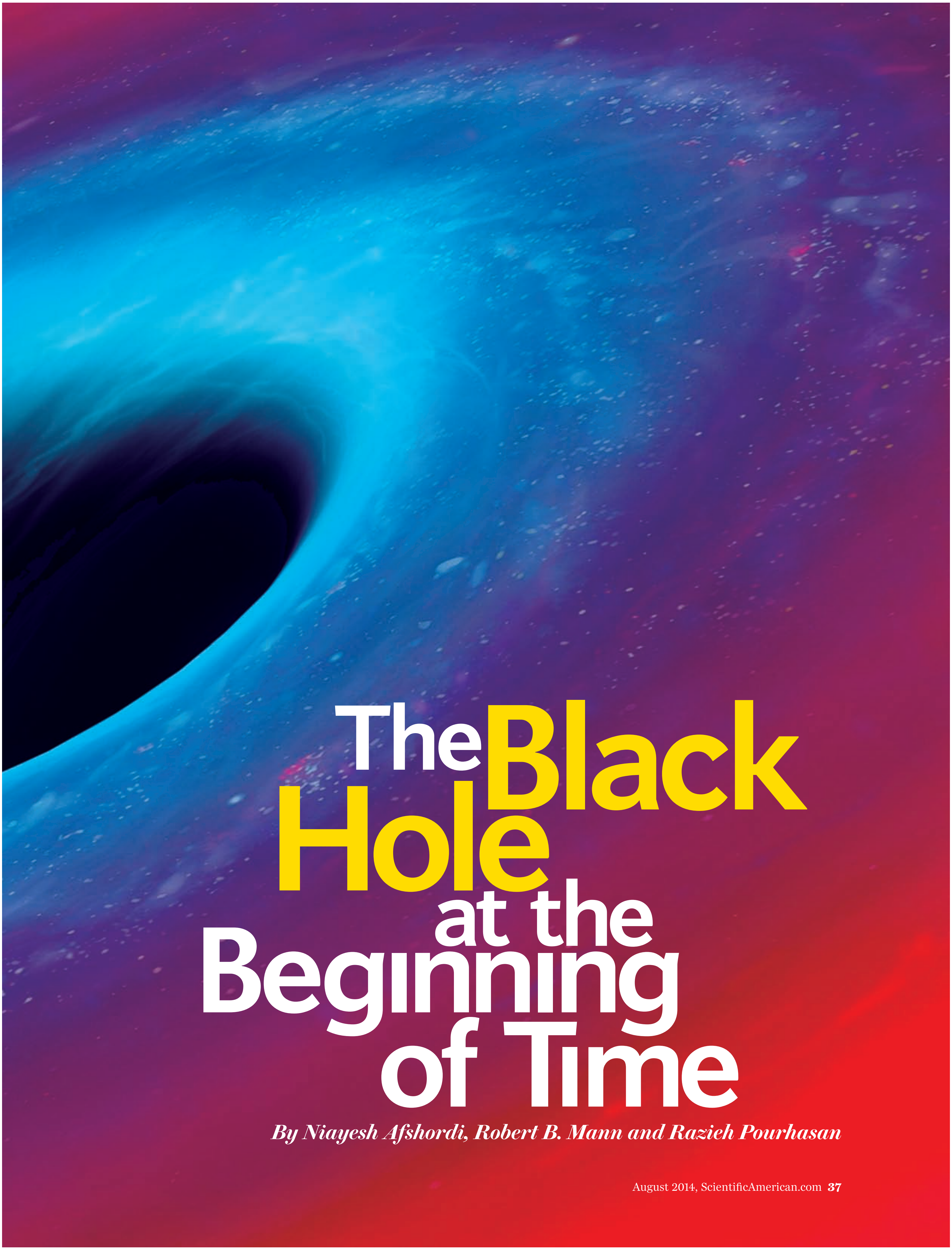
COSMOLOGY

Is the big bang, and all that came from it, a holographic mirage from another dimension?



The Black Hole at the Beginning of Time

By Niayesh Afshordi, Robert B. Mann and Razieh Pourhasan

Niayesh Afshordi is an assistant professor of physics and astronomy at the University of Waterloo and an associate faculty member in cosmology and gravitation at the Perimeter Institute for Theoretical Physics. His research and teaching focus on astrophysics, cosmology and the physics of gravity.

Robert B. Mann is a professor and former chair of physics and astronomy at the University of Waterloo and an affiliate faculty member at the Perimeter Institute. A past president of the Canadian Association of Physicists and winner of two teaching awards, his interests include black holes and quantum information.

Razieh Pourhasan is a Ph.D. candidate at the Perimeter Institute and the University of Waterloo. She was born in Shiraz, Iran, and received her B.Sc. and M.Sc. in theoretical physics from Shiraz University in Iran.

IN HIS ALLEGORY OF THE CAVE, THE GREEK PHILOSOPHER PLATO DESCRIBED prisoners who have spent their entire lives chained to the wall of a dark cavern. Behind the prisoners lies a flame, and between the flame and prisoners parade objects that cast shadows onto a wall in the prisoners' field of view. These two-dimensional shadows are the only things that the prisoners have ever seen—their only reality. Their shackles have prevented them from perceiving the true world, a realm with one additional dimension to the world that they know, a dimension rich with complexity and—unbeknownst to the prisoners—capable of explaining all that they see.

Plato was on to something.

We may all be living in a giant cosmic cave, created in the very first moments of existence. In the standard telling, the universe came into being during a big bang that started from an infinitely dense point. But according to recent calculations that we have carried out, we may be able to track the start of the universe back to an era before the big bang—an era with an additional dimension of space. This protouniverse may have left visible traces that upcoming astronomical observations could uncover.

The universe appears to us to exist in three dimensions of space and one of time—a geometry that we will refer to as the "three-dimensional universe." In our scenario, this three-dimensional universe is merely the shadow of a world with *four* spatial dimensions. Specifically, our entire universe came into being during a stellar implosion in this suprauniverse, an implosion that created a three-dimensional shell around a four-dimensional black hole. Our universe is that shell.

Why would we postulate something that sounds, on the face of it, so absurd? We have two reasons. First, our ideas are not idle speculation—they are firmly grounded in the mathematics that describe space and time.

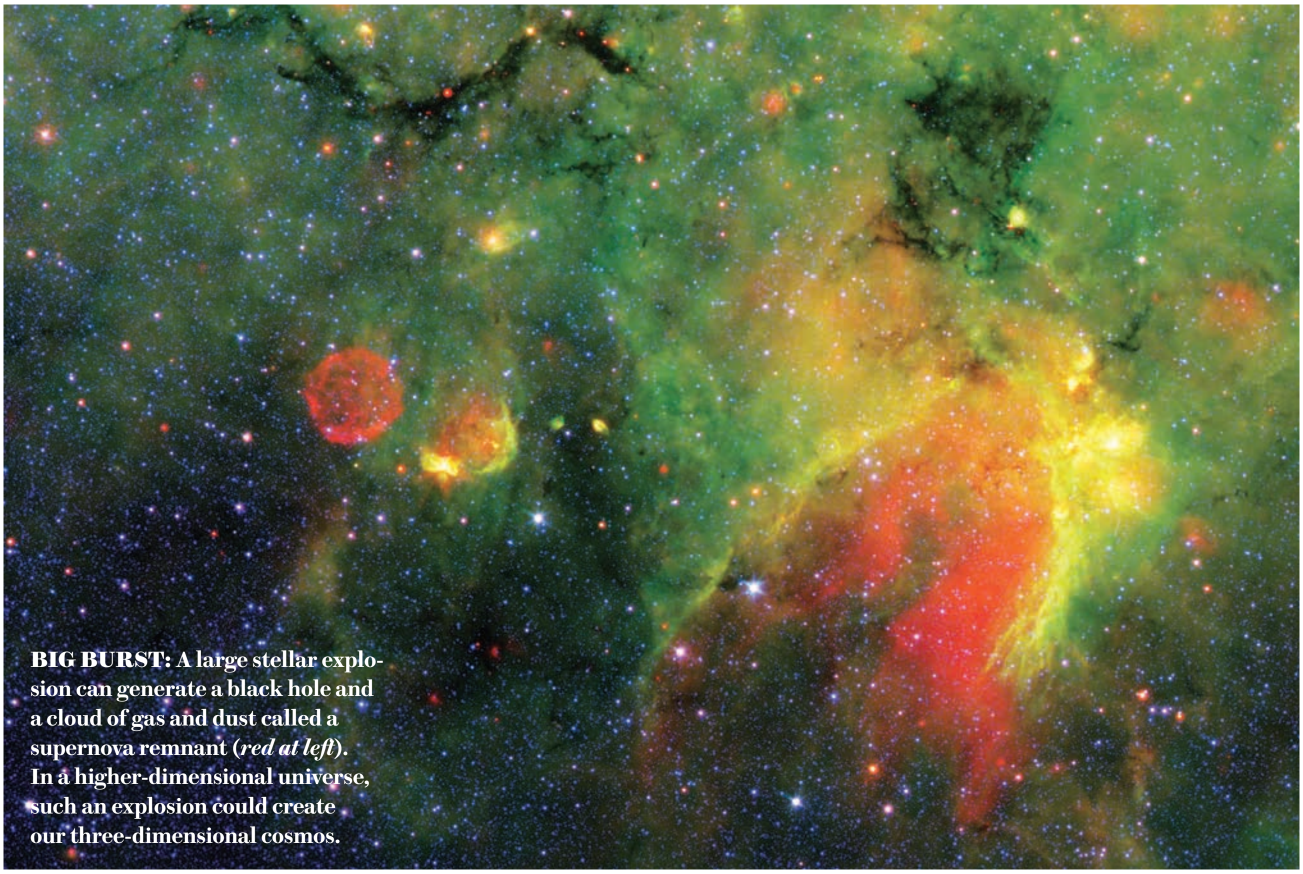
Over the past couple of decades physicists have developed a rich theory of holography, a set of mathematical tools that allows them to translate descriptions of events in one dimension to the physics of a different dimension. For example, researchers

IN BRIEF

Cosmologists have detailed a remarkably accurate description of the history of the universe. But a few profound questions seem to defy all attempts at understanding. **One of these mysteries** is the nature of the big bang itself—the sudden, violent origin of our universe from a point of infinite density.

The authors have developed ideas that would explain how the big bang came to be. They imagine that it emerged as a consequence of the formation of a black hole in a higher-dimensional universe. This theory provides answers to a number of difficult questions. It could also be tested.

PRECEDING PAGES: MARK GARLICK *Getty Images (artist's conception)*



BIG BURST: A large stellar explosion can generate a black hole and a cloud of gas and dust called a supernova remnant (*red at left*). In a higher-dimensional universe, such an explosion could create our three-dimensional cosmos.

COURTESY OF NASA/JPL-CALTECH

can solve relatively straightforward equations of fluid dynamics in two dimensions and use those solutions to understand what is going on in a much more complicated system—for example, the dynamics of a three-dimensional black hole. Mathematically, the two descriptions are interchangeable—the fluid serves as a perfect analogue for the extraordinary black hole.

The success of holography has convinced many scientists that more is at work here than a simple mathematical transformation. Perhaps the boundaries between dimensions are less stable than we thought. Perhaps the rules of the cosmos are written in another set of dimensions and translated into the three we perceive. Perhaps, like Plato's prisoners, our personal circumstances have tricked us into believing the world is three-dimensional when in fact a deeper understanding of what we perceive will come only when we look for explanations in the fourth dimension.

The second reason that our four-dimensional universe is worth thinking about is because a close study of this universe could help us understand deep questions about the origin and nature of the cosmos. Consider, for example, the big bang, the primordial flash that brought our universe into existence. Modern cosmology holds that the big bang was immediately followed by "inflation"—a period of rapid expansion of space in which the early universe increased its volume by a factor of 10^{78} (or more). Yet this expansion provides no insight into what caused the big bang. Our four-dimensional universe, in contrast, gives us an answer to the ultimate mystery: Where did the universe come from?

THE KNOWN AND UNKNOWN COSMOS

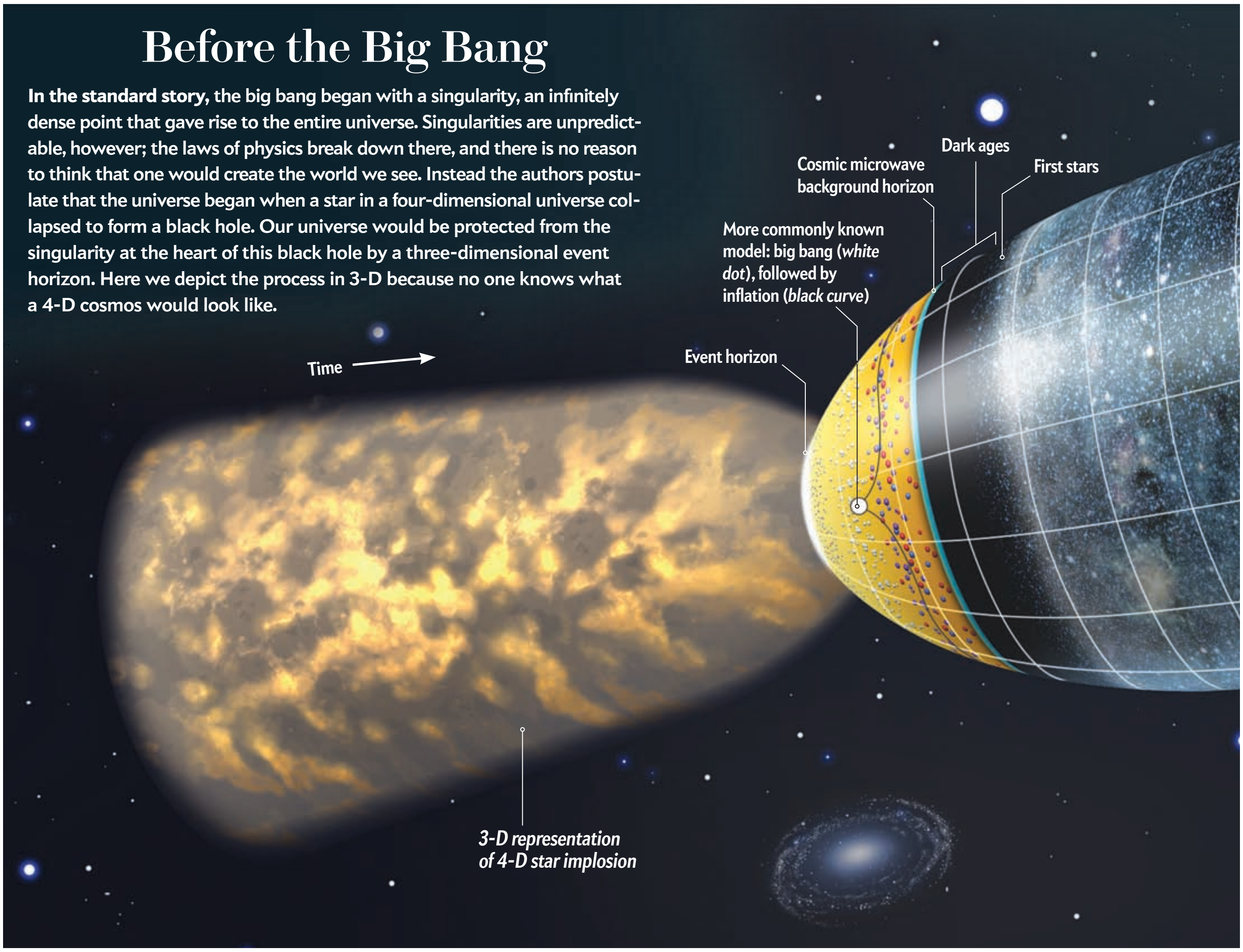
OUR INVESTIGATIONS into the four-dimensional universe came about because of the problems that we have had contemplating the three-dimensional one. Modern cosmology has been fantastically successful, but its successes belie deep and complex mysteries that may lend themselves to a holographic explanation.

Cosmologists can describe the history of the entire universe—from the present day all the way back to a fraction of a fraction of a second after the big bang—using only a few equations (chief among them the ones provided by Albert Einstein) and five independent numbers, or parameters. These parameters include the densities of ordinary matter, dark matter and dark energy (more on these in a moment), along with the amplitude and shape of quantum fluctuations in the early universe. This model—the Lambda Cold Dark Matter (Λ-CDM) cosmological paradigm—describes hundreds (if not thousands) of observational data points, covering scales from a million light-years to 10 billion light-years across, right up to the edge of our observable universe. But these observational successes do not mean our task is complete. The story of the universe is pocked with troublesome holes. We are confronted by fundamental questions about the nature of the cosmos—problems that we have not, as of yet, been able to answer.

Problem 1:* *We don't understand the five parameters. Consider the density of matter and energy in the universe. Only a few decades ago astronomers believed that ordinary matter—the elements that make up the periodic table—would be the

Before the Big Bang

In the standard story, the big bang began with a singularity, an infinitely dense point that gave rise to the entire universe. Singularities are unpredictable, however; the laws of physics break down there, and there is no reason to think that one would create the world we see. Instead the authors postulate that the universe began when a star in a four-dimensional universe collapsed to form a black hole. Our universe would be protected from the singularity at the heart of this black hole by a three-dimensional event horizon. Here we depict the process in 3-D because no one knows what a 4-D cosmos would look like.



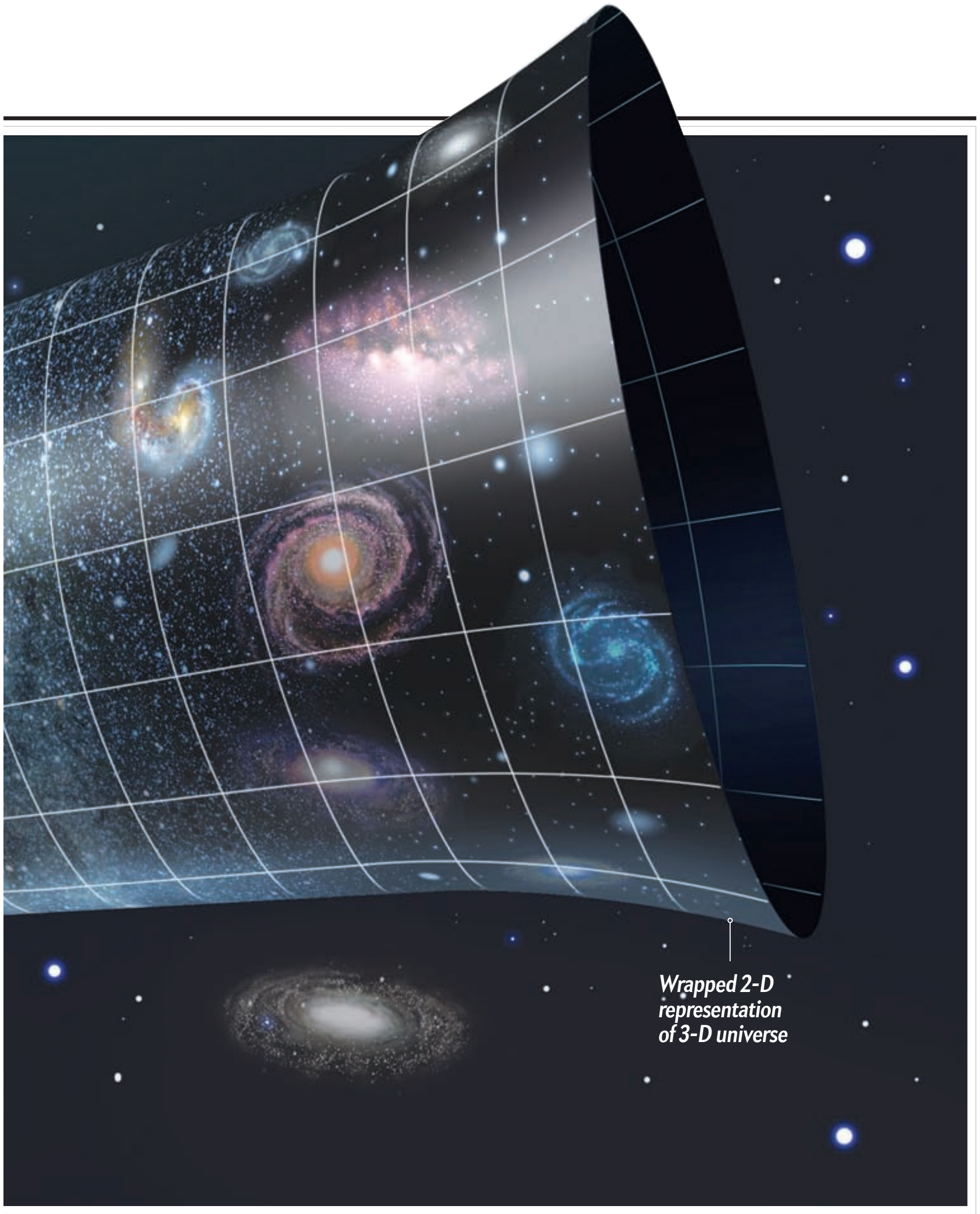
dominant form of mass-energy. Cosmological observations have radically revised this picture (and secured three Nobel Prizes along the way). We now know that the density of ordinary matter is only 5 percent of the universe's total energy density. Another 25 percent comes in the form of dark matter, an unknown form of matter whose existence is inferred from its gravitational attraction. And 70 percent of the universe is made of dark energy, the mysterious stuff that is causing the expansion rate of our universe to speed up (instead of slowing down, as originally expected from gravitational attraction). What are dark matter and dark energy, and why do they make up 25 and 70 percent of the universe, respectively? We do not know.

Perhaps answers would come if we better understood the big bang—the abrupt origin of space and time in a hot plasma of radiation and particles at a temperature above 10^{27} degrees. It is very difficult to imagine how a situation like the universe in the moments after the big bang could lead to what we observe today—a cosmos of nearly uniform temperature and with a flat large-scale spatial curvature (in which the angles of triangles sum up to 180 degrees).

Cosmic inflation might be the best idea we have for understanding the large-scale structure of the universe. Inflation would tend to "flatten" the universe, smoothing out any curved regions of spacetime, and bring it to a uniform temperature. Like a cosmic magnifier, inflation also amplifies tiny quantum fluctuations in energy density to cosmic size during this process. These fluctuations in turn become the seeds for the growth of structures such as galaxies, stars, planets and even living organisms such as ourselves.

Inflation is generally regarded as a very successful paradigm [*see box above*]. For decades cosmologists have been checking on inflation's predictions by observing the cosmic microwave background (CMB) radiation, a cosmic record of density fluctuations in the early universe. Recent observations by the European Space Agency's Planck satellite confirm that our universe is flat (or very nearly so) and that it is uniform to better than one part in 60,000—both key predictions of inflation. Furthermore, the observed amplitude and shape of primordial matter fluctuations are in broad agreement with how we would expect inflation to magnify the quantum vacuum.

Illustration by George Retseck



Problem 2:* *We don't really understand inflation.

We might ask what drove this inflation, which took a lot of energy. We imagine that, shortly after the big bang, the universe was filled with energy that takes the form of a hypothetical particle called the inflaton (pronounced "IN-flah-tahn"). The Higgs particle, recently discovered by the Large Hadron Collider at CERN near Geneva, shares many similar properties with, and is a possible candidate for, the proposed inflaton. The inflaton would be responsible for both early accelerated expansion and for structure in our universe because the only significant density differences in the early universe are caused by the tiny quantum fluctuations in the inflaton field's energy.

Yet the inflaton does not solve our problems; it just pushes them back a step. We do not know the inflaton's properties, or where it came from, or how to find it. We are not sure whether it really exists.

In addition, physicists do not understand how to naturally end inflation—the so-called graceful exit problem. If some kind of energy field drives an exponentially expanding universe, what would make that field suddenly turn off? We also do not have a satisfactory explanation for the origin of the five parameters of the Λ-CDM model, some of which must be very precisely chosen to agree with observations. And we lack a satisfactory description of the history of our cosmos before the inflationary era—those first trillionths of trillionths of trillionths of a second after the big bang.

Problem 3:* *We don't understand how it all began.

Cosmology's greatest challenge is understanding the big bang itself—the sudden, violent emergence of all space, time and matter from an infinitely dense point called a singularity. A singularity is an unimaginably bizarre thing, a point where space and time curve in on themselves, making it impossible to distinguish the future from the past. All the laws of physics break down. A singularity is a universe without order or rules. Out of a singularity could come anything that might logically exist. We have no reason to think that a singularity would generate a universe as ordered as the one we see.

We would expect the emergence of a universe from a singularity to be unthinkably chaotic, marked by huge temperature fluctuations from one point to the next. Furthermore, the magnifying power of inflation might be expected not to smooth everything out. In fact, if these fluctuations are too large, inflation may never get a chance to begin. The problems of a singularity cannot be solved by inflation alone.

Singularities are strange, but not unfamiliar. They also form at the centers of black holes, those collapsed remains of giant stars. All stars are nuclear furnaces that fuse lighter elements (primarily hydrogen) into heavier ones. This process of nuclear fusion powers a star for most of its life, but eventually the star exhausts all its nuclear fuel, and gravity takes over. A star at least 10 times more massive than our sun will collapse on itself before exploding as a supernova. If the star is even larger—15 to 20 solar masses or more—the supernova will leave behind a dense core that goes into a runaway collapse, contracting into a point of zero size—a black hole.

Black holes can be thought of as regions of space from which not even light can escape. Because the speed of light is the maximum speed attainable by any form of matter, the boundary of a black hole—a two-dimensional surface called the event horizon—is a point of no return: once stellar matter (or anything else) falls within this boundary, it is cut off from the rest of the universe and inexorably pulled toward the singularity at the center.

As with the big bang, the laws of physics break down at this singularity as well. *Unlike* the big bang, however, a black hole is surrounded by an event horizon. This surface acts like armored wrapping paper—it prevents any information about the singularity

OBSERVATIONS

Whispers from Creation

The recent discovery of gravitational waves emerging from the big bang may point a way forward


DARK POLE: Telescopes at the South Pole search for clues about the universe's first moments.

Apart from the terrible weather hanging around from an unusually cold winter, the second week of March started like any other week. But then rumors started floating around in the cosmology community about an imminent announcement out of the Harvard-Smithsonian Center for Astrophysics. The rumors spread to Facebook, Twitter and the blogosphere by the weekend. Details began to emerge. This was not any ordinary announcement but rather the kind that, if correct, would happen once per lifetime. It was something that most of us dreamed we could see only in a few decades if we were lucky, if at all.

On Monday, March 17, 2014, BICEP-Keck collaboration, which operates an array of microwave telescopes located at the geographical South Pole, announced the discovery of patterns in the polarization of the cosmic microwave background that could have been generated in the early universe. If this interpretation of the observations is correct, it could confirm a 30-year-old prediction of the cosmic inflation theory: that the simplest models of inflation can generate an observable level of gravitational waves, comparable to density or temperature fluctuations in the early universe. It would also be our first direct evidence for the quantum nature of gravity, the most outstanding puzzle in theoretical physics over the past century.

Yet in science, as in life, things are rarely as simple as they first appear. For example, the simple inflationary models that predict observable levels of gravitational waves also suggest that hints of these waves should have been seen in the temperature fluctuations observed by the European Space Agency's Planck satellite. But they were not! Furthermore, microwave emission from dust in our galaxy tends to be polarized, which could confuse BICEP-Keck observations, at least to some extent.

What does all this mean for our holographic theory of the big bang? When it comes to the observations of the early universe, we are limited to a handful of (now seemingly contradictory) probes. The Planck team is expected to release additional data in October, and other teams will also weigh in soon. Reconstructing the first moments of the universe is difficult business. Only with time—and perhaps some luck—will we know how it all began.

—N.A., R.B.M. and R.P.

from leaking out. The event horizon of the black hole shields outside observers from the singularity's catastrophically unpredictable effects (a situation referred to as cosmic censorship).

Cloaked by an event horizon, the singularity is rendered impotent. Its disturbing effects cannot escape, making it possible for the laws of physics to describe and predict all that we observe. Seen from a distance, a black hole is a very simple, smooth and uniform structure, described only by its mass and angular momentum (and electric charge if it has any). Physicists quip that "a black hole has no hair"—no distinguishing features beyond the basics of mass, angular momentum and electric charge.

In contrast, the big bang singularity (as commonly understood) is not cloaked. It has no event horizon. We would like to have a way to shield ourselves from the big bang's singularity

COURTESY OF STEFFEN RICHTER *Harvard University*

SCIENTIFIC AMERICAN ONLINE For a video about what happened at the beginning of everything, visit ScientificAmerican.com/aug2014/big-bang

and its catastrophic unpredictability, perhaps with something akin to an event horizon.

We have proposed just such a scenario—one that turns the big bang into a cosmic mirage. Our picture would cloak the singularity at the big bang just as an event horizon cloaks the singularity at the heart of a black hole. It would protect us from the singularity's mercurial and nefarious effects.

EXTRADIMENSIONAL COLLAPSE

SUCH A CLOAK would differ from an ordinary event horizon in one critical way. Because we perceive that our universe has three spatial dimensions, the event horizon that cloaks the singularity at the heart of the big bang must also have three spatial dimensions—not just two. If we imagine that this event horizon also came about as a result of a cosmic collapse—just as a black hole's two-dimensional event horizon is formed by the collapse of a three-dimensional star—then the collapse would have to take place in a universe with four spatial dimensions.

This kind of extradimensional scenario, in which the number of dimensions of space exceeds the obvious three, is an idea almost as old as general relativity itself. It was originally proposed by Theodor Kaluza in 1919 and expanded by Oskar Klein in the 1920s. Their idea was largely forgotten for more than half a century before being picked up by physicists studying string theory in the 1980s. More recently, scientists have used it to build a cosmology of so-called brane worlds.

The basic idea of a brane world is that our three-dimensional universe is a subuniverse embedded in a larger space of four or more spatial dimensions. The three-dimensional universe is called a brane, and the larger universe is called the bulk. All known forms of matter and energy are stuck to our three-dimensional brane like a movie projected on a screen (or the shadow reality for Plato's prisoners in the cave). The exception is gravity, which permeates all of the higher-dimensional bulk.

Let's think about the bulk suprauniverse of four spatial dimensions that may have existed before the big bang. We can imagine that this bulk universe was filled with objects such as four-dimensional stars and four-dimensional galaxies. These higher-dimensional stars might run out of fuel, just as our three-dimensional stars do, and collapse into black holes.

What would a four-dimensional black hole look like? It would also have an event horizon, a surface of no return from which no light could escape. But instead of a two-dimensional surface, as we have in ordinary black holes, a four-dimensional black hole would generate an event horizon with three spatial dimensions.

Indeed, by modeling the collapsing death of a four-dimensional star, we find, under a variety of circumstances, that the material ejected from the stellar collapse can form a slowly expanding three-brane surrounding this three-dimensional event horizon. Our universe is this three-brane—a hologram of sorts for a four-dimensional star collapsing into a black hole. The cosmic big bang singularity becomes hidden to us—locked forever behind a three-dimensional event horizon.

IS THIS REAL?

OUR MODEL has a number of things going for it, starting with the fact that it eliminates the naked singularity that gave rise to the universe. But what of the other long-standing cosmological problems, such as the near flatness and high uniformity of the cosmos? Because the four-dimensional bulk universe could have existed for an infinitely long time in the past, any hot and cold spots in the bulk would have had plenty of time to come to equilibrium. The bulk universe would be smooth, and our three-brane universe would inherit this smoothness. In addition, because the four-dimensional black hole would also appear to be nearly featureless (or without "hair"), our emergent three-brane universe would likewise be smooth. The larger the mass of the four-dimensional star, the flatter the three-brane, and so the flatness of our universe is a consequence of it being residual detritus from the collapse of a heavy star.

In this way, our model of a holographic big bang resolves not only the main puzzles of uniformity and near flatness of standard cosmology without resorting to inflation but also nullifies the damaging effects of the initial singularity.

The idea may sound crazy, but there are several ways one might be able to test it. One way is by studying the cosmic microwave background radiation. Outside of our three-brane, we would expect there to be some extra four-dimensional bulk matter—something pulled close by the gravitational pull of the black hole. We can show that thermal fluctuations in this extra matter will create fluctuations on the three-brane that in turn distort the CMB by small but potentially measurable amounts. Our calculations differ from the latest data from the European Space Agency's Planck space observatory by about 4 percent. But this discrepancy may be the result of secondary effects that we have not yet properly modeled.

In addition, if the four-dimensional black hole is spinning (it is very common for black holes to spin), then our three-brane may not look the same in all directions. The large-scale structure of our universe would appear slightly different in different directions. Astronomers may also be able to find this directionality by studying subtle variations in the CMB sky.

Of course, even as the holographic big bang resolves one giant question—the origin of our universe—it simultaneously raises a new set of mysteries. Foremost among them: Where did our universe's *parent* universe come from?

For an answer to this puzzle, we might again turn to Plato. When Plato's prisoners emerged from the cave, the light of the sun burned their eyes. It took them time to adjust to the brightness. At first, the prisoners were only able to make out shadows and reflections. Soon they could see the moon and the stars. Finally, they correctly concluded that the sun was "the author of all that we see"—day, night, season and shadow. Plato's prisoners didn't understand the powers behind the sun, just as we don't understand the four-dimensional bulk universe. But at least they knew where to look for answers. SA

MORE TO EXPLORE

Out of the White Hole: A Holographic Origin for the Big Bang. Razieh Pourhasan, Niayesh Afshordi and Robert B. Mann in *Journal of Cosmology and Astroparticle Physics,* Vol. 2014, Article No. JCAP04(2014)005; April 2014.

FROM OUR ARCHIVES

Out of the Darkness. Georgi Dvali; February 2004.
The Illusion of Gravity. Juan Maldacena; November 2005.
Origin of the Universe. Michael S. Turner; September 2009.

scientificamerican.com/magazine/sa