshua Frieman of the University of Chicago. "They suffer from different sources of error, so if they agree, that gives you confidence in the result." The survey could begin in 2011 with observations from Cerro Tololo's 4-meter Blanco Telescope.

Harvard's Christopher Stubbs concurs. "Supernovae misbehaving at high redshift won't affect the density of clusters, nor will observations of large-scale-structure formation affect supernova luminosities."

Owing to the difficulty in making these observations, no one will believe an answer unless it's obtained using more than one investigative method. Data so far show dark energy to be a much weaker form of Einstein's cosmological constant, but the precision isn't high enough to rule out other interpretations.

As California Institute of Technology cosmologist Sean Carroll puts it, "All we can do is keep improving the precision until we lose interest." Astronomers are far from that point now. "We are incredibly lucky to be working just at the moment when the pieces of the cosmic jigsaw puzzle are falling into place," he says. And dark energy constitutes the biggest puzzle piece of all. ■