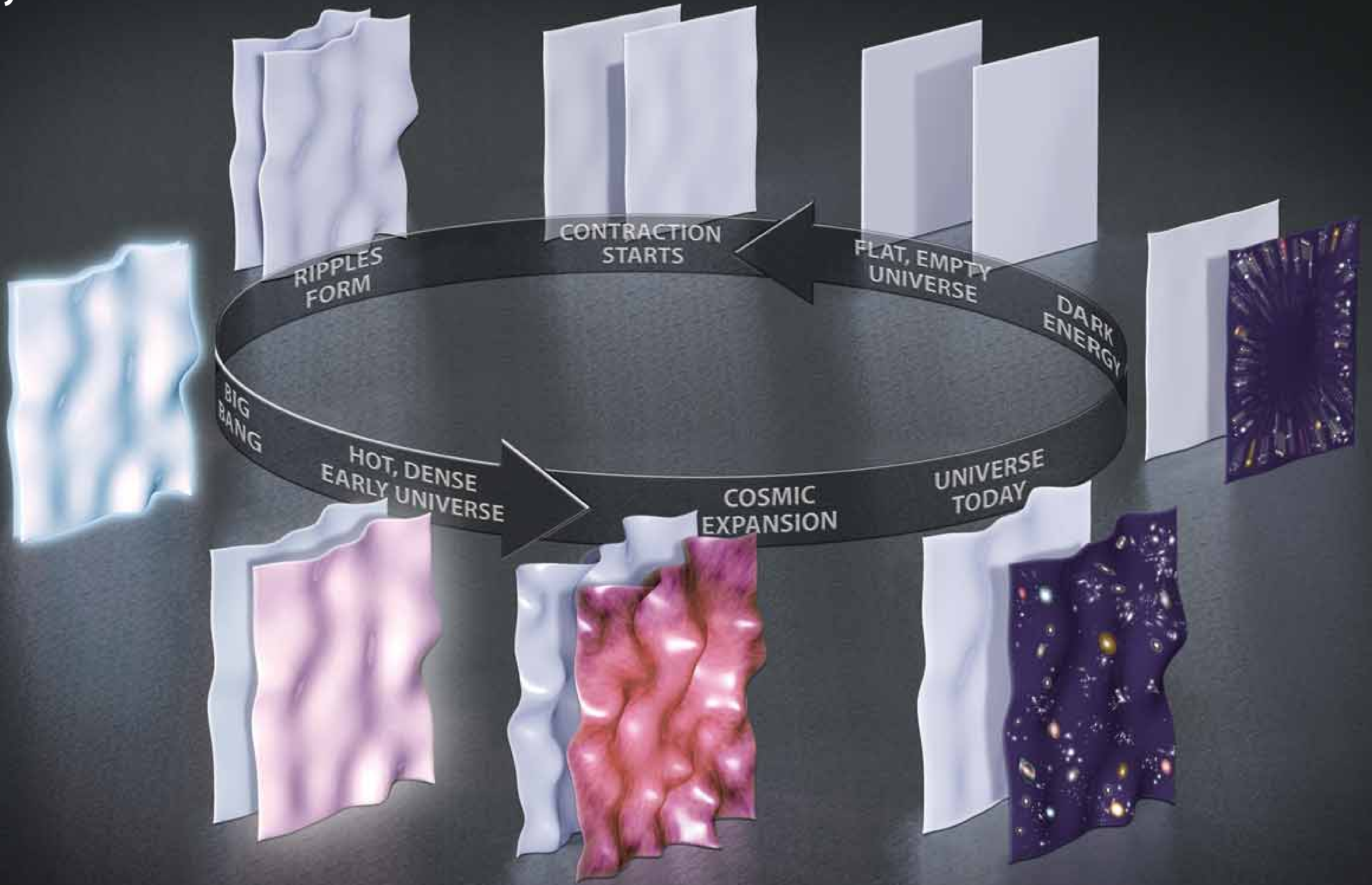
Why the universe had **no beginning**

The Big Bang may not have been the instant of creation, but a single event in an infinite cycle. **by Paul J. Steinhardt**

The conventional Big Bang model of the universe says our cosmic origins can be pinned down with remarkable precision. It claims that everything — space, time, matter, and energy — sprang into being some 13.7 billion years ago in a dramatic instant known as the "Big Bang." At birth, the universe occupied an infinitesimal volume filled with a hot, dense gas of matter and radiation.

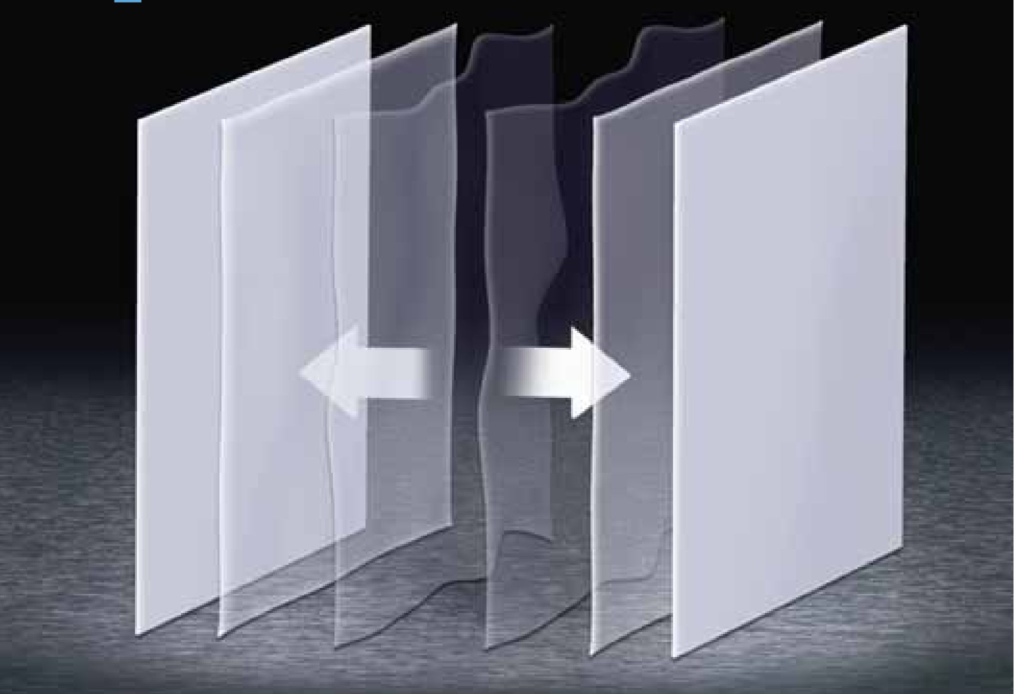
Over the course of the next 13.7 billion years, the tiny volume expanded and cooled, evolving eventually into the vast expanse of galaxies, stars, and planets we see today. And everything that has ever transpired throughout the history of the universe has occurred since that initial instant.

Or did it? Could this picture be flawed? Most cosmologists would bristle at this question. They would rise to the Big Bang model's defense by pointing to the litany of evidence that shows how the cosmos was once hotter and denser and that traces the formation of galaxies and the universe's large-scale structure. The evidence is both voluminous and detailed. Yet all these data come from events that supposedly occurred 1 or more seconds after the Big Bang. Currently, there is not a shred of empirical evidence or a reliable theory of gravity to inform us about the Big Bang itself.



In the cyclic universe model, our entire cosmos exists on a three-dimensional membrane ("brane" for short) in close proximity to a second such brane. This depiction shows our universe as the foreground brane in each pair. In the cyclic model, the Big Bang marks the moment when the two branes collide at the end of a long period of slow approach. The branes then rebound, and structure begins to form in our brane, leading to the universe we see today. Dark energy will soon come to dominate, however, pushing galaxies ever farther apart until the universe becomes empty. Springlike forces eventually bring the branes together again, repeating the endless cycle. *Astronomy*: Roen Kelly

1 Flat, empty universe



Two flat, smooth, and empty branes (the one in front is our universe) appear nearly static in this scene from our cosmic prehistory. But a springlike force between the branes will soon bring the two together in a fiery collision. *Astronomy*: Roen Kelly

Albert Einstein's general theory of relativity, which describes how gravity works, breaks down at the high temperatures and densities near the Big Bang. Improved theories of gravity, such as string theory, do exist. Yet scientists have not developed these theories far enough to give a definite description of what actually happened at the beginning.

And this isn't the only concern. Some of the evidence cited in favor of the Big Bang picture makes sense only if scientists add major components that significantly complicate it.

A brief period of extraordinary expansion, called inflation, must smooth the universe immediately after the Big Bang and create small wrinkles in the distribution of matter to lay the seeds for galaxies. Dark matter must exist to explain the speed at which large-scale structure formed. And dark energy, or something like it, must come into play to explain the accelerating expansion of the universe discovered in the 1990s.

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It appears that the uncertainties and increasing complexity associated with the standard Big Bang model leave room for an alternate theory of the history of the universe. Of course, any such new view must be consistent with existing observations of cosmic evolution.

In the cyclic model, dark energy restores space to a uniform state that leads to the next bang.

Cyclic universe

These thoughts provided some of the motivations that led Cambridge University physicist Neil Turok and me to develop the "cyclic model of the universe." This radically new proposal offers a different idea of what happened at the Big Bang and a novel vision of our past and future.

According to this model, the universe is endless. It undergoes limitless cycles of expansion and cooling, each of which begins with a Big Bang and ends in a Big Crunch. The event that occurred 13.7 billion years ago is only the most recent bang. Although this moment created the matter contained in everything we see, space, time, and energy existed before the bang. And more Big Bangs await us in the future.

We based the cyclic model on three underlying notions. First, the Big Bang is not the beginning of space or time. Instead, it's the moment when gravitational and other forms of energy are transformed into new matter and radiation and a new period of expansion and cooling begins.

Second, bangs occurred periodically in the past and will continue periodically in the future. The cycle repeats perhaps once every trillion years. Third, the sequence of events that sets the large-scale structure of the universe we observe today took place during a long period of slow contraction that preceded the bang. Similarly, the events that will occur over the next trillion years will set the large-scale structure for the cycle to come.

Although the cyclic model differs radically from the conventional Big Bang-inflationary picture in terms of the physical processes that shape the universe and their overall outlook on cosmic history, both theories match all current observations with the same degree of precision. The two pictures will not remain indistinguishable, however. They differ significantly in their predictions of primordial gravitational waves and the fine-scale statistical distribution of matter. Scientists should be able to test these predictions during the next decade.

Inside cosmic cycles

In the cyclic picture, hot, dense matter and radiation fills the universe immediately after the bang. The cosmic temperature reaches about 100 billion billion (10^{20}) times that of the Sun's core. At this temperature, matter breaks down into its elemental constituents: quarks, electrons, photons, and the like. Even so, the temperature remains modest compared with that expected in the usual Big Bang.

During the following 9 billion years, the cosmos expands and cools. The elemental constituents clump into protons and neutrons, and eventually atoms, molecules, planets, stars, galaxies, and larger structures all form.

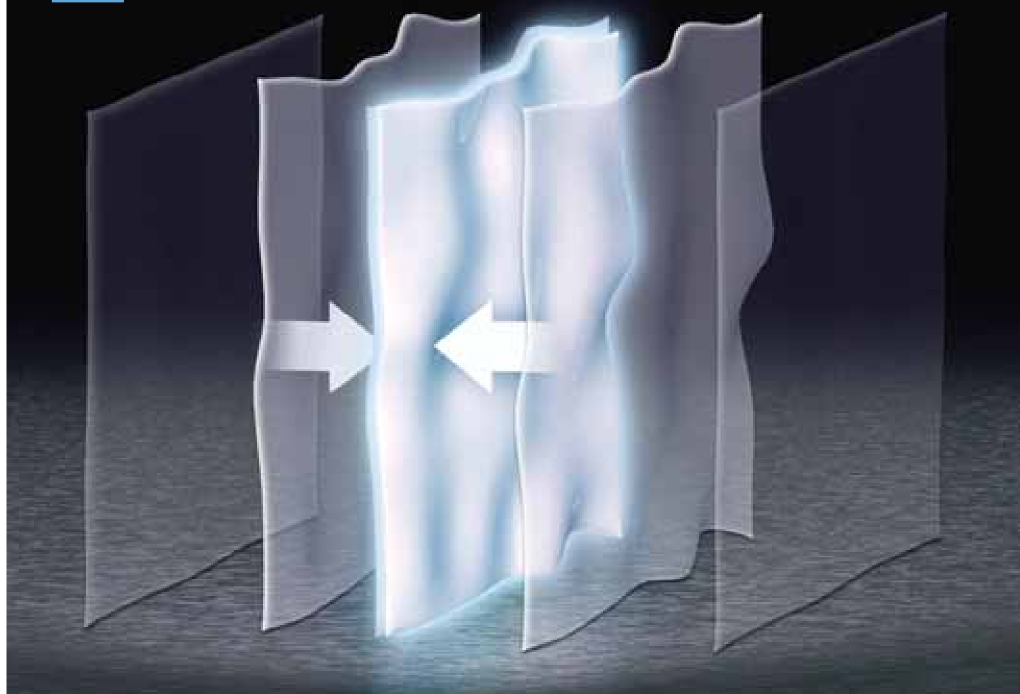
At this point, some 9 billion years after the bang, the matter density of the universe drops so low that a new form of energy overtakes the universe. This "dark energy" doesn't behave like matter and more familiar forms of energy. These forms are gravitationally self-attractive and resist the expansion of the universe.

Dark energy, on the other hand, is gravitationally self-repulsive and causes cosmic expansion to speed up. This explains recent observations of distant supernovae and the cosmic microwave background radiation that prove the expansion of the universe has been accelerating for the past 5 billion years.

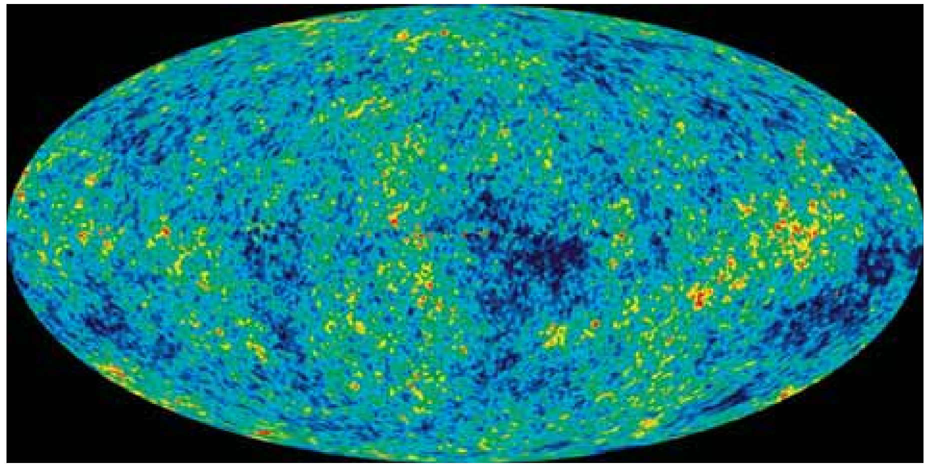
During the next trillion years, the accelerating expansion will continue and rapidly dilute the universe of the matter and lumpy structures formed since the last bang. So far, this scenario matches the conventional Big Bang model, but with an important difference. In the standard Big Bang picture, dark energy has no purpose. Theorists simply add it to the model separately to account for the observations.

In the cyclic model, we integrate dark energy into the theory, and it plays an essential role. It naturally and efficiently restores space to a simple, uniform, and pristine state that leads to the next bang — and ensures this process repeats in every cycle.

2 The Big Bang



As the branes approach each other, gravitational potential energy turns into kinetic energy and ripples develop on their surfaces. When the branes collide, the kinetic and potential energy convert partially to matter and radiation. A universe is born — ours. *Astronomy*: Roen Kelly



The cosmic microwave background radiation supports the Big Bang model of the universe's creation, but it also agrees with the cyclic universe model. Tiny temperature fluctuations, which show up here as color differences, are the seeds around which galaxy clusters formed. NASA/WMAP Science Team

In the Big Bang model, dark energy will dominate the universe for the rest of cosmic history. It transforms space into a vacuous wasteland. In the cyclic model, dark energy is unstable. It will decay near the cycle's end into a form of extremely high-pressure energy (where pressure exceeds the energy density) that causes the universe to contract ultra-slowly.

A slowly contracting universe filled with this high-pressure form of energy produces two important effects. First, space becomes increasingly smooth and flat as the contraction proceeds. This sets those conditions leading up to and immediately after the bang. Second, quantum physics causes random fluctuations in the high-pressure form of energy. This produces tiny variations both in the contraction rate and in the time when new matter and radiation fill different regions of space.

These two effects combine to create an almost perfectly smooth universe after the bang. The only deviations: a pattern of tiny temperature variations just like those observed in the cosmic microwave background radiation, and tiny variations in the concentration of matter just like those needed to explain the current distribution of galaxies.

Braneworlds in the cyclic model

Developments in string theory inspired the cyclic model. Chief among these are the ideas of braneworlds and extra dimensions. ("Braneworld," often called simply "brane," is short for "membrane-like world.") Although the cyclic model does not require these ideas — or even

3 The universe today

After the collision, the branes separate and the hot, dense universe expands and cools. The ripples from the previous stage cause the slight temperature variations that show up in the cosmic microwave background radiation and form the seeds for large-scale structure. Nearly 14 billion years later, galaxies and galaxy clusters dominate the universe. *Astronomy*: Roen Kelly

string theory, for that matter — they suggest an intuitive and appealing geometrical interpretation of the cyclic model.

According to a version of string theory known as M theory, our entire three-dimensional universe is actually a braneworld embedded in a space possessing four spatial dimensions. And our braneworld lies a microscopic distance from a second three-dimensional braneworld. In the full version of string theory, six additional dimensions exist, but they play a minor role in the cyclic cosmology that we can ignore.

The braneworlds are elastic — they can expand, wiggle, and warp. They can also move around. The laws of string physics constrain matter on our brane to move only in our three dimensions. Consequently, we cannot reach into the fourth spatial dimension or see, touch, or feel the neighboring braneworld. However, gravity attracts the braneworlds to each other, and additional fields can generate springlike forces between the braneworlds.

In the braneworld depiction, the gravitational and springlike forces drawing the two braneworlds together cause regularly repeating collisions — the cyclic model in a nutshell. The collision itself produces a Big Bang.

This picture immediately makes it clear that the Big Bang does not represent the "beginning." A collision necessarily implies that the braneworlds — that is, space and time — exist before and after the bangs. The bang merely marks the moment of collision when some of the gravitational potential energy and braneworld kinetic energy convert into hot matter and radiation and return the universe to a high temperature and matter density. After the bang, the branes bounce apart and begin to stretch along the three large dimensions. This causes the matter and radiation to expand, cool, and clump into the large-scale structure we see today.

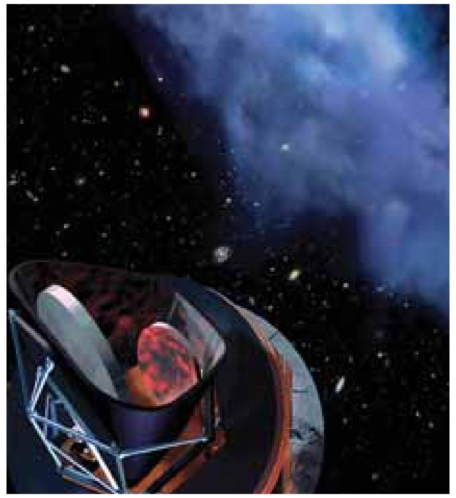
The new dark energy

In this view, dark energy is the gravitational potential energy stored in the springlike forces that draws the branes together. Once the branes have stretched enough that this stored energy density exceeds the matter density, the stretching of the branes speeds up. This explains the accelerating expansion observed today.

Unlike the standard Big Bang model, however, this phase won't last forever. Eventually, after perhaps a trillion years, the accelerated expansion of the branes stops and the springlike forces draw the branes together. At the next collision, some of the potential and kinetic energy converts to new matter and radiation. Not only does gravitational energy add to the collision's impact, its contribution ensures that the spring never winds down and the collisions can continue forever.

In the colliding braneworld picture, the cycling reflects the expansion and contraction of the extra dimensions. The two braneworlds themselves expand throughout. In this sense, the cyclic model really becomes a hybrid — steady growth occurs along the usual three dimensions while periodic oscillations occur along the extra dimension.

The Hercules galaxy cluster (Abell 2151) epitomizes the universe today. Rich galaxy clusters like this congregate into even larger and more massive superclusters, which form the backbone of cosmic large-scale structure. CFHT/Jean-Charles Cuillandre/Coelum



Europe's Planck spacecraft may settle the debate between the Big Bang and cyclic models within a decade. Planck will search for the tiny but measurable difference between the two theories as it examines the cosmic microwave background at unprecedented sensitivity. ESA

Which picture is right?

The cyclic model and the Big Bang model produce remarkably different pictures of the past history and future evolution of the universe. In the Big Bang view, the Big Bang marks the beginning of time, so the universe is only 13.7 billion years old. A period of inflation after the Big Bang sets the large-scale structure of the universe.

Theorists introduced dark energy to explain the universe's current accelerating expansion, but otherwise it serves no needed role. Once introduced, however, dark energy dominates the future of the universe. It will turn the space we observe into an eternal, dark, vacuous wasteland.

In contrast, the cyclic view says 13.7 billion years represents only the time since the last bang and the creation of the matter and radiation we see today. The universe has had many such cycles — perhaps infinitely many — prior to the present one. And the true age of the universe is far more than 13.7 billion years.

The theory has no need for inflation because large-scale structure derives from events that lead up to each bang. Dark energy is an essential element integrated into the cosmology. The future becomes more hopeful: Although space will become dark and vacuous for a period, a new cycle eventually will begin. The space we observe will be infused with new matter, galaxies, stars, planets, and life.

The universe has had many cycles — perhaps infinitely many — prior to the present one.

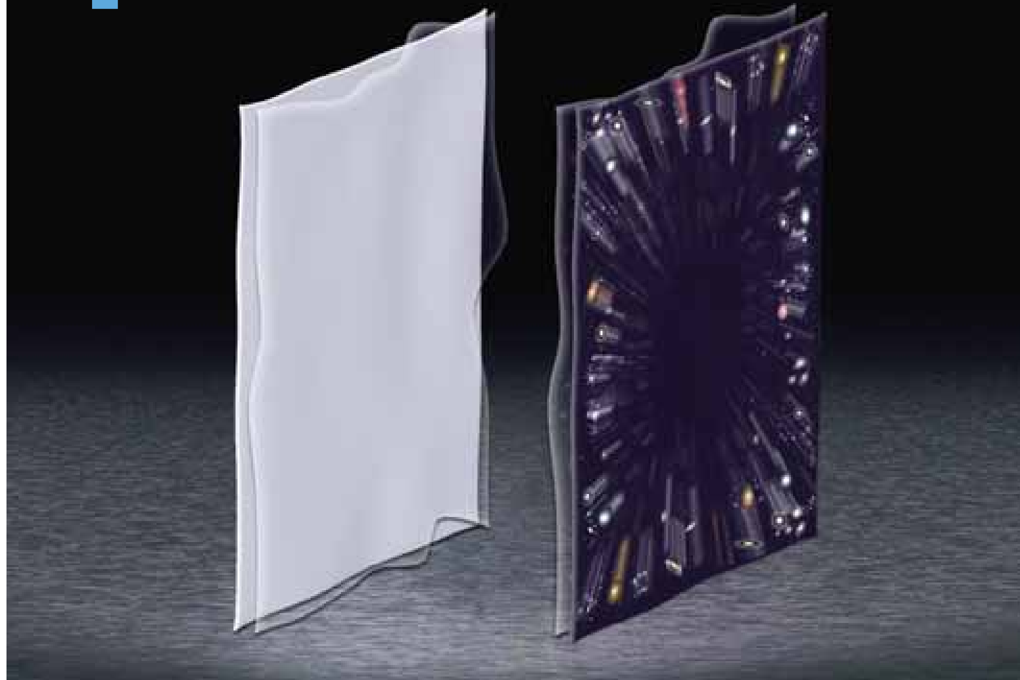
Although the two theories explain equally well all the astronomical and cosmological observations scientists have collected thus far, two key tests will be able to distinguish them. First, inflation produces a spectrum of detectable gravitational waves. These wrinkles in space propagate through the universe and should produce a measurable polarization pattern in the cosmic microwave background radiation. The cyclic model has no period of inflation and produces gravitational waves far too weak to be detected.

Second, the inflationary picture predicts that the statistical distribution of temperature variations in the cosmic microwave background should follow a bell curve almost precisely. The cyclic model predicts a larger, measurable deviation from a bell curve.

During the next decade, scientists will conduct a number of experiments capable of detecting polarization and our predicted deviations in the cosmic microwave background radiation. First up: the European Space Agency's Planck mission, scheduled for launch this year.

The outcome of these experiments should determine which cosmic history is correct — and whether the future will be a vast wasteland or a precursor that leads to cosmic rebirth. ◑

4 Dark energy dominates



In the distant future, the cosmos keeps spreading out faster and faster as its stored energy density exceeds its matter density. This is what we perceive as dark energy, which started to have an effect some 9 billion years after the bang. The whole cycle from one bang to the next takes roughly 1 trillion years. *Astronomy*: Roen Kelly

See a computer simulation of the cyclic universe at www.Astronomy.com/toc.