Cosmic questions, answers pending

Throughout human history, great missions of exploration have been inspired by curiosity, the desire to find out about unknown realms. Such missions have taken explorers across wide oceans and far below their surfaces, deep into jungles, high onto mountain peaks and over vast stretches of ice to the Earth's polar extremities.

Today's greatest exploratory mission is no longer Earthbound. It's the scientific quest to explain the cosmos, to answer the grandest questions about the universe as a whole.

What is the identity, for example, of the "dark" ingredients in the cosmic recipe, composing 95 percent of the universe's content? And just what, if anything, occurred more than 13.7 billion years ago, when the universe accessible to astronomical observation was born? Will physicists ever succeed in devising a theory to encompass all the forces and particles of nature in one neat mathematical package (and in so doing, perhaps, help answer some of these other questions)? Will that package include the supposedly basic notions of space and time, or will such presumed preexisting elements of reality turn out to be mere illusions emerging from ur-material of impenetrable obscurity? And finally (fittingly), what about cosmic finality? Will the universe end in a bang, a whimper or the cosmic equivalent of a Bruce Willis movie (everything getting blown apart)?

In the pages that follow, *Science News* writers assess the state of the evidence on these momentous issues. In none of these arenas are the results yet firm. But as string theorist Brian Greene wrote in his book *The Elegant Universe*, "sometimes attaining the deepest familiarity with a question is our best substitute for actually having the answer."

—Tom Siegfried, Editor in Chief

MISSION: REVEAL THE SECRETS OF THE UNIVERSE

THE OBJECTIVE

For millennia, people have turned to the heavens in search of clues to nature's mysteries. Truth seekers from ages past to the present day have found that the Earth is not the center of the universe, that countless galaxies dot the abyss of space, that an unknown form of matter and dark forces are at work in shaping the cosmos. Yet despite these heroic efforts, big cosmological questions remain unresolved:

Find tools for the mission on Page 32. For pdfs of this section, and more resources, visit www.sciencenews.org/cosmicquestions

THE WHEREABOUTS

Understanding the universe requires recognizing its immense scale. Zooming out from Manhattan reveals the Earth, solar system, galaxies and then walls of galaxies separated by voids. At the most distant scales, the universe looks uniform.

THE VITAL STATISTICS

13.75 billion years (uncertainty +/–0.11): Time since the Big Bang, the creation of the universe.

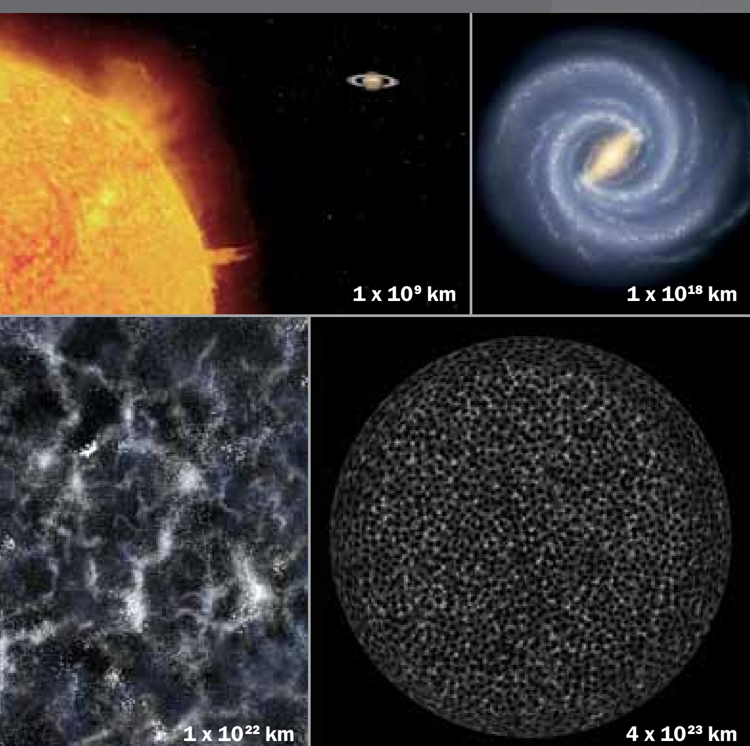
377,730 years (+3,205/–3,200): Time after the Big Bang when photons stopped interacting with charged matter and produced the relic radiation known as the cosmic microwave background.

70.4 kilometers/second/megaparsec (+1.3/–1.4): Expansion rate of the universe assuming its spacetime geometry is flat. Also known as the Hubble constant.

90 billion light-years: Rough diameter of the known universe.

–0.980 (+/–0.053): Equation of state, a measure of the (negative) pressure exerted by dark energy divided by its density. An unvarying value of –1 suggests that dark energy is Einstein's cosmological constant.

1.0023 (+0.0056/–0.0054): Value of omega, the total mass-energy density relative to the critical mass-energy density. Omega equal to 1 signifies a universe with flat spatial geometry.



PAST MISSION FINDINGS

1543 Nicolaus Copernicus publishes a mathematical description of planetary motion, assuming that the sun is the center of the solar system. Later work by Johannes Kepler, Galileo Galilei and Isaac Newton provides further evidence.

1666 Isaac Newton formulates the law of gravity and laws of motion, published in 1687.

1900 Max Planck formulates the first description of quantum theory, which will eventually explain the nature of matter and energy on the subatomic scale.

1917 Albert Einstein applies general relativity to the universe. Later work by Willem de Sitter and independently by Aleksandr Friedmann implies the possibility that the universe is expanding.

1924 Edwin Hubble announces that the "spiral nebulae" sit beyond the Milky Way and later that the Milky Way is just one of many galaxies.

1929 Hubble finds that the universe is expanding, after analyzing the redshifts of distant galaxies.

1933 Fritz Zwicky examines galaxies in the Coma cluster and determines that there is unseen mass, what scientists call "dark matter."

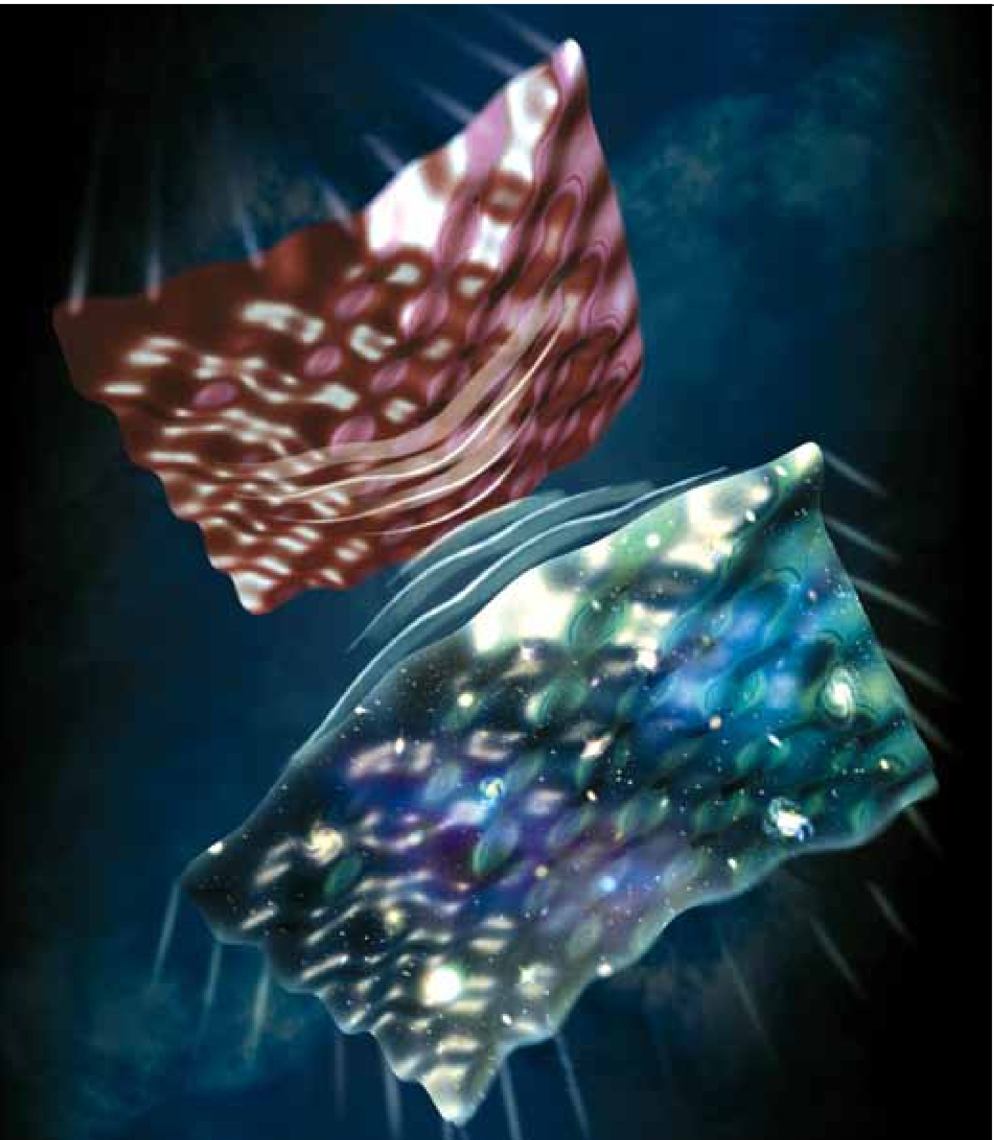
1960s Steven Weinberg, Abdus Salam and Sheldon Glashow independently propose a theory to unify electromagnetism and the weak nuclear force.

1964 Arno Penzias and Robert Wilson discover the cosmic microwave background radiation; in 1990 NASA's COBE mission confirms that the radiation's properties verify the universe's birth in a Big Bang.

1986 Astronomers Margaret Geller, John Huchra and Valérie de Lapparent map a section of the observable universe, revealing a structure that encompasses large walls and giant voids.

1998 Researchers discover that the universe is expanding at an accelerating rate, suggesting a mysterious force dubbed "dark energy" might be at work.

TOP, FROM LEFT: USGS, NASA EARTH OBSERVATORY; RETO STÖCKLI AND ROBERT SIMMON, MODIS/GSFC/NASA, USGS, DMSP; JPL-CALTECH/NASA, T. PYLE/SSC, ADAPTED BY T. DUBÉ; R. HURT/SSC, JPL-CALTECH/NASA; BOTTOM, FROM LEFT: DAVID PARKER/PHOTO RESEARCHERS; NICOLLE RAGER FULLER; NICOLLE RAGER FULLER; TABLET: VIKTOR GMYRIA/SHUTTERSTOCK.COM



WHAT HAPPENED BEFORE THE BIG BANG?

Pre-Bang branes and bubbles

By Ron Cowen ▪ Illustration by Nicolle Rager Fuller

If the universe occupies a sheetlike membrane, the Big Bang may have been just one in a series of collisions, each "Big Bounce" refreshing the cosmos.

Cosmologists Paul Steinhardt and Neil Turok liken the early history of the universe to a play in which the protagonists — matter and radiation — move across the stage according to the laws of physics. Astronomers are actors who arrived on the scene 13.7 billion years too late to know what happened.

But that hasn't stopped Steinhardt, Turok and other researchers from pondering whether the universe was born in a giant fireball around that time or might have existed before that.

The modern-day notion of the cosmos's tumultuous beginning — known as the Big Bang — has its roots in Edwin Hubble's 1929 discovery that the universe is expanding. At the time, scientists envisioned the universe explosively flying outward from a single point in space and time.

Though this simple version of the Big Bang idea can't fully explain what people see in the cosmos today, Alan Guth of MIT added a new ingredient in 1981. Early in its history, the universe underwent a brief period of faster-than-light expansion, known as inflation, he proposed. In the years since Guth's suggestion, inflation has been wildly successful in explaining the structure of the universe and its arrangement of galaxies.

Bubbling over

Some scientists think that if inflation happened once, it could happen many more times — hinting at a cosmos alive and well eons before the Big Bang. Rapid expansion, in these interpretations, isn't confined to just one neck of the cosmic woods, like a single expanding balloon. Instead, distant patches of space keep inflating, like a child continually blowing soap bubbles, says Alex Vilenkin of Tufts University in Medford, Mass.

Every inflated patch becomes a separate universe, with its own Big Bang beginning (*SN: 6/7/08, p. 22*). In this "eternal inflation" scenario, the fireball that begot the universe seen with today's telescopes was preceded by a multitude of others just as surely as it will be followed by many more, each popping off at different times in different parts of the cosmos, Vilenkin says.

Just as the sun is merely one of billions of stars in the Milky Way galaxy, the visible universe may be one of countless in the cosmic firmament. Cosmologists call this ensemble of universes the multiverse.

Not only might there have been a plethora of universes that came before the one people know, but each one may also have been different from the others. In combining eternal inflation with string theory, an idea that has become popular because it could help unify the four known forces in nature (see Page 26), each inflated universe would have its own set of physical properties. Although the known universe is chockablock with galaxies, for example, gravity in another, earlier universe could have been too weak to form galaxies.

Bounce not bang

String theory itself — which calls for a space with many rolled-up dimensions — may suggest a different type of pre–Big Bang picture. In a model developed by Steinhardt, now at Princeton University, and Turok, now director of the Perimeter Institute in Waterloo, Canada, the Big Bang is replaced with an endless cycle of contractions and bounces; 13.7 billion years is merely the time since the last "Big Bounce."

In this picture, the known universe resides on a three-dimensional version of a sheet, called a brane, which can travel along an extra dimension. Another brane resides a tiny distance away.

When they are separated, the two branes are perfectly wrinkle-free, representing a universe nearly devoid of matter. As the two branes pull closer, they develop tiny wrinkles. These wrinkles are the seeds of galaxies. When the branes finally collide and bounce apart, they unleash an enormous amount of energy, some of which is converted to matter and radiation. To an observer on one of the branes, this Big Bounce would look just like a Big Bang (*SN: 9/22/01, p. 184*).

While the branes are separated, they stretch and smooth out; the cosmos is expanding just as it is today. But eventually, the two branes are pulled back together for another round of collisions and bounces. Each cycle may last a trillion years or more.

In the Big Bounce model, the universe not only existed before the Big Bang, it retains the memory of what came before. All of the stars, galaxies, and large-scale structures now present owe their existence to the composition of the universe in the previous cycle. Though the details might be different, the underlying physical laws would remain the same.

Cosmic clues

Whether the Big Bounce or the multiverse captures reality — if either one does at all — remains a mystery. One observation, though, could distinguish between the Big Bounce and any inflationary scenario, Steinhardt notes. Gravitational waves, tiny ripples in the fabric of spacetime, are generated during each cycle of the Big Bounce. But in this scenario, the waves would be too weak to be detected. Inflation, in contrast, would produce a much more powerful set of the waves — strong enough to leave a noticeable imprint on the cosmic microwave background, the radiation left over from the Big Bang.

The European Space Agency's Planck spacecraft is now searching for the telltale signs that gravitational waves would leave in the cosmic microwave background (*SN: 4/11/09, p. 16*). If the imprint is found, "we're done," says Steinhardt. The Big Bounce would fall flat.

Whether or not inflation implies a multiverse is another story, but Planck may offer clues about that too.

As bubble universes expand, they can collide with each other. If another universe happened to have struck the one in which people reside, Planck might be able to detect a particular pattern of hot and cold spots in the microwave background.

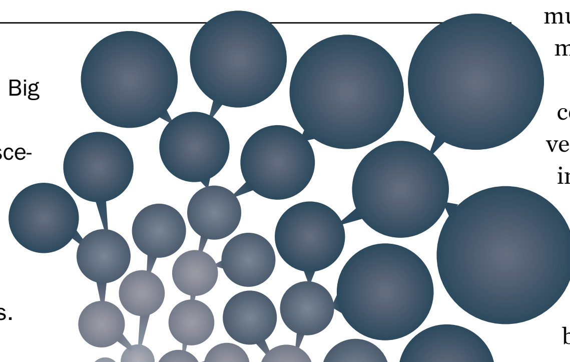
Even if no sign of a collision can be spotted, though, other bubble universes may still exist. Bumps could be so infrequent that observers might have to wait a millennium to find the pattern.

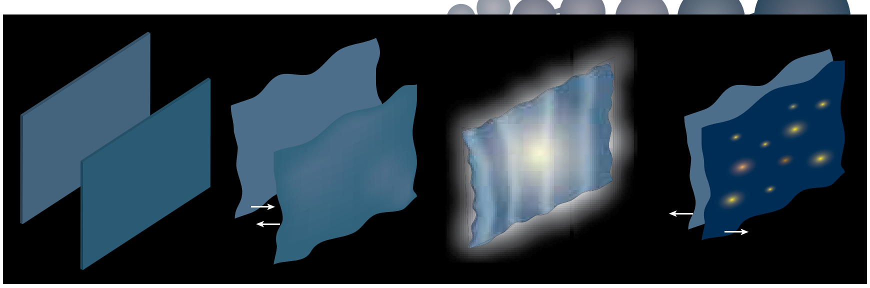
If that prolonged uncertainty about cosmic genesis sounds a bit like purgatory, consider the words of an unnamed man quoted in St. Augustine's *Confessions*. When asked what God was doing before making heaven and Earth, the man replied: "He was preparing Hell for those who pry too deep."

St. Augustine, himself, found the answer facetious: "More willingly would I have answered, 'I do not know what I do not know.' " ■

In the beginning

Not knowing what came before the Big Bang doesn't stop physicists from theorizing. In the eternal inflation scenario, the known universe bubbled out of a larger multiverse (right). Another model (below) suggests that the universe cycles through a series of contractions and bounces.





In the cyclic model, the known universe occupies a sheetlike surface, a "brane." Another brane sits a small distance away.

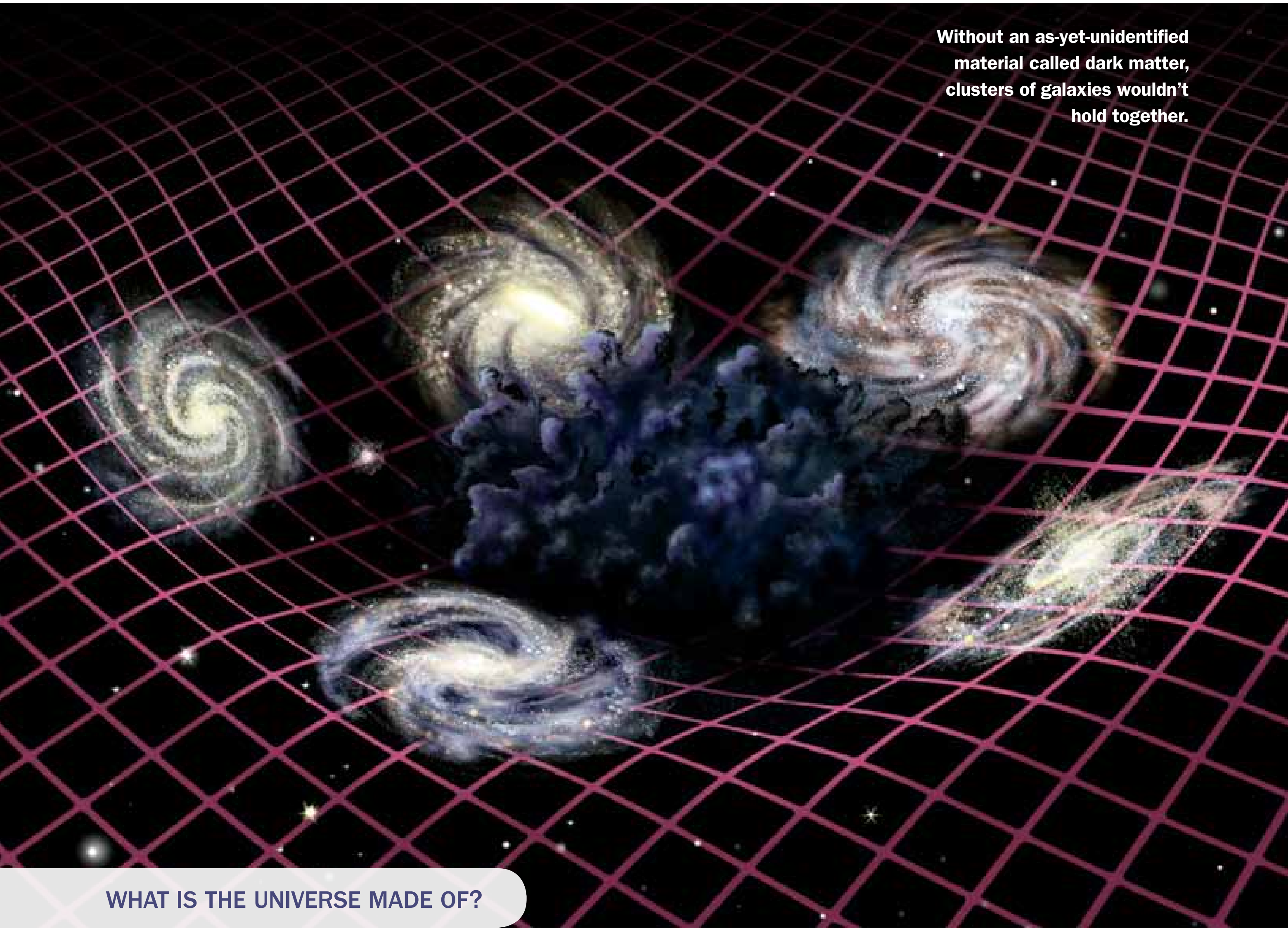
An interbrane force pulls the two sheets together, amplifying quantum ripples and creating wrinkles in the branes.

The branes collide and then rebound, releasing energy in what looks like a Big Bang.

Once the branes separate, galaxies and other cosmic structures form. The matter spreads out and the cycle repeats.

SOURCE: P. STEINHARDT

E. FELICIANO



Without an as-yet-unidentified material called dark matter, clusters of galaxies wouldn't hold together.

WHAT IS THE UNIVERSE MADE OF?

In the dark

By Alexandra Witze ▪ Illustration by Nicolle Rager Fuller

In ancient times, listing the ingredients of the universe was simple: earth, air, fire and water. Today, scientists know that naming all of that, plus everything else familiar in everyday life, leaves out 95 percent of the cosmos's contents.

From the atoms that make up an astronomer, to the glass and steel of a telescope, to the hot plasma of the stars above — all ordinary stuff accounts for less than 5 percent of the mass and energy in the universe. "All the visible world that we see around us is just the tip of the iceberg," says Joshua Frieman, an astrophysicist at the University of Chicago and the Fermi National Accelerator Laboratory in Batavia, Ill.

The rest is, quite literally, dark. Nearly one-quarter of the universe's composition is as-yet-unidentified material called dark matter. The remaining 70 percent or so is a mysterious entity — known as dark energy — that pervades all of space, pushing it apart at an ever-faster rate.

"Dark" is an appropriate adjective, as scientists have little insight into where dark matter and dark energy come from. But figuring out dark matter would illuminate what holds galaxies together. Figuring out dark energy might help reveal the universe's ultimate fate (see Page 30).

It's little wonder that scientists regard the identities of dark matter and dark energy as among today's biggest astronomical puzzles.

A different matter

Dark matter made its debut in 1933, when Swiss astronomer Fritz Zwicky measured the velocities of galaxies in a group known as the Coma cluster and found them moving at different rates than expected. Some unseen and large amount of "*dunkle Materie*," he proposed in German, must exist, exerting its gravitational effects on the galaxies within the cluster.

Astronomer Vera Rubin confirmed dark matter's existence in the 1970s, after she and colleagues had measured the speeds of stars rotating around the centers of dozens of galaxies. She found that, counterintuitively, stars on the galaxies' outer fringes moved just as rapidly as those closer in — as if Pluto orbited the sun as quickly as Mercury. Rubin's work demonstrated that each galaxy must be embedded in some much larger gravitational scaffold.

Ever since, other lines of evidence have strengthened the case for dark matter. It resembles ordinary matter in that it interacts via the well-understood gravitational force; that's why it affected Zwicky's and Rubin's galaxies. But scientists know that dark matter is not ordinary; if it were, it would have affected ratios of chemical elements born in the early universe and thus thrown off the abundances of such elements observed today.

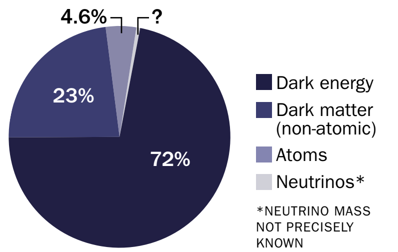
The leading candidate for a dark matter particle is the vaguely named "weakly interacting massive particle," or WIMP. Such particles would be "weakly interacting" because they rarely affect ordinary matter, and "massive" because they must exceed the mass of most known particles, possibly weighing in at as much as 1,000 times the mass of the proton. But nobody has yet definitively detected a WIMP, despite decades of experiments designed to spot one.

Results from dark matter experiments are mixed: One group in Italy claims to see a WIMP signal seasonally, with more WIMPs hitting detectors as the Earth moves into a stream of galactic dark matter debris, and fewer when Earth moves away. But other researchers haven't been able to confirm those results. Recent reports from other experiments, including one buried in Minnesota's Soudan mine, hint that WIMPs might be lighter than theorists had expected, on the order of 10 proton masses (*SN: 8/28/10, p. 22*).

The sensitivity of many long-running experiments is now improving to the point that WIMPs and other candidate particles should be either spotted or ruled out in the near future.

Mostly unfamiliar The stuff that makes up people, planets, stars and interstellar gas accounts for just under 5 percent of the universe. The rest is made of mysterious entities dubbed dark matter and dark energy.

Mass-energy content of the universe



SOURCE: WMAP

Mysterious forces

Spotting dark matter may prove to be easier than understanding dark energy, whose mysteries make scientists feel like mental wimps.

Albert Einstein unknowingly ushered dark energy onto the stage in 1917, while modifying his new equations of general relativity. Einstein wondered why gravity didn't make the universe contract in on itself, like a balloon with the air sucked out of it. He thus made up a "cosmological constant," a fixed amount of energy in the vacuum of space that would provide an outward push to counter gravity's inward pull.

In 1929, though, Edwin Hubble solved Einstein's problem by reporting that distant galaxies were flying away from each other. The universe, Hubble showed, was expanding. It had been zooming outward ever since the Big Bang gave birth to it.

Einstein happily ditched his cosmological constant, but in 1998 astronomers showed that it should have been recycled rather than trashed. That year, two research teams reported their studies of distant supernovas. These exploded stars can be calibrated to serve like standard light bulbs, shining with a particular brightness. The scientists reported that many distant supernovas were dimmer than expected, even accounting for an expanding universe. It was as if someone had quickly moved the light bulbs into a more distant room. The universe was not only getting bigger — it was doing so at an accelerating rate.

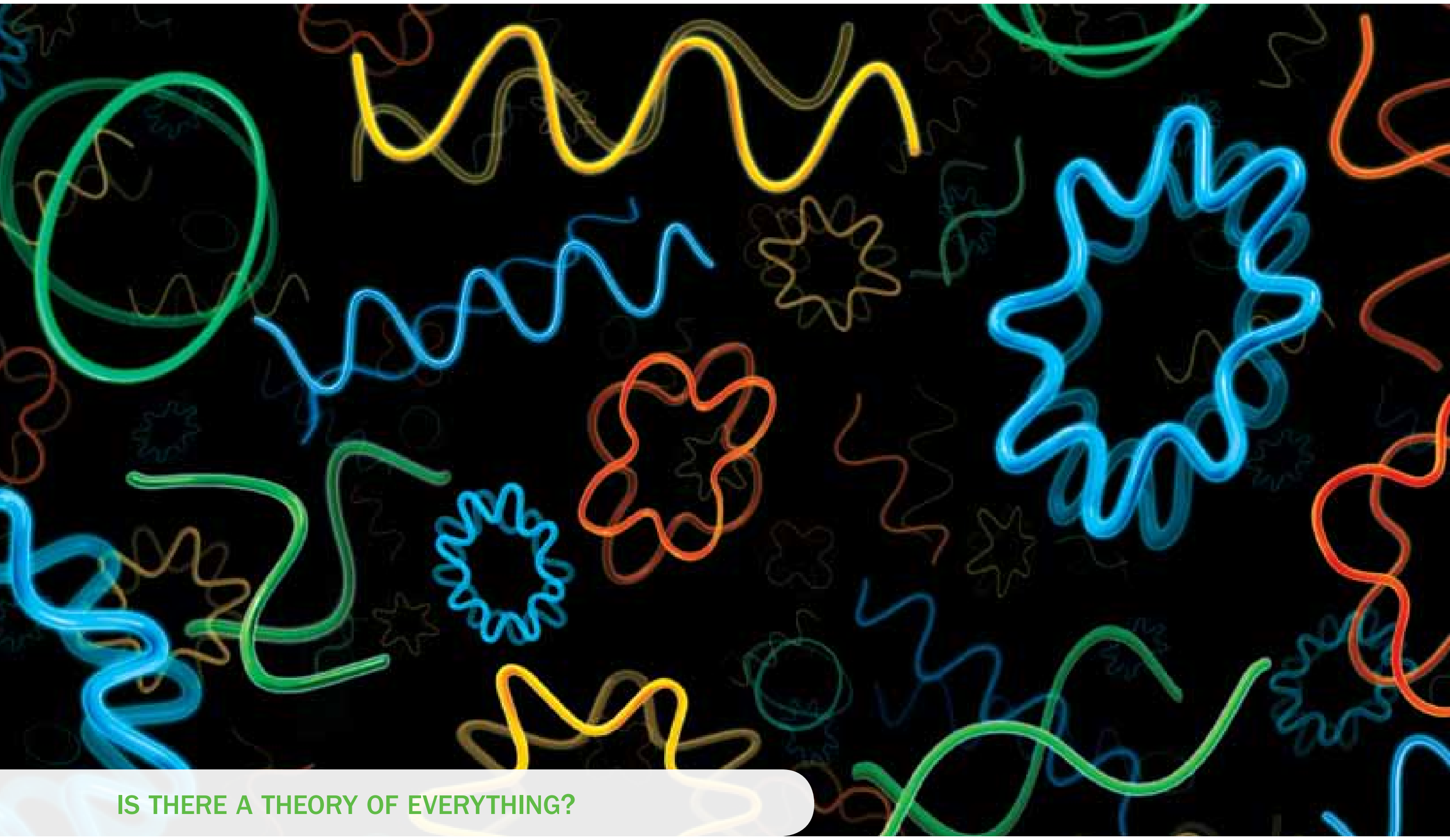
Something funny was going on, giving the cosmos a repulsive push. So Michael Turner, a cosmologist at the University of Chicago, dubbed the thing "funny energy" at first, before settling on "dark energy."

More than a decade later, scientists still don't have a concrete clue to what dark energy is (*SN: 2/2/08, p. 74*). Theorists have done their best to explain it, putting forward ideas including a seething "vacuum energy" created as particles pop in and out of existence, and "quintessence" — named after Aristotle's postulated fifth element — that changes its strength depending on its place or time in the universe.

Meanwhile, observers have spent the last decade dreaming up ways to probe dark energy from the ground and in space (see Page 32). In particular, precision measurements of many distant galaxies could help pin down the nature and distribution of dark energy. A new camera, optimistically called the Dark Energy Survey, will see first light this autumn at the Cerro Tololo Inter-American Observatory in Chile. Real light — insight into the dark — may take some time. ■

In this false-color image of galaxies colliding, the majority of the mass (blue) is separate from most normal matter (pink), direct evidence of dark matter.

TOP: T. DUBÉ; BOTTOM, X-RAY: M. MARKEVITCH *ET AL*, CXC/NASA, CFA, OPTICAL: STSCI/NASA, D. CLOWE *ET AL*, MAGELLAN/UNIV. OF ARIZONA, LENSING MAP: STSCI/NASA, ESO WFI, D. CLOWE *ET AL*, MAGELLAN/UNIV. OF ARIZONA



IS THERE A THEORY OF EVERYTHING?

Strung together

By Matt Crenson ▪ Illustration by Nicolle Rager Fuller

Physics is really two sciences. There's quantum mechanics, the weird tumultuous world where particles pop into and out of nothingness and cats can be simultaneously living and dead. And there's general relativity, Einstein's majestic vision of massive objects bending space and time.

Ever since these two very different views of the universe emerged early in the 20th century, generations of physicists have tried to unite them in a single theory that would ideally describe all four of nature's basic forces to boot. Even Einstein tried, and failed. Now, after an especially frustrating few decades with little new evidence to guide them, today's physicists may be about to get some tantalizing hints about how the forces fit together.

The clues are expected to come from the Large Hadron Collider, a ring of superconducting magnets in the Alps designed to smash protons together at energies never before seen on Earth. The collider began operating in March 2010 and is expected to reach full power in 2014, when it will attempt to smash its protons together with double the violence it does today.

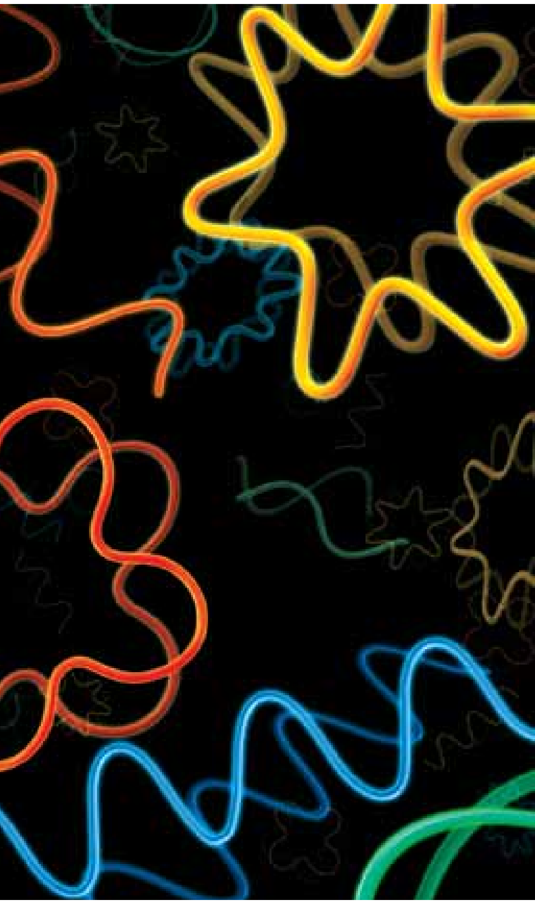
Even then, the LHC will be far from powerful enough to re-create the single, unified force that physicists believe existed for a fraction of a second after the Big Bang — you'd need a collider as big as the universe itself for that. But the LHC might be able to test some of the predictions made by the leading theory that joins gravity and the other forces.

Superstring theory — string theory for short — ties all of physics into one neat package by reducing the bewildering taxonomy of particles in the current bestiary of physics, the Standard Model, to identical snippets of string, each less than a billionth of a billionth of a billionth of a centimeter long. According to string theory, the particles that carry the three forces included in the Standard Model — the photon (electromagnetism), the gluon (strong force) and the W and Z bosons (weak force) — are all just the same tiny dancers each following their own distinct rhythms.

And unlike the Standard Model, string theory has room for gravity.

Though proposals besides string theory attempt to explain how all the forces of nature might fit together, most of those other theories come with major flaws. Some predict the existence of particles that can't exist, for example.

String theory's primary drawback is that it requires there be much more to the universe than physicists can probe, making the theory very difficult to test.



For example, most versions of string theory require that the universe have 10 or 11 dimensions — nine or 10 of space and one of time, rather than the four that people experience: up-down, front-back, left-right and past-future.

"The forces are unified in 11 dimensions, but they split apart when you go to four dimensions," says Gordon Kane, a physicist at the University of Michigan in Ann Arbor.

Superstring theory attempts to unify gravity with quantum mechanics by describing particles and forces as tiny vibrating strands and loops.

For string theory to say anything about how the forces arise, physicists have to figure out how all those extra dimensions roll up, or "compactify," into the four familiar ones.

String theory also conjures up a shadow population of partner particles for all of the ones currently known to exist — a notion called supersymmetry. In fact, supersymmetry may be necessary to join the strong, weak and electromagnetic forces, so it is important even if string theory isn't correct.

When forces collide

Many physicists have high hopes that the LHC will find evidence for both supersymmetric particles and extra spatial dimensions.

"Even if we don't go out to the other dimensions, in some sense the other dimensions can come to us," says Harvard physicist Lisa Randall.

Working in the 1990s with colleague Raman Sundrum, now at the University of Maryland in College Park, Randall showed that it might be possible to detect the decay of a gravity-carrying particle coming from an extra dimension. Finding such a particle at the LHC would both verify the existence of extra dimensions and suggest why gravity is much weaker than the other three forces.

"I think it would be somewhat surprising," Randall says. "But this is one of the things we could find, and this is one of the things they should be looking for."

Most physicists think it's more likely that the LHC will find evidence for supersymmetric partners of the particles in the Standard Model. Which partners appear, and their properties, would put some helpful constraints on how the universe compactifies the 11 dimensions predicted by string theory.

For example, if the lightest superparticle turned out to be the wino, the superpartner of the weak force–carrying W boson, that would be consistent with a version of string theory known by the pithy moniker "M-theory compactified on 7-D manifold of G_2 holonomy."

Such supersymmetric particles may already have been observed, in fact — not on Earth, but in space. Some of the dark matter that is thought to make up more than 80 percent of the matter in the universe could be composed of supersymmetric particles left over from the universe's earliest moments (see Page 24). In the last few years two space-based instruments, the Fermi Gamma-ray Telescope and the Italian-led PAMELA mission, have seen evidence of dark matter in the Milky Way in the form of gamma rays and antimatter that could have been produced by supersymmetric particles colliding.

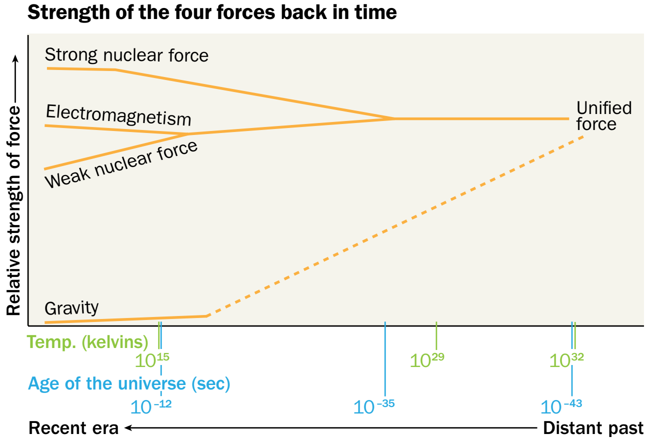
Because the LHC and any future colliders can carry physicists only so far back toward the moment just after the Big Bang, science's understanding of a unified theory is ultimately going to have to come from exploring the vastness of the universe. Some physicists wonder if such a strategy, which relies on finding and interpreting clues left behind by nature, can produce results comparable to the high-precision experimental data that led to the Standard Model during the 20th century.

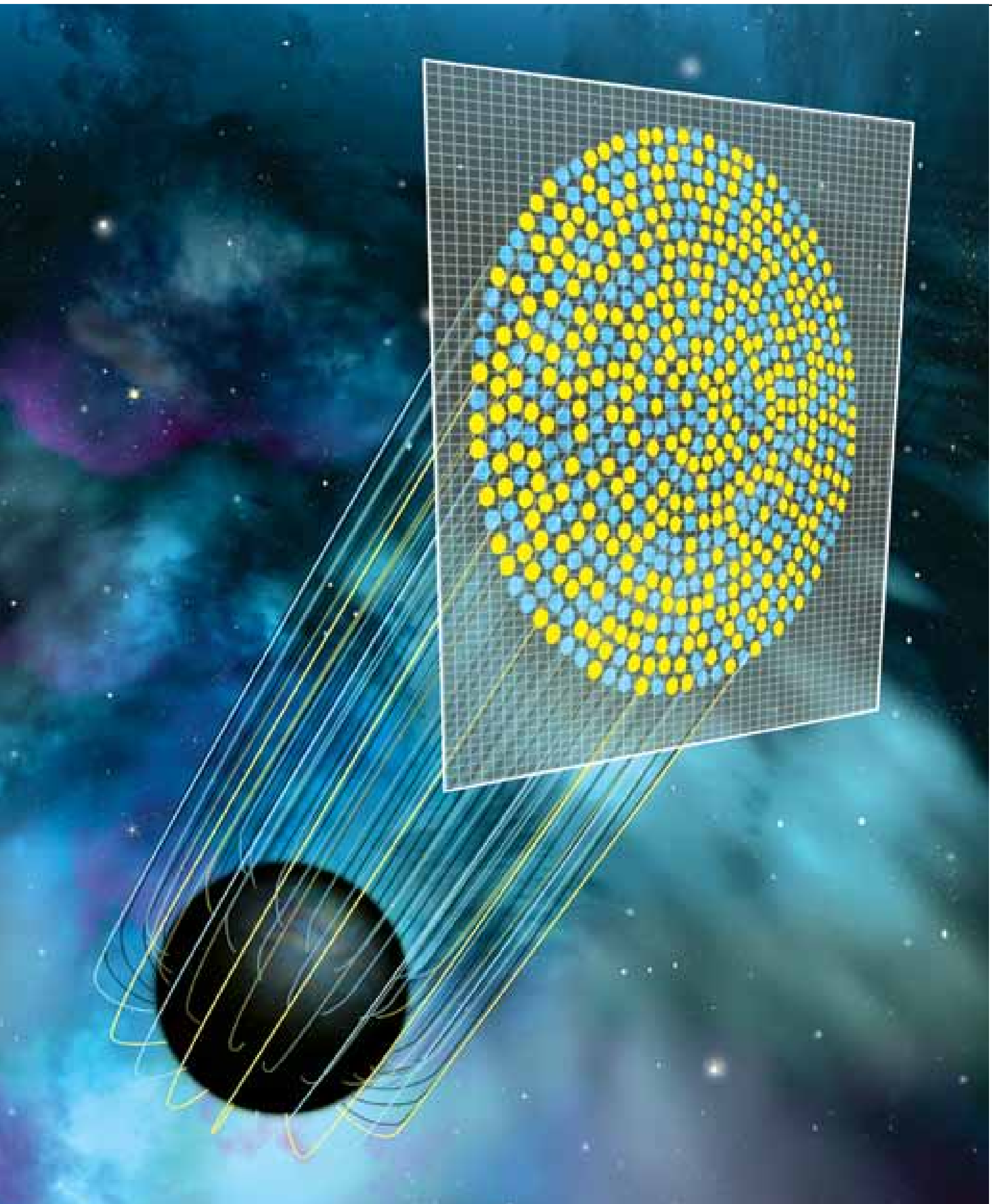
But string theory is not 20th century science — in fact, string theorist Edward Witten has described it as "21st century physics that fell accidentally into the 20th century." Now that the 21st century has arrived, it's string theory's time to be put to the test. ■

Back to one

One of the enduring puzzles in physics is why gravity — which guides matter on the scale of planets and galaxies — is so much intrinsically weaker than the other three forces. In the moments just after the Big Bang, some researchers think, the forces may have been united as one, separating into forces with differing strengths as temperatures decreased.

Strength of the four forces back in time





A 2-D projection contains all the details needed to map a 3-D black hole. Some physicists think space and time may emerge via a similar correspondence.

ARE SPACE AND TIME FUNDAMENTAL?

Out of the fabric

By Tom Siegfried ▪ Illustration by Nicolle Rager Fuller

Of all the mysteries of life and the universe, none resist the sleuthing of science's best private eyes more obstinately than the ultimate nature of space and time.

Every several centuries or so, profound insights do occur, immortalizing the names of the investigators who achieved them: Euclid (who cataloged the insights preceding him), Galileo, Newton, Einstein. Yet each advance left deeper questions unanswered. And now the 21st century's best brains still cannot say for sure whether space and time are fundamental building blocks of natural existence, or are themselves built from more primordial ingredients, so far unperceived.

Newton simply declared space and time as absolute and constant, providing a convenient arena for the operation of his laws of motion and gravity. Einstein saw, and showed, that space and time actually shift shape or speed as events unfold; mass and motion warp space and alter the flow of time.

Coping with these inconveniences required a merger, space and time becoming spacetime. From that merger emerged a bonus: a model for the evolution of the cosmos, from an initial speck of matter and energy to a gigantic ballooning multigalactic network.

Nowadays, though, spacetime's ability to accommodate nature's phenomena has begun to fade as physicists push their probes to the limits of distance and duration. Below a certain very tiny distance, the dimension of length can no longer be explored, or even defined. Time faces a similar limit when durations approach the very brief.

Today's leading theories for answering the greatest cosmic questions suggest that neither time nor space appear in reality's ultimate recipe. Somewhere between the stove and the table, space and time emerge, cooked up out of equations underlying an existence without rulers and clocks. At least that is "the widespread current belief," says physicist Joe Polchinski of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara.

Space as society

To illustrate this, Fotini Markopoulou of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, compares space to society. Space, like society, has features that can be described — geometry textbooks catalog space's properties and their implications. But space as reflected in geometry need not have been present at the beginning. It could have emerged from the interactions of matter and forces, just as society materializes from interactions among people.

"We have capitalist societies, agricultural societies, totalitarian societies," Markopoulou wrote in a 2008 paper (arXiv.org/abs/0909.1861). Nobody is confused by phrases such as "our society is addicted to credit." But that doesn't mean society is a fundamental feature of existence.

"A society does not exist independent of its members," Markopoulou pointed out. "We can see spacetime geometry as the analog to society, with the role of individuals played by matter and its dynamics."

As Polchinski notes, specifying spacetime's status in relation to matter is part of the quest for a theory of quantum gravity — the math that would unify Einstein's relativity theory, which describes spacetime in bulk, with the quantum physics that governs the microworld (see Page 26). A key clue in that quest is a correspondence between the surface of a black hole, a gravitational bottomless pit from which nothing can escape, and the space within it. It turns out that a mathematical description of the black hole's outer boundary (the point of no return for objects falling in) contains all the information needed to specify the three-dimensional interior. In essence, that means the 3-D space inside somehow emerges from the physics of the 2-D surface.

Time materialized

Generalizing the peculiarities of black holes to ordinary space and time remains a research challenge for quantum gravity physicists. But most agree that sooner or later space and time will have to go. String theory — the most-studied approach to quantum gravity — offers several examples of how space, rather than being fundamental, emerges into existence, as physicist Nathan Seiberg of the Institute for Advanced Study in Princeton, N.J., outlined in a 2006 paper (arXiv.org/abs/hep-th/0601234).

If matter at its most basic is made of tiny vibrating strings, for instance, it becomes impossible to probe space to any arbitrarily short distance, Seiberg observes. That's another way of saying that at distances less than some (very short) length, the idea of space becomes meaningless.

Further study of spaceless theories may help solve serious problems confronting physicists today, Seiberg believes. String theory implies countless possible vacuum states — that is, spaces of differing physical properties — with no obvious method for determining which one the visible universe should have chosen. Knowing how space emerges from spacelessness might help explain why humans exist in one particular space from among the countless possibilities.

Doing away with time poses more difficult problems, Seiberg acknowledges. Basic notions in physics, such as that of causes preceding effects, or predicting the outcome of experiments before the experiment is done, seem to lose their meaning if there is no time to define before and after. So some physicists, Markopoulou for one, have suggested that even if space is emergent, time may remain fundamental. In fact, she conjectures, time is needed to allow quantum processes to create the illusion of space. Space may not have been around at the beginning, but that beginning would be stillborn without time to get reality going.

Seiberg, though, believes time and space will both go down the cosmic drain together.

"My personal prejudice is that these objections and questions are not obstacles to emergent time," Seiberg writes. "Instead, they should be viewed as challenges and perhaps even clues to the answers."

More intriguingly, he observes, space and time's ultimate status in nature may have something to say about the practice of science. Much of modern science is based on the concept of reductionism — explaining large-scale phenomena from laws operating at smaller scales. That notion will eventually break down if there's a smallest scale below which space no longer exists.

"Therefore, once we understand how spacetime emerges, we could still look for more basic fundamental laws, but these laws will not operate at shorter distances," he writes. "This follows from the simple fact that the notion of 'shorter distances' will no longer make sense. This might mean the end of standard reductionism." And the beginning of a new view of not only space and time, but of science itself. ■

As small as it gets

Current theories are unable to describe space and time below certain limits defined by what are called "natural units." These units, proposed by the German physicist Max Planck, are derived from fundamental quantities such as the speed of light. A theory uniting quantum mechanics with gravity will be needed to reveal whether space and time are meaningful concepts at smaller scales.

Planck length: 1.616×10^{-35} meters

The Planck length is derived from Newton's gravitational constant, the speed of light and Planck's own constant from quantum theory. It is unfathomably small: Comparing its size to a bacterium is like comparing the size of a bacterium to the visible universe. Many physicists believe that at shorter lengths space cannot be probed and the concept of distance becomes no longer meaningful.

Planck time: 5.391×10^{-44} seconds

The Planck time is also calculated from the gravitational constant, the speed of light and Planck's constant in such a way that moving at one Planck length per one Planck time would be equal to the speed of light. Current theories are unable to describe the universe at an age younger than the Planck time; physicists hope that a theory of quantum gravity could illuminate that epoch.

WHAT IS THE FATE OF THE UNIVERSE?

Hanging in the balance

By Elizabeth Quill ▪ Illustration by Nicolle Rager Fuller

The fate of the universe was supposed to be sealed by the turn of the millennium.

"I imagined we'd be walking around holding a sign saying 'the world is coming to an end' or 'the world is not coming to an end,'" recalls astrophysicist Saul Perlmutter.

But as Y2K soothsayers readied for impending doom, Perlmutter and his colleagues delivered a surprising discovery suggesting that the world's fate would stay in limbo long after the Times Square ball dropped and any leftover champagne went flat. More than a decade later, scientists are still vigorously debating what their finding means not only for the universe's future, but also for all of cosmology.

Perlmutter, of the University of California, Berkeley, led one of two teams that set out in the early 1990s to get a grip on the far future by studying distant supernovas. These stellar explosions serve as distance markers to help astronomers measure how fast the universe is expanding — a key factor in determining if and when it will meet its end. But after analyzing the data, both teams reported in 1998 that the universe's expansion isn't just cruising along — it is accelerating. Some mysterious force, now known as dark energy (see Page 24), is driving space apart, faster and faster.

A dark twist

Before dark energy's discovery, the forecast was surprisingly simple. If the gravitational pull of all the matter in the cosmos was strong enough to rein in expansion — like the Earth's pull on a rocket that can't quite reach escape velocity — the universe would eventually come crashing in on itself. That ending, dubbed the Big Crunch, would mirror the Big Bang that started the cosmic expansion in the first place. If, though, the universe's expansion escaped the claws of gravity, it would go on growing forever. Expansion would slow but never halt, and instead of ending, the universe would

In one end-time scenario, the entire universe — from galaxies down to atoms — would rip apart at its seams.

become a cold, dark, lonely place where life could not survive — a Big Freeze.

But dark energy gives the fleeing rocket some extra oomph, making end-time predictions quite a bit fuzzier.

"A crucial issue is how the dark energy will behave in time," says cosmologist Rocky Kolb of the University of Chicago. "Until we have some way to grapple with that, the fate of the universe hangs in the balance."

If the strength of dark energy's extra push remains forever unchanging, it could be the cosmological constant — a term Albert Einstein added to his equations for general relativity in 1917 and later dismissed as his "biggest blunder." In this case, something like the Big Freeze would play out. But if dark energy's strength decays over time, then a Big Crunch of sorts remains an option.

If instead dark energy grows stronger, exceeding the repulsive force of Einstein's cosmological constant, a more painful scenario awaits: "In a finite amount of time, dark energy gets infinitely dense," says cosmologist Max Tegmark of MIT. "First denser than our galaxy, and our galaxy flies apart. Then denser than Earth, and that flies apart. Then denser than atoms, and atoms fly apart. In a finite time, everything is ripped apart."

Figuring out whether the universe would end with this Big Rip, or a Freeze or Crunch, requires determining a property of dark energy called its equation of state. That quantity is the ratio of the pressure exerted by the dark energy to its density. The most recent findings, based on data that come from seven years of mapping the glowing radiation left over from the Big Bang, suggest that the equation of state is close to that expected for the cosmological constant, deviating by no more than 14 percent.

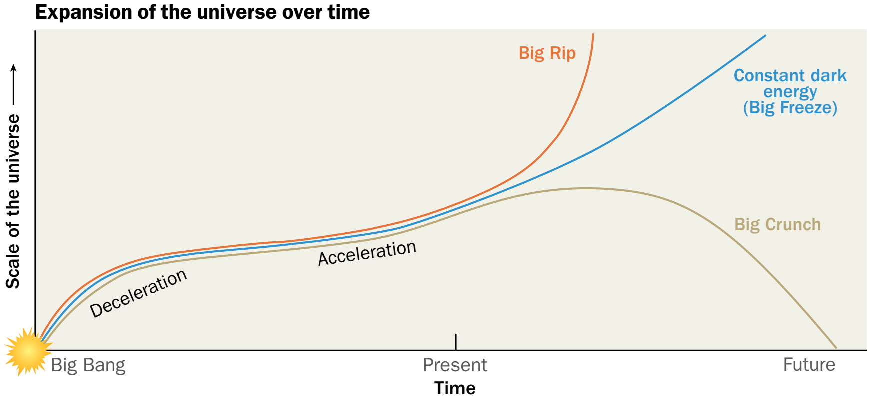
But over billions of years, even a much tinier deviation — undetectable with current instruments — could dramatically alter the universe's fate, especially if the dark energy's strength is not constant but can change over time.

"The million dollar question is an experimental question," Tegmark says. Scientists need better measurements to determine whether dark energy's equation of state is perfectly constant.

So some experimentalists are turning back to those very same stellar explosions that revealed dark energy's existence to begin with. A paper by Perlmutter and collaborators, appearing in 2009 in the *Astrophysical Journal*, describes an ongoing effort to compile the world's supernova datasets. Many scientists have their hopes set on a future observatory, WFIRST, which would look for the signal of dark energy in the appearance of distant galaxies and in the imprint of the cosmic equivalent of sound waves in the early universe. A proposed mission named Euclid, from the European Space Agency, and a camera mounted on a telescope in the Andes will further the efforts.

Cosmic Armageddon The discovery of dark energy made the fate of the universe much more difficult to forecast. Scientists typically talk about three possible endings (depicted below), depending on what this mysterious force actually is and how it behaves over time.

Expansion of the universe over time



SOURCE: CXC/NASA, M. WEISS

Beyond the end

But others say that a theoretical breakthrough is necessary. Measuring the equation of state with enough precision, they argue, is impossible; a tiny deviation could always linger.

"We don't just want to measure a number," Kolb says. "We want to understand how this crucial piece of physics fits into the overall fabric of the theory of nature. And until we do that, I am not going to be comfortable with any explanation of dark energy."

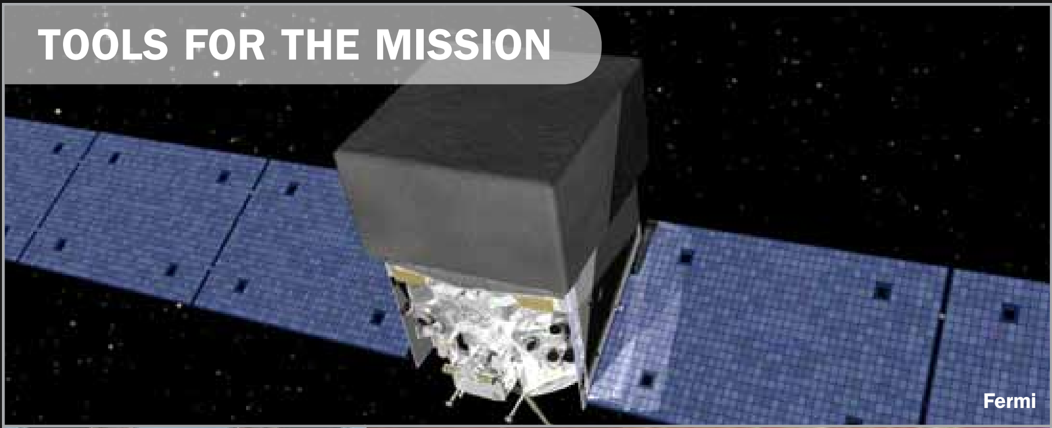
Kolb thinks no current proposal adequately explains dark energy, thus no proposal decides among a Freeze, Crunch or Rip scenario.

Of course, the right theory might even predict that the universe meets its doom by some other, unknown means. One such possibility presents itself if the observable universe is just one of many bubble universes constantly being created and growing in some larger space. In this "multiverse" scenario, bubble universes can collide. If another bubble encroached on the bubble that people occupy, it would be bad news, says Anthony Aguirre of the University of California, Santa Cruz. "We would just be sitting around," he says, "and this other bubble would smash into us at the speed of light with some huge energy and we would die."

Beyond predicting another possible end, the multiverse ushers in a new way of thinking about what an "end" actually means. "We'd have to be living in a lucky (for cosmologists) or simple universe for the part that we see to be telling us about the whole thing," Aguirre says.

Imagining the death of the observable universe as the ultimate end may be just as naïve as imagining that the destruction of the Earth, for that matter, means the end of all life in the galaxy. There might be much more out there. Even if the bubble occupied by people bursts, other universes could live long and prosper. ■

TOOLS FOR THE MISSION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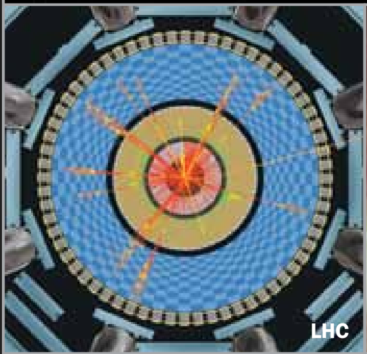

LHC


Planck

Hunting data

A number of instruments now operating or proposed can troll the skies or otherwise help to answer some of the most puzzling questions about the universe.

Planck A European Space Agency observatory launched in 2009, Planck is recording a more detailed picture of the cosmic microwave background, the relic radiation left over from the Big Bang, than its predecessors COBE and WMAP did. The mission is searching for primordial gravitational waves, which could provide a test for inflation theory, and looking for clues to the nature of dark matter and dark energy.

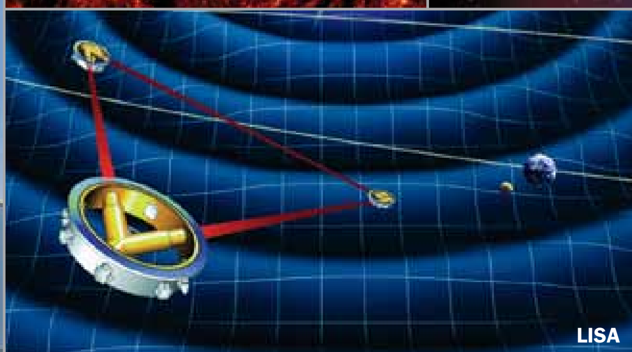
Fermi Launched in 2008, the Fermi Gamma-ray Space Telescope has opened scientists' eyes to astronomical objects that emit very high-energy radiation, including supermassive black holes and colliding neutron stars. Since its launch, Fermi has found evidence of antimatter above thunderstorms on Earth (*SN: 12/5/09, p. 9*) and captured unexpected changes in emissions from the Crab Nebula (*SN: 1/1/11, p. 11*). Fermi could offer clues to the identity of dark matter and to the birth of the universe.

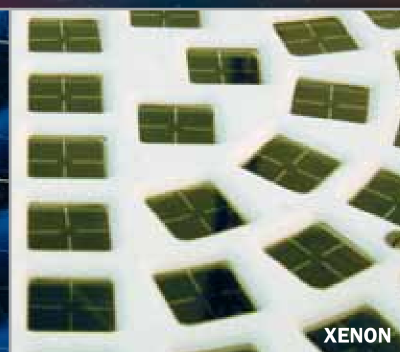
WFIRST The Wide-Field Infrared Survey Telescope, a proposed NASA observatory, would probe a wide swath of the sky with two main goals: to settle key questions about dark energy by mapping large-scale structures and to look for signs of extrasolar planets in the Milky Way's central bulge.

LHC By smashing protons together at high speeds, the Large Hadron Collider is re-creating energies present just after the Big Bang. In the spew of particles emitted (computer-generated image shown), scientists hope to spot signs of supersymmetry and find evidence for string theory—possibly pointing to a theory that unifies the forces of nature. The collider, in a 27-kilometer tunnel straddling the border of Switzerland and France, began regular operations in 2010 but has yet to operate at full energy.

LSST Proposed to sit atop Cerro Pachón in the Chilean Andes, the Large Synoptic Survey Telescope (mirrors and lenses depicted) will capture the entire visible sky twice each week, helping astronomers better understand the large-scale structure of the universe throughout its history. Knowing how stars, galaxies and galaxy clusters are distributed can offer insight into cosmic ingredients, including dark matter's distribution and dark energy's strength.

Dark Energy Survey Atop another mountain in the Chilean Andes—Cerro





Tololo — researchers are mounting a sensitive digital camera on an existing 4-meter telescope in an attempt to uncover the nature of dark energy. The camera will survey a large swath of the southern sky over five years to gather information about more than 300 million galaxies. An effort that includes scientists from 23 institutions, the survey is expected to see first light in fall.

Dark matter experiments The XENON Dark Matter Project, operating underground at Gran Sasso National Laboratory in Italy, looks for signs of dark matter particles by recording scintillations in liquid xenon (detector shown above). The DAMA/LIBRA experiment, at the same lab, records seasonal variations in faint flashes of light from 25 sodium iodide detectors. And an experiment in a mine in northern Minnesota, the Cryogenic Dark Matter Search, tries to spot dark matter jostling germanium and silicon detectors. Though claims of detection have been made, dark matter's identity remains unknown.

JWST The James Webb Space Telescope will have a primary mirror 6.5 meters across and will orbit about 1.5 million kilometers from Earth. The observatory will probe how stars and galaxies first emerged and will look for Earthlike planets. Launch had been scheduled for 2014, but has been pushed back to no earlier than 2016 because of cost overruns (*SN: 4/25/11, p. 22*).

Euclid Named for the father of geometry, the proposed Euclid spacecraft (two concepts shown) would measure dark matter distribution and try to understand the nature of dark energy by looking back 10 billion years, before dark energy began to dominate over matter in the universe.

IXO Proposed by NASA, the European Space Agency and the Japan Aerospace Exploration Agency, the International X-ray Observatory would take in radiation emitted from neutron stars and from the vicinity of black holes. Searching in the X-ray regime would allow the observatory to peer through dust and gas clouds that might otherwise obscure its view. IXO may reveal how matter behaves in extreme conditions and help reveal the nature of dark matter and dark energy.

LISA The Laser Interferometer Space Antenna, a proposed NASA-ESA mission, would actually be three identical spacecraft that form a triangle. By recording how the craft move in relation to each other, scientists hope LISA will detect gravitational waves. Background undulations left over from the early universe could offer clues to its origin and expansion history.

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