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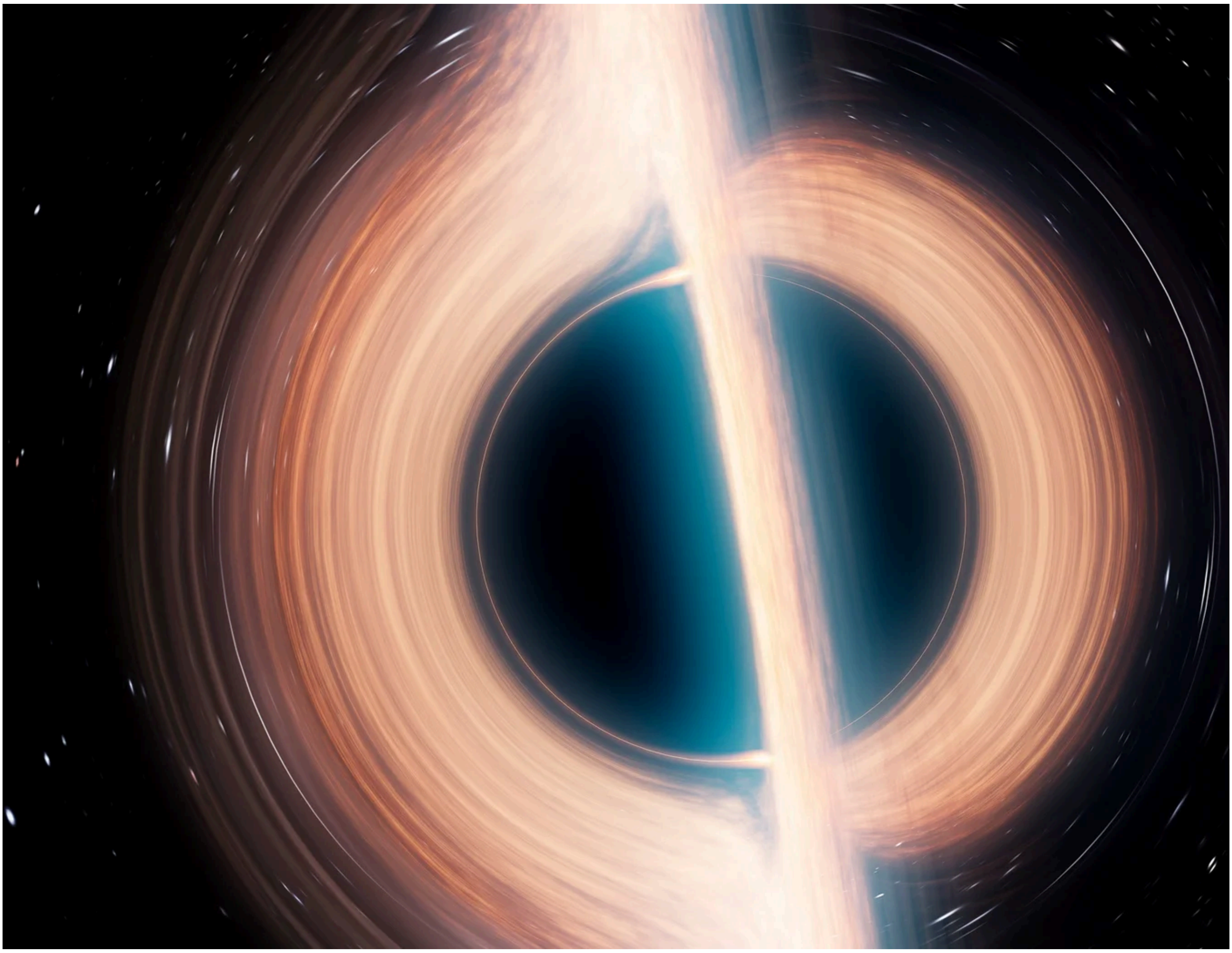
Physicists Build a 'Black Hole Bomb' in the Laboratory

Astronomical amounts of energy could be extracted from black holes—to build a gigantic bomb, for example. Experts have now implemented this principle in the laboratory

BY MANON BISCHOFF EDITED BY LEE BILLINGS



An artist's rendition of a black hole surrounded by a glowing accretion disc of material, the light from which is warped by the strong gravity. In principle, energy could be harvested from a spinning black hole—and lab-based demonstrations are beginning to show physicists how this could occur. Mark Garlick/Science Photo Library/Getty Images

Black Holes

A bomb from a black hole would probably be the most destructive weapon in the universe. Hypothetically, it could be created by wrapping one of these cosmic monsters in mirrors and waiting for it to go "boom." Now Hendrik Ulbricht of the University of Southampton in England and his colleagues have demonstrated this principle, called superradiance, in the lab using a rotating metal cylinder instead of a black hole. They submitted their results, which have not yet been peer-reviewed, to the preprint server arXiv.org in late March. "This work shows that a 'black hole bomb' can actually be built in the laboratory," says physicist Vitor Cardoso of the Niels Bohr Institute in Denmark, who was not involved in the study. "It thus provides a solid basis for studying the entire physics of black holes."

Among the strangest objects in the universe, black holes pack so much mass into such a small space that they can radically warp spacetime. A black hole's gravitational pull is so strong that within a certain distance, nothing can escape it—not even light. Theorist Roger Penrose is one of the pioneers who first studied black holes mathematically in detail—work for which he shared the Nobel Prize in Physics in 2020. And amid that early work, he realized something surprising.

As Penrose knew, nothing stands still in our cosmos, not even black holes. These massive monsters can spin, distorting spacetime in the process to form a kind of vortex. An approaching object can be caught up in this vortex and spiral around the spinning black hole. Even before the object passes the event horizon, beyond which not even light can escape gravity's clutches, it reaches an area that physicists call the "ergosphere." There the object would have to move faster than light to escape the rotation around the black hole.

This ergosphere is a strange place, as Penrose noted, because objects there can possess negative energy. A particle, for example, could split into two equal-but-opposite parts: one with negative energy and another with positive energy. The former would then crash into the black hole (thus reducing the black hole's energy), allowing the latter to escape the cosmic behemoth's mighty grip. An external observer would see a particle with a certain energy falling toward the black hole, only to apparently rebound outward with higher energy. The black hole loses part of its rotational energy in the process.

BLACK HOLE MINING AND SUPERRADIANCE

In principle, this would allow black holes to serve as gigantic sources of energy. The process could not only imbue massive objects with more energy but also amplify electromagnetic waves in a phenomenon called superradiance. This realization spurred some physicists to even imagine how advanced alien civilizations might use superradiance to generate energy. But despite how relatively simple it is to describe on paper, no one knew how the signal of superradiance could be observed in real black holes. Thus, the concept initially remained mere speculation.

In 1971, however, two years after Penrose first described this phenomenon, physicist Yakov Zel'dovich published research that suggested that black holes aren't the only objects that can be tapped as superradiant energy sources. Any rotating, axially symmetrical body that absorbs electromagnetic radiation—such as a metal cylinder—can also exhibit superradiance under certain circumstances. "Roughly speaking, the rotating absorber must rotate faster than the phase rotation of the incident radiation," explains physicist Maria Chiara Braidotti of the University of Glasgow in Scotland, who was involved in the latest work. "If this condition is met, the absorption coefficient of the cylinder changes sign, thus amplifying the radiation."

Zel'dovich even went one step further by showing that superradiance could also take place in a vacuum and wouldn't require an incoming electromagnetic wave. That's because on quantum scales the vacuum is anything but empty. At any time, pairs of virtual particles and antiparticles can pop into existence, although they typically immediately annihilate each other again. The phenomenon is known as vacuum fluctuation. And these fluctuations could also be amplified in the vicinity of black holes —or a rotating metal cylinder. "Stephen Hawking didn't believe this idea and tried to refute it," explains Marion Cromb, a researcher in Ulbricht's group at the University of Southampton and a contributor to the new work. "Not only did [Hawking] admit that Zel'dovich was right but he was also able to prove that even nonrotating black holes—without an ergosphere—spontaneously emit radiation." This realization led to the discovery of Hawking radiation.

According to the theoretical calculations, however, vacuum-based superradiance would be so faint that it could not be detected—unless, that is, it was somehow amplified. As Zel'dovich described, the rotating body (black hole or metal cylinder) could be encased in mirrors to reflect the amplified radiation back to the rotating body, intensifying it over and over again. As physicists William Press and Saul Teukolsky realized, so much energy could accumulate

inside the mirrors that a gigantic explosion would occur. Press and Teukolsky, therefore, referred to the setup as a black hole bomb.
Depending on how much rotational energy the black hole or the metal cylinder has, a result other than a gigantic explosion is conceivable, though. Cardoso and his colleagues described this possibility in a paper published in 2004 that showed how superradiance can cease if the black hole or metal cylinder loses too much angular momentum, thus defusing the explosion.

EXPLOSIONS IN THE LABORATORY

Ulbricht, Braidotti and their colleagues now wanted to test all these theoretical predictions in the laboratory. "Originally, we thought it would be too difficult to observe the actual effect," Braidotti says, nothing that a cylinder would have to rotate so fast that it would be destroyed in the process. For this reason, she initially turned her attention to simpler systems in which superradiance can occur, including a setup with sound waves. "The breakthrough was our noticing how to reduce the frequencies of electromagnetic fields in a very simple way so that they are smaller than the rotation frequencies of the metal cylinders," Ulbricht explains. The researchers only needed alternating current circuits for this. "This finding opened up the possibility of conducting the experiment with electromagnetic waves," Braidotti says.

The team then turned its attention to electromagnetic superradiance. "The experimental setup itself is quite simple: it consists of a rotating cylinder and the stator coils of a commercially available induction motor, combined with some capacitors and resistors," Cromb says. These devices were placed around the metal cylinder to generate a magnetic field inside it, which produced electromagnetic radiation. At the same time, these devices also served as mirrors because they reflected the electromagnetic waves back toward the cylinder.

"The biggest difficulty was that things were constantly exploding," Cromb says. "It was a balancing act between measuring a reasonable signal and overloading the system. When the current through the coils became too high, the resistors in the circuit exceeded their rated voltage and burned out. This interrupted the electrical circuit, thus destroying the 'mirror.'"

The researchers initially feared that these overloads would prevent any observation of superradiance. But they were lucky. "The reinforcement was

large enough to overcome the loss and enter the area of instability," Cromb says. In fact, the team was able to show that the voltage in their structure increased exponentially, as predicted by Zel'dovich. This underpins the researchers' claim of the first-ever lab-based demonstration of an electromagnetic version of a black hole bomb.
Note, however, that despite the martial connotations of the name, the "bomb" Ulbricht and his team built in their lab isn't anything like a military-grade munition—or even a firecracker. It would be quite useless as a weapon because its yield is only on the order of a millijoule of energy—that is, about the same amount involved in pressing a single key on a mechanical keyboard.

RADIATION-FREE SUPERRADIANCE?

Next, Cromb and the team used their setup to study whether superradiance can also take place in a vacuum: Would an electromagnetic signal arise in their apparatus even without a magnetic field? Because the experiment took place at room temperature, thermal fluctuations overshadowed any vacuum fluctuations—meaning that the team could not directly detect the latter. But that very same thermal background noise, the researchers realized, would spontaneously generate electromagnetic waves that could theoretically be amplified.

And that is what they did manage to demonstrate: by choosing the appropriate rotation speed of the cylinder, they generated electromagnetic waves out of nowhere, so to speak. Their work also confirmed the "defusing" scenario predicted by Cardoso: the metal cylinder was able to lose enough rotational energy to halt superradiance and stave off any explosion.

According to Ulbricht, the most special thing about the work is its sheer simplicity. "Many physicists think that all the simple experiments have already been done and that new insights into the fundamentals of physics can only come from very complex and very expensive projects," he says. "We proved the opposite."

"I didn't expect that someone would be able to carry out such an experiment now," Cardoso says. On the day the new work was posted to arXiv.org, he recalls, he was giving a series of lectures at Bangalore University in India. "I talked about superradiance and told the audience that no one had ever proven

the electromagnetic superradiance or the bomb effect in the laboratory. So you can imagine my surprise when I saw the paper shortly afterwards!"
The new work could lead to deeper insights about black holes, Cardoso says. "Superradiance is a little-known classical effect that plays an important role in the physics of black holes," he explains. For example, extremely light particles, such as axions or special types of photons considered candidates for dark matter, could absorb the rotational energy of black holes, amplifying their signals. "This means that black holes can be used as gigantic particle detectors," Cardoso explains. With a lab-based black hole bomb, physicists could test such hypotheses more precisely than ever before.

In the future, Ulbricht would like to carry out the quantum version of the experiment, which would entail observing the spontaneous generation of electromagnetic waves and their amplification from the vacuum. Such direct experiments with vacuum fluctuations could open up completely new possibilities for the scientific community and the world, he says, potentially representing "a major breakthrough for physics." Perhaps, Ulbricht muses, that work could allow researchers "in a few decades to understand whether it is possible in principle to generate energy from the vacuum—which would be an inexhaustible new source of energy."

MANON BISCHOFF is a theoretical physicist and an editor at *Spektrum der Wissenschaft,* the German-language sister publication of *Scientific American*.

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There has never been a more important time for us to stand up and show why science matters. I hope you'll support us in that mission.

Thank you,
David M. Ewalt, Editor in Chief, *Scientific American*

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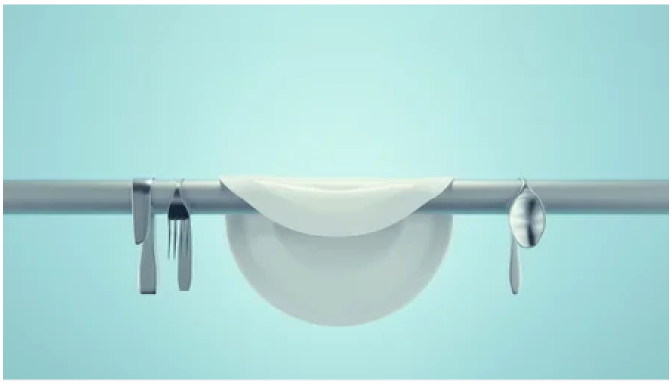

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