DARK ENERGY & The Preposterous Universe

By Sean Carroll

About 70 percent of our universe takes the form of an unknown energy field that is accelerating cosmic expansion.

WHAT IS THE UNIVERSE MADE OF? This question has been asked, in one form or another, for thousands of years. But now, thanks to a set of increasingly precise and complementary measurements, we think we're closing in on the answer.

It's not an answer anyone would have expected. Of all the energy in the universe, only about 5 percent consists of familiar matter — the kinds of particles we have observed in laboratories. About 25 percent of the universe is *dark matter,* presumably some type of particle that we have detected only because it gravitationally pulls on stars, gas, and galaxies. The remaining 70 percent is even more mysterious: some form of *dark energy* that is spread uniformly throughout space and that evolves very slowly, if at all.

We're a long way from truly understanding dark energy, but compelling evidence favors its existence. Because the nature of dark energy remains elusive, we cannot claim that we really know what the universe is made of. We know dark energy's characteristic properties — its density is nearly constant through space and time — but not really what it *is.* The quest to make sense of dark energy is guaranteed to teach us something profound about the universe.


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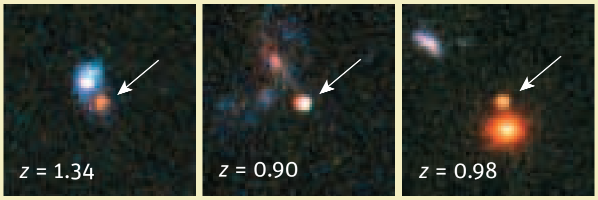
Evidence for Dark Energy



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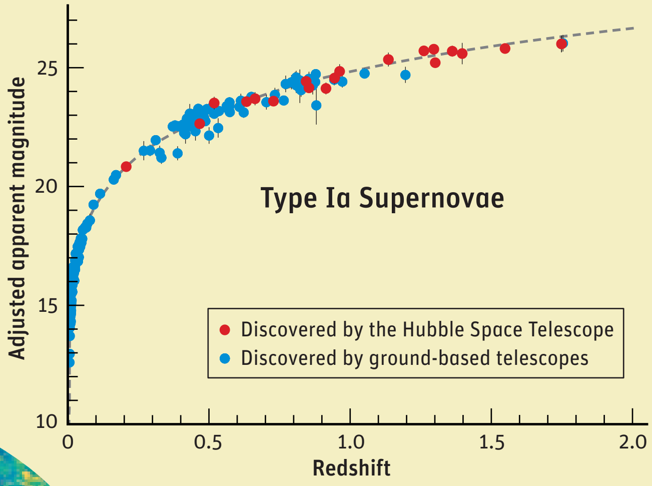
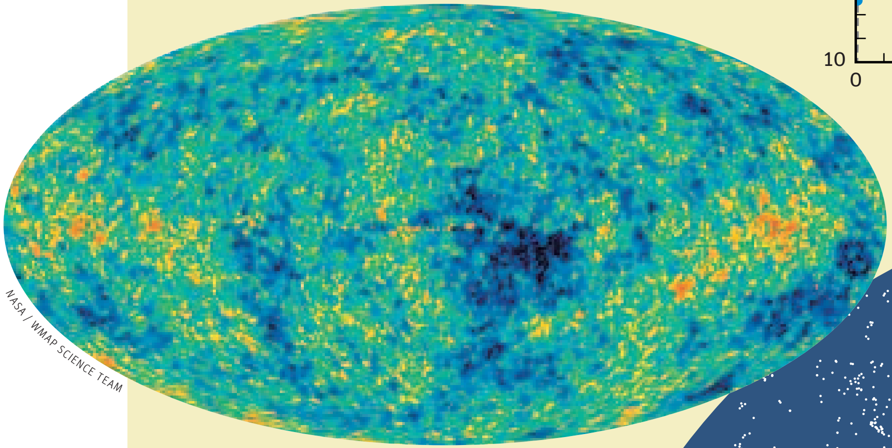


SOURCE: ADAM G. RIESS ET AL.



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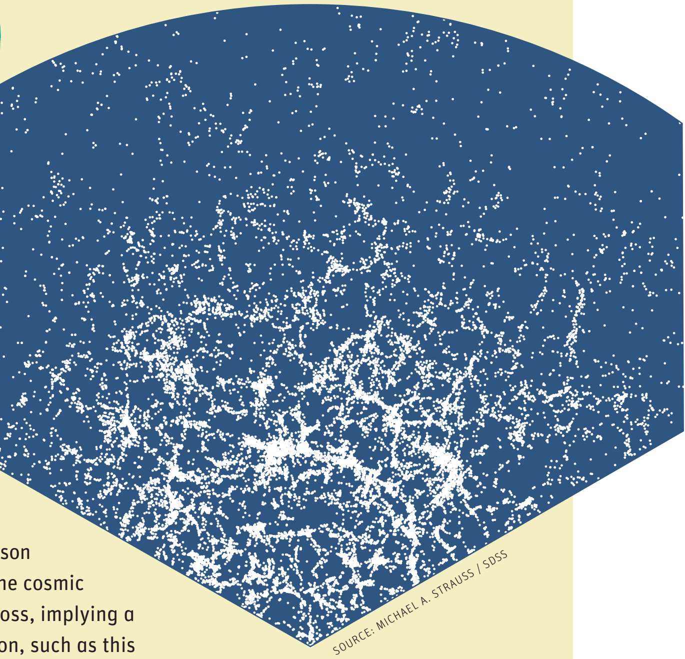


SOURCE: MICHAEL A. STRAUSS / SDSS

At least three lines of evidence support the existence of dark energy. *Upper left:* The Hubble Space Telescope's Advanced Camera for Surveys captured images of these very distant Type Ia supernovae. By comparing the distance and redshift of such standard candles, cosmologists have determined that the universe's expansion is accelerating. *Upper right:* The observed brightnesses and redshifts of dozens of Type Ia supernovae fit beautifully to a model universe (dotted line) with 30 percent matter and 70 percent dark energy. *Above:* The Wilkinson Microwave Anisotropy Probe measured small-scale temperature fluctuations in the cosmic microwave background. Hot spots (red) and cold spots (blue) are typically 1° across, implying a spatially flat universe that requires dark energy. *Right:* Maps of galaxy distribution, such as this example from the Sloan Digital Sky Survey, are consistent with models that invoke dark energy.

The Expanding Universe

With approximately 100 billion galaxies, the observable universe is big, and it's getting even bigger as it expands. Not everything *within* the universe is expanding, however. Bound systems like atoms, galaxies, and human beings aren't. (If you *are* expanding, it's for noncosmological reasons!) But the spaces between distant galaxies increase with the passage of time.

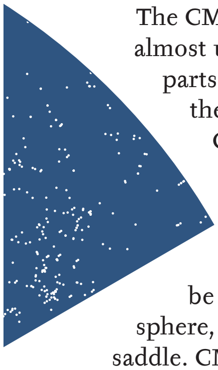
The observable universe is, by definition, limited to the parts we can see. How can we be sure that we aren't missing something? We have detected dark matter indirectly by seeing its gravitational influences. But we have been able to determine this only because matter settles into galaxies and clusters, where we can see its gravitational effects concentrated in one region (see page 26). Could there be some form of perfectly smooth energy that doesn't concentrate into dense regions? Such smoothly distributed energy wouldn't measurably affect how matter moves *within* individual galaxies or clusters, but it would still affect the overall expansion of the universe.

It is reasonable to expect that cosmic expansion should gradually slow down since galaxies exert gravitational pulls on one another. It therefore came as a shock when, in 1998, two groups — the High-Z Supernova Search Team and the Supernova Cosmology Project — announced that the expansion is actually *accelerating* (*S&T:* September 1998, page 38). Both groups used Type Ia supernovae (which originate from exploding white dwarfs) as "standard candles" — objects whose intrinsic brightnesses are known. If a standard candle appears dim, it must be far away. By measuring a supernova's redshift, astronomers can tell how much the universe has expanded since the object emitted its light, because the amount of redshift depends directly on cosmic expansion. The observed supernovae were dimmer and thus farther away than we had expected given their redshifts, a telltale sign of cosmic acceleration.

Detecting the Undetectable

The best explanation for the universe's unexpected acceleration is dark energy — some mysterious form of energy whose density is nearly or perhaps exactly the same in every cubic centimeter of space, diminishing slowly (if at all) as the universe expands. Dark energy's persistence provides a constant impulse to the universe, accelerating its expansion (see "Why Dark Energy Makes the Universe Accelerate" at lower right).

Dark energy is a mind-boggling concept. How can we be certain we're on the right track? Fortunately, we have other handles on dark energy besides supernovae. A smooth energy density affects not only the cosmic expansion rate but also the overall curvature of space itself. This curvature, in turn, shapes the temperature fluctuations that we can observe in the cosmic microwave background, or CMB (*S&T:* October 2003, page 30).



The CMB, leftover radiation from the Big Bang, appears almost uniform, but its temperature differs by a few parts per hundred thousand from place to place on the sky. The curvature of space can distort the CMB's "hot" and "cold" spots, changing their apparent size. Running the numbers, cosmologists predict that the fluctuations should appear strongest at an angular scale of 1° if space is flat like a tabletop. This scale would be larger if space were positively curved like a sphere, and smaller if space were negatively curved like a saddle. CMB observations from ground-based experiments, balloon-borne experiments, and satellites indicate that the CMB is lumpiest right at 1°, indicating that space is indeed very close to flat. But luminous and dark matter combined provide only 30 percent of the energy density required to make the universe flat (according to $E = mc^2$, matter is a form of energy). There must be some additional energy component that doesn't allow itself to be gathered into galaxies or galaxy clusters.

Projects such as the Two Degree Field (2dF) Galaxy Redshift Survey (*S&T:* February 2003, page 32) and the Sloan Digital Sky Survey (February issue, page 34) reveal how galaxies are arranged in large-scale structures. These configurations depend mostly on dark matter, but dark energy also influences the way galaxies cluster into sheets and walls. The galaxy-distribution maps produced by 2dF and Sloan closely match predictions for a universe dominated by dark energy.

Thus, the concept of dark energy has received spectacular observational support: supernovae, CMB fluctuations, and galaxy clustering fit theoretical expectations perfectly in a universe with about 5 percent familiar matter, 25 percent dark matter, and 70 percent dark energy. Disbelieving the existence and dominance of dark energy requires the simultaneous failure of at least three completely independent kinds of measurements.

Dark energy is a mind-boggling concept. How can we be certain we're on the right track?

Vacuum Energy

But such a universe makes no sense to us. Two features in particular come as a complete surprise. For one, though it may seem counterintuitive, dark energy is inexplicably feeble. For another, the present densities of dark energy and dark matter are comparable — within a factor of 3.

To understand these issues, consider the most straightforward dark-energy candidate: *vacuum energy,* an energy present in empty space that is perfectly uniform everywhere in the universe. The idea of vacuum energy dates back to Albert Einstein, who introduced the "cosmological constant" into his general theory of relativity in 1917. At the time, astronomers thought the universe was neither expanding nor collapsing, so he used the cosmological constant to balance the attraction of matter. Once Edwin P. Hubble discovered cosmic expansion in 1929, Einstein realized that the cosmological constant was superfluous, and he abandoned the concept. Although he was wrong twice, we have no reason to feel superior, since we are still at a loss to understand this mysterious quantity.

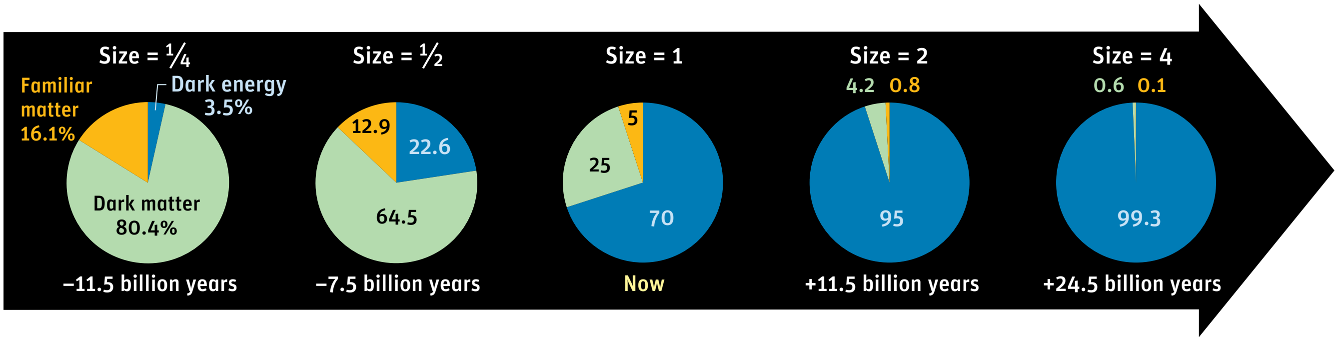
Vacuum energy is not a gas, a fluid, or any other substance; it is rather a *property* of space-time itself. It is simply the minimum amount of energy present in any region of space, the energy that remains when we remove any kind of "stuff" from the region. In general relativity, this quantity could be positive or negative, with no special reason why it should be zero.

Why Dark Energy Makes the Universe Accelerate

According to Einstein's general theory of relativity, the universe's expansion rate, as measured by the Hubble parameter H, depends directly on the energy density: the amount of energy per cubic centimeter. At early times, when the universe was smaller and denser, H was extremely large. Matter dominated, and the energy density came mostly from the rest mass of particles such as protons and electrons, through $E = mc^2$. But cosmic expansion diluted the particle number density and thus the energy density in matter, and H decreased rapidly. Its value today (denoted H_0) is rather paltry — about 71 kilometers per second per megaparsec.

Now we're in an era where dark energy dominates, and since its energy density remains essentially constant, so too does H —meaning that the universe now expands at a constant rate.

How can a constant expansion rate be called "accelerating"? Consider a galaxy 100 million light-years away. In 14 billion years its distance will have doubled to 200 million light-years. In another 14 billion years it will have doubled again, to 400 million light-years. In each successive interval, the galaxy takes a bigger step away, meaning its velocity is increasing — that is, it is accelerating. So the statements "the expansion rate of the universe is approximately constant" and "distant galaxies appear to be accelerating away from us" are perfectly consistent with each other.



SOURCE: SEAN CARROLL

The universe's mixture of dark energy (blue), dark matter (green), and familiar matter (yellow) evolves due to cosmic expansion. Matter dominated the early universe. But as the universe creates more space, matter is diluted and dark energy takes control of the universe's fate. Many physicists would love to know why we live at a time when the energy densities of dark energy and matter are nearly equal.

The microscopic world obeys the laws of quantum mechanics, which say that our understanding of any system's state entails an unavoidable uncertainty (Werner Heisenberg's uncertainty principle). Energy fields will thus fluctuate even in empty space. In these "vacuum fluctuations," virtual particles pop in and out of existence. They contribute to the vacuum energy, but contrary to popular opinion, they are not its sole cause, since general relativity allows for an arbitrary vacuum energy without taking these fluctuations into account. Einstein certainly wasn't thinking of virtual particles when he conceived the cosmological constant.

If it is the dark energy, the observed vacuum energy is small — the amount within Earth's volume is equal to an average American's annual electricity consumption. Physicists have calculated how much energy vacuum fluctuations should contribute to the total vacuum energy, and the answer is an unspeakable 10^{120} times greater than the observed amount. If the theoretical value were correct, a single cubic centimeter of vacuum energy would equal the electrical consumption of the entire United States for 10^{85} years. This is the most embarrassing discrepancy between theory and observation in all of physics. Admittedly, some unknown process might precisely negate the vacuum energy from quantum fluctuations, but nobody can think of a reason why this cancellation should occur.

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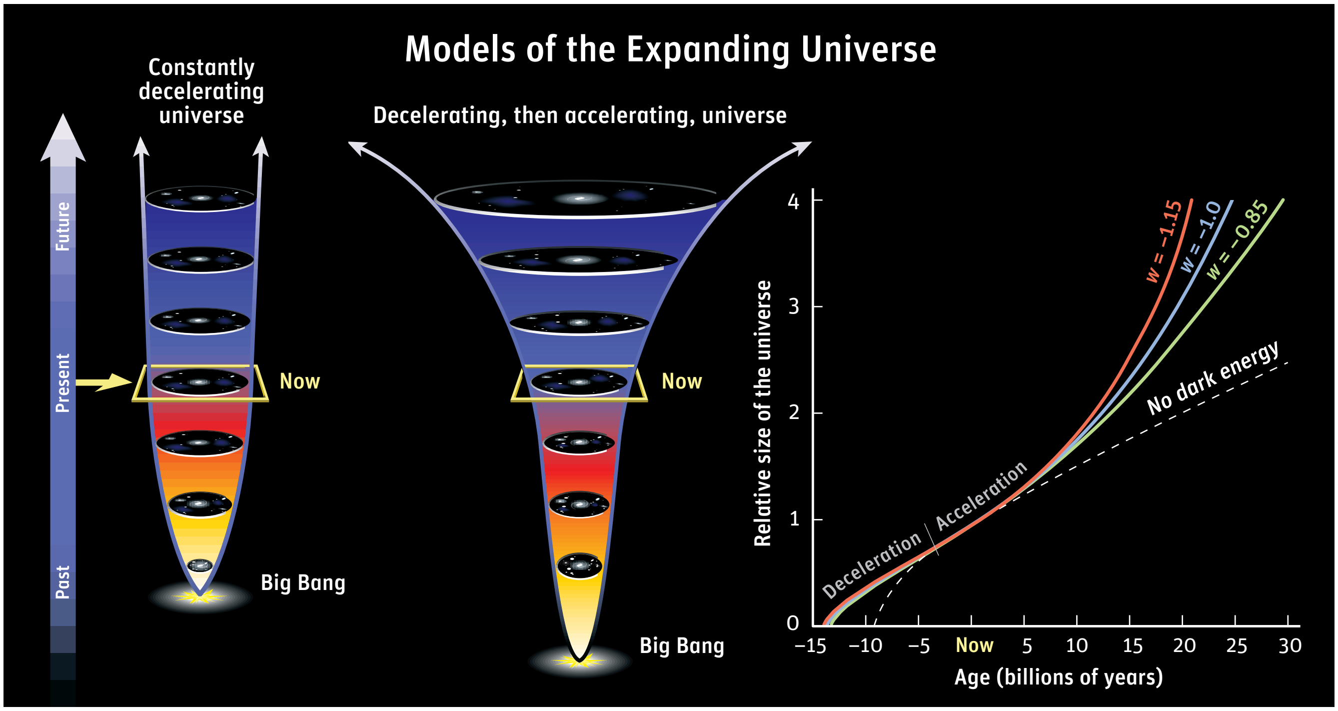
Not only is the vacuum energy much smaller than it "should" be, but if it really is the dark energy, its density is suspiciously close to that of matter. Matter is diluted as the universe expands, while the vacuum energy in each cubic centimeter of space remains constant. So if dark matter and dark energy are of comparable density today, their relative strengths were very different in the past. When the CMB was emitted, for example, the matter density was more than a billion times greater than that of vacuum energy. And in the future, as cosmic expansion creates more space, vacuum energy will completely dominate the universe's evolution. So why do we live at a time when the two quantities are nearly comparable? And what could be making the vacuum energy so much smaller than we think it should be?

Searching for Solutions

We don't have any very good answers, but some theories address the problem in provocative ways. Two plausible examples are supersymmetry and extra dimensions. Supersymmetry is the idea that every type of elementary particle has a "superpartner" with a different intrinsic spin. The idea of extra dimensions, meanwhile, posits the existence of

Dark-Energy Candidates

Type	Properties	Pros	Cons
Global vacuum energy	Cosmological constant; unchanging with time and the same throughout the entire universe	Might ultimately be explained from first principles in terms of known laws of physics	No such explanation has been found
Local vacuum energy	Constant throughout our observable universe, but differing in extremely distant regions	Could explain the cosmological constant's apparent smallness in our region — life doesn't arise in regions with large vacuum energy	Requires multiple cosmic domains; gives up calculating the vacuum energy from first principles
Dynamical dark energy	Slowly varying and smoothly distributed energy source	Can gradually evolve to zero energy density; observationally testable	Hard to understand why it hasn't already been detected
Modified gravity	Replaces dark energy with a modification of Einstein's general relativity on cosmological scales	Doesn't require any new sources of energy	Hard to modify general relativity without violating existing experimental constraints



S&T: GREGG DINDERMAN. SOURCE: NASA / STSCI / SEAN CARROLL

The red, blue, and green curves represent possible cosmological scenarios for all but the first second of the universe's evolution. Early in cosmic history, when matter reigned supreme, gravity caused the expansion to decelerate. But as space expanded, dark energy began to take over, with the transition from deceleration to acceleration occurring approximately 5 billion years ago (about the time the solar system was born). Measuring the value of *w* will allow cosmologists to distinguish between dynamical dark energy (or modified gravity) and a cosmological constant. The dashed white curve represents a hypothetical flat universe that contains only matter and therefore continues to decelerate. Most cosmologists accepted this model of the universe until the late 1990s.

more than our three familiar spatial dimensions (*S&T:* June 2003, page 38). In either case, the new phenomena must be somehow hidden to explain why they haven't been detected.

Nevertheless, these hidden mechanisms can work behind the scenes to alter the vacuum energy dramatically. Superpartners might act to cancel the vacuum fluctuations from known particles, while extra dimensions may be able to absorb the excess gravitational effects of dark energy. But theorists have yet to turn these interesting ideas into compelling models. Physicists are working hard to paint a complete picture in which the observed value for dark energy comes out naturally from particle physics.

In desperation, some physicists have suggested that the vacuum energy has very different values in large regions of the universe that are out of contact with one another. In their view, we find ourselves in an area where the vacuum energy is quite gentle. In a region where it was large and positive, it would rip apart galaxies and atoms. If it were large and negative, it would cause space to collapse quickly. Thus, we might be measuring a small vacuum energy because we couldn't exist in any section with such extreme properties (*S&T:* March 2004, page 42).

It is quite a leap to imagine a fantastic number of regions, all of which have different vacuum energies, and all of which are outside the reach of any possible observation. But recent ideas in inflation and string theory suggest that we might have to accept that ours is such a universe.

Beyond Vacuum Energy

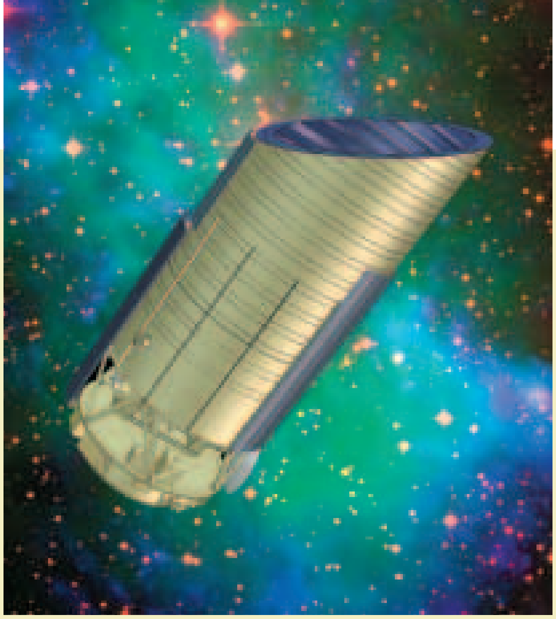
Since the vacuum energy is apparently very small, it might be easier to invent a theory that sets it all the way to zero rather than one that suppresses it exactly to its observed tiny value. Although physicists haven't concocted such a theory, let's assume that we will find one someday. In that case, the observed dark energy would not be vacuum energy but some other smooth and slowly evolving form. Several candidates have been proposed, though none seems completely natural. One of the favorites is *quintessence,* an invisible field (similar to electromagnetic and gravitational fields) that changes slowly as the universe expands. Some quintessence-like field may have inflated the early universe, only with much higher energy. The energy driving inflation converted itself into matter and radiation moments after the Big Bang.

Determining whether the dark energy is dynamical like quintessence rather than strictly constant like the vacuum energy is a prime goal of cosmology. Dark-energy evolution directly affects cosmic expansion, so cosmologists are striving to map the expansion history as carefully as possible. Constraints on dark energy's evolution are often stated in terms of the "equation-of-state parameter," denoted *w,* which is the dark energy's pressure divided by its energy density. If the dark energy is a pure, unchanging vacuum energy, we will measure *w* to be –1. Such a universe will continue to expand at an accelerated rate, with all stars eventually cooling off and dying in a "Big Chill." Observations show that *w* is close to –1.

The situation becomes more interesting if *w* is slightly greater than or less than –1. If *w* is greater (less negative) than –1, this means the dark-energy density is decreasing with time, which is consistent with quintessence. A *w* value

Future Experiments

Future experiments may enable physicists to unravel the dark-energy mystery. *Right:* An artist's depiction of the SuperNova Acceleration Probe (SNAP). SNAP would pinpoint distant Type Ia supernovae and measure their brightnesses and redshifts. These data could trace the universe's expansion history in exquisite detail. *Below, left:* A drawing of an accelerator tube in Europe's Large Hadron Collider (LHC). When the LHC begins operation in 2007, it could yield deep insights into the nature of matter and space. *Below, right:* Ongoing tabletop experiments such as this one at the University of Washington could reveal deviations from Newton's inverse-square law of gravity at submillimeter scales, demonstrating that extra spatial dimensions may exist and may play a major role in dark energy.



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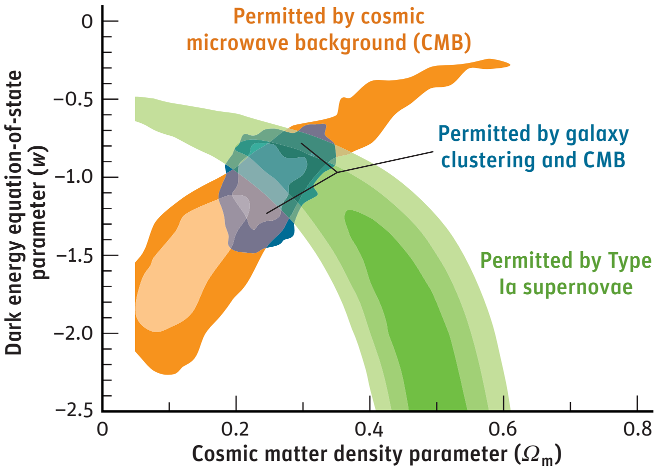
less than −1 corresponds to a dark-energy density that is growing slowly as the universe expands. If *w* remains less than −1, some physicists have speculated that the universe will someday find itself in a state known as the "Big Rip," when cosmic expansion overwhelms the electromagnetic force and rips atomic matter to shreds. (Few scenarios for the long-term fate of the universe could be described as "pleasant.") Until we have a reliable understanding of dark energy, no measurement of its current behavior will tell us for certain what will happen in the future. We even need to keep an open mind to the remote possibility that the universe will someday collapse in a "Big Crunch."

One obvious method for measuring *w* is to continue observing Type Ia supernovae, but in greater numbers and with higher precision. Scientists are studying the development of the SuperNova Acceleration Probe (SNAP), a space telescope with a wide-field camera optimized for this purpose. Meanwhile, supernova searches using ground-based



SOURCE: LICIA VERDE (UNIVERSITY OF PENNSYLVANIA)

Observations of Type Ia supernovae, the cosmic microwave background, and galaxy clustering place complementary constraints on the universe's equation-of-state parameter *(w)* and the energy density contained in matter. The value of *w* appears to be near −1, and the energy density of matter is about 30 percent of the amount required for a flat universe. Future observations will narrow the uncertainties even further, which should help scientists determine the nature of dark energy.

OMAR LOPEZ-CRUZ / IAN SHELTON / NOAO / AURA / NSF

The Coma galaxy cluster lies roughly 350 million light-years from Earth. If cosmic expansion continues to accelerate, distant clusters like Coma will eventually be redshifted by such extreme amounts that they will become too dim to be observed. Many billions of years from now, astronomers will be restricted to observing their local galaxy cluster, which gravity will hold together despite the "repulsive" force of dark energy.

observatories and the Hubble Space Telescope are improving both the precision of our measurements and our confidence in the results. Future missions such as the European Space Agency's Planck satellite will improve CMB maps, and CMB polarization measurements will constrain the amount of dark energy.

Cosmologists also hope to use the number and evolution of galaxy clusters as sensitive probes of cosmic expansion (*S&T:* December 2004, page 32). Hot gas collects in clusters, which astronomers can study directly, through the material's X-ray emission, and indirectly, by how it distorts the CMB's spectrum (the Sunyaev-Zel'dovich effect). Combining these observations should provide a new tool for precision cosmology. With all of these different methods, and perhaps other future space missions, we can look forward to a wealth of data on cosmic expansion in the years to come.

No Congratulations Yet

Cosmologists are not the only scientists trying to comprehend dark energy. Physicists will use particle accelerators to try to understand why the vacuum energy is so small. These experiments will include searches for supersymmetry (by creating the heavy superpartners of known particles) as well as efforts to find extra dimensions (through the escape of energy into the new dimensions), not to mention possible surprises. The Tevatron at Fermilab outside Chicago is currently our highest-energy accelerator, but it will be surpassed in 2007 by the Large Hadron Collider at the European Organization for Nuclear Research near Geneva, Switzerland. Plans are on the drawing board for a powerful new international linear particle accelerator at a site yet to be determined. Meanwhile, tabletop experiments are testing Newton's inverse-square law at submillimeter scales to see if gravity leaks into extra dimensions.

If the dark energy is a dynamical field like quintessence, we may get even luckier: dynamical fields tend to interact with other fields, so the dark energy might not be completely "dark." We can look for its effects by studying whether natural constants (such as the charge of the electron) seem to change gradually over billions of years. Additionally, quintessence fields give rise to "fifth forces" that experiments on Earth can search for — objects of different compositions should fall at slightly different rates due to their interactions with quintessence. Any believable discovery along these lines would be of tremendous importance.

We should also keep in mind the possibility that we have been completely misled. Maybe there is no dark energy, and instead general relativity is breaking down on cosmological scales. This theory has been tested in a wide range of circumstances — from the solar system and binary pulsars to nuclear reactions in the very early universe. But the possibility remains for some unexpected effect at very large distances. Theorists are currently building models along these lines, and experimenters are working overtime to devise clever new tests of Einstein's superbly successful theory.

We live in a preposterous universe: the observed mixture of familiar matter, dark matter, and dark energy doesn't seem to make much sense. Inevitably, someone pointedly suggests that it's not the universe that is preposterous; it's our theories that fall short of making perfect sense of it. Of course, this is exactly the point. To say that the universe is "preposterous" is just a joke; it's the only universe we have, and value judgments are not particularly appropriate or helpful. The fact that astronomical observations have revealed such surprises is a reminder that we still have a lot to learn.

It's not the universe that is preposterous; it's our theories that fall short of making perfect sense of it.

Physicists are fearlessly advancing new ideas, and a panoply of novel experimental techniques are being brought to bear on the nature of dark matter and dark energy. We should feel pride in having figured out the universe's basic constituents. But we shouldn't pause for very long to congratulate ourselves. There is every reason to believe that the near future will witness another round of surprises as well as leaps forward in understanding. ✴

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