Doubled sensitivity could allow gravitational wave detectors to reach deeper into space

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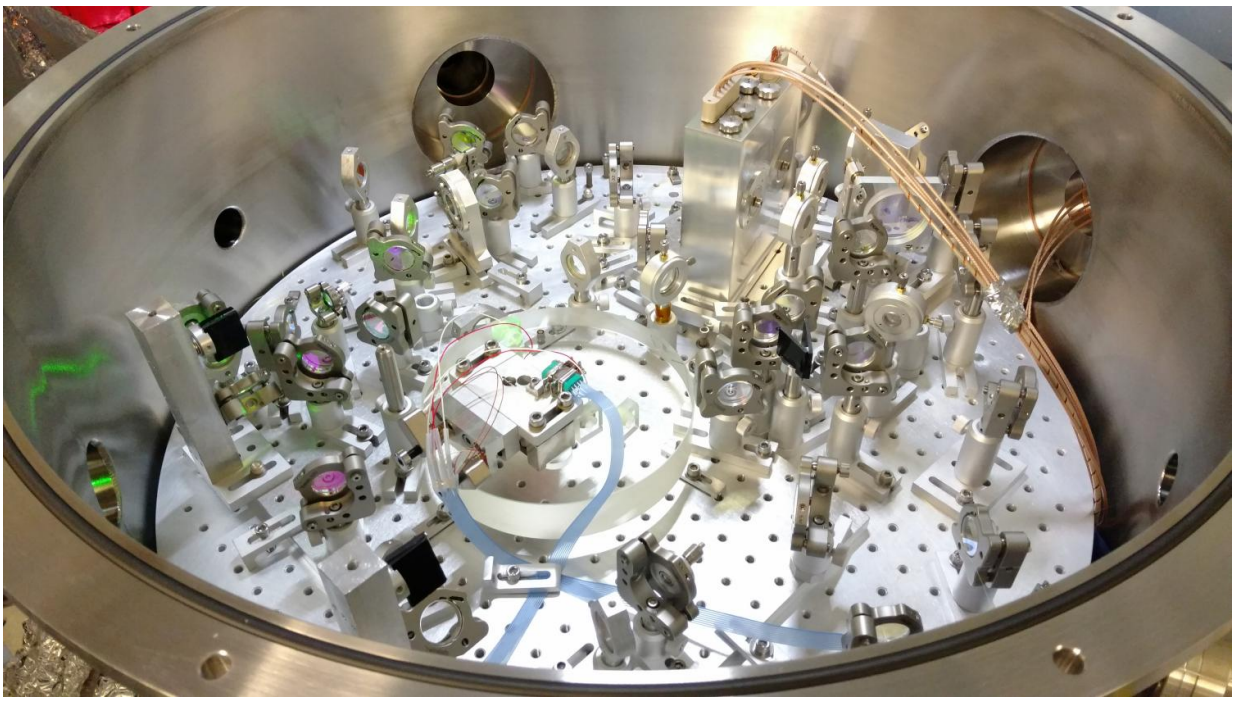

A new squeezed vacuum source could make gravitational wave detectors sensitive enough to study neutron stars. Credit: Eric Oelker, Massachusetts Institute of Technology

Researchers from the Massachusetts Institute of Technology (MIT) and Australian National University have developed new technology that aims to make the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) even more sensitive to faint ripples in space-time

called gravitational waves.

Scientists at Advanced LIGO announced the first-ever observation of gravitational waves earlier this year, a century after Albert Einstein predicted their existence in his general theory of relativity. Studying gravitational waves can reveal important information about cataclysmic astrophysical events involving black holes and neutron stars.

In The Optical Society's journal for high impact research, *Optica*, the researchers report on improvements to what is called a squeezed vacuum source. Although not part of the original Advanced LIGO design, injecting the new squeezed vacuum source into the LIGO detector could help double its sensitivity. This would allow detection of gravitational waves that are far weaker or that originate from farther away than is possible now.

A wrinkle in space-time

For millennia, people have used light as a way of viewing the universe. Telescopes magnify what is visible with the naked eye, and newer telescopes use non-visible parts of the electromagnetic spectrum to provide a picture of the universe surrounding us.

"There are many processes in the universe that are inherently dark; they don't give off light of any color," said Nergis Mavalvala, part of the MIT Kavli Institute for Astrophysics and Space Research team and a leader of the research team. "Since many of those processes involve gravity, we want to observe the universe using gravity as a messenger."

Researchers from the California Institute of Technology and MIT conceived, built, and operate identical Advanced LIGO detectors in Livingston, Louisiana and Hanford, Washington. Each observatory uses a 2.5-mile long optical device known as an interferometer to detect

gravitational waves coming from distant events, such as the collision of two black holes detected last year.

Laser light traveling back and forth down the interferometer's two arms is used to monitor the distance between mirrors at each arm's end. Gravitational waves will cause a slight, but detectable variation in the distance between the mirrors. Both detectors must detect the variation to confirm that gravitational waves, not seismic activity or other terrestrial effects, caused the distance between mirrors to change.

Studying neutron star collisions

"We want to use the Advanced LIGO detectors to sense the farthest gravitational wave or weakest gravitational wave possible," said Mavalvala. "However, this is limited by the quantum fluctuations of the laser light, which create a certain level of noise. If a gravitational wave is weaker than that level of noise, then we can't detect it. Thus, we have a big impetus to decrease that noise, and we can do that using our squeezed vacuum source."

The researchers are planning to add their new squeezed vacuum source to Advanced LIGO in the next year or so. Once implemented, it will improve the sensitivity of the gravitational detectors, particularly at the higher frequencies important for understanding the composition of neutron stars. These extremely dense stars contain the mass of the sun, which has a radius of 700,000 kilometers, within just a 10-kilometer diameter.

"Nobody knows exactly how the neutrons in these stars behave when you crush them into such a dense package," said Mavalvala. "These neutron stars sometimes collide with each other, and at the moment that they are ripping each other apart, you can study the properties of this nuclear matter by detecting gravitational waves that occur at higher frequencies."

How can a squeezed vacuum state help?

Mavalvala explains that the laser light used in the LIGO detectors can be thought of as a type of ruler. "The phase noise that results from the quantum fluctuations of the laser light is like trying to measure the length of a piece of paper while the ruler's tick marks keep wiggling and moving about," she said. "Because this noise causes the tick marks on our meter stick to jitter, we want to reduce that by injecting this special squeezed vacuum state that has smaller fluctuations, or produces less jitter on the tick marks of our ruler."

Creating the squeezed vacuum source involved modifying a vacuum state, which is the quantum state with the lowest possible energy. "We captured part of this electromagnetic vacuum in an optical cavity by first building the experiment with laser beams and then making the squeezed vacuum state by dialing down the laser power until there is no light, and only the vacuum is left," said Mavalvala. "Then, everything we would have done to the light, we can do to the squeezed vacuum state."

The improved squeezed vacuum source builds on work conducted by researchers at Leibniz University of Hannover and the University of Hamburg, both in Germany. The new squeezed vacuum source exhibits about ten times less phase noise than previously reported sources. The researchers accomplished this by decreasing vibrations that can adversely affect the squeezed state and by making improvements to a system that corrects any remaining phase noise.

"The best approach is to try to reduce the amount of intrinsic phase noise, but if you can't do that, you can measure how much it's jittering and then use feedback to correct it," said Eric Oelker, first author of the paper. "We used a variation of a correction scheme that has been employed before, but our version allowed us to increase the bandwidth of the feedback loops, suppressing the phase noise in a completely new

way."

The researchers say that the new squeezed vacuum source is almost ready to deploy in Advanced LIGO. In separate research, they have shown that they can also reduce optical losses that can degrade a squeezed vacuum state. "By combining the optical losses that we think we can achieve and this new lower phase noise result, we're aiming for a factor of two in improvements for Advanced LIGO," said Mavalvala. "We hope to achieve greater improvements in gravitational wave sensitivity than was previously thought possible."

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