

Future gravitational-wave detectors aim to probe early universe

The promise of multimessenger astronomy drives the field, brings together scientific communities.

Word traveled fast when gravitational-wave detectors in the US and Europe announced the detection of a binary black hole merger on 14 September 2015. Then on 17 August 2017 the detection of merging neutron stars marked the beginning of multimessenger cosmic science with gravitational waves. (See *PHYSICS TODAY*, April 2016, page 14, and December 2017, page 19.) Once that alert went out, dozens of telescopes were pointed toward the merger; radio astronomers are still watching it. Hundreds of papers followed, including one with more than 3500 authors. The excitement created by those detections has the gravitational-wave community chomping at the bit to lay plans for more powerful observatories.

Scientists in Europe put forward a design for the Einstein Telescope in 2011. (See *PHYSICS TODAY*, September 2015, page 20.) Their US counterparts held off because NSF, which funded the bulk of the Laser Interferometer Gravitational-Wave Observatory (LIGO), encouraged

them to score a detection before focusing on future observatories. So the US Cosmic Explorer design is less far along. But both future facilities would seek to increase sensitivity by at least a factor of 10.

"A new era has opened," says Michele Punturo of Italy's National Institute for Nuclear Physics (INFN) in Perugia and the scientific coordinator for the Einstein Telescope. "With more-sensitive instruments we move from the local universe out to high redshifts. We can do cosmology." The full population of black hole mergers can be explored; independent methods to study the expansion of the universe and test general relativity become possible; and the rate of coalescence of neutron stars can be inferred—and used to determine the rate of heavy element production throughout time. "A wide spectrum of scientific achievement becomes possible," he says.

Third-generation designs

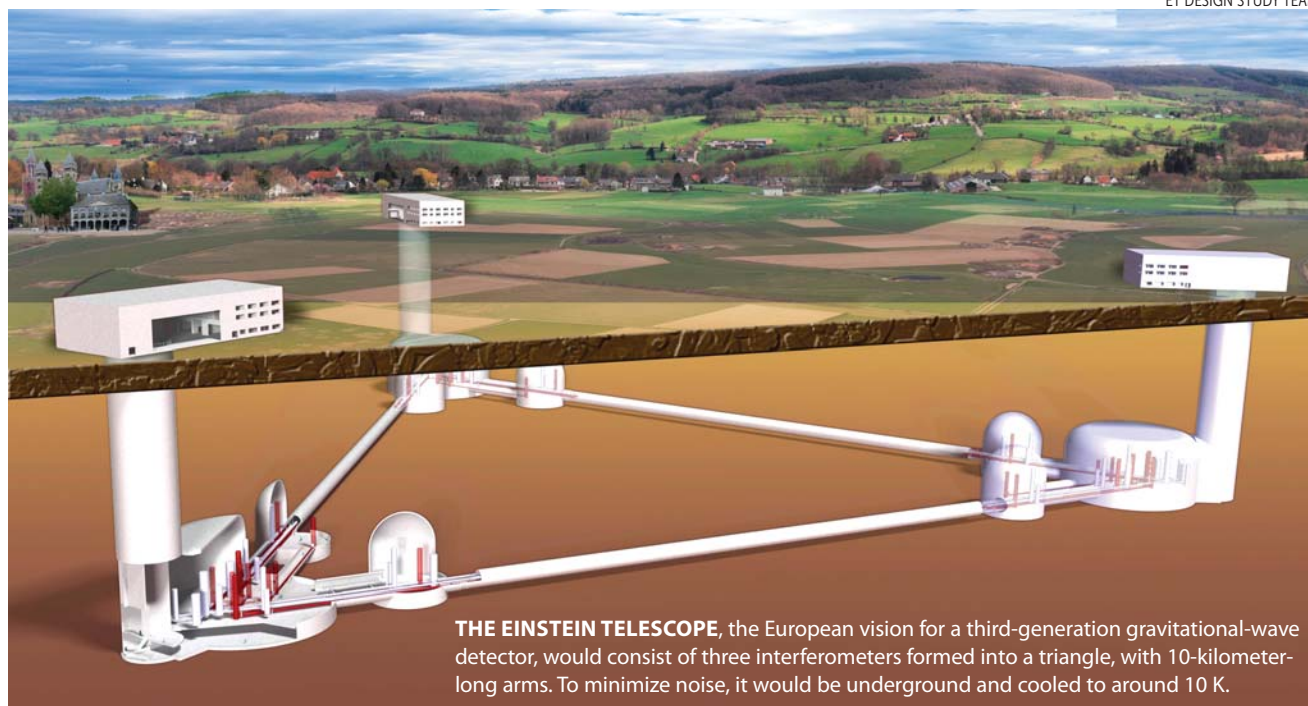
Punturo and Harald Lück of the Max Planck Institute for Gravitational Physics

in Hanover, Germany, started sketching out plans for a next-generation gravitational-wave detector more than a decade ago. Their intention was to create an infrastructure that "could host almost any evolution of the project," says Punturo. With their colleagues they came up with a triangular design with three interwoven interferometers, one formed from each pair of arms. The facility would be 100–200 meters underground to minimize the influence of residual seismic and environmental noise, and cooling to around 10 K would suppress thermal noise; both measures improve the sensitivity at low frequencies to extend the reach below 10 Hz.

As in current gravitational-wave detectors, a relative phase change in laser light in the arms of a Michelson interferometer is the sought-after signal. Such a phase change is caused by a gravitational wave stretching or shrinking the length of the interferometer arms ever so slightly—orders of magnitude less than the diameter of a proton; the length change is different in different directions. With two interferometers, the polarization of a gravitational wave can be resolved. With three, the signals can be combined to verify whether a signal is indeed from a gravitational wave or noise.

Each interferometer in the Einstein Telescope would consist of two nested

ET DESIGN STUDY TEAM



THE EINSTEIN TELESCOPE, the European vision for a third-generation gravitational-wave detector, would consist of three interferometers formed into a triangle, with 10-kilometer-long arms. To minimize noise, it would be underground and cooled to around 10 K.

detectors to optimize for different frequency ranges. Sensitivity at high frequencies (up to 10 kHz for the Einstein Telescope) is increased by high power, which, due to heat absorption, radiation pressure, and other factors, conflicts with cryogenics and low laser power needed for low frequencies (2–40 Hz). The laser wavelengths, mirror materials, and mirror suspensions would also differ for the low and high frequencies. The data would be combined into a single output. Separating the frequencies, says Punturo, “reduces risk and adds complications. There is no free lunch.”

With the low-frequency interferometers, scientists aim to detect massive objects, such as coalescing black holes—each tens or hundreds of solar masses in size—and to investigate general relativity in intense gravitational fields. With the interferometers that are optimized for higher frequencies, they will, for example, pursue the details of binary neutron star mergers and look for signals from supernova explosions. And, Punturo notes, using the full system will allow scientists to alert electromagnetic telescopes before the merging phase of neutron stars that generates gamma-ray bursts.

The frequency-optimized interferometers are among the features of the Einstein Telescope that will be refined, says Punturo. The observatory was designed to be the world’s sole third-generation gravitational-wave detector. If more are built, he says, “we can relax constraints on the Einstein Telescope.”

With Cosmic Explorer, the US is going with a “super-LIGO” approach—an L-shaped interferometer with arms 40 kilometers long, 10 times the length of LIGO’s arms. “To win in gravitational science,” says MIT’s Matthew Evans, “you need a long detector. Ten times longer will give you a factor of 10 in sensitivity.” Given the high cost of digging tunnels, US scientists are counting on getting more length for their buck by staying on the surface. To make up for Earth’s curvature, Cosmic Explorer’s arms would have to be either raised or trenched.

Evans heads a team that in August won a grant from NSF to look broadly at next-generation gravitational-wave detectors. Researchers from five universities have about \$2.2 million over three years to assess what would make the best global constellation of gravitational-

wave detectors, determine the likely science targets for third-generation detectors, and participate in international planning of gravitational-wave astronomy.

“The first part of our study,” says Evans, “is to look at the scientific potential of a network of detectors. What is the best composition of this network?” For example, he says, if the world has one facility like the Einstein Telescope, which would extend to the lowest frequencies, “we might be best served by having one or two Cosmic Explorer-type observatories.” Existing facilities, including the underground cryogenic Kamioka Gravitational Wave Detector in Japan, which is set to turn on next year, will be part of a future network of gravitational-wave observatories. Sources can be more accurately located by triangulation with more observations from spread-out sites. The NSF exercise, Evans says, will “set the foundation to move on to a detailed design study” for Cosmic Explorer.

In the meantime, LIGO will undergo upgrades, which will feed into decisions about future observatories. The facility is scheduled for an upgrade to be completed in 2024 to nearly double the sensitivity. The improvements will include squeezing light to reduce the quantum noise of the laser across the entire frequency band from 10 Hz to 10 kHz. (See PHYSICS TODAY, November 2011, page 11.) Another planned measure is to reduce thermal noise by changing the mirror coatings. “And there are a bunch of smaller things—changing the thickness of suspension fibers, using bigger beam splitters, and the like,” says the University of Florida’s David Reitze.

Beyond the planned upgrades, says Reitze, “we think it’s possible to get another factor of two in sensitivity on LIGO.” That would involve replacing fused-glass mirrors with silicon and cooling to 123 K, at which the thermal expansion goes to zero. The improvements tested on LIGO would also be implemented on Cosmic Explorer, where they could up the sensitivity even beyond the factor of 10 achieved by increasing the arm length.

Last year the Gravitational Wave International Committee, established in 1997, formed a subcommittee focused on third-generation facilities. GWIC is made up of representatives from the ground-based observatories; the pulsar-timing

gravitational-wave projects (see PHYSICS TODAY, July 2017, page 26); and LISA, the Laser Interferometer Space Antenna that the European Space Agency plans to launch in 2034 (see PHYSICS TODAY, June 2011, page 22). The third-generation subcommittee, chaired by Punturo and Reitze, has delegated groups to look for ways to optimize international collaboration in technology development, science, governance, and more. The next-generation detectors will cost upwards of a billion dollars apiece.

Science revolutions

Bangalore Sathyaprakash of the Pennsylvania State University and Cardiff University cochairs a GWIC subcommittee on science. By the end of the year, the subcommittee is to have prioritized the science for third-generation facilities.

Among the most important questions that gravitational-wave observatories can address, says Sathyaprakash, is the equation of state of dense matter. “How does matter behave when you make it more and more dense?” It may seem strange that it’s possible to learn something about nuclear physics from gravitational-wave observatories, “but nature has provided neutron stars. When they spiral toward each other, they exert tidal forces, and that makes them merge faster. The signature of the neutron star structure is present in gravitational waves.”

Multimessenger studies with neutrinos and cosmic rays contribute to “an era that is not too far in the future,” says Sathyaprakash. For example, the relative delay of neutrinos compared with gravitational waves coming from the same source could provide an independent measurement of neutrino masses.

For cosmology, says Sathyaprakash, take a binary merger. A gravitational-wave observation provides the distance to the host galaxy, and an electromagnetic observation can give the redshift. From their relationship, the Hubble constant can be inferred using current detectors, and more-sensitive detectors will be able to pin down the universe’s energy content in terms of dark energy, dark matter, and baryons. And, he says, because the redshifts of binary neutron stars can be inferred from gravitational-wave observations alone, it should one day be possible to do cosmology





THE US VISION for a future gravitational-wave observatory is a souped-up version of the detectors currently employed by the Laser Interferometer Gravitational-Wave Observatory. The Cosmic Explorer would have 40-kilometer-long arms and sit on Earth's surface; land is plentiful in the US. The top shows a visualization of a black hole merger.

with just gravitational-wave detectors.

Another research area for the next generation of gravitational-wave detectors will be black hole demographics. It may be possible to learn how the compact objects that seeded galaxies in the early universe came to be, says Sathyaprakash. Some galaxies harbor supermassive black holes—up to 10 billion solar masses—at their centers. “We don’t know how they got there and how they got so big.” Mergers of really big black holes may be observed by LISA, which with its arm length of 2.5 million kilometers will be sensitive to lower frequencies, but if small black holes formed first and then merged, “you would need something like the Einstein Telescope or the Cosmic Explorer,” he says.

Future detectors would allow scientists to differentiate between black holes and speculative objects like wormholes and gravastars, says Sathyaprakash. According to the no-hair theorem, a black hole is completely characterized by its mass, charge, and spin. As a black hole

merger settles down, its emitted gravitational radiation should depend only on the combined mass and spin—astrophysical black holes are not expected to be electrically charged. “It would be fantastic to test the no-hair theorem,” he says.

Going forward

The next step for the Einstein Telescope is to land a spot on the road map of the European Strategy Forum on Research Infrastructures. That stamp of approval is key to getting funding both from individual countries and from the European Union. The application, to be made sometime next year for the 2020 road map, will include at least three possible sites—so far testing is under way for sites in Sardinia; in Hungary’s Mátra mountain range northeast of Budapest; and at the border region of the Netherlands, Belgium, and Germany. A site is to be selected in 2022, the design completed by 2023, and commissioning begun in 2030, says Punturo. Cosmic Explorer

could start up sometime in the mid 2030s.

LIGO and its European counterpart, Virgo, started as competitors and later collaborated. Now, as the world’s gravitational-wave scientists look to future facilities, they are working to exploit synergies early on. “Many of us are convinced that putting forces together, given the difficulty of the task, will increase the scientific payoff,” says Giovanni Losurdo, an INFN researcher in Pisa and a member of the GWIC subcommittee on R&D.

No single technical challenge stands out, Losurdo says, but there is an ambitious set of goals to improve the detector sensitivity across the whole frequency range, go underground, design a better vibration-isolation system, and optimize materials for the mirrors, coatings, and suspensions. “The combination constitutes a fantastic challenge, but we do not see any showstoppers so far.”

A focus of GWIC is to determine how to run the next-generation gravitational-wave detectors. Everything is being considered, from a rigid organization akin to CERN’s—albeit without treaties since the US would then be unlikely to sign on—to a collaboration of collaborations, as with the current cadre of gravitational-wave detectors. “I’m for a unified model with a strong central management,” says Reitze. Setting up agreements among scientists and agencies will be difficult, he admits, but if it happens, the facilities “could cost less, and you could allocate people to solve problems. A central management guarantees coordinated planning for observing.” The GWIC subcommittee looking into organization and management is set to present recommendations in 2019.

The most important thing right now, says Barry Barish, who shared the 2017 Nobel Prize for his role in LIGO, is to set scientific priorities to make the most out of finite cash. “One extreme approach is to use a cookie-cutter design and build five [observatories] around the world; the other is to make the best possible single facility—the European approach so far. It’s different science, that’s why you need science priorities.” And, he adds, “We are not limited by nature. We just have to figure out how to milk the current generation of facilities and then how best to evolve.”

Toni Feder