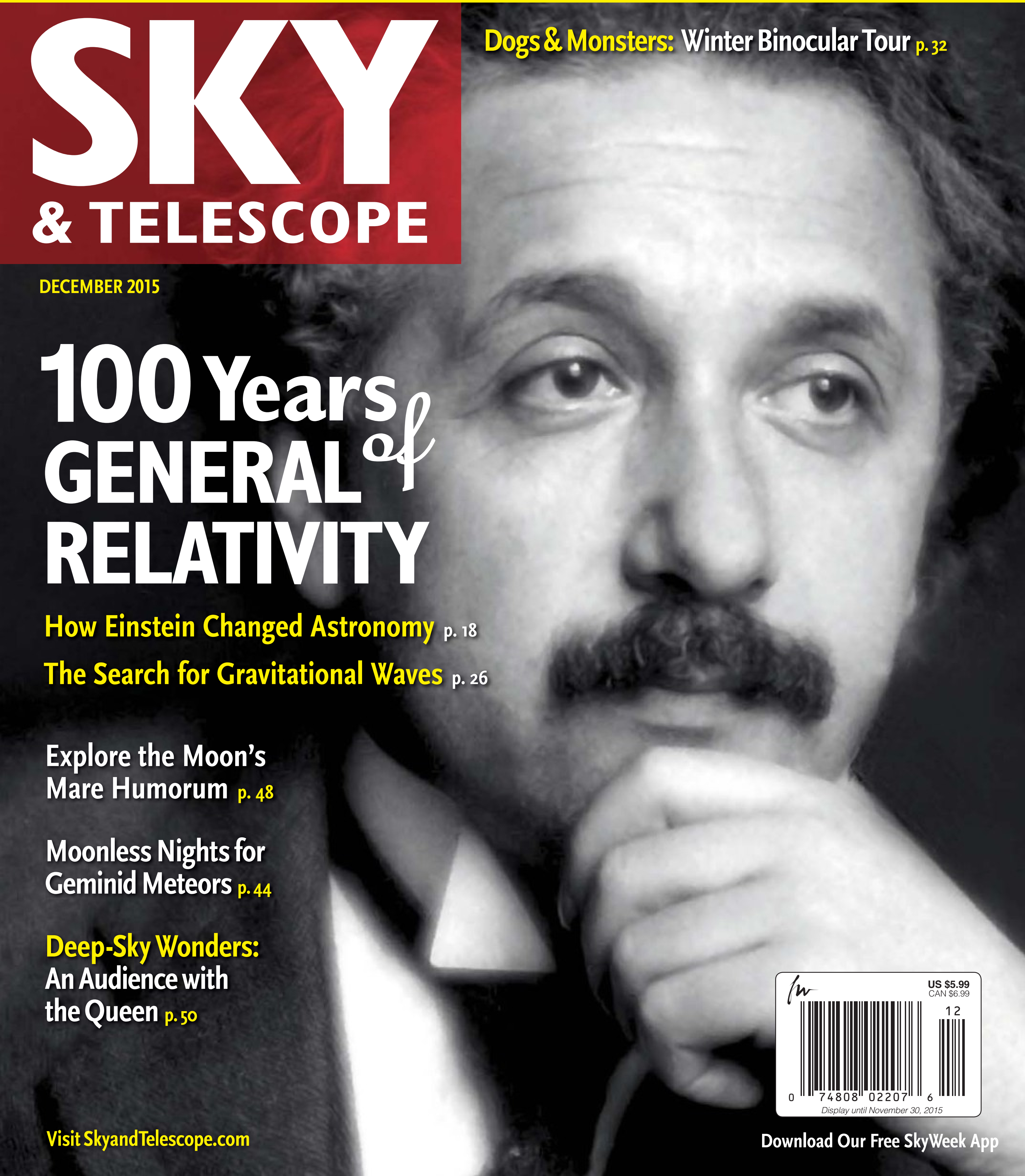
Book Review: ENCYCLOPEDIC DEEP-SKY HANDBOOK p. 65

Test Report: 3 GREAT $200 TELESCOPES p. 54

Daytime Challenge: MOON OCCULTS VENUS p. 46

THE ESSENTIAL GUIDE TO ASTRONOMY

SKY & TELESCOPE



Dogs & Monsters: Winter Binocular Tour p. 32

DECEMBER 2015

100 Years of GENERAL RELATIVITY

How Einstein Changed Astronomy p. 18

The Search for Gravitational Waves p. 26

Explore the Moon's Mare Humorum p. 48

Moonless Nights for Geminid Meteors p. 44

Deep-Sky Wonders: An Audience with the Queen p. 50

US $5.99
CAN $6.99
Display until November 30, 2015

Visit SkyandTelescope.com

Download Our Free SkyWeek App

100 YEARS OF GENERAL RELATIVITY:

Gravitational Waves

Gravitational Waves Hit Prime Time

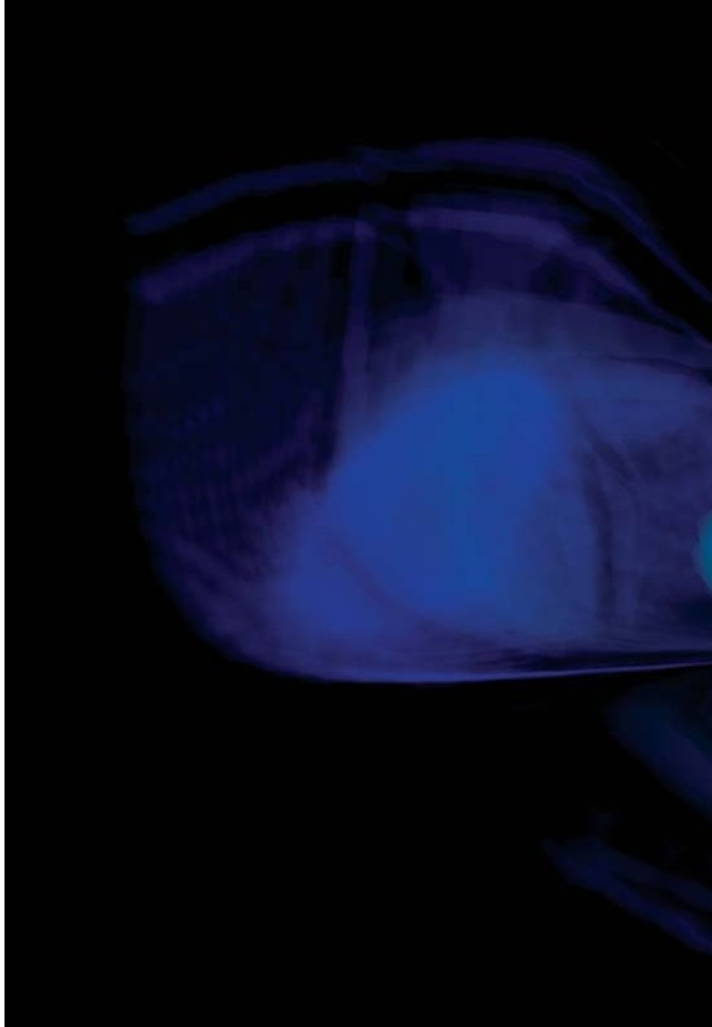
A century after Einstein predicted the existence of weak ripples in spacetime, scientists say they're on the verge of directly detecting these gravitational waves, thereby opening a revolutionary new window on the universe.

GOVERT SCHILLING

Just over 70 years ago, a plutonium reactor at the Department of Energy's Hanford Site, north of Richland, Washington, produced the nuclear fuel for the atomic bomb that exploded over the Japanese city of Nagasaki. Now, the desolate area is home to a very different kind of physics project. Here, one of the most sensitive scientific instruments ever built is poised to detect elusive spacetime ripples from the distant universe.

Researchers have recently outfitted the Laser Interferometer Gravitational-wave Observatory (LIGO) at Hanford with new powerful lasers, ultra-stable mirrors, and superfast computers for data analysis to dig out the waves' weak signal. "People will be very surprised if nothing is found," says observatory head Frederick Raab.

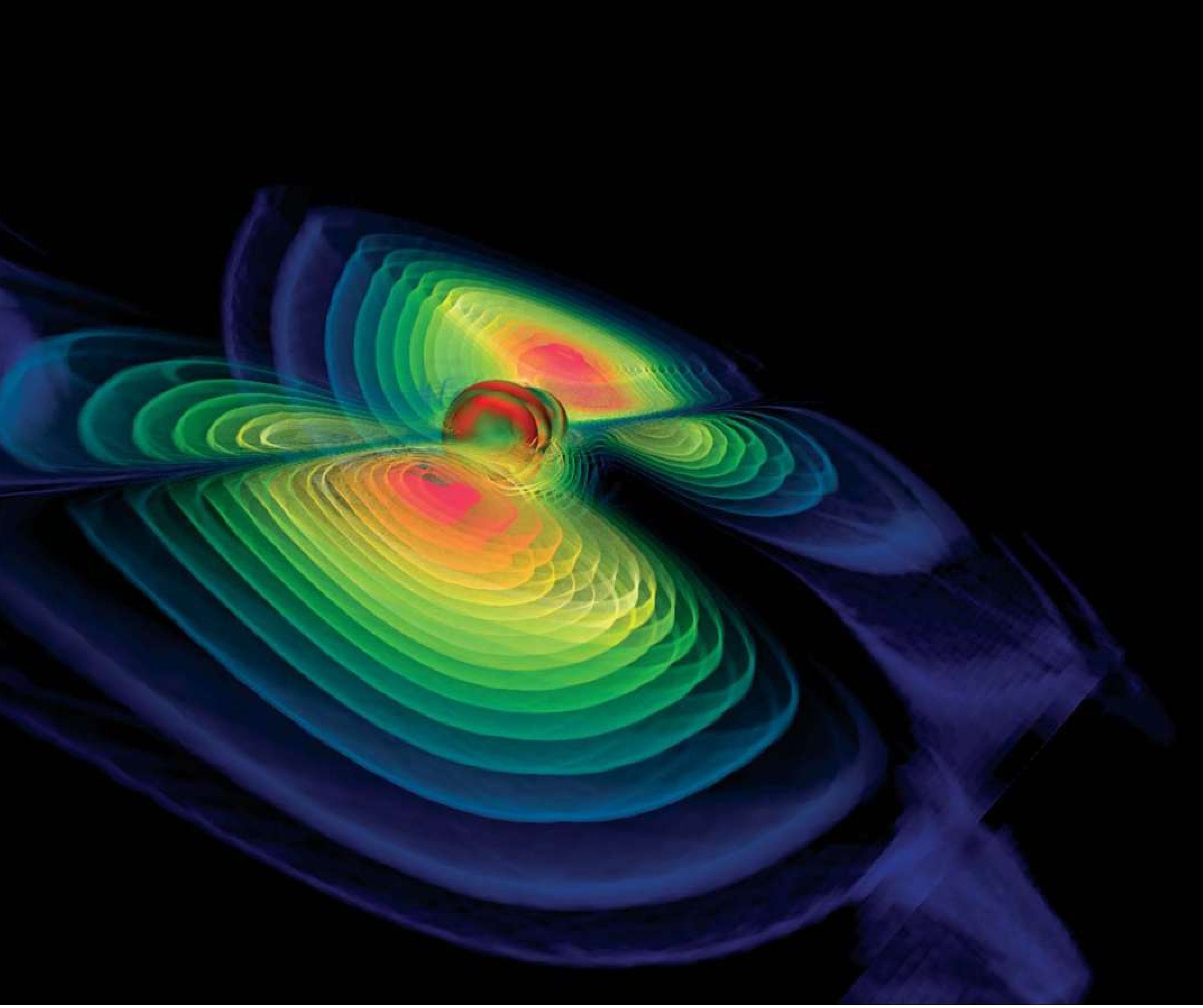
Other scientists are equally optimistic. At the 11th Edoardo Amaldi Conference on Gravitational Waves, held earlier this year in Gwangju, South Korea, there was a general consensus among attendees that we can expect the first direct detection of the elusive ripples any time now. "Listening" to these telltale cosmic waves will provide a completely new way of studying the universe, says Bernard Schutz, one of the founding directors of the Max Planck Institute for Gravitational Physics in Germany. "You can learn much more about a jungle by not just looking around, but also listening to all the sounds," he says. "Our universe is a jungle filled with mysterious creatures, and within one or two years I believe we will begin to listen to these wild animals."



WHEN BLACK HOLES MERGE This simulation shows the moment right after the merger of two black holes, when a common event horizon has just formed. The spheres in the center represent the event horizon, and the colors indicate the spacetime curvature on the horizon. The merger creates a burst of gravitational radiation, shown as cutaway surfaces, which travel out into space at the speed of light. In this simulation, one black hole was 1.5 times more massive than the other.

The LIGO Hanford Observatory is not alone in its quest. In Livingston, Louisiana, lies an identical observatory that has also been completely refurbished over the past few years. The two sites need to work together to make a reliable detection; the first joint run occurred this fall. Next year, the two LIGO detectors will join forces with the European Virgo interferometer near Pisa, Italy. A smaller instrument, called Geo600, is located near Hannover, Germany. Not to be outdone, Japan is constructing a huge underground facility to search for gravitational waves, and India has plans, too.

Meanwhile, radio astronomers all over the world are teaming up to use remote pulsars — the most stable clocks in nature — as measurement tools to look for longer, slower gravitational waves than the ones these instruments will (hopefully) sense.



MAX PLANCK INST. FOR GRAVITATIONAL PHYSICS (ALBERT EINSTEIN INST.) / ZUSE INST. BERLIN / CTR FOR COMPUTATION & TECHNOLOGY AT LOUISIANA STATE UNIV.

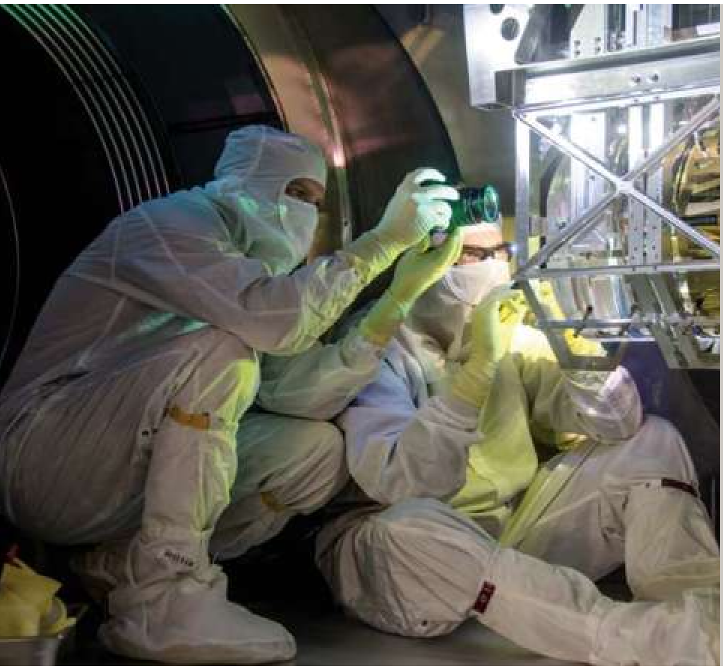
And although the first direct detection of a gravitational wave has not yet been bagged, engineers are already eyeing the future of the field. As you read this, the European LISA Pathfinder spacecraft sits atop a Vega rocket, awaiting its launch from Kourou, French Guiana. LISA Pathfinder is a technology testbed mission for eLISA, the first gravitational-wave observatory in space, planned for 2034.

Making Waves

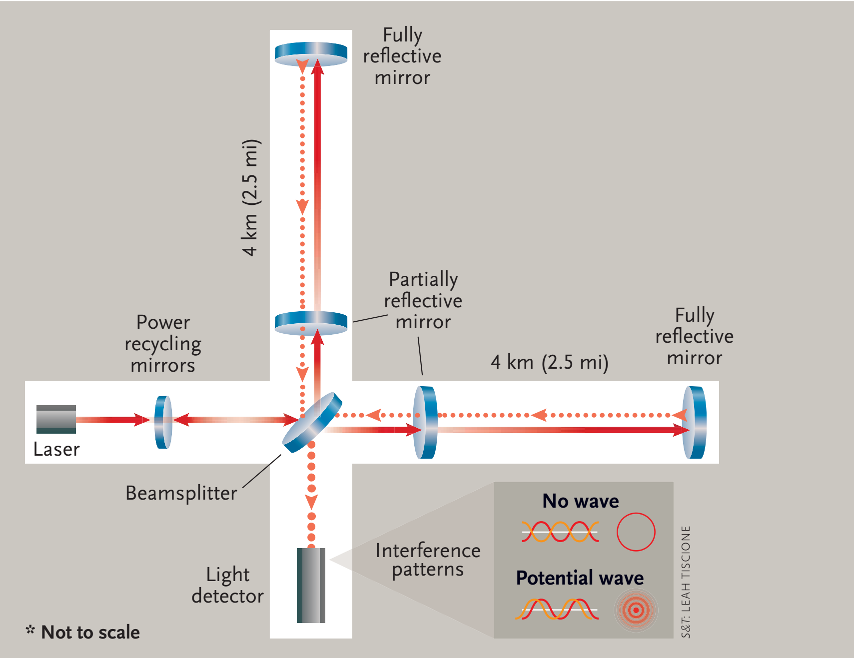
Gravitational waves have nothing to do with sound. For starters, they travel at the speed of light — 300,000 kilometers (186,000 miles) per second. But they're not part of the electromagnetic spectrum either, like radio waves or X-rays are. Instead, gravitational waves are extremely small-amplitude undulations in the very fabric of spacetime. They are produced when masses accelerate. (Think exploding stars or orbiting black holes.) The bigger the mass and the stronger the acceleration, the more powerful the gravitational waves that the system "radiates." As they're radiated, the waves carry energy away from the system. And they're all over the universe. "They're everywhere, because space is everywhere," explains Schutz (now at Cardiff University, UK).

These spacetime swells come in a wide range of frequencies, from less than a nanohertz (corresponding to a wavelength of about 300 light-years) to a few kilohertz (a few kilometers).

Scientists can't decide when to celebrate the centenary of the prediction of gravitational waves. Albert Einstein first described them in a 1916 paper, as a consequence of his general theory of relativity. However, that origi-



MICHAEL FYFFE / LIGO



S&T: LEAH TISCIONE

QUALITY CHECK ***Left:*** **Team members inspect one of LIGO's partially reflective "input" mirrors.** ***Right:*** **A schematic of LIGO. A beamsplitter sends light along two paths perpendicular to each other. Each beam then bounces between two mirrors, one of which allows a fraction of the light through. When the two transmitted beams meet and interfere, they'll cancel each other out — if the length of the path they've each traveled has remained constant. But if a gravitational wave passes through, it'll warp spacetime and change that distance, creating an interference pattern that the system will detect.**

nal publication contained a mathematical error, which Einstein didn't repair until 1918, when he wrote a second paper. Nevertheless, he never believed that the minuscule quiverings of spacetime might actually be detectable.

Until the mid-1970s, just a handful of physicists cared about gravitational waves — one of them being Joseph Weber (University of Maryland, College Park), who constructed several massive *resonant bar* detectors in the late 1960s and early 1970s that were supposed to start "ringing" when a gravitational wave with the right frequency passed through. But that all changed in 1974 with the Nobel Prize–winning discovery of the now-famous binary pulsar PSR B1913+16. Within a few years, precision measurements of the pulsar's periodic Doppler shift revealed that the system was slowly shrinking: the two neutron stars are closing in on each other at 3.5 meters per year, heading for a merger in 300 million years or so. The corresponding energy loss — at present over 7 quadrillion gigawatts! — exactly matches the loss expected through the emission of gravitational waves. The message was loud and clear: gravitational waves exist. Now scientists only needed to be clever enough to directly detect them.

Mirror Magic

LIGO Hanford Observatory head Frederick Raab is confident that the new facility — aptly named Advanced LIGO — is up to the task. An earlier, less sensitive path-finder version of LIGO has been operational since 2002, both in Louisiana and Washington. But, says Raab, right from the start it was evident that two generations of detectors would be needed, to gain enough experience. "This was already part of the initial 1989 proposal to the National Science Foundation," he adds. "Initial LIGO had a small chance to maybe get one detection. That's not science, that's a stunt. You need to move forward." In fact, during eight years of operation, Initial LIGO did not detect a single gravitational wave. At a much higher sensitivity, Advanced LIGO is expected to make at least a few and maybe a few dozen detections per year.

LIGO's detection technique is pretty straightforward. Two coherent laser beams are fired into two vacuum tunnels, each four kilometers long and at right angles to each other — it takes a 10-minute car drive to get from one end of the observatory's L to the other. The laser beams are bounced up and down the tunnels a couple hundred times by high-precision mirrors, increasing the effective path length to many hundreds of kilometers. Then they are recombined in such a way that the two light waves cancel each other out — so long as the distance they travel doesn't change. If a powerful gravitational wave passes through, however, space is periodically stretched and squeezed, and the distance the two laser beams travel will change minutely. If that happens, the light waves won't continuously cancel each other out.

The problem is that gravitational waves are so

MICHAEL FYFFE / LIGO

GRAVITY MISSION CONTROL *Left:* Team members put the finishing touches on one of the power recycling mirrors, which bounce the laser beams inside LIGO back into the interferometer, boosting the power and sharpening the interference pattern. *Above:* Operations specialist Michael Fyffe took this shot of the LIGO Livingston Observatory control room. The green numbers on the wall (left) give atomic time, used in GPS satellites and stations; researchers use this clock to precisely report when an event happens. The red numbers (right) are Pacific Time (for LIGO Hanford), Central Time (Livingston), and Greenwich Mean Time (for reporting to the worldwide collaboration).

unimaginably weak. LIGO is designed to be sensitive to the powerful waves produced when two neutron stars collide — the fate of PSR B1913+16. But the fabric of spacetime is incredibly stiff, so despite the enormous energies involved, the resulting ripples are extremely small. In fact, when a gravitational-wave signal from a neutron star merger 25 million light-years away passes through, the 4-kilometer separation between the end mirrors in each interferometer arm is expected to change by no more than a billionth of a nanometer a few hundred times per second. Needless to say, engineers needed to isolate the mirrors perfectly from seismic noise and other terrestrial tremors.

With its more powerful lasers and improved mirror system, Advanced LIGO should be able to detect gravitational waves from neutron star mergers out to an extraordinary distance of some 500 million light-years — a big enough volume of space to catch at least a couple of events per year from the million or so galaxies in that volume. Scientists need a simultaneous detection by both LIGO observatories to rule out local noise sources. Teaming up with Virgo and Geo600 in Europe — and, in the future, with similar facilities in Japan and India — will make it possible to broadly localize the source of the gravitational waves on the sky, enabling wide-angle optical telescopes to quickly carry out follow-up observations, like paparazzi photographers responding to sounds, voices, or other audible cues.

"That would be something like a cosmic version of Where's Waldo," Samaya Nissanke (Radboud University, the Netherlands) told the Edoardo Amaldi Conference in Gwangju. "But we're ready; an optical hunt is possible today."

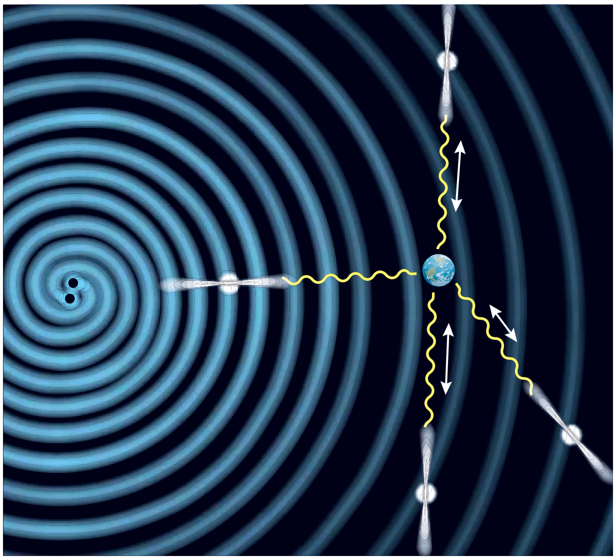
Taking the Pulse

But will interferometers like LIGO really be the first to catch a wave? Maybe not. Radio astronomers are pursuing a completely different way to detect them, using pulsars in our Milky Way Galaxy. If space is periodically stretched and squeezed, the argument goes, this should show up as minute variations in the pulse arrival times, because the pulsars' distances are periodically changing. By monitoring a number of pulsars at known distances spread across the sky, it should be possible to spot a passing wave. In a sense, it's comparable to using the bobbing motions of floats on a pond to discover waves on the water's surface. Sounds easy, and relatively cheap, too.

Primordial Waves

In March 2014, scientists working with the BICEP2 telescope claimed they'd discovered a swirly pattern in the polarization of the cosmic background radiation. They interpreted this *B-mode pattern* as an imprint from primordial gravitational waves spawned by cosmological inflation, the exponential burst of expansion when the universe was only a tiny fraction of a second old. (Astronomers can't use polarization to look for more "mundane" gravitational waves from inspiraling black holes and other systems: no black holes were around to stretch and squeeze the cosmic plasma soup and create a polarization signal. Plus, even *if* astrophysical sources could leave their mark, it'd be so weak we couldn't detect it.)

Within a few months, astronomers working with data from the European Planck mission showed that the BICEP2 results could instead be explained by dust in our own Milky Way Galaxy (*S&T:* Sept. 2014, p. 12). However, this is not to say that primordial gravitational waves from the inflationary epoch do not exist. Other submillimeter telescopes, both in Antarctica and northern Chile, might still detect their subtle fingerprints in the polarization patterns of the cosmic background radiation.



S&T: LEAH TISCIONE

HOW A PULSAR TIMING ARRAY WORKS Pulsars broadcast regular "beats" to us as their radiation jets spin in and out of view. The arrival time of those beats depends on the distance between us and the pulsar. Normally, that distance doesn't suddenly change, and so neither does the pulse's arrival time. But when gravitational waves (concentric arcs) pass between us and a pulsar, they will slightly stretch and squeeze the space perpendicular to their direction of motion — in the 2D representation here, both in the direction of the double arrows and in and out of the page. The pulsar's distance thus oscillates, making some pulses arrive earlier and others later than expected. How much the arrival time changes depends on how everything lines up: in the 2D visualization here, where all objects are in the plane of the waves' propagation, the effect will be stronger for pulsar-Earth lines that are closer to being at right angles with the wave's direction of motion (length of arrows). By combining arrival times for several pulsars in different parts of the sky, astronomers should be able to figure out where the gravitational waves came from.

Of course, it's not as straightforward as it seems. There are loads of other effects that could subtly influence pulse arrival times, explains Ryan Shannon (CSIRO, Australia), all of which astronomers have to fully understand and compensate for. Moreover, pulsar distances are generally not known precisely enough to accurately apply the technique. Still, by measuring a large ensemble of pulsars, and by carrying out a complicated statistical analysis, the pulsar timing array (PTA) technique has a lot of potential. Astrophysicists are excited by the prospects: while LIGO-like interferometers are sensitive to the high-frequency gravitational waves from merging neutron stars (a few hundred hertz), PTAs would detect the long-wavelength, very low-frequency waves from binary black holes in distant galaxies (see graph on facing page).

In fact, says Shannon, the fact that a decade-long data set from the Australian Parkes Pulsar Timing Array (PPTA, published in 2013) didn't show any evidence for those nanohertz waves has already ruled out many existing evolutionary models that predict the frequency of merging galaxies and coalescing supermassive black holes. Meanwhile, similar programs are now in progress in Europe (European Pulsar Timing Array, EPTA) and the United States (North American Nanohertz Observatory for Gravitational Waves, NANOGrav); together the three constitute the International Pulsar Timing Array (IPTA). The hope is that a firm, statistically significant detection will be made soon. Says Pablo Rosado (Swinburne University of Technology, Melbourne): "With so many models already ruled out by our current non-detection, we're starting to get worried."

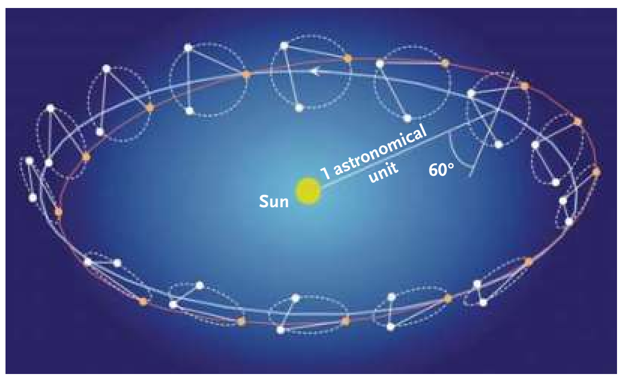
Frankly, you can't blame gravitational-wave scientists for being at least a *bit* worried. Between 2002 and 2010, Initial LIGO did not detect a single neutron star merger within 50 million light-years, although that would've been a lucky catch. But searches for long-duration "continuous wave signals" — from known X-ray binaries like Scorpius X-1 or from young, rapidly spinning neutron stars that are not perfectly spherical — also have come up empty. PTAs: nothing yet. Advanced LIGO — well, you would've seen front-page headlines if there had been a detection by now.

Still, confidence abounds. "If there are no signals out there, how would you explain the binary pulsar?" asks Raab. And in Gwangju, a self-assured Deirdre Shoemaker (Georgia Institute of Technology) told her audience that "the first gravitational-wave signal that we're going to detect has already passed Proxima Centauri." In other words: we'll hit the jackpot before 2019.

Discovery Space

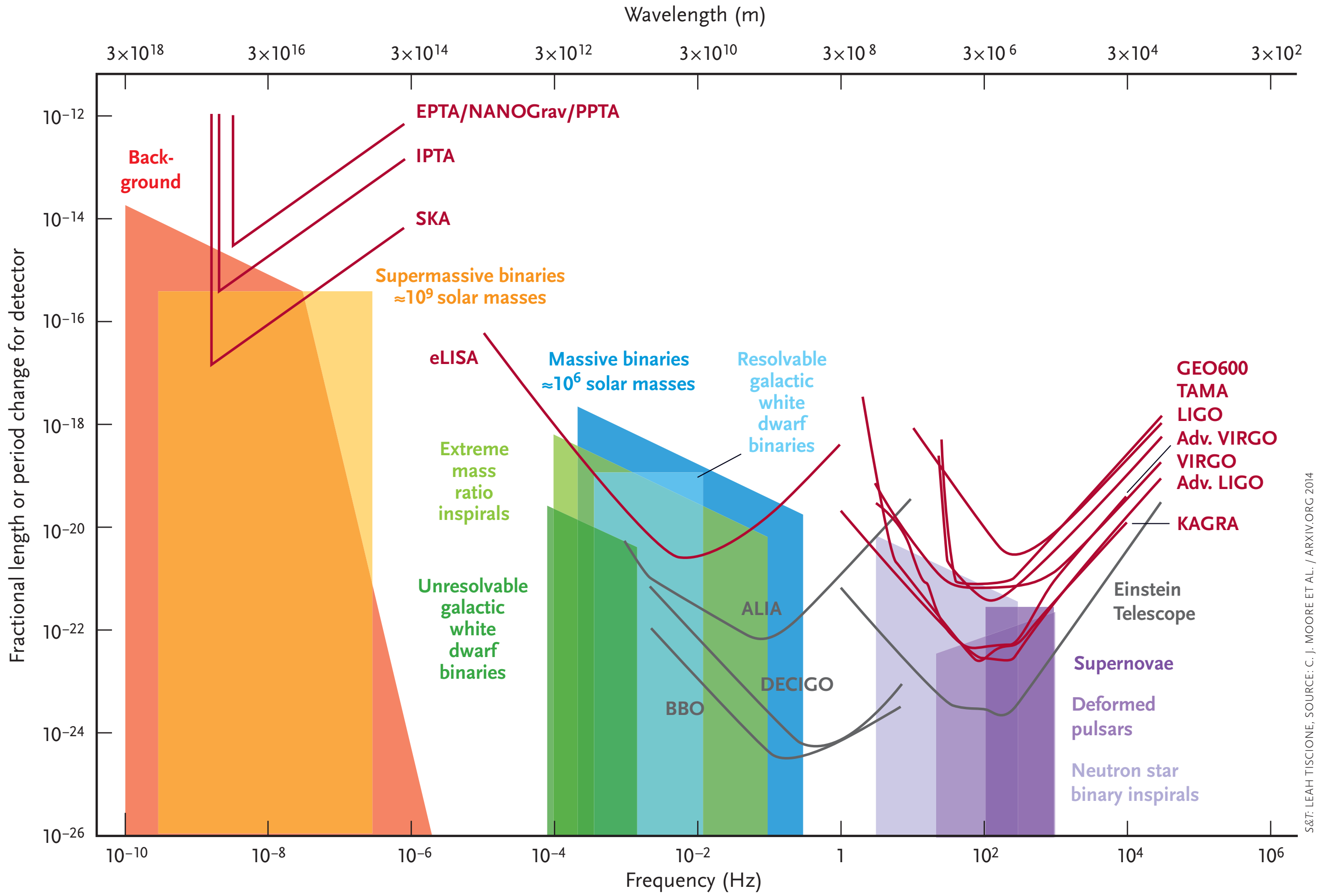
OK, so let's assume that we're indeed on the doorstep of a revolutionary discovery — the confirmation of a century-old prediction of general relativity, and the opening up of a new window on the high-energy universe. Then what?

Fast forward two decades. Somewhere on the planet — most likely in Europe — construction workers are



NASA

eLISA ORBIT ESA's eLISA mission will comprise three spacecraft flying in a triangle about a million kilometers on a side. Tilted 60° to the ecliptic, the triangle formation will cartwheel around the Sun behind Earth in our planet's orbit. Free-falling masses inside each spacecraft will hover undisturbed by forces other than gravitation.



HUNTING FOR GRAVITATIONAL WAVES Gravitational waves — and the experiments designed to find them — cover a wide range of frequencies. Last year Christopher Moore, Robert Cole, and Christopher Berry (then all at the University of Cambridge, UK) calculated approximate signal ranges and sensitivities for various gravitational wave detectors, shown here. Experiments in dark gray are proposals; those in red are in development or operational. Don't mentally extend the curves beyond where they're drawn: the limits' endpoints are intentional, because beyond these points sensitivities degrade. The team calculated each source's signal range (shaded regions) based on the characteristics of a representative (theoretical) member of that category.

digging huge tunnels to house the Einstein Telescope, a triangular underground super-LIGO with interferometer arms 10 kilometers long and capable of detecting neutron star mergers out to billions of light-years. Meanwhile, the European Space Agency (ESA) is preparing for the launch of eLISA, the first space-born gravitational-wave observatory. "eLISA will cover the millihertz frequency range, which cannot be studied from the ground because of seismic noise," says Jonathan Gair (University of Cambridge, UK). The observatory will detect gravitational waves from relatively lightweight supermassive black holes (tens of thousands to tens of millions of solar masses) in the cores of galaxies, from thousands of compact binary stars in the Milky Way, and maybe even from cosmological sources like cosmic strings — hypothetical defects in spacetime produced in the newborn universe.

The eLISA mission will use three separate spacecraft floating in a huge triangle formation. Laser beams will fire, reflect, and recombine across distances of a million kilometers to create a giant interferometer. The LISA Pathfinder mission, due for launch before year's end,

Learn more about gravitational waves — with animations, a 20-minute documentary, and more — at http://is.gd/gwtutor.

will test all necessary eLISA technologies using two test masses free-floating some 40 centimeters apart within a single hollow spacecraft.

Twenty years from now, LISA Pathfinder will be history, just like Einstein's doubts about the existence of gravitational waves, the fuss around Weber's claims of measuring the waves with his bar detectors, and, hopefully, the worrisome non-detections by pulsar timing arrays. By then, gravitational-wave astronomy should have evolved into a rich and fruitful discipline, shedding light on a wide variety of astronomical objects and processes, from the Big Bang and galaxy mergers to supernova explosions, gamma-ray bursts, and compact binary stars. Who would have imagined that back in 1915? ✦

Dutch astronomy author and Sky & Telescope *Contributing Editor* ***Govert Schilling*** *plans to write a popular-level book on the hunt for gravitational waves.*