Study finds more stable clocks could measure quantum phenomena, including the presence of dark matter

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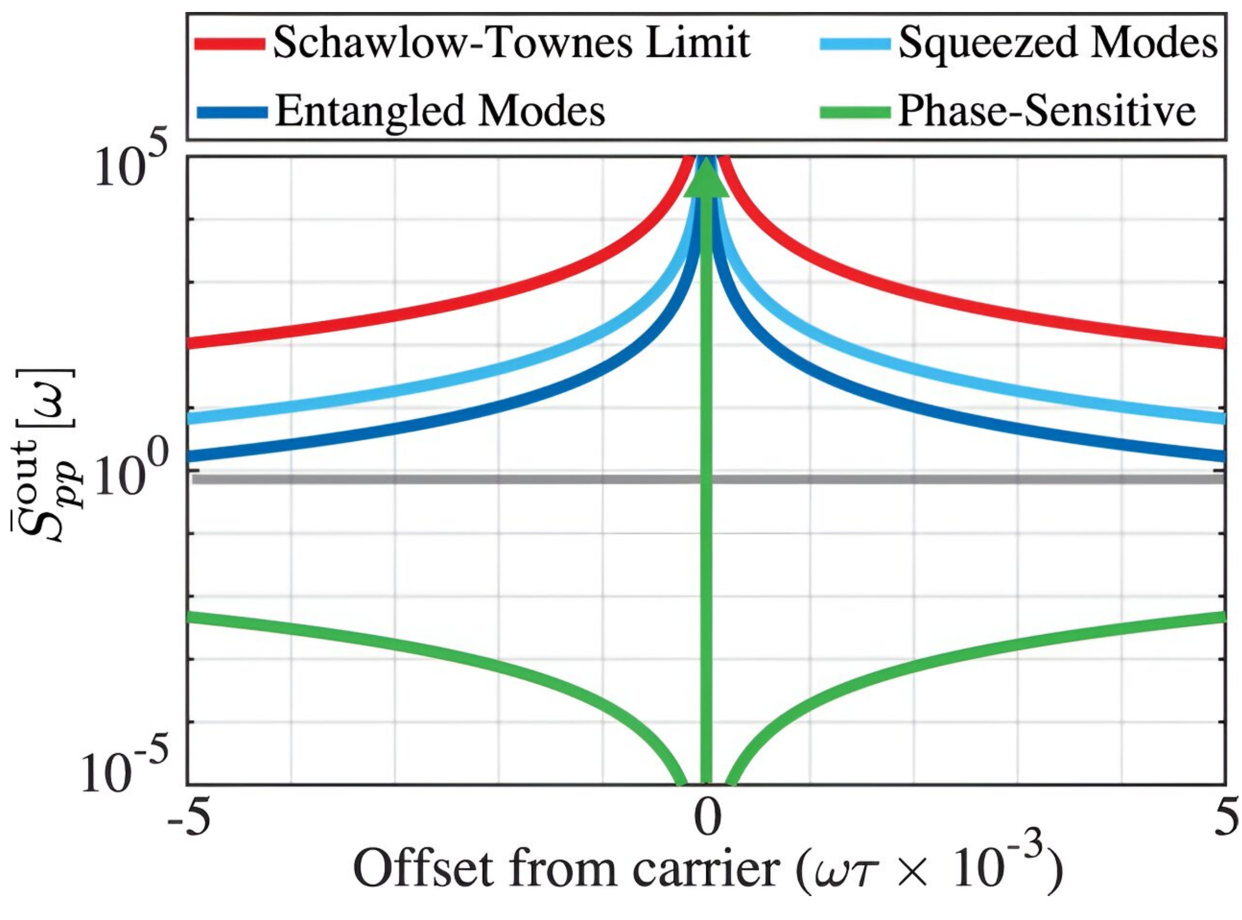

Phase noise of quantum-enhanced feedback oscillators. Spectra of the output phase quadrature for four types of quantum noise-limited oscillators. Red shows the Schawlow-Townes spectrum of an oscillator with phase-insensitive amplifier and the in-coupled and ancillary modes in vacuum. Light and darker blues depict the case where these modes are squeezed (light blue) and entangled (dark blue) (both with 12 dB of squeezing). Green shows the case where the in-loop amplifier is purely phase-sensitive. Credit: *Nature Communications* (2023). DOI: 10.1038/s41467-023-42739-9

The practice of keeping time hinges on stable oscillations. In a grandfather clock, the length of a second is marked by a single swing of the pendulum. In a digital watch, the vibrations of a quartz crystal mark much smaller fractions of time. And in atomic clocks, the world's state-of-the-art timekeepers, the oscillations of a laser beam stimulate atoms to vibrate at 9.2 billion times per second. These smallest, most stable divisions of time set the timing for today's satellite communications, GPS systems, and financial markets.

A clock's stability depends on the noise in its environment. A slight wind can throw a pendulum's swing out of sync. And heat can disrupt the oscillations of atoms in an atomic clock. Eliminating such environmental effects can improve a clock's precision. But only by so much.

A new MIT study finds that even if all noise from the outside world is eliminated, the stability of clocks, laser beams, and other oscillators would still be vulnerable to quantum mechanical effects. The precision of oscillators would ultimately be limited by quantum noise.

But in theory, there's a way to push past this quantum limit. In their study, the researchers also show that by manipulating, or "squeezing," the states that contribute to quantum noise, the stability of an oscillator could be improved, even past its quantum limit.

"What we've shown is, there's actually a limit to how stable oscillators like lasers and clocks can be, that's set not just by their environment, but by the fact that quantum mechanics forces them to shake around a little bit," says Vivishek Sudhir, assistant professor of mechanical engineering at MIT. "Then, we've shown that there are ways you can even get around this quantum mechanical shaking. But you have to be more clever than just isolating the thing from its environment. You have to play with the quantum states themselves."

The team is working on an experimental test of their theory. If they can demonstrate that they can manipulate the quantum states in an oscillating system, the researchers envision that clocks, lasers, and other oscillators could be tuned to super-quantum precision. These systems could then be used to track infinitesimally small differences in time, such as the fluctuations of a single qubit in a quantum computer or the presence of a dark matter particle flitting between detectors.

"We plan to demonstrate several instances of lasers with quantum-enhanced timekeeping ability over the next several years," says Hudson Loughlin, a graduate student in MIT's Department of Physics. "We hope that our recent theoretical developments and upcoming experiments will advance our fundamental ability to keep time accurately, and enable new revolutionary technologies."

Loughlin and Sudhir detail their work in an open-access paper published in the journal *Nature Communications*.

Laser precision

In studying the stability of oscillators, the researchers looked first to the laser—an optical oscillator that produces a wave-like beam of highly synchronized photons. The invention of the laser is largely credited to physicists Arthur Schawlow and Charles Townes, who coined the name from its descriptive acronym: light amplification by stimulated emission of radiation.

A laser's design centers on a "lasing medium"—a collection of atoms, usually embedded in glass or crystals. In the earliest lasers, a flash tube surrounding the lasing medium would stimulate electrons in the atoms to jump up in energy. When the electrons relax back to lower energy, they give off some radiation in the form of a photon.

Two mirrors, on either end of the lasing medium, reflect the emitted photon back into the atoms to stimulate more electrons, and produce more photons. One mirror, together with the lasing medium, acts as an "amplifier" to boost the production of photons, while the second mirror is partially transmissive and acts as a "coupler" to extract some photons out as a concentrated beam of laser light.

Since the invention of the laser, Schawlow and Townes put forth a hypothesis that a laser's stability should be limited by quantum noise. Others have since tested their hypothesis by modeling the microscopic features of a laser. Through very specific calculations, they showed that indeed, imperceptible, quantum interactions among the laser's photons and atoms could limit the stability of their oscillations.

"But this work had to do with extremely detailed, delicate calculations, such that the limit was understood, but only for a specific kind of laser," Sudhir notes. "We wanted to enormously simplify this, to understand lasers and a wide range of oscillators."

Putting the 'squeeze' on

Rather than focus on a laser's physical intricacies, the team looked to simplify the problem.

"When an electrical engineer thinks of making an oscillator, they take an amplifier, and they feed the output of the amplifier into its own input," Sudhir explains. "It's like a snake eating its own tail. It's an extremely liberating way of thinking. You don't need to know the nitty gritty of a laser. Instead, you have an abstract picture, not just of a laser, but of all oscillators."

In their study, the team drew up a simplified representation of a laser-like oscillator. Their model consists of an amplifier (such as a laser's atoms), a delay line (for instance, the time it takes light to travel between a laser's mirrors), and a coupler (such as a partially reflective mirror).

The team then wrote down the equations of physics that describe the system's behavior, and carried out calculations to see where in the system quantum noise would arise.

"By abstracting this problem to a simple oscillator, we can pinpoint where quantum fluctuations come into the system, and they come in in two places: the amplifier and the coupler that allows us to get a signal out of the oscillator," Loughlin says. "If we know those two things, we know what the quantum limit on that oscillator's stability is."

Sudhir says scientists can use the equations they lay out in their study to calculate the quantum limit in their own oscillators.

What's more, the team showed that this quantum limit might be overcome, if quantum noise in one of the two sources could be "squeezed." Quantum squeezing is the idea of minimizing quantum fluctuations in one aspect of a system at the expense of proportionally increasing fluctuations in another aspect. The effect is similar to squeezing air from one part of a balloon into another.

In the case of a laser, the team found that if quantum fluctuations in the coupler were squeezed, it could improve the precision, or the timing of oscillations, in the outgoing laser beam, even as noise in the laser's power would increase as a result.

"When you find some quantum mechanical limit, there's always some question of how malleable is that limit?" Sudhir says. "Is it really a hard stop, or is there still some juice you can extract by manipulating some quantum mechanics? In this case, we find that there is, which is a result that is applicable to a huge class of oscillators."

More information: Hudson A. Loughlin et al, Quantum noise and its evasion in feedback oscillators, *Nature Communications* (2023). DOI: 10.1038/s41467-023-42739-9

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