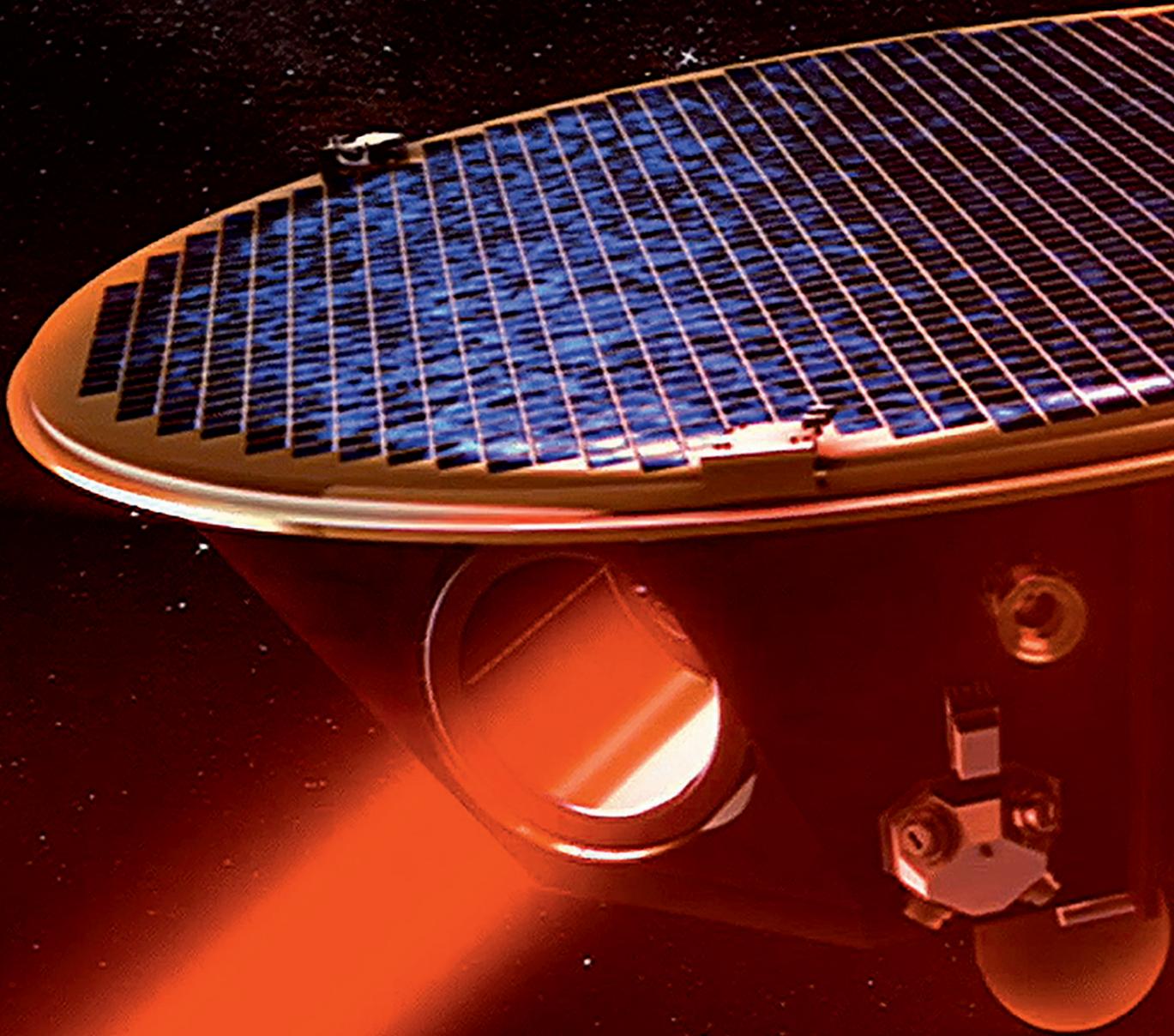
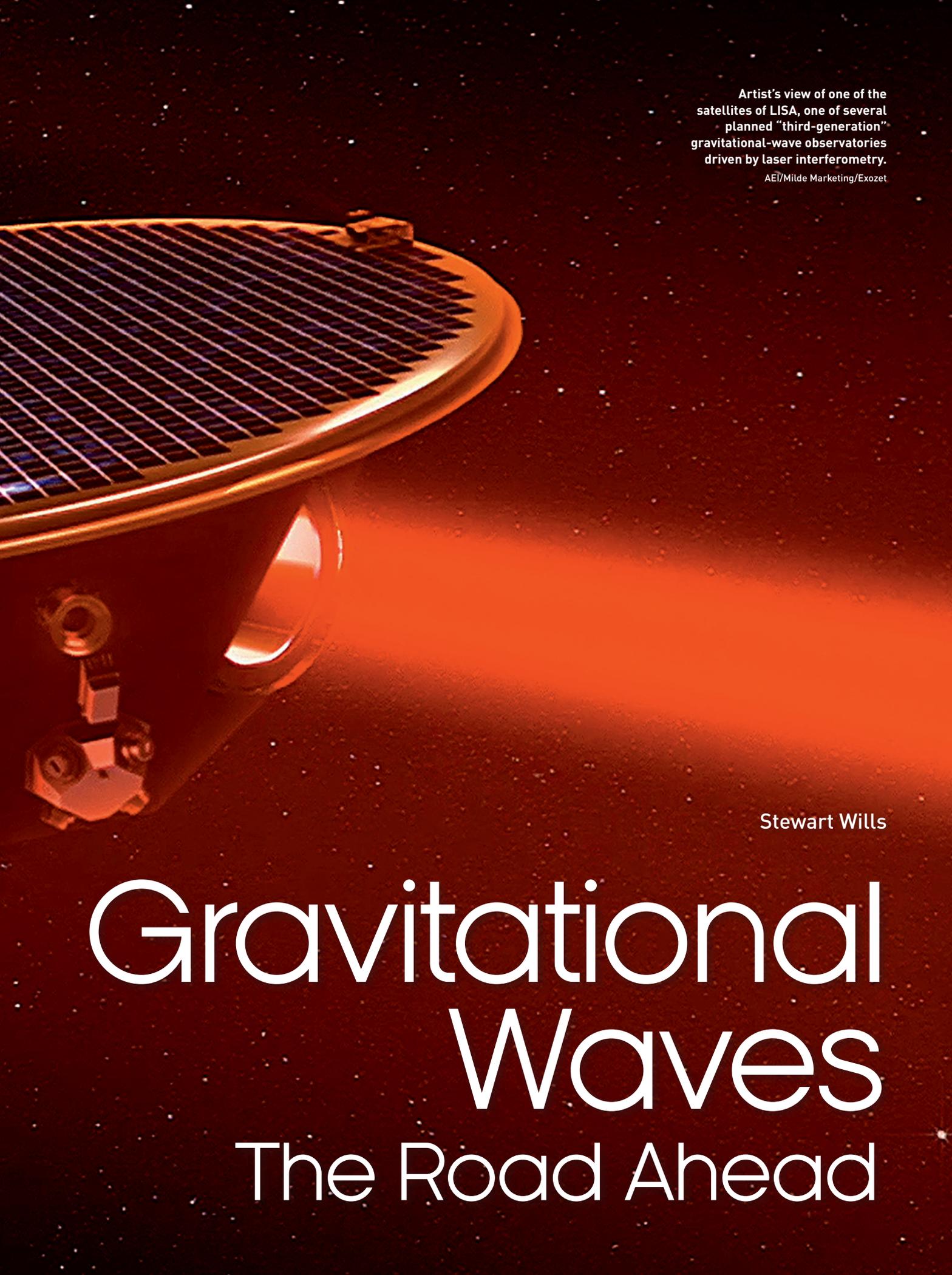


LIGO and Virgo have opened up a new window into the local universe. But the global gravitational-wave community isn't stopping there.



An artist's rendering of a satellite component, likely part of the LISA mission, set against a dark, starry background. The component is a circular, metallic structure with a grid-like pattern on its top surface. It is illuminated from the side, creating a bright orange glow. The background is a deep black with numerous small, white stars scattered throughout.

Artist's view of one of the satellites of LISA, one of several planned "third-generation" gravitational-wave observatories driven by laser interferometry.

AEI/Milde Marketing/Exozet

Stewart Wills

Gravitational Waves

The Road Ahead

It was one of 2017's big scientific moments. On 16 October, researchers from the Advanced LIGO and Advanced Virgo gravitational-wave (GW) observatories and from an array of astronomical telescopes announced their observation of the collision of two dense neutron stars, 130 million light years away. News of that distant event had first reached Earth in August, in a long rumble of GWs, the low-frequency ripples in spacetime that the giant LIGO and Virgo laser interferometers were built to pick up. After that, the astronomers quickly jumped in, pointing their telescopes—which covered the electromagnetic spectrum from radio waves to gamma rays—at the patch of sky where the GW observatories had told them to look.

The combined observations, involving more than 70 separate instruments and thousands of scientists, yielded an incredible harvest of astrophysical information. It also marked the debut of gravitational-wave multi-messenger astronomy, the long-promised era when GW observatories and more traditional astronomical facilities would join forces to deliver a raft of new insights on previously inaccessible questions.

But to tackle the deepest questions of all—those at the very edges of the observable universe—the GW interferometers will need to step up their game. “As much as what’s already been detected is terribly exciting, we’re still to some extent probing only our local universe,” says Sheila Rowan, the director of the Institute for Gravitational Research (IGR) at the University of

Glasgow, U.K. Extending observations to “a larger fraction of the cosmos,” she asserts, will require upping the already exquisite sensitivity of today’s GW detectors.

Fortunately, the worldwide GW-observing community, an unusually cohesive scientific population with a gift for long-term planning, is on the case. Efforts are underway at LIGO and Virgo to use quantum optics, materials science and more to squeeze as much sensitivity as possible out of the existing detector network. And plans are afoot for even larger, “third-generation” detectors, on Earth and in space, to snag GWs from sources sending messages dating to near the beginning of time.

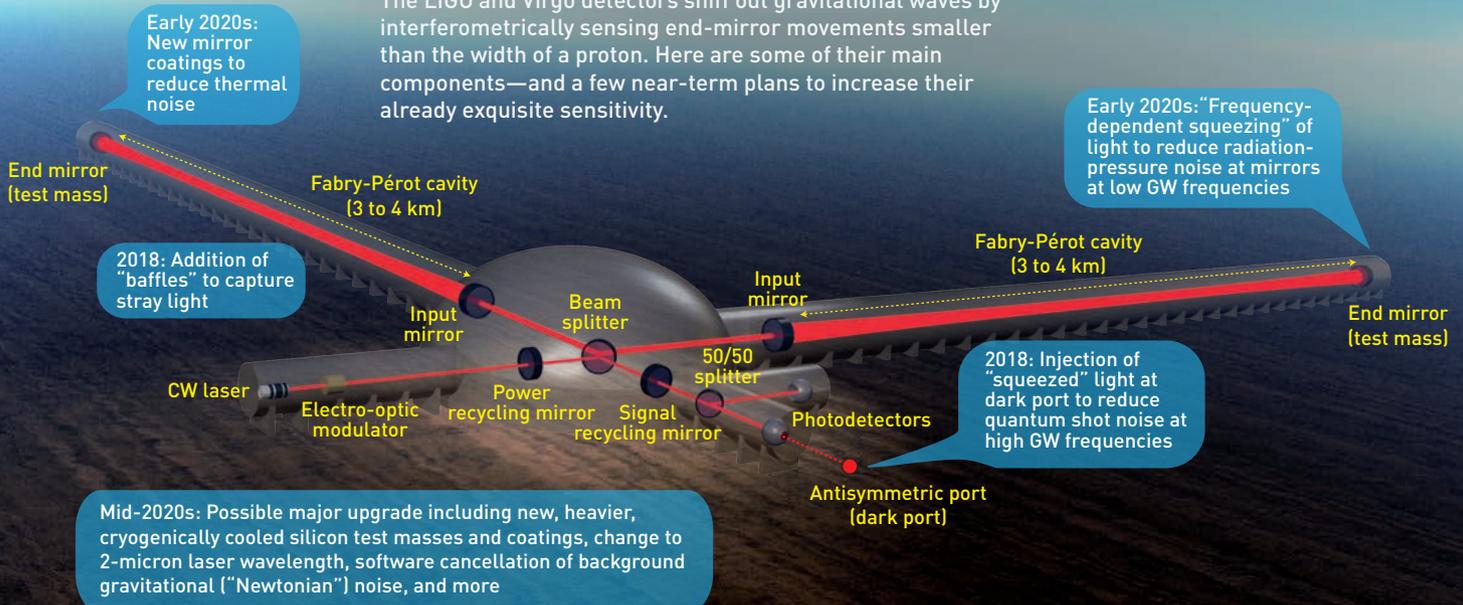
Numerator and denominator

To understand how to improve the sensitivity of laser interferometer GW detectors, it helps to think about the arms of the L-shaped devices—4 km long for the LIGO facilities in Hanford, Wash., and Livingston, La., USA, and 3 km long for the Virgo facility near Pisa, Italy—as giant strain meters. As a passing GW churns the fabric of spacetime around the interferometer, it nudges, by an infinitesimal amount, the large mirrors, known as test masses, at the end of each interferometer arm. Those displacements shorten one interferometer arm and lengthen the other. That differential length change, in turn, shows up as a change in amplitude and an interference pattern read at the interferometer’s “dark port” (also called the antisymmetric port).

Illustration by Phil Saunders

LIGO and Virgo: Taming the noise

The LIGO and Virgo detectors sniff out gravitational waves by interferometrically sensing end-mirror movements smaller than the width of a proton. Here are some of their main components—and a few near-term plans to increase their already exquisite sensitivity.



The current LIGO and Virgo detectors can sense strains approaching 10^{-22} , and displacements a thousand times smaller than the width of a proton.

Since, physically, strain is defined as a change of length per unit length ($\Delta L/L$), there are two ways to increase a GW interferometer's sensitivity. "The idea is that you want to measure as small a displacement, the numerator of that quantity, as possible," says David Reitze of the California Institute of Technology, the executive director of the LIGO project, "and you want to measure it over as long a baseline as possible—the L that's in the denominator." So "one obvious thing you can do," according to Reitze, "is make your detector longer, but that requires new observatories."

For now, the LIGO and Virgo scientists are stuck with the baselines they have, so they're working to hammer down the numerator. That's a daunting proposition, given the already mind-bending sensitivity of the facilities—which feature ultrastable low-noise lasers, state-of-the-art suspension systems to isolate the test masses from seismic waves, angstrom-level polishing of mirror surfaces, and more (see OPN, March 2015, p. 44). The current LIGO and Virgo detectors can sense strains approaching 10^{-22} , and displacements a thousand times smaller than the width of a proton.

How can you do better than that? The LIGO-Virgo team has some ideas.

Banishing stray light

Last August, just days after detecting the neutron-star collision, the LIGO and Virgo detectors went offline, ending LIGO's second observing run (nicknamed O2) and entering a yearlong upgrade phase. "We're trying to understand the underlying sources of noise that limit our sensitivity at different frequency bands," says Reitze. "And we believe that there are a number of places where improvements can be made."

One lies simply in managing scattered light in the interferometer, where passive amplification in its vast Fabry-Pérot cavities boosts the power of the facility's light source from 50 W to 200 kW. "Stray light is a huge problem," says Rana Adhikari, a professor of physics at Caltech. "We have hundreds of kilowatts of laser power running around, and at the dark port of the interferometer, where the signal comes out, we need to measure power fluctuations on the order of tens of picowatts."

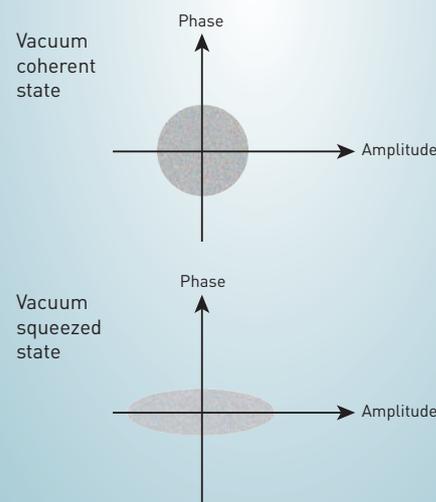
To keep stray light from gumming up that tiny signal, scattered-light suppressors, called baffles, will be installed in the facilities during the upgrade. And the team continues to attack stray light on the materials-science side, by seeking more and more absorptive materials. "One thing people don't know," says Adhikari, "is that we spend a lot of time studying things that are black."

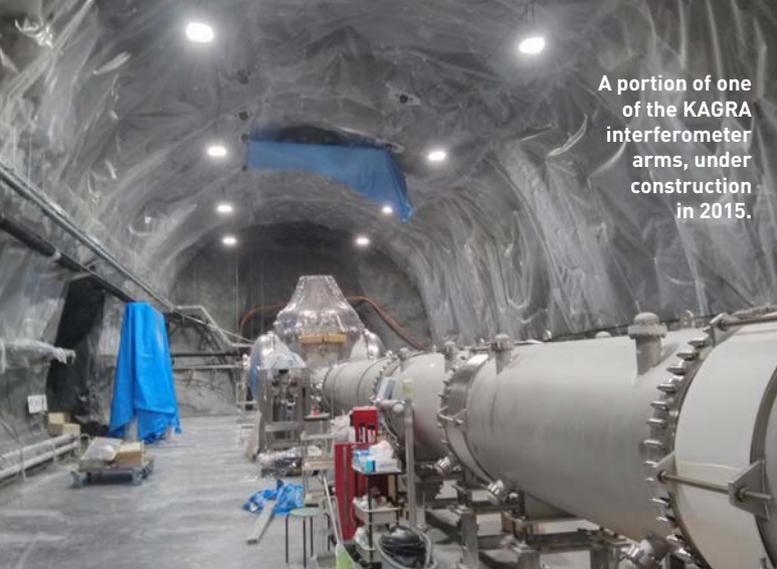
Quantum noise

Another target is the detectors' quantum shot noise, or photon-counting noise. That noise arises from

Squeezing out uncertainty

In the framework of quantum optics, a light field can be described by two orthogonal quadratures—one of them, loosely speaking, associated with amplitude and the other associated with phase. In a coherent state of light or a coherent vacuum state, each of those quadratures has an equal uncertainty, with the product of the two limited by Heisenberg's uncertainty principle. Using nonlinear techniques such as optical parametric amplification, however, it's possible to transfer uncertainty out of the phase quadrature to the amplitude quadrature, squeezing the uncertainty circle into an ellipse, but keeping the total uncertainty in line with Heisenberg's principle.





A portion of one of the KAGRA interferometer arms, under construction in 2015.

Wikimedia Commons/Christopher Berry

KAGRA and LIGO India

Even as the second-generation facilities Advanced LIGO and Advanced Virgo undertake planned and proposed upgrades through the first half of the 2020s, two other second-gen interferometers are slated to join the network. One of those is KAGRA, a laser interferometer with 3-km arms [comparable to Virgo's] that has been under construction in Japan since 2010.

The KAGRA project has walked a different technical path than LIGO and Virgo, with its own suite of challenges. To reduce seismic noise, the facility is located underground, in a portion of the abandoned Kamioka mine—the same location that hosts the huge Super-Kamiokande neutrino detector. Moreover, rather than using fused-silica test masses operating at room temperature, KAGRA will employ suspended, sapphire test masses cryogenically cooled to 20 K, which will all but silence thermal noise in the structures.

Takaaki Kajita of the University of Tokyo, who won a Nobel Prize for his neutrino work at Super-Kamiokande and is now the P.I. for KAGRA, says that the biggest challenge in getting the project operational relates to the cryogenic cooling. "Inevitably, the cryocooler generates some kind of vibration, and we have to have essentially no vibration at the mirror," he notes. The underground-mine location has also created problems with water infiltration, especially after spring snowmelts, which creates other kinds of detector noise.

Nonetheless, Kajita and the KAGRA team hope to operate a simple interferometer with a cryogenic mirror this spring, and are pushing for the site to become operational by fall 2019, to overlap with at least the end of the next LIGO-Virgo observing run. Once launched, says Kajita, the facility's location in Japan "is in a sense ideal" to combine with LIGO and Virgo observations to pin down the sky location of GW events and to extract GW polarization data.

In addition to KAGRA, another project, LIGO India, would build a clone of Advanced LIGO at a location in India still being determined, using a spare set of components from the LIGO project. LIGO's David Reitze says that the India facility could come online by 2025 if all goes according to plan.

uncertainties in photon arrival times, owing to quantum fluctuations in the vacuum field entering at the interferometer's antisymmetric port. The phase fluctuations in the vacuum field mix in the antisymmetric port with the signal field from the interferometer, leading to noise at the photodetector that measures the output.

In the current LIGO-Virgo upgrade, the detector engineers will tackle that noise source by replacing the vacuum fluctuations with a "squeezed" state of light—a nonlinear-optics trick that reduces the Heisenberg uncertainty associated with the light's phase by transferring it to its amplitude (see sidebar, p. 47). By injecting such a squeezed state into the antisymmetric port, and tuning it to the phase of the light field from the interferometer, the photon-counting noise can be dramatically reduced for relatively high GW frequencies (that is, above 100 Hz). Manipulating the Heisenberg uncertainty principle in this way, says Reitze, could improve the instrument's sensitivity by 1.5 times or more at those frequencies.

But squeezing light also has its dark side, according to Matthew Evans of the Massachusetts Institute of Technology (MIT), USA. "If we squeeze the phase quadrature very hard," he says, "it produces a lot of low-frequency noise in the amplitude," which shows up as fluctuations in the radiation pressure at frequencies below around 50 Hz. The radiation pressure "pushes our mirrors around," Evans adds, and can look like a GW signal at low frequencies.

To handle that, in the early 2020s, the LIGO and Virgo engineers will add "frequency-dependent squeezing," reducing phase uncertainty at higher frequencies to handle shot noise, and amplitude uncertainty at lower frequencies to take care of radiation-pressure noise. Under that scheme, "we squeeze both quadratures at the same time, but not at the same frequency," says Evans. "So Heisenberg is always happy."

Stray light and quantum noise aren't the only gremlins that GW facility engineers are attacking. Future upgrades will also likely include improved coatings for the test-mass mirrors, to reduce thermal noise. There's even so-called Newtonian noise—background gravitational fluctuations attributable to local motions of the Earth. Adhikari explains that, while the test mass suspension systems keep LIGO and Virgo isolated from direct seismic coupling, changes in background gravity are something that "we can't shield ourselves from." To address Newtonian noise, the team hopes to use seismometer arrays to get an estimate of the local motions, and then use software to subtract out the resulting

In the current LIGO-Virgo upgrade, engineers are tackling quantum shot noise by replacing vacuum fluctuations entering the antisymmetric port with “squeezed light.”

gravitational fluctuations—like “Bose noise-canceling headphones, but for seismic waves,” says Adhikari.

On to Voyager

After additional upgrades slated to start in fall 2019, after the third observing run (O3), the existing GW facilities are expected to reach their “design sensitivity” by 2020. For LIGO’s Hanford and Livingston observatories, that sensitivity would mean the ability to detect binary neutron star collisions slightly less than 620 million light years (190 megaparsecs) away, on average, with a longer range for some optimally oriented systems. The same timeframe should see another GW detector, the Japanese KAGRA facility, added to the global network, with a fifth detector, LIGO India, to follow a few years later.

What’s next? For the LIGO detectors in particular, the answer could lie in an ambitious, yet-to-be-funded project called LIGO Voyager.

Targeted for the second half of the next decade, Voyager would bring a major upgrade to the optics within the existing LIGO facilities. Along with other steps being researched now, such as frequency-dependent squeezing and Newtonian-noise cancellation, Voyager’s centerpiece would be a dramatic change to the mirrors, or test masses, that provide the signal from passing GWs. The envisioned project would replace the current, 40-kg test masses, made of fused silica, with 200-kg masses of pure crystalline silicon with amorphous-silicon coatings. The shift, according to Adhikari, should slash the level of mechanical dissipation, and thus the Brownian thermal noise and vibrations, in the test masses.

That change, however, would pose formidable research and engineering challenges. The mirrors would need to be operated cryogenically, at 123 K, with new cryogenic suspensions to support the heavier masses. Creating, milling and polishing such sizable mirrors out of sufficiently pure silicon—“to sub-angstrom figure errors, over a beam size of 20 centimeters,” according to Adhikari—also would break new ground.

Most daunting of all would be a change in the wavelength of the driving laser, from LIGO’s current, 1064-nm diode-pumped Nd:YAG laser to a 2-micron source. Because of the material properties of the silicon

coatings, explains Adhikari, absorption levels drop off dramatically near 2 microns, so that “we can operate our systems at really high power levels without worrying about thermal problems.” Such a development would significantly boost the facility’s signal-to-noise ratio.

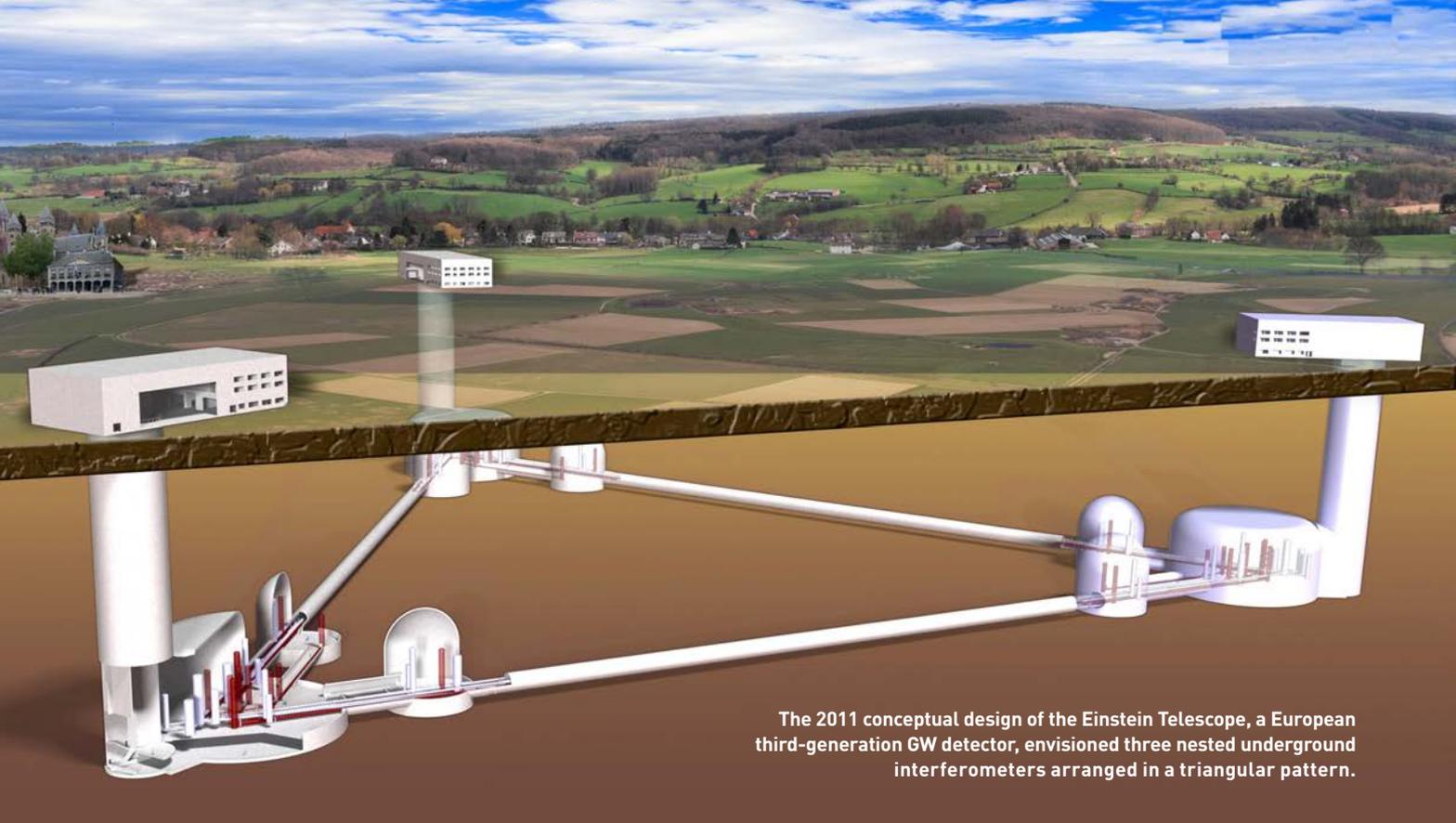
But shifting to 2 microns will require a range of new technologies. For instance, photodetectors with quantum efficiencies of greater than 99 percent—a must-have for frequency-dependent squeezing—don’t yet exist at these wavelengths, whereas the options are plentiful at 1064 nm and at the 1550-nm telecom wavelength. “We’re starting to appreciate how easy we had it at one micron,” says Adhikari. “Everything is off the shelf.”

Extending the baseline

The Voyager upgrades, if funded and implemented, would push the existing LIGO facilities’ ability to measure infinitesimal displacements—the numerator of the strain equation—about as far as it can go, enabling them to pick up neutron-star collisions from distances of 1.1 gigaparsecs (around 3.6 billion light years). But the GW community also has plans to attack the denominator, with proposed new, longer-baseline laser interferometers on Earth and even in space.

One such “third-generation” project, in Europe, is the Einstein Telescope (ET), in discussion since the late 2000s. A 2011 conceptual design study of the ET envisioned a set of three nested laser-interferometer detectors, with an arm length of 10 km, laid out in an equilateral triangle, to be buried 100 to 200 m underground to isolate the detectors from near-surface seismic noise. The three-detector, triangular geometry would let the ET capture information not just on a passing GW’s amplitude, but also on its polarization. The 2011 design also called for technologies now being considered for LIGO and Virgo as well, such as cryogenically operated silicon mirrors, frequency-dependent squeezing and Newtonian-noise reduction.

According to Michele Punturo of the Istituto Nazionale di Fisica Nucleare (INFN), Italy, a co-leader of ET activities, the basic specs for the facility haven’t fundamentally changed. “It’s still quite a valid design,” he says, “even if some technical parts could be improved.”



The 2011 conceptual design of the Einstein Telescope, a European third-generation GW detector, envisioned three nested underground interferometers arranged in a triangular pattern.

Nikhef/Marco Kraan

But by the time the facility comes online—an event targeted for the beginning of the 2030s, if funding can be arranged—it’s possible it will no longer include at least one distinctive feature: the triangular configuration.

“The triangular shape has many advantages,” says Punturo. “But it has a big disadvantage: cost.” When first envisioned, he explains, the ET was the only third-generation game in town, and getting polarization from a single facility seemed to be a necessity. “But now,” says Punturo, “the concept of ‘third generation’ is a global concept,” with the possibility of multiple detectors, which could work together to obtain polarization information. “So maybe we won’t need the triangular shape.”

A high-redshift view

Another proposed third-generation detector, still at the early conceptual stage, is known as LIGO Cosmic Explorer (CE). This concept, explains Matthew Evans of MIT, involves a LIGO-like, L-shaped interferometer with 40-km-long arms. That’s a tenfold increase in length relative to LIGO, and would yield a comparable increase in strain sensitivity out of the box. CE would also be tricked out with the suite of optical and noise-reduction technologies being considered for LIGO Voyager.

Even in the most optimistic scenario, CE wouldn’t become a reality until the mid-2030s at the earliest. Present activities center on building a science case for investment in such a facility, as a prelude to a proposal

to fund a design study. One particularly powerful argument, Evans notes, is that facilities such as the ET and CE “let us get out beyond the local universe”—to the reaches where astrophysicists talk not in terms of megaparsecs or light years, but in cosmological-redshift numbers.

Even with the improvements envisioned for the current LIGO facilities, Evans explains, “we’re still limited to things which are relatively close to us—for example, with a binary neutron star collision, less than a redshift of 1.” A project like CE, he continues, would enable detection of astrophysical events at redshifts of 10 or even 20. Those would be signals coming from only a few hundred million years after the Big Bang, when the first stars were forming in the universe. “It really opens up the distant, high-redshift universe in a way that none of the existing facilities can,” says Evans.

Taking it to space

Perhaps the ultimate long-baseline GW interferometer won’t reside on Earth. The Laser Interferometer Space Antenna (LISA) project, spearheaded by the European Space Agency (ESA), would use three spacecraft, arranged at the vertices of an equilateral triangle, to construct a GW interferometer with arms 2.5 million km long.

At that arm length, LISA could pick up GWs at frequencies between 100 μ Hz and 1 Hz—a part of the GW spectrum beyond the reach of even third-generation ground-based observatories, which will sample the

Perhaps the ultimate long-baseline gravitational-wave interferometer won't reside on Earth.

Hz-to-kHz range. That would put within LISA's grasp a range of phenomena inaccessible on the ground, including mergers of massive black holes at the centers of galaxies, and the earliest "seed" black holes, at redshifts of 20 or more—in the cosmic "dark age," less than 150 million years after the Big Bang.

Conceptually, LISA will work very much like Earth-based GW facilities. Each spacecraft will include two free-falling test masses, 2-kg, gold-coated cubes of a platinum/gold alloy. Stable, 1064-nm, 2-W lasers will continually shine between the spacecraft across the vacuum of space. As passing GWs move the free-falling test masses, changes in travel-time measurements between the three spacecraft will be digitally processed in "virtual" Michelson interferometers on the ground, to back out the GW signal. As a bonus, because LISA will contain multiple interferometers in a triangular setup (much like the ET concept), the space-based observatory will yield data on GW polarization as well as amplitude.

This extraordinary mission's prospects have recently brightened. One reason is the spectacular success of LISA Pathfinder, a mission launched in December 2015 to verify the ability to place two test masses in free fall within a distant spacecraft and to measure their relative motions. The final Pathfinder results, published in February 2017, came in nearly an order of magnitude better than required for the full LISA mission. "LISA Pathfinder didn't only exceed its goals," says Reitze of Caltech, "it shattered them." Meanwhile, in mid-2017, the full LISA mission was selected as the third large-class mission (the so-called L3 mission) in ESA's science program. That puts LISA on a path to launch by 2034.

Between now and then, though, there's a great deal of technical work to be done. "LISA Pathfinder showed that you can put two test masses in free fall, at an extreme level of purity," says Pathfinder mission P.I. Stefano Vitale of the University of Trento and INFN, Italy, who now chairs the ESA Science Program Committee. "The big challenge now is to show and convince ourselves that spacecraft-to-spacecraft interferometry can be done at the performance required. All of the studies done in the past have shown that it looks feasible; now we need to be more concrete and finalize the technology."

Long-term vision

Laser interferometers aren't the only way to get at GWs. To find GWs with frequencies even lower than the microhertz levels targeted by LISA, for example, radio telescopes are tracking arrays of pulsars for tiny changes in the timing of their radio emissions. And analysis of the polarization of the cosmic microwave background, the celebrated "echo" of the Big Bang, could soon yield evidence of a corresponding cosmic GW background—a messenger literally from the beginning of the universe.

All of this puts a premium on international cooperation and long-term planning. Fortunately, according to Sheila Rowan of IGR in Glasgow, that's an area where the GW community particularly excels. "One of the reasons the field has been successful in making such a difficult, complicated measurement," she says, "is that it globally has been very good at pulling together and having vision and foresight on a long timescale for where it wants to go."

Rowan, herself a long-standing research contributor in GW detection, says that this planning and coordination takes place partly via the Gravitational Wave International Committee (GWIC), a working group of the International Union of Pure and Applied Physics. GWIC has a membership spanning the global GW community and all of its projects, both current and planned. Between 2007 and 2010, she observes, the committee put together a 20-to-30-year roadmap articulating the science case and needs for new observatories. That roadmap's vision, she says, "remains pretty good," even in light of the intervening years. That said, Rowan, who is now GWIC's chair, adds that the committee is working on a new version, expected in the next nine months to a year.

Having that long-term vision, according to Rowan—"making sure that, alongside delivering the science now, we're putting in place preparations for the additional science to come"—holds a key to keeping GW science moving forward. "We're really just at the start," she says. "And it's an exciting road to be on." 

References can be found online at www.osa-opn.org/gw-future.

Stewart Wills is OPN's editor and content director.