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A different kind of gravitational wave detector

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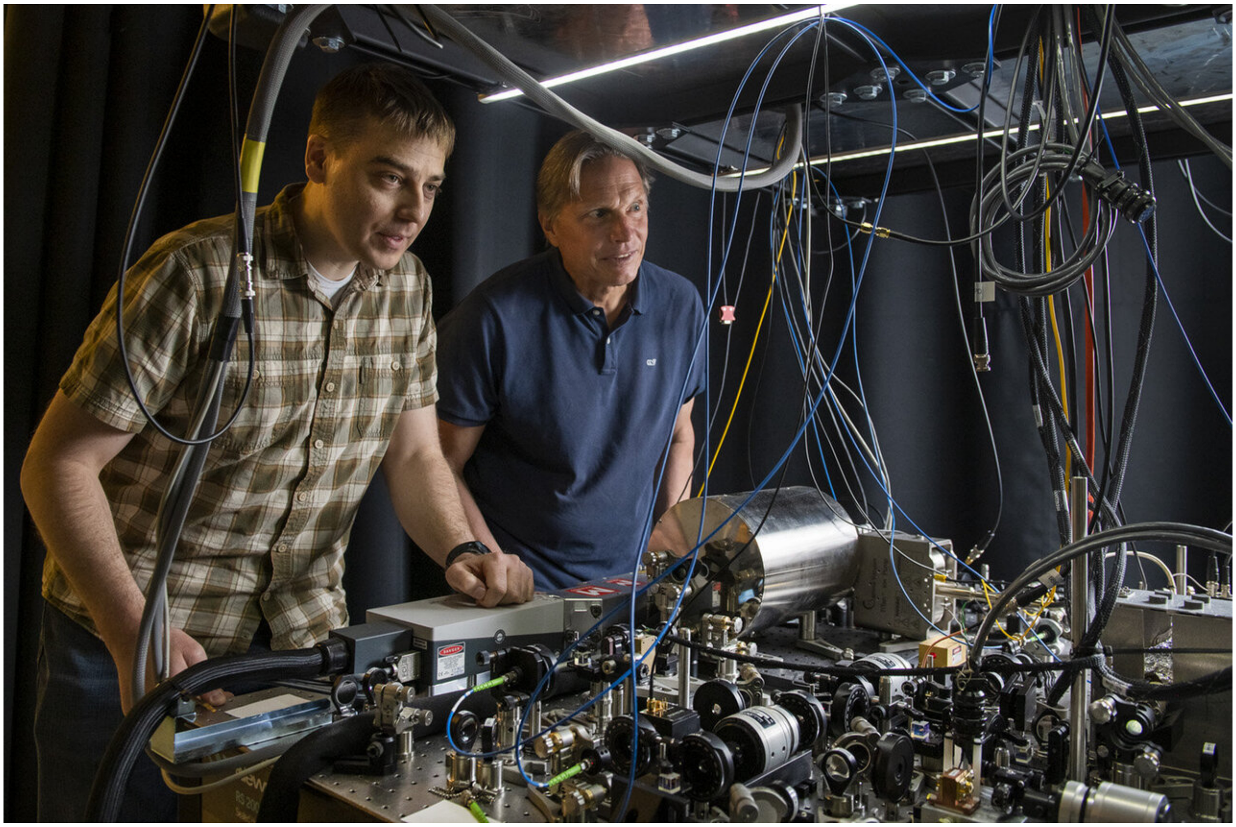

Physicists Jason Hogan and Mark Kasevich are developing a smaller-scale technique for measuring gravitational waves. Credit: L.A. Cicero

Hidden deep in a basement at Stanford stands a 10-meter-tall tube, wrapped in a metal cage and draped in wires. A barrier separates it from the main room, beyond which the cylinder spans three stories to an apparatus holding ultra-cold atoms ready to shoot upward. Tables stocked with lasers to fire at the atoms—and analyze how they respond to forces such as gravity—fill the rest of the laboratory.

The tube is an atom interferometer, a custom-built device designed to study the wave nature of atoms. According to quantum mechanics, atoms exist simultaneously as particles and waves. The Stanford instrument represents a model for an ambitious new instrument ten times its size that could be deployed to detect gravitational waves—minute ripples in spacetime created by energy dissipating from moving astronomical objects. The instrument also could shed light on another mystery of the universe: dark matter.

Stanford experimental physicists Jason Hogan and Mark Kasevich never intended for their device to be implemented this way. When Hogan began his graduate studies in Kasevich's lab, he focused instead on testing gravity's effects on atoms. But conversations with theoretical physicist Savas Dimopoulos, a professor of physics, and his graduate students—often lured downstairs by an espresso machine housed directly across the hall from Kasevich's office—led them to start thinking about its utility as a highly sensitive detector.

"We were just talking physics, as physicists often do," says Kasevich, a professor of physics and applied physics at Stanford's School of Humanities and Sciences. One thing led to another and the group landed on a bold plan for creating an atom interferometer capable of detecting gravitational waves that no one has seen before.

Their idea fits into another wave sweeping through physics, one that involves co-opting exquisitely sensitive instruments developed for other purposes to answer fundamental questions about nature.

A new detection method

In 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected a brief signal from a 1.3 billion-year-old collision between two supermassive black holes. Since then, LIGO has cataloged more gravitational waves passing through Earth, providing astronomers with a powerful new lens with which to study the universe.

Gravitational waves are ripples in space-time, much like ocean waves—except they distort space, not water. In theory, any accelerating mass, whether a waving hand or an orbiting planet, produces gravitational waves. These movements, however, occur at levels far below our ability to detect them. Only gravitational waves from immense astronomical phenomena cause large enough shifts in space-time that they can be recognized by sensors on Earth.

Just as different frequencies make up the electromagnetic spectrum, gravitational waves also vary. LIGO and other current gravitational wave detectors sense a very narrow range—high-frequency waves such as those from the moment two black holes collide—but other parts of the gravitational wave spectrum remain unexplored. And just as astronomers can learn new things about a star by studying its ultraviolet light versus its visible light, analyzing data from other gravitational wave frequencies could help solve mysteries of space that are currently out of reach, including those about the early universe.

"We identified a region of the spectrum that wasn't well-covered by any other detector, and it happened to be a match for the methods that we were already developing," said Hogan, an assistant professor of physics in the School of Humanities and Sciences.

During Hogan's graduate studies, he and his colleagues constructed the 10-meter-tall atom interferometer to test some of their ideas. However, in order to increase the sensitivity of the device—necessary to detect space-time wiggles smaller than the width of a proton—they need a bigger detector. And thus the 100-meter Matter-wave Atomic Gradiometer Interferometric Sensor, or MAGIS-100, experiment was born.

With help from a $9.8 million grant from the Gordon and Betty Moore Foundation, scientists plan to make an existing underground shaft at Fermilab, a Department of Energy National Laboratory in Illinois, MAGIS-100's new home.

"You can find holes in the ground, but it's kind of hard to find a hole in the ground with a lab attached to it," said Rob Plunkett, a senior scientist at Fermilab involved with the project.

Conceptually, MAGIS-100 will work similar to LIGO. Both experiments harness light to measure the distance between two test masses, much like radar ranging. But while LIGO has mirrors, MAGIS-100 favors atoms.

"The atom turns out to be an amazing test mass for these purposes," said Hogan. "We have very powerful techniques for manipulating it and allowing it to be insensitive to all the background sources of noise."

LIGO's mirrors hang on glass threads, meaning that an earthquake could set off its sensors. MAGIS-100, on the other hand, has measures in places to prevent such sources of extraneous noise from affecting its data.

After being cooled to a fraction of a degree above absolute zero, the atoms are dropped vertically into the shaft like dripping water droplets from a faucet. The frigid temperature puts the atoms into a state of rest, so they remain still as they fall, and because the shaft is a vacuum, the atoms plummet without risk of veering off course. The shaft's vertical orientation also ensures that a shaking Earth won't affect the measurements.

Lasers then manipulate the falling atoms and the team can measure how long they are in an excited state. Hogan and Kasevich hope to employ strontium as their test mass—the same element used in atomic clocks—to determine whether there are any time delays when light excites atoms. A delay would suggest a gravitational wave passed through.

In addition, MAGIS-100 scientists can use the atomic data to test predictions made by dark matter models. According to some models, the presence of dark matter could lead to variations in atomic energy levels. The supersensitive laser technology allows Plunkett and collaborators to look for these variations.

Looking toward space

MAGIS-100 is a prototype, another step toward building an even larger device that would be many times more sensitive. Hogan and Kasevich said they envision one day building something on the scale of LIGO, which is 4-kilometers long.

Because a future full-scale MAGIS-100 should detect low-frequency gravitational waves around 1 Hertz, such as those emitting from two black holes orbiting around each other, it could identify the same events that LIGO has already seen, but before the masses actually collide. The two experiments could thus complement one another.

"We could make a detector that could see the same system, but much, much younger," said Hogan.

Advanced MAGIS-style detectors might also find sources of gravitational waves that fly under LIGO's radar. Primordial gravitational waves, for example, produced moments after the Big Bang.

"Detecting gravitational waves that originated from the early universe can shed light on what actually happened," said Kasevich.

No one knows the frequencies of these primordial gravitational waves or whether the future large-scale detector can pick them up. Hogan said that he believes as many detectors as possible should be built in order to cover a broad range of frequencies and simply see what is out there.

"The known sources that are exciting are these LIGO-like sources," said Hogan. "Then there are the unknown, which we should be open to as well."

Provided by Stanford University

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