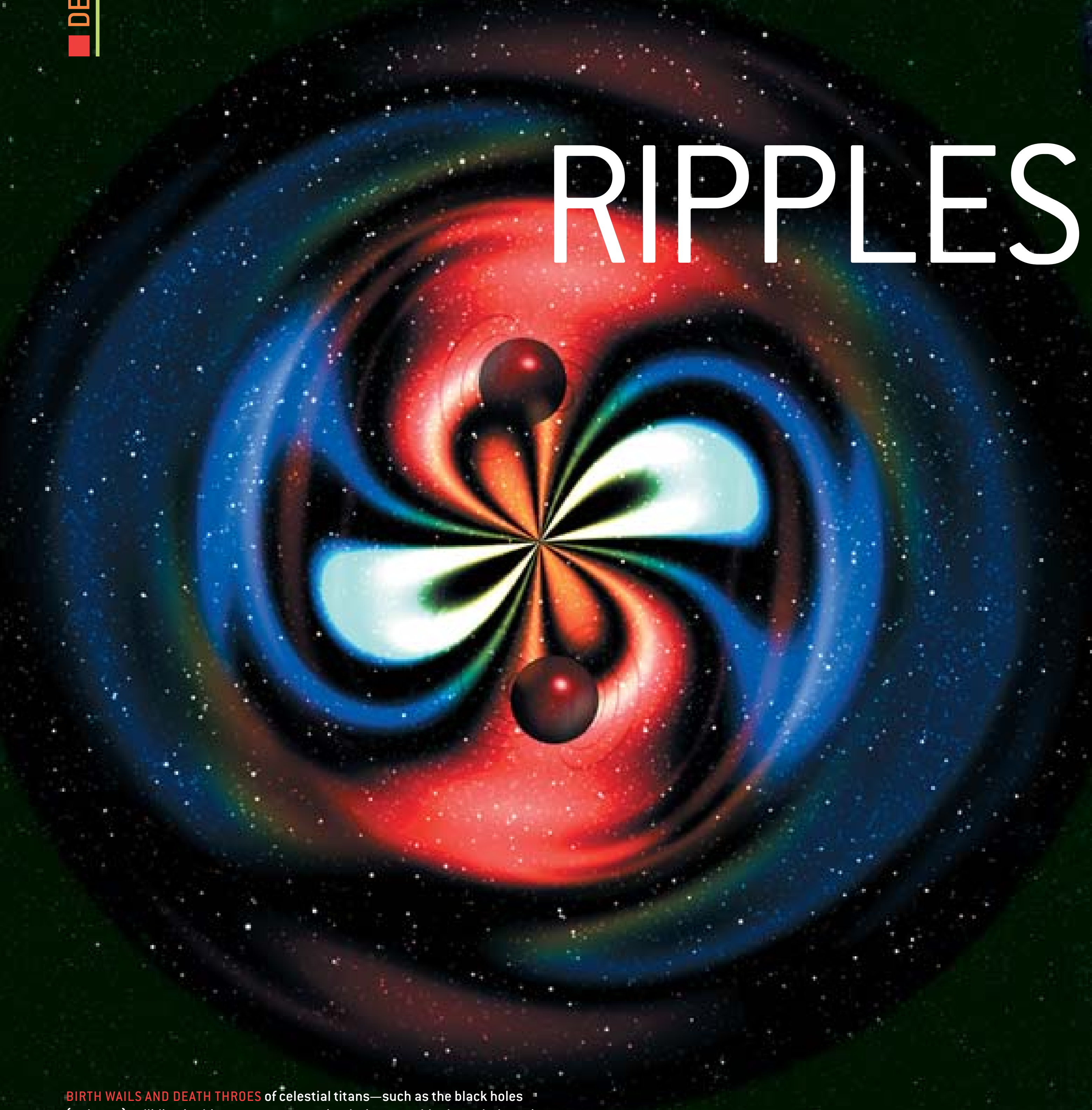
RIPPLES



BIRTH WAILS AND DEATH THROES of celestial titans—such as the black holes (*spheres*) colliding in this supercomputer simulation—rumble through the universe on waves of gravitational energy. This year new instruments of astonishing size and sensitivity are trying to tune in those signals for the first time.

IN SPACETIME

PHYSICISTS HAVE SPENT EIGHT YEARS AND $365 MILLION BUILDING A RADICALLY NEW KIND OF OBSERVATORY TO DETECT GRAVITATIONAL WAVES. BUT WILL IT WORK? A TRIAL RUN PUT IT TO THE TEST

BY W. WAYT GIBBS

HANFORD, WASH., AND LIVINGSTON, LA.—A chill January wind sends a shiver through Frederick J. Raab as he stands, binoculars to his eyes, on a mound near the center of the LIGO Hanford Observatory. He runs his gaze northward down a ruler-straight concrete tunnel to a building four kilometers to the north: there is one end of the observatory. Pivoting 90 degrees, Raab pans westward across the sagebrush-stubbled desert until he spots an identical tube and another building, also four kilometers distant. "When we talk about locking the laser beam" that shines inside those tubes, Raab says, "we mean holding the light waves steady to better than the width of an atom—over that distance."

Raab oversaw the construction of this giant try square, one of a pair that are the largest, most expensive and—if they fulfill the ambition of their designers—most sensitive detectors yet to join the 40-year hunt for gravitational waves. Part ruler, part clock, these two instruments are spacetime meters that will attempt to record how the continuum is rattled by the most violent cataclysms in the universe: detonating stars, colliding black holes, perhaps phenomena not yet imagined. As these ripples expand outward at the speed of light, they alternately stretch and squeeze space, causing the distance between free-floating objects to expand and contract. But by the time the vibrations reach the earth, theorists estimate, they are so unsubstantial that they alter distances by less than one part in a trillion billion.

DETECTING A QUIVER SO MINUSCULE IS LIKE NOTICING THAT SATURN HAS MOVED CLOSER TO THE SUN BY THE WIDTH OF A HYDROGEN ATOM.

For all the cutting-edge technology crammed into LIGO, it is not yet clear whether it can attain that incredible sensitivity. Reduced to such a tiny murmur, the mightiest cosmic events are easily overpowered by the gentlest mundane disturbance. "The tide deforms the earth's crust as well as the oceans," Raab tells me. It moves the buildings here by a third of a millimeter, 100 billion times the displacement a gravitational wave would cause. Every earthquake in the world over magnitude six, the rumble of every truck on nearby roads, the computer fans in the lab next door—all these things shake the ground by more than an atom's width. "Even engine noise from jets passing overhead can work its way in," Raab says.

Down in the control room, we watch as the instrument struggles to compensate for the thumps and bumps. Fourteen days into an 18-day test run that began on December 28, the noise is winning. Raab stares at a panel of graphs projected onto the far wall. A red line bounces up and down, charting the status of the main detector here as it is thrown out of whack, steadies itself and gets knocked out again a few minutes later. A blue line that represents a smaller quality-control detector has gone flat altogether.

During a teleconference, physicist H. Richard Gustafson troubleshoots glitches with his counterparts at the LIGO Livingston Observatory, which sits in the backwoods of Louisiana. Joining the conversation is the director of the GEO 600, a similar but smaller instrument near Hannover, Germany. "Here at Hanford we had an awful night," Gustafson says, recounting troubles with computer crashes and noisy electronics.

The instrument in Louisiana has been more predictable. During the night it runs smoothly, but at 6:30 A.M. its line on the control screen goes flat as morning traffic picks up on Interstate 12 a few miles from the observatory and as Weyerhaeuser loggers begin felling loblolly pines nearby. GEO, with its shorter, 600-meter arms and less demanding precision, has been a model of reliability, on duty more than 90 percent of the time. But scientists need all three instruments up and running, and over two weeks the best stretch of simultaneous operation lasted just over an hour and a half.

Szabolcs Márka, a 32-year-old Hungarian postdoc at LIGO Livingston, seems content with the progress so far on this test run, the fifth that he has managed and the last before the two instruments were to begin routine round-the-clock observations in May. "As usual we are in problem-solving mode," Márka says.

Labor Pains, Death Gasps

EVER SINCE THE FOUNDERS of the LIGO project—Kip S. Thorne and Ronald Drever of the California Institute of Technology and Rainer Weiss of the Massachusetts Institute of Technology—first proposed the Laser Interferometer Gravitational Wave Observatory in 1984, no one has doubted that only a Herculean feat of engineering would make it work. That is one reason that "the project faced tremendous opposition from astronomers," says Harry M. Collins, a sociologist at Cardiff University in Wales who has studied the field's halting expansion from a backwater of physics to Big Science.

"The National Science Foundation turned down our first two proposals," Thorne remembers. "And the third, submitted in 1989, went through five years of very extensive review." High-profile astronomers, notably Jeremiah P. Ostriker of Princeton University, objected to the steep price, which by 1993 had risen to $250 million. They feared that smaller and less risky projects would get elbowed out of the budget. A blue-ribbon panel set up to rank U.S. astronomers' priorities for the 1990s excluded LIGO from its wish list. "It was a unanimous decision," recalls John Bahcall, an astrophysicist at the Institute for Advanced Studies in Princeton, N.J., who chaired the committee. Congress passed on the LIGO proposal at first, not approving funding until 1994.

Thorne and other proponents of LIGO argued that gravitational signals could launch a whole new field of astronomy, because they carry information about the universe that scientists can gather in no other way. These ethereal ripples were predicted in 1918 by Albert Einstein, who saw them as an unavoid-

Overview/*Gravitational-Wave Detectors*

- Although astronomers have never detected gravitational waves directly, Einstein's theory of relativity predicts that violent cataclysms such as black hole collisions will cause the fabric of space itself to vibrate.
- By the time they reach the earth, these ripples are so faint that picking them out of the surrounding noise is comparable to noticing a single grain of sand added to all the beaches of Long Island, N.Y.
- Six ultraprecise interferometers have been built around the world to detect these signals. Three are in the U.S. and began scientific observations in May. But they are still struggling to reach the necessary sensitivity.

PRECEDING PAGES: WERNER BENGER AEI/ZIB [*visualization*]; NUMERICAL RELATIVITY GROUP AT AEI [*simulation/science*]; LBNL/NERSC [*computing facility*]; MAX PLANCK SOCIETY, EU ASTROPHYSICS NETWORK PROJECT, U.S. DEPARTMENT OF ENERGY [*support*]

CONTROL ROOM of the LIGO Livingston Observatory was home away from home for Caltech physicist Szabolcs Márka during the 18-day trial run, which he managed. Despite the challenges, the team was able to collect more than 70 hours of scientific data from all three U.S. interferometers at once.

MAX AGUILERA-HELLWEG

able consequence of his general theory of relativity. The attractive force we call gravity, Einstein famously postulated, occurs because massive bodies warp the four-dimensional fabric of the universe. If a dense object moves violently, space shudders in response.

When a giant star, for example, exhausts its fuel, it can detonate in a flash as luminous as 10 billion suns—a supernova. Astronomers believe that the star's outer layers are blown into space, while its iron core implodes with enough force to combine all its electrons and protons into neutrons and exotic particles. Within minutes, a solid metal sphere as big as the earth collapses into a neutron star less than 20 kilometers across. It is so dense that a teaspoonful of its surface would weigh nearly a billion tons. Scientists expect that a somewhat lopsided supernova would send out neutrinos and a burst of gravitational energy that would hit the earth several minutes before the flash arrived—time enough to alert conventional astronomers to train their telescopes on it. More important, details about the birth of the neutron star could be extracted from the gravitational signal even though the nascent object itself is tiny and swaddled in a blanket of fiery gas.

LIGO was designed to detect the death of neutron stars as well as their birth. Most stars orbit a mate, and occasionally both stars in a binary pair will go supernova yet remain locked in mutual thrall. With each revolution, the two neutron stars lose a little energy as they induce wrinkles in the surrounding fabric of space. Their orbit thus tightens step by step until they rip apart and merge, sometimes creating a black hole. Near the end of their frenetic tango, the massive bodies whirl around each other hundreds of times a second, flapping the bedsheets of spacetime around them. Radio pulses from such binary systems offer the most convincing, if indirect, evidence so far that gravitational waves actually exist.

But it is still anyone's guess whether the Caltech and M.I.T. groups that operate LIGO for the NSF will be able to detect such waves directly. "The curious thing about LIGO," Collins says, "is that, at least in its first instantiation, it cannot promise success."

Spectral Phenomena

THE PROBLEM IS NOT that gravitational waves are weak. "The energy in gravitational waves is amazingly huge," says Gabriela I. González, a physicist at Louisiana State University. During the final minute that neutron stars spiral to their death 65 million light-years from the earth, the gravitational pulse would be so energetic that "if it arrived in the

GLOBAL GRAVITY OBSERVATORY

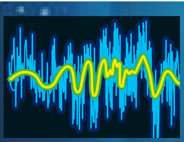
BY THE END OF 2003, six new gravitational-wave detectors should be online: one each near the cities of Livingston, La.; Hannover, Germany; Pisa, Italy; and Tokyo; and two at Hanford, Wash. Although they vary in size, sensitivity and details, all work in more or less the same way (*bottom right; see also box on page 94 for more details*). Because these ultrasensitive devices pick up so much terrestrial noise, scientists will use computers to scan the raw output (*below*) for predicted gravitational-wave patterns, such as the chirp, crash and ring emitted by two black holes in the seconds before and after they collide.

PINPOINTING THE SOURCE

As a gravitational pulse sweeps through the earth, the same waveform (*green*) will hit each detector at a slightly different time, allowing astronomers to pinpoint the source and eliminate other possible causes of the vibration.

LIGO

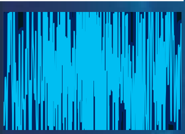
SPONSOR: U.S.
ARM LENGTH: 4 km at Livingston; 4 km and 2 km at Hanford
PEAK SENSITIVITY: Three parts in 10^{23} at 180 Hz
STATUS: Observations began in May 2002
COST: $530 million through 2007



MATCH WITH TEMPLATE, POSSIBLE MERGER

TAMA 300 (NOT SHOWN)

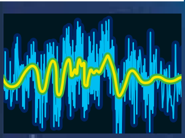
SPONSOR: Japan
ARM LENGTH: 300 m
PEAK SENSITIVITY: Five parts in 10^{21} from 700 to 1,000 Hz
STATUS: Preliminary observations began in 2001
COST: $10 million



OFFLINE BECAUSE OF EARTHQUAKE IN INDONESIA

GEO 600

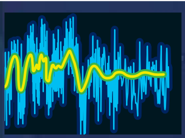
SPONSORS: U.K., Germany
ARM LENGTH: 600 m
PEAK SENSITIVITY: Eight parts in 10^{23} at 600 Hz
STATUS: Observations to begin in 2002
COST: $10 million



MATCH WITH TEMPLATE, POSSIBLE MERGER

VIRGO

SPONSORS: Italy, France
ARM LENGTH: 3 km
PEAK SENSITIVITY: One part in 10^{22} at 500 Hz
STATUS: Observations to begin in 2003
COST: $66 million

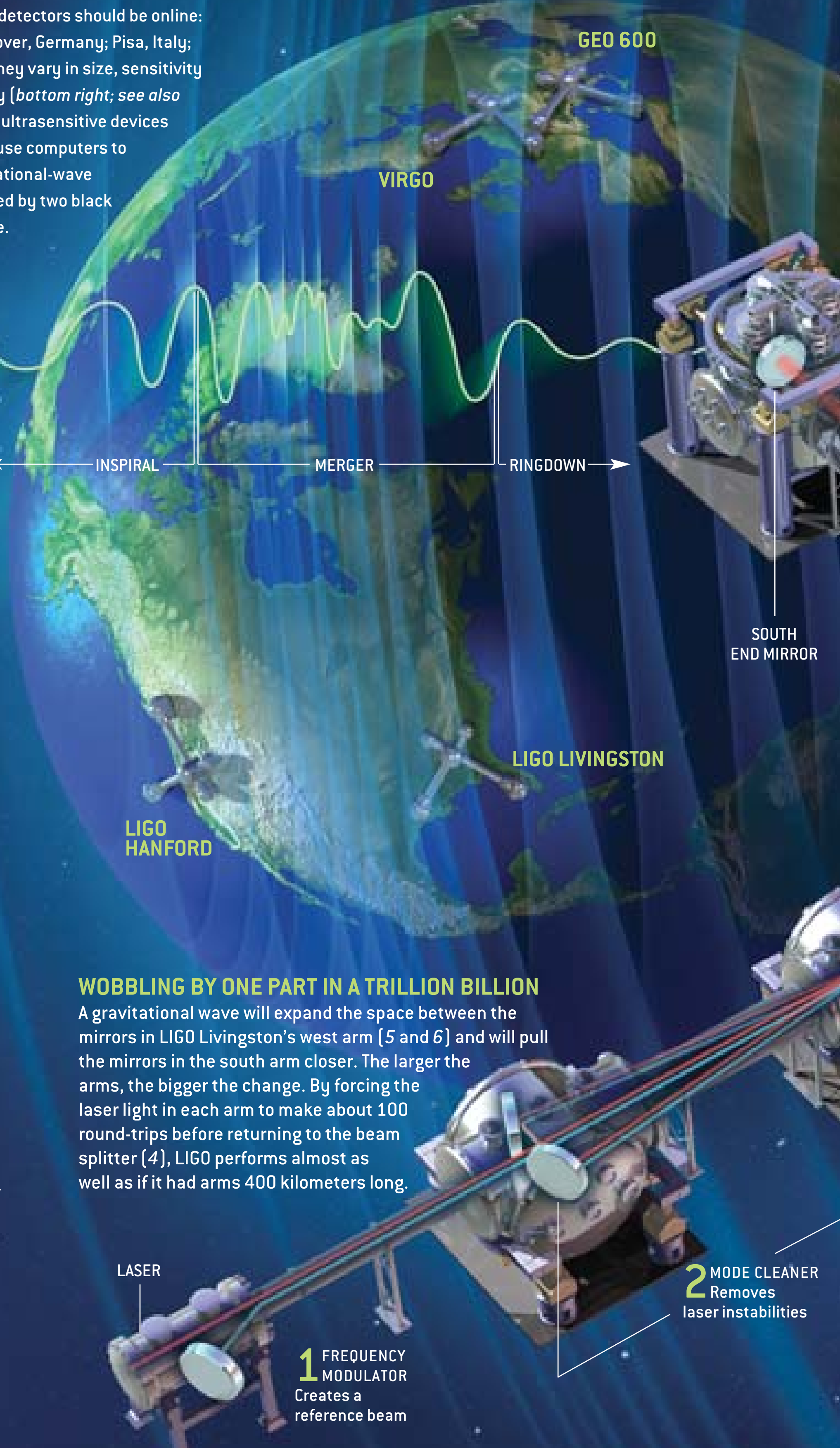


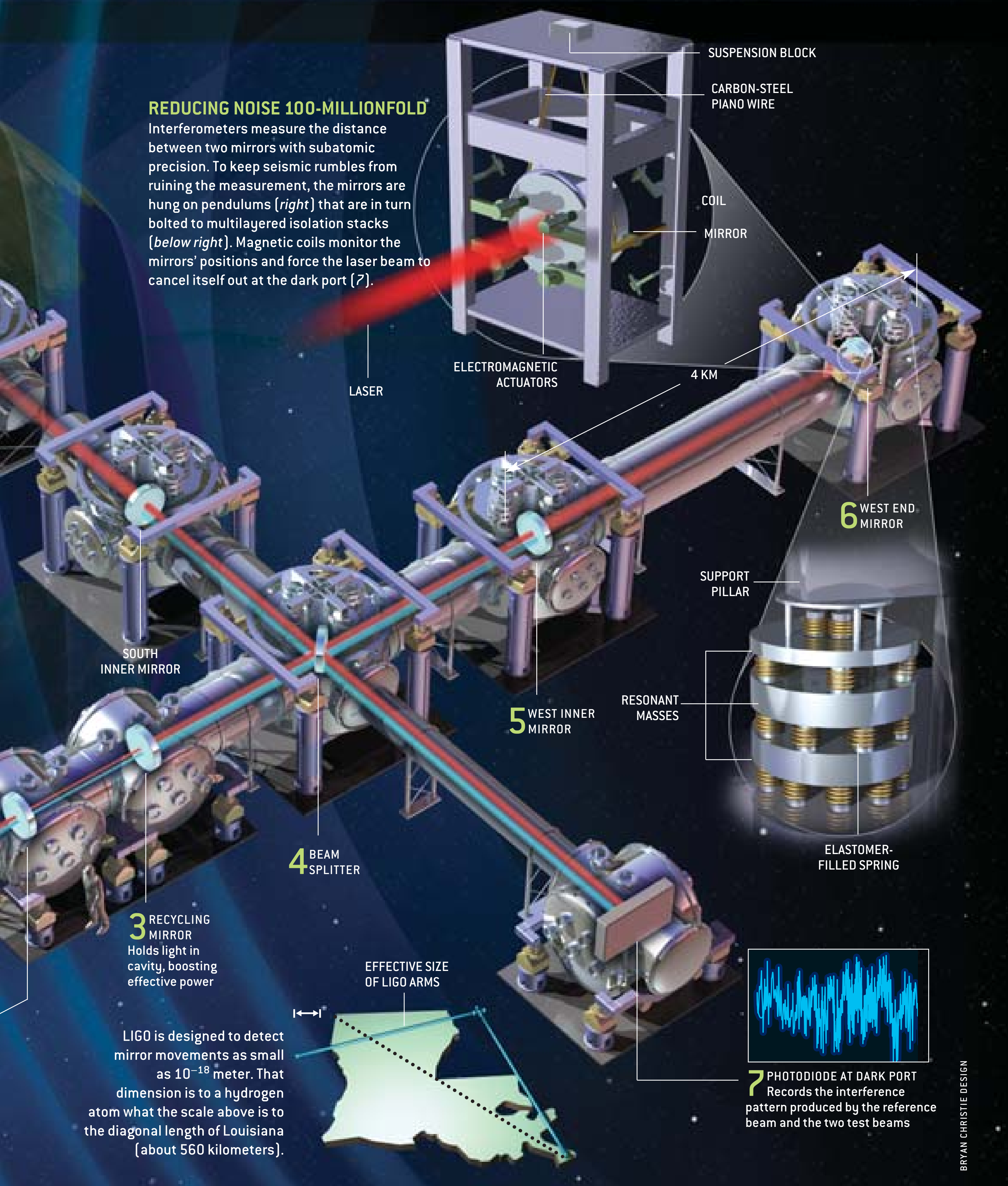
MATCH WITH TEMPLATE, POSSIBLE MERGER

"Peak sensitivity" refers to design goals not yet achieved

WOBBLING BY ONE PART IN A TRILLION BILLION

A gravitational wave will expand the space between the mirrors in LIGO Livingston's west arm (*5* and *6*) and will pull the mirrors in the south arm closer. The larger the arms, the bigger the change. By forcing the laser light in each arm to make about 100 round-trips before returning to the beam splitter (*4*), LIGO performs almost as well as if it had arms 400 kilometers long.





REDUCING NOISE 100-MILLIONFOLD

Interferometers measure the distance between two mirrors with subatomic precision. To keep seismic rumbles from ruining the measurement, the mirrors are hung on pendulums (*right*) that are in turn bolted to multilayered isolation stacks (*below right*). Magnetic coils monitor the mirrors' positions and force the laser beam to cancel itself out at the dark port (7).

3 RECYCLING MIRROR
Holds light in cavity, boosting effective power

7 PHOTODIODE AT DARK PORT
Records the interference pattern produced by the reference beam and the two test beams

LIGO is designed to detect mirror movements as small as 10^{-18} meter. That dimension is to a hydrogen atom what the scale above is to the diagonal length of Louisiana (about 560 kilometers).

BRYAN CHRISTIE DESIGN

form of visible light, it would be brighter than the full moon," González says.

But unlike light, which deposits all its energy when it splats against matter, gravity passes ghostlike through solid objects with only a tingle of interaction. To a gravitational wave, the earth and everything on it are almost perfectly transparent. So even the powerful signal from the merging neutron stars will wiggle the center point of each mirror by just a few attometers (10^{-18} meter), the sensitivity that LIGO was designed to achieve.

As one arm of the observatory swells, the other will shrink. The phase and the frequency of the laser light inside the arms will shift in opposite directions. When the beams from the two arms are superimposed on a reference beam, they will be out of tune, and the wavering beats they generate can be decoded by computers to reveal the changing curvature of spacetime inside the arms. In principle, the technique, known as interferometry, can measure changes in distance much smaller than the wavelength of the infrared laser light—indeed, much smaller than the nucleus of an atom [*see box below*].

Ambitious as LIGO's sensitivity goal is, it leaves astronomers unimpressed. Neutron couplets are relatively rare; their deaths are spectacular but quick. Within 65 million light-years, astronomers estimate, only one such merger occurs every 10,000 years. "So although it is possible that we would see these waves," Thorne says, "it is not highly probable." He thinks it more likely that LIGO would pick up black hole mergers, which are 100 times more powerful than the neutron star variety. But theorists are uncertain by a factor of 1,000 how frequently these events

A Photon's Journey through LIGO

TO UNDERSTAND HOW THE LIGO interferometer works, imagine the adventure of a photon as it passes through the instrument. (We will neglect some details for clarity.) The photon is created in a suitcase-size laser that is as powerful as 20,000 laser pointers. It is one of trillions of photons marching in lockstep in an infrared beam.

1 Part of the beam takes a detour into a device that converts the light into two reference beams, one of slightly higher frequency than the main beam and one of slightly lower frequency. This frequency modulator thus creates a benchmark against which the test beam can be compared at the end of its journey. After the detour, the beams recombine and pass through a quartz window and into the first vacuum chamber. The builders took every precaution to prevent our photon from scattering out of its intended path. Vacuum pumps hold the air pressure below one trillionth of an atmosphere. The mirrors, as wide as dinner plates and 10 centimeters thick, have been polished to an accuracy of better than 16 atoms. And the thickness of reflective films coating the optics varies by no more than two atoms.

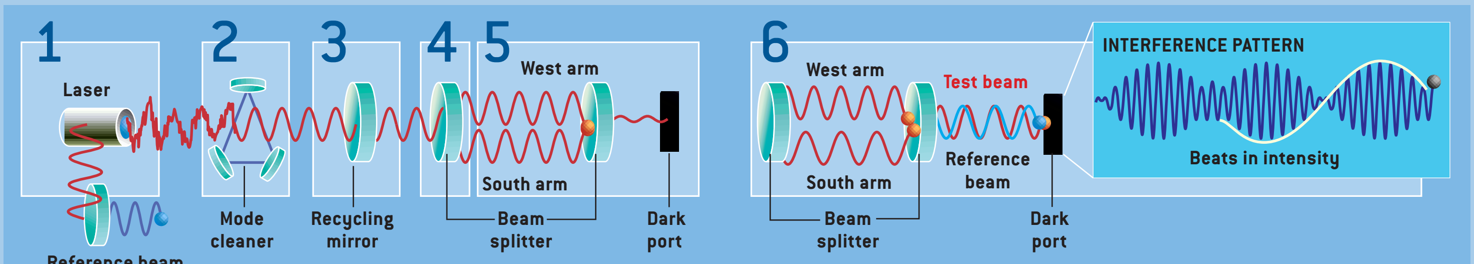
2 The photon enters a loop formed by three mirrors arranged in a narrow triangle. This mode cleaner is a quality checkpoint: the photon can move ahead only if its part of the beam has just the right shape and direction. Any light that is out of place or poorly aimed is tossed out a porthole.

3 The photon next zips through a half-silvered mirror, which blocks most photons that try to head back toward the laser. By trapping photons within the device, this mirror increases the power of the light beam 16-fold or more. Almost 100-fold additional amplification occurs in the instruments' long arms so that the beam inside those arms reaches the power of 20 million laser pointers.

4 At the beam splitter, the photon divides into identical twins. One stream of photons continues forward into the west arm. The other stream is inverted, its peaks flipped to valleys, as it is reflected into the south arm. The two test beams fly through the inner mirrors and into steel tubes four kilometers long. But the frequency-shifted reference beams are denied entry. They retrace their steps toward the beam splitter and circulate among the central optics until photons from the test beams return.

5 Meanwhile our photon and its inverted twin sail down the long arms to bounce off a mirror at each end. Although the atoms on the mirror surface are vibrating with heat, their motion is random and the beam hits trillions of atoms at once. On average the thermal vibrations nearly cancel out. The twin photons carom between the inner and end mirrors inside their respective arms. They make about 100 round-trips before leaking through the inner mirror and reuniting at the beam splitter, which sends them northward toward the dark port. Normally our photon and its alter ego will be at opposite points in their oscillation. Crest will meet trough, and the two will annihilate each other. The dark port will remain dark.

6 But if during the photons' journey, a gravitational wave slices through the apparatus, it will have curved space, lengthening one arm and shortening the other. Crest meets crest, and the dark port will light up. What's more, the reunited photons will combine with the frequency-modulated reference beams. Like musical notes played slightly out of tune, the light will beat, growing dimmer and brighter with the passage of the gravitational wave. Finally hitting a photodiode, the photon is converted into a perceptible electronic signal, the trace of a trembling spacetime. *—W.W.G.*



might occur within LIGO's range. There may be 10 a year or only one a century.

Going out to 300 million light-years would improve the odds, but then a typical event would change the relative length of LIGO's arms by only about one part in 10^{22}. Observers will have to wait for version 2.0 of LIGO to detect such a minuscule quiver, which is comparable to noticing that Saturn has moved closer to the sun by the width of a hydrogen atom.

MARK COLES, director of LIGO's Louisiana facility, is trying to deal with logging, traffic and other sources of noise that thwart his engineers' efforts. "It may be that in the first few years we won't be able to get all the way to full design sensitivity," he says. "But it's still a great project to work on."

The Unquiet Earth

AS IF THAT WERE not difficult enough, LIGO engineers must contend with the fact that mirrors wiggle for lots of reasons that have nothing to do with supernovae, neutron stars or black holes. Heat causes molecules in the mirrors and the wires on which they hang to jostle randomly. This thermal noise can drown out gravitational waves whose frequencies lie between 50 and 200 hertz. At higher frequencies, the interferometer is overwhelmed by the quantum effect called shot noise, which occurs because the number of photons hitting its sensors varies from one instant to the next. "You could turn the laser power up to boost the signal over the noise," explains Norna Robertson, one of the designers of the GEO instrument. "But if you put too much light in, it kicks the mirrors around in random ways."

At the moment, though, the biggest challenge for LIGO is at low frequencies, where the earth is constantly in motion. "At 100 hertz, the ground moves up and down by about 10^{-11} meter," Raab says. "We want to see motions of 10^{-19} meter" because that is a $10^{22\text{nd}}$ of the four-kilometer length of LIGO's arms. "So we need to reduce seismic noise 100-millionfold."

We put on goggles and shoe covers and head over to the high bay that contains the laser and most of the detector's sensors. As he opens the door to the cavernous room, Raab lowers his voice to just above a whisper. I try to tread gently.

Raab walks over to a steel vacuum chamber as big as an upended van. To get from the ground to the mirror inside, a seismic rumble must pass through a stack of devices designed to sap its energy: a one-meter slab of reinforced concrete, scissor jacks, air bearings, four layers of thick custom-made springs, four heavy steel plates (each resonating at a different frequency) and, finally, a pendulum of steel piano wire. "We reduce seismic noise by a factor of 100 in the pendulum suspension and by another factor of a million with the isolation stacks," Raab notes. Some ground movements, such as lunar tides, still must be fought with more active devices, such as computer-controlled electromagnets that push and pull on tiny magnets glued to the mirrors.

Yet sometimes dampening external noise 100-millionfold isn't enough. "Just recently there was a magnitude-seven earthquake in Sumatra; that knocked us offline," Raab says. Strong winds have pulled the Hanford interferometer out of lock as well.

Not all seismic noise is natural. Robert Schofield, a postdoc at the University of Oregon, has become the noise detective for LIGO. One evening he is sitting at a control station frowning at a chart of the latest signals picked up by the detector. "Look at this peak," he says. "Right here at 2.3 hertz. I hadn't noticed it before because it is so narrow, but it accounts for 20 percent of the noise getting into the interferometer." Scanning over readouts from a battery of seismometers that surround the observatory, he concludes that the noise is coming from near the 200 East section of the Hanford Nuclear

BRYAN CHRISTIE DESIGN (*opposite page*); MAX AGUILERA-HELLWEG (*above*)

Reservation, the 1,400-square-kilometer radioactive waste depository that surrounds the LIGO Hanford site.

Schofield marches down the hall, grabs a seismometer and an oscilloscope and hauls them into a van. He drives several miles farther into the reservation, then pulls over and sets up his equipment. We can see the bright lights of some night operation in 200 East several miles away. But we can't get any closer because the area contains tanks of plutonium-laced waste, and it is protected by security forces with submachine guns. Schofield sets the seismometer to listen for almost five minutes. But it reveals no trace of the 2.3-hertz noise. "I think it must be a large piece of rotating machinery doing some fiendish thing out there," he tells co-workers later.

Fortunately, noise near two hertz is not an immediate problem. LIGO, like the other giant gravitational-wave observatories nearing completion—GEO in Germany, TAMA in Tokyo and VIRGO near Pisa, Italy—is tuned to listen for gravitational waves from only 40 to about 3,000 hertz, coincidentally right in the range of human hearing. In the control room, LIGO operators have connected a speaker to sensors on the interferometer; it plays what the device "hears." A nearby supernova might come through as a burst of static. The wail of dying neutron stars would start low and sweep higher in an almost musical chirp.

Noise usually hisses and pops, but occasionally some recognizable sound leaks in. "There is a periscope on the laser table that raises the beam up to the right height," Schofield explains. Various noises can shake the periscope, introducing subtle Doppler shifts in the frequency of light passing through it. "If someone is talking near that periscope," he says, "you can hear their voice on that speaker."

So in addition to the seismographs, LIGO engineers have studded the facility with microphones and magnetometers, as well as sensors that monitor temperature, pressure and wind. A stream of data from about 5,000 sensor channels gets recorded simultaneously. The first thing that scientists would do if they thought they saw a gravitational wave is look for glitches or noise that had leaked into the system.

On the last day of the test run, González hands the director, Mark Coles, a plot of the interferometer output from that morning. It contains a bounce that

THEORISTS HAVE A VERY POOR TRACK RECORD FOR PREDICTING WHAT WE WILL SEE WHEN A NEW WINDOW IS OPENED ON THE UNIVERSE.

Next-Generation Detectors

IF LIGO ACHIEVES the sensitivity for which it was designed, it will still have only a middling chance of detecting gravitational waves. "But our strategy from the beginning has been to do this in two steps," says Caltech physicist Kip S. Thorne: first get the machines working and gain confidence in their reliability, then upgrade to advanced components that will virtually guarantee regular signal detections.

Although the project's leaders have not yet made a formal proposal, they know roughly what they want. "It'll cost on the order of $100 million, begin around 2006 and take about two years to complete," says LIGO director Barry Barish. The laser will be boosted from 10 to 180 watts. Instead of single loops of steel wire, the optics will hang on silica ribbons attached to a three-stage pendulum now being tested in the GEO 600 detector in Germany. And the 11-kilogram silica glass mirrors will be replaced with 30-kilogram sapphire crystals.

The changes will boost sensitivity by a factor of 20, Barish estimates. That will put the instrument, Thorne says, "into the domain where, for the first time in history, humans will be seeing human-size objects behaving quantum-mechanically." Researchers have devised so-called quantum nondemolition techniques that can make measurements twice as precise as normally allowed by the Heisenberg indeterminacy principle. If it all works, "it will increase by 8,000 times the volume of space we can search," Barish says.

The Japanese have also designed a successor to their TAMA 300-meter interferometer, although project manager Yoshihide Kozai says, "I am afraid it will be a few years before we obtain the funds" to start construction. The Large-Scale Cryogenic Gravitational Wave Telescope would have three-kilometer arms built deep underground in the Kamioka mine. Supercooled sapphire mirrors of 51 kilograms each would help it match the sensitivity of LIGO II at frequencies below 40 hertz.

NASA and the European Space Agency are designing an even more ambitious gravitational-wave observatory called LISA. A trio of laser-toting satellites to be launched in 2011 would form an interferometer with arms five million kilometers long—better than 10 times the distance from the earth to the moon. As they orbited the sun, the trio would hold their position relative to one another with one-micron precision. LISA would be no more sensitive than LIGO II, but it could sense gravitational waves of much lower frequency than any detector built on the quaking earth.

"The most likely thing LISA would see is the motion of extremely massive black holes—from a million to billions of times the mass of the sun—orbiting each other in the center of very distant galaxies," Thorne says. "The astronomers are all over themselves about LISA," reports M.I.T.'s Rainer Weiss. "They know for sure they will see events." But because its cost will probably exceed half a billion dollars, Weiss predicts that "it will be much tougher to get LISA through Congress even than it was to get LIGO approved." *—W.W.G.*

STRAIGHTER THAN THE SURFACE OF THE EARTH, **the concrete tunnel that houses the west arm of the LIGO Livingston Observatory rises more than a meter off the ground on its four-kilometer run as the planet curves beneath it. The tunnel houses an airtight steel pipe. Inside the pipe is a vacuum, and through the vacuum shines a beam of infrared light with the power of 20 million laser pointers.**

MAX AGUILERA-HELLWEG

looks like a real signal. It isn't. "We just invented a speedometer for the cattle guard on the entrance road," she says with a laugh. As each axle of a passing truck hits the horizontal rails, a rumble appears in the gravitational-wave channel.

Spurious signals can also be rejected by comparing data from two or more observatories, Márka explains. "If both LIGO sites see the same shape signal within a few milliseconds of each other and so does GEO, which sits on a different continental plate and is connected to a different electrical grid, then it is very, very unlikely to be a fake signal from some common source of noise."

Yet there is only so much they can do to overcome human-generated noise. The problem is especially bad at the Livingston site. "We can see the trains that go by three times a day," Coles says. "We can see the workers hauling trees. We can see when traffic picks up at lunchtime." During this test run, the Livingston instrument was online just 62 percent of the time, not including short blips. All three LIGO interferometers were up simultaneously for only 18 percent of the run.

"We know we have a problem with ground noise at Livingston," acknowledges Rainer Weiss, spokesperson for the LIGO Scientific Collaboration. "And it will get worse still. Society creeps in on us." Barry Barish, head of the project, says new active isolation stacks are being developed and will be installed next year. "I wish we didn't have to do it," Weiss says. "That was an engineering enhancement we had planned to add during the upgrade to LIGO II in 2006." The upgrade will add at least $750,000 to the $365 million that NSF has spent so far on the project and to the $165 million that it has just allotted for the next five years.

Yet even when the systems are locked and working, Weiss says, "we're still miles away—a factor of 1,000 away—from our design sensitivity. We're hoping to get at least 10 times better by June. But beyond that I don't know. There are many things we can try."

The uncertainty still troubles LIGO's old critic, Ostriker: "I have always believed that detecting gravitational waves will provide us insights obtainable in no other way. That said, I think that the LIGO program has been an egregious waste of funds—funds that could have been used for more productive science."

But Thorne sees things differently. "Theorists have a very poor track record for predicting what we will see when a new window is opened on the universe," he says. "Early radio telescopes discovered that the signals were much stronger than theorists expected. That happened again when the x-ray window opened in the 1960s. And when we started looking for neutrinos arriving from the sun, we were surprised by how few there were. In some sense, opening the gravitational window will give us a more radically different view on the universe than those previous advances did." Ripples in spacetime may shake up science yet.

W. Wayt Gibbs is senior writer.

MORE TO EXPLORE

LIGO's main Web site is **www.ligo.caltech.edu**

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