Physicists are preparing the first experiments with a real chance to spy the elusive gravitational ripples predicted by Einstein to fill space. But success may take many years—and come in unexpected guises

LIGO's Mission of Gravity

LIVINGSTON, LOUISIANA—The road from New Orleans to this small town in Livingston Parish crosses great expanses of water and swamps. Mist often engulfs the trees, and the air feels as turbid as the prose in a bad novel by Anne Rice. It seems an unlikely place to build an astrophysical observatory. Nonetheless, a bold new observatory has arisen here, and it promises to expose details of the most exotic events in the cosmos today.

This rural outpost will not collect visible light with giant mirrors or radio waves with vast dishes. Its quarry is another sort of signal entirely: gravitational waves, first predicted by Albert Einstein in 1916 as part of his general theory of relativity. If Einstein's equations are correct, then the gravitational chaos spawned by colliding black holes, exploding stars, and other cataclysms must rend and distort space itself. Imprints of those violent motions should spread through the universe like watery surges from a joyous plunge into a lake.

To catch those waves, physicists have constructed an elaborate apparatus here and a near-twin across the continent in Hanford, Washington, in which lasers gauge precise distances between mirrors that hang 4 kilometers apart. Together, the two facilities form a $365 million venture known as the Laser Interferometer Gravitational-Wave Observatory, or LIGO. Scientists and dignitaries marked the end of construction by inaugurating the facilities last November. Physicists have now started to send their first arrows of light down LIGO's dark tunnels in a commissioning and fine-tuning process that will take about 2 years.

If LIGO succeeds, it will conquer Einstein's own doubts that scientists would ever detect gravitational waves. The physical challenge is daunting. By the time a wave from a disturbance deep in the cosmos reaches Earth, it has grown exceedingly weak. It might stretch and squeeze the 4-kilometer space between a pair of LIGO's mirrors by less than 1/1000th the diameter of a single proton. Only now have technological advances and political wherewithal —courtesy of the National Science Foundation (NSF), which paid for the project— combined to make it feasible for physicists to search for such tiny ripples.

All involved with LIGO acknowledge that it may take years to identify the first gravitational waves, let alone do research with them. The project won't start its first scientific run until mid-2002, and the waves may elude detection until upgrades make the instruments more sensitive by 2007. But the wait should be worth it, says Massachusetts Institute of Technology physicist Rainer Weiss, one of the field's pioneers. LIGO and similar observatories around the world promise the sternest possible tests of general relativity, and they may open a new window on regions of the universe where extreme events are warping space and time on a grand scale. Says Weiss: "It would be the crowning achievement for this field to see physics from a place where gravity is pure Einstein."

Space antenna. Lasers will soon beam through 4-kilometer arms at LIGO's Louisiana site, which slices through a wooded floodplain in Livingston.

Eight jumbo jets

LIGO may be the most impressive effort so far to detect gravitational waves, but it's not the first. In the 1960s, physicist Joseph Weber of the University of Maryland built an aluminum bar that he hoped would quiver in response to a passing gravitational wave, much as a wine glass shatters at just the right high-pitched frequency. Several such "bar detectors" around the world today are tuned to signals from space. They include ALLEGRO, a 2300-kilogram bar at Louisiana State University in Baton Rouge, just down the road from LIGO. With further increases in sensitivity, ALLEGRO and other bars in Italy and Australia may help spot bursts of waves from explosive astrophysical events, such as supernovas or merging neutron stars. However, because of their fixed sizes and modes of vibration, the bars resemble radios that pick up just a few stations while the rest of the programs stream past.

Interferometers, on the other hand, can sense a broad range of gravitational-wave frequencies. These L-shaped devices use the wavelength of light as their measuring stick. In LIGO, a beam splitter at the corner of the L sends infrared laser light down the two identical tubes. The tubes, a bit more than a meter wide and 4 kilometers long, contain one of the largest vacuums on the planet: nearly 10,000 cubic meters, about the same as the volume within the cabins of eight Boeing 747 jets. The light bounces back and forth between two pairs of thick mirrors made of fused silica, specially coated to transmit a little light and reflect the rest. This optical trick effectively stretches the arms of the interferometer as the light bounces back and forth between the mirrors dozens of times. Enough light leaks through the mirrors during each round trip for the detectors to analyze.

When the light beams recombine, a photodetector gauges whether they have traveled the same distance. If so, the beams will produce a bright patch of light, because their waves are in phase and reinforce each other. If their path lengths differ by half a wavelength of light because one of the mirrors has shifted relative to the other, the waves cancel out exactly. That creates a dark "interference fringe," which gives the interferometer its name. (To minimize the photodetector's exposure to light, physicists actually arrange the light paths so that the beams produce a dark fringe when the mirrors aren't moving.)

CREDIT: LIGO LIVINGSTON OBSERVATORY

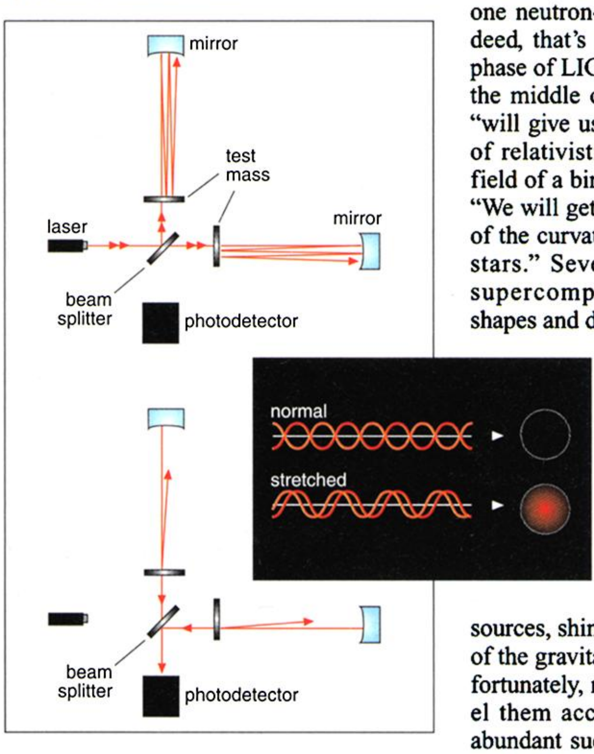
That's the idea in principle. In practice, however, the technical hurdles seem absurdly high. To catch a gravity wave, LIGO must be sensitive to phase shifts as small as a few 10-billionths of a single interference fringe. To accomplish that, physicists and optical engineers are resorting to wizardry never before attempted on such a large scale. "This would be the most powerful device on Earth to measure relative motions," says LIGO physicist Joe Kovalik. "To actually have this built and see a gravitational wave would be amazing."

The key, Kovalik says, is to beat down the noises that constantly threaten to blur the light beams into indecipherable smudges. Counterintuitively, the way to do that is not to bolt the mirrors onto a rock-solid platform but to let them hang freely—almost as if they were in low-Earth orbit, says LIGO physicist Anthony Rizzi: "We want no other forces acting on the test masses except gravity." That means isolating the mirror supports from the thumps of civilization and the whistling winds with a series of thick, fist-sized springs. To separate the mirrors from the rest of the equipment, the physicists dangle them from loops of fine wire that look like high-tech dental floss.

Other sources of noise are more devilish, such as random thermal motions within the mirrors and the surrounding equipment. Quantum mechanics makes life even more complicated by slightly altering the intensity of light—literally, the number of photons—measured within each fraction of a second. That "shot noise" makes it harder to trace the finest of the interference fringes.

Rainer Weiss was well aware of these issues in 1970 when he first broached the idea of using a huge interferometer to detect wiggles far smaller than an atomic nucleus. "People threw me out of the room," he recalls. "They were polite about it, but you could see the snickers on their faces." Weiss withstood the skepticism and enlisted some key physicists to refine his notions, notably theorist Kip Thorne of the California Institute of Technology—who became enamored of Joseph Weber's work as a Princeton graduate student in 1963—and experimentalist Ron Drever of the University of Glasgow, Scotland, who was lured to Caltech. Weiss, Thorne, and Drever managed the budding LIGO project as a troika through the mid-1980s. After much debate in the community, NSF sponsored LIGO as a joint Caltech-MIT initiative, with a 40-meter prototype built on the Caltech campus.

When it became evident in 1987 that NSF would back a full-scale LIGO, Caltech physicist Robbie Vogt took over as director. He shepherded the scientific development as political winds blew around a contentious site-selection process for the two interferometers. As the project grew and pressures mounted for a more accountable management style, internal squabbles arose, especially between Vogt and Drever. In 1994, Caltech and NSF replaced Vogt with Caltech physicist Barry Barish, fresh from his tenure as director of one of the two detector groups for the doomed Superconducting Super Collider (SSC). Barish brought in SSC physicist Gary Sanders as project manager, and many other SSC refugees joined the staff. "LIGO is one of the silver linings in the dark cloud of the demise of the Super Collider," says Sanders, now the project's deputy director. "We were able to attract some very talented individuals who are used to the rhythm of designing and constructing a project that takes years."



Turning gravity. Within LIGO's long arms, mirrors reflect laser light dozens of times (top). At each bounce, some light from each arm reaches a photodetector (bottom). Normally the returning beams cancel, creating no image (inset, top). But if a gravitational wave distorts the apparatus, interference fringes of light will appear (inset, bottom).

SOURCE: LIGO

The truth is out there

Whereas the SSC was designed to hunt for the Higgs boson, a pleasing theoretical construct with no experimental basis, LIGO will search for a theoretical wave with convincing—albeit indirect—experimental support. In 1974, physicists Russell Hulse and Joseph Taylor, both now at Princeton University, observed a binary system in our Milky Way consisting of two ultradense neutron stars. One of the stars was a pulsar; its steady blips allowed Hulse and Taylor to characterize the mutual orbits of the stars with great accuracy. They found that the two stars are slowly spiraling in toward each other, presumably as they lose energy to space in the form of gravitational radiation. The rate of that process matches that predicted by general relativity, an observation for which Hulse and Taylor won the 1993 Nobel Prize in physics.

The stars in the now-famous Hulse-Taylor binary will merge violently in about 240 million years. Astrophysicists estimate that there are about 100 such neutron-star binaries in our galaxy. If LIGO becomes sensitive enough to extend its reach to the nearest 1 million or 2 million galaxies, it might see gravitational ripples from about one neutron-star merger per year. And indeed, that's a primary goal of the second phase of LIGO after a series of upgrades in the middle of this decade. Such a merger "will give us high-precision measurements of relativistic effects in the gravitational field of a binary system," says Kip Thorne. "We will get an exquisitely detailed picture of the curvature of space-time between the stars." Several groups of theorists use supercomputer models to predict the shapes and durations of gravitational waves from such mergers, which will allow LIGO physicists to distinguish them from other events.

Binary systems involving two black holes should be even more promising for LIGO. Their greater masses and more intense gravity should make them powerful sources, shining like beacons above the rest of the gravitational fog in the universe. Unfortunately, no one yet knows how to model them accurately, nor is it known how abundant such binaries are. A paper in the 1 January issue of *Astrophysical Journal Letters* by theorists Simon Portegies Zwart of Boston University and Stephen McMillan of Drexel University in Philadelphia suggested that interactions within globular clusters—old, dense knots of stars that swarm around most galaxies—may create black-hole binaries by the bushel. But most LIGO physicists regard such calculations as interesting guidance rather than gospel. "It gives us some hope, but far from a guarantee, that LIGO [in its first phase] will see gravitational waves from the mergers of these black holes," says Thorne.

A disruption of the cosmos stemming from a single object may trigger LIGO as well. However, any such event must have a high degree of lopsidedness; according to the equations of relativity, symmetric explosions or smoothly rotating spherical objects do not emit gravitational waves. Some astrophysicists think that supernova blasts are inherently asymmetric, perhaps enough to rattle LIGO or even the bar detectors with short bursts. Another possible source, championed by physicist Lars Bildsten of the University of California, Santa Barbara, is a rapidly rotating, slightly lumpy neutron star that rips gas from a companion star like our sun. The accretion of the gas should make the neutron star spin faster and faster. Astrophysical surveys show an unusual clustering of "x-ray binary" pulsars that spin between 300 and 500 times per second, but no faster—even though the theoretical limit is 2000 times per second, at which point they would fly apart. "There is a wall beyond which it is difficult to spin up the star because it sheds angular momentum by emitting gravitational radiation," Bildsten claims. LIGO might be able to detect such gravity waves as periodic, ongoing signals from about 10 such binaries in our galaxy, he says.

Perhaps most intriguing of all, the big bang may have stamped the universe with a gravitational-wave background similar to the cosmic microwave glow that pervades space. Theories vary wildly on how accessible this "stochastic background" will be to LIGO and its successors, and it may prove too faint to perceive. If physicists do manage to detect this background and decipher its signatures, Thorne says, they may glimpse the primordial era when all four of nature's fundamental forces acted as a single force—a "quantum gravity" unification that was severed less than a trillion-trillion-trillionth of a second after the big bang.

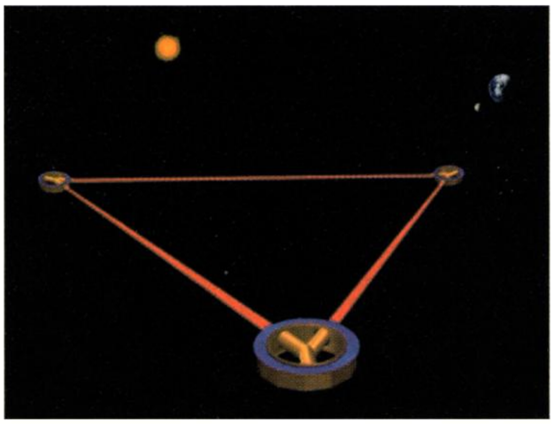
It is even possible that a new theory of gravity lies beyond general relativity, waiting for hints from LIGO to expose it. For example, Einstein predicted that gravitational waves are polarized, like sunlight reflecting off a lake. If LIGO should encounter such polarized waves, one arm of the interferometer will expand while the other shrinks. But alternate theories of gravity, such as so-called scalar-tensor theories, put forth a different possibility: a "breathing" mode in which both arms expand and contract at the same time. Such theories also maintain that the graviton—the hypothesized force-carrying particle of gravity—has a dash of mass. If so, it would travel through space at slightly less than the speed of light. Physicists may be able to use LIGO and its descendants to check the speed of gravitational waves by correlating their arrival with visible signs of a cataclysm in deep space, such as a gamma ray burst.

If some new gravitational theory should arise, it might contain general relativity as a special case, just as Einstein's theory circumscribes Newton's laws. "There is a potential for LIGO to find something new that would modify general relativity in very strong gravitational fields," says physicist Clifford Will of Washington University in St. Louis. "Many of us in our heart of hearts believe that it won't, but even a null result is an important advance. Zero is as good a number as any other number."

LIGO's Laser-Packing Big Sister LISA May Hunt Black Holes From Space

Within 10 years, three satellites may orbit far from Earth in a precise triangular formation, aiming lasers at each other. That may sound like the Strategic Defense Initiative run amok, but in fact it's the next possible step in the search for gravitational waves. Its proponents call it LISA: the Laser Interferometer Space Antenna, a $500 million gleam in the eyes of astrophysicists in the United States and Europe.

Researchers envision LISA as a big sister to the Laser Interferometer Gravitational-Wave Observatory (LIGO) and other gravitational-wave detectors being built on the ground (see main text). But LISA is to LIGO as a radio telescope is to an optical telescope: It would "see" a completely different part of the gravitational spectrum. Each of LISA's three arms would stretch 5 million kilometers, making it sensitive to gravitational waves that span vast distances in space. Such waves might flow for months from binary systems of dense objects, such as a pair of supermassive black holes nearing a titanic merger at the heart of distant galaxies in collision.



Outsize interferometer. LISA spacecraft may watch for gravitational waves distorting a 5-million-kilometer laser triangle.

Indeed, black holes in all their dark variety would be the primary targets of LISA, says astrophysicist Peter Bender of the University of Colorado, Boulder. "The origin of massive black holes is an open question," Bender says. "We don't know whether they form from the collisional growth of seed black holes or the sudden collapse of gas clouds." With the obvious difficulty of peering optically into such environments—especially halfway across the universe—LISA may offer the best chance to resolve that question.

LISA would consist of three identical spacecraft with Y-shaped cores, each aiming its optical assemblies at the other two. Small telescopes would collect the laser light after its 16-second trek across space. The "test masses" determining the positions of the spacecraft would not be mirrors, but metal cubes just 4 centimeters across. Each cube would free-float in space, surrounded by but not touching the rest of the spacecraft. LISA's designers will strive to gauge the relative positions of the cubes to within two-tenths of an angstrom—tiny, to be sure, but about a million times bigger than LIGO's goal of 1/1000th the diameter of a proton.

The project would be a joint endeavor between NASA and the European Space Agency, with the European efforts led by physicist Karstan Danzmann of the University of Hannover in Germany. Although LISA is not yet officially on the drawing board, the team hopes to fly a test mission within a few years and to launch the full-scale array by 2010.

If it works as advertised, LISA should see plenty of sources of long-period gravitational waves. For instance, binary systems of white dwarfs in our own galaxy would create a persistent buzz of gravitational noise. Above a certain frequency, physicists should be able to resolve the signals from thousands of such binaries in the Milky Way, as well as distinct hums from the interactions of massive black holes throughout the universe. Beyond that, any number of new sources could flood LISA's airwaves.

A few scientists even worry that there may be an embarrassment of riches. "I'm concerned that we're going to fly this thing, and there will be so much going on that we will have to work very hard indeed to have a clue what we're looking at," says astronomer Douglas Richstone of the University of Michigan, Ann Arbor. To wave-starved LIGO physicists, that potential data analysis nightmare sounds like a sweet dream. **–R.I.**

CREDIT: LISA/JPL/NASA

Be careful what you say

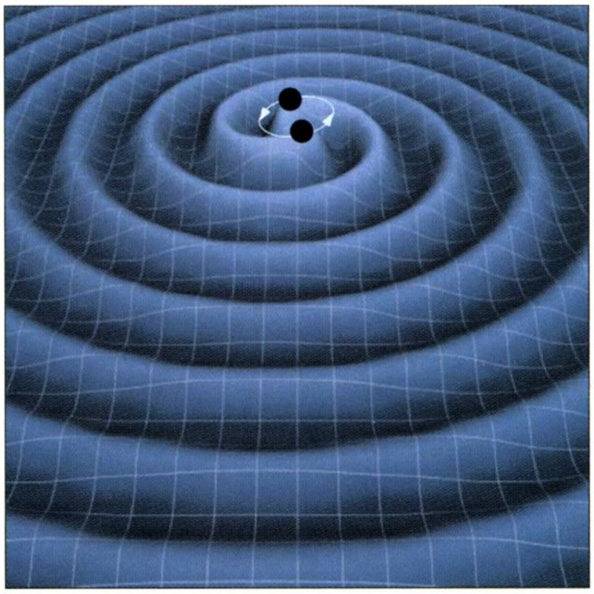
If LIGO physicists do detect a gravitational wave, they will tread carefully before shouting "Eureka!" Everyone wants to avoid repeating what happened in 1969, when Joseph Weber claimed that a passing wave had set his aluminum bar ringing. That claim fell apart under close scrutiny, casting a shadow over the nascent interferometry plans as well. "The whole field was considered very risky," MIT's Weiss recalls.

The LIGO team will safeguard against false detections in several ways. First, "real" signals must appear in both interferometers within 10 milliseconds of each other. That's the travel time of a gravitational wave across the 3030-kilometer distance between Livingston and Hanford. If the delay is longer, it means the blips probably came from local noise rather than from a source in the sky. The shape and amplitude of the wave should be nearly the same in each detector as well. "If it isn't seen in both detectors, it's just not viable," Weiss emphasizes.

As an additional check, the Hanford observatory has a separate interferometer housed in the same tunnel, but with arms that span 2 kilometers rather than four. Real waves should trigger the half-size detector at Hanford, but with half the amplitude of the signal in the full-size interferometer. And ideally, other detectors around the world will observe a wave passing through Earth at the same time. The leading candidate is VIRGO, an Italian-French interferometer under construction near Pisa, Italy. At 3 kilometers, VIRGO's beam tubes are shorter than LIGO's, but its more advanced design for seismic isolation may compensate for that. A German and British team is using daring optical technology to build GEO, an interferometer near Hannover, Germany. However, GEO's size—600-meter arms, less than one-sixth of LIGO's scale—is a significant handicap. A Japanese group has built a 300-meter interferometer called TAMA near Tokyo and plans to scale it up in a few years, while physicists in Australia are pondering plans for a LIGO-sized interferometer later in the decade.

Detection of a short gravitational-wave pulse in three or more detectors worldwide would let researchers triangulate back to its point of origin on the sky. Otherwise, LIGO physicists would need a stroke of luck—simultaneous observation of a gamma ray burst, for instance—to trace the source. If the gravitational waves are periodic and long-lasting, physicists could pinpoint their origin with a single detector by observing how the signals vary as Earth revolves around the sun.

Collaboration among the international teams is collegial—up to a point. "We're still in an era where we are talking about cooperating, but we are competing," says LIGO director Barish. "Everyone wants to be first." LIGO physicists and the other teams recently took a big step toward eventual teamwork by agreeing to record all data in the same format. "That's never been done in high-energy physics," Barish notes. In addition, GEO scientists will design a delicate optics suspension system for the next phase of LIGO, known simply as LIGO 2. For a future orbiting version of LIGO on a grand scale, called LISA (see sidebar), international collaboration has been built in since the first proposals.



Death spiral. Two black holes in the final moments before merging will churn the fabric of space-time with intense gravitational ripples.

CREDIT: K. THORNE/CALTECH AND T. CARNAHAN/NASA (GSFC)

Still in the daytime

The upgrade of LIGO, scheduled to begin in 2005, is critical to the project's success. The chances of detecting a bona fide gravitational wave between 2002 and 2004—the two planned years of full-time operation for LIGO 1—might be "slightly better than 50–50," says Syracuse University physicist Peter Saulson. (Over a lunch of Louisiana seafood, Saulson's colleagues chided him for being overoptimistic.) With the proper improvements to key systems, he says, "the odds for LIGO 2 become darn good." Even with that rosier future scenario, NSF and LIGO physicists opted to go with tried-and-true technology for LIGO 1 to demonstrate that the concept will work.

NSF has budgeted $6 million per year for research and development toward new systems for LIGO 2. For instance, a more powerful laser will pump more photons of light between the mirrors. That will reduce the uncertainty in counting the photons, leading to better measurements of any slight differences in length between the two arms. Better cushioning will shield the laser and mirrors even more carefully from environmental noise. The improved system may include active cancellation of small seismic motions, just as modern astronomical telescopes cancel the blurring of Earth's atmosphere with small flexible mirrors. In the GEO-designed suspension, each mirror will hang within a nested set of three or four pendulums, isolating them far from any moving parts.

The mirrors themselves also will change. Crystals of nearly pure sapphire will replace the fused silica now being used, giving each mirror much more heft and making it less prone to internal vibrations. Sapphire also conducts heat more efficiently than silica, so it can handle the more powerful laser planned for LIGO 2.

Even incremental improvements will make a big difference, Barish observes. For instance, he estimates that replacing the fused silica mirrors with sapphire ones will double the interferometer's sensitivity to gravitational waves. By extending LIGO's reach twice as far into space, the new mirrors will let the instrument probe eight times as much volume—and detect eight times as many sources. Barish believes that all of the planned improvements will make LIGO 2 about 15 times more sensitive than its predecessor. That would increase the volume of the universe accessible to LIGO by a startling factor of about 3000. Depending on funding, Barish envisions a LIGO 3 sometime after 2010 using even bolder technology—such as mirrors cooled to within a whisper of absolute zero for maximum stillness.

In other words, the gravitational window on the universe has barely begun to open. Only the strongest signals will penetrate the initial crack in the window, and LIGO physicists are restless with uncertainty about when those signals will first appear. "The history of astronomy is that each increase in telescope sensitivity has led to a fundamental leap in our knowledge about the universe," says Saulson. "Where we differ with gravitational waves is that we're still in the daytime. No one will tell us how dark we have to make our sky to begin to see the stars."

–ROBERT IRION

Robert Irion is co-author of *One Universe: At Home in the Cosmos* (Joseph Henry Press).