PHYSICS

Photon tricks probe gravity

Suppressing quantum noise could make gravitational-wave detectors more sensitive.

BY ELIZABETH GIBNEY

Gravitational-wave observatories have some of the most sensitive detectors on the planet, which allows them to spot the faint ripples in space-time that pass through Earth from the collisions of massive black holes billions of light years away. But their ability to catch more subtle signals is constrained by fundamental quantum limits. Now physicists are devising tricks to get around this problem. The goal is to peer farther into the Universe and to spot the effects of collisions between less massive objects, such as neutron stars.

The US-based Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) is already planning to use photonics techniques to 'squeeze' light. That should increase LIGO's sensitivity by 50%. Quantum physicists from outside the gravitational-wave community are pitching in with new ideas, too. In *Nature* this week, they describe a technique that could, in theory, double the sensitivity of detectors (C. B. Møller *et al. Nature* **547,** 191–195; 2017).

"We've been eagerly looking for applications where quantum limits have already been reached," says physicist Eugene Polzik at the Niels Bohr Institute in Copenhagen, who led the latest work.

LIGO'S QUANTUM LIMITS

Each of LIGO's detectors, based in Hanford, Washington, and Livingston, Louisiana, consists of two 4-kilometre-long tunnels perpendicular to one another, with mirrors at both ends. A beam of laser light is split and bounced back and forth along each tunnel. A gravitational wave stretches one arm and squeezes the other. Because light then travels a different distance down each arm, the two beams are out of sync when they are recombined. Using this method, LIGO can spot shifts as small as 10^{-19} metres — about one ten-thousandth the width of a proton.

Engineers shield LIGO from the rumble of distant trucks and compensate for tiny temperature fluctuations. But the quantum nature of laser light creates fundamental uncertainties in measurement. It's impossible to know exactly how many photons are in the laser beams that reach LIGO's detectors, creating noise in the distance measurement. Photons also impart a kick of momentum to LIGO's mirrors as they hit them. As photon numbers fluctuate, they shift the mirrors by an unknowable amount, adding further uncertainty. Polzik and his team get round the latter limit by giving photons an opposite kick to compensate. In their set-up, laser light passes through a cloud of caesium atoms before it hits its target — which is a membrane, rather than a mirror. The researchers artificially inverted the atomic spins of the caesium atoms, so that a passing photon's kick flips the atomic spins to a lower, rather than a higher, energy state. By taking measurements of the membrane's position from the point of view of this atomic cloud, the effects of both kicks can be cancelled out — in principle entirely. In practice, the technique allowed the team to cut uncertainty by 34%.

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The method is exciting, says Nergis Mavalvala, a physicist at the Massachusetts Institute of Technology in Cambridge and member of the LIGO collaboration. "Even though exactly how it would work in a gravitational-wave detector is technically quite unexplored, the first calculations look promising," she says. Polzik's team is now working with the University of Moscow and the Russian Quantum Center in Skolkovo near Moscow to develop the idea further. The team is also discussing its method with gravitational-wave researchers at LIGO and at the Max Planck Institute for Gravitational Physics in Hanover, Germany, which operates a smaller gravitational-wave detector, called GEO600. Adapting the technique could take five to ten years, but it has the potential to double the sensitivity of the detectors, says Polzik, which would mean covering an eight times larger volume of the Universe. "Now that begins to sound serious," he says.

SQUEEZED LIGHT

Physicists at LIGO are independently planning to use a technique called squeezed light to suppress quantum noise. This is already used at GEO600 and was trialled in an earlier phase of LIGO. It is impossible to simultaneously reduce uncertainty about two complementary properties of photons — such as position and momentum. But it is possible to 'squeeze' light to reduce uncertainty in one of these dimensions, at the expense of an increase in the other.

The precision with which LIGO can detect high-frequency gravitational waves is limited by fuzziness in the number of photons that hit LIGO's detectors — and researchers can squeeze just that dimension. For detecting low-frequency waves, however, it is fluctuations in momentum that limit precise measurement. To simultaneously reduce the noise for both effects requires light to be differently squeezed for different frequencies of wave. In about five years, LIGO aims to begin using a device called a filter cavity to do this, which should improve sensitivity across LIGO's entire detection band.

Others hope additional quantum tricks will remove the need for extra equipment. Yiqiu Ma at the California Institute of Technology in Pasadena and his colleagues have theorized a way of squeezing light for all frequencies by entangling two beams — meaning that their properties are intrinsically linked, so that measuring the uncertainty in one predicts the uncertainty in the other. The quest to push the limits of quantum measurement can yield benefits beyond gravitational-wave detectors, says Polzik. "These kinds of studies are critical to exploring the very boundaries of quantum mechanics." ■

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