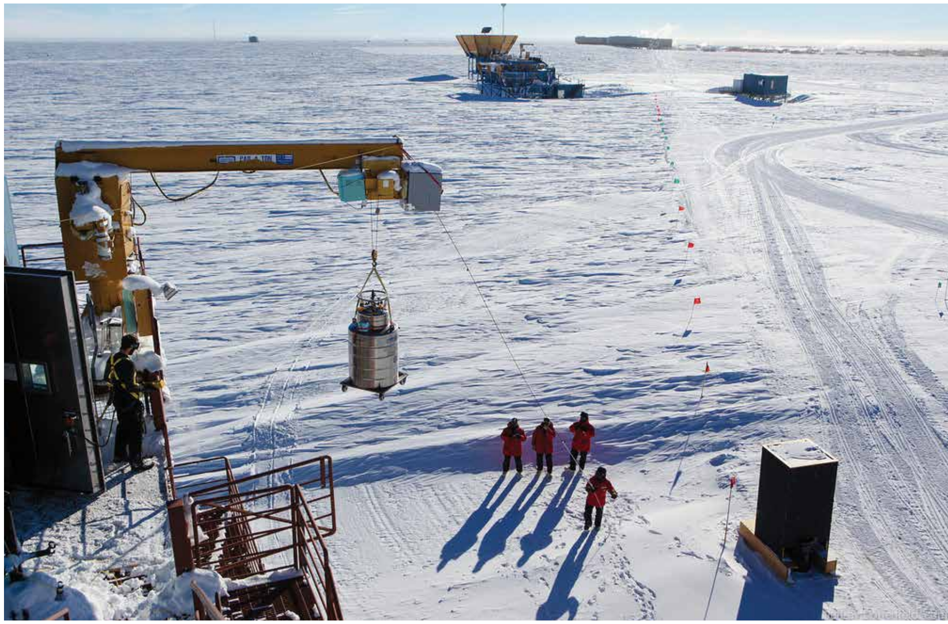

BICEP2 team members lift a liquid helium cryostat to the second floor of the Dark Sector Laboratory to chill the telescope to a temperature near absolute zero.

We're looking forward to hearing the results from these experiments, and of course we are working as hard as we can on our own balloon experiment, Spider."

The Future of Observational Cosmology

It is hard to overstate the significance of BICEP2's findings. In the *New York Times*, Kamionkowski called BICEP2's findings "huge, as big as it gets."

The BICEP2 findings strongly support the theory of inflation (as opposed to non-inflationary cosmologies). Furthermore, only particular models of inflation can account for the abundance of gravitational waves found in the B-modes. So far the simplest models of inflation that were developed by Alan Guth and Andrei Linde match the data.

Primordial gravitational waves are very faint, but with an advanced gravitational-wave interferometer—a futuristic descendant of the Laser Interferometer Gravitational-Wave Observatory, or LIGO (see "Reflections in Research," page 20)—they might actually be detected one day as they pass by Earth.

"It is mind-boggling that we can infer anything about the very instant of the birth of our universe nearly 14 billion years ago," says Bock. "The process that produced the polarization involves physics we don't understand and energies beyond the standard model in particle physics. The primordial gravitational waves were born from quantum fluctuations that were expanded by inflation due to a connection between gravitation—in Einstein's theory of general relativity—and quantum mechanics. This is just the beginning for understanding the exotic physics powering inflation.

"Most of all," Bock continues, "it is amazing to me that our little band of intrepid scientists, students, postdocs—all of whom I consider colleagues and friends—could build a machine that could actually tell us about the birth of the universe." E&S

Jamie Bock is a professor of physics at Caltech and a senior research scientist at JPL.

WHAT BICEP FOUND

BY SEAN CARROLL

The discovery by the BICEP2 experiment of the imprints of gravitational waves on the cosmic microwave background radiation is a historic moment for cosmologists. For the first time, we've directly learned something about the state of the universe one trillionth of a trillionth of a trillionth of a second after the Big Bang.

The result is a great example of the interplay of theory and experiment. Over 30 years ago, Alan Guth of MIT and others formulated the theory of cosmic inflation. In this model, the very early universe underwent a brief period of superfast expansion. That expansion works to smooth out the distribution of matter and energy through space, much like tugging on the edges of a bed sheet will smooth out any wrinkles. Unlike a bed sheet, however, the early universe is governed by the rules of quantum mechanics. And quantum mechanics says that we can't make anything *perfectly* smooth; there will always be some irreducible fluctuations from place to place.

According to inflation, quantum fluctuations are responsible for the tiny deviations in the density of matter that eventually grew into galaxies and clusters in the current universe. The cosmic microwave background, leftover radiation from the Big Bang, displays the influence of those deviations by having a slightly different temperature at different points in the sky. We have seen these temperature differences; what we haven't been sure about is whether inflation is the right theory to account for them. The temperature fluctuations match the prediction of inflation, but maybe there are other theories that would produce the same signature.

Fortunately, inflation makes an additional prediction: not only should the density of matter fluctuate, so should the gravitational field itself. Inflation, in other words, predicts a specific pattern of gravitational waves, which should leave a distinctive imprint on the microwave background. Seeing those waves would be strong evidence that inflation is on the right track.

And that's exactly what BICEP2 has done. In addition to measuring the temperature of the microwave background, the instrument also measured its polarization. Luckily for cosmologists, gravitational waves push and pull on the plasma of the early universe to produce a very particular kind of polarization pattern (the so-called B-modes). BICEP2 was designed to look for this signal, and it found precisely that.

The finding is noteworthy not only because it's a scientific and technological tour de force (although it is that), but also because the gravitational waves were actually relatively easy to find. Inflation predicts a particular pattern, but the overall amplitude of the signal is a free parameter—one that, according to BICEP2, turns out to be just about as big as it could be. That's very good news indeed for cosmologists, as it implies that inflation happened very quickly after the Big Bang. The scientists on BICEP2 have brought us quite a bit closer to understanding how our universe began.

Sean Carroll is a senior research associate in physics at Caltech and the author of From Eternity to Here: The Quest for the Ultimate Theory of Time *(Dutton, 2010) and* The Particle at the End of the Universe: How the Hunt for the Higgs Boson Leads Us to the Edge of a New World *(Dutton, 2012).*