

The Quest for Dark Energy: High Road or Low?

A space telescope could reveal the mysterious stuff that is blowing the universe apart—if those on the ground don't do it first

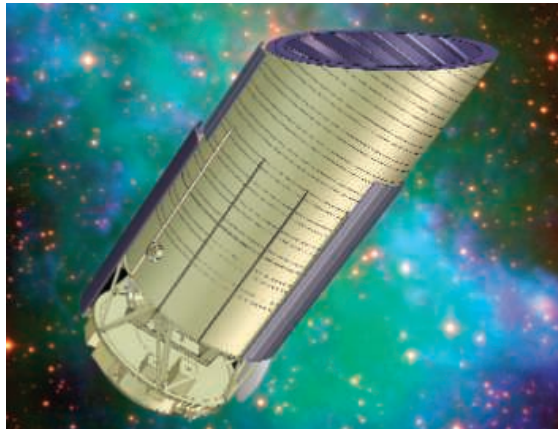
Seven years ago, astrophysicists asked a simple question: "How far?" The answer overturned our understanding of the cosmos.

Since 1929, researchers had known that the universe is expanding. But they assumed the expansion is slowing as the universe's own gravity tugs against it. Two teams set out to observe the slowing by measuring the distances to exploding stars known as supernovae. To the researchers' surprise, the farthest supernovae were farther than expected. That meant the expansion of the universe is accelerating as if driven by some weird space-stretching "dark energy."

"When we first saw the result, I assumed our data was miscalibrated," recalls Saul Perlmutter of Lawrence Berkeley National Laboratory and the University of California, Berkeley. But within a few years, studies of the afterglow of the big bang—the "cosmic microwave background"—and other measurements bolstered the case for dark energy and showed that it accounts for a whopping two-thirds of the universe. "The amazing thing about this discovery is how quickly people accepted it," Perlmutter says.

Yet researchers still don't know what the mysterious stuff is. They believe the answer lies in observing thousands of supernovae and millions of galaxies. Sometime in the next decade, NASA and the U.S. Department of Energy (DOE) are expected to launch a \$600-million space telescope designed to measure dark energy, the Joint Dark Energy Mission (JDEM).

But even as they lay their plans for the satellite, researchers are debating whether they could hammer out key properties of dark energy with observations from the ground. NASA, DOE, and the U.S. National Science Foundation have received dozens of proposals for measuring dark energy from terra firma, and the agencies have assembled a Dark Energy Task Force to evaluate them and report back by year's end. The task



Don't look down. A proposed space telescope such as SNAP (top) faces competition from today's ground-based telescopes such as the Canada-France-Hawaii Telescope on Mauna Kea.

force's report will help the agencies set their near-term priorities and will inform another panel studying proposed methods and technologies for JDEM.

Figuring out what can be done from the ground may be key to keeping JDEM affordable. "Clearly, you should only do from space what you have to do from space," says Rocky Kolb, a cosmologist at the Fermi National Accelerator Laboratory in Batavia, Illinois, and chair of the task force. But deciding what's best done where is tricky, says Charles Bennett, an astrophysicist at Johns Hopkins University in Baltimore, Maryland, and co-chair of the JDEM science definition team. "We don't know what dark energy is, and there are different ways to

measure it and different aspects to measure," Bennett says. "There are unknowns in all directions."

Weird and weirder

So far theorists have dreamed up three ideas of what dark energy might be, each one a challenge to the current conception of the universe, says Sean Carroll, a theoretical physicist at the University of Chicago. "There are no uninteresting possibilities," Carroll says, "which is what makes it so exciting."

Perhaps the simplest explanation is that dark energy is part of the vacuum itself, so that space naturally tends to stretch as if driven by some inherent constant pressure. In 1917, Albert Einstein proposed such a pressure, or "cosmological constant," to counteract gravity and keep the universe from imploding. He later abandoned the notion as unnecessary when astronomers found that the universe is in fact expanding. But Einstein's orphaned idea may be the thing that drives the acceleration of the universe.

If so, it will vex particle physicists. For decades they've known that, thanks to quantum mechanics, the vacuum roils with particles popping in and out of existence, and that such "virtual" particles give the vacuum an energy that could serve as the cosmological constant. Unfortunately, the energy physicists calculate is far too big to fit the data. In the past, theorists have assumed for the sake of simplicity that some still-unknown principle cancels everything out to make the vacuum energy add up to zero. If there is a cosmological constant, Carroll says, that tidy fix won't work.

Alternatively, the dark energy might come from some sort of particle or interaction that propagates through space much as light does and provides the space-stretching push. Such "quintessence" theories skirt the problem with the vacuum energy, but they run into difficulties with other aspects of particle physics. For one, theorists must explain why the new particles don't interact with those already familiar to us.

Finally, the accelerated expansion might not be driven by dark energy at all. Rather it could signal that across billions of light-years, gravity no longer works as Einstein's general theory of relativity predicts it should. "It's very hard to change gravity on large distances without changing it at short distances, too," says Gia Dvali, a theoretical physicist at New York University. But that's a good thing, he says, because it means that theories that modify gravity may be easier to test.

Researchers hope to distinguish between the possibilities by measuring simply how the density of dark energy changed as the uni-

verse expanded. If dark energy is a cosmological constant, then the density should have remained constant (see figure, below). And if the density varied, then dark energy must be something else. To tell the difference, researchers must trace the history of the expansion of the universe, which is encoded in the ancient light from far-flung stars.

How red? How far?

The quest boils down to asking two questions about some astronomical object, such as a supernova or a cluster of galaxies: How far away is it? And how red is its light? The record of the universe's expansion lies in the combination of the two answers, the so-called "distance-redshift relation."

As space expands, light zipping through it stretches to longer and redder wavelengths, much as sound waves in a slide whistle shift to lower pitches as the whistle's plunger descends. Light's wavelength increases more quickly if space is stretching faster. So to accumulate a given amount of stretch, or "redshift," light would have had to travel longer and farther if the universe had expanded more slowly billions of years ago than if the universe had always expanded at its current rate. Astronomers first glimpsed dark energy by noting that supernovae whose light had been stretched by 20% to 100%—that is, with redshifts of 0.2 to 1.0—were farther away than expected (*Science*, 27 February 1998, p. 1298). The leading proposals for JDEM—designs named SNAP, JEDI, and Destiny—all aim to measure thousands of supernovae with redshifts as high as 1.7.

But instead of a supernova, the object in question could be the distance between galaxies, says Daniel Eisenstein, a cosmologist at the University of Arizona in Tucson. Because of a phenomenon known as "baryon acoustic oscillations," galaxies show a slight tendency to space themselves at a specific distance. That distance, about 500 million light years, is determined by how far sound waves traveled in the plasma that filled the primordial universe before atoms formed. By surveying millions of galaxies of a given redshift and measuring how far apart they appear in the sky, researchers can determine their distance and deduce the distance-redshift relation, Eisenstein says.

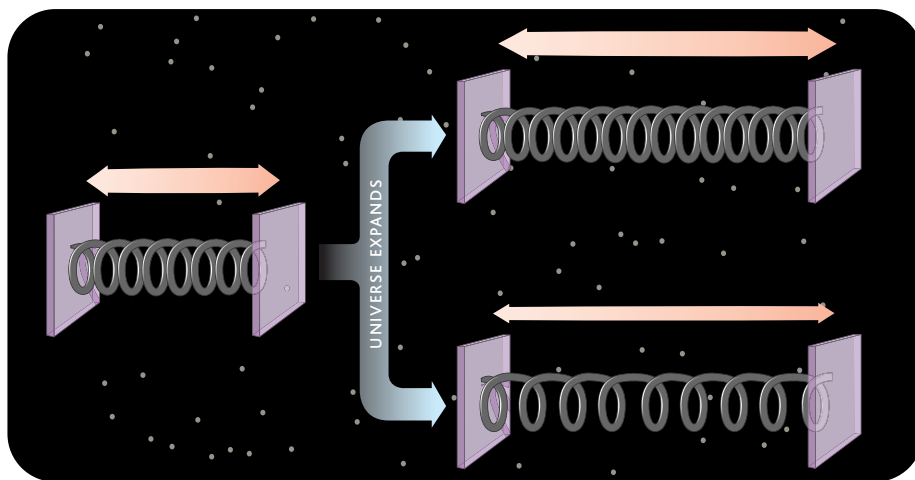
Galaxies might also reveal the evolution of dark energy through a more subtle effect. From studies of the cosmic microwave background, researchers know that almost all the matter in the universe is undetected "dark matter," which fills space with vast filaments that contain the galaxies. Gravity from those threads bends light from more distant galaxies and distorts their appearance so that neighboring galaxies in the sky seem to line up (*Science*, 17 March 2000,

p. 1899). Such "weak gravitational lensing" depends on the distances to the dark-matter "lens" and the observed galaxy. So by comparing the lensing of millions of galaxies at different redshifts, researchers hope to decipher the distance-redshift relation.

Finally, researchers might probe dark energy simply by counting clusters of galaxies in a patch of the sky, says Joseph Mohr, an astronomer at the University of Illinois, Urbana-Champaign. The number of clusters at a given redshift reveals how much volume the patch contains, and the

at the University of Pennsylvania in Philadelphia. So a space-based weak-lensing study might do better than LSST even if it counted only a few hundred-million galaxies. Similarly, the redshifts of galaxies are harder to measure from the ground, says Arizona's Eisenstein, so earth-bound baryon acoustic oscillation measurements could prove impractically slow.

Given the uncertainties, researchers have proposed different strategies for JDEM. The infrared Destiny space telescope would measure only supernovae, says



Loaded question. Dark energy acts like a spring that stretches space. If it's a cosmological constant, the spring grows with space to maintain a constant push (*top*). Otherwise, the push may vary (*bottom*).

size of the patch in the sky reveals how far away it is, just what cosmologists need to know to trace the expansion.

The ups and downs

The question now is where best to make the observations. All agree that supernovae with redshifts greater than 1 can be studied only from space because their light stretches to infrared wavelengths that would get lost in the infrared glare of the atmosphere. Beyond that, consensus vanishes.

"If you're looking at stellar objects, you're better off in space," says Anthony Tyson, an astrophysicist at the University of California, Davis. "If you're looking at galaxies, you're better off on the ground." Tyson leads the team developing the Large Synoptic Survey Telescope (LSST), a ground-based behemoth with an 8.4-meter mirror and a camera with 3 billion pixels, which if funded could take its first look at the sky in 2012 (*Science*, 27 August 2004, p. 1232). Imaging the entire sky and some 3 billion galaxies, LSST should best space-based measurements of weak lensing and baryon acoustic oscillations, Tyson claims.

But others say such cut-and-dried standards are too simplistic. For example, atmospheric distortions can mimic weak lensing, says Gary Bernstein, a cosmologist

Jon Morse, an astrophysicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "Destiny is focused like a laser on this one problem," he says. But that's taking a risk, says Yun Wang, a cosmologist at the University of Oklahoma in Norman and leader of the JEDI project. "We still don't know that supernovae will give you the precision you need to really know what dark energy is," she says. JEDI and SNAP would measure supernovae, weak lensing, and baryon oscillations.

The biggest uncertainties surrounding JDEM may be more political than technical. Both NASA and DOE list JDEM as a priority, but neither has committed to building it. Researchers say they're ready to start now, for a launch before 2011. But JDEM may not launch until 2017. And in the meantime, ground-based measurements will continue to whittle away at our ignorance—and JDEM's potential scientific impact.

"You shouldn't look at a space mission as an improvement over what you know today," says Johns Hopkins's Bennett. "You should look at it as an improvement over what you'll know tomorrow." But as tomorrow gets pushed further into the future, such prognostications grow as murky as the nature of dark energy itself.

—ADRIAN CHO