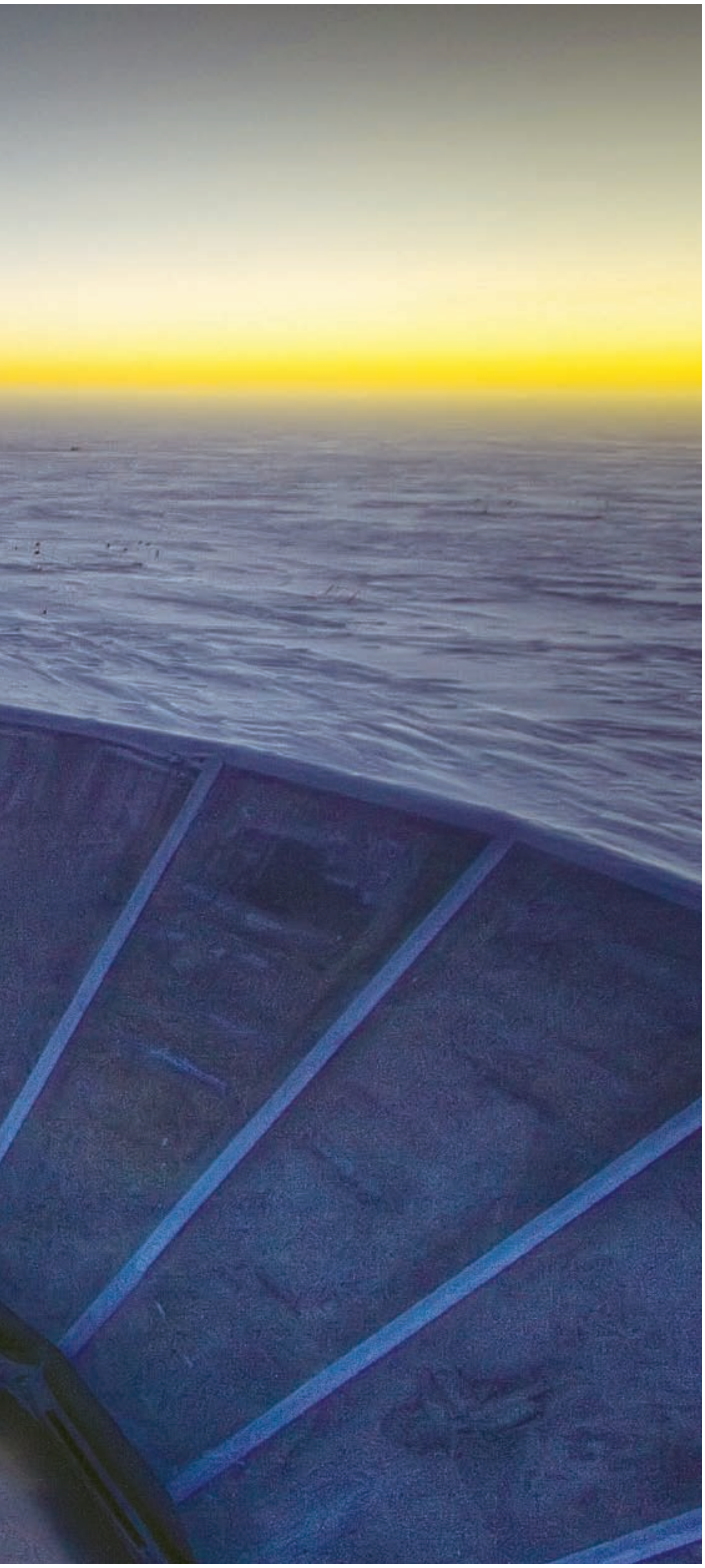
POLAR EYES: The BICEP2 telescope at the Amundsen-Scott South Pole Station observed the same small patch of sky from January 2010 through December 2012, searching for signatures of primordial gravitational waves in ancient light.



COSMOLOGY

A Beacon from the Big Bang

If the recent discovery of gravitational waves emanating from the early universe holds up under scrutiny, it will illuminate a connection between gravity and quantum mechanics and perhaps, in the process, verify the existence of other universes

By Lawrence M. Krauss

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In March a collaboration of scientists operating a microwave telescope at the South Pole made an announcement that stunned the scientific world. They claimed to have observed a signal emanating from almost the beginning of time. The putative signal came embedded in radiation left over from the action of gravitational waves that originated in the very early universe—just a billionth of a billionth of a billionth of a billionth of a second after the big bang.

The observation, if confirmed, would be one of the most important in decades. It would allow us to test ideas about how the universe came to be that hitherto scientists have only been able to speculate about. It would help us connect our best theories of the subatomic (quantum) world with our best theories of the massive cosmos—those based on Einstein's general theory of relativity. And it might even provide compelling (though indirect) evidence of the existence of other universes.

Since that announcement was made, other scientists have questioned whether the signal is real. Their skepticism has injected a new urgency to ongoing observations from other experiments that will definitively confirm or refute the claim, most likely in the next year. Although the jury is out on whether we have indeed seen a beacon from the infant universe, we will not have to wait long to know. The present moment in our exploration of the cosmos is one of heightened anticipation.

THE ROAD TO INFLATION

HOW DID WE GET to this dramatic moment? It started with two apparent paradoxes of the early universe, which this beacon (if it is one) may help resolve.

The first paradox has to do with the large-scale geometry of

IN BRIEF

Earlier this year scientists announced that they had found gravitational waves that emanated from the first moments after the big bang.

If confirmed, the discovery would allow researchers to study the first instants of time—potentially providing a way to unify quantum mechanics and gravity.

It could also provide indirect evidence for the existence of the multiverse—an infinite bubbling of physically separate universes.

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UNIFORM UNIVERSE: **On a grand scale, the universe appears largely the same in every direction we look. We find a similar density of galaxies, on average, in any given patch of sky, such as this image of a patch called the eXtreme Deep Field. Within an area smaller than the full moon, many hours of Hubble Space Telescope observations have revealed thousands of galaxies. The universe's sameness could be explained if space inflated rapidly just after the big bang.**

the universe. In the 13.8 billion years since the universe formed in the big bang, it has been expanding. Even after such a long period of expansion, it has remained almost perfectly flat. A flat, three-dimensional universe is the universe most of us might have imagined we live in—in it, light travels, on average, in straight lines.

The trouble is, general relativity implies that a flat universe is far from guaranteed—in fact, it is a special, perhaps unlikely, outcome. When matter or radiation is the dominant form of energy in the universe, as certainly has been the case for most of its history, then a slightly nonflat universe will quickly deviate from the characteristics of a flat universe as it expands. If it were ever off by just a little bit, the universe today would look open—where space is curved like a saddle—or closed—where space is curved like the surface of a sphere. For the universe to still appear flat today, its early characteristics would have had to have been absurdly fine-tuned.

The second paradox has to do with the fact that the universe appears to be the same in all directions—it is isotropic. This is odd. Light from one side of the vast observable universe has only recently been able to reach the other side. This distance means that far-off regions of the universe could not have previously communicated with one another (physicists say they have not been in "causal contact"). How, then, could they have evolved to be so similar?

In 1980 a young postdoctoral physicist named Alan Guth was pondering these paradoxes when he hit on a solution: the universe, he conjectured based on ideas from particle physics, could have ballooned rapidly shortly after it was born. Guth arrived at the idea, which he called inflation, by thinking about a central part of the Standard Model of particle physics called spontaneous symmetry breaking, which describes what happens when forces that were once unified become separate.

There is good evidence that spontaneous symmetry breaking has already occurred at least once in the universe. According to the electroweak theory, two of the universe's fundamental forces—the electromagnetic force (the force of magnetism and electricity) and the weak force (which is responsible for the radioactive decay of atomic nuclei)—appear dissimilar today only because of an accident of the universe's history. At one time, they were a single, unified force.

But as the universe cooled, when it was about a millionth of a millionth of a second old, it underwent a phase transition (similar to water transitioning from liquid to ice) that changed the nature of empty space. Instead of being empty, it was filled with a background field (something like an electric field but, in this case, a type of field that is not as easily detectable). This background field, known as the Higgs field, developed throughout the universe.

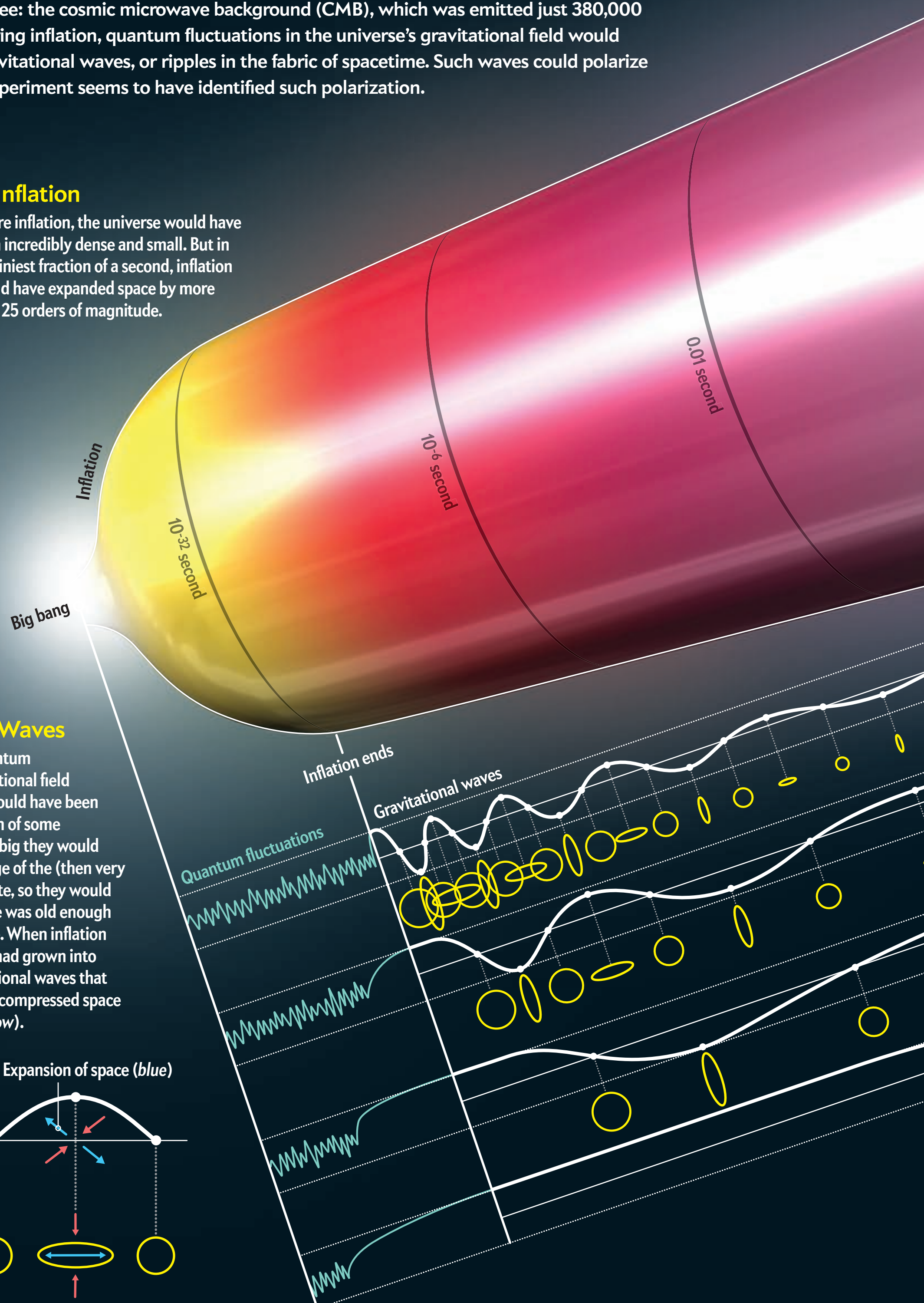
The Higgs field affects the way particles propagate through

From Inflation to Gravitational Waves to Polarized Light

If a period of inflation rapidly stretched the universe just after it was born, we might be able to find proof in some of the oldest light we see: the cosmic microwave background (CMB), which was emitted just 380,000 years after the big bang. During inflation, quantum fluctuations in the universe's gravitational field would have been amplified into gravitational waves, or ripples in the fabric of spacetime. Such waves could polarize the CMB, and the BICEP2 experiment seems to have identified such polarization.

1 Inflation

Before inflation, the universe would have been incredibly dense and small. But in the tiniest fraction of a second, inflation would have expanded space by more than 25 orders of magnitude.



2 Gravitational Waves

During inflation, tiny quantum fluctuations in the gravitational field pervading the universe would have been stretched. The wavelength of some fluctuations would get so big they would require longer than the age of the (then very young) universe to oscillate, so they would "freeze" until the universe was old enough for them to again oscillate. When inflation ended, these oscillations had grown into long-wavelength gravitational waves that alternately stretched and compressed space around them (*ellipses below*).

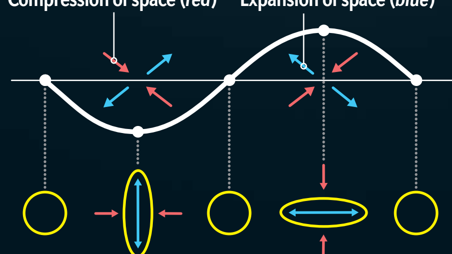
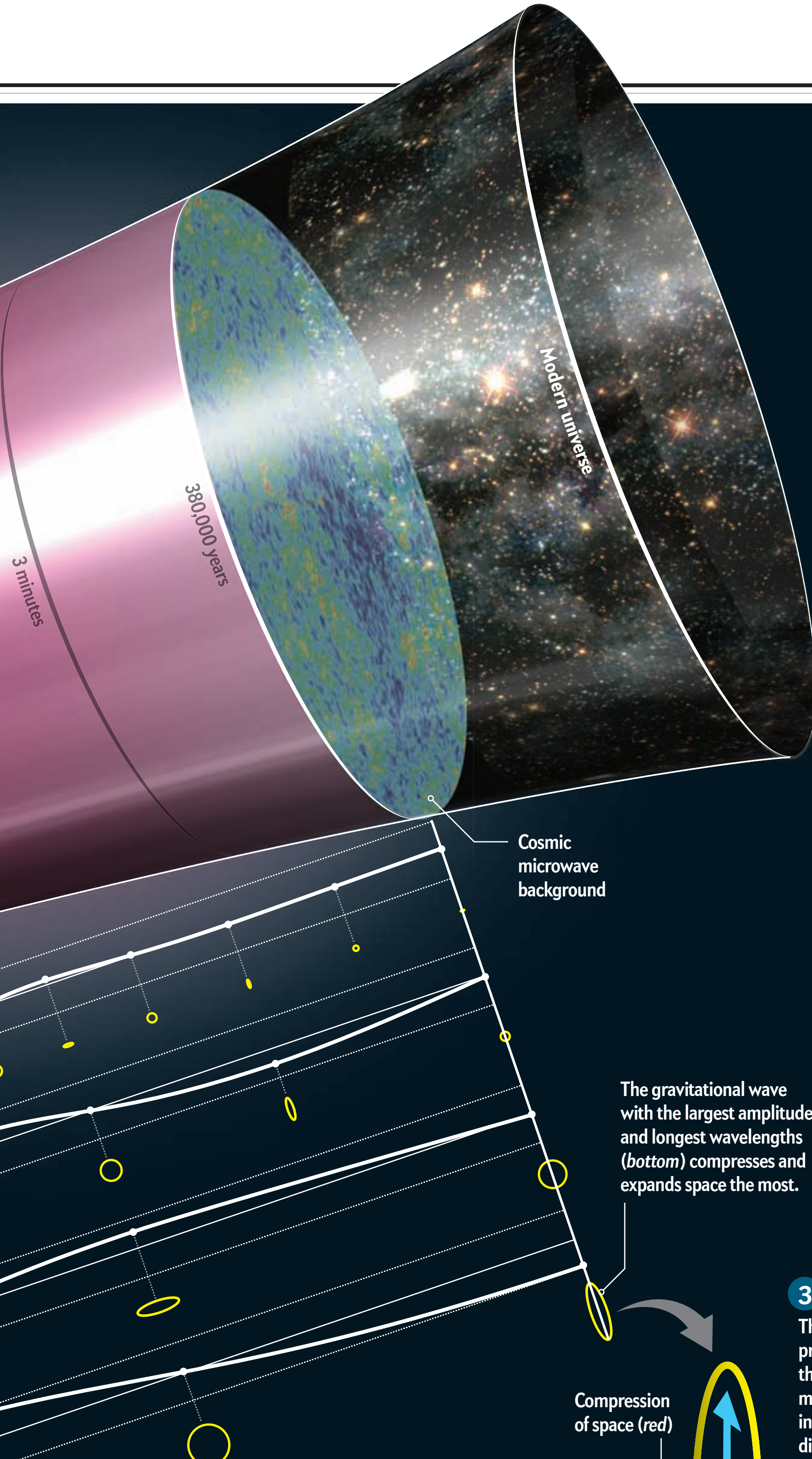
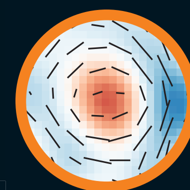


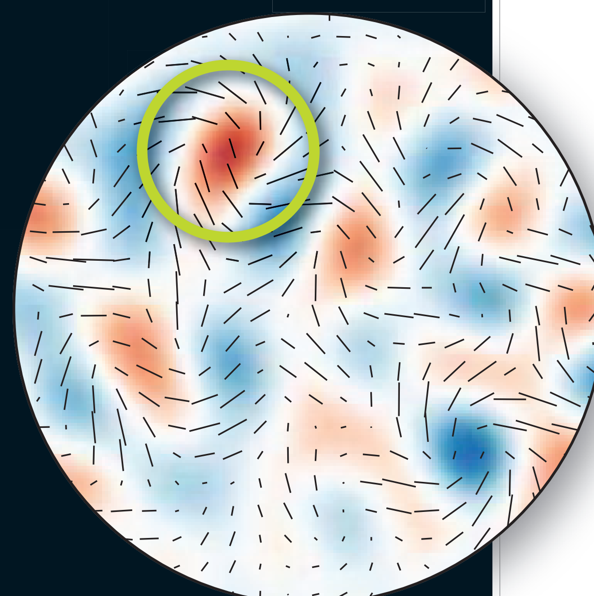
Illustration by Don Foley (universe) and Jen Christiansen (schematics)



4 Pinwheels

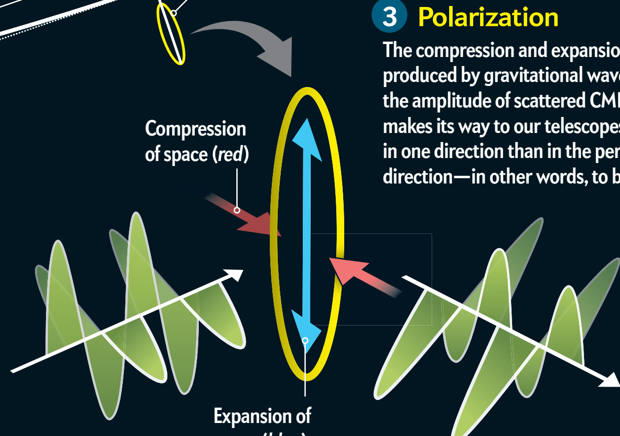
Polarization can take several forms. Normal local temperature and density fluctuations in space produce a radial or circular pattern of polarization (*orange circle*). Gravitational waves, however, produce a striking pinwheel pattern (*below*). Red spots here are where space has been compressed, so photons are packed tighter together and the radiation is hotter. Blue areas are cooler.





3 Polarization

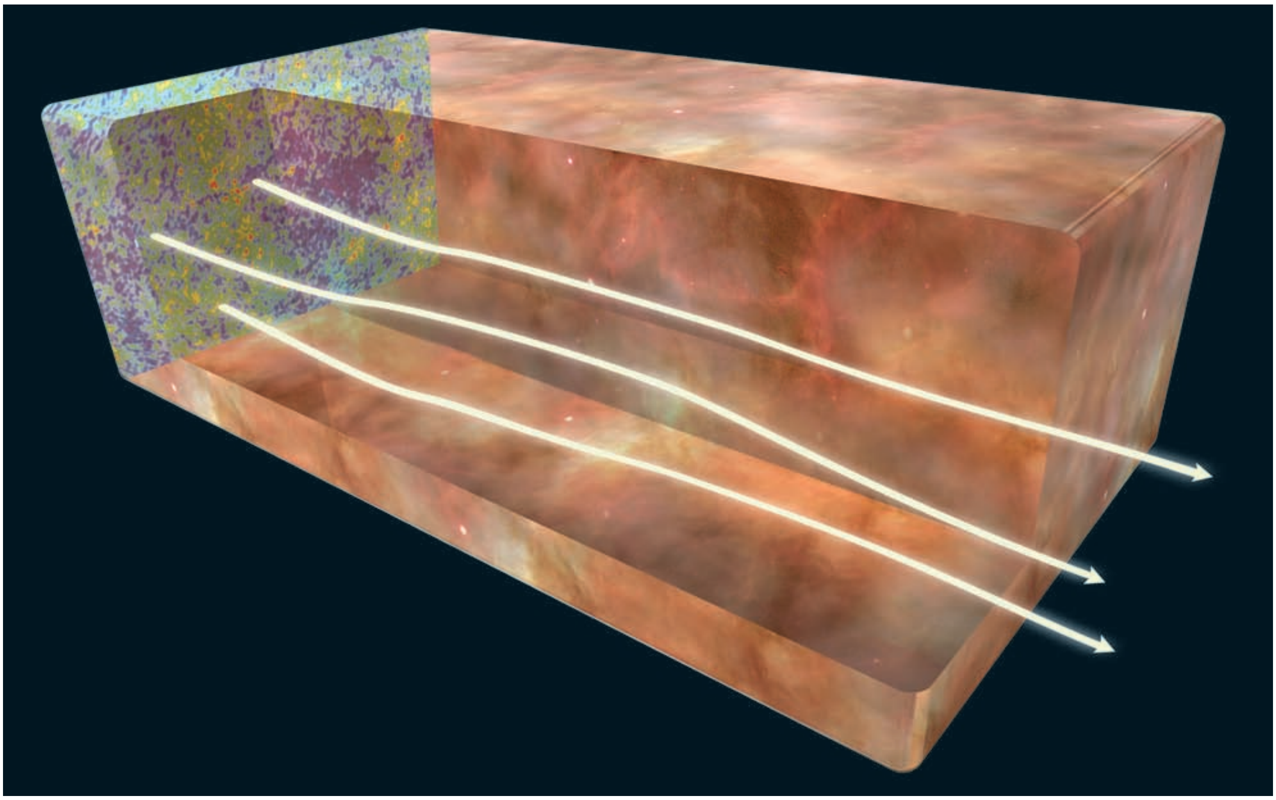
The compression and expansion of space produced by gravitational waves could cause the amplitude of scattered CMB light that makes its way to our telescopes to be larger in one direction than in the perpendicular direction—in other words, to be polarized.



BICEP2 COLLABORATION (*polarization insets*)

Contaminating Effects

The discovery of polarization in the cosmic microwave background (*mottled blue surface*) is not yet definitive evidence of gravitational waves, because other processes may account for the finding. The paths of CMB photons (*curved lines*), for example, have bent around massive galaxy clusters whose gravity warps the spacetime around them in a process called gravitational lensing, which introduces polarization. Dust grains in our Milky Way galaxy also emit polarized light that is hard to distinguish from CMB radiation. Recently the Planck satellite revealed that such dust could be more prevalent than previously thought.



space. Those particles that interact with this field—the ones that convey the weak force, for example—experience a resistance that causes them to behave as massive particles. Those that do not interact with the field—for example, the photon, carrier of the electromagnetic force—remain massless. As a result, the weak force and the electromagnetic force began to behave in different ways, breaking the symmetry that otherwise unified them. This fantastical picture was validated at the Large Hadron Collider (LHC) at CERN near Geneva in 2012, with the discovery of the Higgs boson.

Perhaps, Guth reasoned, a similar symmetry-breaking event occurred even earlier in the universe's past. Before this event, three of the universe's four fundamental forces—the electromagnetic and weak forces, as well as the strong force (responsible for holding protons and neutrons together), but excluding gravity—might have been connected. Indeed, a great deal of indirect evidence suggests that such a phenomenon happened back when the universe was approximately 10^{-36} second old. As the universe cooled, it might have undergone a phase transition that also changed the nature of space involving a background field that caused the electroweak force to begin to behave differently from the strong force—spontaneously breaking their symmetries, or connectedness.

As in the case of the Higgs field, this symmetry-breaking field would lead to exotic and very massive particles, but the masses involved would be much higher than the mass of the Higgs particle. In fact, one would need to build an accelerator 10 trillion times more powerful than the LHC to directly explore the theories behind this phenomenon. We call them grand unified theories, or GUTs, because they unify the three nongravitational forces of the universe into a single force.

Guth realized that such spontaneous symmetry breaking in the early universe could solve all the problems of the standard big bang if, for a short period at least, the field responsible for this symmetry breaking got stuck in a "metastable state."

Water goes into a metastable state when, say, the ambient temperature drops quickly below freezing, but water on the street does not freeze immediately; when it eventually does freeze—when the phase transition is completed—the water releases energy, called latent heat.

Illustration by Don Foley

In a similar fashion, the field that caused the GUT phase transition might have briefly stored tremendous latent energy throughout space. During the short period of inflation, this energy would have produced a gravitational repulsion that could have caused the universe to expand exponentially fast. What is now the observable universe could have increased in size by more than 25 orders of magnitude in less than 10^{-36} second. Like blowing up a balloon, such extreme expansion would also tend to make the universe we observe today flat and isotropic, thus naturally addressing the two apparent paradoxes of the large-scale structure of the universe.

As compelling as the idea of inflation may be, however, as of yet we do not have a fundamental theory of exactly how inflation would have played out, largely because we do not know the details associated with grand unification, such as the precise energy level at which the forces would have been unified. While the simplest inflation theories explain much of what we observe in the cosmos today, different versions of inflation could have produced radically different universes.

What we really need is a way to directly probe the universe for evidence that it actually underwent inflation and, if so, to explore the detailed physics associated with it. Gravitational waves, it turns out, provide just such an opportunity.

GRAVITATIONAL-WAVE SIGNATURES

WHEN ALBERT EINSTEIN published his general theory of relativity in 1915, he recognized that it implied the existence of an exciting new physical phenomenon. In general relativity, a gravitational field is just a distortion in the underlying global fabric of spacetime. A time-varying source of energy—for example, the motion of a planet around its sun or of one star around another—would produce a time-varying distortion that would propagate away from the source at the speed of light. As gravitational waves pass by, the distance between nearby objects changes very slightly.

Because gravity is so weak compared with electromagnetism, gravitational waves are extremely difficult to detect. Einstein doubted whether they would ever be found. Nearly 100 years after he first predicted them, we have not been able to directly measure such gravitational waves emanating from catastrophic astrophysical phenomena such as colliding black holes (although researchers think they are getting close). Fortunately, however, the universe can provide us with a much more powerful source of gravitational waves: the fluctuating quantum fields in the moments after the big bang.

When the universe was very young, before the time of inflation, it was compressed into a volume much, much smaller than the size of an atom. At such tiny scales, the rules of quantum mechanics reign. And yet because the amount of energy packed into each bit of that tiny space was extremely high, this large energy requires us to use the theory of relativity to describe it. To understand the properties of the early universe, we need to use, as Guth did, the ideas of quantum field theory, which incorporates both quantum mechanics and special relativity—the theory that relates space and time together. Quantum field theory tells us that at very small scales, all quantum-mechanical fields are wildly fluctuating. If all other quantum fields behave similarly during the period when the inflationary energy density dominated the expansion of the universe, then the gravitational fields may have fluctuated as well.

During the exponential expansion of inflation, any initial quantum fluctuation with a small wavelength will be stretched along with the expansion. If the wavelength becomes large enough, the time the fluctuation takes to oscillate will grow larger than the age of the (extremely young) universe. The quantum fluctuation will essentially become "frozen" until the universe becomes old enough for it to start oscillating again. During inflation, the frozen oscillation will grow, a process that amplifies these initial quantum oscillations into classical gravitational waves.

Around the time when Guth was proposing inflation, two sets of Russian physicists, Aleksei A. Starobinsky and Valery A. Rubakov and his colleagues, independently pointed out that inflation always produces such a background of gravitational waves and that the intensity of the background simply depends on the energy stored in the field that is driving inflation. In other words, if we can find the gravitational waves from inflation, we get not only a smoking-gun confirmation that inflation once took place but also a direct view into the quantum processes that drove inflation.

SMOKE FROM THE GUN

A POTENTIALLY UNAMBIGUOUS signature for inflation is only useful, however, if it is detectable. And whereas the scale of inflation is expected to be close to the scale at which quantum-gravitational wiggles could be large, the weakness of gravity itself would seem to make the likelihood of actually probing gravitational waves from inflation difficult at best.

Difficult but not impossible. The cosmic microwave background, or CMB, might help. The CMB is radiation that emerged from a time when the young universe first cooled sufficiently so that protons could capture electrons to form neutral atoms, making the universe transparent to light, which could then propagate to us. In this sense, it is the oldest visible light in the universe. If gravitational waves existed on large scales at the time the CMB was created, when the universe was 380,000 years old, then we might be able to see signs of it in the CMB. Back then, free electrons would have been immersed in a radiation bath that was slightly more intense in one direction than another because large-scale gravitational waves would have been compressing space in one direction and stretching it in another. If the effect were large enough, it could have produced a small distortion in the CMB that might be detectable. But gravitational waves can also have another, more subtle effect. The spatial distortion produced by gravitational waves could cause the electron-scattered CMB radiation to have a greater amplitude along one axis than along the perpendicular one. In other words, the CMB can be polarized.

Measuring polarization in the CMB is not by itself evidence of the existence of gravitational waves. There are many other possible causes of polarization—they could be created by underlying temperature fluctuations in the CMB or emission by possible foreground sources such as polarized dust in our galaxy. One can, however, try to separate the possible effects of gravitational waves from other sources by exploring the spatial pattern of polarization in the sky.

In particular, a twisting pattern would be characteristic of gravitational waves. Other polarization sources would tend to produce patterns without such twisting. The two possible spatial polarization modes are called E and B modes. B modes, the twisty kind, are associated with gravitational waves, and E modes tend to be produced by other sources.

This insight, which came in 1997, energized the CMB community because it meant that even if the direct temperature variations that might be induced by primordial gravitational waves were too small to be directly detected amid other temperature distortions in the CMB, a measurement of the polarization of the CMB could identify a much smaller gravitational-wave signal. Over the intervening decade or so, a host of experiments, both terrestrial and space-based, have been designed to seek out this possible holy grail of inflation.

Because experimentalists have already measured temperature fluctuations in the cosmic microwave background, researchers present their results in terms of a ratio: the ratio of a possible gravitational-wave polarization signal to the magnitude of the measured temperature fluctuation signal. This ratio is denoted by *r* in the literature.

THE NEW RESULTS

UNTIL THIS YEAR, only upper limits on the polarization of the CMB have been reported—that is, we knew they could not be larger than these limits, or we would have seen them. The European Space Agency's Planck satellite reported that, according to its measurements, *r* could be anywhere from zero, implying no gravitational waves, all the way to an upper bound of about 0.13. Thus, the physics world was stunned in March, when the Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2) experiment at the South Pole announced that it had found an *r* of about 0.2—larger than the limit indicated by Planck—suggesting that gravitational waves exist. It also declared, at the time, that the chance that a spurious background produced the observed signal was less than one in a million. Everything about the signal reflects the character of a signal expected from inflation.

Alas, as of this writing, the situation remains unsettled. Polarization observations are very difficult, and although statistically, the signal is clear, other possible astrophysical processes could produce effects that might mimic a gravitational-wave signal from inflation.

While the BICEP2 team examined a number of possible contaminants, the hardest to discount is radiation emitted by polarized dust in our galaxy. The BICEP2 collaboration studied what it envisaged were likely dust concentrations in our galaxy and concluded that these sources did not strongly contaminate its signal. But in the intervening months, the Planck satellite has reported new measurements that indicate the Milky Way may contain more dust than assumed by the BICEP2 team. Several groups have tried to reanalyze the BICEP2 signal in light of these new data, as well as incorporating more sophisticated models of dust backgrounds from other experiments, and have concluded that it is possible that dust could reproduce all (or most of) the claimed BICEP2 polarization signal.

Although these developments have dampened the exuberance of many in the physics community regarding the BICEP2 result, the BICEP2 team stands by its estimates—but it now admits that it cannot rule out a dust explanation. The scientists point out, however, that the shape of the observed spectrum fits the inflationary prediction remarkably well—somewhat better than dust predictions do.

More important, a host of new experiments are coming online that can shed light on dust emission and explore for a polarization signal on different scales and in different directions. In the best tradition of science, empirical confirmation or refutation of BICEP2 should be possible within a year or so after this article appears.

WHAT GRAVITATIONAL WAVES REVEAL

IF THE BICEP2 SIGNAL is confirmed, our empirical window on the universe will have increased by a greater amount than at essentially any other time in human history. Gravitational waves interact so weakly with matter that they can travel basically unimpeded from the beginning of time. Not only would the BICEP2 findings represent the first detection of gravitational waves themselves—a fundamental prediction of general relativity—these waves would give us a direct signal of the physics operating when the universe may have been only 10^{-36} second old, 49 orders of magnitude earlier than when the CMB light was created.

If the BICEP2 signal is indeed the smoking gun from inflation, we will have much more to learn about the universe. In the first place, the inferred strength of the gravitational-wave signal would imply that inflation occurred at an energy scale that is very close to the energy scale at which the three nongravitational forces in nature would come together in a grand unified theory—but only if a new symmetry of nature, called supersymmetry, exists. The existence of supersymmetry, in turn, could imply the existence of a plethora of new particles with masses in the range that can be probed by the LHC when it turns on again in 2015. Thus, if BICEP2 is correct, 2015 may be another banner year for particle physics, unraveling new phenomena that might explain the nature of fundamental forces.

If BICEP2 is correct and if it is measuring gravitational waves from inflation, gravity must be described by a quantum theory.

There is another, less speculative implication of the discovery of gravitational waves from inflation. As I described earlier, such waves should be generated when primordial quantum fluctuations in the gravitational field are amplified during inflation. But if this is the case, then it suggests that gravity must be described by a quantum theory.

This issue is particularly important because we have, as of yet, no well-defined quantum theory of gravity—that is, a theory that describes gravity using the rules governing the behavior of matter and energy at the tiniest scales. String theory is perhaps the

SCIENTIFIC AMERICAN ONLINE See a video about primordial gravitational waves at ScientificAmerican.com/oct2014/krauss

best attempt so far, but there is no evidence that it is correct or that it can consistently resolve all the problems that a complete quantum theory of gravity must address. Moreover, as Freeman Dyson of the Institute for Advanced Study in Princeton, N.J., has pointed out, there is no terrestrial device capable of detecting individual gravitons, the presumed quantum particles that carry the force of gravity, because any such detector would need to be so large and dense that it would collapse to form a black hole before it could complete an observation. Thus, as he has speculated, we can never claim to be sure that gravity is described by a quantum theory after all.

If gravitational waves from inflation do show up, however, it would seem that they could obviate Dyson's argument. But one loophole remains. If we find gravitational waves from inflation, which are classical (nonquantum) objects, we can calculate the origin of these waves using quantum mechanics. Yet every classical physics result, including the motion of a baseball, can be calculated quantum-mechanically. Just seeing a baseball in flight does not prove that quantum mechanics is behind it—indeed, its motion would be identical even if quantum mechanics did not exist. What we need to prove is that the generation of gravitational waves from inflation, unlike the motion of a baseball, derives from quantum processes.

Recently my colleague Frank Wilczek of the Massachusetts Institute of Technology and I closed this remaining loophole. Using the most basic technique in physics, so-called dimensional analysis, which explores physical phenomena in terms of their representation in units describing mass, space and time, we were able to demonstrate, on very general grounds, that a gravitational-wave background caused solely by inflation would vanish if Planck's constant, the quantity that governs the magnitude of quantum-mechanical effects in the world, were to vanish. Thus, if BICEP2 is correct and if it is measuring gravitational waves from inflation, gravity *must* be described by a quantum theory.

IMPLICATIONS FOR THE MULTIVERSE

FROM THE PERSPECTIVE of understanding the very origins of our universe and the vexing question of why it exists at all, probing inflation by the observation of gravitational waves has the potential of turning what many consider to be one of the grandest metaphysical speculations of all into hard physics.

Recall that inflation is driven by a field that stores and releases tremendous amounts of energy during a phase transition. It turns out that the necessary characteristics of this field imply that once the process starts, the field driving inflation will tend to continue to inflate the universe ad infinitum. Inflation will go on without end, preventing the creation of the universe as we know it because any preexisting matter and radiation would have been diluted away by the expansion, leaving nothing but rapidly expanding empty space.

Yet Andrei Linde, a physicist at Stanford University, found a way to escape this problem. He showed that as long as some small region of space completed its phase transition after sufficient expansion, this region could encompass our entire observed universe today. In the rest of space, inflation could continue forever, with small "seeds" forming in different locations where the phase transition might be completed. In each such seed, an isolated universe undergoing a hot big bang expansion would emerge.

In such a picture of "eternal inflation," our universe is then a part of a much bigger structure that could be infinitely big and might ultimately contain an arbitrarily large number of disconnected universes that may have formed, may be forming or will form. Moreover, because of the way the phase transition ending inflation in each seed can occur, the physics governing each resulting universe can be different.

This possibility has become known as the multiverse hypothesis, suggesting our universe may be one of a possibly uncountably large number of separate, physically different universes. In this case, it is possible that the underlying physical constants in our universe are what they are simply by accident. If they were any different, beings like us could not evolve to measure them.

This suggestion, often somewhat pompously labeled the anthropic principle, is abhorrent to many and leads to a number of possible problems that physicists have yet to resolve. And for many people, multiverses and the anthropic principle are indications of how far fundamental physics may appear to be diverging from what is otherwise considered to be sound empirical science.

But if BICEP2 (along with the LHC and other experiments) enables us to probe the phenomena of inflation and grand unification, we may be able to uniquely determine the fundamental physics governing the universe at these scales of energy and time. One of the results may be that the inflationary transition producing our observed universe requires Linde's eternal inflation. In this case, while we may never be able to directly observe other universes, we will be as confident of their existence as our predecessors in the early 20th century were of the existence of atoms, even though they, too, could not have been observed directly at the time.

Will BICEP2 provide as revolutionary a guidepost to understanding the physics of the future as the early experiments that led to a quantum theory of atoms did? We do not yet know. But the possibility is very real that it, or perhaps a subsequent CMB polarization probe, could open a new window on the universe that will take us back to the beginning of time and out to distances and phenomena that may make the wild ride that physics provided in the 20th century pale by comparison. SA

MORE TO EXPLORE

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