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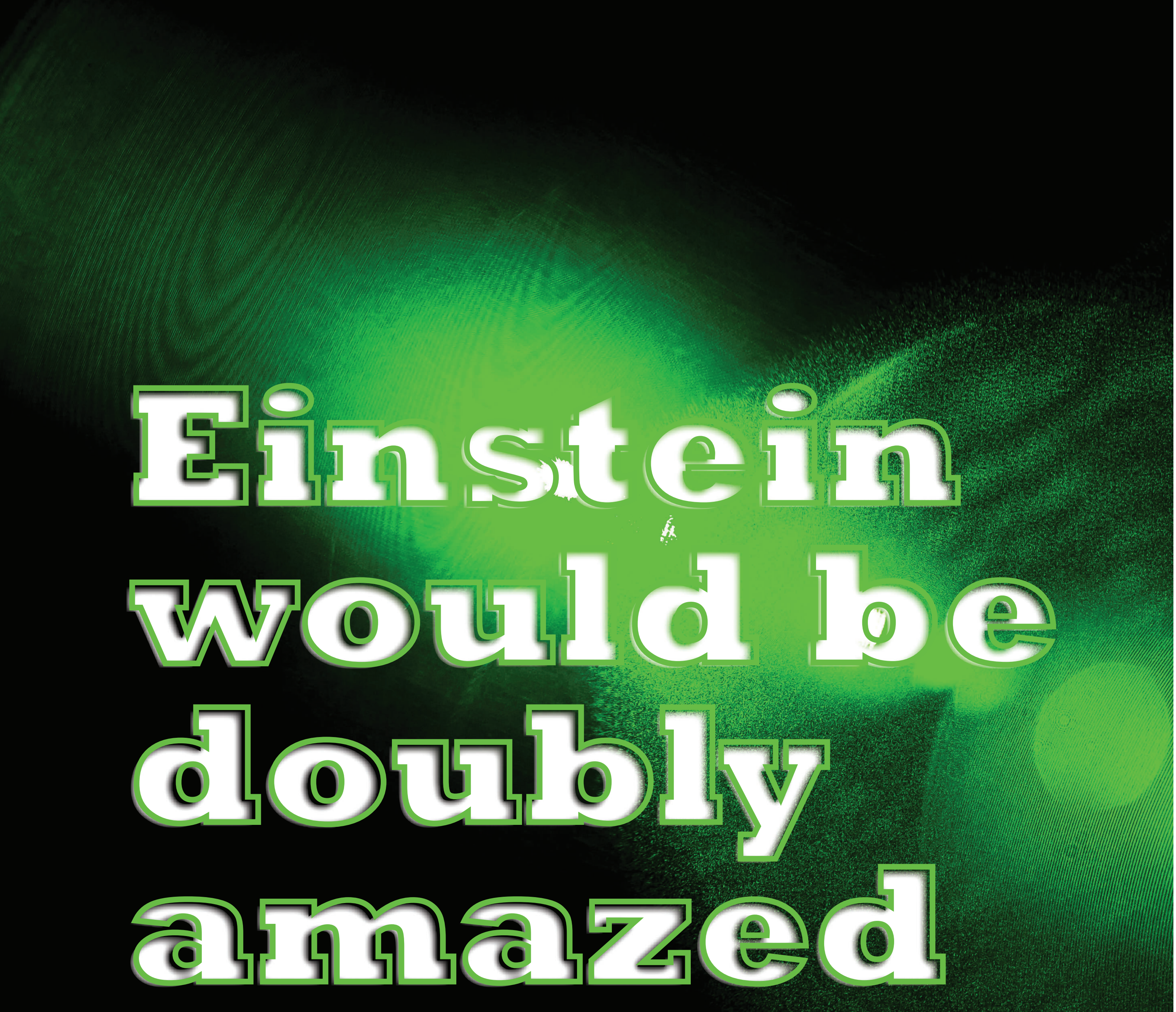

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Quantum-correlated light embodies all the weirdness of quantum physics. Now it is being used to aid in the observation of another exotic phenomenon: gravitational waves.

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Scientific history was made with the first observation of gravitational waves in 2015. The signal recorded by the Laser Interferometer Gravitational-Wave Observatory (LIGO) came from 1.3 billion light-years away and was generated by the merging of two black holes.[1] (For more on LIGO and gravitational-wave detection, see PHYSICS TODAY, April 2016, page 14, and the article by Barry Barish and Rainer Weiss, PHYSICS TODAY, October 1999, page 44.) The data were published the following year, 100 years after Albert Einstein's prediction of gravitational waves.[2]

Interestingly, during his later life, Einstein was no longer convinced that gravitational waves existed. In 1936 he prepared a manuscript that claimed he had mathematically proven their nonexistence. But after Howard Percy Robertson convinced him that the proof was flawed, Einstein completely rewrote it and subsequently said that he did not know whether there were gravitational waves (see the article by Daniel Kennefick, PHYSICS TODAY, September 2005, page 43). Since the existence of gravitational waves was only rigorously deduced from the general theory of relativity after Einstein's death, it can be assumed that his thoughts remained inconclusive on the question.

Einstein was also concerned with a particular consequence of quantum physics, namely quantum entanglement, or more generally quantum correlation. The effect was first mentioned as a thought experiment, now known as the EPR paradox, in a 1935 paper written by Einstein and his colleagues Boris Podolsky and Nathan Rosen.[3] The authors hypothesized that quantum correlations proved the incompleteness of quantum theory. Today, however, we know that Einstein and his colleagues were wrong, and it has since been proven that quantum theory is complete within its scope. Still, physicists struggle to make the physics of quantum-correlated systems understandable without adding assumptions that go beyond quantum theory.[4]

Without question, Einstein would be amazed that we are now using gravitational waves to understand the universe, that the first observations have already discovered a larger number of black holes in the universe than previously assumed, and that future observatories are expected to probe the first fractions of a second of the Big Bang. But I suspect that he would be doubly amazed to know that the quantum correlations that he and his two colleagues described in 1935, which still elude a self-evident physical understanding, are now being used as a tool to improve observations of gravitational waves.

The weirdness of quantum physics

In general, characterizing the spread of a quantum measurement's uncertainty requires a so-called ensemble measurement using many copies of the system of interest. All copies must be in the same quantum state, and the measurements need to be identical and precise enough to resolve the spread of the uncertainty. Although the settings for the measurements are identical, the individual outcomes nevertheless scatter around a mean value. The scatter range is the quantum uncertainty. In most cases, its size is completely characterized by the value of its standard deviation.

The scatter is truly random because quantum theory is complete; there are no hidden variables that could cause a particular value to occur. In quantum optics, for example, a system of interest is a Fourier-limited wave packet. The mathematics and physics of the Fourier transform enforce that the energy of such a wave packet, which is given by its quantum states, is homogeneously smeared over the entire wave packet. Measurements that resolve the energy distribution of the wave packet must therefore have results with a random distance from the mean. Such measurement results are used as quantum random numbers—they cannot be predicted, not even by a quantum computer, simply because they are truly random.

Quantum correlations refer to patterns within that randomness. A pattern of any kind could logically be viewed as counterevidence of randomness, and it is understandable that the existence of quantum correlations led scientists in the mid 20th century to question the true randomness in quantum physics. Einstein, Podolsky, and Rosen suspected the existence of so-called hidden variables, which are not part of quantum theory and would precisely specify the results of quantum measurements. The existence of hidden variables would make quantum theory incomplete,[3] and quantum randomness would never be real, only apparent. Einstein spent the rest of his life searching for a complete theory, albeit unsuccessfully.

By the 1980s the experimental violation of so-called Bell inequalities finally made it clear that quantum theory is complete, that it has no hidden variables, and that wave-packet-resolving measurements must lead to truly random results.[4] The experiments also confirmed that quantum correlations within quantum uncertainties exist—a finding that seemingly contradicts the randomness of quantum measurements. That weirdness still has not been resolved. Famous quantum-correlated states include EPR entangled states, Schrödinger-cat states, and squeezed states.

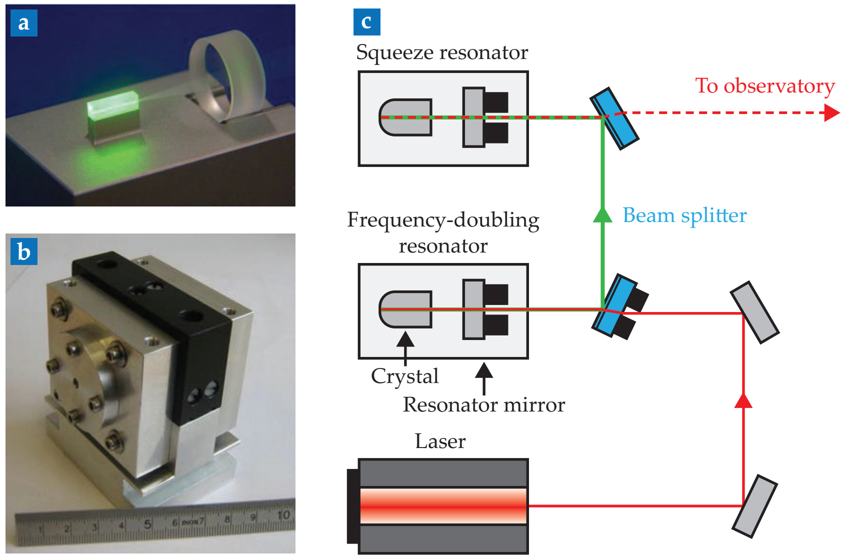

FIGURE 1. GENERATING SQUEEZED LIGHT. (a) The semimonolithic squeeze resonator shown here uses a periodically poled potassium titanyl phosphate crystal with a mirrored back and a separate resonator mirror to generate squeezed light. The crystal is pumped with green laser light with a wavelength of 532 nm. The squeezed light is created at the invisible wavelength of 1064 nm. **(b)** To produce a measurable squeezing effect, a squeeze resonator must be housed in a temperature-stabilized device like this one to maintain a specific temperature, typically 40 °C, at which both wavelengths have the same propagation speed over the entire crystal. **(c)** To generate squeezed light for gravitational-wave detectors, laser light (red) with the same frequency *f* as the light in the interferometer undergoes frequency doubling in a resonator. That light, with frequency 2*f* and shown in green, goes through a beam splitter that's highly reflective at *f* and highly transmissive at 2*f*. It is then used to pump the squeeze resonator. (Adapted from ref. 5.)

Exploiting correlations with randomness

Squeezed light is produced by pumping a crystal inside a laser resonator (see figure 1), similar to how a conventional laser works. What's different is that the crystal is pumped with laser light, rather than light from a hot lamp, and that light must have exactly twice the frequency of the desired squeezed light. And the crystal needs to have a high second-order nonlinearity; that is, it needs to be suitable for frequency doubling of laser light.

Squeezed-light generation is based on degenerate optical parametric down-conversion, which is the reverse of the process used for frequency doubling of conventional laser light. A nonlinear crystal converts the pumping field, with optical frequency $2f$, into two indistinguishable fields with frequency f. The amplitude of any optical field must have a quantum uncertainty, and the same is true for the individual down-converted fields, which leads to an interesting situation: The amplitudes of the fields are uncertain, but they are nevertheless always identical. The result is the abovementioned quantum correlation—the correlation within a random measurement results from quantum uncertainty.

Squeezed light has its strongest quantum correlations when the laser producing it operates slightly below its oscillation threshold.[5] As a result, its beam is dim. To make a bright amplitude-squeezed laser beam, it must overlap with a conventional laser beam of the same wavelength with the optimal phase difference. Measurements on such a beam produce squeezed photon-counting noise like that in figures 2b and 2d.

LIGO and two other gravitational-wave observatories, GEO600 and Virgo, are now using squeezed states of light to reduce the noise in light's quantum uncertainty and thereby improve the observatories' sensitivities.[5–9] Figure 3 shows a schematic of the underlying optical layout. In addition to a conventional laser, the setup requires a laser that produces squeezed light whose optical field exhibits quantum correlations in time. When light from the two lasers is superimposed in an interferometer, the light fields in its arms become EPR entangled. And, more importantly, the output field at the photodiode—which would contain any gravitational-wave signal—exhibits squeezed quantum noise. Figure 2 illustrates the improvement in photon-number statistics caused by using squeezed light. The reduction in standard deviation between figures 2a and 2b, which is caused by squeezing, improves the visibility of the gravitational-wave signal shown in figures 2c and 2d.

By itself, the best conventional laser produces a distribution of photon counts that is truly randomly distributed around a mean value $\langle N \rangle$. Consider, for example, a quasi-monochromatic laser beam whose residual spectral energy distribution is Gaussian with a half width Δf. The mathematics of the Fourier transformation enforces that the energy in the laser beam must be homogeneously smeared over a Gaussian wave packet with half width $\Delta t = 1/(4\pi\Delta f)$, where Δt corresponds to half the wave's coherence time.

Now imagine that photodiode measurements determine the beam's energy in a short time window $\Delta T \ll 2\Delta t$. It's well known that the energy values are integer multiples of the photon energy. But it is impossible for the detected photons to be in the short time window ΔT before the measurement because the Fourier transform forces their energy to be homogeneously smeared over $2\Delta t$. Consequently, the photon events recorded must have occurred only during the measurement and in a truly random manner.

In the absence of any quantum correlations, the photon statistics would reflect mutually independent random parti-

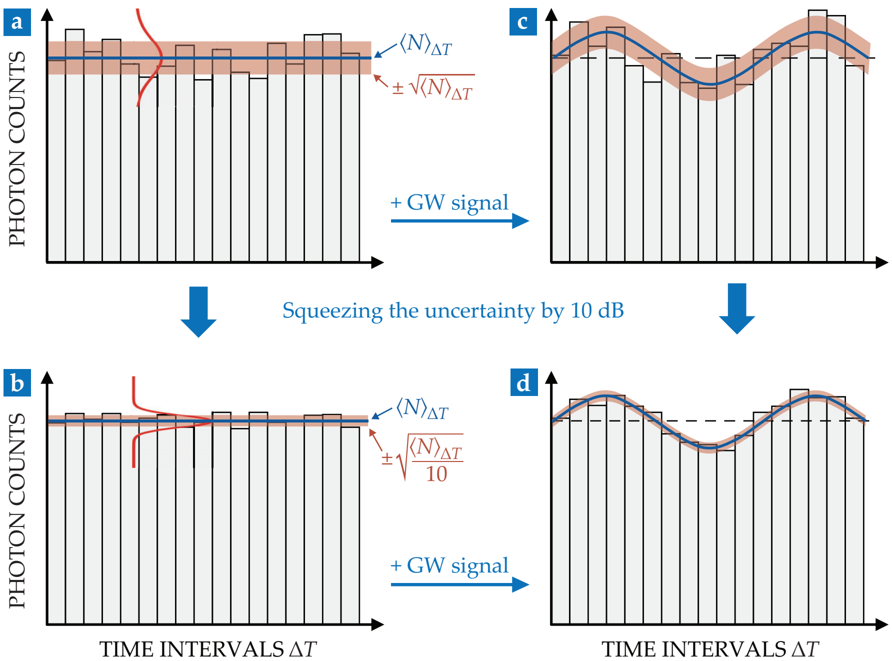

FIGURE 2. QUANTUM STATISTICS of photon counts. **(a)** The photon numbers measured in short time intervals $\Delta T \ll \Delta t$, where Δt is the coherence time of the light, are uncorrelated; they correspond to random, mutually independent photon events. If the mean number of photons per time window is large, $\langle N \rangle_{\Delta T} \gg 1$, the quantum uncertainty in the photon number is described by a Gaussian distribution (red curve) with standard deviation $\Delta N_{\Delta T} = \sqrt{\langle N \rangle_{\Delta T}}$. **(b)** For a beam that has the same coherence time but is in an amplitude-squeezed state, the photon counts are random but correlated with each other, which produces a narrower distribution; here it's squeezed by a factor of $\sqrt{10}$. **(c)** Adding a sinusoidal gravitational-wave (GW) signal to the photon-count noise illustrates the difficulty presented by conventional quantum noise. **(d)** Using a squeezed light improves the signal-to-noise ratio for the same GW signal. (Adapted from ref. 10.)

cles, as shown in figure 2a, and the light measured during the interval ΔT would be in a so-called coherent state. In that case, the properties of the Poisson distribution apply: If $\langle N \rangle$ photons are found on average over ΔT, the standard deviation is $\sqrt{\langle N \rangle}$.

With squeezed light, the spectral width Δf of the detected light is constant, so the photons still cannot be localized in the short time window ΔT—the mathematics of the Fourier transform cannot be avoided! And the photons must occur randomly, as with a conventional laser. Curiously, though, the photon numbers for squeezed light measured over ΔT vary less than $\sqrt{\langle N \rangle}$. The distribution's unexpectedly sharp peak is a manifestation of the quantum weirdness that is observed in all gravitational-wave observatories.[10] Since the Fourier-transform constraint still holds, the photon numbers measured in each time window must still result from a truly random process. At the same time, such processes must be correlated. Both of those facts must be reflected in the yet-to-be-found solution to the apparent weirdness.

Observatory incorporation

Since April 2019, all gravitational-wave observatories worldwide have been using lasers that produce squeezed light as additional light sources. The squeezed light is spatially overlapped with the conventional, more powerful beams in the interferometer arms to produce squeezed-photon statistics—and therefore less noise—at the photodiode detector (see figure 3). LIGO and Virgo register on average more than one gravitational-wave event per week when they're taking data, and quantum-noise squeezing has improved the signal-to-noise ratio of those events.[11,12] It has also increased the average detection rate of binary-neutron-star mergers by up to 50% in LIGO and 20% in Virgo.[8,9] Discoveries aided by squeezed light also include black hole mergers and binary systems consisting of a black hole and a neutron star, all of which are recorded in a catalog of gravitational-wave events.[11,12]

The gravitational-wave detector GEO600 took on a pioneering role with its implementation of squeezed light[7] in 2010 (see Physics Today, November 2011, page 11). Figure 4 shows a photo of the GEO600 squeezed-light laser, which was designed and built by my group at Leibniz University Hannover in Germany in 2009. It was the first such laser that was designed for indefinite use and started completely at the push of a button. The device has since been an integral part of GEO600's search for gravitational waves and is still in operation.[13,14] Many physicists had previously argued that quantum-correlated light would be too error prone for gravitational-wave observatories, given that their goal is to record data 24 hours a day and, if possible, 365 days a year. But the GEO600 detector's squeezed-light source was so reliable that scientists at LIGO and Virgo decided to start using squeezed light as well.

Why wasn't squeezed light built into gravitational-wave observatories much earlier? One reason is that the technology had yet to be developed. Reference 6 provides a review of the challenges. The main reason, however, was that squeezed light was unnecessary as long as the light power in the interferometer's arms could be increased without major difficulties. At 10 times the light power, the gravitational-wave signal's power also increases tenfold, but the quantum noise only increases by $\sqrt{10}$, thereby providing greater sensitivity. From the beginning, gravitational-wave observatories were designed for high light powers. Building up the power in the arm resonators and incorporating minimally absorbing mirror materials and coatings significantly improved the observatories' sensitivities.

Squeezed light was not planned for Advanced LIGO, Advanced Virgo, or GEO600 at the start of construction. In the early 2000s, however, it became clear that the residual absorption of the light in the mirrors and beam splitters of all three observatories would make achieving the design sensitivities difficult, costly, and perhaps impossible on the targeted time scales. The major technological breakthroughs in the production of squeezed light for gravitational-wave detection[6] occurred in the groups of David McClelland and Ping Koy Lam at the Australian National University in Canberra and in my

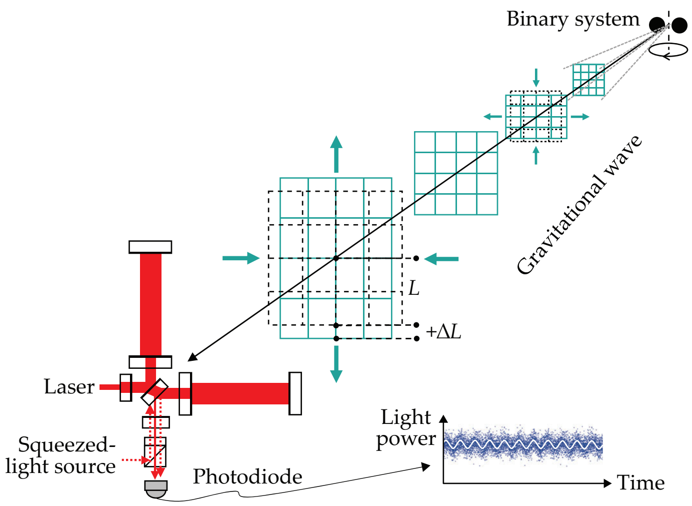

FIGURE 3. GRAVITATIONAL-WAVE DETECTION. A gravitational wave with amplitude $\Delta L/L$ dynamically expands and compresses spacetime perpendicular to its direction of propagation. Laser light propagating along an expanding spacetime axis is redshifted, whereas light moving along a shrinking spacetime axis is blueshifted. The effect is observed with Michelson interferometers that translate those frequency shifts into changes in the power output. All mirrors are suspended as pendulums and are decoupled to the greatest possible extent from environmental forces. The squeezed light reduces photon shot noise at the photodiode such that the sinusoidal signal in the noisy blue data becomes visible. (Adapted from ref. 10.)

group at Leibniz University Hannover between 2004 and 2009. Implementing squeezed-light production in GEO600 improved the detector's sensitivity without increasing the light output.

Pushing performance

The use of quantum correlations in gravitational-wave observatories has been more than just a demonstration. Squeezed light has established itself as a technology that can improve performance at lower cost than potential alternatives. The cost of constructing a suitable laser that produces squeezed light can be estimated at a few hundred thousand euros. On the other hand, increasing the arm length of an observatory is a significantly more expensive proposition. The fact that GEO600, LIGO, and Virgo are still operating with optical powers in the arms below the design specifications reflects how valuable squeezed light is for improving photon statistics.

So far, the highest squeeze factor achieved in the signal output of a gravitational-wave observatory was at GEO600 with the laser shown in figure 4. The corresponding sensitivity improvement is equivalent to what would be achieved by a factor-of-four increase in light power in the arms.[14] Although lasers can deliver squeezed light with larger squeeze factors—well over 10 in the case of Virgo's laser—optical losses from decoherence limit the final value. If, for example, only 60% of the squeezed light is registered by the photodiode after passing through the interferometer, the squeeze factor drops[8] from 10 to approximately 2.2. Currently, an optical loss of 40% is typical, given absorption, scattering losses, imperfect beam superposition when the squeezed-light beam couples to the conventional beam, and the imperfect quantum efficiency of the photodiode. But keep in mind that today's observatories were not designed to use squeezed light. Future observatories could achieve losses of less than 10%, in which case a squeeze factor of 10 could become realistic.

Loss caused by decoherence is a fundamental problem with the use of quantum-correlated states. If energy is lost to the environment, the strength of the quantum correlation decreases. Fortunately, squeezed states are still relatively insensitive to decoherence. And, to put the problem in perspective, reducing optical loss is indicated as the way to increase sensitivity at gravitational-wave observatories regardless of whether they use quantum correlations. Incorporating squeezed light just increases the benefit of reducing losses.

Optical loss is also the reason why no quantum-correlated states are being planned for the Laser Interferometer Space Antenna, or LISA, a future space-based gravitational-wave observatory. The huge arm lengths of 2.5 million kilometers will cause so much divergence of the laser radiation that only a small fraction of the photons will be registered. The gain from squeezed light would be minimal. Still, squeezed light has become an indispensable part of gravitational-wave astronomy. It will be an important factor in achieving the significantly increased measurement sensitivities targeted by the next generation of proposed ground-based gravitational-wave observatories, such as the Einstein Telescope and Cosmic Explorer.

More uses for squeezing

Light with squeezed quantum uncertainty has a clear benefit when increasing light output is no longer straightforward. But it's also useful if mirror masses can no longer be easily increased. The four mirrors that form the arm resonators in the LIGO observatories each have a mass of 40 kg. They each consist of a piece of fused silica with low optical absorption and high mechanical quality, and they are shaped like cylinders and polished on all sides. Future gravitational-wave observatories should have mirror masses of 200 kg or more. The main reason for heavy mirror masses is that uncertainty in the laser light's properties results in uncertain radiation pressure on the mirrors—and, therefore, uncertain mirror momenta and random position changes. The result is what's called quantum radiation-pressure noise. A larger mirror mass reduces the disturbing effect.

It has been known only since the 1990s that the photon statistics on the photodiode (see figure 2) can be squeezed at the same time as the radiation-pressure uncertainty on the mirrors. It was previously thought that because of the Heisenberg uncertainty principle, reducing one type of quantum noise would lead to an increase in the other. Because of breakthroughs in understanding the nature of quantum correlations, we now know that simultaneously reducing both quantum-noise processes leads to a quantum correlation between the light field and the movement of the reflecting mirror. Those correlations were recently observed in one of the LIGO observatories using squeezed light.[15,16]

In the targeted Einstein Telescope, quantum correlations between mirror movement and reflected laser light should help the device achieve its desired sensitivity in the 2030s, thereby making the cosmic gravitational-wave background observable

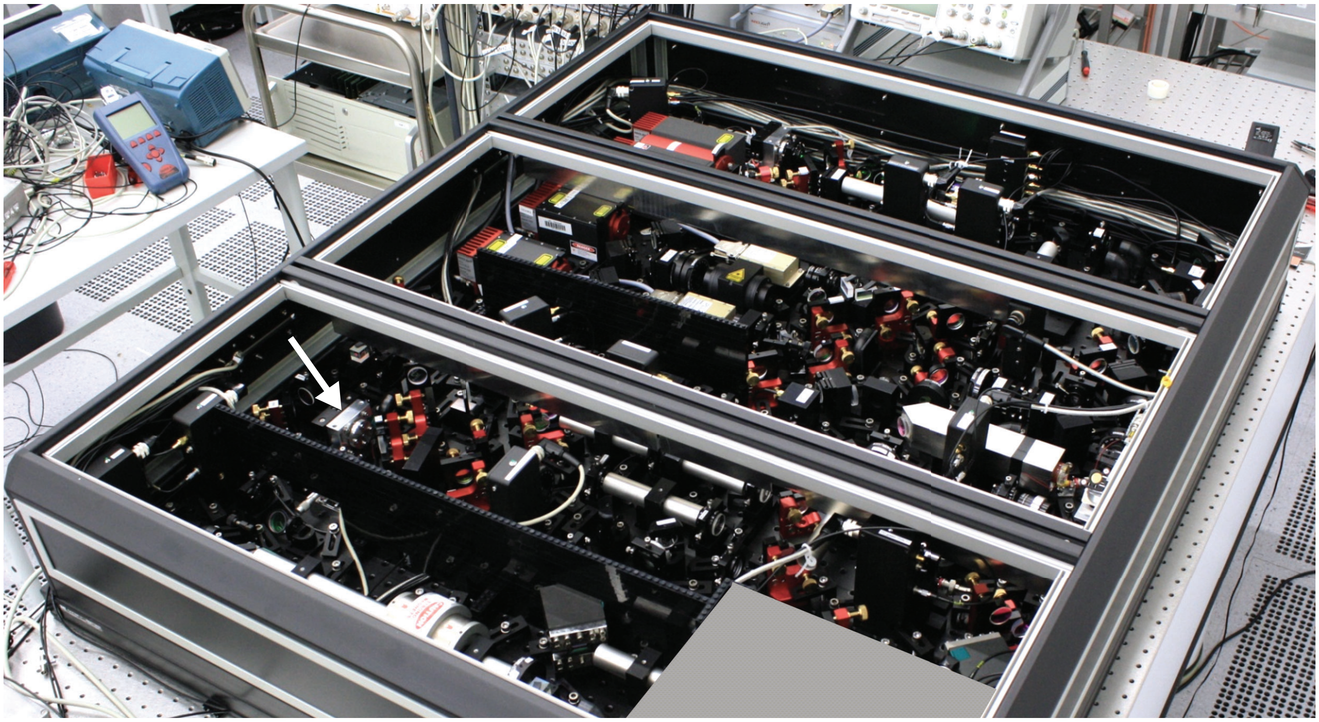

FIGURE 4. GEO600 SQUEEZED-LIGHT LASER. The device's base-plate dimensions are 135 cm × 113 cm. In keeping with the laser wavelength of today's gravitational-wave observatories, this laser produces squeezed light at 1064 nm. The white arrow indicates the squeeze resonator. Also included are three commercial lasers, a frequency-doubling resonator, lenses and mirrors to couple the light into the resonator, and other components that enable long-term stable phase control of all laser beams in the device. This laser increased the GEO600 detector's signal-to-noise ratio by up to 3.5 dB when it was first implemented[7] in 2011. That improvement has since increased[14] to as much as 6 dB. (Courtesy of Henning Vahlbruch.)

for the first time. Astronomy based on electromagnetic radiation can look back a maximum of around 380 000 years after the Big Bang, but in earlier times, the universe was opaque to electromagnetic radiation. Observations of the gravitational-wave background offer the unique possibility to gain information about the first tiny fraction of a second after the Big Bang.

Quantum-correlation technology

Advances in optical measurement technology for gravitational-wave astronomy can also be applied to similar technology for industry and medicine. If light output can no longer be easily increased to improve a device's sensitivity, using quantum-correlated light is an alternative as long as the measuring method allows enough quantum-correlated light to be captured. Light output may be difficult to increase for many reasons. If it is above the eye-safe range, for example, costs for laser protection arise. Light sensitivity is also often a problem in the use of lasers to probe medical and biological samples. With squeezed light one could achieve higher measuring sensitivities with lower light output to avoid cell damage.

Many scientists and governments are expecting a so-called second quantum revolution. The first quantum revolution was driven by, among other things, the development of the laser, which is now a part of many everyday devices. The second quantum revolution could be broader. The best-known development would be the quantum computer, which is based on quantum-correlated building blocks. (See, for example, the article by Lieven Vandersypen and Mark Eriksson, Physics Today, August 2019, page 38.) Another example is secure communication and quantum cryptography. Approaches with quantum correlations make it possible to secure not only the communication channel but also the laser devices and measuring equipment. (See the article by Marcos Curty, Koji Azuma, and Hoi-Kwong Lo, Physics Today, March 2021, page 36.)

Quantum technologies can rely on quantum physics with or without quantum correlations. But those that do use correlated systems are now enabling advances that could be appropriately dubbed quantum-correlation technologies. Although squeezed light has so far been developed into an end-user product in gravitational-wave observatories, its potential uses in industry and medicine could lead to one of the first commercial quantum-correlation devices.

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