Back to the Big Bang

A faint signal hidden in the universe's earliest light might reveal what happened in the first moment after cosmic birth.

Bruce Lieberman

THE SKY ABOVE CERRO TOCO in Chile's Atacama Desert slides quickly from a crystalline blue to hues of purple and charcoal gray as the western horizon dims like embers in a fading campfire. The southern sky's brightest stars begin to emerge overhead, then the Milky Way and Magellanic Clouds materialize, all three galaxies breathtakingly surreal.

Here, at 17,000 feet above sea level in a desolate, rust-colored landscape evocative of Mars, is where the hunt is on for the signature of inflation — the hypothesized epoch immediately after the Big Bang when the universe expanded exponentially for a tiny fraction of a second. Cosmologists predict that inflation's signature will appear as vanishingly faint patterns of polarized light embedded in the cosmic microwave background (CMB), the radiation released when the universe's primordial soup cooled enough to allow photons to travel freely across the expanding universe. Researchers call these polarization patterns *B-modes*, and many say that finding them would provide "smoking-gun" evidence that inflation actually happened.

For this reason, numerous experiments today are racing to detect these predicted but never-before-seen B-modes. One of them is called Polarbear, which stands for "Polarization of Background Radiation," and it saw first light in early 2012 at this high-altitude site below the peak of Cerro Toco. Its team members hope that their precise observations of the CMB, which fills every cubic centimeter of the cosmos with about 400 microwave photons, will reveal the imprint of inflation's physics.

Looking for Inflation's Signature

Inflation is a pillar of Big Bang cosmology and explains key features of the universe we see today. Among them are the uniform distribution of matter on large scales and the pattern of temperature variations in the CMB. But inflation is still merely a theoretical framework. If it did happen, many cosmologists expect that it should have generated ripples in spacetime called gravitational waves, born from quantum fluctuations in gravity itself that were then stretched during inflation's superluminal cosmic expansion. These waves would have left the B-mode imprint on the CMB.

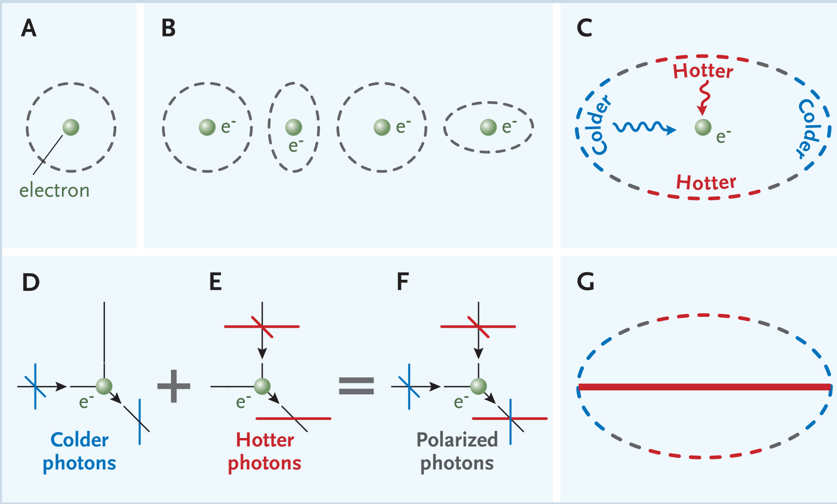
Like all polarization types, B-modes are a particular orientation of light. A wave of light oscillates perpendicular

UPPER LEFT ILLUSTRATION BY PATRICIA GILLIS-COPPOLA, PHOTO BY THE AUTHOR

How Gravitational Waves Create Polarization

Gravitational waves created polarization patterns in the cosmic microwave background (CMB) by stretching and squeezing space — and therefore the plasma soup of primordial photons and electrons — as the waves passed.

(A) Before a wave hits it from behind, a cross-section of space with an electron in the middle looks normal. But when the wave hits, the cross-section stretches and squeezes one way, then another, in an oscillating pattern (B). Instead of a uniform soup, the electron "sees" around it a universe a bit hotter in the squeezed direction and a bit colder in the stretched direction (C). Originally, a photon's wave wiggles in all planes perpendicular to the photon's motion (D and E, incoming crosses). When photons scatter off the electron, they become polarized, wiggling in only one plane (outgoing lines). The resulting pattern (F) is a sum of the cold and hot photons' polarizations. But because photons from hotter regions have more energy, their pattern "wins out," meaning the overall polarization is parallel to the hot regions (G).



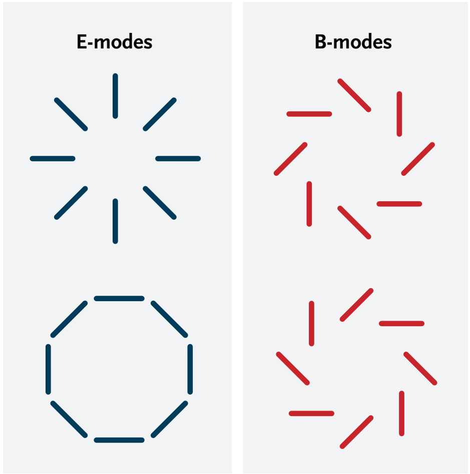
S&T: LEAH TISCIONE

to the direction in which it travels. For a light beam that is unpolarized, there is no preferred angle of vibration — the waves wiggle in random orientations about the axis of motion. For polarized light, the waves collectively have a preferred angle of vibration.

Unpolarized sunlight can become polarized when it reflects off a flat, nonmetallic surface, such as a lake, so that the reflected waves vibrate parallel to that surface as they travel toward our eyes. We see the reflected light as glare. Polarized sunglasses are designed to block that light and thereby reduce the glare.

The CMB's light should be polarized in two different patterns: E-modes and B-modes. Both would have been created 380,000 years after the Big Bang, when the CMB photons were released and scattered off electrons for the last time before flying off freely into space. Scattered photons are generally polarized, but an electron being bombarded by photons of the same energy from all sides will scatter those photons uniformly in all directions, thereby canceling out the polarization signature.

RING AROUND THE ROSIE E- and B-mode polarization patterns look different. E-modes have no "handedness" — if you draw a line down the pattern's center and reflect the pattern, nothing changes. B-modes look like spirals and don't reflect. Although gravitational waves can create both types, primordial B-modes can only be made by gravitational waves.



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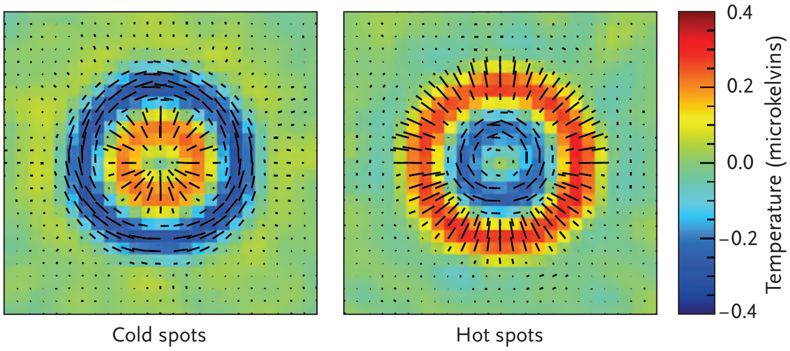


PLANCK COLLABORATION

PLANCK CATCHES E-MODES By stacking maps of more than 11,000 cold and 10,000 hot spots in the CMB, researchers on the science team for the European Space Agency's Planck satellite revealed the related E-mode polarization patterns to high precision. The team is now analyzing Planck's polarization data and hopes to release results for B-modes and the largest angular scales in 2015.

But if a gravitational wave comes by, it will squeeze spacetime in one direction and stretch it in another. That means the electron will see a universe that is a little bit hotter in one direction (where the wave squeezed spacetime) and a little bit colder in the other direction (where the wave stretched spacetime). When photons come at the electron from these different regions, the electron still scatters them all, but it does so with a preferred direction. The polarization pattern of the hotter (and therefore more energetic) photons wins out over that of the cooler ones, leaving a mark in the CMB.

These marks from the universe's many electrons drew both E- and B-mode patterns. E-modes have already been detected and studied. But other mechanisms besides gravitational waves also produced E-modes, such as photons scattering off the early universe's higher-density regions, which later grew into galaxies and clusters. The primordial B-mode pattern, in contrast, only could have originated from the stretching and squeezing of spacetime by gravitational waves, so cosmologists depend on it for evidence of inflation. "It would be a very beautiful confirmation of another important feature that inflation predicts," says inflation architect Alan Guth (MIT).

No Wiggle Room

So, what will each polarization pattern look like? CMB light waves oscillate at distinct angles in the plane perpendicular to the waves' direction of travel. On CMB polarization maps, those angles of vibration can be drawn as line segments angled in a particular direction. As you go from one point in the sky to another, the segments' orientations create collective patterns. E-modes look like rings, or rays on a stick-figure Sun (see facing page). But the B-mode patterns should trace out spirals as you move from one line segment to another. These curls appear to turn either clockwise or counterclockwise.

The B-mode pattern is expected to be incredibly hard to detect. The CMB's temperature varies only a few parts in 100,000; in comparison, to detect primordial B-modes detectors must have a sensitivity equivalent to distinguishing temperature differences that vary only a few hundred parts per billion. E-modes are about 10 times stronger than that.

Despite these hurdles, cosmologists say that they should be able to detect this B-mode imprint in the CMB. The pattern should be most apparent across regions roughly 2° wide on the sky.

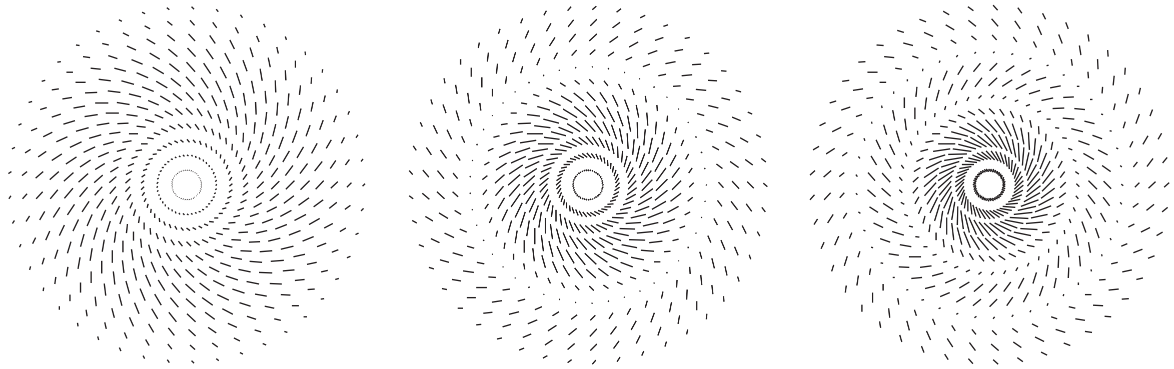
For B-modes to be detectable, they must have been imprinted by gravitational waves whose amplitude corresponds in a specific way to the energy stored in empty space right after the Big Bang, when three of the four fundamental forces — the electromagnetic force, the weak nuclear force, and the strong nuclear force — were joined together. Physicists think this unification of forces existed until about 10^{-35} second after the Big Bang, meaning the forces split right around the time inflation ended.

Measuring the intensity of gravitational waves would essentially be a direct measurement of how much energy was stored in space itself when inflation happened, says Guth. "It would be the first time that we would have an observational handle on that question."

Observing the CMB from Cerro Toco

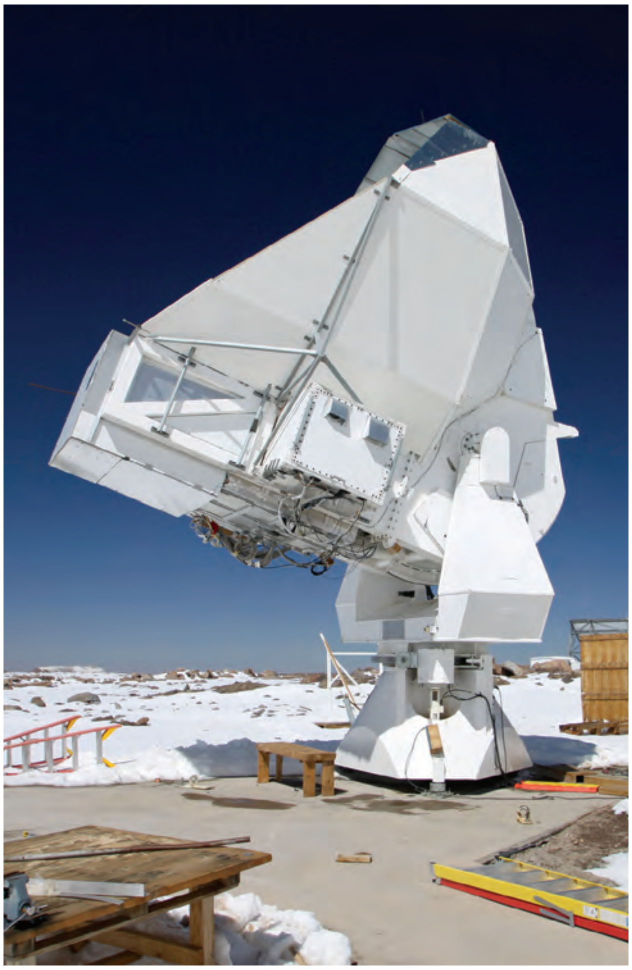
Polarbear is an international, multi-institution experiment at the eastern fringe of Chile's Atacama Desert near the Bolivian border, where the thin and dry atmosphere above the barren volcanic landscape makes the site one of the premier places on Earth for microwave astronomy. The telescope, which collects microwave light with a 3.5-meter parabolic dish, is situated in the Chajnantor Scientific Reserve, where numerous high-profile astronomical projects are under way. Just a short walk from Polarbear is the 6-meter Atacama Cosmology Telescope (ACT) — which will also hunt for B-modes — and a few miles to the south is the Atacama Large Millimeter/submillimeter Array (ALMA), its dozens of antennas gleaming white in the bright midday Sun.

Polarbear is in its second year of observations. By 2016



SOURCE: ANTONY LEWIS

PEEK AT THE UNSEEN Three examples of what primordial B-modes might look like. Unlike the E-modes detected by Planck, such B-modes would not be associated with hot and cold spots in the CMB: they're created by gravitational waves (see sidebar "How Gravitational Waves Create Polarization"). Cosmologists expect these patterns to appear in the sky on scales of a few degrees or larger.



BRUCE LIEBERMAN

ADRIAN LEE

THE WHOLE SHEBANG ***Top:*** **A side view of the Polarbear telescope in Chile. The scope's shield hides the primary mirror, but the receiver box beneath it is visible.**

Bottom: **Hideki Morii (KEK, Japan) and Zigmund Kermish (now at Princeton) fine-tune the Polarbear detectors (see page 28). Notice the oxygen lines to their noses: at 17,000 feet above sea level, the Atacama site can pose a health hazard to the unprepared.**

the single telescope will be joined by two others to create an array of three scopes called the Simons Array that will measure CMB polarization.

"If we can see a signal from this earliest time in the universe . . . we will have a window to high-energy fundamental physics that people don't have on the Earth right now," says principal investigator Adrian Lee (University of California, Berkeley), who proposed the project in 2000. "For me, to have a chance at opening a window on that kind of physics would be a dream come true."

Polarbear faces competition from numerous other endeavors (see sidebar on facing page). Among them is SPTpol, a polarization experiment at the 10-meter South Pole Telescope led by the University of Chicago, and the Columbia University-led EBEX (the "E and B Experiment"), a balloon that was launched in December from McMurdo Station in Antarctica for three weeks of high-altitude observations. Neighboring ACT was outfitted this spring with a new detector called ACTPol so that it can search for B-mode signals in the CMB.

"These projects take a long time, and someone who decides to devote five or 10 years of their lives to this — it means they really think they have a chance to do it," says cosmologist Scott Dodelson (University of Chicago), who has made fundamental contributions to understanding the CMB. "There are probably hundreds of people [working on B-mode search projects], so that is a pretty good indication that it's a big prize."

Back in 2002, when Polarbear scientist Brian Keating (University of California, San Diego) helped propose the BICEP experiment at the South Pole to look for B-modes, scientists thought detections of these signatures in the CMB were improbable, if not impossible. "And they may be," he says. "B-modes from inflation may not exist at the level of detectability, or they may not exist at all. Inflation may not have happened — although that seems unlikely."

B-modes will not readily show themselves: they will only become apparent after much abstract mathematical analysis of the data, which should reveal the patterns in the CMB sky, Lee says. "The real sky maps will largely look like noise, but once separated by mathematical analysis, you can see that there are B-modes."

In addition to detecting primordial B-mode signals, Polarbear, like several other polarization experiments, will also look for "lensed B-modes." These are actually E-modes converted into B-modes through gravitational lensing. During its journey across the cosmos, some of the CMB radiation traveled too close to the universe's cosmic web of dark matter and galaxy clusters, and the gravity of those objects acted as a lens, bending the photons' paths. That distortion converted a fraction of primordial E-modes to B-modes.

Studying lensed B-modes, which were detected for the first time this past July by the South Pole Telescope team, could lead to insights about the large-scale structure of the universe and nearly massless, relativistic particles called neutrinos, Keating says. The lensed polarization signals could help researchers map the predicted cosmic neutrino background, as well as determine the contribution of neutrinos to dark matter. That calculation could help researchers indirectly determine the mass of the neutrino, which has not yet been measured. "It is somewhat of an embarrassment that we physicists do not know the mass of the neutrino — arguably the fourth most important particle after the proton, neutron, and electron!" adds Keating.

Understanding the nature of lensed B-modes also will help researchers distinguish them from primordial B-modes and subtract them out as unwanted noise. Fortunately, lensed B-modes are found on the sky at very small angular scales, on the order of 10 arcminutes, Lee says — one-tenth the size of primordial B-modes. Polarbear's neighbor ACTPol is actually optimized to find lensed B-modes, although it's expected to also look for the primordial ones.

Scanning the Chilean Sky

The Polarbear site is designed as much as possible to be self-contained. It includes a small complex of white shipping containers converted into a lab and control room, equipment storage, several onsite generators, and a toolshed where team members can assemble and repair the telescope's components. Team members almost always carry oxygen tanks in small backpacks, and, like scientists at other high-altitude projects around the world, they wear many different hats: astronomer, physicist, engineer, technician, construction worker, handyman, and tinkerer — frequently in the face of rapidly changing weather conditions. Here at 17,000 feet, there are no Home Depots; scientists must react quickly and resourcefully to the technical glitches that invariably pop up.

B-Mode Search Projects Underway

Ground-Based (Chile):

POLARBEAR: Polarization of Background Radiation

ACTPOL: Atacama Cosmology Telescope – Polarization

ABS: Atacama B-mode Search

Ground-Based (Antarctica):

SPTPOL: South Pole Telescope's polarization-sensitive camera

BICEP2: Background Imaging of Cosmic Extragalactic Polarization (and Keck Array)

QUBIC: Q&U Bolometric Interferometer for Cosmology

Ground-Based (Canary Islands):

QUIJOTE: Q-U-I JOint TEnerife

Balloon Experiments:

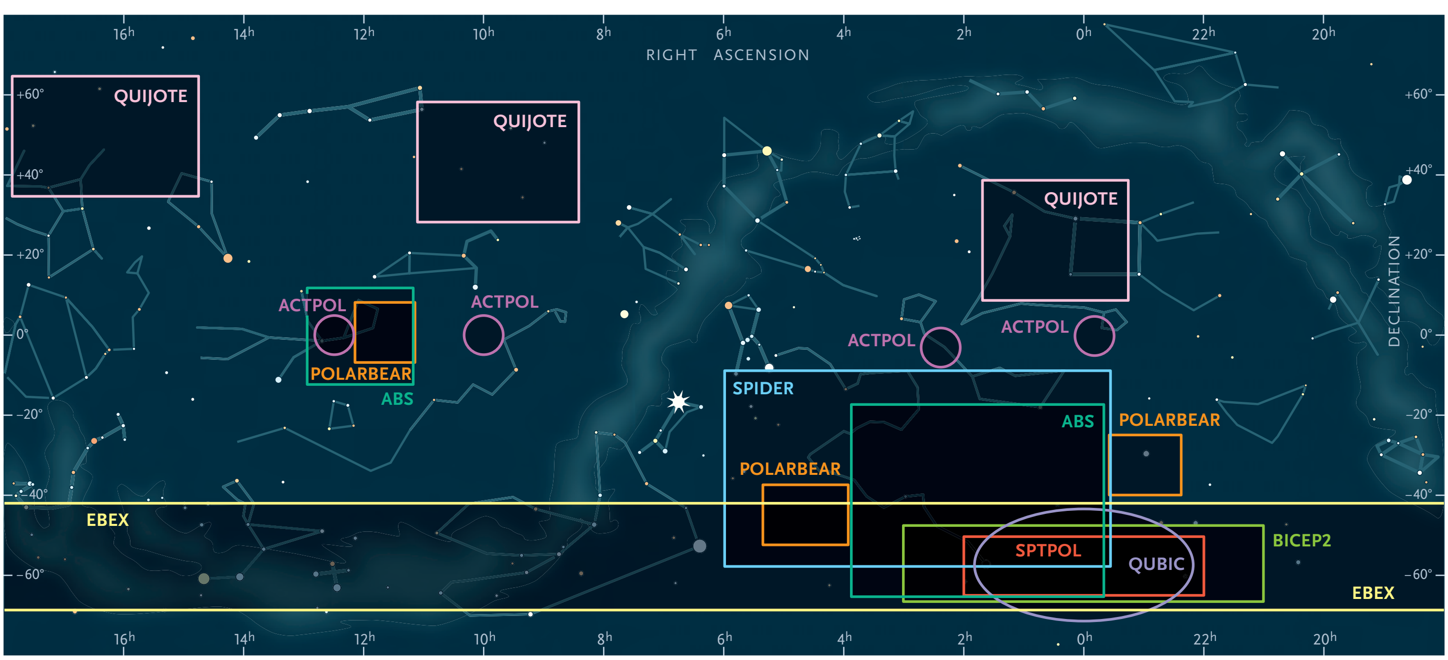
EBEX: E and B Experiment

SPIDER: Suborbital Polarimeter for Inflation

ESA Satellite Mission:

PLANCK

RACE TOWARD THE BIG BANG Several projects are currently hunting for the polarization signature of inflation. Shown below are the fields of view for active projects (except for Planck, which is all-sky). Fields are approximate and distorted by projection at high declinations.



S&T: GEGG DINDERMAN

Right now Polarbear only comprises the Huan Tran Telescope (HTT), an off-axis Gregorian Mizuguchi-Dragone design fabricated in Italy by VertexRSI, now part of General Dynamics. (Huan Tran, the telescope's principal architect, died in an accident in 2010 while on his way to the Polarbear site during its engineering run in the Inyo Mountains of California.) The off-axis HTT telescope has the advantage of having an unobstructed aperture, because it doesn't need the secondary support structures required for on-axis telescopes. HTT's antenna has a 2.5-meter primary mirror precision-machined from a single piece of aluminum and a lower-precision guard ring that extends the dish out to 3.5 meters.

Housed in a 2.1-meter receiver that is anchored below and forward of the primary is a focal plane of 1,274 antenna-coupled, polarization-sensitive bolometers that measure the angle of vibration of incoming light waves (see image at right). Put enough measurements together, and astronomers can determine how the CMB is polarized across that section of sky.

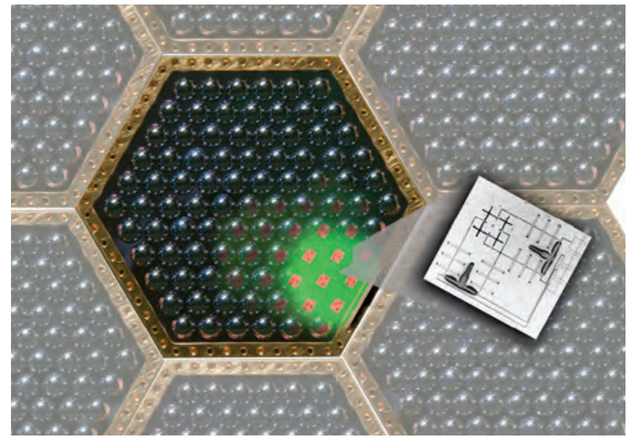
This year Polarbear will move to observing three 15° × 15° patches of the southern sky, carefully chosen to minimize the amount of foreground contamination, primarily by dust from the Milky Way. The telescope currently observes in a single spectral band centered at 148 GHz, but eventually three scopes will work together as the planned Simons Array to observe the sky at multiple frequencies. The second two telescopes will be identical to the first but with improved receivers containing more detectors. An updated receiver will eventually be installed on HTT, too.

The team is analyzing data from the first season's observing run in 2012 and expects to report results this fall. To prevent unsuspected biases from creeping in, the researchers are first working on a small portion of data and analyzing it completely — "*except for looking for the B-modes*," Keating says. "We do every possible test that you can do to ensure that the data have high quality, and we strive to avoid at all costs the spurious effects, the systematic effects." Only then will they look for B-modes.

Forward, Cautiously

Sitting in the high-altitude lab during a short break from work at the observatory site, Polarbear scientist Hans Paar (University of California, San Diego) says that, like other teams searching for the prized B-mode signal, his team is vigilant about not rushing toward a result.

"We are hemmed in between the desire to be right and the desire to be first," Paar says. "The desire to be first is not a scientific desire; it's a human desire. The desire to be right is a scientific desire. You don't want to mislead your community with something that's incorrect."


POLARBEAR TEAM

DETECTING POLARIZATION A single antenna can only pick up light polarized in one direction, so researchers need multiple antennas to detect all polarization angles. In Polarbear's tick-tack-toe arrangement, each antenna is sensitive to polarization perpendicular to the antenna slot, allowing the team to detect both horizontal and vertical polarizations. The bolometers (the T-shapes in the zoom image) act like receivers that convert incoming microwaves into signals. To detect polarization angles between horizontal and vertical, the team subtracts one from the other. Waves polarized at 45° thus disappear, so other antennas in the array are rotated 45° from the one shown to compensate.

And what if there are no B-modes to be found?

"I would say that if we don't find B-modes, it in no way suggests that inflation did not happen," Guth says. "It does mean, of course, that we are not getting the opportunity to see a new piece of evidence that would tell us that inflation did happen." If the current generation of experiments fails to detect B-modes, it could simply mean that the signal is far fainter than cosmologists expect, he says. But that could indicate that inflation occurred at a lower energy level. "So it would have an effect on inflationary theorizing, even if it's a negative result," he adds.

Nobel laureate John Mather (NASA/Goddard Space Flight Center), who worked on the Cosmic Background Explorer (COBE) satellite that revolutionized CMB science in the early 1990s, says the detection of B-modes would be "tremendously important" but that the signal's absence would also be progress.

"For an astronomer, a measurement is a measurement, so we would be thrilled to have a measurement," Mather says. "We don't have a textbook that says it's supposed to be one way or another. We're in the discovery mode here. So, I would be happy to know that it's there or that it's not there. Then we just go on and try to understand it." ✦

Learn more about these projects at skypub.com/CMBpolarization.

Bruce Lieberman *is a freelance science writer with nearly 25 years' experience in the news business. He has written about astronomy and other space-related subjects for* Air & Space, Scientific American, *and the Kavli Foundation.*