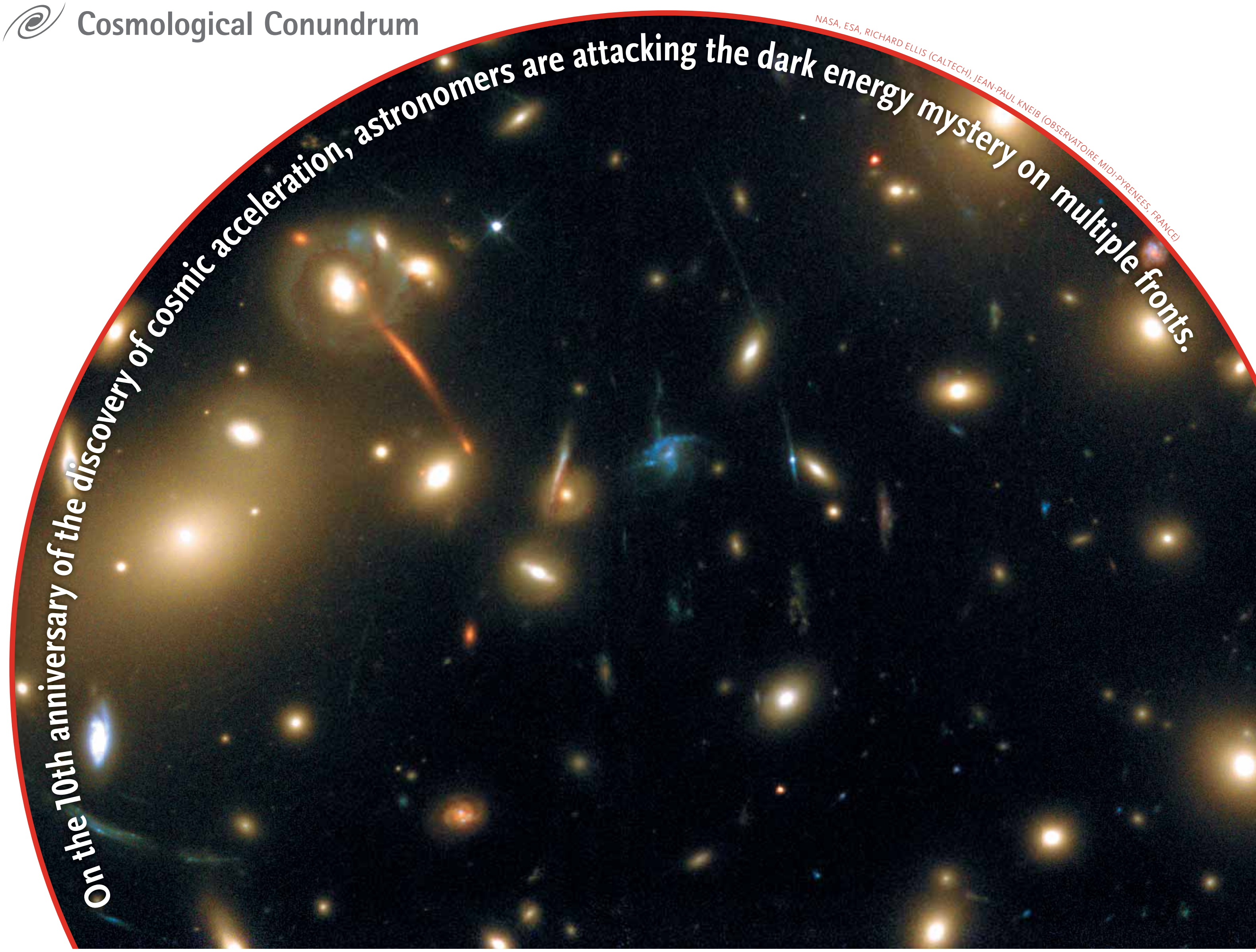


On the 10th anniversary of the discovery of cosmic acceleration, astronomers are attacking the dark energy mystery on multiple fronts.

NASA, ESA, RICHARD ELLIS (CALTECH), JEAN-PAUL KNEIB (OBSERVATOIRE MIDI-PYRENEES, FRANCE)

Going Over the Dark Side

RICHARD PANEK

THIS PAST MAY, at a symposium honoring the tenth anniversary of a landmark discovery, the director of the Space Telescope Science Institute (STScI) in Baltimore offered a history lesson. “It’s not often that astrophysics challenges fundamental physics,” Matt Mountain told his guests. “In the last 400 years you can count on one hand, perhaps on two, when these instances have occurred.”

Such a list would presumably begin with Galileo’s discoveries in 1610: the moons of Jupiter, which vividly demonstrated that there are more objects in the night sky than meet the naked eye; and the phases of Venus, which validated the Copernican view of the universe. In physics, Galileo’s observations led to Newton’s law of universal gravitation; in philosophy, they led to the Enlightenment. Now, a hundred of the world’s leading cosmologists gathered for a four-day celebration of the latest addition to the list: the 1998 discovery that the expansion of the universe appears to be not slowing down as astronomers had expected, but speeding up.

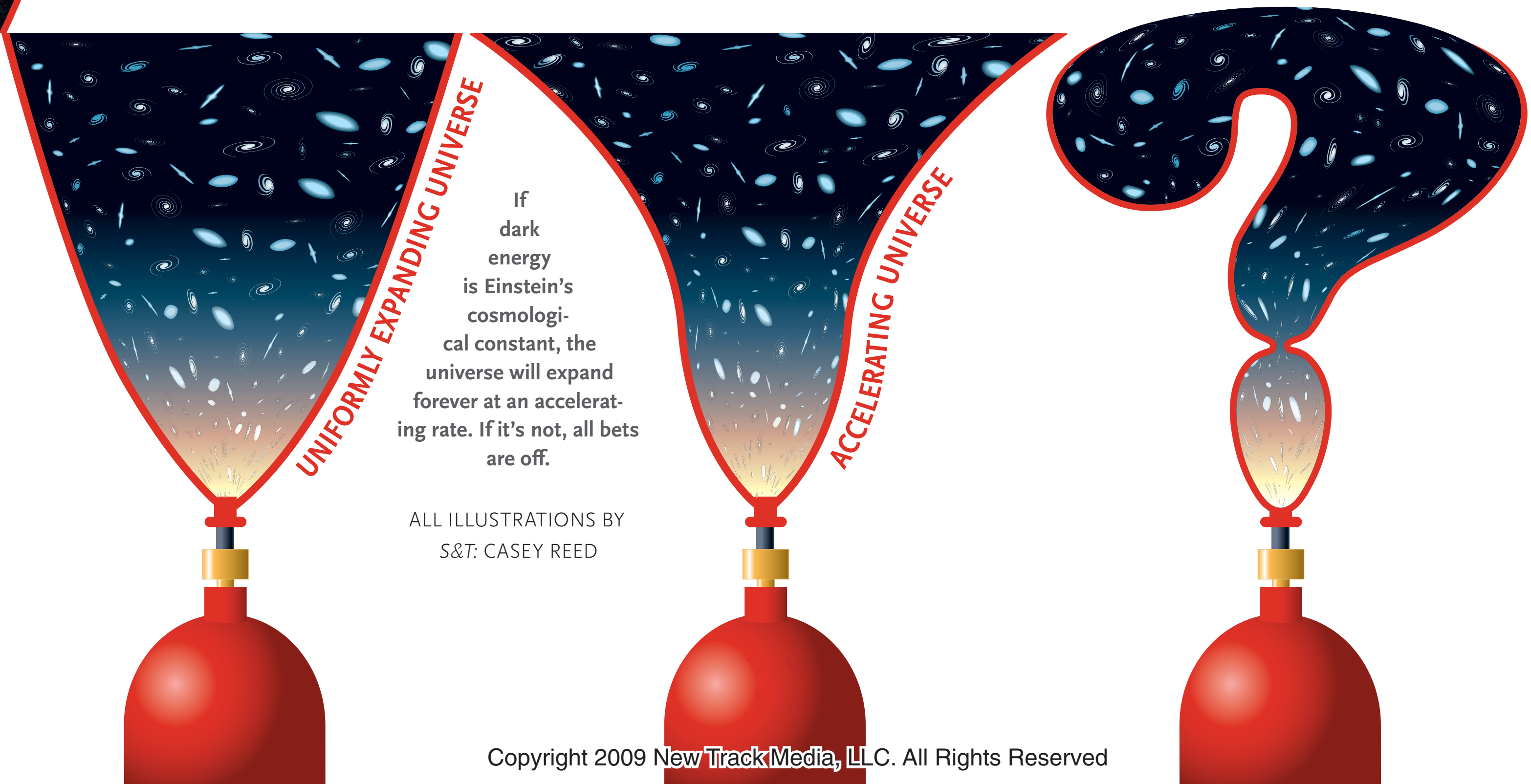
“This is game-changing science,” theorist Michael Turner (University of Chicago) repeatedly emphasized during the STScI symposium. It demands “nothing short of a revolution in our understanding of fundamental physics.” It might also turn out to be civilization-changing science — one that inaugurates nothing short of the next Copernican revolution in how we conceive our place in the universe. Ten years after the discovery, observers and theorists are finding plenty to celebrate, including several highly promising new techniques for investigating whatever it is that seems to be accelerating cosmic expansion. But they’re also voicing new concerns about how much they might ultimately be able to learn. As Mountain said, “We’re placing a large bet using the credibility of our community that we actually know what we’re doing.”

Starting a Revolution

The revolution began in the 1970s, when Vera Rubin (Carnegie Institution of Washington) and others found that in spiral galaxy after spiral galaxy, the outer arms were revolving at roughly the same rate as the central stars. According to Newton, these galaxies should be shredding apart — unless they contain some sort of stabilizing “dark matter.” By the end of the 1970s, most astronomers concluded that the universe contains even more than meets the telescopic eye.

But how much more? In a universe that’s churning with matter and operating under the laws of gravity, the expansion should be slowing down. Is the amount of matter sufficient to eventually reverse the expansion, or is it just enough that the expansion will eventually peter out?

Two teams of astronomers spent much of the 1990s trying to resolve this very question. Under the direction of Saul Perlmutter (Lawrence Berkeley National Laboratory) and Brian Schmidt (Australian National University), the rival groups used Type Ia supernovae as “standard can-



If dark energy is Einstein’s cosmological constant, the universe will expand forever at an accelerating rate. If it’s not, all bets are off.

ALL ILLUSTRATIONS BY *S&T:* CASEY REED

dles" — phenomena whose roughly uniform brightness allows astronomers to apply a simple dimmer-is-farther formula to calculate distances. In late 1997 and early 1998, both teams noticed that the more distant supernovae seemed dimmer, and therefore farther, than predicted. The two teams independently concluded that they were not measuring cosmic deceleration; instead, they were measuring cosmic *acceleration*.

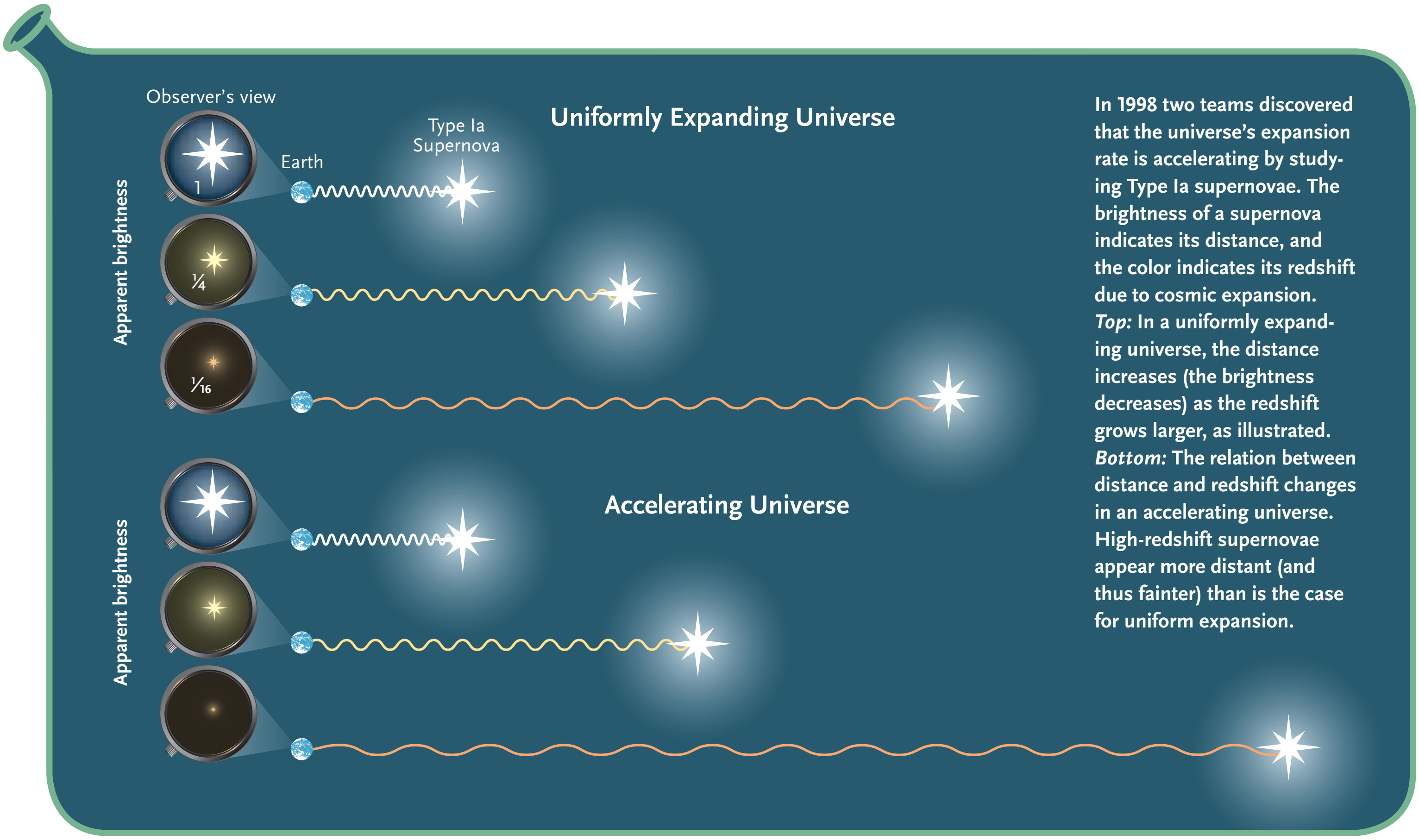
"The two groups really hated each other," says Turner. Partly because of this unlikely agreement between two rival groups, the astrophysical community found the surprising result easier to accept than if only one team had attained it. That same year, Turner coined the term "dark energy" for whatever it is that's causing the apparent acceleration.

Over the past decade, observations using several different methods have reinforced the 1998 results and arrived at virtually identical measurements of the mass-energy composition of the universe: 73% dark energy and 23% dark matter. That leaves only 4% for the stuff of galaxies, stars, planets, and people — the ordinary matter that has always been the subject of our physical and philosophical investigations, and that now seems to be, cosmically speaking, "a bit of pollution" according to Lawrence Krauss (Arizona State University).

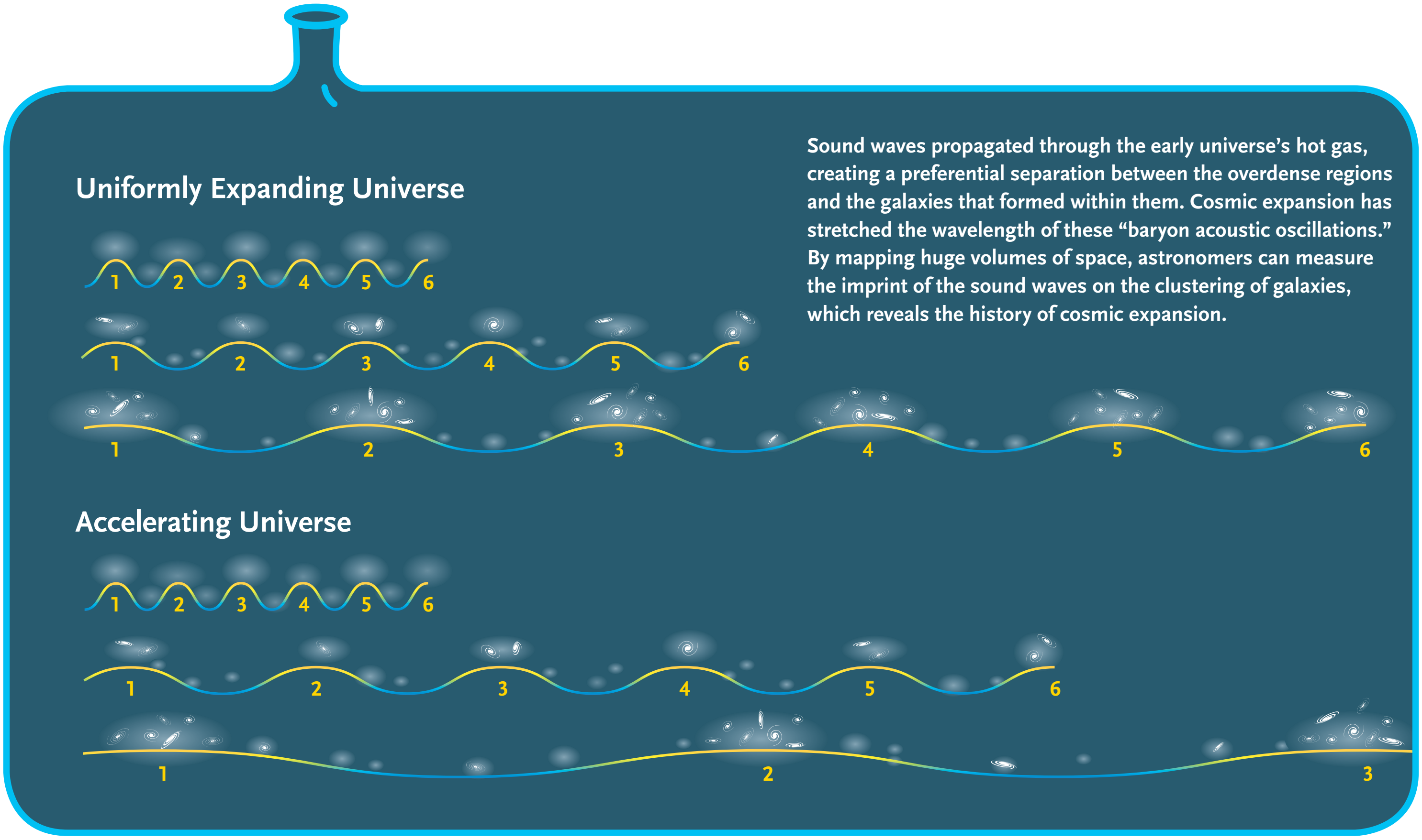
Antigravity

The term "dark energy" is new, but not the idea. In 1917, only a year after publishing his general theory of relativity, Albert Einstein considered the cosmological implications of his space- and mind-bending equations. In order to keep the universe he had created on paper as seemingly stable as the universe visible through telescopes, he had to infer the existence of some kind of cosmic force to counterbalance gravity. He represented this energy source in his equations with the Greek letter lambda (Λ). When Edwin Hubble found evidence for cosmic expansion in 1929, Einstein abandoned lambda. Today, with the news that the expansion seems to be speeding up, astronomers have reintroduced the term to represent a kind of "antigravity" that operates over large scales.

But what form does this energy take? If you know, reserve yourself a flight to Stockholm. Regarding dark matter, scientists have at least managed to round up a couple of suspects, neutralinos and axions, hypothetical particles that would solve some problems with the Standard Model of particle physics (*S&T:* August 2008, page 30). Now all that researchers have to do, albeit with great difficulty, is find them. But dark energy presents a more daunting challenge. The task is not to detect it but to *define* it — to figure out how it *works*.



In 1998 two teams discovered that the universe's expansion rate is accelerating by studying Type Ia supernovae. The brightness of a supernova indicates its distance, and the color indicates its redshift due to cosmic expansion. *Top:* In a uniformly expanding universe, the distance increases (the brightness decreases) as the redshift grows larger, as illustrated. *Bottom:* The relation between distance and redshift changes in an accelerating universe. High-redshift supernovae appear more distant (and thus fainter) than is the case for uniform expansion.



Sound waves propagated through the early universe's hot gas, creating a preferential separation between the overdense regions and the galaxies that formed within them. Cosmic expansion has stretched the wavelength of these "baryon acoustic oscillations." By mapping huge volumes of space, astronomers can measure the imprint of the sound waves on the clustering of galaxies, which reveals the history of cosmic expansion.

If dark energy doesn't change over time and space, then it behaves like Einstein's *cosmological constant*. If it changes over time and space, then it could be *quintessence*. But both terms, like "dark energy" itself, are placeholders — labels that scientists have adopted in lieu of understanding the nature of the phenomenon.

Einstein's cosmological constant proposes that a given volume of space should contain an inherent amount of energy, and that this energy suffuses the universe and remains constant over time. As the universe expands, and the volume of space increases, dark energy's effect becomes greater and greater, leading to acceleration. But according to quantum theory, the energy density of space should have a value 10^{120} times greater than the measured 73% of the universe's energy density. The early universe would have expanded so fast that gravity never could have reined in matter to form stars and galaxies.

As for quintessence, which stems from the ancient name for a hypothetical fifth element, it would be some kind of dynamical field previously unknown to physics. In principle, it could decelerate cosmic expansion in the distant future since its effects would change over time.

Distinguishing between the two alternatives would be a start, and that program has mobilized the entire cosmological community. A 2003 National Research Council report included "What Is the Nature of Dark Energy?" among the 11 most pressing scientific mysteries of the new century. In 2006 the National Science Foundation, NASA, and the Department of Energy (DOE) sponsored a Dark Energy Task Force report that listed the four most promising avenues for trying to answer that question.

Measuring Cosmic Expansion

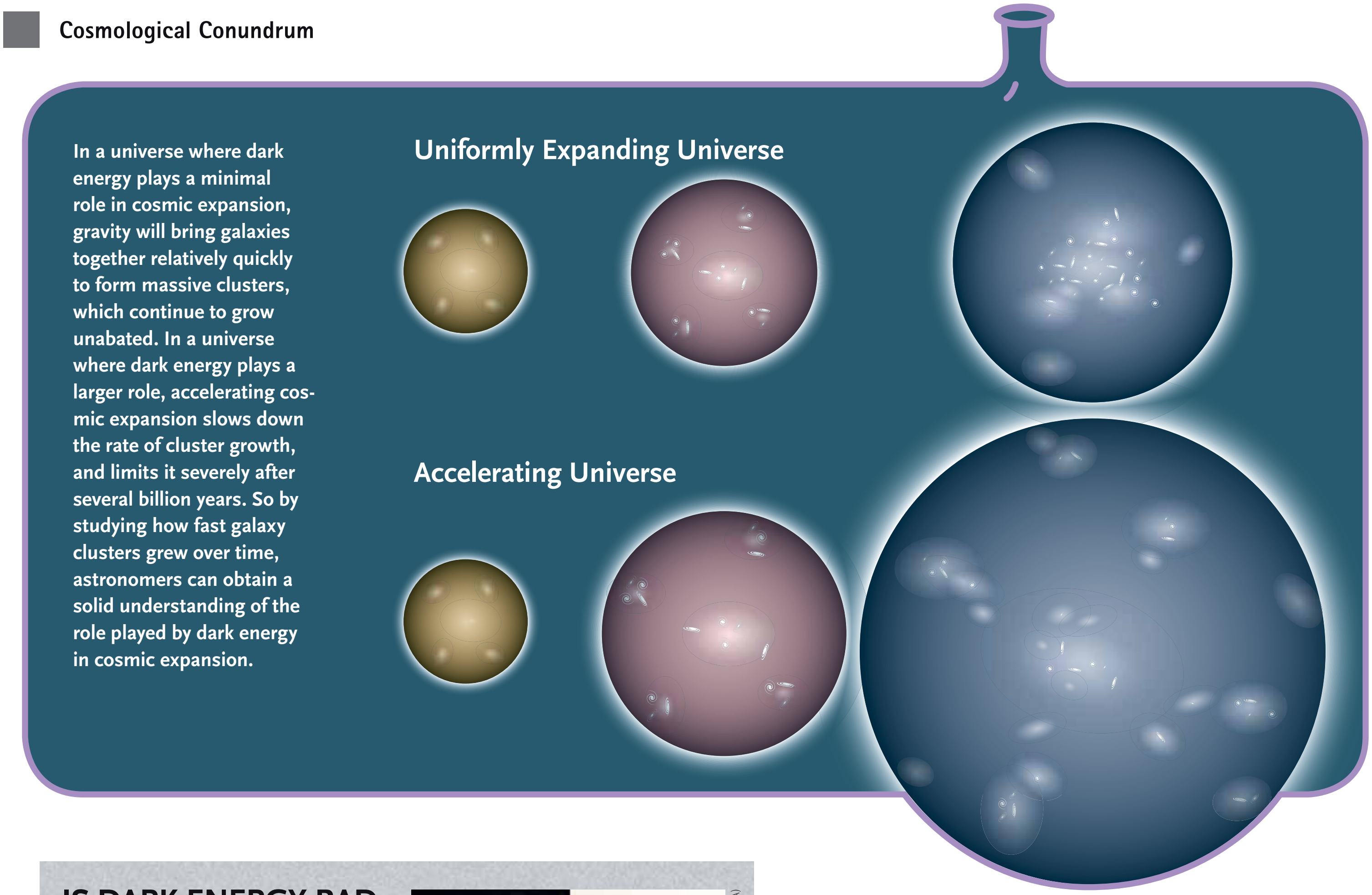
The first method is to use tried-and-true Type Ia supernovae, which result from exploding white dwarfs. Over the past decade numerous follow-up supernova surveys, some led by Perlmutter or by Schmidt's primary 1998 collaborator, Adam Riess (Johns Hopkins University), have significantly refined the evidence for cosmic acceleration by analyzing supernovae both near and far.

But supernova surveys alone are not definitive because nobody really understands the mechanics of how white dwarfs explode. "One of our main findings," the Task Force concluded, "is that no single technique can answer the outstanding questions about dark energy." Astronomers have stepped into that observational vacuum by introducing several ingenious new techniques to complement supernova surveys in determining the universe's expansion history, which is presumably the key for unraveling the dark energy mystery.

ESOTERIC THEORIES

The nature of dark energy is such a perplexing mystery that scientists are also considering esoteric theories that defy experimentation, at least for the foreseeable future: parallel universes, extra dimensions, and the anti-Copernican idea that we're special after all — that our visible universe is an unusually low-density region of a much larger cosmos.

Besides Type Ia supernovae, astronomers can measure *baryon acoustic oscillations* (BAOs). Early in the universe, sound waves ("acoustic oscillations") coursed through



In a universe where dark energy plays a minimal role in cosmic expansion, gravity will bring galaxies together relatively quickly to form massive clusters, which continue to grow unabated. In a universe where dark energy plays a larger role, accelerating cosmic expansion slows down the rate of cluster growth, and limits it severely after several billion years. So by studying how fast galaxy clusters grew over time, astronomers can obtain a solid understanding of the role played by dark energy in cosmic expansion.

the primordial gas, creating peaks at intervals of 436,000 light-years (*S&T:* May 2008, page 18). As the universe has expanded, so has the spacing between these peaks; today they are 476 million light-years apart. And because galaxies tended to form on the peaks of these very large waves, astronomers can measure galaxy distributions at different eras, allowing them to see how the peak spacing changed over time, and thus how fast the universe has expanded. Whereas Type Ia supernovae behave like standard candles, the spacing between galaxies acts like a standard ruler.

A third approach advocated by the Task Force involves *weak lensing,* the distortion of light from distant galaxies through the gravitational influence of foreground clusters of galaxies. Astronomers can use this method to determine the shapes of millions of galaxies at various distances, which provides a direct probe of the mass of intervening clusters. Using weak lensing, astronomers can also measure how fast galaxies congregated together into clusters. The clustering rate depends very strongly on how fast the universe was expanding at different epochs, so it's an excellent way to study the effects of dark energy.

The final approach involves another method for taking a census of galaxy clusters. Astronomers can find clusters efficiently by looking for the effect they produce on the cosmic microwave background (CMB). The hot, X-ray emitting gas that envelops clusters distorts the CMB in

IS DARK ENERGY BAD FOR ASTRONOMY?


THE HUBBLE HERITAGE TEAM (AURA/STSCI/NASA)

In 2007 Simon White (Max Planck Institute for Astrophysics, Germany) wrote a controversial paper (see http://arxiv.org/abs/0704.2291) titled "Fundamentalist Physics: Why Dark Energy Is Bad for Astronomy." White argued that the pursuit of dark energy could fail to produce significant progress, while draining precious resources from traditional astronomical research. He also argued that dark energy is a problem for particle physicists, who represent a different culture and use different techniques to address scientific questions. "By uncritically adopting the values of an alien system," he wrote, "astronomers risk undermining the foundations of their current success and endangering the future vitality of their field."

Physicist Edward "Rocky" Kolb (University of Chicago) countered with a paper (http://xxx.lanl.gov/abs/0708.1199) arguing that the two disciplines are "bound fast by a thousand invisible cords that cannot be broken," and that collaborations between astronomers and particle physicists have a proven track record of being mutually beneficial in humanity's quest to understand the origin and evolution of the universe.

Please let us know what *you* think about this controversy by visiting SkyandTelescope.com/darkenergy.

***Robert Naeye** is Editor in Chief of* Sky & Telescope**.**

a distinctive way that will be relatively easy to spot with two new instruments: the South Pole Telescope and the Atacama Cosmology Telescope. Unfortunately, determining a cluster's mass is notoriously difficult. The best method is to measure the X-ray emission from the hot gas. This result, however, is subject to an uncertainty that limits the reliability of this method.

The Magic Number

Cosmologists are hoping that all of these techniques ultimately converge on one number — what they call dark energy's equation of state, and which they designate with the letter *w*.

In quantum theory, a ratio of the negative pressure of dark energy to its energy density exactly equal to –1 would represent a property of space itself that doesn't change over time — i.e., the cosmological constant. In that case, even the slightest discrepancy from –1 would eliminate the cosmological constant in favor of something else, possibly quintessence. In order to distinguish between a cosmological constant and quintessence, the Task Force recommended that the government make a dark-energy space mission a top priority.

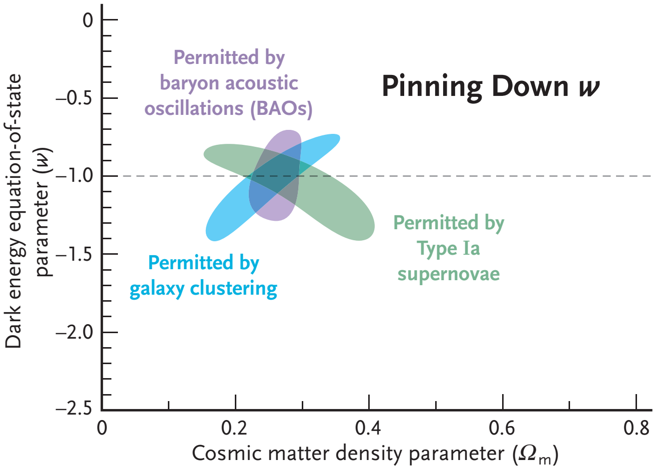
Last September, NASA and the U.S. Department of Energy agreed to collaborate on the construction of an $800 million Joint Dark Energy Mission (JDEM), which would extend the reach of observations that can be made from the ground. Funding for JDEM is planned to ramp up next year, with the goal of launching around 2015.

Observations using the various methods seem to be converging on a *w* equal to –1, although a team led by Will J. Percival (University of Portsmouth, UK) recently reported that its BAO analyses might indicate a slightly stronger acceleration in recent times, leading to a value of *w* slightly less than –1. This kind of "discrepancy" — or "headache," as he also calls it — often goes away under further scrutiny. But as Riess himself points out, "I remember this one time in 1998 it did not."

Many astronomers are questioning the rationale for JDEM, and whether the mission will have sufficient funding to do its job. How much could a new space telescope improve on previous observations? And if a space mission found a deviation from the magic number of –1, would the margin of error be so well characterized that cosmologists would believe the result? As Krauss said, "We need to do better than anything we're ever going to be able to do in our lifetime, I expect, experimentally."

Closing One Chapter, Opening Another

And what if astronomers received all the funding they wanted and then managed to measure *w* with reasonable confidence and high precision? As scientists have recognized from the start, they still wouldn't know how to make sense of the answer.



By comparing how the results from different methods overlap, astronomers should one day achieve a good understanding of the universe's expansion history. This, in turn, will constrain the value of *w*, dark energy's equation of state. This information will rule out numerous possible explanations for cosmic acceleration.

Cosmologists are even willing to consider that the answer might be neither a cosmological constant nor quintessence. Instead, it could require a modification of Einstein's equations of gravity. The prospect of "new physics" is precisely why so many cosmologists think they should be pursuing dark energy. "In spite of the fact that you're likely to spend the rest of your lives measuring stuff that won't tell us what we want to know," Krauss said to the observers at the STScI symposium, "you should keep doing it."

At a UCLA dark energy tenth-anniversary commemoration in February, science historian Robert P. Crease (Stony Brook University) took the centuries-long view and declared, "We are closing one chapter and opening another." He later elaborated: "Certain discoveries in astronomy are significant not only because they rearrange the objects in the heavens, but also because they affect the way we humans view ourselves and our place in the universe. The dark energy discovery is of that kind."

To hear a podcast interview with the author, visit SkyandTelescope.com/darkenergy.

It's one thing to say that we don't know what some of the universe is made of, as is the case with dark matter. It's quite another to realize, after four centuries of heroic observations and theorizing, that we don't even know how it works. ✦

A 2008 Guggenheim Fellow in Science Writing, ***Richard Panek*** *is researching a book on dark matter and dark energy, tentatively titled* Let There Be Dark *(Houghton Mifflin, 2010). His previous books include* Seeing and Believing: How the Telescope Opened Our Eyes and Minds to the Heavens *and* The Invisible Century: Einstein, Freud, and the Search for Hidden Universes.