Searching for the *shape* of the *universe*

Inflation, an early period of cosmic hyper-expansion, may be the key to proving the universe has six extra dimensions. /// **BY STEVE NADIS**

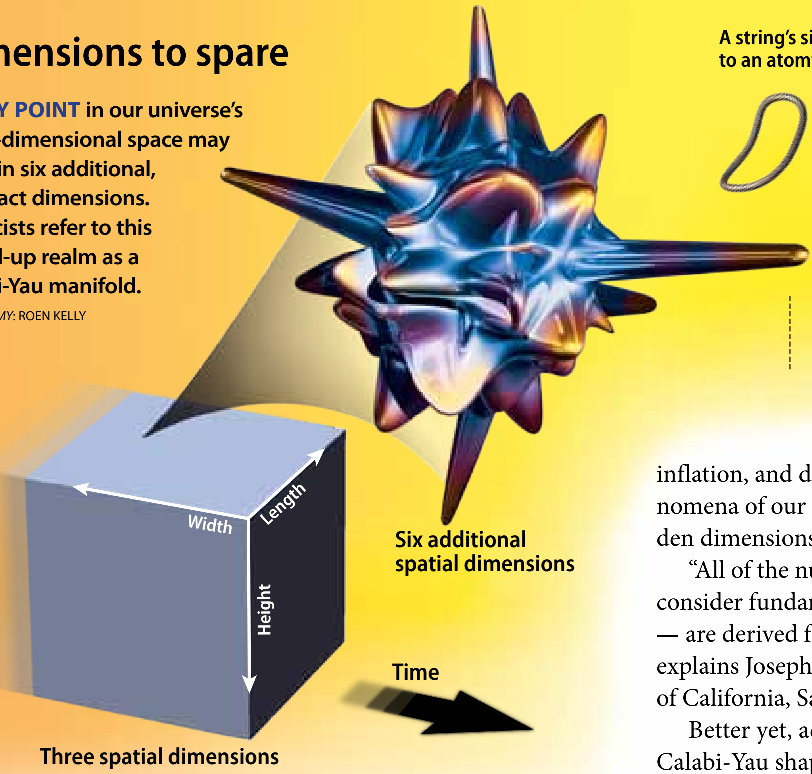
For as long as people have studied the sky and wondered where it ends, or how, they've wondered about the universe's shape. Information from the Wilkinson Microwave Anisotropy Probe (WMAP), which is mapping the whisper of microwaves emitted 380,000 years after the universe's birth, indicates the universe is flat to within a 2-percent margin of error. If the universe is big enough, the cosmos could appear flat whether it's shaped like a pancake, a meatball, or a bagel.

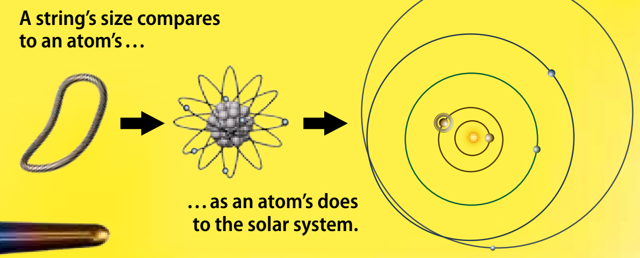
But "outer space" — the seemingly immeasurable gulf containing billions of galaxies — isn't the only part of the universe that may have shape. Physicists say there's also an "inner space" — a concealed, microscopic realm tucked away so tightly we can't experience it directly. It's here that string theory, often regarded as our leading explanation of nature, postulates the presence of a 10-dimensional

THEORISTS SUSPECT our universe has extra dimensions that lie curled up at every point around us. From these higher dimensions, our universe may appear to be a three-dimensional membrane attached to a warped "throat" extending from the compact dimensions. Cosmological studies may help theorists separate the effects of one higher-dimensional configuration over another, and, in the process, validate string theory. *ASTRONOMY*: ROEN KELLY

Dimensions to spare

EVERY POINT in our universe's three-dimensional space may contain six additional, compact dimensions. Physicists refer to this curled-up realm as a Calabi-Yau manifold. *ASTRONOMY:* ROEN KELLY





THE TWISTED DIMENSIONS of Calabi-Yau manifolds may be similar in size to superstring theory's hypothetical strings. *ASTRONOMY:* ROEN KELLY

universe — the normal three dimensions of space we're familiar with, plus time, plus six other dimensions.

Six pack

Einstein's theory of general relativity unified space and time as a four-dimensional space-time a century ago, so where do string theory's extra dimensions reside? According to scientists, they're curled up into tiny geometrical containers called Calabi-Yau manifolds, where they remain forever hidden from us.

"If string theorists are right," says Harvard University physicist Lisa Randall, "everywhere in visible space — at the tip of your nose, at the north pole of Venus, at the spot above the tennis court where your racket hit the ball the last time you served — there would be a six-dimensional Calabi-Yau manifold of invisibly tiny size." This higher-dimensional geometry therefore exists at every point in space.

Physicists classify these intricate, twisted, geometric forms as compact —"something you can put in the trunk of your car," they often say. That's a bit of scientific understatement meant to convey that Calabi-Yau manifolds have no infinitely long structures. Their actual size remains an open question. Physicists initially regarded them as exceedingly small, with diameters on the order of the Planck scale (10^{-33} centimeters). Current thinking holds they're 10,000 trillion times larger than this, perhaps similar to the spatial scale of string theory's hypothesized strings — larger, perhaps, but still too small to detect.

Theorists are keenly interested in the shape of these complex, six-dimensional spaces. They believe the manifold's geometry dictates the laws of particle physics and influences gravity, cosmic inflation, and dark energy. If they're right, these dominant phenomena of our cosmos may either spring directly from these hidden dimensions or be profoundly affected by them.

"All of the numbers we measure in nature — all of the things we consider fundamental, such as the masses of quarks and electrons — are derived from the size and shape of Calabi-Yau space," explains Joseph Polchinksi, a theoretical physicist at the University of California, Santa Barbara.

Better yet, according to string theory, the number of possible Calabi-Yau shapes is linked to the number of possible universes — a "multiverse," as it's sometimes called. In fact, many of today's biggest problems in physics and cosmology reduce to a single geometry problem: determining the shape of extra dimensions.

So, what can we learn about inner space's geometry? Investigators have two main goals: to secure evidence for the existence of these dimensions, and obtain hints about their underlying geometry. The picture is still crude. Researchers have described these shapes, or parts of them, as ice cream cones, throats, cigars, gloves, and even anteaters.

"How are the extra dimensions of string theory curled up?" asks University of Wisconsin physicist Gary Shiu. He leads a team of researchers who think they've hit on a way to answer this question. "We argue that precise measurements of the cosmic microwave background [CMB] can give us clues," he says.

Steve Nadis *is a contributing editor of* Astronomy. *He's working with Harvard University's Shing-Tung Yau on a book tentatively titled* The Shape of Inner Space.

BRANES, STRINGS, AND THE CMB

BRANE
Any of the extended objects that arise in string theory. A 1-brane is a string, a 2-brane is a membrane, and a 3-brane has three spatial dimensions.

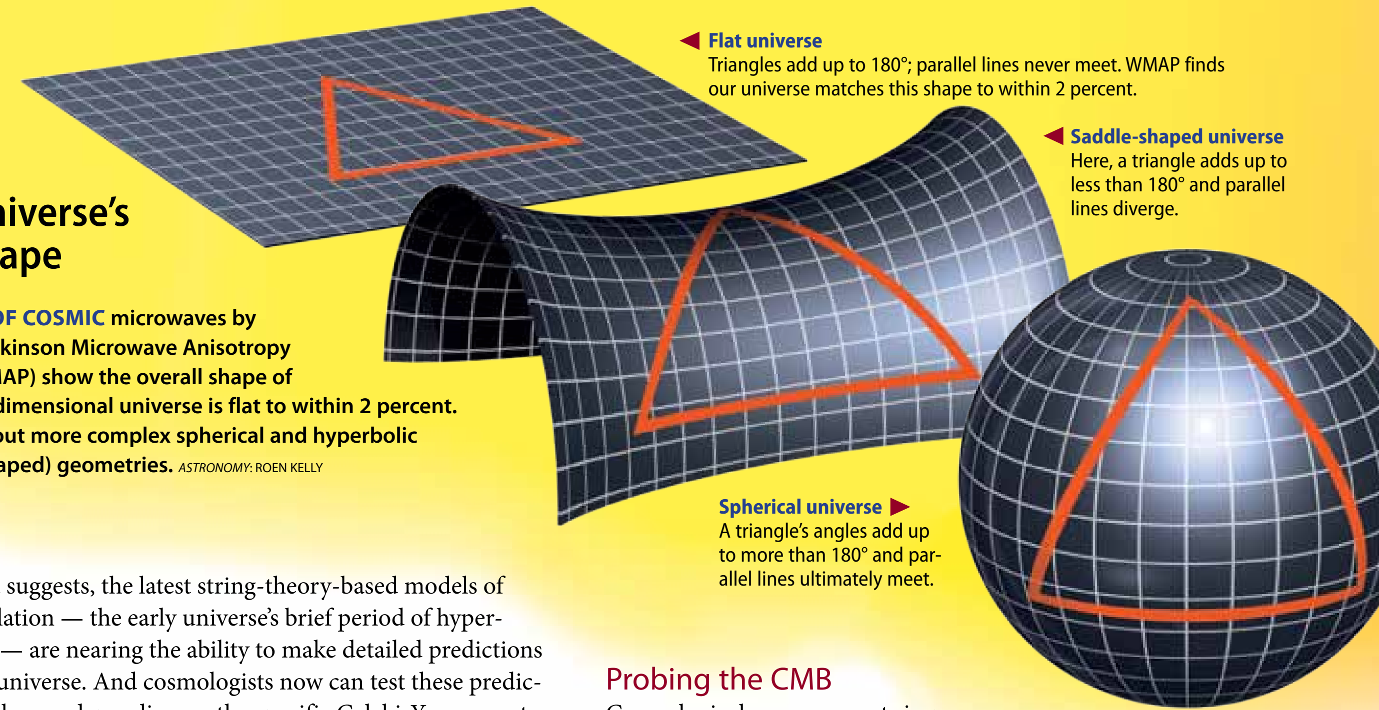
COSMIC MICROWAVE BACKGROUND (CMB)
Microwave radiation suffusing the universe that was originally light produced 380,000 years after the Big Bang.

STANDARD MODEL
A theory of interactions of nature's most fundamental known particles (i.e., electrons and quarks) developed in the late 1960s and early 1970s. Its inability to explain gravity suggests a more fundamental theory exists.

STRING THEORY
A unified theory of the universe postulating that nature's fundamental ingredients are not particles but one-dimensional filaments called strings. String theory unites quantum mechanics and general relativity, which are otherwise incompatible; short for superstring theory.

The universe's 3-D shape

STUDIES OF COSMIC microwaves by NASA'S Wilkinson Microwave Anisotropy Probe (WMAP) show the overall shape of our three-dimensional universe is flat to within 2 percent. This rules out more complex spherical and hyperbolic (saddle-shaped) geometries. *ASTRONOMY:* ROEN KELLY



As Shiu suggests, the latest string-theory-based models of cosmic inflation — the early universe's brief period of hyperexpansion — are nearing the ability to make detailed predictions about our universe. And cosmologists now can test these predictions, which vary depending on the specific Calabi-Yau geometry assumed responsible for inflation's birth, against CMB data.

Brane damage

The basic premise is that the motions and interactions of large, membrane-like structures called "branes" actually drove cosmic inflation. In this scenario, a brane and its opposite counterpart, an antibrane, slowly move toward each other in higher dimensions.

The two branes possess a mutual attraction, so their separation represents a vast source of potential energy — enough to trigger inflation. This fleeting process, which expanded our four-dimensional universe by more than a trillion trillion times, continued until the branes collided and annihilated each another. In this view, inflation occurs before the Big Bang. In fact, it's the energy released in the branes' mutual destruction that created and powered our Big Bang.

So the thing we've traditionally called our universe sits on a three-dimensional brane that would be a mere speck, or point, in a six-dimensional Calabi-Yau manifold. But how can our vast, and apparently infinite, cosmos fit into higher-dimensional space's ultracompact domain? Researchers say our three spatial dimensions are independent of the Calabi-Yau dimensions.

"Rather than pointing in the same direction, they point in orthogonal directions, so there's no trouble fitting in," explains Princeton University physicist Liam McAllister. Adds Henry Tye of Cornell University: "We're just sitting in a tiny corner of six-dimensional space."

The brane and antibrane responsible for inflation moved around in the early universe. "The fact that the branes have been moving allows us to learn much more about that space than just sitting in the corner," Tye says. "Just like at a cocktail party: You don't pick up much if you stay in one corner. But if you move around, you're bound to learn more." As it turns out, brane movement prior to inflation leaves an indelible imprint on the cosmic microwave background.

> The dominant phenomena of our cosmos may spring directly from *hidden dimensions* or be profoundly affected by them.

Probing the CMB

Cosmological measurements impose constraints on the kind of Calabi-Yau space we live in. Observational data are now getting precise enough that researchers can determine whether a given Calabi-Yau manifold is consistent with experiment, a development physicists find encouraging.

"You can take inflation models and divide them in half — those that are favored by observations and those that are not," says physicist Cliff Burgess of Ontario's Perimeter Institute for Theoretical Physics. "The fact that we can now distinguish between inflation models means we can also distinguish between the geometric constructions that give rise to those models."

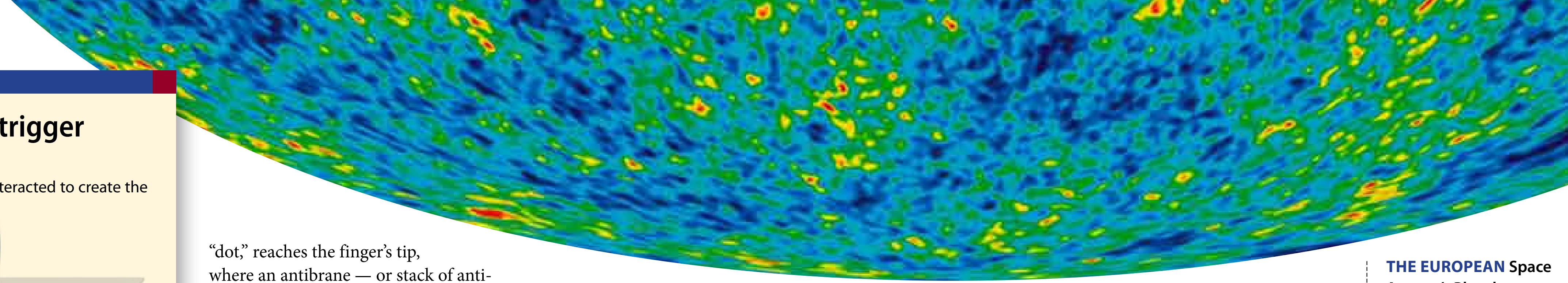
For example, a 2006 study led by Liam McAllister explored the observational signals of inflation occurring in an extended portion of a Calabi-Yau manifold called a "warped throat." The scientists found that different Calabi-Yau geometries lead to different observational signatures.

Ice cream cones and anteaters

A "throat" is the most common defect found in Calabi-Yau space. It's a cone-shaped bump that naturally protrudes from the surface. McAllister suggests the image is reminiscent of a large scoop of ice cream — the bulk of those tightly wrapped dimensions — sitting atop a slender cone.

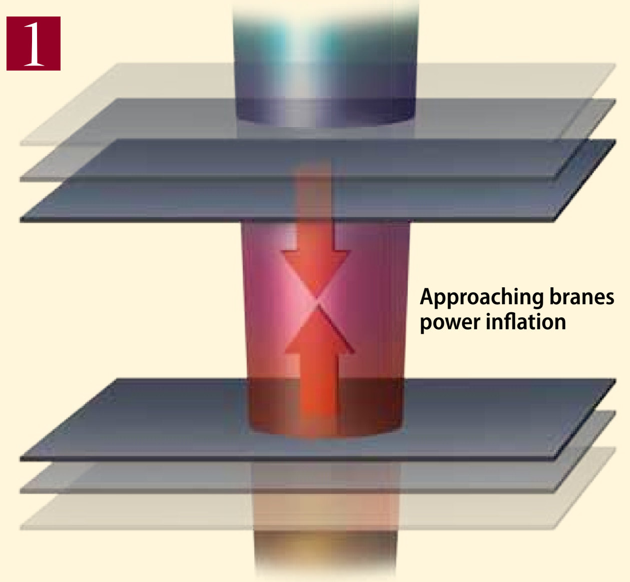
This throat becomes even more distended and warped by the magnetic fields, or fluxes, posited by string theory. "The flux exerts a force on the tip of the cone, stretching it out into a long, narrow neck like the snout of an anteater," explains Stanford University physicist Leonard Susskind.

Any given Calabi-Yau space is likely to have more than one warped throat, so Cornell University astronomer Rachel Bean prefers the analogy of a rubber glove to that of an ice cream cone. "Our three-dimensional universe is like a dot moving down the finger of a glove," she explains. Inflation ends when the brane, or

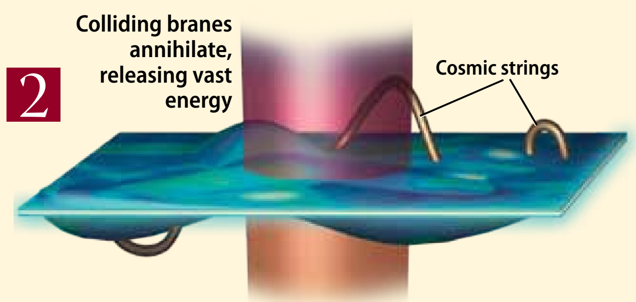


Did annihilating branes trigger the Big Bang?

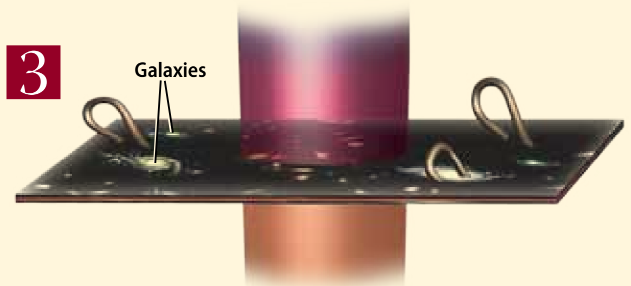
Physicists suggest a brane-antibrane pair interacted to create the Big Bang. Here's how it might have worked:



A brane and an anti-brane spanning our universe's three spatial dimensions move together. As they approach, inflation begins. The size of the universe grows a trillion trillion times and possibly creates ripples in space-time called gravitational waves.



Inflation ends when the branes collide and annihilate each another. The energy release heats up our universe, initiating the hot Big Bang. The collision may also create cosmic strings. Such structures may reveal themselves by gravitational lensing of distant background objects or by polarizing the CMB.



Density fluctuations produced during inflation become the seeds for today's cosmic structures. They also created the temperature fluctuations now being mapped in the CMB. *ASTRONOMY*: ROEN KELLY

"dot," reaches the finger's tip, where an antibrane — or stack of antibranes — patiently waits. Because the finger's shape constrains the brane's motion, she says, the specific features of inflation stem from its geometry.

Suppose inflation occurred within the confines of two different warped-throat geometries. Could we tell them apart? Gary Shiu and his graduate student Bret Underwood looked at this question in a 2007 study. The scientists picked two relatively well-known throat models — named Klebanov-Strassler and Randall-Sundrum — and then looked at how inflation under these two different conditions would affect the CMB.

In particular, they focused on a standard CMB measurement: temperature fluctuations in the early universe. These fluctuations should appear roughly the same on small and large scales. Scientists call the rate at which these fluctuations change from small to large scales the "spectral index." Shiu and Underwood found a 1-percent spectral-index difference between the two scenarios. So, the choice of geometry has a measurable effect on that number.

In cosmology, a 1-percent difference can be significant. The European Space Agency's planned Planck spacecraft, the next-generation CMB mapper scheduled for a July launch, could measure such differences. Planck data may allow one throat geometry as a possible shape for higher dimensions and eliminate another.

"Away from the tip, the two geometries look almost identical, and people used to think they could be used interchangeably," Underwood notes. "Shiu and I showed that the details do matter." Still, he admits that going from the spectral index, which is a single number, to the geometry of extra dimensions is a big leap.

If researchers have enough data on the CMB, can they determine what Calabi-Yau shape it is? Cliff Burgess doesn't think this will be possible in the next 2 decades. Liam McAllister also is skeptical. "We'll be lucky in the next decade just to be able to say inflation did or did not occur," he says. "I don't think we'll get enough experimental data to flush out the full shape of the Calabi-Yau space, though we might be able to learn what kind of throat it has or how many branes it has."

Shiu is more hopeful. "If you can only measure the spectral index, it's hard to say something definitive about the geometry," he says. But you'd get much more information if you could measure non-Gaussian features of the CMB — ways in which matter's clumpiness in the early universe deviates from a purely random distribution. A clear indication of this would impose more constraints on the underlying geometry. "Instead of one number, like the spectral index, it's a whole function — a whole bunch of numbers that are all related to each other," he adds.

If matter were particularly clumpy, it could point to a specific version of brane inflation known as Dirac-Born-Infeld (DBI) occurring within a well-defined throat geometry. "Depending on the precision of the experiment," Shiu says, "such a finding could, in fact, be definitive."

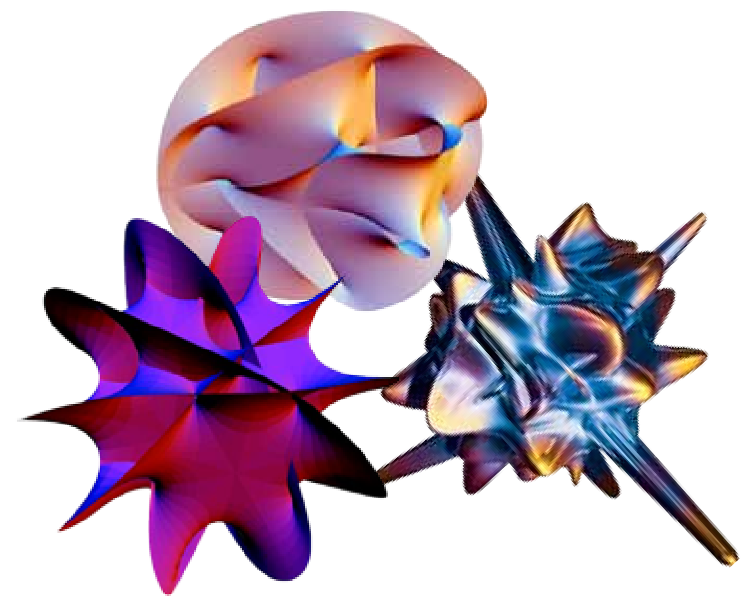
Columbia University physicist Sarah Shandera notes that a string-theory-motivated inflation model like DBI may prove important even if string theory fails as the ultimate description of nature. "It gives cosmologists something new to look for," she says. As in any experimental science, knowing what questions to ask, and how to frame them, is a big part of cosmology's game.

In the abstract realm of theoretical physics, warped throats are considered both fundamental and generic. They're features "that arise naturally from six-dimensional Calabi-Yau space," according to Princeton's Igor Klebanov. "No one can say how the universe works, yet I still think warped throats are a crucial part of the geometry of nature," he says. That belief may or may not be true, but warped throats offer theorists a setting rich in possibilities.

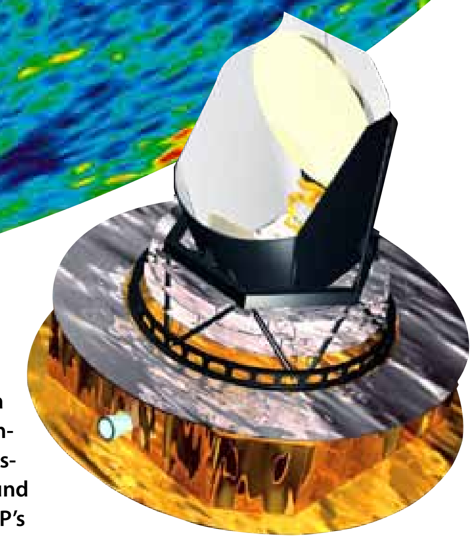
Strings across the cosmos

If inflation's driving force originated in a warped throat, then gravitational waves — ripples in the fabric of space-time — might bear clues about the specific manifold that generated them. Inflation should create such waves, but no one's detected them yet.

Hypothetical defects in space called cosmic strings, produced at the end of inflation, might yield even more telling signals. Cosmic strings are like the tiny strings of string theory, but they span the entire universe. Their presence would leave a distinct pattern in the cosmic microwave background. "The details of that signature would depend on the shape of the extra dimensions," Polchinski says.



CALABI-YAU MANIFOLDS wrap their extra dimensions in a variety of shapes. No one knows which geometry best describes our universe, but cosmology may help narrow down the possibilities. TOP AND LEFT: ANDREW J. HANSON (INDIANA UNIV.); RIGHT: *ASTRONOMY*: ROEN KELLY



THE EUROPEAN Space Agency's Planck spacecraft (right) is slated for a July launch. Planck's high-resolution view of the cosmic microwave background is designed to best WMAP's (above). With enough detail, physicists could determine which possible Calabi-Yau geometries our universe cannot contain. TOP: NASA/WMAP SCIENCE TEAM; SPACECRAFT: ESA

Warped-throat inflation models predict not just one cosmic string but a spectrum of them formed in brane-antibrane annihilations. The strings would have a range of tensions, similar to the properties of rubber bands of varying thicknesses. "Evidence of different types of cosmic strings would be a truly dramatic finding," Klebanov adds.

Getting a handle on the shape of Calabi-Yau space will require precise measurements of the CMB's spectral index, sightings of non-Gaussian clumping, and the detection of gravitational waves or cosmic strings. "Although we now have confidence in the standard model of physics, that model did not materialize overnight," Shiu notes. "It came from a whole sequence of experiments over the course of many years. In this case, we'll need to bring a lot of measurements together to get an idea of whether extra dimensions exist or whether string theory seems to be behind it all."

Patience, he says, is also in order, because researchers' overall goal is not just to probe the geometry of hidden dimensions. They also want to put to the test string theory itself, a branch of physics that has been criticized for lacking experimental support. The general strategy makes sense to Bret Underwood. He considers cosmology one of the most promising ways to test string theory because the energy scale of inflation is close to the energy scale needed to make strings.

"It's possible that string theory will predict a finite class of models, none of which are consistent with inflation," says Liam McAllister, "in which case we could say the theory is excluded by observation. Some models already have been excluded, which is exciting because it means the cutting-edge data really make a difference." At the moment, he says, warped-throat inflation is one of the best models produced so far, but, he cautions: "In reality, inflation may not occur in warped throats, even though the picture looks quite compelling."

In the end, the ultimate correctness of such models may not be their most important feature. "These models are based on geometries coming out of string theory for which we can make detailed predictions that we can then go out and test," says Rachel Bean. "In other words, they're a way of making a start."

WEB EXTRA Learn more about how the CMB tells scientists about hidden dimensions at www.Astronomy.com/toc.