

GENERAL PHYSICS TO ASTROPHYSICS VOL 6

The 18 biggest unsolved mysteries in physics

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Profound physics



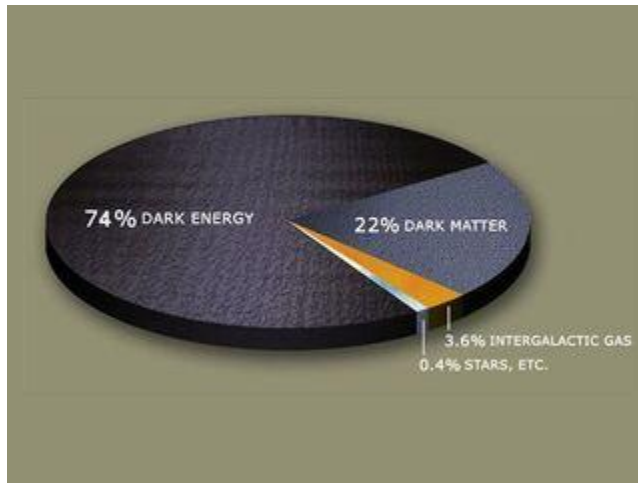
(Image credit: [Image](#) via Shutterstock)

In 1900, the British physicist Lord Kelvin is said to have pronounced: "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." Within three decades, [quantum mechanics and Einstein's theory of relativity](#) had revolutionized the field. Today, no physicist would dare assert that our physical knowledge of the universe is near completion. To the contrary, each new discovery seems to unlock a Pandora's box of even bigger, even deeper physics questions. These are our picks for the most profound open questions of all.

Related: Check out the 14 [biggest historical mysteries](#) that may never be solved.

Inside you'll learn about parallel universes, why time seems to move in one direction only, and why we don't understand chaos.

What is dark energy?



(Image credit: NASA)

No matter how astrophysicists crunch the numbers, the universe simply doesn't add up. Even though gravity is pulling inward on space-time — the "fabric" of the cosmos — it keeps expanding outward faster and faster. To account for this, astrophysicists have proposed an invisible agent that counteracts gravity by pushing space-time apart. They call it [dark energy](#). In the most widely accepted model of dark energy, it is a "cosmological constant": an inherent property of space itself, which has "negative pressure" driving space apart. As space expands, more space is created, and with it, more dark energy. Based on the observed rate of expansion, scientists know that the sum of all the dark energy must make up more than 70 percent of the total contents of the universe. But no one knows how to look for it. The best researchers have been able to do in recent years is narrow in a bit on where dark energy might be hiding, which was the [topic of a study](#) released in August 2015.

What is dark matter?



(Image credit: ESO/L. Calçada)

Evidently, about 84 percent of the matter in the universe does not absorb or emit light. "Dark matter," as it is called, cannot be seen directly, and it hasn't yet been detected by indirect means, either. Instead, dark matter's existence and properties are inferred from its gravitational effects on visible matter, radiation and the structure of the universe. This shadowy substance is thought to pervade the outskirts of galaxies, and may be composed of

"weakly interacting massive particles," or WIMPs. Worldwide, there are several detectors on the lookout for WIMPs, but so far, not one has been found. One recent study suggests dark matter might form long, fine-grained streams throughout the universe, and that such streams might [radiate out from Earth](#) like hairs. [Related: [If Not Dark Matter, then What?](#)]

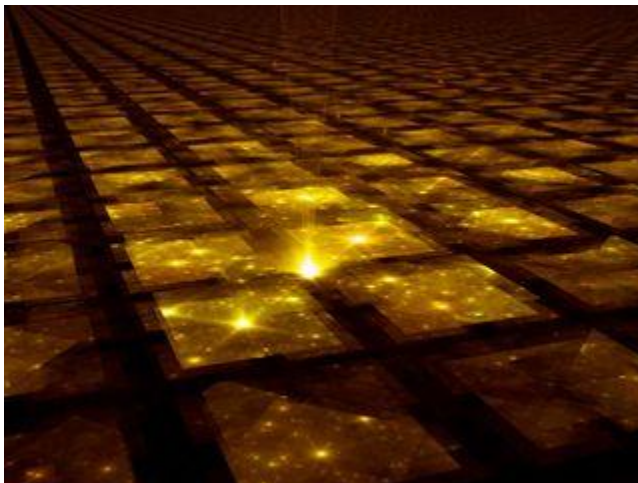
Why is there an arrow of time?



(Image credit: [Image](#) via Shutterstock)

Time moves forward because a property of the universe called "entropy," roughly defined as the level of disorder, only increases, and so there is no way to reverse a rise in entropy after it has occurred. The fact that entropy increases is a matter of logic: There are more disordered arrangements of particles than there are ordered arrangements, and so as things change, they tend to fall into disarray. But the underlying question here is, why was entropy so low in the past? Put differently, why was the universe so ordered at its beginning, when a huge amount of energy was crammed together in a small amount of space?

Are there parallel universes?

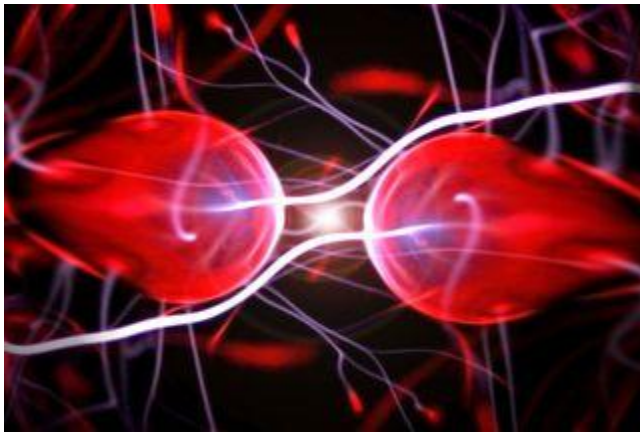


(Image credit: [Image](#) via Shutterstock)

Astrophysical data suggests space-time might be "flat," rather than curved, and thus that it goes on forever. If so, then the region we can see (which we think of as "the universe") is

just one patch in an infinitely large "quilted multiverse." At the same time, the laws of quantum mechanics dictate that there are only a finite number of possible particle configurations within each cosmic patch ($10^{10^{122}}$ distinct possibilities). So, with an [infinite number](#) of cosmic patches, the particle arrangements within them are forced to repeat — infinitely many times over. This means there are infinitely many parallel universes: cosmic patches exactly the same as ours (containing someone exactly like you), as well as patches that differ by just one particle's position, patches that differ by two particles' positions, and so on down to patches that are totally different from ours. Is there something wrong with that logic, or is its bizarre outcome true? And if it is true, how might we ever detect the presence of parallel universe?

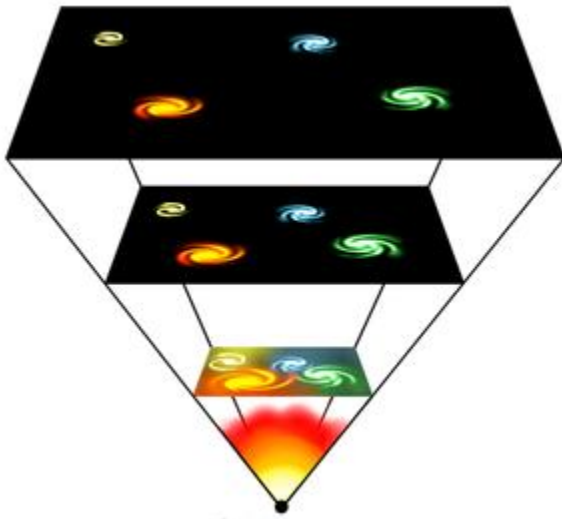
Why is there more matter than antimatter?



(Image credit: [Image](#) via Shutterstock)

The question of why there is so much more matter than its oppositely-charged and oppositely-spinning twin, antimatter, is actually a question of why anything exists at all. One assumes the universe would treat matter and antimatter symmetrically, and thus that, at the moment of the Big Bang, equal amounts of matter and antimatter should have been produced. But if that had happened, there would have been a total annihilation of both: Protons would have canceled with antiprotons, electrons with anti-electrons (positrons), neutrons with antineutrons, and so on, leaving behind a dull sea of photons in a matterless expanse. For some reason, there was excess matter that didn't get annihilated, and here we are. For this, there is no accepted explanation. The [most detailed test](#) to date of the differences between matter and antimatter, announced in August 2015, confirm they are mirror images of each other, providing exactly zero new paths toward understanding the mystery of why matter is far more common.

What is the fate of the universe?



(Image credit: Creative Commons Attribution-Share Alike 3.0 Unported | Bjarmason)

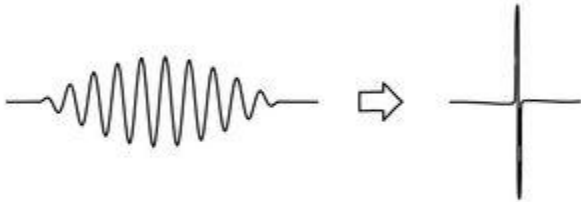
The fate of the universe strongly depends on a factor of unknown value: Ω , a measure of the density of matter and energy throughout the cosmos. If Ω is greater than 1, then space-time would be "closed" like the surface of an enormous sphere. If there is no dark energy, such a universe would eventually stop expanding and would instead start contracting, eventually collapsing in on itself in an event dubbed the "Big Crunch." If the universe is closed but there *is* dark energy, the spherical universe would expand forever.

Alternatively, if Ω is less than 1, then the geometry of space would be "open" like the surface of a saddle. In this case, its ultimate fate is the "Big Freeze" followed by the "Big Rip": first, the universe's outward acceleration would tear galaxies and stars apart, leaving all matter frigid and alone. Next, the acceleration would grow so strong that it would overwhelm the effects of the forces that hold atoms together, and everything would be wrenched apart.

If $\Omega = 1$, the universe would be flat, extending like an infinite plane in all directions. If there is no dark energy, such a planar universe would expand forever but at a continually decelerating rate, approaching a standstill. If there is dark energy, the flat universe ultimately would experience runaway expansion leading to the Big Rip. Regardless how it plays out, the universe is dying, a fact [discussed in detail](#) by astrophysicist Paul Sutter in the essay from December, 2015.

Que sera, sera.

How do measurements collapse quantum wavefunctions?



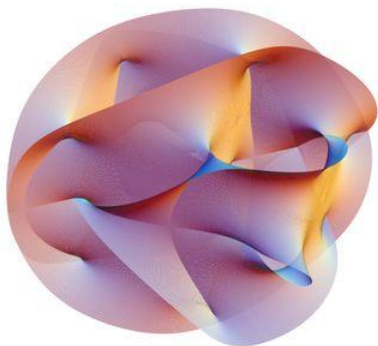
(Image credit: John D. Norton)

In the strange realm of electrons, photons and the other fundamental particles, quantum mechanics is law. Particles don't behave like tiny balls, but rather like waves that are spread over a large area. Each particle is described by a "wavefunction," or probability distribution, which tells what its location, velocity, and other properties are more likely to be, but not what those properties are. The particle actually has a range of values for all the properties, until you experimentally measure one of them — its location, for example — at which point the particle's wavefunction "collapses" and it adopts just one location.

[[Newborn Babies Understand Quantum Mechanics](#)]

But how and why does measuring a particle make its wavefunction collapse, producing the concrete reality that we perceive to exist? The issue, known as the measurement problem, may seem esoteric, but our understanding of what reality is, or if it exists at all, hinges upon the answer.

Is string theory correct?



(Image credit: Creative Commons | Lunch)

When physicists assume all the elementary particles are actually one-dimensional loops, or "strings," each of which vibrates at a different frequency, physics gets much easier. [String theory](#) allows physicists to reconcile the laws governing particles, called quantum mechanics, with the laws governing space-time, called general relativity, and to unify the

four [fundamental forces of nature](#) into a single framework. But the problem is, string theory can only work in a universe with 10 or 11 dimensions: three large spatial ones, six or seven compacted spatial ones, and a time dimension. The compacted spatial dimensions — as well as the vibrating strings themselves — are about a billionth of a trillionth of the size of an atomic nucleus. There's no conceivable way to detect anything that small, and so there's no known way to experimentally validate or invalidate string theory.

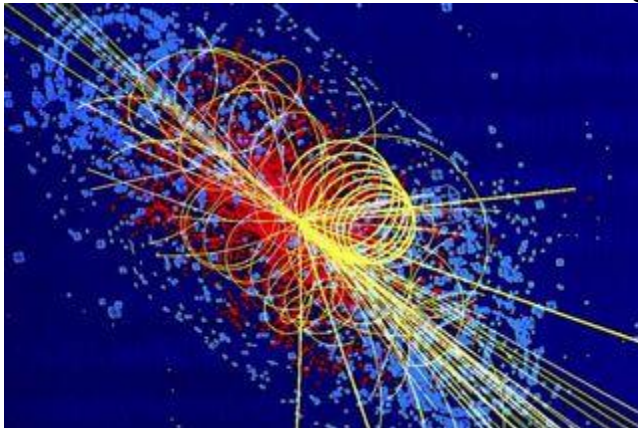
Is there order in chaos?



(Image credit: [Image](#) via Shutterstock)

Physicists can't exactly solve the set of equations that describes the behavior of fluids, from water to air to all other liquids and gases. In fact, it isn't known whether a general solution of the so-called Navier-Stokes equations even exists, or, if there is a solution, whether it describes fluids everywhere, or contains inherently unknowable points called singularities. As a consequence, the nature of chaos is not well understood. Physicists and mathematicians wonder, is the weather merely difficult to predict, or inherently unpredictable? Does turbulence transcend mathematical description, or does it all make sense when you tackle it with [the right math](#)?

Do the universe's forces merge into one?



(Image credit: Lucas Taylor/CMS)

The universe experiences four fundamental forces: electromagnetism, [the strong nuclear force](#), the weak interaction (also known as [the weak nuclear force](#)) and [gravity](#). To date, physicists know that if you turn up the energy enough — for example, inside a particle accelerator — three of those forces "unify" and become a single force. Physicists have run particle accelerators and unified the electromagnetic force and weak interactions, and at higher energies, the same thing should happen with the strong nuclear force and, eventually, gravity.

But even though theories say that *should* happen, nature doesn't always oblige. So far, no particle accelerator has reached energies high enough to unify the strong force with [electromagnetism](#) and the weak interaction. Including gravity would mean yet more energy. It isn't clear whether scientists could even build one that powerful; the Large Hadron Collider (LHC), near Geneva, can send particles crashing into each other with energies in the trillions of electron volts (about 14 tera-electron volts, or TeV). To reach grand unification energies, particles would need at least a trillion times as much, so physicists are left to hunt for indirect evidence of such theories.

Besides the issue of energies, Grand Unified Theories (GUTs) still have some problems because they predict other observations that so far haven't panned out. There are several GUTs that say protons, over immense spans of time (on the order of 10^{36} years), should turn into other particles. This has never been observed, so either protons last much longer than anyone thought or they really are stable forever. Another prediction of some types of GUT is the existence of magnetic monopoles — isolated "north" and "south" poles of a magnet — and nobody has seen one of those, either. It's possible we just don't have a powerful enough particle accelerator. Or, physicists could be wrong about how the universe works.

What happens inside a black hole?



(Image credit: ESO/L. Calçada)

What happens to an object's information [if it gets sucked into a black hole](#)? According to the current theories, if you were to drop a cube of iron into a black hole, there would be no way to retrieve any of that information. That's because a black hole's gravity is so strong that its escape velocity is faster than light — and [light is the fastest thing there is](#). However, a branch of science called quantum mechanics says that [quantum information](#) can't be destroyed. "If you annihilate this information somehow, something goes haywire," said

Robert McNees, an associate professor of physics at Loyola University Chicago. [[How to Teleport Info Out of a Black Hole](#)]

Quantum information is a bit different from the information we store as 1s and 0s on a computer, or the stuff in our brains. That's because quantum theories don't provide exact information about, for instance, where an object will be, like calculating the trajectory of a baseball in mechanics. Instead, such theories reveal the most likely location or the most likely result of some action. As a consequence, all of the probabilities of various events should add up to 1, or 100 percent. (For instance, when you roll a six-sided die, the chances of a given face coming up is one-sixth, so the probabilities of all the faces add up to 1, and you can't be more than 100 percent certain something will happen.) Quantum theory is, therefore, called unitary. If you know how a system ends, you can calculate how it began.

To describe a black hole, all you need is mass, angular momentum (if it's spinning) and charge. Nothing comes out of a black hole except a slow trickle of thermal radiation called Hawking radiation. As far as anyone knows, there's no way to do that reverse calculation to figure out what the black hole actually gobbled up. The information is destroyed. However, quantum theory says that information can't be completely out of reach. Therein lies the "[information paradox](#)."

McNees said there has been a lot of work on the subject, notably by Stephen Hawking and Stephen Perry, who suggested in 2015 that, rather than being stored within the deep clutches of a black hole, [the information remains on its boundary](#), called the event horizon. Many others have attempted to solve the paradox. Thus far, physicists can't agree on the explanation, and they're likely to disagree for some time.

Do naked singularities exist?



(Image credit: NASA E/PO, Sonoma State University, Aurore Simonnet)

A [singularity](#) occurs when some property of a "thing" is infinite, and so the laws of physics as we know them break down. [At the center of black holes](#) lies a point that is infinitely teensy and dense (packed with a finite amount of matter) — a point called a singularity. In [mathematics](#), singularities come up all the time — dividing by [zero](#) is one instance, and a vertical line on a coordinate plane has an "infinite" slope. In fact, the slope of a vertical line is just undefined. But what would a singularity look like? And how would it interact with

the rest of the universe? What does it mean to say that something has no real surface and is infinitely small?

A "naked" singularity is one that can interact with the rest of the universe. Black holes have event horizons — spherical regions from which nothing, not even light, can escape. At first glance, you might think the problem of naked singularities is partly solved for black holes at least, since nothing can get out of the event horizon and the singularity can't affect the rest of the universe. (It is "clothed," so to speak, while a naked singularity is a black hole without an event horizon.)

But whether singularities can form without an event horizon is still an open question. And if they can exist, then [Albert Einstein's theory of general relativity](#) will need a revision, because it breaks down when systems are too close to a singularity. Naked singularities might also function as [wormholes](#), which would also be time machines — though there's no evidence for this in nature.

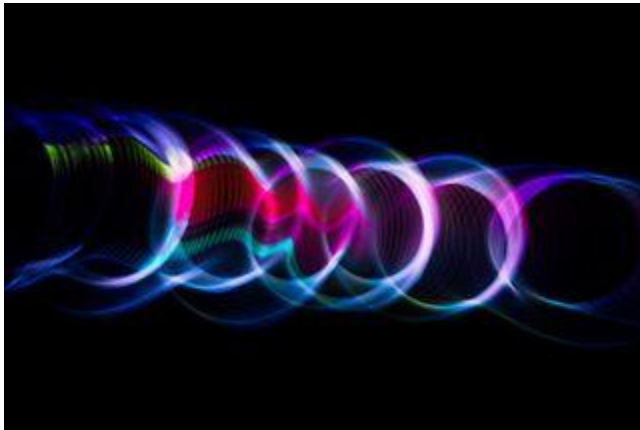
Violating charge-parity symmetry



(Image credit: agsandrew | Shutterstock.com)

If you swap a particle with its antimatter sibling, the laws of physics should remain the same. So, for example, the positively charged proton should look the same as a negatively charged antiproton. That's the principle of charge symmetry. If you swap left and right, again, the laws of physics should look the same. That's parity symmetry. Together, the two are called CP symmetry. Most of the time, this physics rule is not violated. However, certain exotic particles violate this symmetry. McNees said that's why it's strange. "There shouldn't be any violations of CP in quantum mechanics," he said. "We don't know why that is."

When sound waves make light

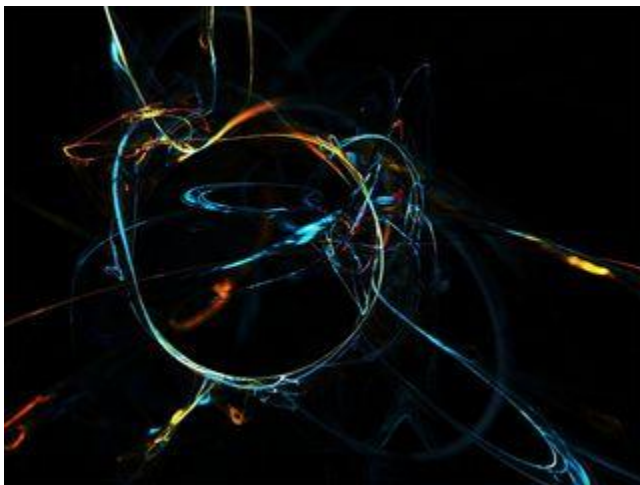


(Image credit: DmitrySteshenko/Shutterstock)

Though particle-physics questions account for many unsolved problems, some mysteries can be observed on a bench-top lab setup. Sonoluminescence is one of those. If you take some water and hit it with sound waves, bubbles will form. Those bubbles are low-pressure regions surrounded by high pressure; the outer pressure pushes in on the lower-pressure air, and the bubbles quickly collapse. When those bubbles collapse, they emit light, in flashes that last trillionths of a second.

The problem is, it's far from clear what the source of the light is. Theories range from tiny nuclear fusion reactions to some type of electrical discharge, or even compression heating of the gases inside the bubbles. Physicists have measured high temperatures inside these bubbles, on the order of tens of thousands of degrees Fahrenheit, and taken numerous pictures of the light they produce. But there's no good explanation of how sound waves create these lights in a bubble.

What lies beyond the Standard Model?



(Image credit: [Robert Spriggs](#) | [Shutterstock](#))

The Standard Model is one of the most successful physical theories ever devised. It's been standing up to experiments to test it for four decades, and new experiments keep showing that it is correct. The Standard Model describes the behavior of the particles that make up everything around us, as well as explaining why, for example, particles have mass. In fact, [the discovery of the Higgs boson](#) — a particle that gives matter its mass — in 2012 was a historic milestone because it confirmed the long-standing prediction of its existence. But the Standard Model doesn't explain everything. The Standard Model has made many successful predictions — for example, the Higgs boson, the W and Z boson (which mediate the weak interactions that govern radioactivity), and quarks among them — so it is difficult to see where physics might go beyond it. That said, most physicists agree that the Standard Model is not complete. There are several contenders for new, more complete models — string theory is one such model — but so far, none of these have been conclusively verified by experiments.

Fundamental constants



(Image credit: [Andreas Guskos](#) | [Shutterstock.com](#))

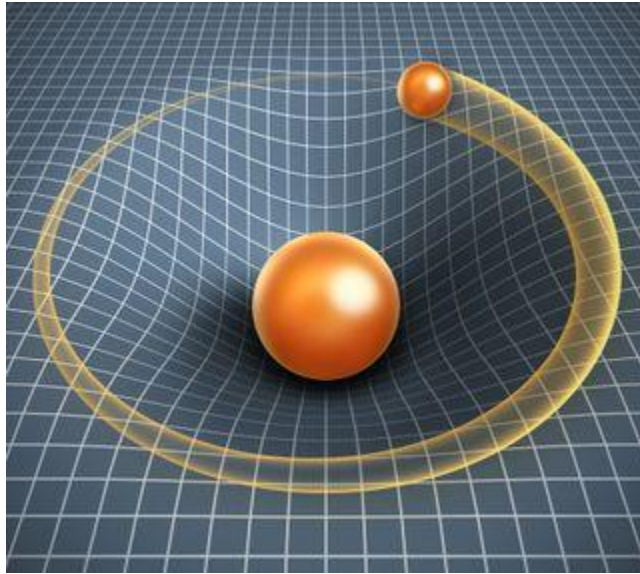
Dimensionless constants are numbers that don't have units attached to them. The speed of light, for example, is a [fundamental constant](#) measured in units of meters per second (or 186,282 miles per second). Unlike the speed of light, dimensionless constants have no units and they can be measured, but they can't be derived from theories, whereas constants like the speed of light can be.

In his book "Just Six Numbers: The Deep Forces That Shape the Universe" (Basic Books, 2001), astronomer Martin Rees focuses on certain "dimensionless constants" he considers fundamental to physics. In fact, there are many more than six; about 25 exist in the Standard Model. [[The 9 Most Massive Numbers in Existence](#)]

For example, the fine structure constant, usually written as α , governs the strength of magnetic interactions. It is about 0.007297. What makes this number odd is that if it were any different, stable matter wouldn't exist. Another is the ratio of the masses of many fundamental particles, such as electrons and quarks, to the Planck mass (which is 1.22×10^{19} GeV/c²). Physicists would love to figure out why those particular numbers have the values they do, because if they were very different, the universe's physical laws wouldn't

allow for humans to be here. And yet there's still no compelling theoretical explanation for why they have those values.

What the heck is gravity, anyway?



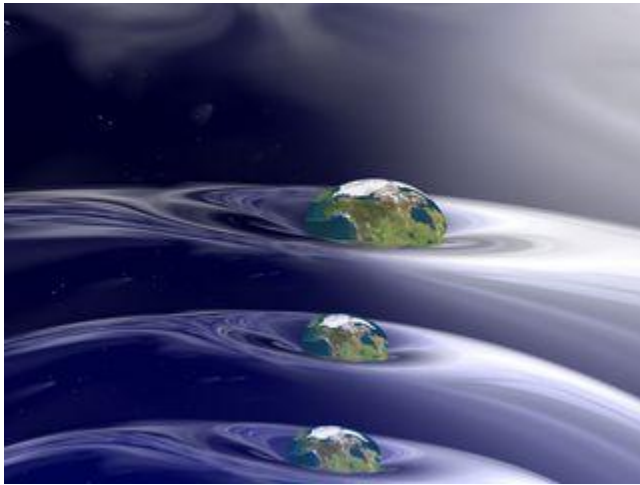
(Image credit: [koya979](#) | [Shutterstock](#))

What is gravity, anyway? Other forces are mediated by particles. Electromagnetism, for example, is the exchange of photons. The **weak nuclear force** is carried by W and Z bosons, and gluons carry the strong nuclear force that holds atomic nuclei together. McNeese said all of the other forces can be quantized, meaning they could be expressed as individual particles and have noncontinuous values.

Gravity doesn't seem to be like that. Most physical theories say it should be carried by a hypothetical massless particle called a graviton. The problem is, nobody has found gravitons yet, and it's not clear that any particle detector that could be built could see them, because if gravitons interact with matter, they do it very, very rarely — so seldom that they'd be invisible against the background noise. It isn't even clear that gravitons are massless, though if they have a mass at all, it's very, very small — smaller than that of neutrinos, which are among the lightest particles known. String theory posits that gravitons (and other particles) are closed loops of energy, but the mathematical work hasn't yielded much insight so far.

Because gravitons haven't been observed yet, gravity has resisted attempts to understand it in the way we understand other forces — as an exchange of particles. Some physicists, notably Theodor Kaluza and Oskar Klein, posited that gravity may be operating as a particle in extra dimensions beyond the three of space (length, width, and height) and one of time (duration) we are familiar with, but whether that is true is still unknown.

Do we live in a false vacuum?



(Image credit: Shutterstock/Sandy MacKenzie)

The universe seems relatively stable. After all, it's been around [for about 13.8 billion years](#). But what if the whole thing were a massive accident?

It all starts with the Higgs and the universe's vacuum. Vacuum, or empty space, should be the lowest possible energy state, because there's nothing in it. Meanwhile, the Higgs boson — via the so-called Higgs field — gives everything its mass. Writing in the journal *Physics*, Alexander Kusenko, a professor of physics and astronomy at the University of California, Los Angeles, said the energy state of the vacuum can be calculated from the potential energy of the Higgs field and the masses of the Higgs and top quark (a fundamental particle).

So far, those calculations appear to show that the universe's vacuum might not be in the lowest possible energy state. That would mean it's a false vacuum. If that's true, our universe might not be stable, because a false vacuum can be knocked into a lower energy state by a sufficiently violent and high-energy event. If that were to happen, there would be a phenomenon called bubble nucleation. A sphere of lower-energy vacuum would start growing at the speed of light. Nothing, not even matter itself, would survive. Effectively, we'd be replacing the universe with another one, which might have very different physical laws.

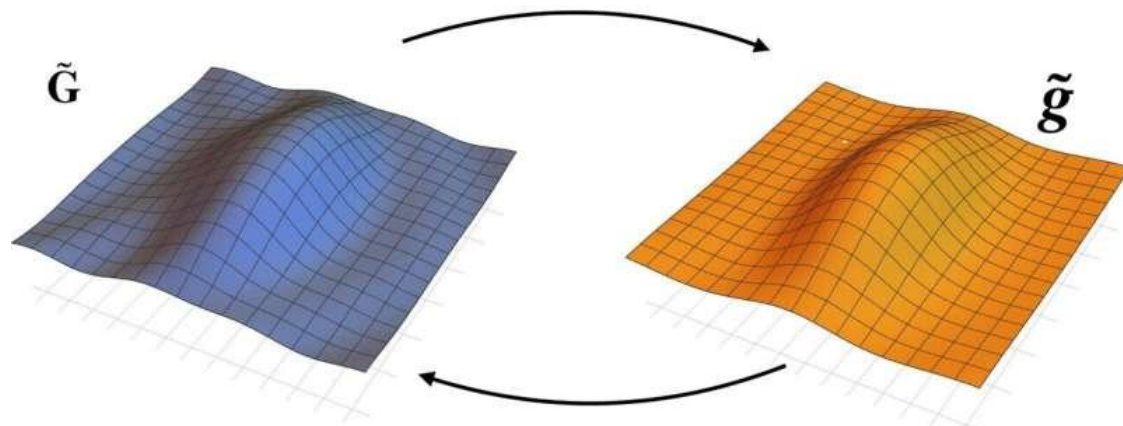
That sounds scary, but given that the universe is still here, clearly there hasn't been such an event yet, and astronomers have seen [gamma-ray bursts](#), supernovas, and quasars, all of which are pretty energetic. So it's probably unlikely enough that we wouldn't need to worry. That said, the idea of a false vacuum means that our universe might have popped into existence in just that way, when a previous universe's false vacuum was knocked into a lower energy state. Perhaps we were the result of an accident with a particle accelerator.

MARCH 4, 2025

Gravity from entropy: A radical new approach to unifying quantum mechanics and general relativity

by [Queen Mary, University of London](#)

$$\mathcal{L} = \text{Tr} \tilde{g} \ln \tilde{G}^{-1} = -\text{Tr}_F \ln \tilde{G} \tilde{g}^{-1}$$



Diagrammatic representation of the entropic quantum gravity action. The action for gravity is given by the quantum relative entropy between the metric of the manifold and the metric induced by the matter field and the geometry. Credit: *Physical Review D* (2025). DOI: 10.1103/PhysRevD.111.066001

In a [new study](#) published in *Physical Review D*, Professor Ginestra Bianconi, Professor of Applied Mathematics at Queen Mary University of London, proposes a new framework that could revolutionize our understanding of gravity and its relationship with quantum mechanics.

The study, titled "Gravity from Entropy," introduces a novel approach that derives [gravity](#) from quantum relative entropy, bridging the gap between two of the most fundamental yet seemingly incompatible theories in physics: [quantum mechanics](#) and Einstein's general relativity.

The challenge of quantum gravity

For decades, physicists have struggled to reconcile the principles of quantum mechanics with those of general relativity. While quantum mechanics governs the behavior of particles at the smallest scales, general relativity describes the force of gravity on cosmic scales. Unifying these two frameworks has been one of the most elusive goals in modern science.

Professor Bianconi's work offers a fresh perspective by treating the metric of spacetime, a key concept in general relativity, as a quantum operator. This innovative approach uses quantum relative entropy, a concept from [quantum information theory](#), to describe the interplay between spacetime geometry and matter.

The role of entropy and the G-field

The study introduces a new entropic action, which quantifies the difference between the metric of spacetime and the metric induced by matter fields.

This approach leads to modified Einstein equations that, in the low coupling regime, i.e., low energies and small curvature, reduce to the classical equations of general relativity. However, the theory goes further, predicting the emergence of a small, positive cosmological constant—a value that aligns with experimental observations of the universe's accelerated expansion much better than for other pre-existing theories.

A key feature of the theory is the introduction of the G-field, an auxiliary field that acts as a Lagrangian multiplier. The G-field not only plays a crucial role in the modified equations of gravity but also opens the door to new interpretations of dark matter—a mysterious substance that makes up a significant portion of the universe's mass but has yet to be directly observed.

Wider implications and future directions

The implications of this research are profound. By linking gravity to quantum information theory, the study provides a potential pathway to a unified theory of quantum gravity. Moreover, the G-field could offer new insights into the nature of dark matter, a long-standing puzzle in cosmology.

"This work proposes that quantum gravity has an entropic origin and suggests that the G-field might be a candidate for dark matter," explains Professor Bianconi. "Additionally, the emergent cosmological constant predicted by our model could help resolve the discrepancy between theoretical predictions and experimental observations of the universe's expansion."

While further research is needed to fully explore the implications of this theory, the study represents a significant step forward in the quest to understand the fundamental nature of the universe.

Professor Bianconi's work challenges conventional wisdom and opens up exciting new avenues for exploration. By treating spacetime as a quantum entity and leveraging the power of entropy associated with the spacetime metrics, this research could pave the way for a deeper understanding of gravity, quantum mechanics, and the cosmos itself.

More information: Ginestra Bianconi, Gravity from entropy, *Physical Review D* (2025). DOI: [10.1103/PhysRevD.111.066001](https://doi.org/10.1103/PhysRevD.111.066001)
Journal information: *Physical Review D*
 Provided by [Queen Mary, University of London](#)

MARCH 4, 2025

High-speed energy-efficient electro-optic switch developed

by [Optica](#)

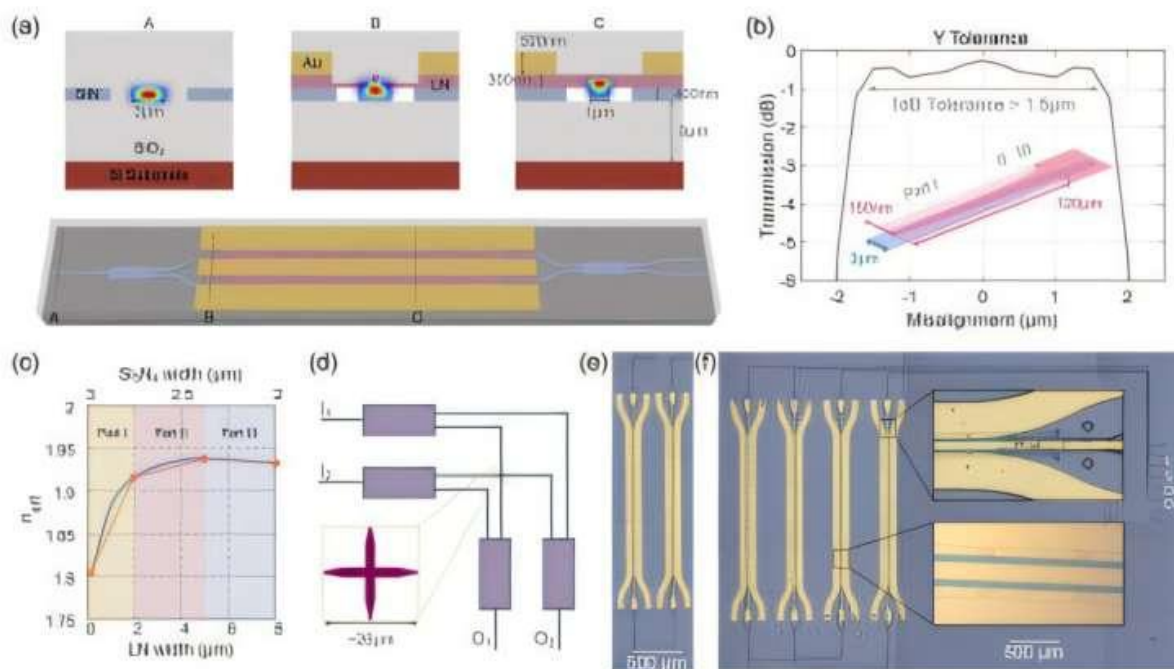


Fig. 1. (a) Schematic of the 1×2 optical switch element based on the LN-Si₃N₄ hybrid waveguide. **(b)** Misalignment tolerance of the evanescent coupler in the Y direction. **(c)** Effective index of the LN-Si₃N₄ hybrid waveguide vs. waveguide width. **(d)** Schematic structure of the 2×2 cascaded switch architecture. **(e, f)** Optical micrographs of (e) 1×2 and (f) 2×2 optical switch elements.

(a) Schematic of the 1x2 optical switch element based on the Ln-Si₃N₄ hybrid waveguide. (b) Misalignment tolerance of the evanescent coupler in the Y direction. (c) Effective index of the Ln-Si₃N₄ hybrid waveguide vs. waveguide width. (d) Schematic structure of the 2x2 cascaded switch architecture. (e, f) Optical micrographs of 1x2 and 2x2 optical switch

elements and 2x2 cascaded optical switches. Credit: Jinwei Su, Shanghai Jiao Tong University

Researchers have developed a high-speed electro-optic switch that is energy-efficient, has low crosstalk and works across a broad bandwidth. Made using a scalable, chip-friendly process, this switch could enhance data capacity in optical networks and data centers by improving signal routing and switching.

Jinwei Su from the Shanghai Jiao Tong University in China will present this research at [Optical Fiber Communications Conference and Exhibition](#) (OFC), the global event for [optical communications](#) and networking, which will take place 30 March–3 April 2025 at the Moscone Center in San Francisco.

As artificial intelligence and cloud computing rapidly advance, the demand for high-capacity data exchange continues to rise. Optical switching, with its broad bandwidth and low latency, is emerging as one of the most promising solutions to address this challenge. To achieve nanosecond-scale [optical switching](#), the researchers fabricated a 2x2 cascaded electro-optic switch by micro-transfer printing pre-etched thin-film lithium niobate (TFLN) onto [silicon nitride](#).

The 2x2 cascaded electro-optic switch consists of four 1x2 Mach-Zehnder interferometer structures formed by silicon nitride waveguides with a TFLN coupon integrated onto the interferometer arms via micro-transfer printing to create hybrid phase shifters. This design takes advantage of the superior modulation capabilities of TFLN and the exceptional passive properties of silicon nitride, ensuring optimal performance for the optical switch.

Tests of the switches showed a broad 3-dB bandwidth exceeding 100 nm, an insertion loss of about 1.3 dB at a 1550-nm wavelength and low crosstalk below -45 dB. In addition, the TFLN enabled high-speed switching with a response time of less than 3 ns while consuming little power.

"Building on our study, our next steps will focus on further reducing insertion loss through optimized coupler design and ensuring backend compatibility with commercially available ultra-low-loss silicon nitride platforms," said Su.

"Additionally, we plan to develop large-area coupon-based massive micro-transfer printing to integrate multiple elements in a single process. These improvements will thereby scale our switch design toward practical, commercial applications in next-generation optical communication systems."

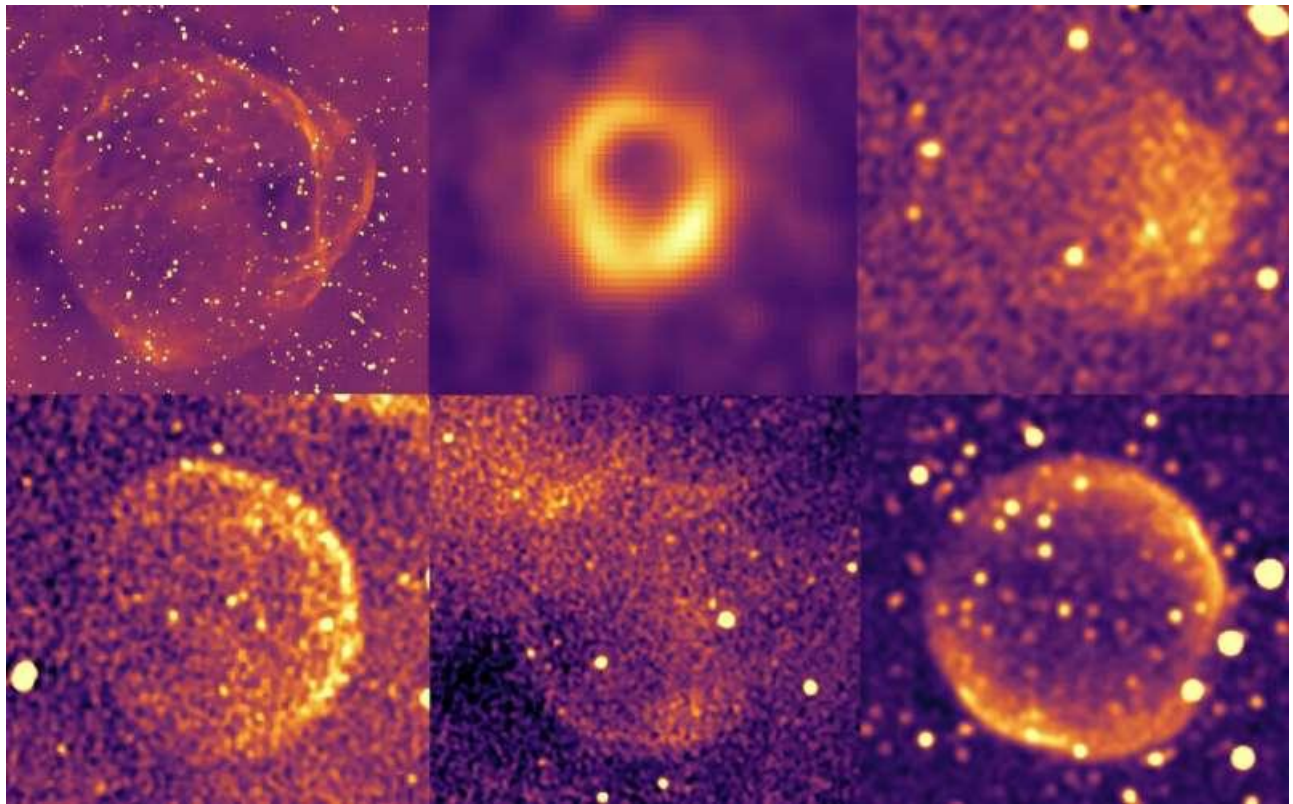
OFC will feature over 650 high-impact, peer-reviewed scientific presentations, including this one, during the five-day technical conference in San Francisco.

Provided by [Optica](#)

MARCH 4, 2025

'Ghosts of the radio universe': Astronomers have discovered a slew of faint circular objects

by Miroslav Filipovic, Andrew Hopkins, Luke Barnes and Nicholas Tothill, [The Conversation](#)



Some of the objects captured by ASKAP. Credit: Miroslav Filipovic, Andrew Hopkins, Luke Barnes and Nicholas Tothill

Radio astronomers see what the naked eye can't. As we study the sky with telescopes that record radio signals rather than light, we end up seeing a lot of circles.

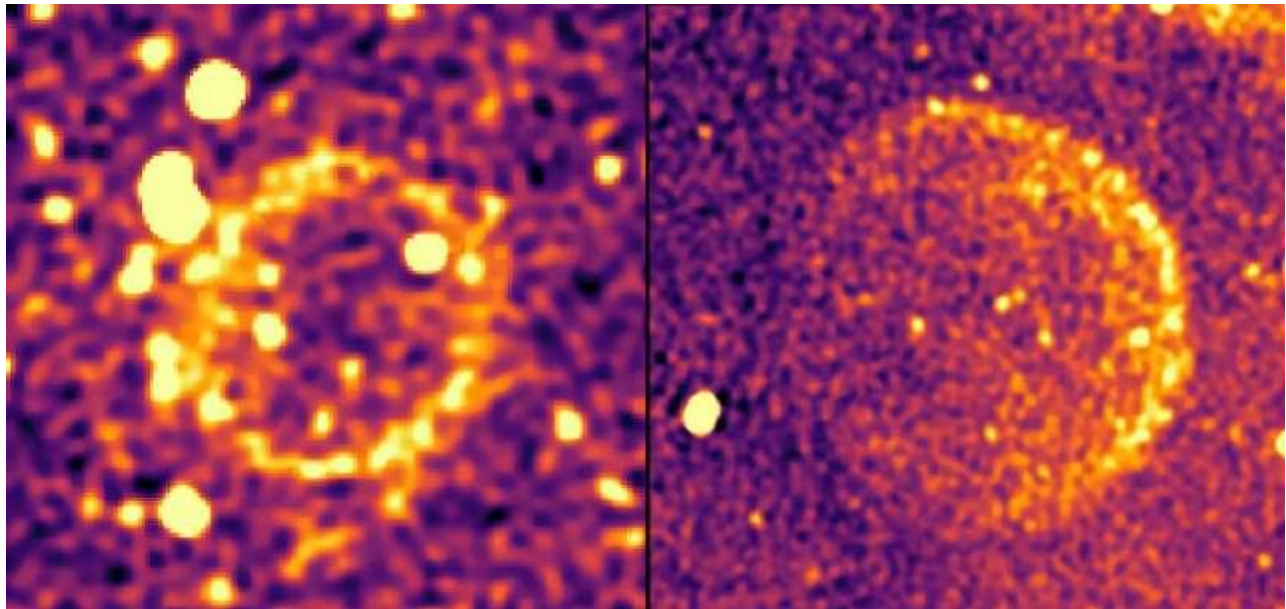
The newest generation of radio telescopes—including the [Australian Square Kilometre Array Pathfinder](#) (ASKAP) and [MeerKAT](#), a telescope in South Africa—is revealing incredibly faint cosmic objects, never before seen.

In astronomy, [surface brightness](#) is a measure that tells us how easily visible an object is. The extraordinary sensitivity of MeerKAT and ASKAP is now revealing a new "low surface brightness universe" to radio astronomers. It's comprised of radio sources so faint they have never been seen before, each with their own unique physical properties.

Many of the ASKAP results presented here were obtained with one of its major observing programs called EMU ([Evolutionary Map of the Universe](#)). EMU is mapping the entire southern sky with an unprecedented sensitivity and will deliver the most detailed map of the southern hemisphere sky to date—a spectacular new radio atlas that will be used for decades to come.

EMU's all-hemisphere coverage paired with ASKAP's exceptional sensitivity, especially within the Milky Way, is what's yielded so many recent discoveries.

Here's what they're teaching us.



Kyklos (left) and WR16 (r). Credit: Miroslav Filipovic, Andrew Hopkins, Luke Barnes and Nicholas Tothill

Unstable stars

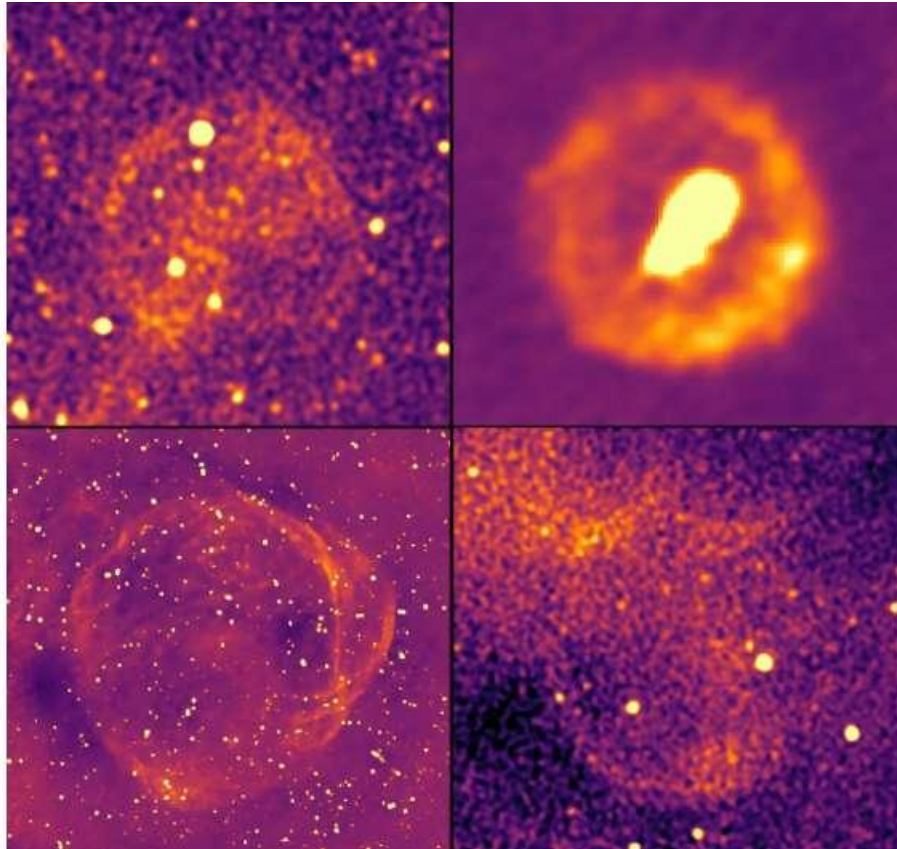
The ghostly ring [Kýklos](#) (from the Greek κύκλος, circle or ring) and the object WR16 both show the environment of rare and unusual celestial objects known as Wolf-Rayet stars.

When big stars are close to running out of fuel, they become unstable as they enter one of the last stages of the stellar life cycle, becoming a Wolf-Rayet star. They begin surging and pulsing, shedding their outer layers which can form bright nebulous structures around the star.

In these objects, a previous outflow of material has cleared the space around the star, allowing the current outburst to expand symmetrically in all directions. This sphere of stellar detritus shows itself as a circle.

Exploded stars

Stingray 1, [Perun](#), [Ancora](#) and [Unicycle](#) are supernova remnants. When a big star finally runs out of fuel, it can no longer hold back the crush of gravity. The matter falling inwards causes one final explosion, and the remains of these violent star deaths are known as supernovas.



Left to right clockwise: the supernova remnants Stingray 1, Perun, Ancora and Unicycle. Credit: Miroslav Filipovic, Andrew Hopkins, Luke Barnes and Nicholas Tothill
Their expanding shockwaves sweep up material into an expanding sphere, forming beautiful circular features.

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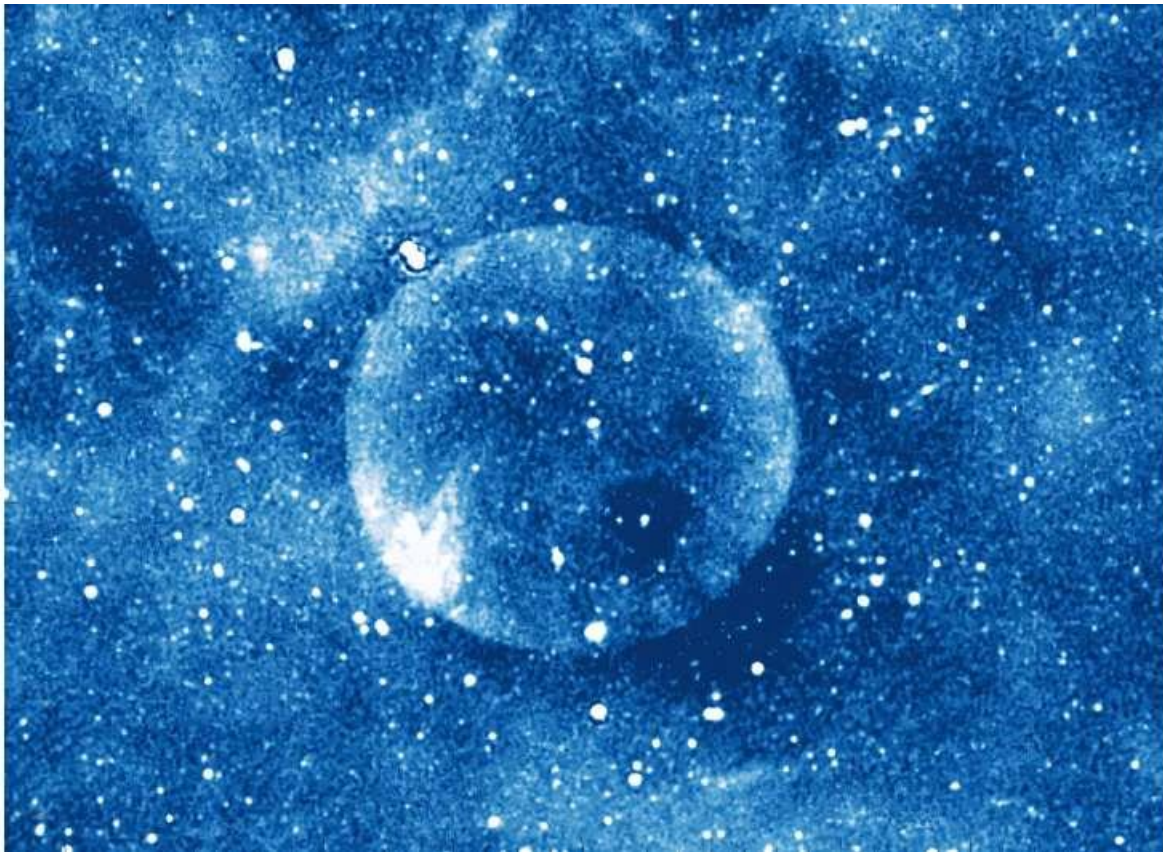
The supernova remnant will be deformed by its environment over time. If one side of the explosion slams into an interstellar cloud, we'll see a squashed shape. So, a near-perfect circle in a messy universe is a special find.

Teleios—named from the Greek Τελειος ("perfect") for its near-perfectly circular shape—is shown below. This unique object has never been seen in any wavelength, including [visible light](#), demonstrating ASKAP's incredible ability to discover new objects.

The shape indicates Teleios has remained relatively untouched by its environment. This presents us with an opportunity to make inferences about the initial supernova explosion, providing rare insight into one of the most energetic events in the universe.

At the other extreme, we can take an object and discover something entirely new about it. The Diprotodon supernova remnant is shown below.

This remnant is one of the largest objects in the sky, appearing approximately six times larger than the Moon. Hence the name: the animal Diprotodon, [one of Australia's most famous megafauna](#), a giant wombat that lived about 25,000 years ago.



ASKAP EMU radio image of the Teleios supernova remnant. Credit: Miroslav Filipovic, Andrew Hopkins, Luke Barnes and Nicholas Tothill

ASKAP's sensitivity has uncovered the object's full extent. This discovery led to further analysis, uncovering more of the history and the physics behind this object. The messy internal structure can be seen as different parts of the expanding shell slam into a busy interstellar environment.

A cosmic mirror

Lagotis is another object that can show how new telescope data can reclassify previously discovered objects. The reflection nebula VdB-80 has been seen before, within the plane of our Milky Way galaxy. The light we see was emitted by nearby stars, and then reflected off a nearby cloud of gas and dust.

However, with newly available ASKAP EMU data, we were able to discover an associated cloud of ionised hydrogen (known as an HII region, pronounced "aitch two"), where stellar energy has caused the gaseous matter to lose its electrons.

This HII region is seen to coexist with the reflection nebula, sharing the same stellar center, and is created from the star pushing into a molecular cloud. This movement is akin to burrowing, so the object earned the name Lagotis after *Macrotis lagotis*, the Australian greater bilby.

Outside the galaxy



ASKAP radio image of Diprotodon, a supernova remnant. Green circle shows the previous measured size, and the yellow circle shows the new ASKAP measured size. Earth's Moon size is shown in the top right for scale, and Diprotodon's namesake is shown in the top left. Credit: Miroslav Filipovic, Andrew Hopkins, Luke Barnes and Nicholas Tothill

ASKAP and MeerKAT are also illuminating objects from outside our Milky Way galaxy—for example, "radio ring" galaxies. When we use visible light to look at the stars in this galaxy, we see a rather plain disk.

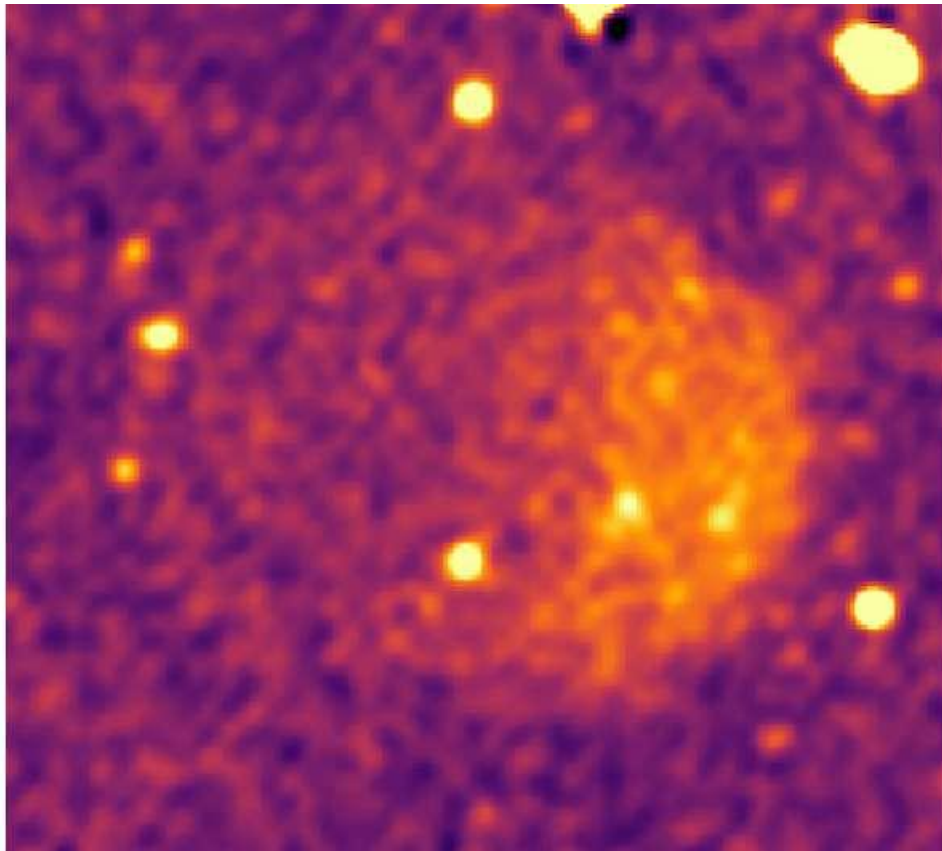
But in radio light, we see a ring. Why is there a hole in the middle? Perhaps the combined force of many exploding supernovas has pushed all the radio-emitting clouds out of the center. We're not sure—we're looking for more examples to test our ideas.

Finally, LMC-ORC is an Odd Radio Circle (ORC), a prominent new class of objects with unfamiliar origins. Only being visible in radio light, they are perhaps the most mysterious of all.

The next generation

MeerKAT and ASKAP are revealing incredible insights into the low surface brightness universe. However, they are precursors for the Square Kilometre Array, an international collaborative endeavor that will increase the abilities of radio astronomers and reveal even more unique features of the universe.

The low-surface brightness universe presents many mysteries. These discoveries push our understanding further. Currently, the EMU survey using ASKAP is only 25% complete.



Lagotis, with its cloud of ionised hydrogen or HII region seen on the right. Credit: Miroslav Filipovic, Andrew Hopkins, Luke Barnes and Nicholas Tothill

As more of this survey becomes available, we will discover many more unique and exciting objects, both new to astrophysics and extensions on previously known objects.

Provided by [The Conversation](#)

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MARCH 5, 2025

Distinguishing classical from quantum gravity through measurable stochastic fluctuations

by Tejasri Gururaj , Phys.org

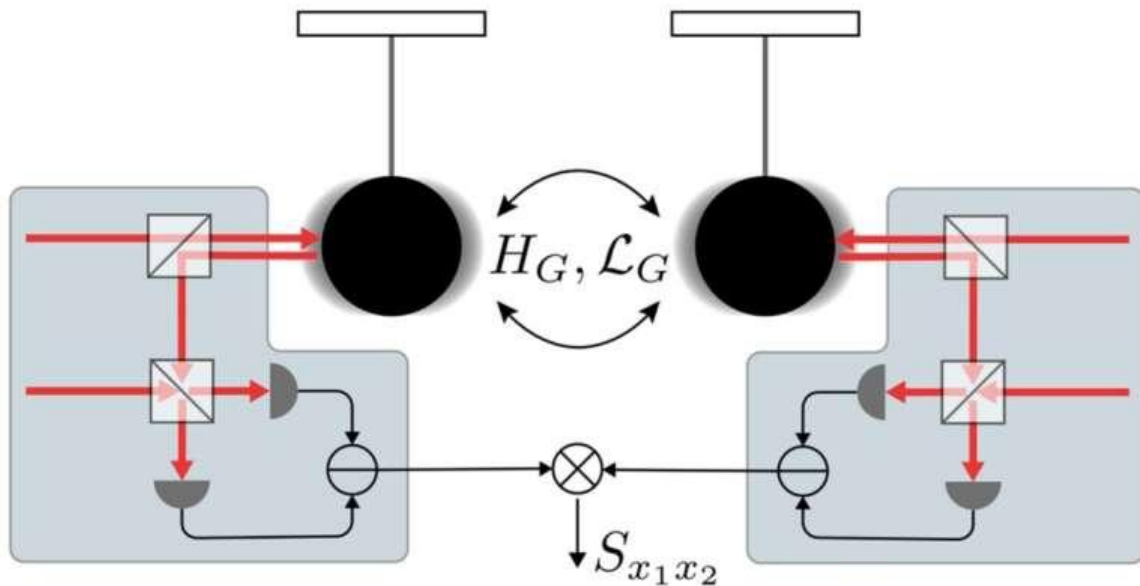


Illustration of an experiment that can be used to determine if gravity is classical or quantum. Two quantum masses are suspended at some distance away from each other and interact gravitationally. Credit: Serhii Kryhin.

In a new [Physical Review Letters study](#), researchers propose an experimental approach that could finally determine whether gravity is fundamentally classical or quantum in nature.

The nature of gravity has puzzled physicists for decades. Gravity is one of the four fundamental forces, but it has resisted integration into the quantum framework, unlike the electromagnetic, strong, and weak nuclear forces.

Rather than directly tackling the challenging problem of constructing a complete quantum theory of gravity or trying to detect individual gravitons—the hypothetical mediator of gravity—the researchers take a different approach.

Phys.org spoke to the researchers behind the study to gain insight into their unique approach.

"Several proposals have appeared in the past years that, in principle, allow us to determine gravity's nature experimentally, but their experimental requirements are extraordinarily challenging. So our motivation was to come up with a more feasible experiment that would

have the power to at least falsify that gravity is classical," explained Serhii Kryhin, a third-year graduate student at Harvard University and a co-author of the study.

The researchers aimed to rephrase the age-old question into one that could provide more concrete results: "What measurable differences would tell us whether gravity needs to be quantized?"

Quantum vs. classical fluctuations

"The idea is very simple yet remained unnoticed all this time. If gravity is quantum, as a long-range force, it should be able to induce quantum entanglement of distant matter. However, if gravity is fundamentally classical, no entanglement can be produced," said Vivishek Sudhir, Associate Professor at MIT and co-author of the study.

The insight is that if gravity is classical, it must exhibit irreducible stochastic fluctuations. These fluctuations are a necessity, stemming from a fundamental inconsistency that would arise without them—the deterministic nature of gravity (due to being classical) would violate the principles of quantum mechanics.

The brilliance comes in recognizing that these fluctuations would leave behind a signature in the cross-correlation spectrum as a phase shift, differing from what would be produced if gravity was quantum.

"Quantum fluctuations always arise as quantum fluctuations of dynamic degrees of freedom of general relativity. From a practical perspective, the main difference between quantum and classical gravity fluctuations comes in the magnitude. Being [relativistic effects](#), quantum fluctuations are notoriously weak and thus incredibly challenging to measure," said Kryhin.

"On the other hand, classical fluctuations, if they exist and have to remain consistent with everything else we know, appear to be much larger," added Prof. Sudhir.

Mathematical framework

The researchers propose a theoretical framework for this quantum-classical interaction in the Newtonian limit of gravity. In this framework, classical gravity and quantum matter co-exist.

They created a quantum-classical master equation describing how quantum matter and classical gravity evolve together. They also derived a Hamiltonian for Newtonian gravity's interaction with quantum masses through two complementary approaches—Dirac's theory of constrained systems and the Newtonian limit of gravity.

Next, they formulated a modified quantum Newton's law that accounts for stochastic gravitational effects and finally calculated the distinctive correlation patterns between two quantum oscillators interacting gravitationally.

This mathematical framework led them to a closed Lindblad equation (Markovian master equation) for quantum matter interacting with classical gravity. This equation includes a term proportional to the parameter ϵ , which distinguishes between classical gravity ($\epsilon \neq 0$) and quantum gravity ($\epsilon = 0$).

Identifying measurable quantities

The researchers derived several crucial results. They showed that, contrary to previous claims, a consistent theory of classical gravity interacting with quantum matter is indeed possible.

Their calculations reveal that classical gravity would induce fluctuations distinct from its quantum counterpart. Crucially, they identify an experimentally measurable signature.

When two quantum harmonic oscillators interact gravitationally, their cross-correlation spectrum shows a characteristic phase shift of π or 180 degrees at a specific detuning from resonance if gravity is classical.

To test these predictions, the researchers propose what amounts to a quantum version of the historic Cavendish experiment, using two highly coherent quantum mechanical oscillators coupled gravitationally.

The researchers could observe the characteristic [phase shift](#) by precisely measuring the cross-correlation of their motions.

What distinguishes this approach from previous proposals is its experimental feasibility. Unlike other tests that might require creating massive objects in quantum superposition states, this experiment relies on correlations between quantum oscillators within the reach of current or near-future technology.

Prof. Sudhir noted, "Semiclassical models of gravity usually explicitly neglect the backaction of quantum fluctuations of matter onto the classical gravity dynamics. In contrast, our theory allows self-consistent dynamics of classical gravity field and quantum matter."

Jury's still out

An experimental confirmation that gravity is classical would have profound implications for our physical theories.

"At present, it is taken as a self-evident fact that gravity has to be quantum, although nobody precisely knows what that means!" said Kryhin.

"Immense effort has been made to understand the behavior of quantized [general relativity](#) and construct a complete theory of quantum gravity, which resulted in the construction of string theory as one of the byproducts. If experimentally proven that gravity is classical, we will have to start from the beginning in a search for a satisfactory ontological picture of the world."

While the study offers a fresh perspective on a question that has plagued physicists for decades, they acknowledge the many problems to be addressed, from formalism development and model-building to demonstrating the technologies required for the experiment.

"From an experimental standpoint, we need two gravitating masses, noise isolation, and measurement techniques, all of which need to come together to realize the sensitivity needed for a decisive experiment," concluded Kryhin.

More information: Serhii Kryhin et al, Distinguishable Consequence of Classical Gravity on Quantum Matter, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.061501](https://doi.org/10.1103/PhysRevLett.134.061501). On arXiv: DOI: [10.48550/arxiv.2309.09105](https://doi.org/10.48550/arxiv.2309.09105)

Journal information: [Physical Review Letters](#) , [arXiv](#)

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MARCH 5, 2025

Quantum leap: Computing's next frontier takes form



Credit: AI-generated image

After several dashed predictions, quantum computing is accelerating rapidly with actual use cases and scientific breakthroughs expected within years, not decades.

US tech giants, startups, banks and [pharmaceutical companies](#) are pouring investments into this revolutionary technology.

Here's what to know about tech that may change the world, but can be hard to decipher:

Beyond 0 and 1

While classical computing relies on bits with just two states (0 or 1), quantum computing harnesses "qubits" with infinite possible states.

Each added qubit theoretically doubles computing capacity, allowing quantum computers to analyze countless possibilities simultaneously, solving in minutes what might take millions of years classically.

"Classical computers are speaking the wrong language. In quantum we're almost speaking the language of nature," said John Levy, CEO of hybrid chip developer SEEQC. "This unlocks previously unsolvable problems."

Microsoft recently unveiled [quantum technology](#) based on an entirely new state of matter—neither solid, gas, nor liquid.

Levy's verdict: "They should win a Nobel Prize."

'Efficiency race'

Given its exponential computing power, Levy believes quantum's potential exceeds our "limited imagination," especially when paired with AI.

Some even view quantum computing as the only path to "superintelligent" AI with superior cognitive abilities.

Practically speaking, quantum technology will dramatically accelerate discovery of new molecules—extending the periodic table learned at school.

This will mean new materials, breakthrough medications, advanced fabrics, complex financial models, and super-efficient batteries.

Philosopher and investor Anders Indset foresees an "efficiency race" transforming everything from agriculture to transportation: "We'll have hyper-efficient, lighter cars and cheaper, cleaner air travel methods."

Too much noise

Quantum computers already operate today.

IBM claims its quantum services have generated sales of \$1 billion, though current applications remain limited mainly to research.

The market will initially expand through servers equipped with specialized chips and systems.

"We are now switching from quantum theory to the quantum economy," said Indset.

This explains why cloud leaders Amazon, Microsoft, and Google are jumping in.

"The drive is to be leader in trillion dollar industries," Indset added.

The giants, already in a furious race to lead on AI, are heavily investing to solve quantum's biggest challenge: calculation errors.

Qubits require sub-freezing temperatures and are extremely sensitive to environmental "noise"—vibrations, heat, [electromagnetic interference](#)—that cause computational errors.

Google's new Willow quantum chip and Amazon's Ocelot semiconductor prototype aim to dramatically reduce these errors and costs.

"We're witnessing the creation of an ecosystem," said Levy, the CEO, noting that pharmaceutical giant Merck is investing in SEEQC to secure access to future quantum tools.

Is it safe?

The US and China are racing ahead in quantum development, with Washington imposing export restrictions on the technology.

Beyond competition, [quantum computing](#) poses serious cybersecurity concerns.

Since qubits can test countless combinations simultaneously, they could potentially break conventional encryption methods.

US government agencies and [tech companies](#) like Apple are already developing "post-quantum" encryption to prepare for this new reality.

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MARCH 5, 2025

Cold atoms on a chip: Opening the doors to accessible quantum research

by Sonia Fernandez, [University of California - Santa Barbara](#)

Daniel Blumenthal. Credit: Matt Perko, UC Santa Barbara
UC Santa Barbara researchers are working to move cold atom quantum experiments and applications from the laboratory tabletop to chip-based systems, opening new possibilities for sensing, precision timekeeping, quantum computing and fundamental science measurements.

"We're at the tipping point," said electrical and computer engineering professor Daniel Blumenthal.

In an invited article that was also selected for the cover of [Optica Quantum](#), Blumenthal, along with graduate student researcher Andrei Isichenko and postdoctoral researcher Nitesh Chauhan, lays out the latest developments and future directions for trapping and

cooling the atoms that are fundamental to these experiments—and that will bring them to devices that fit in the palm of your hand.

Cold atoms are atoms that have been cooled to very low temperatures, below 1 mK, reducing their motion to a very low energy regime where quantum effects emerge. This makes them sensitive to some of the faintest electromagnetic signals and fundamental particles, as well as ideal timekeeping, navigation devices and quantum "qubits" for computing.

In order to capitalize on these properties, many researchers currently work with highly sensitive laboratory-scale atomic optical systems to confine, trap and cool the atoms.

Conventionally, these systems use free-space lasers and optics, generating beams that are guided, directed and manipulated by lenses, mirrors and modulators. These [optical systems](#) are combined with magnetic coils and atoms in a vacuum to create [cold atoms](#) using the ubiquitous 3-dimensional magneto-optical trap (3D-MOT).

The challenge that researchers face is how to replicate the laser and optics functions onto a small, durable device that could be deployed outside of the highly controlled environment of the lab, for applications such as gravitational sensing, precision timekeeping and metrology, and [quantum computing](#).

The *Optica Quantum* review article covers recent and rapid advancements in the realm of miniaturizing complex cold-atom experiments via applications of compact optics and integrated photonics. The authors reference photonics achievements across a variety of sub-fields, ranging from telecommunications to sensors, and map the technology development to cold atom science.

"There's been a lot of really great work miniaturizing beam delivery," said Isichenko, "but it's been done with components that are still considered free-space optics—smaller mirrors or smaller gratings—but you still couldn't integrate multiple functionalities onto a chip."

Enter the researchers' photonic integrated 3D-MOT, a miniaturized version of equipment used widely in experiments to deliver beams of light to laser cool the atoms. Embedded into a low-loss silicon nitride waveguide integration platform, it's the part of a photonic system that generates, routes, expands and manipulates all the beams necessary to trap and cool the atoms.

The review article highlights the photonic integrated 3D-MOT—or "PICMOT" [demonstrated by the UC Santa Barbara team](#) as a major milestone for the field.

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"With photonics, we can make lasers on chip, modulators on chip and now large-area grating emitters, which is what we use to get light on and off the chip," Isichenko added.

Of particular interest is the atomic cell, a vacuum chamber where the atoms are trapped and cooled. One feat the researchers accomplished was to route the input light from an [optical fiber](#), which is less than the width of a hair, via waveguides to three grating emitters that generate three collimated free-space intersecting beams 3.5 mm wide.

Each beam is reflected back on itself for a total of six intersecting beams that trap a million atoms from the vapor inside the cell and, in combination with magnetic fields, cool the atoms to a temperature of just 250 uK. The larger the beams, the more atoms can be trapped into a cloud and interrogated, Blumenthal noted, and the more precise an instrument can be.

"We created cold atoms with integrated photonics for the first time," said Blumenthal.

The implications of the researchers' innovations are far-reaching. With planned improvements to durability and functionality, future chip-scale MOT designs can take advantage of a menu of photonic components, including [recent results with chip-scale lasers](#).

This can be used to optimize technology for applications as diverse as measuring volcanic activity to the effects of sea level rise and glacier movement by sensing the [gradient of gravity on and around the Earth](#).

Integration of the 3D-MOT can give quantum scientists and time-keepers new ways to send today's earthbound instruments into space and conduct new fundamental science, and enable measurements not possible on Earth.

Additionally, the devices could advance research projects by decreasing the time and effort spent establishing and fine tuning optical setups. They can also open the door to accessible quantum research projects for future physicists.

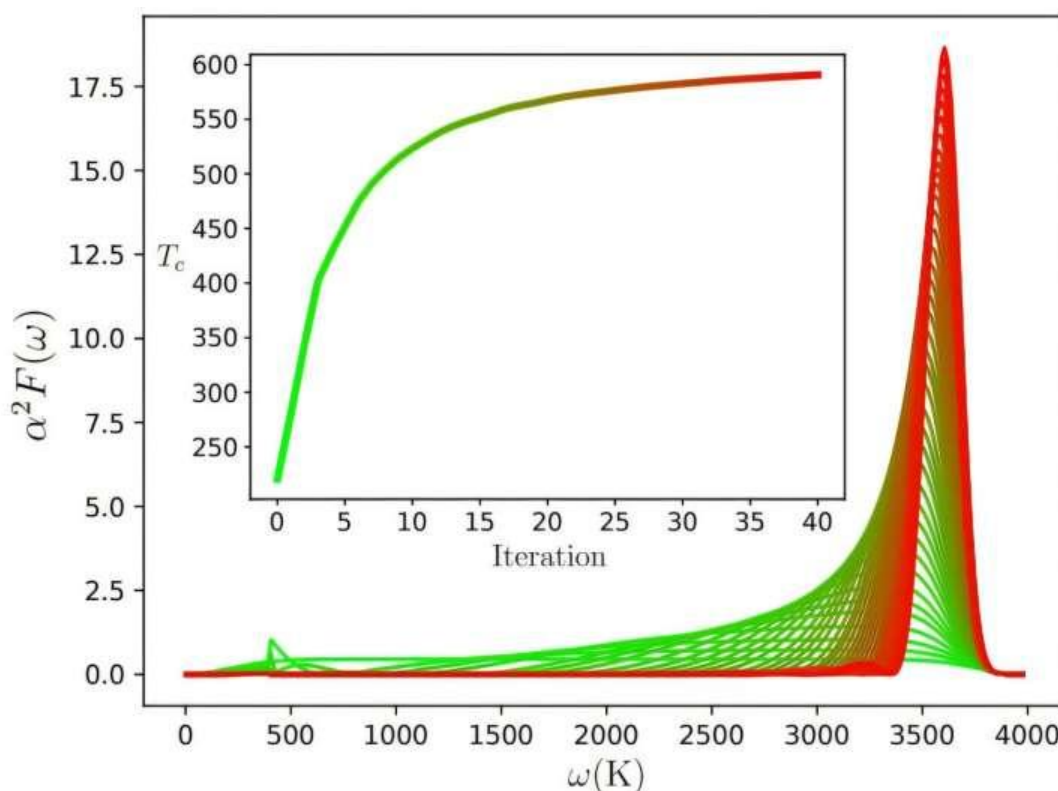
More information: Daniel J. Blumenthal et al, Enabling photonic integrated 3D magneto-optical traps for quantum sciences and applications, *Optica Quantum* (2024). DOI: [10.1364/OPTICAQ.532260](https://doi.org/10.1364/OPTICAQ.532260)

Provided by [University of California - Santa Barbara](#)

MARCH 5, 2025

Room-temperature superconductors: Fundamental constants suggest they could exist within our universe

by [Queen Mary, University of London](#)



The evolution of the Eliashberg function $\alpha^2 F(\omega)$ and corresponding T_c (inset) is optimized. Red (green) lines are later (earlier) iterations in the optimization. Credit: arXiv (2024). DOI: 10.48550/arxiv.2406.08129

In a new development that could help redefine the future of technology, a team of physicists has uncovered a fundamental insight into the upper limit of superconducting temperature.

This [research](#), accepted for publication in the *Journal of Physics: Condensed Matter*, suggests that room-temperature [superconductivity](#)—long considered the "holy grail" of condensed matter physics—may indeed be possible within the laws of our universe.

Superconductors, materials that can conduct electricity without resistance, have the potential to revolutionize energy transmission, [medical imaging](#), and quantum computing. However, until now, they have only functioned at [extremely low temperatures](#), making them

impractical for widespread use. The race to find a superconductor that works at ambient conditions has been one of the most intense and elusive pursuits in modern science.

In their latest work, Queen Mary University of London Professor Kostya Trachenko and colleagues reveal that the upper limit of superconducting temperature T_C is intrinsically linked to the fundamental constants of nature—the electron mass, electron charge, and the Planck constant.

Constants such as these govern everything from the stability of atoms to the formation of stars and synthesis of carbon and other elements essential to life. The team's finding shows that the upper limit ranges from hundreds to a thousand Kelvin—a range that comfortably includes room temperature.

"This discovery tells us that room-temperature superconductivity is not ruled out by fundamental constants," said Professor Pickard of the University of Cambridge, co-author of this study. "It gives hope to scientists: The dream is still alive."

The results have already been independently confirmed in a separate study, adding weight to the team's conclusions. But the implications go even further. By exploring how different values of these fundamental constants could alter the limits of superconductivity, the researchers have opened a fascinating window into the nature of our universe.

Imagine a world where the fundamental constants are different and set the upper limit for T_C at a mere millionth of a Kelvin. In such a universe, superconductivity would be undetectable, and we would never have discovered it. Conversely, in a universe where the limit is a million Kelvin, [superconductors](#) would be common—even in your electric kettle.

"The wire would superconduct instead of heating up," Professor Trachenko explains. "Boiling water for tea would be a very different challenge."

It therefore appears that the very reason the community is busy chasing up a room-temperature superconductor is that our fundamental constants set the upper limit of T_C in the range 100–1000 K (the range of planetary conditions) where our "room" temperature is.

This research not only advances our understanding of superconductivity but also highlights the delicate balance of the constants that make our universe—and life within it—possible. For scientists and engineers, this work also provides a renewed sense of direction.

"The fact that room-temperature superconductivity is theoretically possible, given our [universe's](#) constants, is encouraging," Professors Trachenko and Pickard add. "It's a call to keep exploring, experimenting, and pushing the boundaries of what's possible."

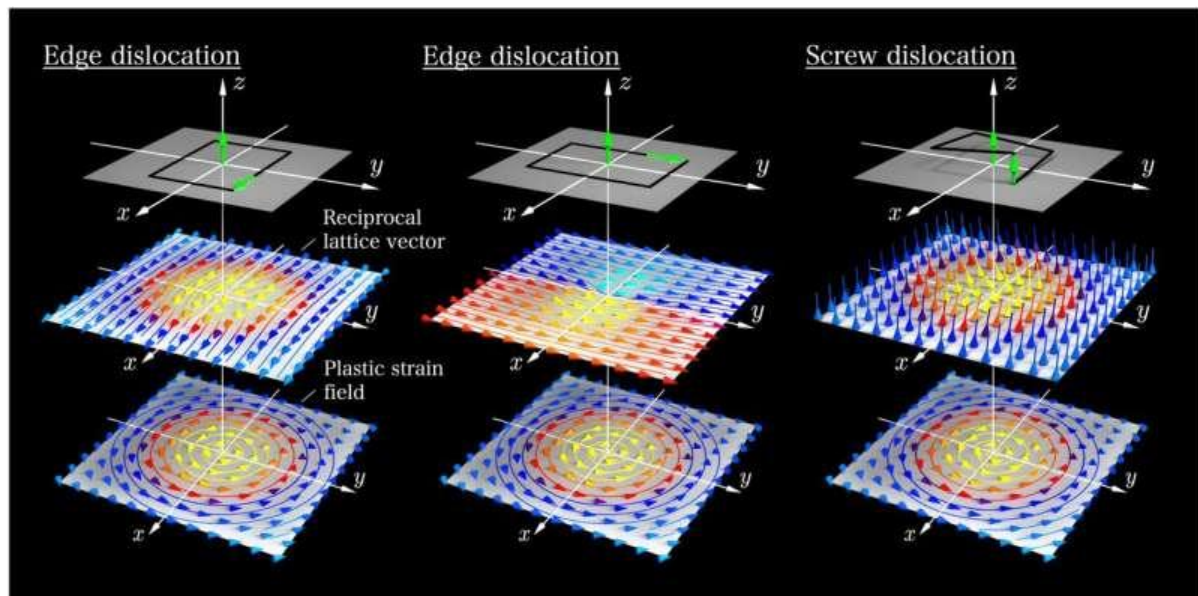
More information: Kostya Trachenko et al, Upper bounds on the highest phonon frequency and superconducting temperature from fundamental physical constants, *Journal of Physics: Condensed Matter* (2025). DOI: [10.1088/1361-648X/adbc39](https://doi.org/10.1088/1361-648X/adbc39). On arXiv: DOI: [10.48550/arxiv.2406.08129](https://doi.org/10.48550/arxiv.2406.08129)

Journal information: [arXiv](#)

Provided by [Queen Mary, University of London](#)

An unexpected connection between the equations for crystalline lattice defects and electromagnetism

by [Osaka University](#)



The reciprocal lattice vectors of a crystal caused by the three types of dislocations and the plastic strain fields obtained through their Helmholtz decomposition. In all cases, the plastic strain fields are observed to exhibit right-handed screw rotation along the dislocation line (the z -axis in the diagram). Furthermore, this characteristic aligns perfectly with the static magnetic fields generated around steady electric currents. Credit: *Royal Society Open Science* (2025). DOI: 10.1098/rsos.241568

A fundamental goal of physics is to explain the broadest range of phenomena with the fewest underlying principles. Remarkably, seemingly disparate problems often exhibit identical mathematical descriptions.

For instance, the rate of heat flow can be modeled using an equation very similar to that governing the speed of particle diffusion. Another example involves wave equations, which apply to the behavior of both water and sound. Scientists continuously seek such connections, which are rooted in the principle of the "universality" of underlying physical mechanisms.

In a study published in the journal *Royal Society Open Science*, researchers from Osaka University uncovered an unexpected connection between the equations for defects in a [crystalline lattice](#) and a well-known formula from electromagnetism.

They demonstrated that the fields representing the strain generated around lattice dislocations in [crystalline materials](#), modeled by Cartan's First Structure Equation, obey the same equations as the more familiar Biot-Savart law. The former can be quite complex and challenging to visualize, while the latter describes how [electric currents](#) generate magnetic fields, and is essential for understanding numerous modern devices, including electric motors.

"Searching for universality relationships can be valuable in emerging scientific fields, especially when the governing equations are newly established, and the nature of their solutions remains elusive," explains lead author of the study Shunsuke Kobayashi.

The Biot-Savart law states that an electrical current flowing through a wire will generate a [magnetic field](#) around itself represented by vectors that twist around like a vortex. Similarly, the effect of certain types of atomic dislocation in a crystalline lattice will induce a strain vector field on the surrounding atoms.

Using the analogous Biot-Savart law from electromagnetism, it will be possible to analytically determine the effect of dislocations, instead of the more arcane Cartan Structure Equations.

"This discovery is expected to serve as a fundamental theory for describing the plastic deformation of crystalline materials, opening the way for a wide range of applications in [material science](#)," senior author Ryuichi Tarumi says. The researchers also believe that finding these kinds of connections across areas of study can spur new discoveries.

More information: Biot-Savart law in the geometrical theory of dislocations, *Royal Society Open Science* (2025). DOI:

[10.1098/rsos.241568](https://doi.org/10.1098/rsos.241568). royalsocietypublishing.org/doi/10.1098/rsos.241568. On arXiv: DOI: [10.48550/arxiv.2409.03443](https://arxiv.org/abs/2409.03443)

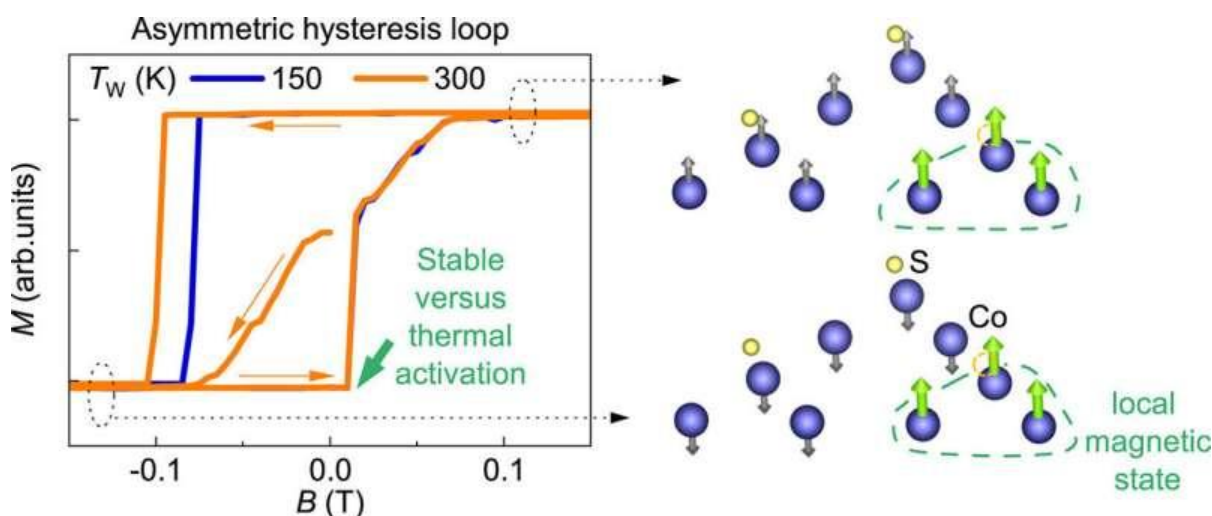
Journal information: [Royal Society Open Science](#) , [arXiv](#)

Provided by [Osaka University](#)

MARCH 5, 2025

Tunable asymmetric hysteresis loop: Researchers develop method to control magnetic reversal in Weyl semimetal

by Zeng Qingqi; Zhao Weiwei, [Chinese Academy of Sciences](#)



Graphical abstract. Credit: *Materials Today Physics* (2025). DOI: 10.1016/j.mtphys.2024.101642

Recently, a research team found a new way to control the magnetic reversal in a special material called $\text{Co}_3\text{Sn}_2\text{S}_2$, a Weyl semimetal. The team was led by Prof. Qu Zhe from the Hefei Institutes of Physical Science of the Chinese Academy of Sciences, in collaboration with Prof. Liu Enke from the Institute of Physics of the Chinese Academy of Sciences.

"This discovery could help switch the magnetization of devices that rely on [magnetic properties](#)," said Prof. Qu, "such as hard drives and spin-based technologies."

The results were [published](#) in *Materials Today Physics*.

$\text{Co}_3\text{Sn}_2\text{S}_2$ is a magnetic Weyl semimetal with a unique structure, where its magnetic properties are linked to its topological features. The exchange bias (EB) effect, important for stability in [magnetic devices](#), has been observed in this material, but the exact mechanisms behind it are still unclear.

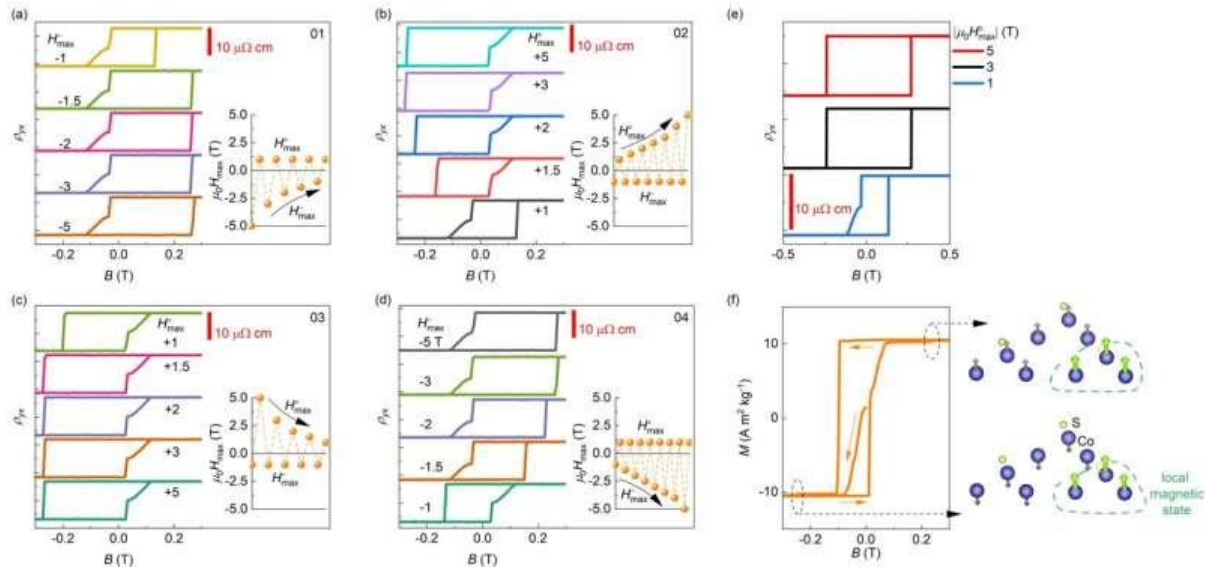


Figure (a–d) Tunable asymmetric Hall loops at 5 K (magnetic histories are shown in insets). (e) Symmetric loops under high enough external magnetic field. (f) Sketch of the influence of positively aligned local magnetic state to magnetic reversals. Credit: ZENG Qingqi
In this study, researchers found that by adjusting the maximum external magnetic field (H_{max}) and thermal history, they could control the material's magnetic reversal. When H_{max} was high enough, the material's coercive fields became symmetric, and the EB-like behavior disappeared.

The researchers proposed that local magnetic states play a key role in the tunable magnetic reversals: below certain flipping fields, these states help form reverse magnetic domains, lowering the coercive field. When H_{max} exceeds a critical value, these states align with the magnetization direction, no longer affecting the reversal process.

This discovery offers a new explanation for the asymmetric hysteresis loop in $\text{Co}_3\text{Sn}_2\text{S}_2$, different from the usual EB effect. "By adjusting the maximum external magnetic field, we can control the material's magnetic reversal and its magnetic-topological properties, effectively tuning the symmetry of the hysteresis loop," said Dr. Zeng Qingqi, a member of the team.

More information: Qing-Qi Zeng et al, Asymmetric hysteresis loop due to hidden local magnetic state in a Weyl semimetal, *Materials Today Physics* (2025). DOI:

[10.1016/j.mtphys.2024.101642](https://doi.org/10.1016/j.mtphys.2024.101642)

Provided by [Chinese Academy of Sciences](#)

Scientists Just Turned Light Into a ‘Supersolid’: Both Solid and Liquid at The Same Time

Light was turned into a quasiparticle that simultaneously behaved like a crystal and wave.

A supersolid is a paradox of physics — a material that is both solid and liquid at the same time. This contradictory form of matter was first proposed more than 60 years ago, and, for a long time, people thought it was too nuts to actually exist. But we’re talking about the realm of quantum mechanics, and normal expectations should be thrown out the window.

[In 2007](#), researchers at ETH Zurich and MIT unveiled the world’s first supersolids, starting with superflooding sodium and rubidium, respectively.

Now, an international team of researchers has unveiled an entirely new route to supersolidity, harnessing light-matter particles known as polaritons to create an exotic, flowing crystal.

In other words, this is a supersolid made not from atoms, but from light itself.

“We actually made light into a solid. That’s pretty awesome,” Dimitris Trypogeorgos, a physicist at the National Research Council (CNR) in Italy and a member of the international team behind the discovery, told [New Scientist](#).

What Is a Supersolid, Anyway?

Supersolids are a state of matter that exists only in the quantum realm. They combine the rigid structure of a solid with the frictionless flow of a superfluid. Imagine a crystal that can move without resistance, its atoms hopping freely within a fixed lattice. Physicists have been fascinated by them since the 1950s, when they first theorized that supersolids might exist.

For decades, scientists searched for supersolids in ultracold atoms, particularly in helium-4. In 2004, researchers thought they had glimpsed supersolid helium-4 under extreme pressure, but the results turned out to be a red herring caused by other quantum effects. So, creating a supersolid remained an elusive goal until very recently.

In their new study, researchers across the world took a radically different approach. Instead of using ultracold atoms, they used laser light and a specially designed semiconductor. They fired a laser at a piece of gallium arsenide, a material etched with precise tiny ridges. When the light hit the ridges, it interacted with the semiconductor to create polaritons — quasiparticles (a collective excitation of a large number of particles that behaves as if it were a single particle) that are part light and part matter.

These polaritons were confined by the ridges, forcing them into a crystal-like arrangement. But unlike ordinary solids, this structure also allowed the polaritons to flow without resistance, exhibiting zero viscosity.

The result was a supersolid made entirely of light — a first in the history of physics. “This is really at the beginning of something new,” says Trypogeorgos.

To confirm that their system had entered a supersolid phase, the researchers measured the density of the polaritons. They exhibited a “distinct modulation” in space, as if it were crystallizing. But they also observed signs of coherence — a sign that the system maintained its superfluid character. This means that, despite forming a rigid lattice, the polaritons still moved together in an unbroken wave.

What’s Cool About It?

Light-based supersolids open up new avenues for exploring quantum states of matter. Unlike supersolids made from atoms, which require temperatures close to absolute zero, light-based supersolids might be easier to manipulate and study at room temperature. This could help physicists better understand the nature of supersolids and other exotic quantum phenomena.

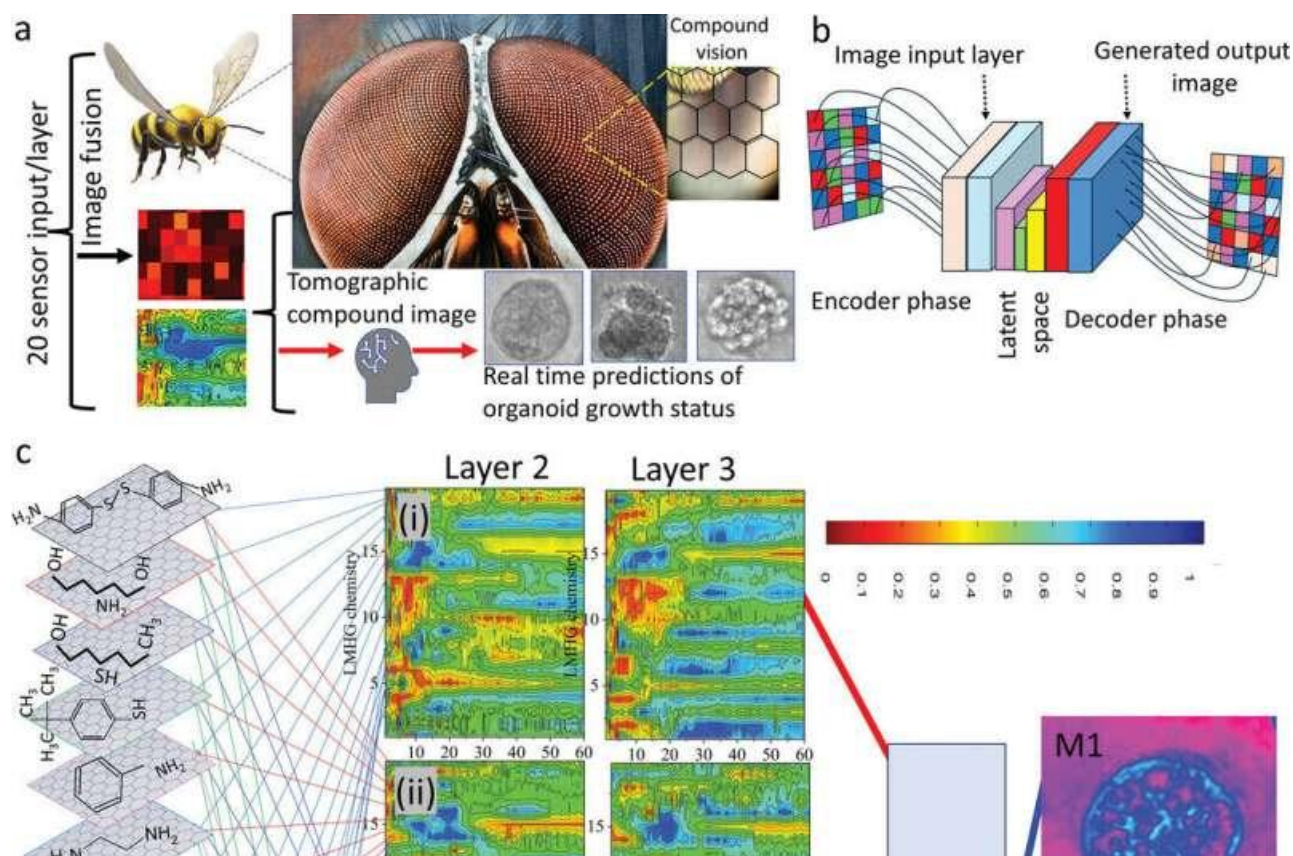
Such findings may help physicists better understand how quantum matter can change states. The research also has potential practical implications for quantum technologies, such as ultra-efficient energy transport and novel computing systems.

For now, the supersolid polaritons exist only in a controlled laboratory setting. But with further refinement, researchers hope that this new phase of matter might one day find applications beyond the lab, harnessing the weirdness of quantum physics for future technologies.

The findings appeared in the journal [Nature](#).

Insect vision inspires noninvasive method for deep tissue molecular mapping

by [Technion - Israel Institute of Technology](#)



Chemical tomographic image processing inspired from 'ommatidium' mechanism in 'bee vision' to predict organoid's heterogeneity. a) Creation of hybrid compound mosaic images (2D tomography) by amalgamating sensor chemistries within distinct layers. These images are then harnessed in deep neural network image processing to predict the specific organoid's image pixel by pixel. b) Generative deep learning models for organoid image synthesis using a typical encoder-decoder based U-net architectures (see details in Figure S14 of the Supporting Information). c) The utilization of 20 sensor chemistry from spatiotemporally-resolved spectrometer yields synthetic superpositions for layer 2 and 3, resulting in distinctive mosaic arrangements as shown for (i-iii) M1-M3, but also set them apart from media backgrounds (iv-v). Credit: *Advanced Materials* (2025). DOI: 10.1002/adma.202413017

The journal *Advanced Materials* recently [published](#) a study introducing a new method for monitoring molecular processes deep within tissue. Developed at the Technion–Israel Institute of Technology, the innovation is expected to accelerate key advancements in personalized medicine, cancer diagnosis, and early disease detection.

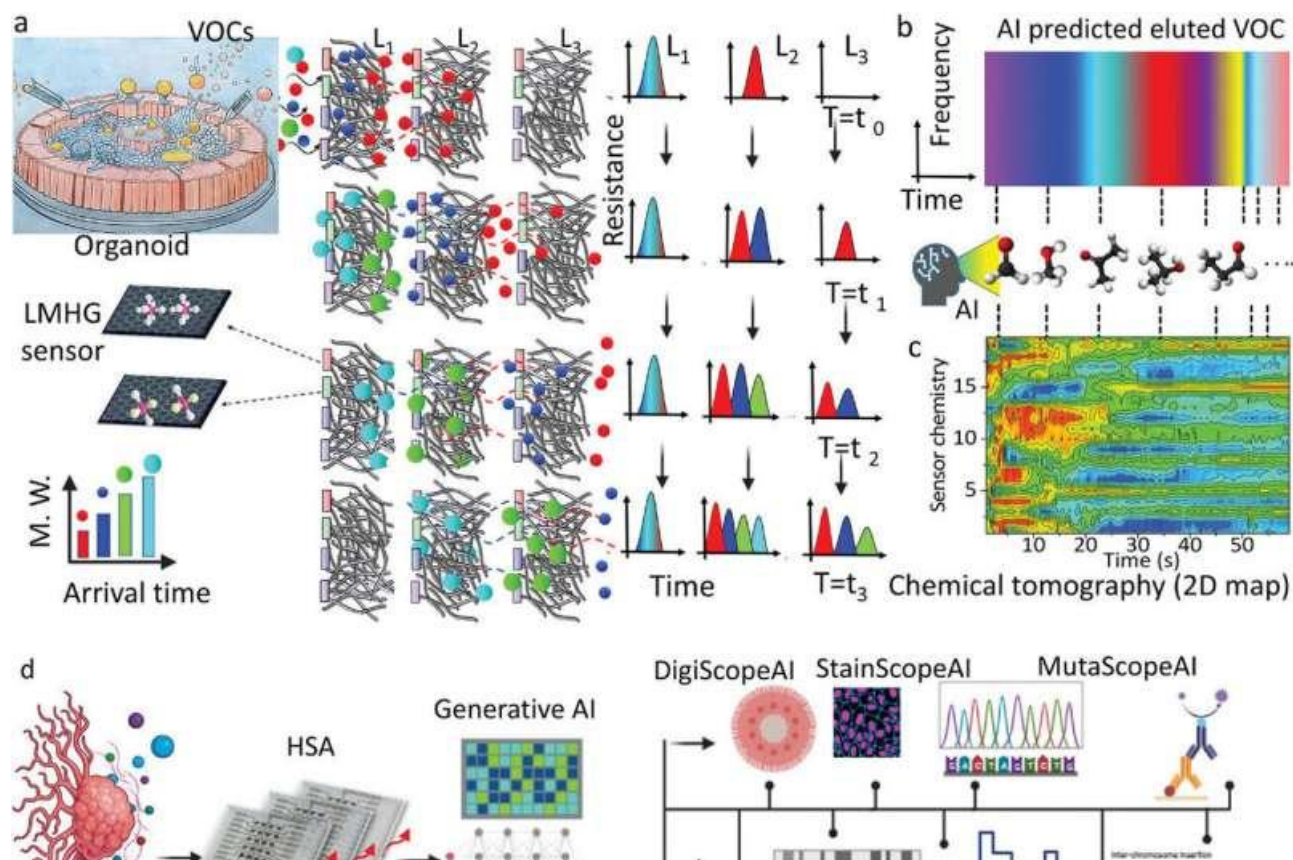
The research was led by Prof. Hossam Haick, postdoctoral fellow Dr. Arnab Maity, and Ph.D. student Vivian Darsa Maidantchik from the Wolfson Faculty of Chemical Engineering at the Technion. The study also involved Dr. Dalit Barkan, research assistant Dr. Keren Weidenfeld, and Prof. Sarit Larisch from the University of Haifa's Faculty of Natural Sciences.

The Technion researchers' method enables functional and molecular mapping of organoids—three-dimensional cell-based models that replicate the structural and functional characteristics of natural tissues. Organoids play a critical role in [biomedical research](#) by allowing scientists to study health and disease states and assess the effects of various treatments on organs and tissues.

Despite their potential, organoids face major technological challenges, particularly in monitoring internal tissue processes. Current methods are expensive and have the following significant limitations:

- Some techniques destroy the tissue (e.g., RNA sequencing)
- Others are blind to deep-tissue processes (e.g., confocal microscopy)

Technion's breakthrough overcomes these limitations with a low-cost, accurate, and non-invasive approach that allows for continuous monitoring of structural and molecular changes within organoids.



a) Illustration of the spatiotemporal separation and mapping of VOCs from organoids fusing the spatiotemporally-resolved spectrometer. b) Frequency domain VOCs spectrogram of the examined organoids. c) 2D chemical tomography through sensor fusion. d) Schematic representation of bridging VOCs with multi-dimensional imaging as well as cyto-proteogenomics using generative AI for each separate program. e) A stepwise scheme obreast cancer progression (normal (MCF10A (M1)), premalignant (MCF10AT (M2)) and malignant (MCF10CA1h (M3)) breast cells) and its characterization with f–h) DAPI staining, i–k) microscope imaging (Magnification x40, Bar= 50 μ m) with l) 3D rendition and m) western blot (WB) for the expression of mesenchymal markers ((i) fibronectin and (ii) vimentin) and (iii) E-Cadherin (epithelial marker) with a (iv) simple protein loading (tubulin). n,o) Quantification of fibronectin and vimentin levels from WB results. Densitometry values were normalized to M1. Columns; mean, bars; SD, n = 3. *p < 0.05, **p < 0.01, ***p < 0.001. Credit: *Advanced Materials* (2025). DOI: 10.1002/adma.202413017

Chemical tomography: New method in deep-tissue monitoring

The researchers' new method, called chemical tomography, provides insights into tissue function by analyzing [volatile organic compounds](#) (VOCs). These molecules are present in exhaled breath, saliva, sweat, and other bodily fluids. Prof. Haick is a leading global expert in the use of VOCs for early disease detection. His prior research has led to the development of multiple diagnostic technologies based on VOC analysis.

In this study, VOC monitoring enabled the dynamic molecular and functional mapping of a human breast tissue organoid, revealing key protein and genomic data associated with the transformation of healthy breast tissue into cancerous tissue.

The system detects VOCs using a graphene-based sensor array, with the collected data analyzed through generative artificial intelligence (AI). The inspiration for this technology comes from the compound eye of insects—a structure composed of multiple small eyes that send numerous images to the insect's brain for analysis. In the system, the graphene sensors function as the compound eye, while AI acts as the brain, processing and interpreting the data.

The new system provides real-time, dynamic mapping of organoids at a significantly lower cost than existing alternatives, without damaging the tested tissue. This method enables researchers to:

- Track cancer progression at different stages
- Gain a deeper understanding of cancer biology
- Map biochemical pathways, metabolic markers, and [molecular processes](#) involved in cancer development

Using this new approach, the researchers identified six biochemical pathways responsible for producing 12 different types of VOCs, which could serve as biomarkers for disease states.

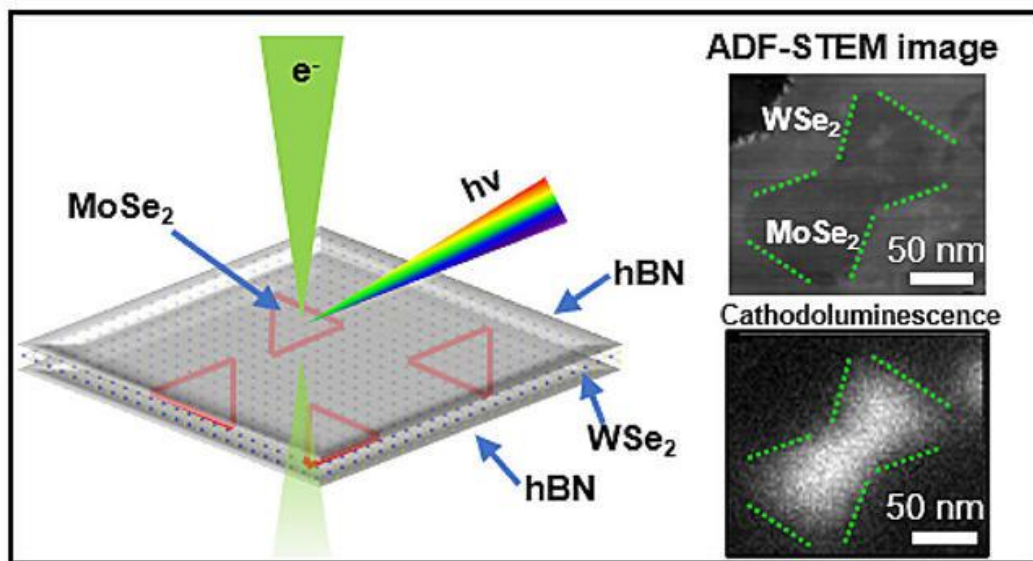
According to Prof. Haick, "Beyond cancer applications, our system has the potential to diagnose issues in various organs, including the kidneys, brain, and liver. It could also transmit real-time internal health data to an external monitoring system via an antenna, enabling continuous tracking of [tissue](#) health and early disease warnings. This is a breakthrough in integrating artificial intelligence into medicine, particularly in personalized health care."

More information: Arnab Maity et al, Chemical Tomography of Cancer Organoids and Cyto-Proteo-Genomic Development Stages Through Chemical Communication Signals, *Advanced Materials* (2025). DOI: [10.1002/adma.202413017](https://doi.org/10.1002/adma.202413017)

Journal information: [Advanced Materials](#)

Provided by [Technion - Israel Institute of Technology](#)

'Nanodot' control could fine-tune light for sharper displays and quantum computing



Credit: ACS Photonics (2024). DOI: 10.1021/acsp Photonics.4c01739

Newly achieved precise control over light emitted from incredibly tiny sources, a few nanometers in size, embedded in two-dimensional (2D) materials could lead to remarkably high-resolution monitors and advances in ultra-fast quantum computing, according to an international team led by researchers at Penn State and Université Paris-Saclay.

In a recent study, [published](#) in *ACS Photonics*, scientists worked together to show how the light emitted from 2D materials can be modulated by embedding a second 2D material inside them—like a tiny island of a few nanometers in size—called a nanodot. The team described how they achieved the confinement of nanodots in two dimensions and demonstrated that, by controlling the nanodot size, they could change the color and frequency of the emitted light.

"If you have the opportunity to have localized light emission from these materials that are relevant in quantum technologies and electronics, it's very exciting," said Nasim Alem, Penn State associate professor of materials science and engineering and co-corresponding author on the study. "Envision getting light from a zero-dimensional point in your field, like a dot in space, and not only that, but you can

also control it. You can control the frequency. You can also control the wavelength where it comes from."

The researchers embedded nanodots made of a 2D material called molybdenum diselenide inside another 2D material, tungsten diselenide, and then aimed a beam of electrons at the structure to make it emit light. This technique, called cathodoluminescence, allowed the team to study how individual nanodots in the material emit light at high resolution.

"By combining a light detection tool with a transmission electron microscope, which is a powerful microscope that uses electrons to image samples, you can see much finer details than with other techniques," said Saiphaneendra Bachu, first author who served as the primary doctoral student on the study before earning a doctorate from Penn State in 2023 and is now a TEM analysis engineer at Samsung Austin Semiconductor. "Electrons have tiny wavelengths, so the resolution is incredibly high, letting you detect light from one tiny dot separately from another nearby dot."

They found that larger dots give off one type of glow, while smaller dots produce another. When the dots are extremely tiny—less than 10 nanometers wide, which is about the size of 11 hydrogen atoms arranged in a line—they behave in a unique way, trapping energy and emitting light with higher frequency, which equates to a smaller wavelength.

According to Alem, this phenomenon is called quantum confinement. It occurs when the dots are contained in a space so small that their energy becomes quantized, meaning it becomes a discrete characteristic that enables new properties, including novel electronic and optical capabilities. In this case, the researchers confirmed that nanodots confined fundamental particle pairs known as excitons at the interface of molybdenum diselenide and tungsten diselenide.

Excitons can transport energy but do not carry a net charge, and they can influence how semiconductors—the chips underpinning smartphones, computers and more—behave. By precisely controlling the excitons in materials, scientists can manipulate the light they emit more effectively, which they said could lead to faster and more secure quantum systems, as well as other customizable, energy-saving devices like higher resolution screen displays.

"Think about how OLED displays work," Bachu said. "Each pixel has its own tiny light source behind it so you can control the exact color or brightness of each one. This lets the screen show true black and accurate colors like red, green and blue. If you improve this process, you make the picture much sharper and more vibrant."

The control comes from adjusting the band gap—essentially the energy threshold electrons must cross to make a material emit light—of a semiconductor material. Materials with lower dimensions, like a single layer of 2D tungsten diselenide, can have a direct band gap, which is more efficient at emitting light compared to its thicker, indirect bandgap counterpart, Alem said.

But light emission efficiency and other electronic and optical properties vary even among a family of related 2D materials—like molybdenum disulfide, tungsten disulfide, molybdenum diselenide and tungsten diselenide—because they each have different band gap energies.

"By mixing them—like combining molybdenum diselenide and tungsten diselenide in specific ratios—you can fine-tune the band gap to emit light at a specific color," Bachu said. "This process, called band gap engineering, is possible because of the wide variety of materials in this family, making them an excellent platform for studying and creating these light sources."

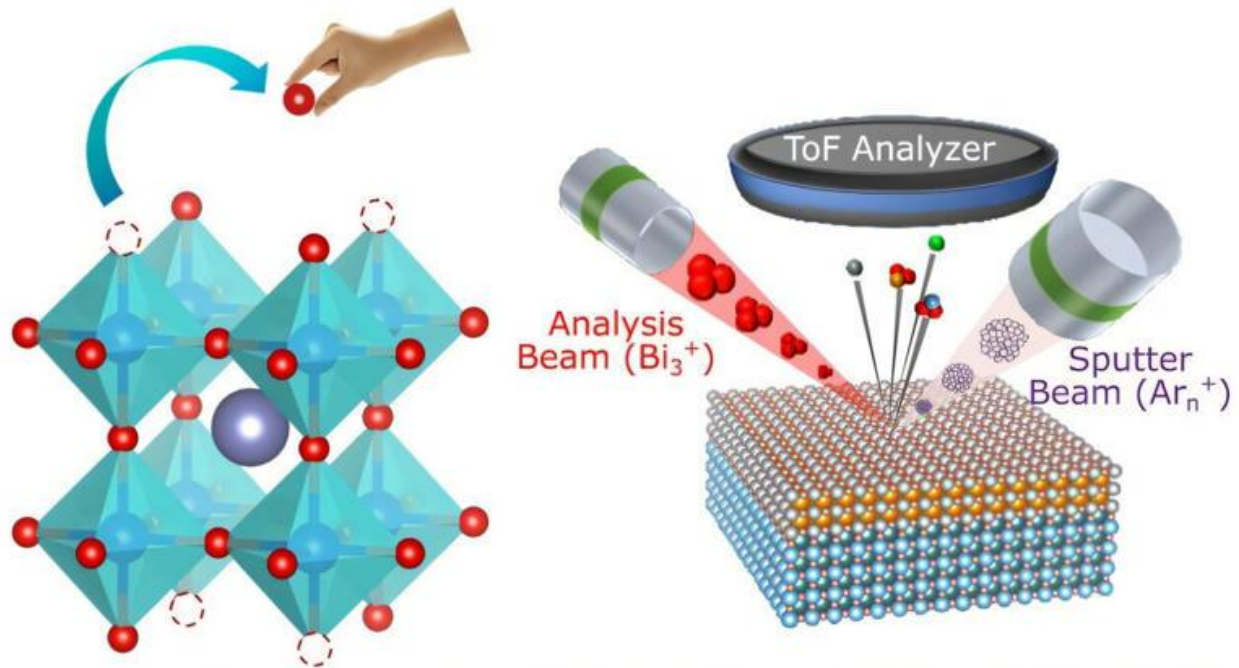
The researchers said they are now planning to build on this work.

"This is just the tip of the iceberg," Alem said. "By exploring the role of atomic structure, chemistry and other factors in controlling light emission while expanding on lessons learned in this study, we can move this research to the next level and develop practical applications."

More information: Saiphaneendra Bachu et al, Quantum Confined Luminescence in Two Dimensions, *ACS Photonics* (2024). DOI: [10.1021/acsphotonics.4c01739](https://doi.org/10.1021/acsphotonics.4c01739)

Provided by Pennsylvania State University

Pure nickel oxide research refutes hydrogen-superconductivity link



(Left) the topotactic reduction process via oxygen atom removal using calcium-hydrate for achieving superconductivity. This method is used in the experiments for the synthesis and characterization of superconducting nickelate films. (Right) Ion mass spectrometry measurements of thin film nickelates for detecting hydrogen after the topotactic reduction process. Credit: Nature Communications

Physicists from the National University of Singapore (NUS) have synthesized very pure superconducting materials and redefined the critical role of hydrogen in the newly discovered nickel-oxide superconductors.

Their findings were published concurrently in the journals [*Nature Communications*](#) and [*Physical Review Letters*](#).

Superconductivity is an exciting phenomenon where electrical resistance disappears, and it holds transformative potential for revolutionizing energy technologies. Despite its potential, the origin and fundamental mechanism of superconductivity remain one of the greatest mysteries in physics.

More than a century after the discovery of superconductivity, only a subgroup of superconducting materials, mainly elemental metals and hydrogen-based compounds, can be explained using the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity, which was awarded the Nobel Prize in Physics in 1972.

However, there exists a large group of superconducting materials classified as "unconventional superconductors" in which their superconducting mechanism cannot be explained by this theory. The recently discovered nickel oxide superconductor is one such example.

In a recent study published in the journal *Nature*, researchers proposed that hydrogen plays a key role in nickel oxide superconductivity. Using an ionic detection technique known as secondary ion mass spectrometry which measures the concentration of hydrogen, the researchers suggested a link between hydrogen and superconductivity, attributing the phenomenon to mechanisms consistent with the BCS theory.

A research team led by Professor Ariando from the Department of Physics at NUS in two independent efforts with various international collaborators (Agency of Science and Technology and Research (A*STAR) in Singapore, National Institute of Standards and Technology (NIST), Harvard University, University of Southern California, Arizona State University, and Cornell University from the United States of America) synthesized very pure superconducting nickel oxide samples to reexamine the role of hydrogen in nickel oxide superconductors.

Contrary to the previous findings reported in *Nature*, Prof Ariando's team and collaborators conclusively demonstrated that there is an insignificant presence of hydrogen in the pure nickel oxide materials. They also established that there is no correlation between hydrogen and superconductivity.

One of the authors, Mr. Lin Er Chow, a Ph.D. student said, "Surprisingly, hydrogen is not even abundantly present in pure superconducting nickel oxide. This observation suggests that hydrogen does not play an important role in the origin of superconductivity in these materials."

"These findings help guide the research direction towards understanding the fundamental superconducting mechanism of the high critical-temperature unconventional superconductors," added Prof Ariando.

More information: Shengwei Zeng et al, Origin of a Topotactic Reduction Effect for Superconductivity in Infinite-Layer Nickelates, *Physical Review Letters* (2024). DOI: [10.1103/PhysRevLett.133.066503](https://doi.org/10.1103/PhysRevLett.133.066503)

Purnima P. Balakrishnan et al, Extensive hydrogen incorporation is not necessary for superconductivity in topotactically reduced nickelates, *Nature Communications* (2024). DOI: [10.1038/s41467-024-51479-3](https://doi.org/10.1038/s41467-024-51479-3)

Provided by National University of Singapore

New recipe for gravity could unite Einstein's general relativity with quantum physics — and probe the dark universe

If gravity arises from entropy, scientists could unite Einstein's general relativity with the quantum realm while shedding light on dark matter and dark energy.



An illustration shows a disordered universe. Could gravity arise from entropy? (Image credit: Robert Lea (created with Canva))

A new recipe for gravity could help solve some of the universe's greatest mysteries. It suggests that the concept of "quantum gravity" could arise from entropy, possibly solving puzzles put forth by the elusive dark universe — and, if true, this novel theory could also finally unite Albert Einstein's general relativity with the quantum realm.

Since the beginning of the 20th century, [Einstein's theory of general relativity](#) has been the best description we have of how gravity works. However, right around when Einstein came up with general relativity, scientists also developed the foundations of [quantum mechanics](#).

Since then, both theories have been tested, revised and improved, standing the test of time and winning over skeptics in the scientific community. There's a problem, though — a big one. They can't work together.

As both theories have been perfected, they continue to defy attempts to unify them. A "theory of everything" that encompasses both general relativity and quantum physics has thwarted the efforts of minds as great as [Stephen Hawking](#), and even Einstein himself. One of the major stumbling blocks here concerns the fact that there is no theory of "quantum gravity." But this is where Ginestra Bianconi, a professor of Applied Mathematics at Queen Mary University of London, comes in.

She suggests a framework that would see quantum gravity arising from so-called "quantum relative entropy," a concept that measures how dissimilar two quantum states are.

General relativity and the dark universe

Developed in 1915, general relativity suggests that gravity arises because bodies with mass cause the fabric of spacetime (the four-dimensional [unification of space and time](#)) to warp. The greater the mass of an object, the more extreme the warping of spacetime and, thus, the more powerful the object's gravitational influence.

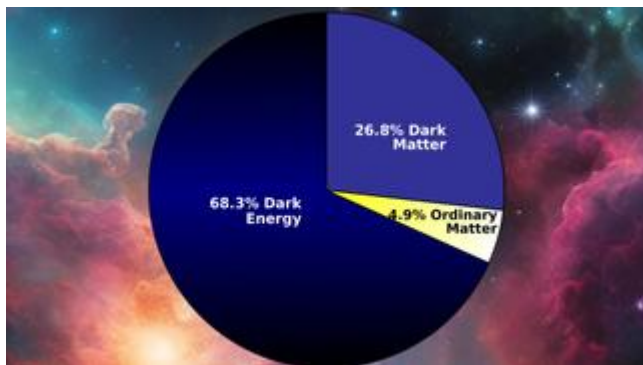
This has been verified time and time again, thus enabling general relativity to supersede [Newton's theory of gravity](#) as the best description of the universe on cosmic scales.

However, general relativity cannot explain everything.

[Dark matter](#), the mysterious substance that outweighs ordinary matter by a factor of five, and [dark energy](#), the unknown component of the universe driving its accelerated expansion, for instance, are not accounted for by general relativity.

That's a big problem because dark energy accounts for 68% of the total matter and energy in the universe, and dark matter accounts for another 27% or so. That means the "dark universe" accounts for around 95% of the matter-energy budget of the cosmos, so the "stuff" we can comfortably describe with general relativity represents just 5% of the energy and matter in the universe.

Then, there's the fact that Einstein's theory of gravity won't "play nice" with quantum physics.

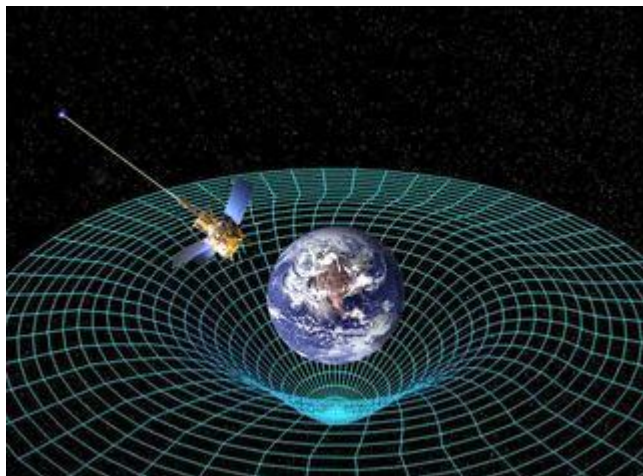


A pie chart showing the universe's matter-energy budget. (Image credit: Robert Lea (created with Canva))

The new framework — or "recipe" for gravity, if you will — takes the metric of spacetime from general relativity, which describes the geometry of space and time based on distances and intervals between events, and treats it like a mathematical entity called an operator.

Operators are used in quantum physics to perform transformations on quantum states arising through changes in physical factors. This general-relativity-based operator leads to a new "entropic action," and to modified Einstein equations.

At low energies and in regions of space where there is little curvature, and thus little gravity, these equations replicate those of general relativity.



Einstein's theory of general relativity predicted that the spacetime around Earth would be not only warped but also twisted by the planet's rotation. (Image credit: NASA)

This new research goes further, though. It predicts the emergence of a small positive valued cosmological constant. That's significant because its value better aligns with [observations of the universe's accelerated expansion](#) under the influence of dark energy than other current theories do.

In addition to this, something called a "G-field" emerges from this theory that could account for the gravitational influence of dark matter.

"This work proposes that quantum gravity has an entropic origin and suggests that the G-field might be a candidate for dark matter," Bianconi [said in a statement](#). "Additionally, the

emergent cosmological constant predicted by our model could help resolve the discrepancy between theoretical predictions and experimental observations of the universe's expansion."

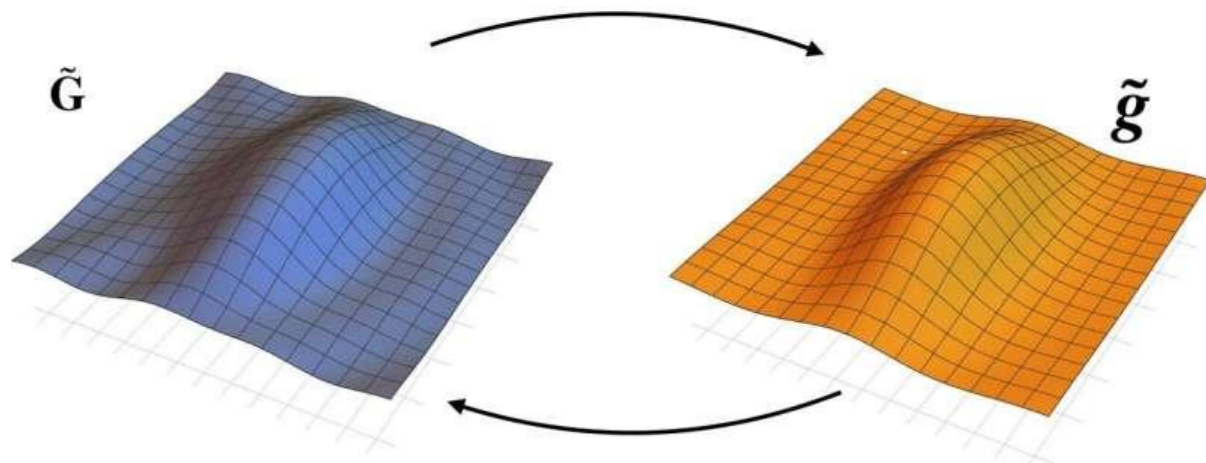
Of course, it is still very early days for this theory, but given how profound its implications could be for our fundamental understanding of the cosmos, it's likely worth exploring.

MARCH 4, 2025

Gravity from entropy: A radical new approach to unifying quantum mechanics and general relativity

by [Queen Mary, University of London](#)

$$\mathcal{L} = \text{Tr} \, \tilde{g} \ln \tilde{G}^{-1} = -\text{Tr}_F \ln \tilde{G} \tilde{g}^{-1}$$



Diagrammatic representation of the entropic quantum gravity action. The action for gravity is given by the quantum relative entropy between the metric of the manifold and the metric induced by the matter field and the geometry. Credit: *Physical Review D* (2025). DOI: 10.1103/PhysRevD.111.066001

In a [new study](#) published in *Physical Review D*, Professor Ginestra Bianconi, Professor of Applied Mathematics at Queen Mary University of London, proposes a new framework that could revolutionize our understanding of gravity and its relationship with quantum mechanics.

The study, titled "Gravity from Entropy," introduces a novel approach that derives [gravity](#) from quantum relative entropy, bridging the gap between two of the most fundamental yet seemingly incompatible theories in physics: [quantum mechanics](#) and Einstein's general relativity.

The challenge of quantum gravity

For decades, physicists have struggled to reconcile the principles of quantum mechanics with those of general relativity. While quantum mechanics governs the behavior of particles at the smallest scales, general relativity describes the force of gravity on cosmic scales. Unifying these two frameworks has been one of the most elusive goals in modern science.

Professor Bianconi's work offers a fresh perspective by treating the metric of spacetime, a key concept in general relativity, as a quantum operator. This innovative approach uses quantum relative entropy, a concept from [quantum information theory](#), to describe the interplay between spacetime geometry and matter.

The role of entropy and the G-field

The study introduces a new entropic action, which quantifies the difference between the metric of spacetime and the metric induced by matter fields.

This approach leads to modified Einstein equations that, in the low coupling regime, i.e., low energies and small curvature, reduce to the classical equations of general relativity. However, the theory goes further, predicting the emergence of a small, positive cosmological constant—a value that aligns with experimental observations of the universe's accelerated expansion much better than for other pre-existing theories.

A key feature of the theory is the introduction of the G-field, an auxiliary field that acts as a Lagrangian multiplier. The G-field not only plays a crucial role in the modified equations of gravity but also opens the door to new interpretations of dark matter—a mysterious substance that makes up a significant portion of the universe's mass but has yet to be directly observed.

Wider implications and future directions

The implications of this research are profound. By linking gravity to quantum information theory, the study provides a potential pathway to a unified theory of quantum gravity. Moreover, the G-field could offer new insights into the nature of dark matter, a long-standing puzzle in cosmology.

"This work proposes that quantum gravity has an entropic origin and suggests that the G-field might be a candidate for dark matter," explains Professor Bianconi. "Additionally, the emergent cosmological constant predicted by our model could help resolve the discrepancy between theoretical predictions and experimental observations of the universe's expansion."

While further research is needed to fully explore the implications of this theory, the study represents a significant step forward in the quest to understand the fundamental nature of the universe.

Professor Bianconi's work challenges conventional wisdom and opens up exciting new avenues for exploration. By treating spacetime as a quantum entity and leveraging the power of entropy associated with the spacetime metrics, this research could pave the way for a deeper understanding of gravity, quantum mechanics, and the cosmos itself.

More information: Ginestra Bianconi, Gravity from entropy, *Physical Review D* (2025). DOI: [10.1103/PhysRevD.111.066001](https://doi.org/10.1103/PhysRevD.111.066001)
Journal information: [Physical Review D](#)
Provided by [Queen Mary, University of London](#)

MARCH 3, 2025

Superconducting quantum processor prototype operates 10^{15} times faster than fastest supercomputer

by Liu Danxu, Ge Shuyun, [University of Science and Technology of China](#)



Schematic diagram of the Zuchongzhi-3 chip. 105 qubits and 182 couplers are integrated on the same chip to perform quantum random circuit sampling tasks. Credit: USTC
Zuchongzhi-3, a superconducting quantum computing prototype with 105 qubits and 182 couplers, has made significant advancements in random quantum circuit sampling. This

prototype was successfully developed by a research team from the University of Science and Technology of China (USTC).

This prototype operates at a speed that is 10^{15} times faster than the [fastest supercomputer](#) currently available and one million times faster than the latest results published by Google. This achievement marks a milestone in enhancing the performance of quantum computation, following the success of Zuchongzhi-2. The research findings have been [published](#) as the cover article in *Physical Review Letters*.

Quantum supremacy is the demonstration of a quantum computer capable of performing tasks that are infeasible for classical computers. In 2019, Google's 53-qubit Sycamore processor completed a random circuit sampling task in 200 seconds, a task that would have taken approximately 10,000 years to simulate on the world's fastest supercomputer at the time.

However, in 2023, USTC demonstrated more advanced classical algorithms, completing the same task in about 14 seconds using over 1,400 A100 GPUs. With the use of Frontier supercomputers equipped with larger memory, the task is expected to be completed in just 1.6 seconds. As a result, Google's claim of "quantum computational supremacy" at that time was overturned.

Subsequently, using the optimal classical algorithm as the benchmark, the same team of USTC achieved the first rigorously proven quantum supremacy with the "Jiuzhang" photonic quantum computing prototype in 2020. This was followed in 2021 by the achievement of the same task in a superconducting system, achieved with the Zuchongzhi-2 processor.

In 2023, the team's development of the 255-photon Jiuzhang-3 demonstrated quantum supremacy that surpassed classical supercomputers by 10^{16} times. In October 2024, Google's 67-qubit superconducting quantum processor, Sycamore, demonstrated quantum supremacy by outperforming classical supercomputers by nine orders of magnitude.

Building upon the 66-qubit Zuchongzhi-2, the USTC research team significantly enhanced key performance metrics to develop Zuchongzhi-3, which features 105 qubits and 182 couplers. The quantum processor achieves a coherence time of 72 μ s, a parallel single-qubit gate fidelity of 99.90%, a parallel two-qubit gate fidelity of 99.62%, and a parallel readout fidelity of 99.13%. The extended coherence time provides the necessary duration for performing more complex operations and computations.

To evaluate its capabilities, the team conducted an 83-qubit, 32-layer random circuit sampling task on the system. Compared to the current optimal classical algorithm, the computational speed surpasses that of the world's most powerful supercomputer by 15 orders of magnitude. Additionally, it outperforms the latest results published by Google in October of last year by 6 orders of magnitude, establishing the strongest quantum computational advantage in the superconducting system to date.

Following the achievement of the strongest quantum computational advantage with Zuchongzhi-3, the team is actively advancing research in [quantum error correction](#), [quantum entanglement](#), quantum simulation, quantum chemistry, and other

areas. Researchers adopted a 2D grid qubit architecture, facilitating efficient interconnections among qubits and enhancing data transfer rates.

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Based on this architecture, the team integrated surface code and is actively researching quantum error correction with a distance-7 surface code. Plans are in place to increase this distance to 9 and 11, paving the way for massive integration and manipulation of quantum bits.

The team's work holds profound significance and has received widespread acclaim. One journal reviewer described it as "benchmarking a new superconducting quantum computer, which shows state-of-the-art performance," and a "significant upgrade from the previous 66-qubit device (Zuchongzhi-2)."

The research team included Pan Jianwei, Zhu Xiaobo, and Peng Chengzhi, in collaboration with Shanghai Research Center for Quantum Sciences, Henan Key Laboratory of Quantum Information and Cryptography, China National Institute of Metrology, Jinan Institute of Quantum Technology, School of Microelectronics at Xidian University, and the Institute of Theoretical Physics under the Chinese Academy of Sciences.

More information: Dongxin Gao et al, Establishing a New Benchmark in Quantum Computational Advantage with 105-qubit Zuchongzhi 3.0 Processor, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.090601](https://doi.org/10.1103/PhysRevLett.134.090601). On arXiv: DOI: [10.48550/arxiv.2412.11924](https://arxiv.org/abs/10.48550/arxiv.2412.11924)

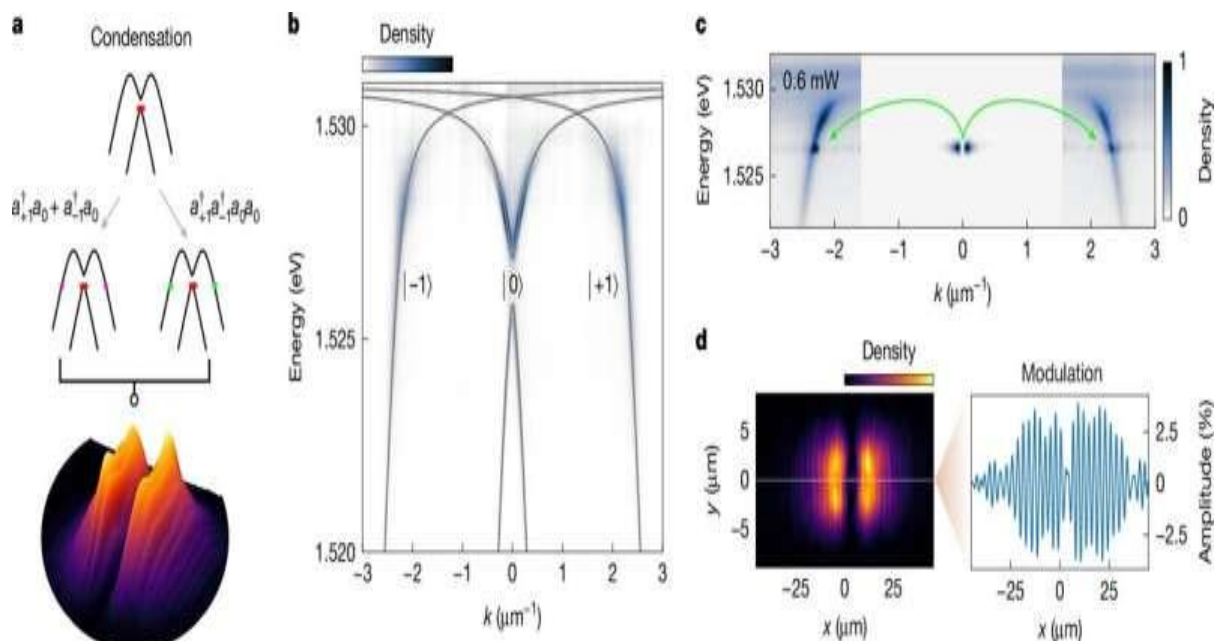
Journal information: [Physical Review Letters](#) , [arXiv](#)

Provided by [University of Science and Technology of China](#)

MARCH 6, 2025

Laser light made into a supersolid for the first time

by Bob Yirka , Phys.org



System in reciprocal and coordinate space. Credit: *Nature* (2025). DOI: 10.1038/s41586-025-08616-9

A small international team of nanotechnologists, engineers and physicists has developed a way to force laser light into becoming a supersolid. Their paper is [published](#) in the journal *Nature*. The editors at *Nature* have published a [Research Briefing](#) in the same issue summarizing the work.

Supersolids are entities that exist only in the quantum world, and, up until now, they have all been made using [atoms](#). Prior research has shown that they have zero viscosity and are formed in crystal-like structures similar to the way atoms are arranged in salt crystals.

Because of their nature, supersolids have been created in extremely cold environments where the [quantum effects](#) can be seen. Notably, one of the team members on this new effort was part of the team that demonstrated more than a decade ago that light could become a fluid under the right set of circumstances.

To create their supersolid, the researchers fired a laser at a piece of gallium arsenide that had been shaped with special ridges. As the light struck the ridges, [interactions](#) between it and the material resulted in the formation of polaritons—a kind of hybrid particle—which were constrained by the ridges in a predesigned way. Doing so forced the polaritons into forming themselves into a supersolid.

The research team then set themselves the task of testing it to make sure it truly was a supersolid—a task made more difficult by the fact that a supersolid made from light had never been created before. Despite the difficulties, they were able to show that their supersolid was both a solid and a fluid and that it had no viscosity.

The team plans to continue their work with the light-made [supersolid](#) to learn more about its structure. They note that supersolids made from light might be easier to work with than those made with atoms, which could help us better understand the nature of supersolids in general.

More information: Dimitrios Trypogeorgos et al, Emerging supersolidity in photonic-crystal polariton condensates, *Nature* (2025). DOI: [10.1038/s41586-025-08616-9](https://doi.org/10.1038/s41586-025-08616-9)

A supersolid made using photons, *Nature* (2025). DOI: [10.1038/d41586-025-00637-8](https://doi.org/10.1038/d41586-025-00637-8)

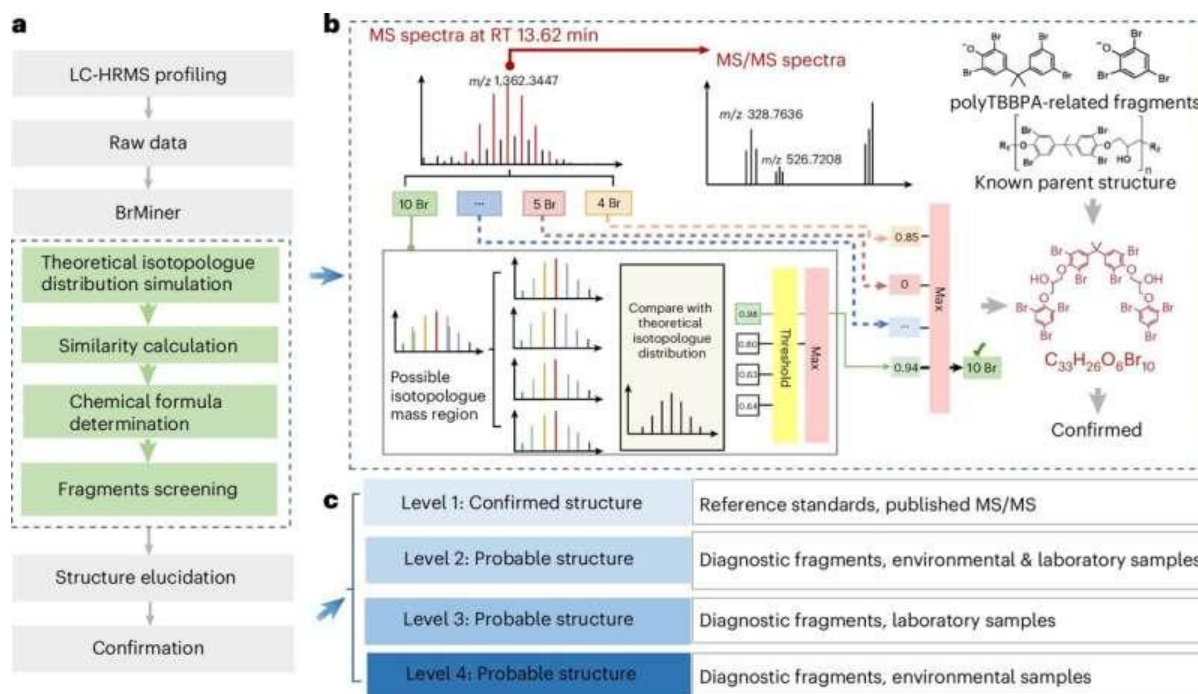
Journal information: [Nature](#)

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MARCH 3, 2025

A chemical 'trojan horse': Polymers used in everyday products can degrade into toxic chemicals, study finds

by Green Science Policy Institute



Establishing the BrMiner strategy. Credit: *Nature Sustainability* (2025). DOI: 10.1038/s41893-025-01513-z

The scientific community has long believed that polymers—very large molecules—are too big to migrate out of products into people and therefore pose no health risks. As a result, polymers have largely evaded regulation. For example, polymers are exempt from the major toxics acts: [Toxic Substances Control Act](#) in the U.S. and [REACH](#) in the E.U. However, a study published today in *Nature Sustainability* demonstrates that polymers used as flame retardants can break down into smaller harmful chemicals.

"Our study suggests polymers can act as a trojan horse for [toxic chemicals](#)," said Da Chen, senior author and scientist at Jinan University in China. "They are added to products as inert [large molecules](#), but over time they can degrade, exposing us to their harmful breakdown products."

The researchers tested two polymeric brominated flame retardants (polyBFRs) that were developed as "non-toxic" alternatives to banned flame retardants. They found that both polyBFRs broke down into dozens of types of smaller molecules. Toxicity testing of these smaller molecules in zebrafish showed significant potential for causing mitochondrial dysfunction and developmental and cardiovascular harm.

The scientists went on to search for these [polymer](#) break-down products in the environment and, further raising alarm, detected them in soil, air, and dust. The levels were highest near electronic waste recycling facilities and lessened moving away from the facilities. These results confirm that the use of polyBFRs in electronics leads to the release of toxic breakdown products into the environment with potential for human and wildlife exposure and harm.

"Widespread use of these polyBFRs in electronics may result in exposures when these products are manufactured, when they're in our homes, and when they're discarded or recycled," said Miriam Diamond, co-author and professor at the University of Toronto. "Since it is suspected that production volumes are very high (the chemical industry does not disclose the volumes), the potential for pollution—and resulting serious harm to people and wildlife—greatly concerns me."

The chemical producers and their trade groups promote polyBFRs as environmentally friendly and non-hazardous substitutes for banned monomeric [flame retardants](#) (e.g., hexabromocyclododecane and decabromodiphenyl ether) to meet flammability standards for electronics, building materials, and vehicles. However, real-world fire-safety benefits for many of these standards have not been demonstrated.

The study also has implications for other types of polymers used in [consumer products](#), such as per- and polyfluoroalkyl substances (PFAS). PFAS polymers have been put into textiles, including children's uniforms, food packaging, and cosmetics, to name a few uses.

Similar to this study, previous research has shown that fluorinated polymers contain numerous impurities and release smaller toxic molecules. Although the producers of PFAS argue that fluorinated polymers should be exempt from regulation, scientists [maintain](#) that fluorinated polymers are members of the class of PFAS and that the use of the whole class of PFAS should be avoided.

"To escape regulation, flame retardant and PFAS producers are increasingly pivoting to polymers for use in everyday products," said Arlene Blum, co-author and Executive Director of the Green Science Policy Institute.

"As a result, problematic polymers emit toxic small molecules from products we touch, sit on, wear, and keep in our homes. Regulators need to close this loophole to protect consumers—especially children—from the possibility of serious chemical harm."

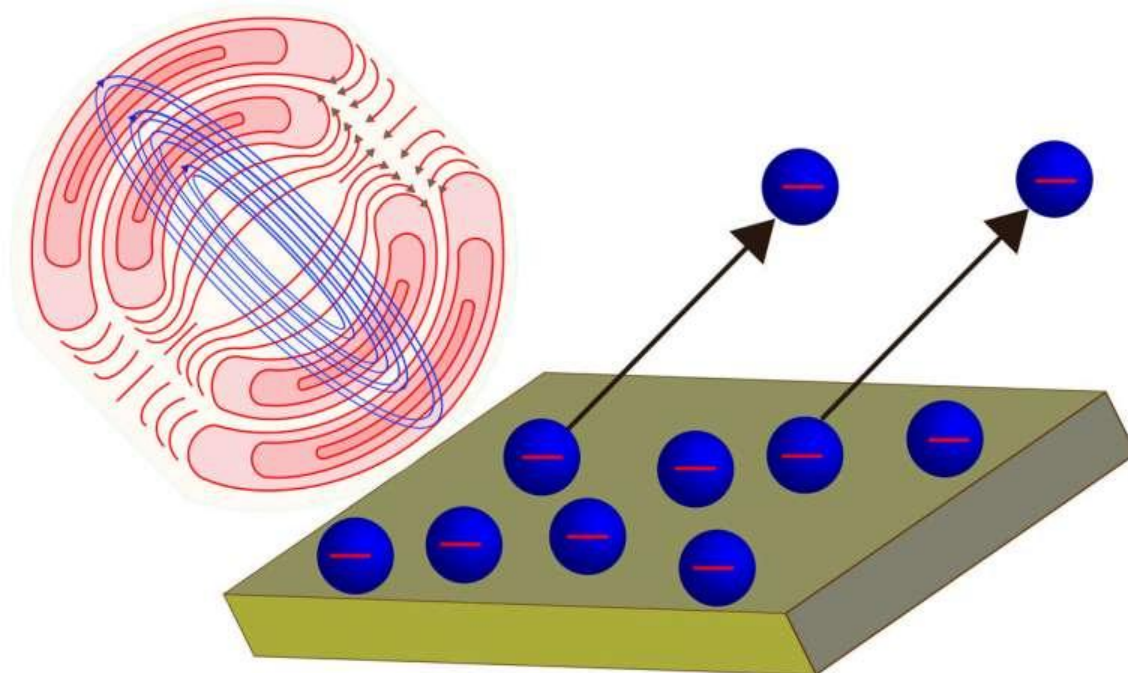
More information: Xiaotu Liu et al, Environmental impacts of polymeric flame retardant breakdown, *Nature Sustainability* (2025). DOI: [10.1038/s41893-025-01513-z](https://doi.org/10.1038/s41893-025-01513-z)

Journal information: [Nature Sustainability](#)
Provided by Green Science Policy Institute

MARCH 3, 2025

Einstein's light quanta through the lens of Maxwell's equations

by Dhiraj Sinha



Electromagnetic field excitation of electrons Credit: Dhiraj Sinha

Light was long considered to be a wave, exhibiting the phenomenon of interference in which ripples like those in water waves are generated under specific interactions. Light also bends around corners, resulting in fringing effects, which is termed diffraction. The energy of light is associated with its intensity and is proportional to the square of the amplitude of the electric field, but in the photoelectric effect, the energy of emitted electrons is found to be proportional to the frequency of radiation.

This observation was first made by Philipp Lenard, who did initial work on the photoelectric effect. In order to explain this, in 1905, Einstein suggested in *Annalen der Physik* that light comprises quantized packets of [energy](#), which came to be called photons. It led to the theory of the dual nature of light, according to which light can behave like a wave or a particle depending on its interactions, paving the way for the birth of quantum mechanics.

Although Einstein's work on photons found broader acceptance, eventually leading to his Nobel Prize in Physics, Einstein was not fully convinced. He wrote in a 1951 letter, "All the 50 years of conscious brooding have brought me no closer to the answer to the question: What are light quanta?"

A new focus on light

In a recent work [published](#) in the *Annals of Physics*, I have shown that light's interpretation as quantized packets of energy or particles is an outcome of a more subtle kind of phenomenon, which is associated with the quantization of magnetic flux.

The work illustrates that the fundamental aspect of coupling between energy from light into electrons can be simply derived by using Faraday's law of [electromagnetic induction](#), where the energy of an electron of charge e in the field of time varying magnetic flux j of electromagnetic radiation, is edj/dt . I have further shown that its frequency or phasor domain representation is ejw , where w is the angular frequency of radiation..

Albert Einstein, in 1905, presented the revolutionary idea of light quanta of energy which equals $\hbar w$, where $\hbar$ is reduced Planck's constant. There is plenty of experimental evidence on magnetic flux quantization from superconducting loops to two-dimensional electron gas, which is observed in the quantum Hall effect.

I have pursued an approach through classical electromagnetism to derive the expression of energy ejw , which is equal to Einstein's concept of light quanta or photons. I have further argued that the energy of an electron can be discrete, and measurements of those discrete energy levels can give the appearance of the particle-like nature of light.

Quantum mechanics can explain and recover classical results under some specific approximations. However, deriving quantum mechanical results strictly from classical assumption is generally not possible due to fundamental differences in their frameworks. I feel that my work fills a major gap in our comprehension of the nature of light.

I have focused attention on the quantized nature of magnetic flux. I have also shown that the concept of photons emerges as a natural consequence of magnetic flux quantization against the framework of classical electromagnetism.

The work is partially derived from a [prior study](#) first [published](#) in *Physical Review Letters* in 2015, where we argued that radiation is an outcome of broken symmetry of the electromagnetic field.

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Historical gaps and the road ahead

Max Planck did not believe in electrons and he did not consider the work by Lorentz and Thomson (Nobel Lecture, 1922), but he knew about the electronic oscillator-based experiments by Hertz. He pushed forward the idea of quantized atomic oscillators with energy $\hbar w$ in 1901, which was used by Einstein in his photon theory based on heuristics in 1905, which was published in *Annalen Der Physik*.

Bruce Wheaton, a noted science historian, writes in the journal *Historical Studies in the Physical Sciences*, "German thought of the 1890s laid great emphasis on ethereal explanation of electric charge than on material interpretation... Millikan's experiments did not bring about the acceptance of light quanta. In this period (1913–1923), there was simply no convincing explanation of the photoelectric effect. At its end, light quantum was reluctantly accepted to relieve what had become an intolerable state of affairs."

The article holds special importance for research in the field of energy as we now understand that [solar cells](#) as well as electromagnetic generators work on the same physical law. A special focus of the article is on the fact that the fabric of Maxwell's equations allows for quantization of charges. When Thomson discovered electrons, it was proved that electric flux is quantized. Magnetic flux quantization was discovered in the 1960s, but its study has remained confined to superconducting loops.

A number of leading academics with a background in quantum mechanics have offered feedback on the paper.

Lawrence Horowitz, emeritus professor of physics at the University of Tel Aviv says, "This article is indeed a valuable contribution to the theory of photons and electrons; an important complement to the book of Jauch and Rohrlich, particularly on classical aspects of the theory."

Steven Verrall, who recently retired from the Department of Physics, University of Wisconsin La Crosse, says, "Dr. Sinha provides a new semiclassical approach to modeling quantum systems. I also think that Dhiraj Sinha's unique approach may ultimately add valuable insights to the continued development of semiclassical effective field theories in low energy physics."

In a personal note to the author, a leading physicist from the University of Bristol, UK, commented, "You want to use flux quantization to derive quantum mechanics, rather than deriving flux quantization from quantum mechanics. Probably you are correct, because with any physical theory there is freedom to define what is fundamental and what is derived."

He further added, "We learned from Einstein that Maxwell's equations were relativistic (i.e., invariant under Lorentz transformation) 40 years before relativity. Now we know that they were already quantum, 60 years before quantum mechanics! I find this amazing."

This story is part of [Science X Dialog](#), where researchers can report findings from their published research articles. [Visit this page](#) for information about Science X Dialog and how to participate.

More information: Dhiraj Sinha, Electrodynamical excitation of electrons, *Annals of Physics* (2024). DOI: [10.1016/j.aop.2024.169893](#)

Journal information: [Physical Review Letters](#)

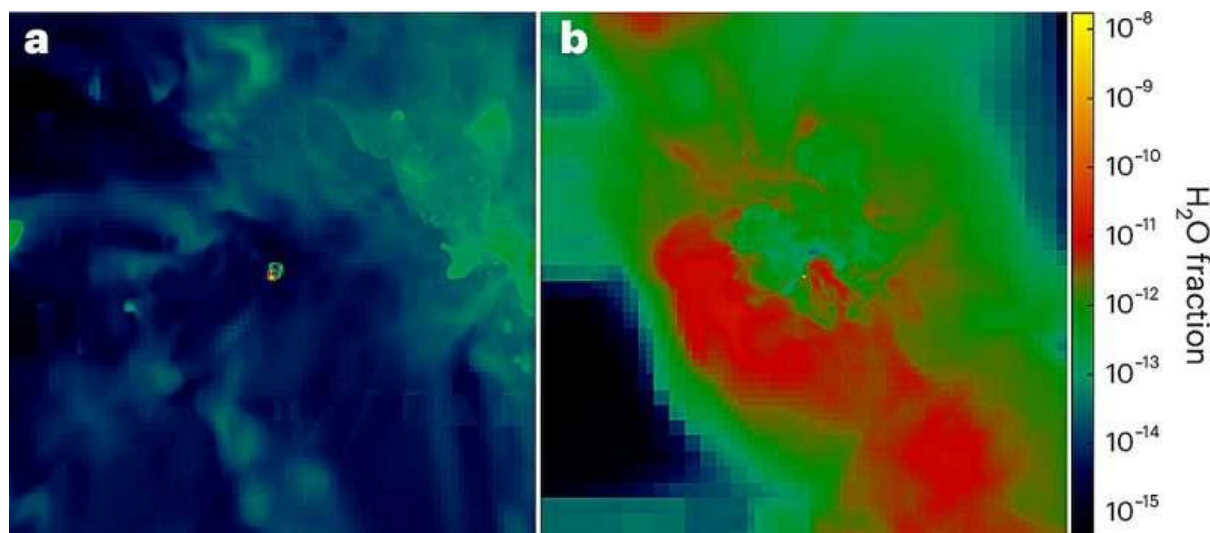
Dhiraj Sinha holds a doctorate in electrical engineering from the University of Cambridge, U.K. and has spent the larger part of his research career working on the foundational aspect of electromagnetic radiation and associated symmetries. A part of the work was carried out

at Massachusetts Institute of Technology, where he was a postdoctoral researcher, prior to his current appointment. He left Massachusetts Institute of Technology toward the end of 2019 and is currently teaching at Plaksha University, a newly established technology university in India led by a team of business leaders, educationists and philanthropists.

MARCH 3, 2025

Water might be older than we first thought, forming a key constituent of the first galaxies

by [Nature Publishing Group](#)



Water vapor in primordial haloes. **a,b**, Images simulated at 1 kpc distance of water vapor in the $13 M_{\odot}$ CC supernova at 90 Myr after the explosion (**a**) and the $200 M_{\odot}$ PI supernova at 3 Myr after the explosion (**b**). Mass fractions for diffuse water vapor in the haloes vary from 10^{-14} to 10^{-12} in the CC supernova and 10^{-12} to 10^{-10} in the PI supernova. Dense clumps with much higher water masses are visible as the yellow specks in the centres of both images. Credit: *Nature Astronomy* (2025). DOI: 10.1038/s41550-025-02479-w

Water may have first formed 100–200 million years after the Big Bang, according to a modeling paper [published](#) in *Nature Astronomy*. The authors suggest that the formation of water may have occurred in the universe earlier than previously thought and may have been a key constituent of the first galaxies.

Water is crucial for life as we know it, and its components—hydrogen and oxygen—are known to have formed in different ways. Lighter chemical elements such as hydrogen, helium and [lithium](#) were forged in the Big Bang, but heavier elements, such as oxygen, are

the result of nuclear reactions within [stars](#) or supernova explosions. As such, it is unclear when water began to form in the universe.

Researcher Daniel Whalen and colleagues utilized computer models of two supernovae—the first for a star 13 times the [mass of the sun](#) and the second for a star 200 times the mass of the sun—to analyze the products of these explosions. They found that 0.051 and 55 [solar masses](#) (where one solar mass is the mass of our sun) of oxygen were created in the first and second [simulation](#), respectively, due to the very high temperatures and densities reached.

Whalen and colleagues found that as this gaseous oxygen cooled and mixed with the surrounding hydrogen left behind by the supernovae, water formed in the leftover dense clumps of material. These clumps were likely to be sites for the formation of the second generation of stars and planets.

In the first simulation, the authors found that the mass of water reached quantities that were about the equivalent of one hundred millionth to one millionth of a solar mass in 30 to 90 million years following the supernova. In the second simulation, the amount of water reached roughly 0.001 solar masses after 3 million years.

The authors suggest that if water could survive the formation of the first galaxies, a potentially destructive process, it could have been incorporated into the formation of planets billions of years ago.

More information: D. J. Whalen et al, Abundant water from primordial supernovae at cosmic dawn, *Nature Astronomy* (2025). DOI: [10.1038/s41550-025-02479-w](https://doi.org/10.1038/s41550-025-02479-w)

Journal information: [Nature Astronomy](#)

Provided by [Nature Publishing Group](#)

MARCH 5, 2025

Distinguishing classical from quantum gravity through measurable stochastic fluctuations

by Tejasri Gururaj , Phys.org

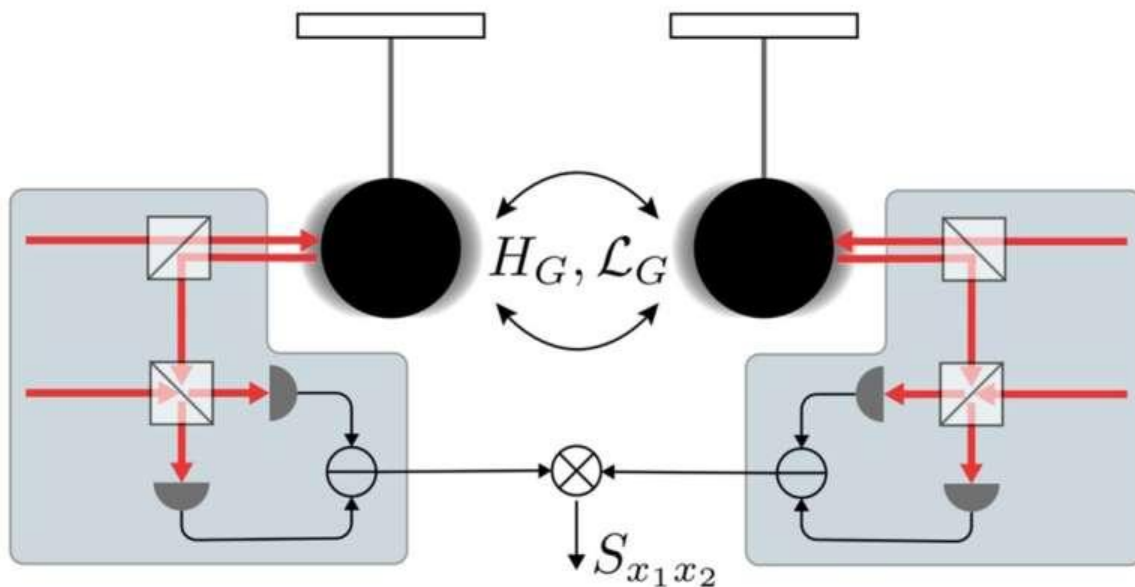


Illustration of an experiment that can be used to determine if gravity is classical or quantum. Two quantum masses are suspended at some distance away from each other and interact gravitationally. Credit: Serhii Kryhin.

In a new [Physical Review Letters study](#), researchers propose an experimental approach that could finally determine whether gravity is fundamentally classical or quantum in nature.

The nature of gravity has puzzled physicists for decades. Gravity is one of the four fundamental forces, but it has resisted integration into the quantum framework, unlike the electromagnetic, strong, and weak nuclear forces.

Rather than directly tackling the challenging problem of constructing a complete quantum theory of gravity or trying to detect individual gravitons—the hypothetical mediator of gravity—the researchers take a different approach.

Phys.org spoke to the researchers behind the study to gain insight into their unique approach.

"Several proposals have appeared in the past years that, in principle, allow us to determine gravity's nature experimentally, but their experimental requirements are extraordinarily challenging. So our motivation was to come up with a more feasible experiment that would have the power to at least falsify that gravity is classical," explained Serhii Kryhin, a third-year graduate student at Harvard University and a co-author of the study.

The researchers aimed to rephrase the age-old question into one that could provide more concrete results: "What measurable differences would tell us whether gravity needs to be quantized?"

Quantum vs. classical fluctuations

"The idea is very simple yet remained unnoticed all this time. If gravity is quantum, as a long-range force, it should be able to induce quantum entanglement of distant matter. However, if gravity is fundamentally classical, no entanglement can be produced," said Vivishek Sudhir, Associate Professor at MIT and co-author of the study.

The insight is that if gravity is classical, it must exhibit irreducible stochastic fluctuations. These fluctuations are a necessity, stemming from a fundamental inconsistency that would arise without them—the deterministic nature of gravity (due to being classical) would violate the principles of quantum mechanics.

The brilliance comes in recognizing that these fluctuations would leave behind a signature in the cross-correlation spectrum as a phase shift, differing from what would be produced if gravity was quantum.

"Quantum fluctuations always arise as quantum fluctuations of dynamic degrees of freedom of general relativity. From a practical perspective, the main difference between quantum and classical gravity fluctuations comes in the magnitude. Being [relativistic effects](#), quantum fluctuations are notoriously weak and thus incredibly challenging to measure," said Kryhin.

"On the other hand, classical fluctuations, if they exist and have to remain consistent with everything else we know, appear to be much larger," added Prof. Sudhir.

Mathematical framework

The researchers propose a theoretical framework for this quantum-classical interaction in the Newtonian limit of gravity. In this framework, classical gravity and quantum matter co-exist.

They created a quantum-classical master equation describing how quantum matter and classical gravity evolve together. They also derived a Hamiltonian for Newtonian gravity's interaction with quantum masses through two complementary approaches—Dirac's theory of constrained systems and the Newtonian limit of gravity.

Next, they formulated a modified quantum Newton's law that accounts for stochastic gravitational effects and finally calculated the distinctive correlation patterns between two quantum oscillators interacting gravitationally.

This mathematical framework led them to a closed Lindblad equation (Markovian master equation) for quantum matter interacting with classical gravity. This equation includes a term proportional to the parameter ϵ , which distinguishes between classical gravity ($\epsilon \neq 0$) and quantum gravity ($\epsilon = 0$).

Identifying measurable quantities

The researchers derived several crucial results. They showed that, contrary to previous claims, a consistent theory of classical gravity interacting with quantum matter is indeed possible.

Their calculations reveal that classical gravity would induce fluctuations distinct from its quantum counterpart. Crucially, they identify an experimentally measurable signature.

When two quantum harmonic oscillators interact gravitationally, their cross-correlation spectrum shows a characteristic phase shift of π or 180 degrees at a specific detuning from resonance if gravity is classical.

To test these predictions, the researchers propose what amounts to a quantum version of the historic Cavendish experiment, using two highly coherent quantum mechanical oscillators coupled gravitationally.

The researchers could observe the characteristic [phase shift](#) by precisely measuring the cross-correlation of their motions.

What distinguishes this approach from previous proposals is its experimental feasibility. Unlike other tests that might require creating massive objects in quantum superposition states, this experiment relies on correlations between quantum oscillators within the reach of current or near-future technology.

Prof. Sudhir noted, "Semiclassical models of gravity usually explicitly neglect the backaction of quantum fluctuations of matter onto the classical gravity dynamics. In contrast, our theory allows self-consistent dynamics of classical gravity field and quantum matter."

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Jury's still out

An experimental confirmation that gravity is classical would have profound implications for our physical theories.

"At present, it is taken as a self-evident fact that gravity has to be quantum, although nobody precisely knows what that means!" said Kryhin.

"Immense effort has been made to understand the behavior of quantized [general relativity](#) and construct a complete theory of quantum gravity, which resulted in the construction of string theory as one of the byproducts. If experimentally proven that gravity is classical, we will have to start from the beginning in a search for a satisfactory ontological picture of the world."

While the study offers a fresh perspective on a question that has plagued physicists for decades, they acknowledge the many problems to be addressed, from formalism development and model-building to demonstrating the technologies required for the experiment.

"From an experimental standpoint, we need two gravitating masses, noise isolation, and measurement techniques, all of which need to come together to realize the sensitivity needed for a decisive experiment," concluded Kryhin.

More information: Serhii Kryhin et al, Distinguishable Consequence of Classical Gravity on Quantum Matter, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.061501](https://doi.org/10.1103/PhysRevLett.134.061501).

On *arXiv*: DOI: [10.48550/arxiv.2309.09105](https://doi.org/10.48550/arxiv.2309.09105)

Journal information: [Physical Review Letters](#) , [arXiv](#)

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A Klotho Gene Therapy Extends Life in Male Mice

Female mice experienced serious side effects.

Mar 6, 2025

In *Molecular Therapy*, a team of researchers has described how **increasing the expression of a form of Klotho, a protein that has been frequently found to have rejuvenative effects, leads to longer lifespans in male mice.**

Klotho has various forms

In their introduction, the researchers distinguish between the various forms of Klotho. The full mRNA sequence that generates Klotho creates two homologous effective sections (KL1 and KL2) and a membrane that is meant for transportation between cells: this full version is m-KL [1]. Once enzymes take away this membrane, however, it becomes p-KL, with each section being p-KL1 and p-KL2.

However, this full version interferes with the function of FGF23, a protein that manages the metabolism of minerals [2]. Artificially upregulating this protein, therefore, is not safe [3].

Another form of Klotho, secreted Klotho (s-KL), does not have this problem. s-KL has been found to have multiple anti-aging effects according to a review of 65 studies [4]. Of course, without the transmembrane protein, it is not fit for intercellular transportation.

Therefore, the researchers used an adeno-associated virus (AAV) to deliver a gene therapy that upregulates Klotho in the mice in this experiment.

Improvements in lifespan

The researchers used a total of 96 mice of the Black 6 strain: a group that received the AAV at 6 months, a group that received the AAV at 12 months, and a control group that received an ineffective AAV at 6 months. Both male and female mice were included in this experiment.

The treatment had far different effects in males and females. In female mice, the treatment had similar effects at 6 months and 12 months, but the increase in s-KL was accompanied by serious health problems during the course of the experiment, including skin ulcers and bleeding from the anus. In male mice, the AAV upregulated s-KL much more than in female mice, and it was much more effective at 12 months than at 6 months. Despite having far more s-KL, the males did not experience any of the health problems that the females did; instead, they received significant improvements to their lifespan.

Improvements to tissues and performance

Interestingly, at the age of 24 months, females showed improvements on the rotarod balance test that males did not. Both sexes given the s-KL AAV at 12 months were able to hold onto a horizontal bar longer than their control groups. In a three-trial grip strength test, the AAV-treated males performed far better, while the females performed better during only the first trial. The males also had significant reductions in fibrosis.

Regeneration capability was tested by transplanting muscles from old mice into younger mice. The muscle fibers in the AAV-treated animals became much larger than those from the control group. Muscles derived from the animals treated at 6 months old grew a wider variety of fiber sizes than those derived from animals treated at 12 months. Proliferation markers, and markers relating to a muscle-related fate of stem cells, were increased in the muscles derived from the mice that had received the s-KL AAV.

The researchers also tested bone tissue, seeing significant improvements to bone structure in females treated at 6 months and non-significant improvements in males treated at 12 months. Curiously, while FGF23 was upregulated along with many other

bone-related factors in male mice, it was downregulated in female mice. This may be beneficial for females, as age-related increases in FGF23 have been linked to osteoporosis [5].

While no behavior testing was done in this study, the researchers did examine the mice's brains. They found that, in the treated animals, there were more functional neurons and a thicker cellular layer, and markers of cellular proliferation were increased in the hippocampus. An examination of differently expressed genes revealed that the treated animals had fewer age-related changes than the control group.

The researchers note that this is the first time an AAV for s-KL has demonstrated lifespan increases in wild-type mice; previous experiments used transgenic mice. They believe that further experiments should test mice with different genetic backgrounds, because the side effects they saw in this experiment may or may not be limited to the AAV's effects on Black 6 mice. Further work may elucidate exactly why klotho treatment has such different effects on males and females.

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Ginkgolide B Improves Healthspan and Lifespan in Female Mice

Multiple healthspan metrics showed improvement following the treatment.

Mar 5, 2025

The authors of a recent study describe Ginkgolide B, a compound with senotherapeutic potential that **improved muscle health, metabolism, frailty, inflammation, and senescence metrics and increased lifespan in female mice** [1].

From East Asia to the clinic

Ginkgolide B is a compound that can be extracted from *Ginkgo biloba*, an East Asian tree known as the maidenhair tree. Previous research indicates that Ginkgolide B may offer many health benefits, such as improvements in osteoporosis and muscle regeneration in aged mice [2-7].

Therefore, these researchers hold that Ginkgolide B's good safety, tolerability, and pharmacokinetic profile in humans [8, 9] and promising beneficial effects seen in model organisms make it a good candidate for healthspan and lifespan studies.

Extending lifespan

The researchers tested Ginkgolide B's impact on female mouse lifespan. They started Ginkgolide B administration at 20 months (equivalent to 70- to 80-year-old humans). Ginkgolide B significantly extended the median lifespan by 8.5% and "extended the mean maximal lifespans of the 10% and 20% longest-lived mice by approximately 55" days.

Additionally, the researchers observed a reduced incidence of tumors; however, even the Ginkgolide B-treated mice with tumors still had longer lives, suggesting that Ginkgolide B extends lifespan not only by reducing tumors but through its beneficial impact on multiple organs and molecular processes.

Strengthening muscle

Apart from increasing lifespan, an increase in healthspan was also observed. First, the researchers tested the impact of Ginkgolide B on muscle mass and strength. Ginkgolide B treatment improved female mice's muscle strength, exercise capacity, and balance. It also reversed aging-related muscle wasting symptoms, such as a decreased skeletal muscle-to-body ratio, alterations to protein content in muscle, and muscle atrophy markers in aged skeletal muscle. Ginkgolide B also led to enlargement in the thigh's main (femoral) artery and capillary density, which allowed for increased accessibility of oxygen and nutrients in muscles. However, it didn't improve fatigue resistance or muscle recovery rate.

On the molecular level, Ginkgolide B treatment reversed several age-related changes associated with declining physical performance and muscle contraction; for example, it reduced aging-related increases in intramuscular lipid infiltration and collagen deposition.

Since the researchers focused on female mice, they also investigated sex hormones' role in age-dependent muscle functioning. They surgically removed the mice's ovaries, resulting in estrogen-deficient mice. Loss of estrogen led to muscle deterioration and decreased physical performance. Ginkgolide B treatment restored those functions in a dose-dependent manner, with high doses of Ginkgolide B almost completely restoring measured muscle functions.

Improved aging markers

Apart from declining muscular health, aging results in changes to metabolism, increased frailty, the chronic, low-grade inflammation known as inflammaging, and declining organ health. Ginkgolide B treatment helped alleviate those symptoms, such as by reducing the frailty index by 64.8% and benefiting the heart, kidney, spleen, and liver.

After two months of Ginkgolide B treatment, the body composition of aged mice resembled that of young mice. Similarly, it reversed disruption in biochemical measurements, such as serum triglyceride and total cholesterol levels, in aged mice and improved glucose tolerance and disruptions in glucose metabolism-related genes in skeletal muscle and liver.

Treatment with Ginkgolide B also positively impacted the inflammatory profile of aged mice, making it similar to that of young mice. The researchers also observed changes in the profiles of immune cells in aged mice, such as decreases in pro-inflammatory M1 macrophages and increases in anti-inflammatory M2 macrophages.

Inflammaging, among other aging-related processes, is linked to senescent cells. The researchers observed that Ginkgolide B treatment positively impacted the expression of several senescence-associated markers, such as the senescence-associated secretory phenotype (**SASP**) along with DNA damage, cell cycle, cell size, and cell proliferation in different organs and in cell culture models of induced senescence.

Molecular pathways

The authors of this study also examined aging-induced molecular changes by conducting multiple analyses of gene expression in the mouse leg muscle using either bulk expression data or expression data from single nuclei.

The results indicated that both aging and Ginkgolide B impacted gene expression. Ginkgolide B treatment had slight but measurable impacts in this area, partially reversing some of the changes that are brought about by normal aging in mice.

An analysis that focused on the **hallmarks of aging** showed that multiple genes related to these hallmarks are disrupted during normal aging. Ginkgolide B “partially restored

intercellular communication, cellular senescence, nutrient sensing deregulation and mitochondrial dysfunction.”

Further gene expression analysis was performed separately for different subtypes of nuclei. The authors observed that one of the subtypes, called Runx1+ type 2B myonuclei, which appear in muscle cells, had the most significant alterations to gene expression. They refer to this subtype of cells as having a “host of age-related and GB-rescued signatures at the single-nucleus level.”

These myonuclei were enriched with apoptosis and ROS markers during aging, which were reversed by Ginkgolide B treatment. The authors hypothesize that the enrichment of apoptosis markers suggests that age-related apoptosis in Runx1+ type 2B myonuclei contributes to muscle degeneration.

The authors conducted further database searches and experiments to find a molecular pathway linking Ginkgolide B treatment and Runx1, a transcription factor that controls the expression of multiple genes. They identified miR-27b-3p, a microRNA whose levels are decreased in aged muscles and restored by Ginkgolide B treatment. Restoration of miR-27b-3p levels leads to reduced expression of Runx1.

Senotherapeutic potential

The researchers concluded that Ginkgolide B has a strong senotherapeutic potential, even when started late in life, and can help address aging-related conditions that current senotherapeutics fail to address, such as sarcopenia. However, the obtained results should be investigated in different mouse strains and eventually in humans to confirm their therapeutic value.

Literature

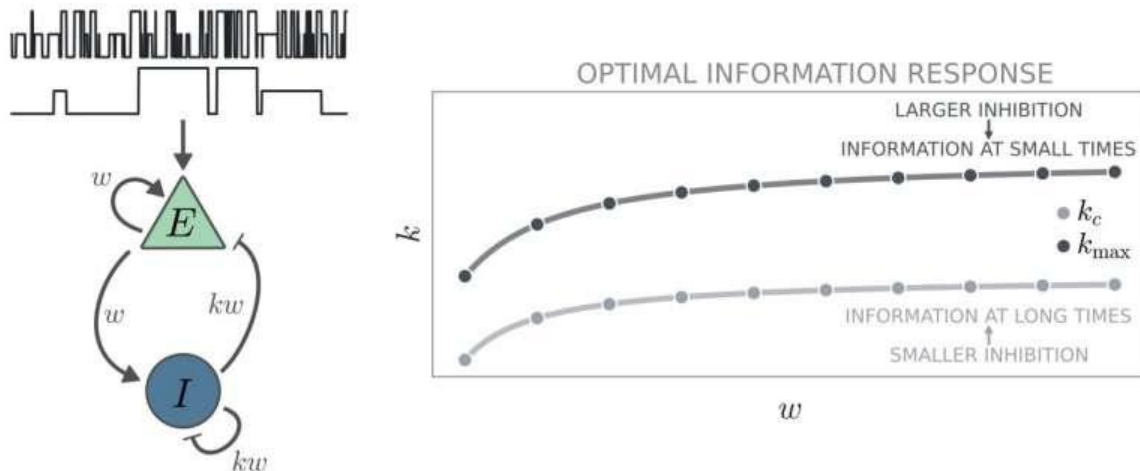
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MARCH 9, 2025

Optimal brain processing requires balance between excitatory and inhibitory neurons, study suggests

by Ingrid Fadelli , Phys.org



(Top-left) Two typical external switching inputs, one acting on a long timescale, and the other on a shorter one. (bottom-left) Schematic of our model of two interacting neural populations, excitatory (E) and inhibitory (I) neurons. (right) Optimal point in the parameter space to have accurate encoding at longer and shorter timescales, highlighting that the larger inhibition favors short-time encoding. Credits: Giacomo Barzon, Daniel M. Busiello, G. Nicoletti Credit: Barzon, Busiello & Nicoletti.

The brain's ability to process information is known to be supported by intricate connections between different neuron populations. A key objective of neuroscience research has been to delineate the processes via which these connections influence information processing.

Researchers at the University of Padova, the Max Planck Institute for the Physics of Complex Systems and École Polytechnique Fédérale de Lausanne recently carried out a study aimed at better understanding the contribution of excitatory and inhibitory neuron populations to the brain's encoding of information. Their findings, [published](#) in *Physical Review Letters*, show that [information processing](#) is maximized when the activity of excitatory and inhibitory neurons is balanced.

"Our research was inspired by a fundamental question in neuroscience: how does the structure of the brain shape its ability to process information?" Giacomo Barzon, co-author of the paper, told Medical Xpress. "The brain continuously receives and integrates sensory inputs, and neurons do not act in isolation—they are part of complex, recurrent networks. One particularly intriguing feature of these networks is the balance between the activity of excitatory and inhibitory neurons, which has been observed across different brain regions."

The key objective of this recent study by Barzon and his colleagues was to determine whether the balance between excitatory and inhibitory neurons does more than stabilize [neural activity](#). Specifically, the team explored the possibility that this balance also optimizes information processing.

"Inspired by several experimental and [theoretical findings](#) highlighting the importance of the balance between excitatory and inhibitory neurons, we analyzed a model that captures the interactions between these two populations and investigated—both analytically and numerically—their response to external signals," explained Daniel M. Busiello, co-author of the paper. "Specifically, by employing tools of information theory, we revealed a fundamental trade-off: [neural networks](#) optimized for accurate encoding over long timescales may be less responsive to rapid changes in the input."

Employing mathematical and theoretical approaches for studying information processing, the researchers showed that information processing is most effective at the edge of stability, a critical state in which the activity of excitatory and inhibitory neurons is balanced. Their results suggest that the fine-tuning of this excitation-inhibition balance could not only stabilize the brain's activity, but could also play a crucial role in its ability to optimally encode information.

"In our study, we were able to show from an information-theoretic perspective that interactions between excitation and inhibition are crucial for allowing neural populations to encode information about time-varying external signals," said Giorgio Nicoletti, co-author of the paper. "This is particularly interesting because excitation-inhibition balance is well-known to be a key ingredient in regulating neural activity. Our approach allows us to quantify such an effect in terms of information as a physical quantity."

This recent work by Barzon, Busiello and Nicoletti could open new avenues for the study of information processing and its underlying neural mechanisms. In their next studies, the researchers plan to build on their results, using the same approach to study more complex brain connectivity structures.

"Moreover, in real neural networks, connectivity is not static—it evolves over time, influenced by both external stimuli and internal network activity," added Barzon. "This dynamic nature of connectivity might play a crucial role in shaping how neural populations process and encode information, potentially offering insights into how learning and adaptive properties affect information encoding in neural systems."

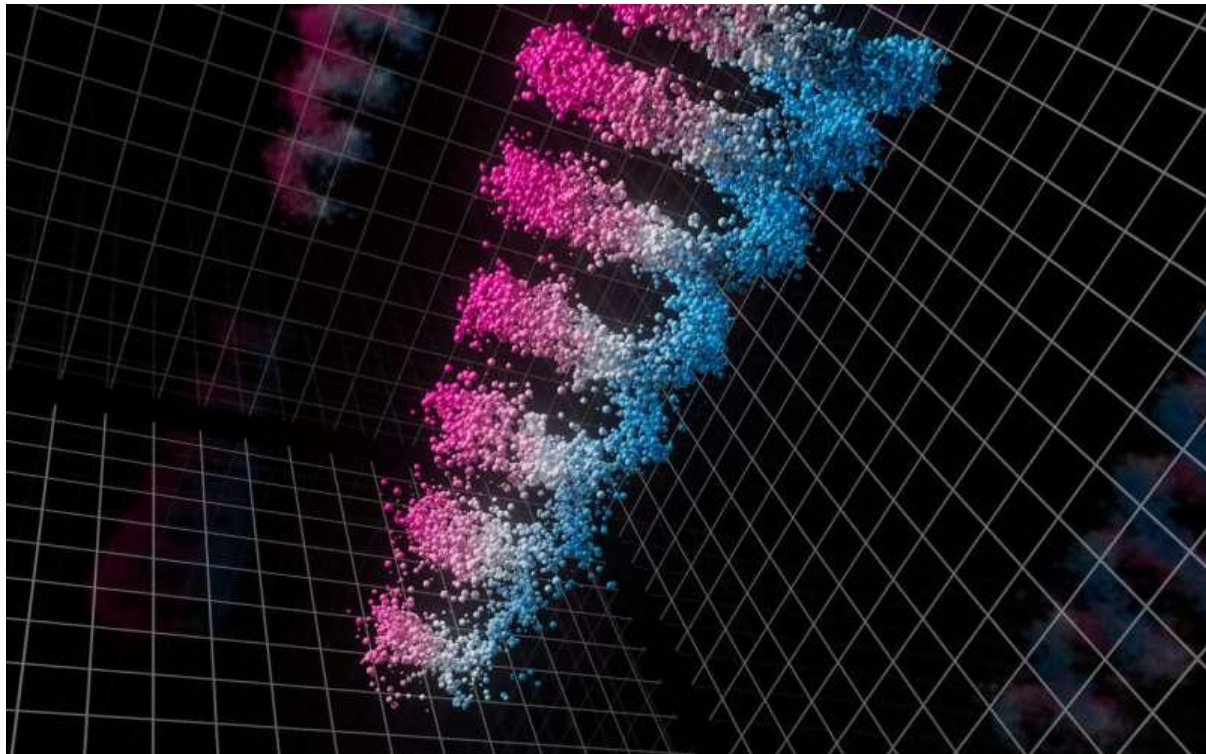
More information: Giacomo Barzon et al, Excitation-Inhibition Balance Controls Information Encoding in Neural Populations, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.068403](https://doi.org/10.1103/PhysRevLett.134.068403).

Journal information: [Physical Review Letters](#) © 2025 Science X Network

MARCH 10, 2025

Quantum tornadoes in momentum space: First experimental proof of a new quantum phenomenon

by Katja Lesser, Würzburg-Dresdner Exzellenzcluster ct.qmat



Quantum tornado in momentum space. Credit: Think-Design | Jochen Thamm
Researchers from Würzburg have experimentally demonstrated a quantum tornado for the first time by refining an established method. In the quantum semimetal tantalum arsenide (TaAs), electrons in momentum space behave like a swirling vortex. This quantum phenomenon was first predicted eight years ago by a Dresden-based founding member of the Cluster of Excellence ct.qmat.

The discovery, a collaborative effort between ct.qmat, the research network of the Universities of Würzburg and Dresden, and international partners, has now been [published](#) in *Physical Review X*.

Scientists have long known that electrons can form vortices in quantum materials. What's new is the proof that these tiny particles create tornado-like structures in momentum space—a finding that has now been confirmed experimentally. This achievement was led by Dr. Maximilian Ünzelmann, a group leader at ct.qmat—Complexity and Topology in Quantum Matter—at the Universities of Würzburg and Dresden.

Demonstrating this [quantum phenomenon](#) marks a major milestone in quantum materials research. The team hopes that the vortex-like behavior of electrons in momentum space could pave the way for new quantum technologies, such as orbitronics, which would use electrons' orbital torque to transmit information in electronic components instead of relying on electrical charge, potentially slashing energy losses.

Momentum space vs. position space

Momentum space is a fundamental concept in physics that describes electron motion in terms of energy and direction, rather than their exact physical position. Position space (its "counterpart") is the realm where familiar phenomena like water vortices or hurricanes occur. Until now, even quantum vortices in materials had only been observed in position space.

A few years ago, another ct.qmat research team [made waves](#) worldwide when they captured the first-ever three-dimensional image of a vortex-like magnetic field in a quantum material's position space.

Theory confirmed

Eight years ago, Roderich Moessner theorized that a quantum tornado could also form in momentum space. At the time, the Dresden-based ct.qmat co-founder described the phenomenon as a "smoke ring" because, like smoke rings, it consists of vortices. However, until now, no one knew how to measure them.

The breakthrough experiments revealed that the quantum vortex is created by orbital angular momentum—electrons' circular motion around atomic nuclei. "When we first saw signs that the predicted quantum vortices actually existed and could be measured, we immediately reached out to our Dresden colleague and launched a joint project," recalls Ünzelmann.

Quantum tornado discovered by refining a standard method

To detect the quantum tornado in momentum space, the Würzburg team enhanced a well-known technique called ARPES (angle-resolved photoemission spectroscopy). "ARPES is a fundamental tool in experimental solid-state physics. It involves shining light on a material sample, extracting electrons, and measuring their energy and exit angle.

"This gives us a direct look at a material's electronic structure in momentum space," explains Ünzelmann. "By cleverly adapting this method, we were able to measure orbital angular momentum. I've been working with this approach since my dissertation."

ARPES is rooted in the photoelectric effect, first described by Albert Einstein and taught in high school physics. Ünzelmann had already refined the method in 2021, gaining international recognition for detecting orbital monopoles in tantalum arsenide. Now, by

integrating a form of quantum tomography, the team has taken the technique a step further to detect the quantum tornado—another major milestone.

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"We analyzed the sample layer by layer, similar to how medical tomography works. By stitching together individual images, we were able to reconstruct the three-dimensional structure of the [orbital angular momentum](#) and confirm that electrons form vortices in momentum space," Ünzelmann explains.

"The experimental detection of the quantum tornado is a testament to ct.qmat's team spirit," says Matthias Vojta, Professor of Theoretical Solid-State Physics at TU Dresden and ct.qmat's Dresden spokesperson. "With our strong physics hubs in Würzburg and Dresden, we seamlessly integrate theory and experiment.

"Additionally, our network fosters teamwork between leading experts and early-career scientists—an approach that fuels our research into topological [quantum materials](#). And, of course, almost every physics project today is a global effort—this one included."

The tantalum arsenide sample was grown in the US and analyzed at PETRA III, a major international research facility at the German Electron Synchrotron (DESY) in Hamburg. A scientist from China contributed to the theoretical modeling, while a researcher from Norway played a key role in the experiments.

Looking ahead, the ct.qmat team is exploring whether tantalum arsenide could be used in the future to develop orbital quantum components.

More information: T. Figgemeier et al, Imaging Orbital Vortex Lines in Three-Dimensional Momentum Space, *Physical Review X* (2025). DOI: [10.1103/PhysRevX.15.011032](https://doi.org/10.1103/PhysRevX.15.011032)

Journal information: [Physical Review X](#)

Provided by Würzburg-Dresdner Exzellenzcluster ct.qmat

MARCH 10, 2025

Mysterious phenomenon at center of galaxy could reveal new kind of dark matter

by [King's College London](#)



Credit: Scott Lord from Pexels

A mysterious phenomenon at the center of our galaxy could be the result of a different type of dark matter.

Dark matter, the mysterious form of unobserved matter which could make up 85% of the mass of the known universe, is one of science's biggest manhunts.

In this first of its kind study, scientists have taken a step closer to understanding the elusive mystery matter. They believe a reimagined candidate for dark matter could be behind unexplained chemical reactions taking place in the Milky Way.

Dr. Shyam Balaji, Postdoctoral Research Fellow at King's College London and one of the lead authors of the study explains, "At the center of our galaxy sit huge clouds of positively charged hydrogen, a mystery to scientists for decades because normally the gas is neutral. So, what is supplying enough energy to knock the negatively charged electrons out of them?"

"The energy signatures radiating from this part of our galaxy suggest that there is a constant, roiling source of energy doing just that, and our data says it might come from a much lighter form of dark matter than current models consider."

The most established theory for dark matter is that it is likely a group of particles known as Weakly Interacting Massive Particles (WIMPs), which pass through regular matter without much interaction—making them extremely hard to detect.

However, this study, [published](#) today in *Physical Review Letters*, has potentially revived another type of dark matter with much lower mass than a WIMP.

The researchers think that these tiny dark matter particles are crashing into each other and producing new charged particles in a process called "annihilation." These newly produced charged particles can subsequently ionize the hydrogen gas.

Previous attempts to explain this ionization process had relied on cosmic rays, fast and energetic particles that travel throughout the universe. However, this explanation has faced some difficulties, as energy signatures recorded from observations of the Central Molecular Zone (CMZ) where this is happening, don't seem to be large enough to be attributed to [cosmic rays](#). Such a process doesn't seem to be possible with WIMPs either.

The research team were left with the explanation that the energy source causing the annihilation is slower than a cosmic ray and less massive than a WIMP.

Dr. Balaji said. "The search for dark matter is science's biggest manhunt, but a lot of experiments are based on Earth. By using gas at the CMZ for a different kind of observation, we can get straight to the source. The data is telling us that dark matter could potentially be a lot lighter than we thought."

"The search for dark matter is one of fundamental science's most important objectives, but a lot of experiments are based on Earth, waiting with hands outstretched for the dark matter to come to them. By peering into the center of our Milky Way, the hydrogen gas in the CMZ is suggesting that we may be closer to identifying evidence of the possible nature of dark matter."

This finding may simultaneously explain wider mysteries of our galaxy, such as a specific type of X-ray observation found at the center of the Milky Way—known as the "511-keV emission line." This specific energy signature could also be due to the same low-mass [dark matter](#) colliding and producing charged particles.

More information: Pedro De la Torre Luque et al, Anomalous Ionization in the Central Molecular Zone by Sub-GeV Dark Matter, *Physical Review Letters* (2025). [DOI: 10.1103/PhysRevLett.134.101001](#)

Journal information: [Physical Review Letters](#)
Provided by [King's College London](#)

Mysterious phenomenon at the heart of the Milky Way could point to new dark matter suspect. 'We may have been overlooking its subtle chemical effects on the cosmos.'

Strange events seen at the very heart of the Milky Way could be smoking gun evidence of a new dark matter suspect. If that is the case, scientists may have been missing the subtle impact of [dark matter](#), the universe's most mysterious "stuff," on cosmic chemistry.

This newly proposed [dark matter candidate](#) would not only be lighter than existing hypothetical suspects, but it would also be self-annihilating. This means that when two particles of dark matter meet, they destroy each other and create a negatively charged [electron](#) and its positively charged equivalent, a [positron](#).

This process and the flood of electrons and positrons would provide the energy needed to strip electrons away from neutral atoms, a process called ionization, in dense gas in the center of the Milky Way. That could explain why there is so much ionized gas in the central region called the [Central Molecular Zone](#) (CMZ).

Galaxy's Core is Packed With Dark Matter

Even if the [annihilation of dark matter](#) is rare, it stands to reason it would occur more frequently at the heart of galaxies where it is thought to conglomerate.

"We propose that dark matter lighter than a [proton](#) [the particles found in the nuclei of atoms] could be responsible for an unusual effect seen in the center of [the Milky Way](#)," team leader and Postdoctoral Research Fellow at King's College London Shyam Balaji told Space.com. "Unlike most dark matter candidates, which are often studied through their gravitational effects, this form of dark matter might reveal itself by ionizing gas, essentially stripping electrons from atoms in the CMZ.

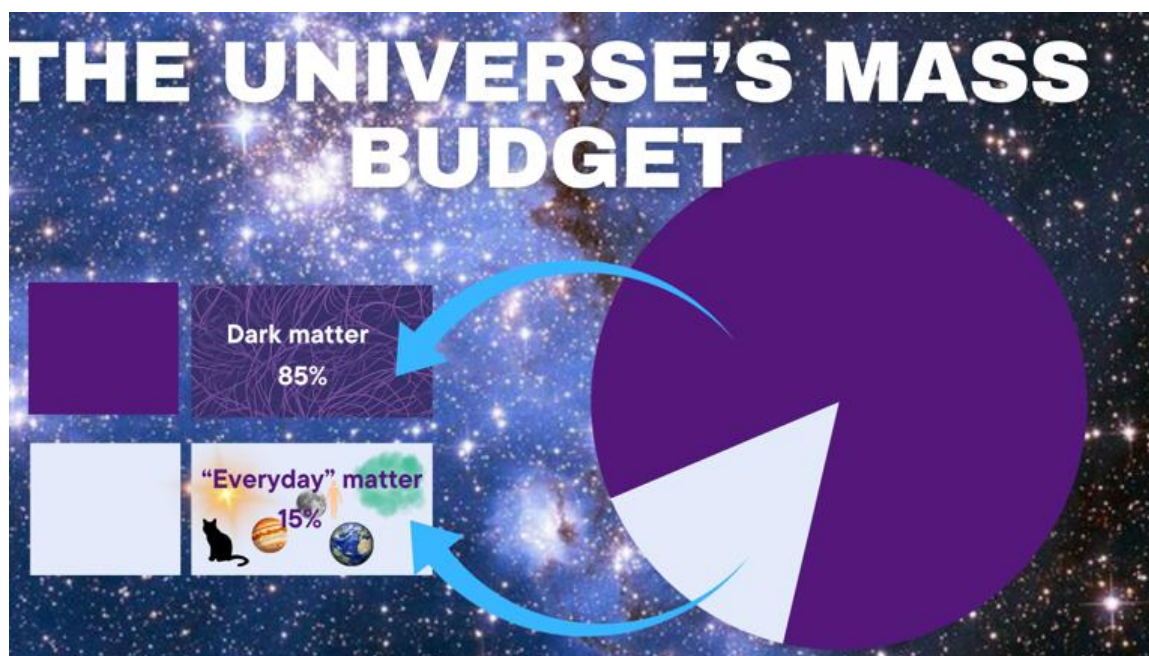
electron-positron pairs, which then interact with the surrounding gas."

Dark matter chemistry

Dark matter is thought to account for around 85% of the "stuff" in the cosmos, but despite its ubiquity, scientists can't "see" it as they do with a great deal of ordinary matter. That's because dark matter doesn't interact with light, or if it does, it does so too weakly and too rarely to be observed.

This tells scientists dark matter can't be composed of the baryonic particles like electrons, protons, and neutrons that compose the atoms that form stars, planets, moons, and everything we see around us on a day-to-day basis.

The only reason scientists theorize that dark matter exists at all is because it does interact with gravity, and this influence impacts light and "ordinary" matter.



A diagram shows the proportion of dark matter to "everyday" matter that composes stars, planets, and even cats (probably). (Image credit: Robert Lea (created with Canva))

This has prompted scientists to look beyond the so-called "standard model of particle physics" to search for particles that could possibly account for dark matter.

These particles vary in mass, given in electronvolts (eV), and in characteristics. It is proposed that some, like this new suspect, could self-annihilate.

[interstellar medium](#), creating a signature in the form of extra ionization, something that axions are typically not expected to do."

Dark matter: It's own worst enemy

In the densely packed CMZ, created positrons can't travel far or escape before they interact with nearby hydrogen molecules, stripping away their electrons. That makes this process particularly efficient in this central region.

"The biggest problem this model helps solve is an excess of ionization in the CMZ," Balaji said. "[Cosmic rays](#), the usual culprits for ionizing gas, don't seem to be strong enough to explain the high levels of ionization we observe."

Cosmic rays are charged particles that travel near the [speed of light](#), but according to this team, the ionization signal from the CMZ seems to indicate a slower moving source that is lighter than many other dark matter candidates.

Also, if cosmic rays were ionizing gas in the CMZ, there should be an associated emission of [gamma rays](#), which are very high-energy particles of light. However, this emission is missing from studies of the CMZ.

"If dark matter is responsible for CMZ ionization, it would mean we're detecting dark matter not by seeing it but by observing its subtle chemical impact on the gas in our galaxy," Balaji said.

There is, however, an unexplained faint gamma-ray glow from the Galactic Center that might also be linked to positrons and ionization.

"If we find a direct connection between ionization and this gamma-ray emission, it could strengthen the case for dark matter," Balaji said. "There is some correlation between these two signals, but we still need more data at this stage to say anything stronger."



Galactic cores, like the center of the Milky Way seen in this photo, are full of gas and debris, making it very hard to get any direct images of the stars or black holes there. (Image credit: NASA/JPL-Caltech, CC BY-NC)

Additionally, this annihilation model of dark matter could also explain a signature light emission from the CMZ arising from positively charged positrons and negatively charged electrons smashing together and combining in a state called [positronium](#), which then decays rapidly into [X-rays](#), light with slightly less energy than gamma-rays.

"The numbers fit much better than we expected. Often, dark matter explanations run into issues because they predict signals that should already have been seen by telescopes," Balaji said. "But in this case, the ionisation rate produced by sub-GeV dark matter fits perfectly within known constraints, without contradicting existing gamma-ray and [cosmic microwave background \(CMB\)](#) observations."

The researcher added that the preliminary confluence with the X-ray emission is also very intriguing.

"That's a rare and exciting situation in dark matter research," Balaji added.

It's early days for this dark matter suspect

Of course, this new dark matter candidate is at the very beginning of its theoretical lifetime; it doesn't even have a snappy name like WIMP (Weakly Interacting Massive Particle) or MACHO (MASSive Compact Halo Object) yet!

For comparison, axions have been around since they were first theorized by theoretical physicists [Frank Wilczek](#) and [Steven Weinberg](#) in 1978.

That means there is a lot of theorizing to be done before this candidate takes its place among axions, WIMPs, MACHOs, primordial black holes, and the rest in the [dark matter suspect line-up](#).

"We need more precise measurements of ionization in the CMZ; if we can map ionization more accurately, we could see whether it follows the expected distribution of dark matter," Balaji said. "If we rule out other potential sources of ionization, the dark matter hypothesis becomes more compelling."

Further evidence of a connection between annihilating dark matter and strange emissions from the CMZ could be delivered by NASA's upcoming [COSI](#) (Compton Spectrometer and Imager) gamma-ray space telescope, set to launch in 2027.

COSI should provide better data regarding MeV (1 million eV) scale astrophysical processes, which could help confirm or rule out this dark matter explanation.

Whatever the case, this research has delivered a [new way to look at the influence of dark matter](#).

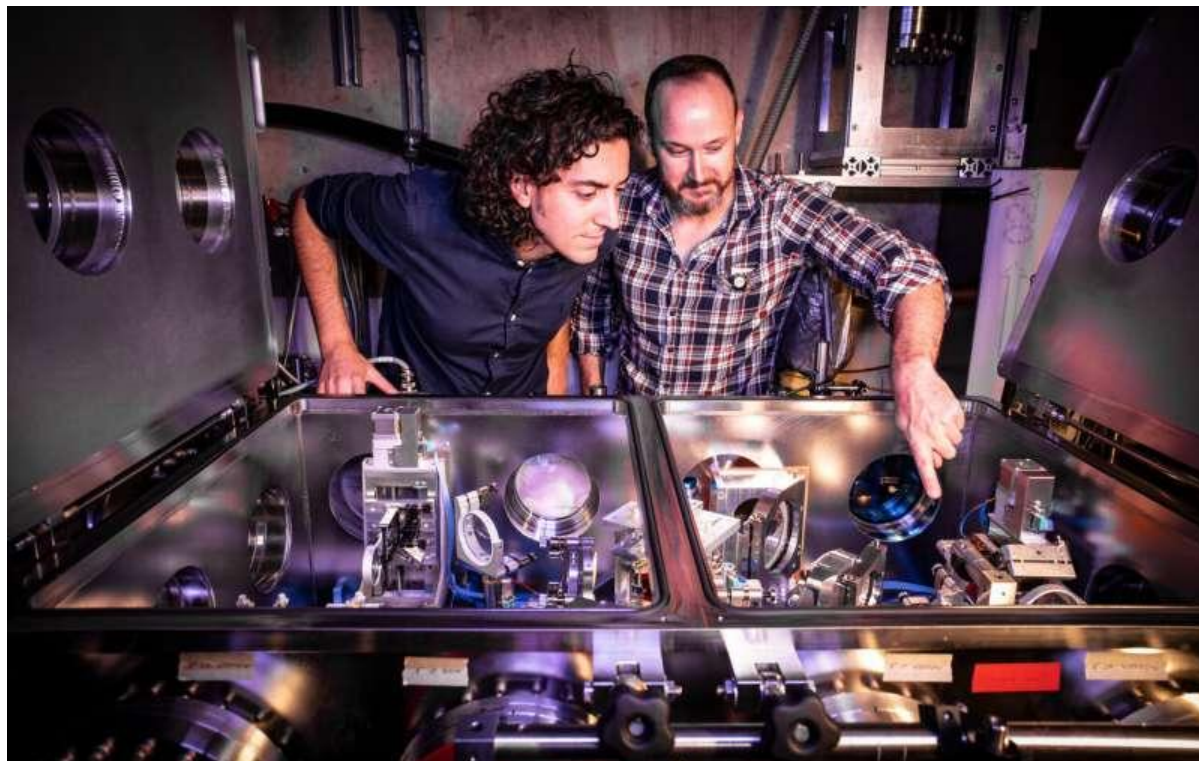
"Dark matter remains one of the biggest mysteries in physics, and this work shows that we may have been overlooking its subtle chemical effects on the cosmos," Balaji concluded. "If this theory holds, it could open up an entirely new way to study dark matter, not just through its gravity, but through the way it shapes the very fabric of our galaxy."

The team's research was published on Monday (March 10) in the journal *Physical Review Letters*.

MARCH 9, 2025

Record-setting electron beam: Five times more powerful than predecessors

by Kimberly Hickok, [SLAC National Accelerator Laboratory](#)



Claudio Emma and Brendan O'Shea examine experimental apparatus at FACET-II in 2022. Credit: Jacqueline Ramseyer Orrell/SLAC National Accelerator Laboratory
Scientists have created an ultrashort electron beam with five times more peak current than any other similar beam on Earth.

Described in a [paper](#) published in *Physical Review Letters*, this achievement addresses one of the grand challenges of particle accelerator and beam physics and opens the door for new discoveries in a broad realm of scientific fields, including [quantum chemistry](#), astrophysics, and material science.

"Not only can we create such a powerful electron beam, but we're also able to control the beam in ways that are customizable and on demand, which means we can probe a much wider range of physical and chemical phenomena than ever before," said Claudio Emma, a staff scientist at the Department of Energy's SLAC National Accelerator Laboratory, who is a researcher at SLAC's Facility for Advanced Accelerator Experimental Tests (FACET-II) and a lead author on the new study.

The power balance

As outlined in the [Accelerator and Beam Physics Roadmap](#) published in 2022, one of the biggest challenges for physicists—until now—has been to produce electron beams that are vastly more powerful while also preserving beam quality.

Traditionally, a microwave field is used to compress and focus the electron beam. The electrons within the field are staggered, so that those further back have more energy than those in the front. It's sort of like runners staggered at the start of a track race, Emma explained.

"We then send them around a bend, so the electrons in the back catch up with electrons in front, and then at the end, you have a bunch of electrons together in a focused beam."

The problem with this approach is that as they accelerate, electrons emit radiation and lose energy, so the quality of the beam deteriorates. That creates a tradeoff between beam energy and quality. "We can't apply traditional methods to compress bunches of electrons at the submicron scale, while also preserving beam quality," Emma said.

Lasers for the win

To solve this issue, SLAC researchers compressed billions of electrons into a length less than one micrometer using a laser-based shaping technique originally developed for X-ray free-electron lasers, such as SLAC's Linac Coherent Light Source (LCLS).

"The big advantage of using a laser is that we can apply an energy modulation that's much more precise than what we can do with microwave fields," Emma said.

But it's not as simple as just shooting a few lasers down a tunnel. "We have a one-kilometer-long machine, and the laser interacts with the beam in the first 10 meters, so you have to get the shaping exactly right, then you have to transport the beam for another kilometer without losing this modulation, and you have to compress it," Emma said. "So it wasn't easy."

After several months of testing and finessing their laser shaping technique, Emma and his team can now repeatedly produce high energy, femtosecond-duration, petawatt peak power electron beams that are about five times higher in current than what could previously be achieved.

An incredible new tool

This new beam will allow scientists to probe a whole series of natural phenomena, including testing hypotheses in [quantum physics](#), materials science, and astrophysics.

In astrophysics, for example, this beam can be directed to a solid or gas target to create a filament similar to those seen in stars. "Scientists know that these filaments occur, but now we can test how they occur and evolve in the lab with a level of power we haven't had before," Emma said.

Fellow FACET-II researchers pounced on the more powerful beam and have already applied it to advancing plasma wakefield technology. Emma is particularly excited about the prospect of further compressing these beams to make attosecond light pulses, further enhancing LCLS's current attosecond capabilities and driving even more pioneering science.

"If you have the beam as a fast camera, then you also have a light pulse that's very short, and now suddenly you have two complementary probes," Emma explained. "That's a unique capability and we can do a lot of things with that."

Emma and his colleagues are excited about the prospects this new [electron beam](#) will bring.

"We have a really exciting and interesting facility at FACET-II where people can come and do their experiments," he said. "If you need an extreme beam, we have the tool for you, and let's work together."

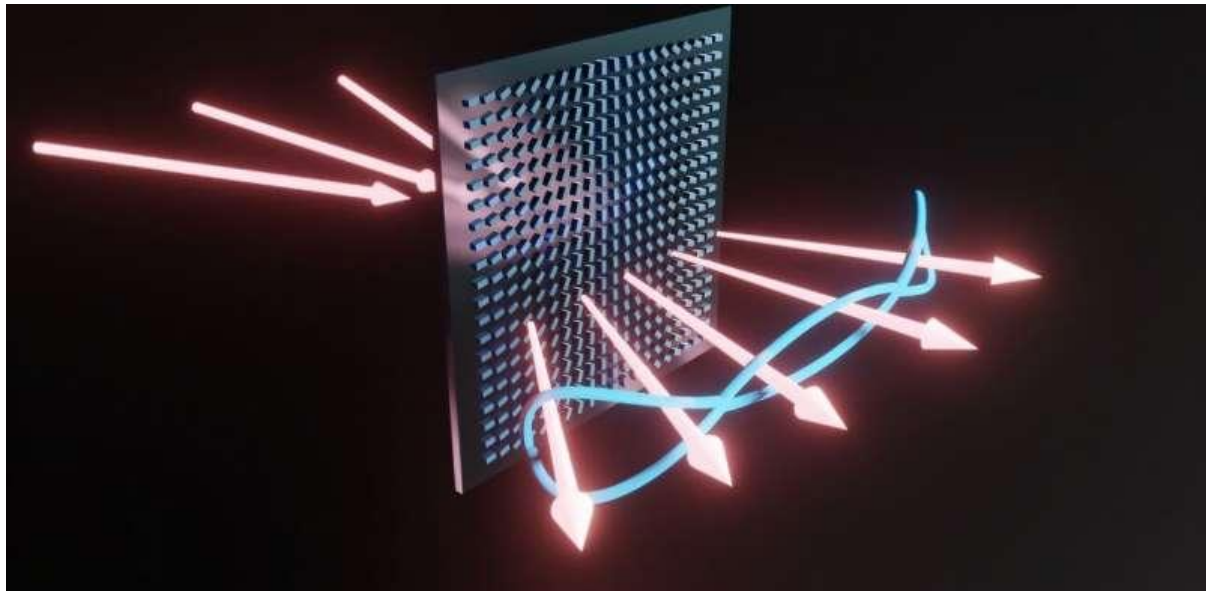
More information: C. Emma et al, Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.085001](https://doi.org/10.1103/PhysRevLett.134.085001)

Journal information: [Physical Review Letters](#)
Provided by [SLAC National Accelerator Laboratory](#)

MARCH 10, 2025

Metasurface technology offers a compact way to generate multiphoton entanglement

by [SPIE](#)



Generating multiphoton entanglement with a tiny metasurface. Credit: Peking University
Quantum information processing is a field that relies on the entanglement of multiple photons to process vast amounts of information. However, creating multiphoton entanglement is a challenging task. Traditional methods either use quantum nonlinear optical processes, which are inefficient for large numbers of photons, or linear beam-splitting and quantum interference, which require complex setups prone to issues like loss and crosstalk.

A team of researchers from Peking University, Southern University of Science and Technology, and the University of Science and Technology of China have made a significant breakthrough in this area.

As reported in [Advanced Photonics Nexus](#), they developed a new approach using metasurfaces, which are planar structures capable of controlling various aspects of light, such as phase, frequency, and polarization. This innovative approach allows for the generation of multiphoton entanglement on a single [metasurface](#), simplifying the process while making it more efficient.

The researchers' method involves sending several single photons into a specially designed gradient metasurface from different directions. The metasurface causes these photons to interfere with each other in a quantum manner, resulting in entangled photons.

This technique not only allows for the creation of different types of entangled states but also enables the fusion of several pairs of entangled photons into larger groups. This advancement means that more quantum information can be packed into a smaller space.

Professor Ying Gu, corresponding author on the report, remarks on this new approach as a fresh perspective for [quantum information processing](#): "It's like finding a shortcut in a maze. Instead of trying to navigate the twists and turns of complex optical setups, we can use a single metasurface to do the job."

"The process of creating and manipulating entangled photons becomes much simpler and more compact. It's perfect for building tiny quantum devices that could fit on a chip, making it a great solution for future quantum computing and communication applications."

With this new method of creating multiphoton entanglement, many quantum applications may become more accessible. For instance, metasurfaces could be used to generate and deliver entangled photons to multiple users, facilitating the creation of a quantum network.

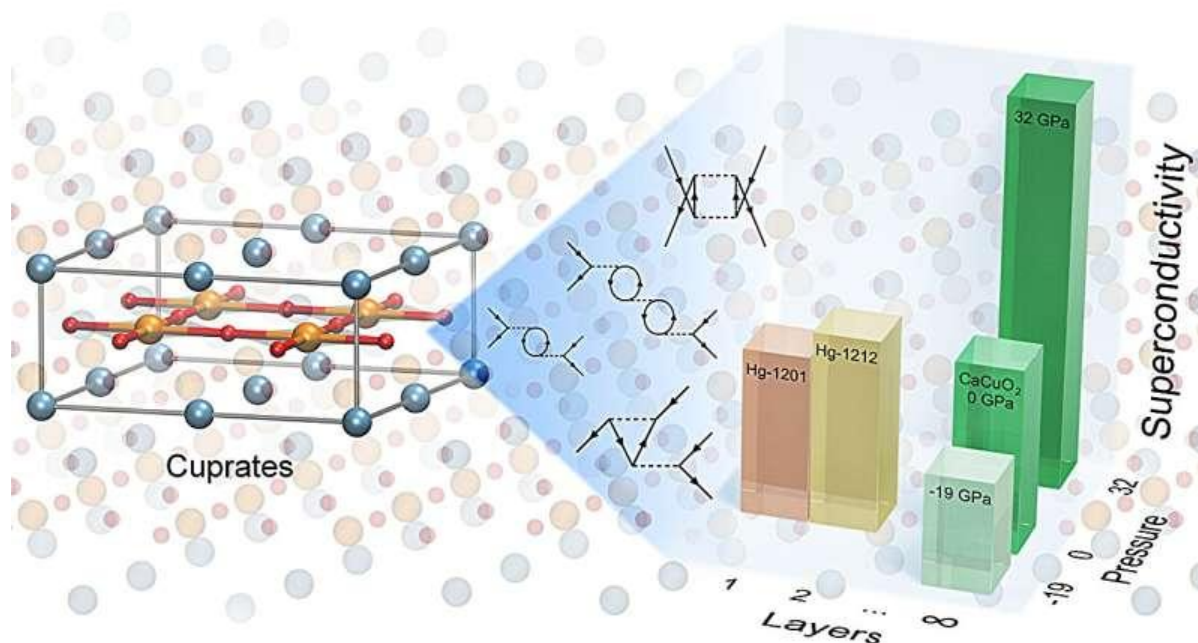
Additionally, metasurfaces could serve as building blocks for handling more photons, potentially leading to the development of quantum computers as small as laptops. Such possibilities are exciting, and this research moves us a step closer to realizing them.

More information: Qi Liu et al, Multiphoton path-polarization entanglement through a single gradient metasurface, *Advanced Photonics Nexus* (2025). DOI: [10.1117/1.APN.4.2.026002](https://doi.org/10.1117/1.APN.4.2.026002)
Provided by [SPIE](#)

MARCH 10, 2025

Unraveling the mystery of high-temperature superconductors from first principles

by Zhi-Hao Cui



The many-body ab initio simulation correctly captures two known experimental trends: the pressure effect, where the pairing order and gap increase with intra-layer pressure, and the layer effect, where the pairing order and gap vary with the number of copper-oxygen layers. Credit: Zhi-Hao Cui

Ever since their discovery almost four decades ago, high-temperature superconductors have fascinated scientists and engineers alike. These materials, primarily cuprates, defy classical understanding because they conduct electricity without resistance at temperatures far higher than traditional superconductors. Yet despite decades of research, we still don't have a clear, comprehensive microscopic picture of how superconductivity emerges in these complex materials.

During my Ph.D. at Caltech, I was intrigued by the profound puzzle presented by high-temperature superconductors: Can we directly compute their [superconducting properties](#) from fundamental quantum mechanics without relying on simplified models or approximations? With this question, I embarked on a challenging but rewarding scientific journey.

Why cuprates are special, and challenging

Cuprates are layered compounds composed primarily of copper-oxygen planes. In their undoped parent state, they are insulators and antiferromagnets, meaning that the [electron spins](#) align antiparallel in adjacent copper atoms. Introducing a small number of holes or electrons dramatically transforms them, causing superconductivity to appear. However, capturing this transition and the detailed pairing mechanism at the atomic scale has proven notoriously challenging for theorists.

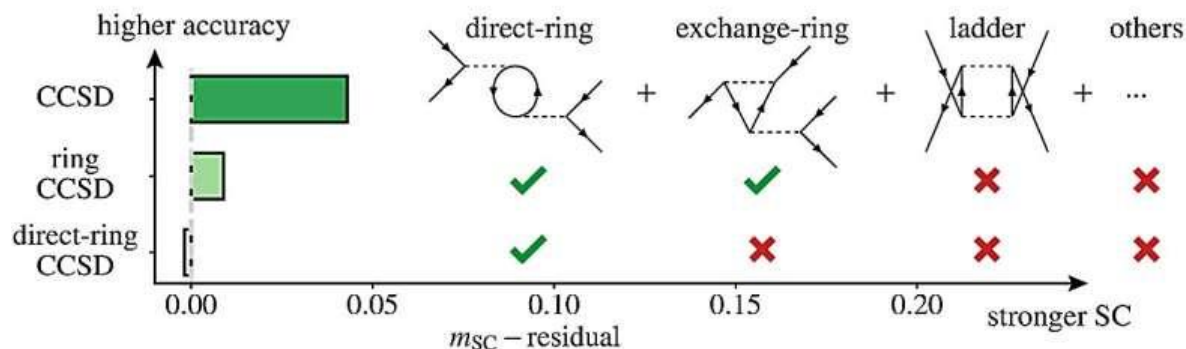
Our recent study tackles this long-standing challenge. Together with collaborators from Caltech, Columbia, and Berkeley, we developed an advanced computational framework to simulate and predict superconductivity from first principles—meaning our calculations start directly from atomic positions without simplifications. The work is [published](#) in *Nature Communications*.

Pressure, layers, and superconductivity—decoding the clues

We focused specifically on two intriguing and widely observed phenomena in [cuprate superconductors](#):

- The pressure effect: When pressure is applied to cuprate planes, their superconducting temperatures typically rise.
- The layer effect: Cuprate superconductors with different numbers of copper-oxygen layers exhibit different superconducting temperatures (first increase with the number of layers and then decrease).

Remarkably, our ab initio simulations successfully reproduced these well-known experimental observations without pre-adjusting parameters or using fitted data. In fact, we could directly observe the pairing order—the essential quantum property behind superconductivity—and calculate pairing gaps, which relate closely to superconducting temperatures.



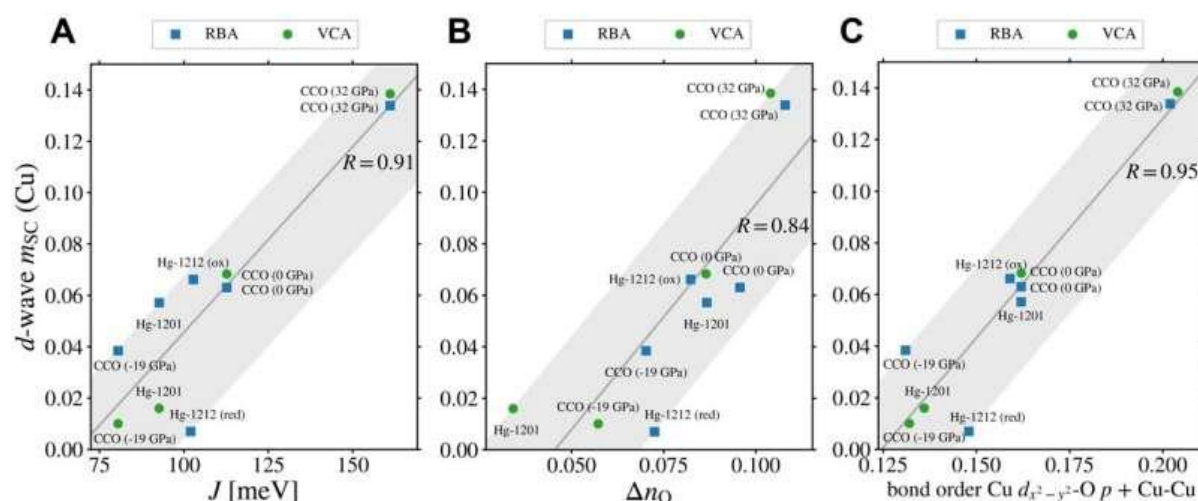
Only direct-ring diagrams (charge-charge fluctuation) are not enough to generate superconductivity. Spin fluctuation (from other diagrams in higher accuracy solvers) is the driving force of superconductivity. Credit: Zhi-Hao Cui

Deep dive: Spin and charge fluctuations drive pairing

What makes superconductivity happen at microscopic scales? Our calculations revealed the key lies in two critical types of quantum fluctuations:

- Spin fluctuations: Short-range [magnetic interactions](#) primarily among copper atoms.
- Charge fluctuations: Movements and rearrangements of electron density among copper and oxygen atoms.

These fluctuations, which occur at short distances—just a few atoms apart—act together to enable superconductivity. Interestingly, it turned out that spin fluctuations are crucial for pairing, while charge fluctuations set the stage by tuning the electronic environment around copper atoms.



The superconducting pairing order correlates strongly with (A) magnetic exchange coupling J , (B) oxygen doping, and (C) Cu–O bond covalency, providing insight into material optimization. Credit: Zhi-Hao Cui

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Identifying the fingerprints of superconductivity

Can we quickly estimate how superconductive a material might be from simpler properties? Our simulations identified two straightforward "descriptors":

- Magnetic exchange coupling (J): A measure of how strongly neighboring spins interact.
- Cu–O covalency: The extent to which electrons are shared between copper and oxygen atoms.

These descriptors correlated strongly with computed superconducting properties, giving valuable hints on how structural changes or chemical substitutions might affect superconductivity.

The way forward—bridging theory and experiment

The ability to reliably simulate [high-temperature superconductors](#) from first principles represents a significant step forward. While our calculations do not yet capture all complexities—like phonons (atomic vibrations), structural disorder, and explicit dopant effects—they illustrate clearly that a complete microscopic description of high-temperature superconductivity is achievable.

Our hope is that this ab initio approach will allow researchers to more quickly identify promising superconducting materials and better understand existing ones. Perhaps most excitingly, the methods we developed could guide experimentalists toward new materials with even higher superconducting temperatures, bringing us closer to practical applications in energy transmission, transportation, and quantum technology.

The mysteries of high-temperature superconductivity have not been fully solved—but we are now closer than ever to understanding them at their most fundamental level. This journey is just beginning, and I'm excited to see where it takes us next.

This story is part of [Science X Dialog](#), where researchers can report findings from their published research articles. [Visit this page](#) for information about Science X Dialog and how to participate.

More information: Zhi-Hao Cui et al, Ab initio quantum many-body description of superconducting trends in the cuprates, *Nature Communications* (2025). DOI: [10.1038/s41467-025-56883-x](https://doi.org/10.1038/s41467-025-56883-x)

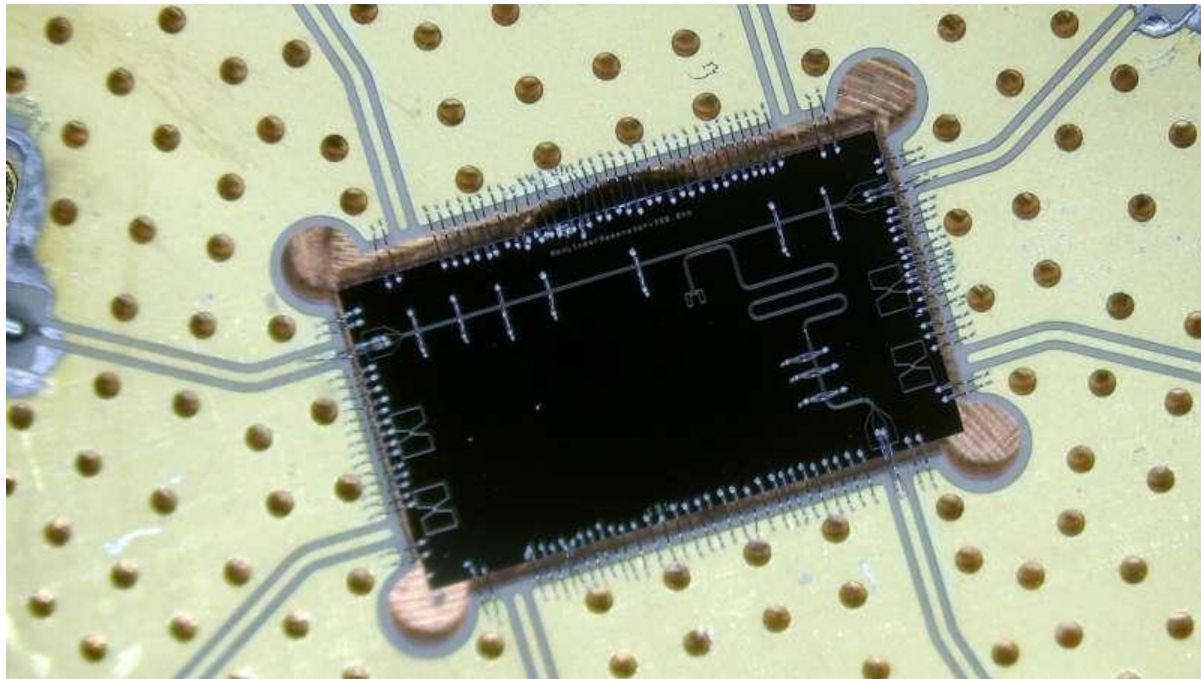
Journal information: [Nature Communications](#)

Dr. Zhi-Hao Cui received his bachelor's degree from Peking University in 2017. He obtained his Ph.D. in Theoretical Chemistry from Caltech in 2023 (under the supervision of Prof. Garnet Chan). He is currently a postdoctoral scholar at Columbia University (working with Prof. David Reichman). Dr. Cui's Ph.D. research has been focused on establishing a theoretical framework for simulations of high-temperature superconductors and other strongly correlated quantum materials. He is now working on electron-boson coupled systems, such as polariton and polaron chemistry. He has published more than 20 scientific papers with an H-index of 18.

MARCH 10, 2025

Unlocking the secrets of phase transitions in quantum hardware

by [Ecole Polytechnique Federale de Lausanne](#)



Nonlinear superconducting resonator circuit for investigating dissipative phase transitions.

Credit: Guillaume Beaulieu, CC BY-SA 4.0

Phase transitions, like water freezing into ice, are a familiar part of our world. But in quantum systems, they can behave even more dramatically, with quantum properties such as Heisenberg uncertainty playing a central role. Furthermore, spurious effects can cause the systems to lose, or dissipate, energy to the environment. When they happen, these "dissipative phase transitions" (DPTs) push quantum systems into new states.

There are different types or "orders" of DPTs. First-order DPTs are like flipping a switch, causing abrupt jumps between states. Second-order DPTs are smoother but still transformative, changing one of the system's global features, known as symmetry, in subtle yet profound ways.

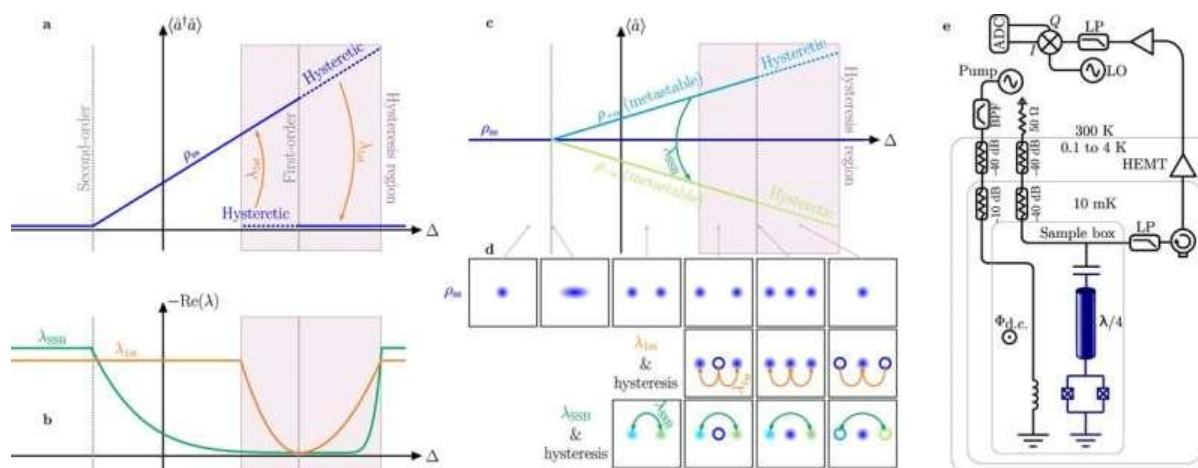
DPTs are key to understanding how quantum systems behave in non-equilibrium conditions, where arguments based on thermodynamics often fail to provide answers. Beyond pure curiosity, this has practical implications for building more robust quantum computers and sensors. For example, second-order DPTs could enhance quantum information storage, while first-order DPTs reveal important mechanisms of system stability and control.

Theoretically, DPTs have been predicted to display specific properties, such as slowing down and bistability, occurring with specific power-law scales. So far, observing them has been a major scientific hurdle—especially the second-order ones.

But now, a team of researchers has done just that. Led by Professor Pasquale Scarlino at EPFL, they developed a superconducting Kerr resonator, a device with controllable quantum properties, and engineered it to experience a two-photon drive, which sends pairs of photons into the system to carefully control its quantum state and study how it transitions between different phases. The work is [published](#) in *Nature Communications*.

By systematically varying parameters like detuning and drive amplitude, the team was able to study the system's transitions from one quantum state to another. The approach allowed them to observe both a first-order and second-order DPT.

To ensure accuracy, the experiments were carried out at temperatures near absolute zero, reducing background noise to almost nothing. The Kerr resonator was pivotal because it can amplify quantum effects that are often too subtle to observe. Because it can respond to two-photon signals with extreme sensitivity, the researchers were able to use it to explore phase transitions with unprecedented precision—something traditional setups simply cannot achieve.



Sketch of the theory of dissipative phase transitions and of the experimental set-up.

Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-025-56830-w

The setup allowed the team to monitor the behavior of photons emitted by the resonator with ultra-sensitive detectors. By using advanced mathematical techniques, like the connection with the spectral properties of the Liouvillian superoperator—a tool that models complex quantum processes—the scientists were able to precisely track and analyze the system's phase transitions.

For the second-order DPT, the team observed a phenomenon called "squeezing," where quantum fluctuations drop to levels lower than the natural background noise of empty space, signaling that the system has reached a highly sensitive and transformative state. Meanwhile, the first-order DPT showed distinct hysteresis cycles, where the system could exist in two states depending on how parameters were tuned.

Second, they found clear evidence of metastable states during the first-order DPT, where the system temporarily remained in one stable state before abruptly transitioning to another. This behavior, leading to a dependence of the system's state on its previous history known as hysteresis, showcases how first-order DPTs involve competing phases.

Last, they observed "critical slowing down" in both types of transitions, reproducing the expected scaling obtained from theoretical consideration. This ultimately demonstrates the validity of theoretical predictions based on the Liouvillian theory used by the authors. Near the critical points, the system's response slowed significantly, highlighting a universal feature of [phase transitions](#) that could be harnessed for more precise quantum measurements.

Understanding DPTs opens new possibilities for engineering [quantum systems](#) that are both stable and responsive. This could revolutionize quantum information technologies, such as error correction in quantum computing or the development of ultra-sensitive quantum sensors.

More broadly, this research showcases the power of interdisciplinary collaboration—blending [experimental physics](#), advanced theoretical models, and cutting-edge engineering to explore the frontiers of science.

"In fact, a very interesting aspect of this work is that it also demonstrates how close collaboration between theory and experiment can lead to results far greater than what either group could have achieved independently," says Guillaume Beaulieu, the paper's first author.

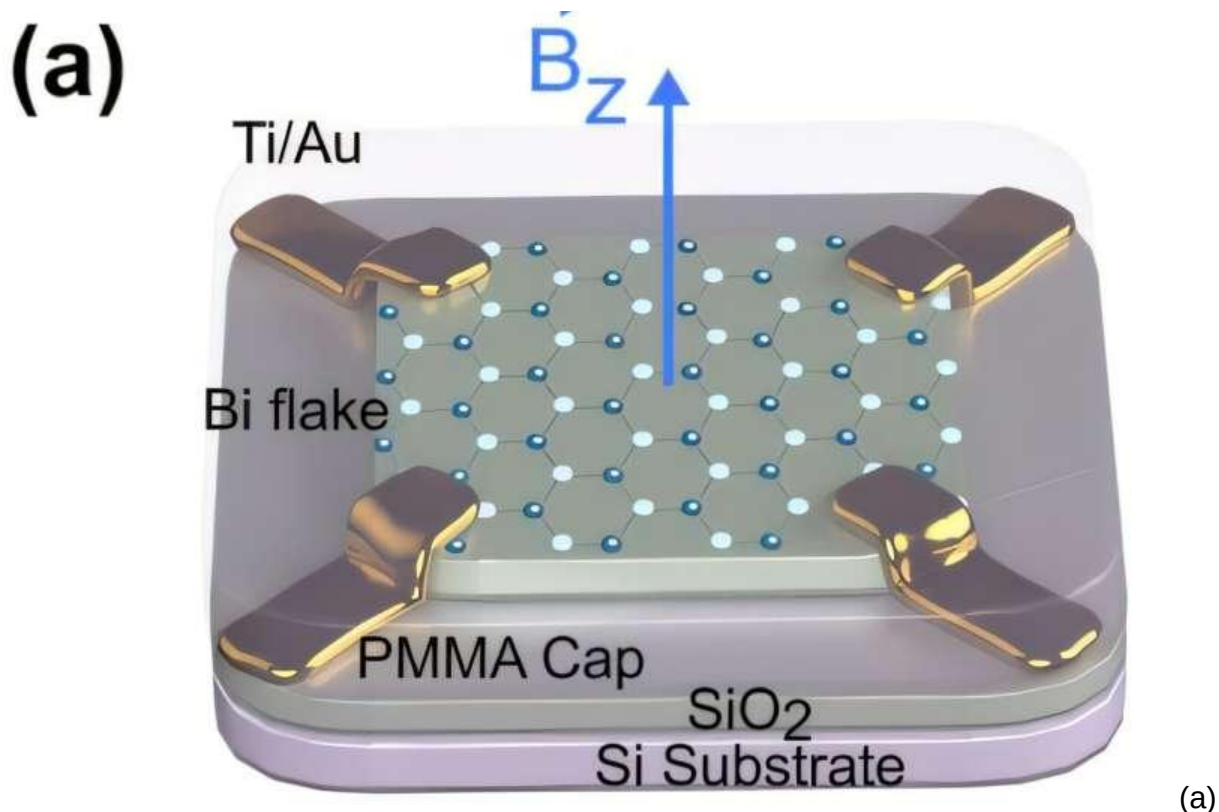
More information: Guillaume Beaulieu et al, Observation of first- and second-order dissipative phase transitions in a two-photon driven Kerr resonator, *Nature Communications* (2025). DOI: [10.1038/s41467-025-56830-w](https://doi.org/10.1038/s41467-025-56830-w)

Journal information: [Nature Communications](#)
Provided by [Ecole Polytechnique Federale de Lausanne](#)

MARCH 10, 2025

Ultra-thin bismuth holds unexpected promise for green electronics

by Claire Loewen, [McGill University](#)



Schematic of the device with an arrow showing the direction of the applied magnetic field B_z . (b) Optical microscope image of the fabricated device where the flake is circled by the red dashed line. Credit: *arXiv*: DOI: 10.48550/arxiv.2406.12134

Electronic devices rely on materials whose electrical properties change with temperature, making them less stable in extreme conditions. A discovery by McGill University researchers that challenges conventional wisdom in physics suggests that bismuth, a metal, could serve as the foundation for highly stable electronic components.

The researchers observed a mysterious electrical effect in ultra-thin [bismuth](#) that remains unchanged across a wide temperature range, from near absolute zero (-273°C) to room temperature.

"If we can harness this, it could become important for green electronics," said Guillaume Gervais, a professor of physics at McGill and co-author of the study.

The finding could lead to the development of more efficient, stable and environmentally friendly electronic components and devices, including for space exploration and medical uses. Bismuth is non-toxic and biocompatible.

"We expected this effect to disappear once we increased the temperature, but it stubbornly refused; we kept going to room temperature and it was still there," said Gervais. "I was so sure it would vanish that I even bet my students Oulin Yu and Frédéric Boivin a bottle of wine. It turned out I was wrong."

Inspired by a cheese grater

Published in *Physical Review Letters*, the [study](#) reports the observation of a temperature-independent anomalous Hall effect (AHE) in a 68-nanometer-thick flake of bismuth. This effect, which creates a voltage perpendicular to an applied current, is typically associated with materials that have [magnetic properties](#). However, bismuth is diamagnetic, meaning it does not usually exhibit such behavior.

To make the discovery, Gervais and his colleagues, including lead author and Ph.D. candidate Yu, developed a new technique for creating ultra-thin bismuth. Inspired by a cheese grater, the team patterned microscopic trenches onto a semiconductor wafer, then mechanically shaved off thin layers of bismuth. They then tested these flakes under extreme magnetic fields—tens of thousands of times stronger than a fridge magnet—at the National High Magnetic Field Laboratory in Florida.

Breaking the rules of physics?

Previous studies suggested that bismuth should not exhibit AHE, making the team's findings all the more puzzling.

"I can't point to one theory that would explain this," said Gervais, "only bits and pieces of a potential explanation."

One hypothesis is that the atomic structure of bismuth constrains electron movement in a way that mimics the behavior of topological materials, recently discovered exotic substances whose surfaces and interiors exhibit different properties. These materials could revolutionize computing.

The research team's next step is to explore whether bismuth's AHE can be converted into its quantum counterpart, the quantum anomalous Hall effect (QAHE). Such a breakthrough could pave the way for [electronic devices](#) that function at higher temperatures than previously possible.

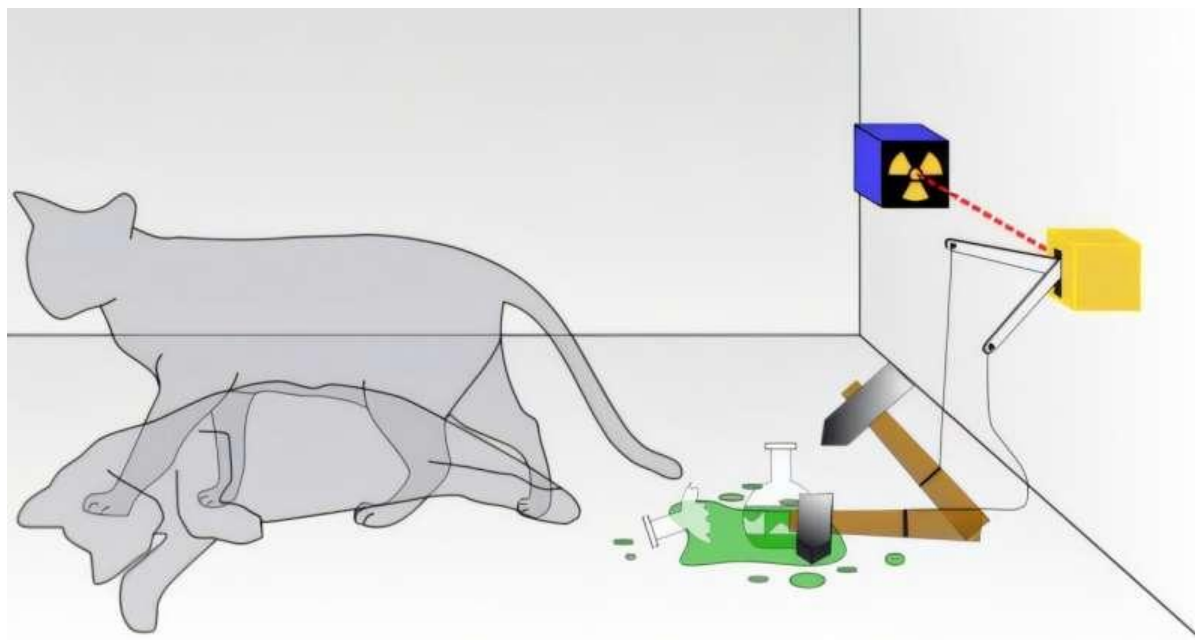
More information: Oulin Yu et al, Observation of Temperature-Independent Anomalous Hall Effect in Thin Bismuth from Near Absolute Zero to 300 K Temperature, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.066603](https://doi.org/10.1103/PhysRevLett.134.066603). On arXiv: DOI: [10.48550/arxiv.2406.12134](https://arxiv.org/abs/10.48550/arxiv.2406.12134)

Journal information: [Physical Review Letters](#) , [arXiv](#)

MARCH 10, 2025

Quantum mechanics: Hypercomplex, or 'just' complex?

by [Friedrich–Alexander University Erlangen–Nurnberg](#)



Schrödinger's cat: a cat, a flask of poison, and a radioactive source are placed in a sealed box. If an internal monitor detects radioactivity (i.e. a single atom decaying), the flask is shattered, releasing the poison that kills the cat. The Copenhagen interpretation of quantum mechanics implies that after a while, the cat is simultaneously alive and dead. Yet, when one looks in the box, one sees the cat either alive or dead, not both alive and dead. This poses the question of when exactly quantum superposition ends and reality collapses into one possibility or the other. Credit: Wikipedia / CC BY-SA 3.0

Today, physicists are still asking themselves whether quantum mechanics needs hypercomplex numbers. FAU researchers Ece Ipek Saruhan, Prof. Dr. Joachim von Zanthier and Dr. Marc Oliver Pleinert have been investigating this question in their research.

Exactly 100 years ago, Werner Heisenberg, Max Born and Pascual Jordan formulated [quantum mechanics](#) and revolutionized our understanding of physics. Only a few months later, Erwin Schrödinger presented an alternative but mathematically equivalent formulation: Wave mechanics based on Schrödinger's equation.

Even though these approaches appeared to be competing at first, they turned out to be physically identical—they describe the same reality, but use different mathematical approaches.

To describe quantum mechanics in mathematical terms, both Heisenberg and Schrödinger used the system of complex numbers. In contrast to real numbers, those we use every day to describe distances or temperatures, complex numbers comprise a real part, like a number on an x axis, and an imaginary part, located on a y axis. This enables them to be shown as points on a two-dimensional plane.

While Schrödinger later speculated that quantum mechanics could be formulated only using real numbers, this theory has since been disproved by a series of experiments.

An additional dimension?

However, another question that remains unanswered to this day goes in the other direction: Could it be necessary to go above and beyond complex numbers in quantum mechanics and to describe it using hypercomplex numbers, for example by using something known as quaternions?

Hypercomplex numbers extend the concept of complex numbers by adding additional dimensions to the imaginary part. Instead of points on a two-dimensional plane, they therefore represent points in multi-dimensional spaces. To this day, there is no conclusive evidence that such a description is necessary, but it has not been ruled out. However, for our understanding of nature, such an extension would be revolutionary.

The founding fathers of quantum mechanics examined this question and investigated hypercomplex formulations of quantum physics. To gain some clarity, physicists also later looked for experiments to prove this hypothesis.

One of the first people to examine this question was Asher Peres. In the 1970s, he proposed an experiment to demonstrate whether quantum mechanics can actually be fully described using complex numbers or whether hypercomplex numbers are required. His basic idea: If quantum mechanics is hypercomplex, certain outcomes of an experiment he proposed should behave differently than if standard quantum mechanics applied.

Specifically, he proposed sending lightwaves through different interferometers with two or three slits and to compare the resulting interference patterns. In standard quantum mechanics, certain combinations of the resulting interference patterns cancel each other out. When this is not the case, this could be an indication for hypercomplex quantum mechanics.

Since then, several researchers have carried out the Peres test in experiments. Early experiments initially used simplified versions of the test with neutrons. Only recently have scientists conducted measurements in the optical and microwave range in accordance with Peres' original concept. Due to the limited measurement accuracy, however, no clear

evidence for or against hypercomplex quantum mechanics has been found to date in an experiment.

Saruhan, von Zanthier and Pleinert at the Department of Physics at FAU recently carried out a thorough theoretical investigation of the Peres test and extended it. The paper is [published](#) in the journal *Physical Review Letters*.

Here, they discuss their findings:

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You developed the Peres test. What exactly did you change?

Saruhan: We put the test on a mathematical foundation, making it generally more applicable. In addition, our approach means that we can interpret the results of the test as volumes in a three-dimensional space. If a description with complex numbers is sufficient, all measurements are located on a plane in this space and the test results in a volume of zero. In contrast, if the volume were different to zero...

...a hypercomplex description would be necessary?

Pleinert: Exactly. Then physical dimensions could only be fully described with hypercomplex numbers. Our extended test method also makes it possible to expand the test to any number of dimensions: You can think of it like this—each additional slit in the experiment adds a further dimension, allowing us to systematically investigate all hypercomplex number systems.

Why is it important?

von Zanthier: The Schrödinger equation is the established standard in quantum mechanics, but its validity has never been formally proven—it just worked. This means that complex numbers seem to have always been enough to describe the observed phenomena. Our test extends the experimental verification of whether complex numbers are actually sufficient to describe quantum mechanics to higher dimensions and can help to clarify this fundamental question of physics.

You have improved the Peres test even further?

Saruhan: Yes, we have extended the procedure so that not just a single light particle, but several light particles are sent through an interferometer with any number of slits at the same time. This allows us to further increase the informative value of the test.

Has the extended test provided new results?

Pleinert: All measurements up to now show that the result is always "zero," which means complex numbers are sufficient for the achieved measurement accuracy. The tests require extremely precise measurements, however. Above all, our aim is to encourage physicists all over the world to use our extended version in order to carry out even more precise tests.

Maybe that will enable us one day to provide a definitive answer as to whether complex numbers are sufficient for quantum mechanics, or whether hypercomplex numbers are required. This would be a significant step forward for quantum research.

More information: Ece İpek Saruhan et al, Multipath and Multiparticle Tests of Complex versus Hypercomplex Quantum Theory, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.060201](https://doi.org/10.1103/PhysRevLett.134.060201)

Journal information: [Physical Review Letters](#)

Provided by [Friedrich–Alexander University Erlangen–Nurnberg](#)

MARCH 10, 2025

Quantum entanglement sensors could test quantum gravity

by Andy Tomaswick, [Universe Today](#)



Artist's concept of SUPREME-QG. Credit: S. Shahriar / NASA

Ask almost any physicist what the most frustrating problem is in modern-day physics, and they will likely say the discrepancy between general relativity and quantum mechanics. That discrepancy has been a thorn in the side of the physics community for decades.

While there has been some progress on potential theories that could rectify the two, there has been scant experimental evidence to support those theories. That is where Selim Shahriar from Northwestern University, Evanston, comes in. He plans to work on a concept called the Space-borne Ultra-Precise Measurement of the Equivalent Principle Signature of Quantum Gravity (SUPREME-QG), which he hopes will help collect some accurate experimental data on the subject once and for all.

To put it bluntly, the experiment is complicated. At its heart, it uses a space-based platform carrying a quantum-entangled sensor and some precise positioning systems. But understanding why it is useful to test quantum gravity first requires some explanation. Let's first look at one of the most famous tenets of General Relativity—the Equivalence Principle.

The Equivalence Principle states that gravity and acceleration are the same. It is at the core of General Relativity, which treats gravity as a curve in spacetime rather than a fundamental force. But plenty of quantum gravity theories predict a deviation from this equivalence on minute scales—where [quantum mechanics](#) starts to take over.

Fraser interviews quantum expert Sean Carroll. Credit: Universe Today

To describe that deviation, physicists use a term known as the Eötvös parameter. It explains how closely gravitational mass and inertial mass are related. In General Relativity, at least, they should be the same. However, as things get closer to the realm of quantum mechanics, some theories that claim to offer a theory of quantum gravity start to see a divergence between the two, which is represented as a non-zero value for the Eötvös parameter.

So far, this parameter's value has been tested down to about 10^{-15} by the MICROSCOPE experiment, which was specially designed to test this theory. The researchers leading that project published a report back in 2022, and it remains our most accurate measurement of the Eötvös parameter to this day.

However, MICROSCOPE used traditional accelerometers, which—while they provided an estimate of more than 100 times what could be obtained on Earth—were not accurate enough to measure down to the 10^{-18} level, where theories such as string theory predict there might be a deviation in the parameter.

Enter Dr. Shahriar and his team. Their goal is to develop a space-based platform that uses atom interferometers to constrain the parameter value down to 10^{-20} , at which point it could potentially prove or disprove some theories of quantum gravity. But to get there, they need to do a lot of groundwork first.

One step in the process is to understand how [quantum entanglement](#) could be utilized in these atom interferometers (AIs). AIs work by using atoms' dual nature (which has a similar wave/particle duality to light) and splitting a beam of atoms onto separate paths using lasers. In the case of Dr. Shahriar's experiment, these would be rubidium atoms. After they are split, if they are not observed, they enter into a state equivalent to the famous Schrödinger's cat experiment of quantum mechanics.

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However, creating such a quantum mechanical state has never been done before, which is the next step in Dr. Shahriar's development work. His team has developed the "generalized echo squeezing protocol," which theoretically allows them to maintain the quantum entangled state for long periods. Doing so would allow for precise measurements of discrepancies between the two states when they are eventually recombined, and those discrepancies could lead to a highly accurate measure of the Eötvös parameter.

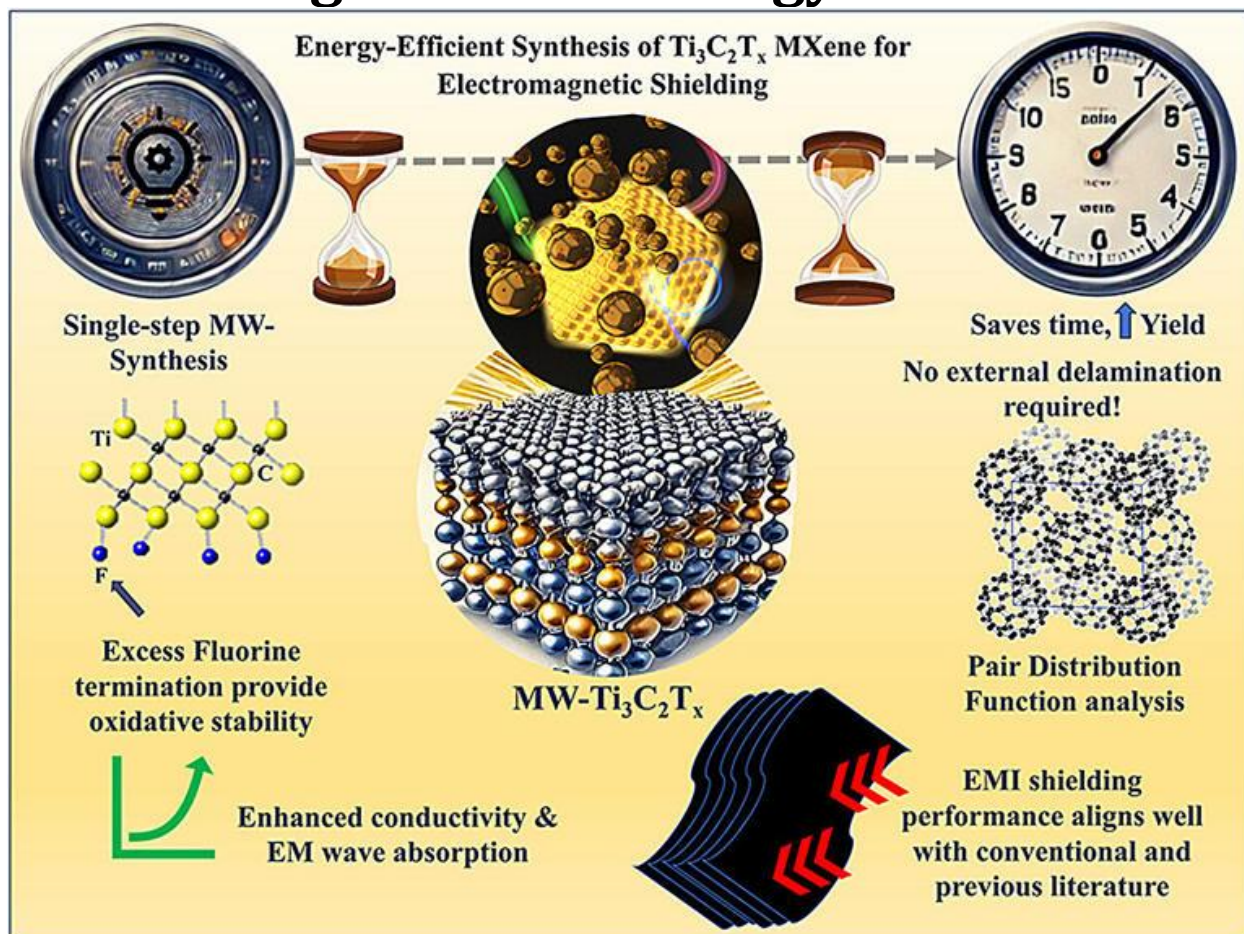
The underlying technology, which the team called a "Schrödinger's Cat Atom Interferometer" (SCAI) in a recent press release, could also be used for applications back

on Earth. If possible, using their theoretical implementation, these sensors would be thousands of times more accurate than typical accelerometers or gyroscopes, which are already used in various applications like guidance and navigation systems and automotive.

There is still much work to be done, even to prove that the theoretical implementation of this technology is possible in the real world. Once people start operating with quantum uncertainties, things tend to get tricky, not just for theoretical cats. But, if Dr. Shahriar and his team do make a functional space-borne SCAI, we will finally be a few steps closer to truly reconciling one of the biggest problems in modern physics.

Provided by [Universe Today](#)

Microwave synthesis produces MXene 25 times faster than traditional methods while using 75% less energy



Credit: Materials Science in Semiconductor Processing (2024). DOI: 10.1016/j.mssp.2024.108966

MXene is a lightweight two-dimensional (2D) material capable of protecting everything—including spacecraft, mechanical components, and maybe even people—from harmful radiation. Because traditional synthesis requires multi-step processes that can take up to 40 hours, MXene is difficult to produce.

By introducing a rapid single-step microwave synthesis method, researcher Reeja Jayan has reduced MXene production time to 90 minutes and cut energy consumption by 75%.

"Our work has implications for the global production of chemicals because almost a third of greenhouse gas emissions come from chemical manufacturing and production," said Jayan, a professor of mechanical engineering at Carnegie Mellon University.

The research, [published](#) in *Materials Science in Semiconductor Processing*, also demonstrates a unique ability to customize MXene's composition to change the type of radiation against which the material can protect. To date, the team has tested their material across the X-band—radio frequencies ranging from 8.0–12.0 GHZ—but to protect against electronic materials in outer space, more testing against cosmic radiation is needed.

"We assumed that because we sped up the process, we would lose some of the shielding performance in return," said Jayan. "We were pleasantly surprised that although there were subtle structural differences, we didn't see any shielding efficiency tradeoff at the lab scale."

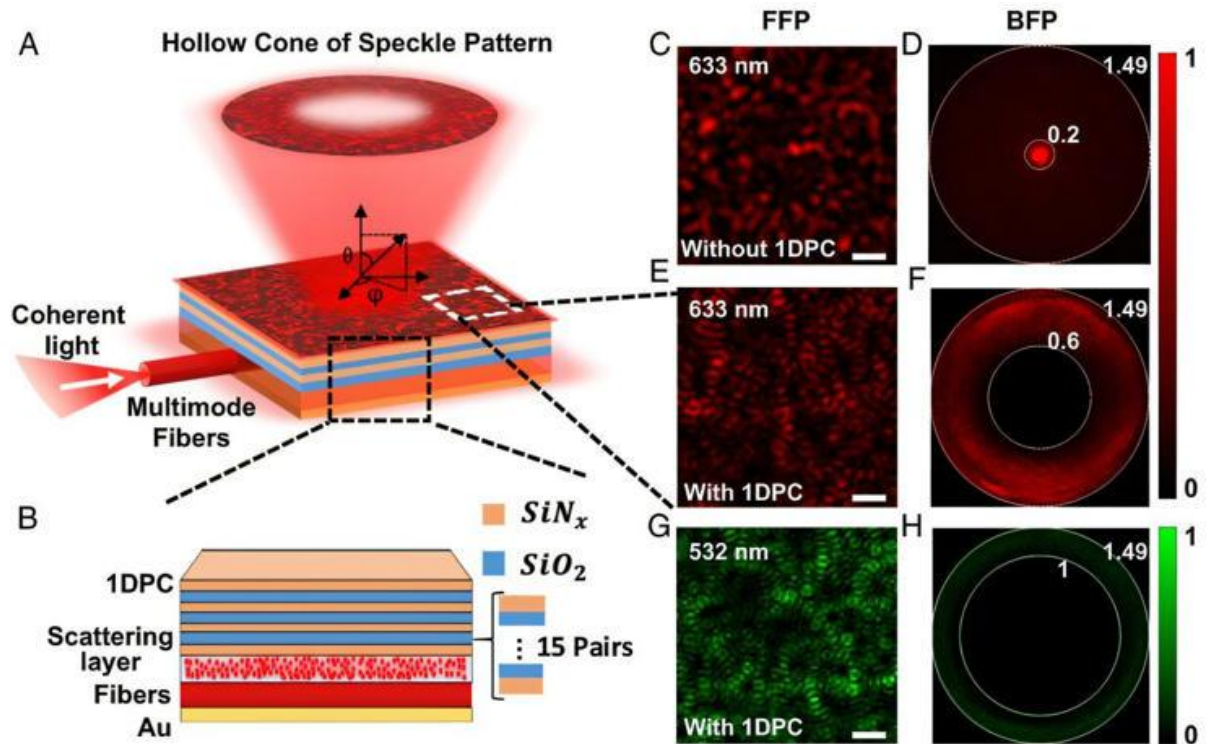
Moving forward, Jayan will test her synthesis process at a larger scale. In partnership with an aerospace materials manufacturer, her team will integrate MXene into test panels for radiation testing.

"We've developed a low-carbon process that significantly saves energy. If it can be scaled up now, more than ever before, we stand to create a critically needed and substantial environmental impact."

More information: H. Renuka et al, Energy-efficient synthesis of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene for electromagnetic shielding, *Materials Science in Semiconductor Processing* (2024). DOI: [10.1016/j.mssp.2024.108966](https://doi.org/10.1016/j.mssp.2024.108966)

Provided by Carnegie Mellon University Mechanical Engineering

Compact optical device achieves super-resolution imaging beyond the diffraction limit



Schematic of the planar device for producing dark-field speckle patterns. (Image from USTC). Credit: Douguo Zhang et al.

Researchers from the University of Science and Technology of China (USTC) have unveiled a planar optical device that significantly enhances the capabilities of dark-field microscopy, achieving super-resolution imaging beyond the diffraction limit. The work was led by Prof. Zhang Douguo and has been published in [the *Proceedings of the National Academy of Sciences*](#).

Dark-field microscopy is a powerful technique used to visualize unstained samples by illuminating them with light at oblique angles, resulting in high-contrast images of weakly scattering objects. However, traditional dark-field microscopy is limited by the diffraction barrier and often requires complex, bulky setups with precise alignment. Super-resolution imaging techniques, which can overcome this barrier, are typically expensive and difficult to operate. The need for a simpler, more accessible solution has long been a challenge in the field.

The study introduces a planar photonic device that integrates a scattering layer, a one-dimensional photonic crystal (1DPC), and a metallic film to generate dark-field speckle patterns. This compact device can be easily integrated into conventional microscopes, eliminating the need for complex optical systems or precise alignment.

The key innovation lies in the use of the 1DPC, which acts as a momentum-space filter to produce hollow cones of speckle patterns. These patterns serve as an illumination source, enabling high-contrast imaging with a 1.55-fold improvement in spatial resolution compared to traditional methods.

The researchers demonstrated the device's capabilities by imaging various samples, including polystyrene beads, nanowires, and biological specimens. Using a Blind-SIM reconstruction algorithm, they successfully resolved adjacent beads with a center-to-center distance as small as 340 nm, which is beyond the diffraction limit. The device also supports optical surface imaging by generating evanescent speckles when the incident wavelength is tuned, further expanding its applications.

The experimental setup involved a standard upright microscope with a X40 objective lens (NA 0.6) and a coherent laser source coupled into multimode fibers. The speckle patterns were dynamically changed by vibrating the fibers, allowing the capture of multiple frames for image reconstruction. The results showed that the proposed technique not only enhances resolution but also maintains high contrast, even for large field-of-view imaging.

This research represents a significant leap forward in microscopy technology. The compact planar device offers a practical and accessible solution for super-resolution imaging, making high-contrast, label-free microscopy available to a broader range of researchers and clinicians. By simplifying the setup and eliminating the need for complex alignment, this innovation could democratize access to advanced imaging techniques.

More information: Zetao Fan et al, Planar device-enabled speckle illumination for dark-field label-free imaging beyond the diffraction limit, *Proceedings of the National Academy of Sciences* (2025). DOI: [10.1073/pnas.2423223122](https://doi.org/10.1073/pnas.2423223122)

Provided by University of Science and Technology of China

NASA researchers battle biofilm in space



The biofilm mitigation research team at NASA's Marshall Space Flight Center assembled its own test stand to undertake a multi-month assessment of a variety of natural and chemical compounds and strategies for eradicating biofilm accretion caused by bacteria and fungi in the wastewater tank assembly on the International Space Station. Testing will help NASA extend the lifecycle of water reclamation and recycling hardware and ensure astronauts can sustain clean, healthy water supplies on long-duration missions in space and on other worlds. Credit: NASA/Eric Beitle© Provided by Phys.org

A small group of scientists on the biofilm mitigation team at NASA's Marshall Space Center in Huntsville, Alabama, study solutions to combat fast-growing colonies of bacteria or fungi, known as biofilm, for future space missions.

Biofilm occurs when a cluster of bacteria or fungi generates a slimy matrix of "extracellular polymeric substances" to protect itself from adverse environmental factors. Biofilm can be found nearly anywhere, from the gray-green scum floating on stagnant pond water to the pinkish ring of residue in a dirty bathtub.

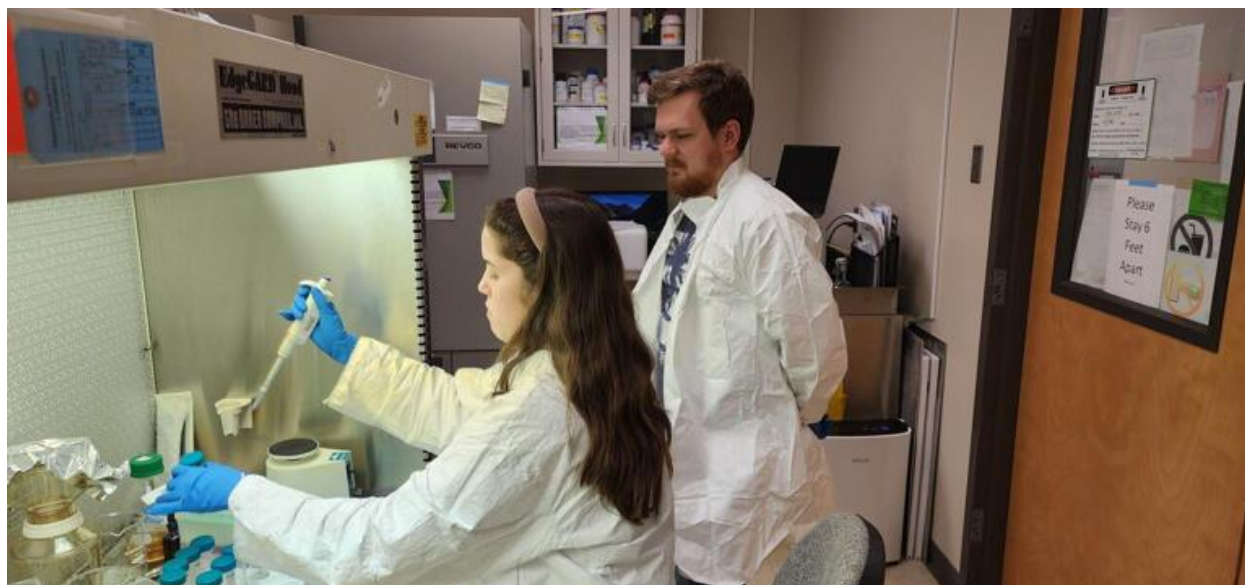
For medical, food production, and wastewater processing industries, biofilm is often a costly issue. But offworld, biofilm proves to be even more resilient.

"Bacteria shrug off many of the challenges humans deal with in space, including microgravity, pressure changes, ultraviolet light, nutrient levels, even radiation," said Yo-Ann Velez-Justiniano, a microbiologist and environmental control systems engineer at Marshall.

"Biofilm is icky, sticky—and hard to kill," said Liezel Koellner, a chemical engineer and NASA Pathways intern from North Carolina State University in Raleigh.

Koellner used sophisticated epifluorescence microscopy, 3D visualizations of 2D images captured at different focal planes, to fine-tune the team's studies.

Keenly aware of the potential hurdles biofilm could pose in future Artemis-era spacecraft and lunar habitats, NASA tasked engineers and chemists at Marshall to study mitigation techniques. Marshall built and maintains the International Space Station's ECLSS (Environment Control and Life Support System) and is developing next-generation air and water reclamation and recycling technologies, including the system's wastewater tank assembly.



Yo-Ann Velez-Justiniano, left, and Connor Murphy, right, both Environmental Control and Life Support Systems engineers at NASA's Marshall Space Flight Center in Huntsville, Alabama, prepare slides for study of cultured bacterial biofilm in the center's test facility. Credit: NASA/Eric Beitle© Provided by Phys.org

"The wastewater tank is 'upstream' from most of our built-in water purification methods. Because it's a wastewater feed tank, bacteria and fungus grow well there, generating enough biofilm to clog flow paths and pipes along the route," said Eric Beitle, ECLSS test engineer at Marshall.

To date, the solution has been to pull and replace old hardware once parts become choked with biofilm. But engineers want to avoid the need for such tactics.

"Even with the ability to 3D-print spare parts on the moon or Mars, it makes sense to find strategies that prevent biofilm buildup in the first place," said Velez-Justiniano.

The team took the first step in June 2023 by publishing the [complete genome sequence](#) of several strains of bacteria isolated from the space station's water reclamation system, all of which cultivate biofilm formation.

They next designed a test stand simulating conditions in the wastewater tank about 250 miles overhead, which permits simultaneous study of multiple mitigation options. The rig housed eight Centers for Disease Control and Prevention biofilm reactors—cylindrical devices roughly the size of a runner's water bottle—each 1/60th the size of the actual tank.

Each bioreactor holds up to 21 unique test samples on slides, bathed continuously in a flow of real or ersatz wastewater, timed and measured by the automated system, and closely monitored by the team. Because of the compact bioreactor size, the test stand required 2.1 gallons of ersatz flow per week, continuously trickling 0.1 milliliters per minute into each of the eight bioreactors.

"Essentially, we built a collection of tiny systems that all had to permit minute changes to temperature and pressure, maintain a sterile environment, provide autoclave functionality, and run in harmony for weeks at a time with minimal human intervention," said Beitle. "One phase of the test series ran nonstop for 65 days, and another lasted 77 days. It was a unique challenge from an engineering perspective."

Different surface mitigation strategies, upstream counteragents, antimicrobial coatings, and temperature levels were introduced in each bioreactor. One promising test involved duckweed, a plant already recognized as a [natural water purification system](#) and for its ability to capture toxins and control wastewater odor. By devouring nutrients upstream of the bioreactor, the duckweed denied the bacteria what it needs to thrive, reducing biofilm growth by up to 99.9%.

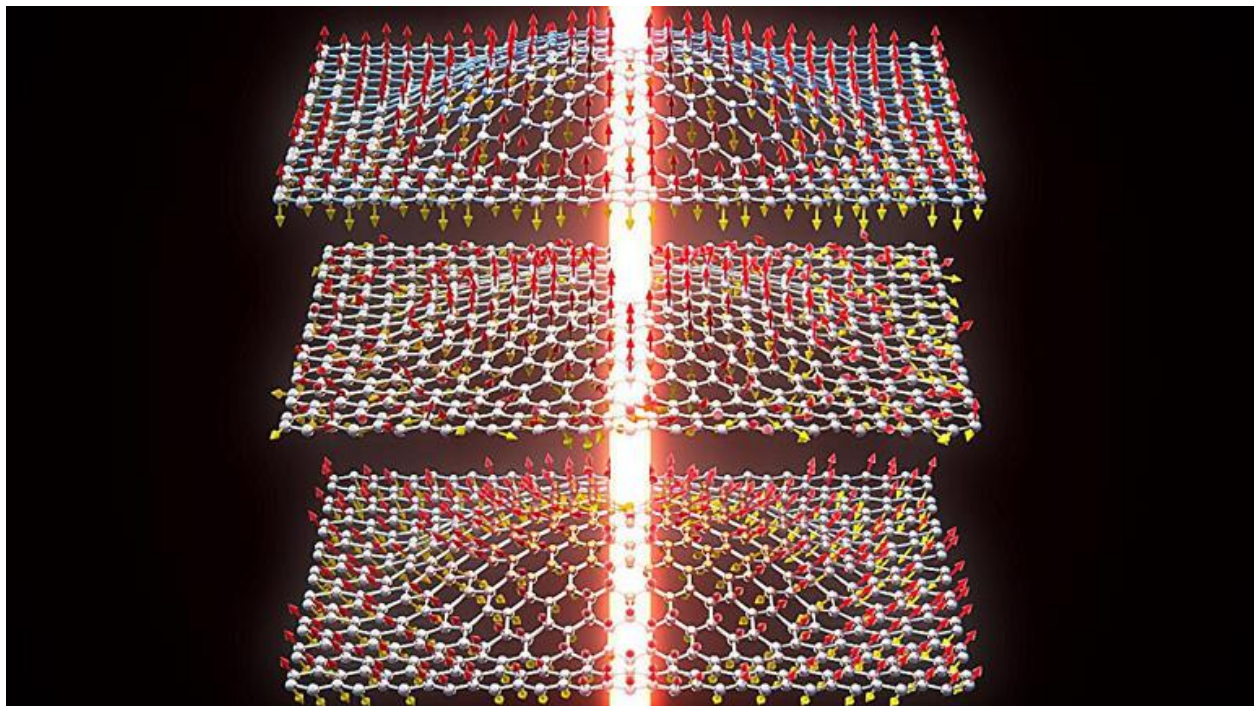
Over the course of the three-month testing period, teams removed samples from each bioreactor at regular intervals and prepared for study under a microscope to make a detailed count of the biofilm colony-forming units on each plate.

"Bacteria and fungi are smart," said Velez-Justiniano. "They adapt. We recognize that it is going to take a mix of effective biofilm mitigation methods to overcome this challenge."

Biofilm poses as an obstacle to long-duration spaceflight and extended missions on other worlds where replacement parts may be costly or difficult to obtain. The biofilm mitigation team continues to assess [and publish](#) findings, alongside academic and industry partners, and will further their research with a full-scale tank experiment at Marshall. They hope to progress to flight tests, experimenting with various mitigation methods in real microgravity conditions in orbit to find solutions to keep surfaces clean, water potable, and future explorers healthy.

Provided by NASA

Decoding nanomaterial phase transitions with tiny drums



An illustration of nanodrums made of FePS_3 , which is just a few atoms thick. Credit: Farbod Alijani, associate professor at the TU Delft Faculty of Mechanical Engineering

When water freezes into ice or boils into vapor, its properties change dramatically at specific temperatures. These so-called phase transitions are fundamental to understanding materials. But how do such transitions behave in nanomaterials?

In [*Nature Communications*](#), a team of scientists led by TU Delft (The Netherlands) present new insights into the complex nature of phase transitions in magnetic nanomaterials. Their findings reveal the coupling between magnetic and mechanical properties, paving the way for ultra-sensitive sensors.

The scientists from TU Delft, together with colleagues from the University of Valencia and the National University of Singapore, studied the 2D nanomaterial FePS₃, which is just a few atoms thick. For the first time, they developed a method to gain deeper insights into the highly complex phase transitions of such materials.

By using tiny, suspended membranes of FePS₃, the team vibrated the material at high amplitudes while sweeping the temperature. This revealed how the material's vibrations change near its phase transition temperature and, with that, its magnetic properties.

"Imagine a drum with a magnetic structure, where the laser light acts as the drumstick—continuously making it vibrate while its rhythm subtly shifts with changing temperature," explains Farbod Alijani, associate professor at the TU Delft Faculty of Mechanical Engineering.

"While warm, this magnetic drum is loose, and its magnetic spins, which are natural turns in particles that make them act like small magnets, are in a disordered phase. But once cold, the drum tightens up, with the spins snapping into an orderly pattern. Now, imagine that while drumming, you slowly change the temperature from warm to cold.

"As you do, you notice not only when the drum starts to feel different but also that this change isn't smooth (linear)—it unfolds in an intricate and irregular (nonlinear) manner, affecting its mechanical properties."

Phase transition temperature

The researchers essentially measured this nonlinear change during the phase transition. By using a nanoscale drum, they could detect the temperature at which this sudden transformation occurs and study how the drum's mechanical behavior changes in detail. "We pinpointed the phase transition temperature at around -160°C," says Makars Šiškins, whose Ph.D. work inspired this study.

"Additionally, we found that the changes in the mechanical response driven by the temperature shifts are directly coupled to the material's magnetic and elastic properties."

Ultra-sensitive sensors

These membranes are exceptionally sensitive to both internal and external forces. Šiškins adds, "This sensitivity positions them as ideal candidates for sensors capable of detecting even very small environmental changes or internal stresses in the material itself."

The team plans to apply this methodology to unveil the secrets of phase transitions in other nanomaterials.

Co-author Herre van der Zant said, "In our lab, we will investigate whether we can detect so-called spin waves with the nanodrum. You can think of spin waves as carriers of information in a magnetic material, much like electrons are for conductive materials."

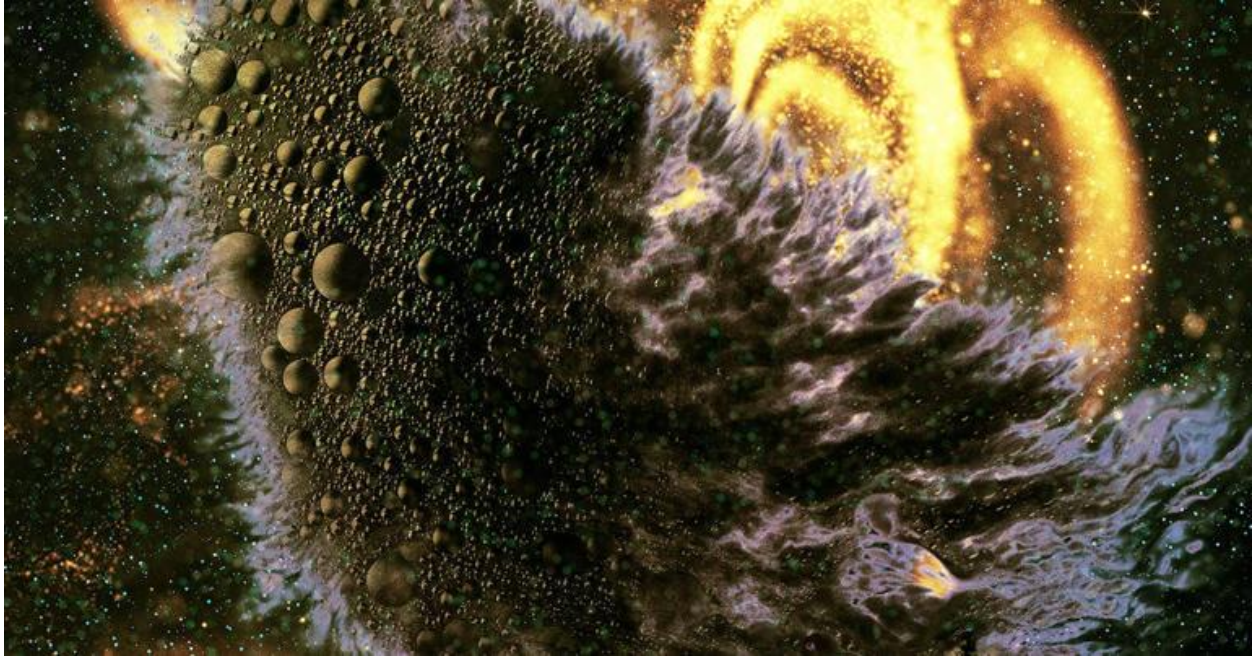
Alijani will focus on translating these findings into practical applications, such as improving sensor performance.

"Understanding these nonlinear processes lays the basis for innovative nanomechanical devices, including ultra-sensitive sensors," he notes.

More information: Makars Šiškins et al, Nonlinear dynamics and magneto-elasticity of nanodrums near the phase transition, *Nature Communications* (2025). DOI: [10.1038/s41467-025-57317-4](https://doi.org/10.1038/s41467-025-57317-4)

Provided by Delft University of Technology

Scientists Find Evidence of a New Form of Dark Matter Swirling at Center of Our Galaxy



Recent research proposes a new form of dark matter that may actually be lighter in mass than other dark matter candidates.

There's a new twist in the hunt for dark matter, the invisible substance believed to make up 85 percent of all the mass in the universe: it may actually be way lighter.

In a [study](#) published in the journal *Physical Review Letters*, an international team of researchers propose a new form of the hypothetical substance that's lower in mass compared to other dark matter candidates, which could explain a mysterious phenomenon at the center of our Milky Way galaxy, in a region called the Central Molecular Zone (CMZ).

"At the center of our galaxy sit huge clouds of positively charged hydrogen, a mystery to scientists for decades because normally the gas is neutral," said study co-lead author Shyam Balaji at King's College London in a [statement](#) about the work. "So, what is supplying enough energy to knock the negatively charged electrons out of them?"

"The energy signatures radiating from this part of our galaxy suggest that there is a constant, roiling source of energy doing just that," Balaji added, "and our data says it might come from a much lighter form of dark matter than current models consider."

While scientists have extensive evidence that dark matter exists, determining what it is and where it resides remains one of the biggest questions in physics, with theories ranging from [parallel universes](#) to [primordial black holes](#). But one of the original and still leading explanations for dark matter is that it comprises a type of nearly undetectable particles called Weakly Interacting Massive Particles, or WIMPs.

As the moniker suggests, WIMPs don't interact strongly with other particles, including light, but are massive enough that they would clump together in the way that astronomers have observed galaxies and other cosmic structures do — which dark matter, through its gravitational influence, is hypothesized to [govern the shapes of from the shadows](#).

But perhaps there's more than one form of it that's less massive than WIMPs, as the researchers suggest. The thinking goes that in the extremely dense environment of the CMZ, these lighter dark matter particles would be constantly colliding and destroying each other upon impact, and subsequently releasing energy. This is a process known as annihilation, and the energy it liberates would then ionize nearby hydrogen gas.

Conversely, the researchers argue that WIMPs and other proposed dark matter particles like axions don't undergo enough annihilation to ionize hydrogen to the extent observed in the CMZ. Nor can the phenomenon be explained by cosmic rays, powerful beams of energetic particles that zip throughout the universe at nearly the speed of light.

"The biggest problem this model helps solve is an excess of ionization in the CMZ," Balaji [told Space.com](#). "Cosmic rays, the usual culprits for ionizing gas, don't seem to be strong enough to explain the high levels of ionization we observe."

There's still a lot of work to be done before the idea gains more steam. But if the theory holds true, Balaji says, we'd have an "entirely new way" to study dark

matter rather than just its gravitational influence; now, we could observe the ionization it causes in gases.

"Dark matter remains one of the biggest mysteries in physics, and this work shows that we may have been overlooking its subtle chemical effects on the cosmos," Balaji told *Space.com*.

ZOOMED ALL THE WAY OUT MAR 9,

Scientists Intrigued by Galactic Structure That's 1.4 Billion Light-Years Wide

Could this really be the largest structure we've ever measured?

[/ Off World/ Dark Matter/ Milky Way/ Superstructures](#)



Scientists say they've uncovered the "[largest known galactic structure](#)" — a cosmic monster that spans a mind-boggling 1.4 *billion* light-years, which is [around 14,000 times the diameter](#) of our own Milky Way galaxy.

The team, led by scientists from the Max Planck Institute for Physics, made the discovery after analyzing data as part of the ROSAT X-ray satellite sky survey.

They found that the structure — dubbed "Quipu" after strings with knots used by the Incas for bookkeeping — stretched across huge swathes of the night sky. The team believes it's largely composed of dark matter, the invisible substance believed to account for 85 percent of all mass in the universe.

The finding could have considerable implications for our understanding of the larger structures lurking in the universe and how to accurately map them.

"If you look at the distribution of the galaxy clusters in the sky in a spherical shell with a distance of 416 to 826 million light-years, you immediately notice a huge structure that stretches from high northern latitudes to almost the southern end of the sky," said project lead and Max Planck Institute associate professor Hans Böhringer in a [statement](#).

Quipu's immense length appears to break the previous record set by the "Sloan Great Wall," which stretches around 1.1 billion light years in a much more distant part of the universe.

But as [Live Science points out](#), there might be even larger structures still, such as the Hercules Corona-Borealis Great Wall, a superstructure that spans an estimated 10 billion light-years across, another 10 billion light-years from Earth. Whether it indeed exists, however, remains a [topic of contention](#) among scientists.

For their latest [study](#), accepted for publication in the journal *Astronomy and Astrophysics*, the Max Planck team analyzed an expansive catalogue of galaxy clusters, which was created using data collected by the Max Planck Institute for extraterrestrial Physics' ROSAT X-ray satellite in 1990.

Apart from Quipu, the team also discovered three other superstructures they're calling the Serpens-Corona Borealis, the Hercules, and the Sculptor-Pegasus.

In addition to Quipu and the Shapley supercluster, a concentration of galaxies in our nearby universe, the five structures contain an estimated 25 percent of all the matter in the observable universe, according to the researchers, or 13 percent of its volume.

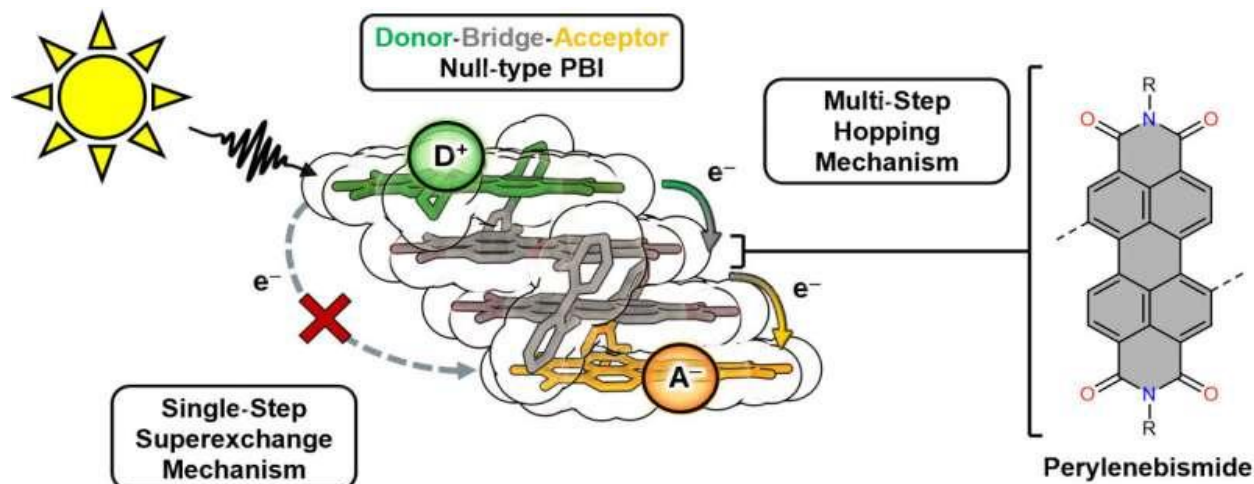
The team argued in its paper that the findings could be "important for astrophysical research," such as the "study of the environmental dependence of galaxy evolution as well as for precision tests of cosmological models."The researchers also suggest these superstructures won't stick around forever.

"In the future cosmic evolution, these superstructures are bound to break up into several collapsing units," they concluded in their paper. "They are thus transient configurations. But at present they are special physical entities with characteristic properties and special cosmic environments deserving special attention."

MARCH 14, 2025

Artificial photosynthesis: Chemists develop dye stack that mimics plant energy conversion

by [University of Würzburg](#)



What the stack of four dyes synthesized in Würzburg looks like. It represents a further step towards artificial photosynthesis because it absorbs light energy and transfers it quickly and efficiently in the stack. Credit: Leander Ernst / University of Würzburg

With artificial photosynthesis, mankind could utilize solar energy to bind carbon dioxide and produce hydrogen. Chemists from Würzburg and Seoul have taken this one step further: They have synthesized a stack of dyes that comes very close to the photosynthetic apparatus of plants. It absorbs light energy, uses it to separate charge carriers and transfers them quickly and efficiently in the stack.

Photosynthesis is a marvelous process: plants use it to produce [sugar molecules](#) and oxygen from the simple starting materials carbon dioxide and water. They draw the energy they need for this complex process from sunlight.

If humans could imitate photosynthesis, it would have many advantages. The free energy from the sun could be used to remove carbon dioxide from the atmosphere and use it to build carbohydrates and other useful substances. It would also be possible to produce hydrogen, as photosynthesis splits water into its components oxygen and hydrogen.

Photosynthesis: A complex process with many participants

So it's no wonder that many researchers are working on artificial photosynthesis. This is not easy, because photosynthesis is an extremely complex process: it takes place in the cells of

plants in many individual steps and involves numerous dyes, proteins and other molecules. However, science is constantly making new advances.

One of the leading researchers in the field of artificial photosynthesis is chemist Professor Frank Würthner from Julius-Maximilians-Universität (JMU) Würzburg in Bavaria, Germany. His team has now succeeded in imitating one of the first steps of natural photosynthesis with a sophisticated arrangement of artificial dyes and analyzing it more precisely.

The results were obtained in collaboration with Professor Dongho Kim's group at Yonsei University in Seoul (Korea). They have been published in *Nature Chemistry*.

The researchers have succeeded in synthesizing a stack of dyes that is very similar to the photosynthetic apparatus in plant cells—it absorbs light energy at one end, uses it to separate [charge carriers](#) and transfers them step by step to the other end via the transport of electrons. The structure consists of four stacked dye molecules from the perylene bisimide class.

"We can specifically trigger the charge transport in this structure with light and have analyzed it in detail. It is efficient and fast. This is an important step towards the development of artificial photosynthesis," says JMU Ph.D. student Leander Ernst, who synthesized the stacked structure.

Next, the JMU research team wants to expand the nanosystem of stacked dye molecules from four to more components—with the aim of ultimately creating a kind of supramolecular wire that absorbs light energy and transports it quickly and efficiently over longer distances. This would be a further step towards novel photofunctional materials that can be used for [artificial photosynthesis](#).

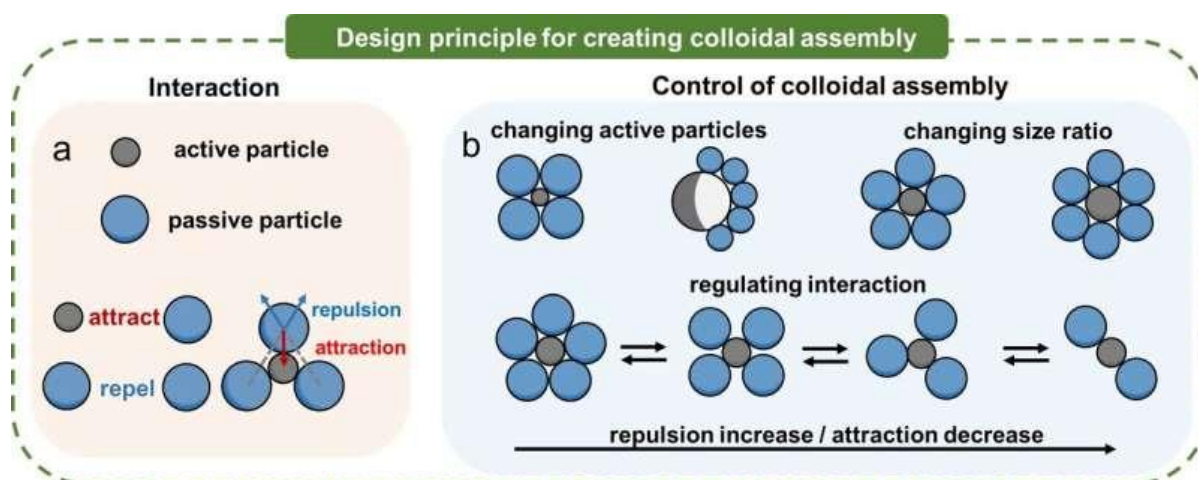
More information: Photoinduced stepwise charge hopping in π -stacked perylene bisimide donor-bridge-acceptor arrays., *Nature Chemistry* (2025). DOI: [10.1038/s41557-025-01770-7](https://doi.org/10.1038/s41557-025-01770-7)

Journal information: [Nature Chemistry](#)
Provided by [University of Würzburg](#)

MARCH 14, 2025

New approach to reconfigurable colloidal assemblies paves way for adaptive smart materials

by Research



Schematic illustration of designing principle for creating reconfigurable colloidal assembly. Credit: 2024 Xi Chen et al.

Colloidal self-assembly is a process where colloidal particles spontaneously organize into ordered structures under specific conditions. Colloidal self-assembly serves as a foundation for designing materials like optoelectronic devices and sensors. One of the most intriguing frontiers in colloidal self-assembly is the development of active colloidal assemblies, which exhibit dynamic behavior and can adapt to external stimuli.

Active colloids—[colloidal particles](#) that convert external energy into autonomous motion—are a typical assembled unit for active colloidal assemblies. Although these [active particles](#) can demonstrate fascinating self-assembly behaviors, controlling these behaviors with precision and in [real-time](#) remains a major challenge. The ability to adjust and manipulate colloidal assemblies dynamically is key to creating adaptive, reconfigurable functional materials.

A research project led by Prof. Wei Wang from Harbin Institute of Technology (Shenzhen) and Dr. Xi Chen from Chengdu University of Technology has introduced a novel strategy for constructing active colloidal assemblies. This work, [published](#) in *Research*, provides fresh insights into the design of smart materials with real-time, on-demand reconfiguration.

In their recent study, the research group took a step forward by combining chemical reactions and [electric polarization](#) to achieve reversible assembly and in situ regulation of assembled structures. The assembled unit includes active and passive colloidal particles, where the active particles react with chemicals in the solution to generate a chemical gradient. This gradient induces phoresis and osmosis, which attract surrounding passive particles to form colloidal clusters.

Furthermore, an alternating electric field is employed to polarize the passive particles, creating dipole-dipole repulsive forces that help assemble the particles into a specific configuration. By fine-tuning the chemical and electric fields, the group achieved [precise control](#) over the attraction and repulsion between particles, enabling the in situ regulation of structures of colloidal assemblies.

Looking ahead, the team envisions applying these strategies to design a wide array of colloidal materials capable of dynamically altering their structure and function. This marks a step toward developing adaptive materials with diverse applications, ranging from responsive sensors to self-healing systems and reconfigurable devices.

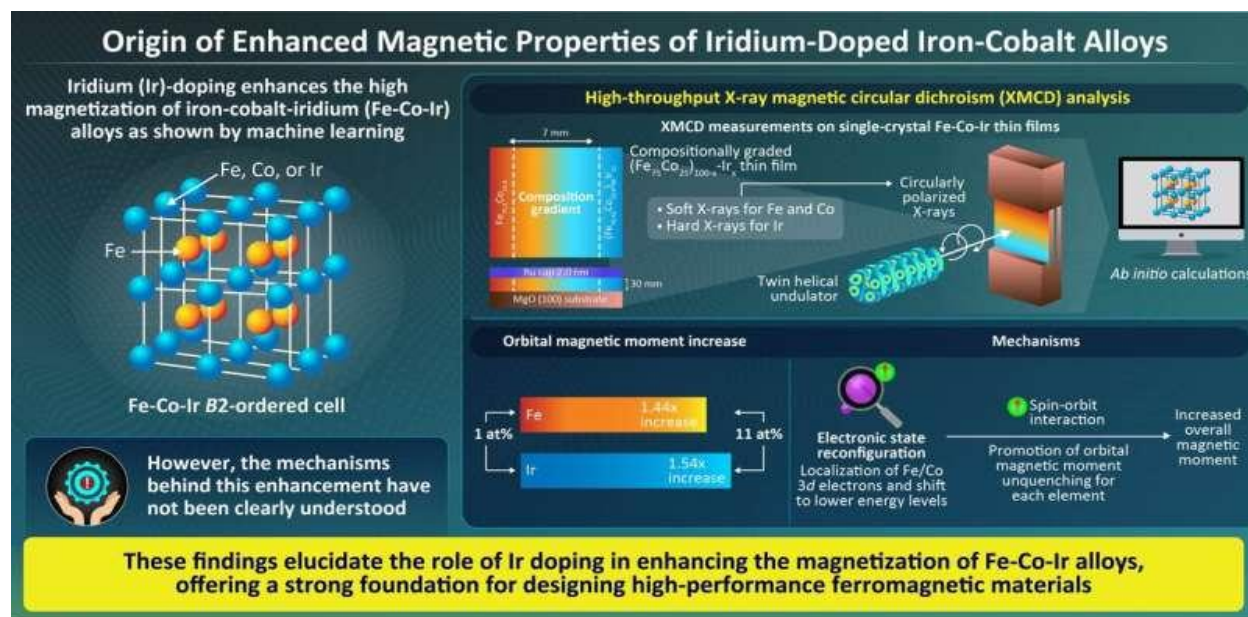
More information: Xi Chen et al, Reconfigurable Assembly of Planar Colloidal Molecules via Chemical Reaction and Electric Polarization, *Research* (2024). DOI: [10.34133/research.0490](https://doi.org/10.34133/research.0490)

Journal information: [Research](#)
Provided by Research

MARCH 14, 2025

Understanding the origin of magnetic moment enhancement in novel alloys

by [Tokyo University of Science](#)



Uncovering the origin of magnetic moment enhancement in Fe-Co-Ir alloys via high-throughput XMCD
Yamazaki et al. (2025) | *Physical Review Materials* | DOI: 10.1103/PhysRevMaterials.9.034408

Addition of iridium leads to increased electron localization and stronger spin-orbit coupling between 3d electrons of iron and cobalt and 5d electrons of iridium, significantly enhancing the magnetic moments. Credit: Takahiro Yamazaki / Tokyo University of Science, Japan

Magnetic materials have become indispensable to various technologies that support our modern society, such as data storage devices, electric motors, and magnetic sensors.

High-magnetization ferromagnets are especially important for the development of next-generation spintronics, sensors, and high-density data storage technologies. Among these materials, the iron-cobalt (Fe-Co) alloy is widely used due to its strong magnetic properties. However, there is a limit to how much their performance can be improved, necessitating a new approach.

Some earlier studies have shown that epitaxially grown films made up of Fe-Co alloys doped with heavier elements exhibit remarkably high magnetization. Moreover, recent advances in computational techniques, such as the integration of machine learning with *ab initio* calculations, have significantly accelerated the search for new material compositions.

Iridium (Ir)-doped Fe-Co alloy (Fe-Co-Ir) is one such material, identified through machine learning, that has been shown to possess large magnetic moments, representing the strength and orientation of magnetic fields, exceeding even those of conventional Fe-Co alloys.

However, identifying the source of these enhanced magnetic properties has been a significant challenge. In particular, the effect of Ir-doping on the magnetic properties of Fe-Co alloys remains poorly understood.

To overcome this challenge, a research team led by Assistant Professor Takahiro Yamazaki from the Department of Material Science and Technology at Tokyo University of Science (TUS) implemented a novel approach. They utilized high-throughput X-ray magnetic circular dichroism (XMCD) on compositionally graded single-crystal thin films.

Their study is published in the journal [*Physical Review Materials*](#).

Asst. Prof. Yamazaki explains, "Unlike previous studies which used polycrystalline thin films, we utilized compositionally graded single-crystal Fe-Co-Ir thin films, offering a more controlled environment for probing the mechanisms behind their enhanced magnetic properties. Furthermore, using the world's largest synchrotron radiation facility, SPring-8, we performed XMCD measurements to systematically investigate their magnetic properties."

The team also included Mr. Takahiro Kawasaki and Prof. Masato Kotsugi from TUS, Dr. Yuma Iwasaki and Dr. Yuya Sakuraba of the National Institute of Materials Science (NIMS), Dr. Naomi Kawamura of the Japan Synchrotron Radiation Research Institute, and Prof. Takuo Ohkochi of the University of Hyogo.

Using the advanced technology at NIMS, the team first fabricated compositionally graded thin films in which the amount of Ir doping increased linearly from one end, consisting of pure Fe-Co alloy, to the other end, consisting of Fe-Co alloy with 11 at% Ir.

The team then performed X-ray magnetic circular dichroism (XMCD) measurements on these films, using both soft and hard X-rays.

Soft X-rays have lower energy than hard X-rays and are therefore better suited for studying lighter metals like Fe and Co, while hard X-rays are more suitable for studying heavy metals like Ir. This approach provided a more detailed understanding of each element's contribution to the material's magnetic behavior.

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The results revealed significant improvements in the magnetic moments of both Fe and Ir due to Ir doping. The magnetic moment of Fe increased by 1.44-fold and Ir by 1.54-fold at 11 at% Ir concentration compared to that at 1 at% Ir concentration. To further validate and understand the origin of these enhancements, the team conducted ab initio calculations.

Fe and Co belong to a class of elements known as 3d transition metals, where their outermost electrons occupy the 3d atomic orbitals, while Ir belongs to 5d transition metals.

The theoretical analysis supported the experimental findings and revealed that Ir addition leads to increased electron localization and stronger spin-orbit coupling between 3d electrons of Fe and Co and 5d electrons of Ir. This interaction results in enhanced magnetic moments, primarily through increased contributions of orbital magnetic moments.

"The findings highlight the critical role of Ir in enhancing the magnetic properties of Fe-Co-Ir alloys," notes Asst. Prof. Yamazaki.

"Our efficient, high-throughput materials evaluation workflow and theoretical analysis method will serve as a foundation for designing high-performance ferromagnetic materials. This could lead to the development of highly efficient [electric motors](#) and next-generation high-density data storage devices, which could ultimately reduce environmental impact and contribute to a more sustainable society," he concludes.

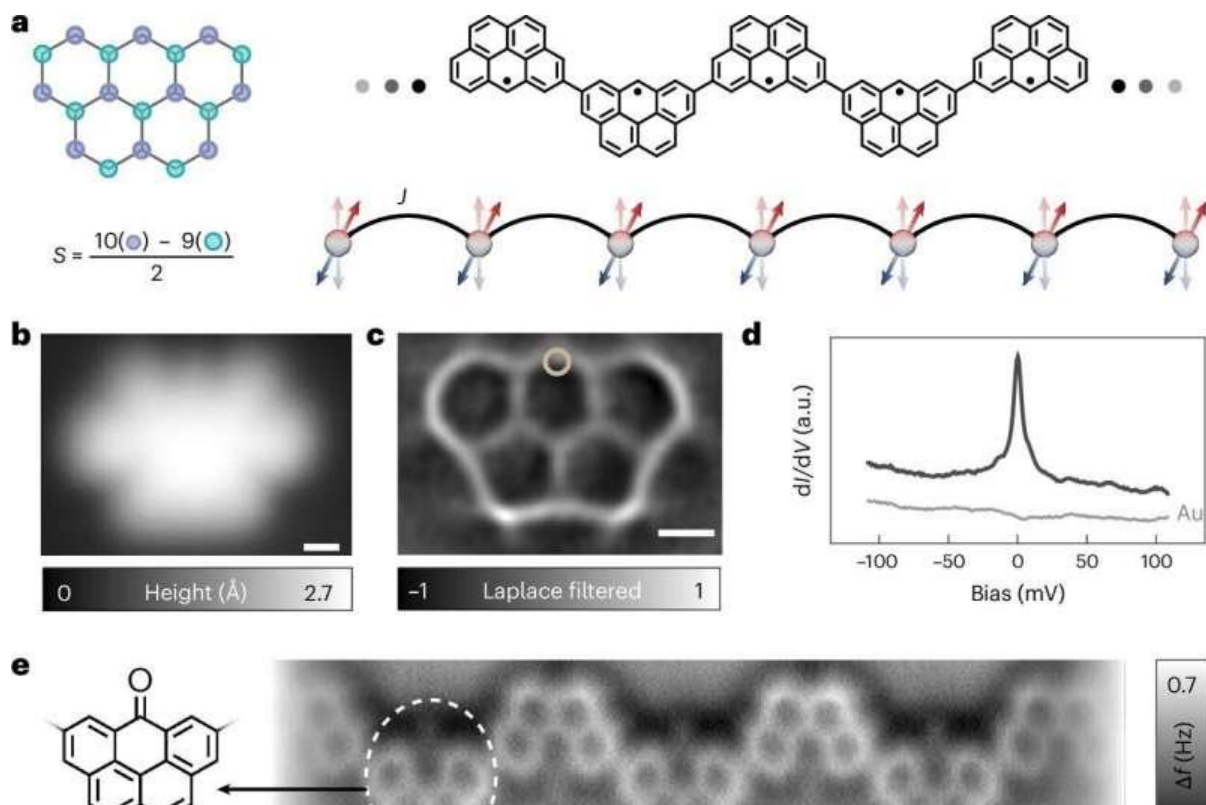
Also, Fe-Co alloy with Ir could help in designing efficient electronic devices that can be made commercially available, with essential testing phases. This alloy has potential implementation in developing cost-effective data storage devices.

More information: Takahiro Yamazaki et al, Uncovering the origin of magnetic moment enhancement in Fe–Co–Ir alloys via high-throughput XMCD, *Physical Review Materials* (2025). DOI: [10.1103/PhysRevMaterials.9.034408](https://doi.org/10.1103/PhysRevMaterials.9.034408)
Provided by [Tokyo University of Science](#)

MARCH 14, 2025

Olympicene molecular chains create quantum spin systems with spintronics applications

by Katja Woldt, [Max Planck Institute of Microstructure Physics](#)



Fabrication of spin-1/2 Heisenberg chain using Olympicene. Credit: *Nature Materials* (2025). DOI: 10.1038/s41563-025-02166-1

In a new [publication](#) in *Nature Materials*, an international team of researchers has developed groundbreaking artificial chains of the iconic “olympicene” molecules to realize the antiferromagnetic (AF) spin- $\frac{1}{2}$ Heisenberg model, a flagship quantum spin model that has been the cornerstone of quantum magnetism, since the seminal work of Bethe, for almost a century now. This study makes nanographenes (NGs) an ideal platform for realizing and studying highly entangled quantum spin systems, with potential applications in insulator-based AF spintronics.

In one-dimensional quantum magnets, strong quantum fluctuations prevent spontaneous symmetry breaking, leading to the formation of quantum-disordered many-body states such as resonating valence bond states. Half-integer spin chains are expected to exhibit a gapless [excitation](#) spectrum in the thermal dynamic limit, with the elemental excitations

comprising at least two fractional spin- $\frac{1}{2}$ with well-defined energy-momentum relation, known as spinons.

In finite length, confinement effects introduce a quantization gap, which gradually approaches zero as the chain length increases ($L \rightarrow \infty$). Despite the theoretical appeal, the experimental realization of the isotropic spin- $\frac{1}{2}$ Heisenberg [model](#) faces significant challenges. Furthermore, the lack of access to well-defined finite chains hampers systematic studies on how spin excitations evolve with chain length and how even- and odd-numbered chains exhibit distinct behaviors.

Scientists from MPI Halle, TU Dresden, the International Iberian Nanotechnology Laboratory (INL), and the Swiss Federal Laboratories for Materials Science and Technology (EMPA) have covalently linked specifically designed open-shell nanographenes, known as Olympices, into chains on an Au(111) surface to establish an isotropic spin- $\frac{1}{2}$ Heisenberg chain.

They achieve unprecedented experimental control over such spin chains by characterizing and manipulating the spin degrees of freedom of individual chain spin sites using the tip of a scanning probe microscope. This approach allows precise, unit-by-unit tuning of the chain length, ranging from dimers to chains with up to 50 units.

Additionally, the spin excitations of these chains are probed using inelastic electron tunneling spectroscopy (IETS), complemented by high-level theoretical calculations. Importantly, the exchange interaction in this system is as large as 38 meV. The power-law decay of spin excitations with chain length indicates quasi-long-range spin-spin correlations, a characteristic feature of a gapless 1D spin liquid phase.

The longest chain with 50 units shows "V-shaped" excitation spectra, reflecting the closing of the excitation gap. Furthermore, the ground state of odd-numbered chains is a wave-packet of a one-spinon state, whose [amplitude modulation](#) across the chain is reflected in the zero bias IETS conductance.

This work demonstrates that theoretical models of quantum physics can be realized using NGs to experimentally test their predictions. It not only opens doors in quantum technologies based on NGs but also inspires us to picture other molecules for achieving different models. Additionally, another Heisenberg model has been experimentally achieved via NGs design in a study that is shortly to be published.

More information: Chenxiao Zhao et al, Spin excitations in nanographene-based antiferromagnetic spin- $\frac{1}{2}$ Heisenberg chains, *Nature Materials* (2025). DOI: [10.1038/s41563-025-02166-1](https://doi.org/10.1038/s41563-025-02166-1)

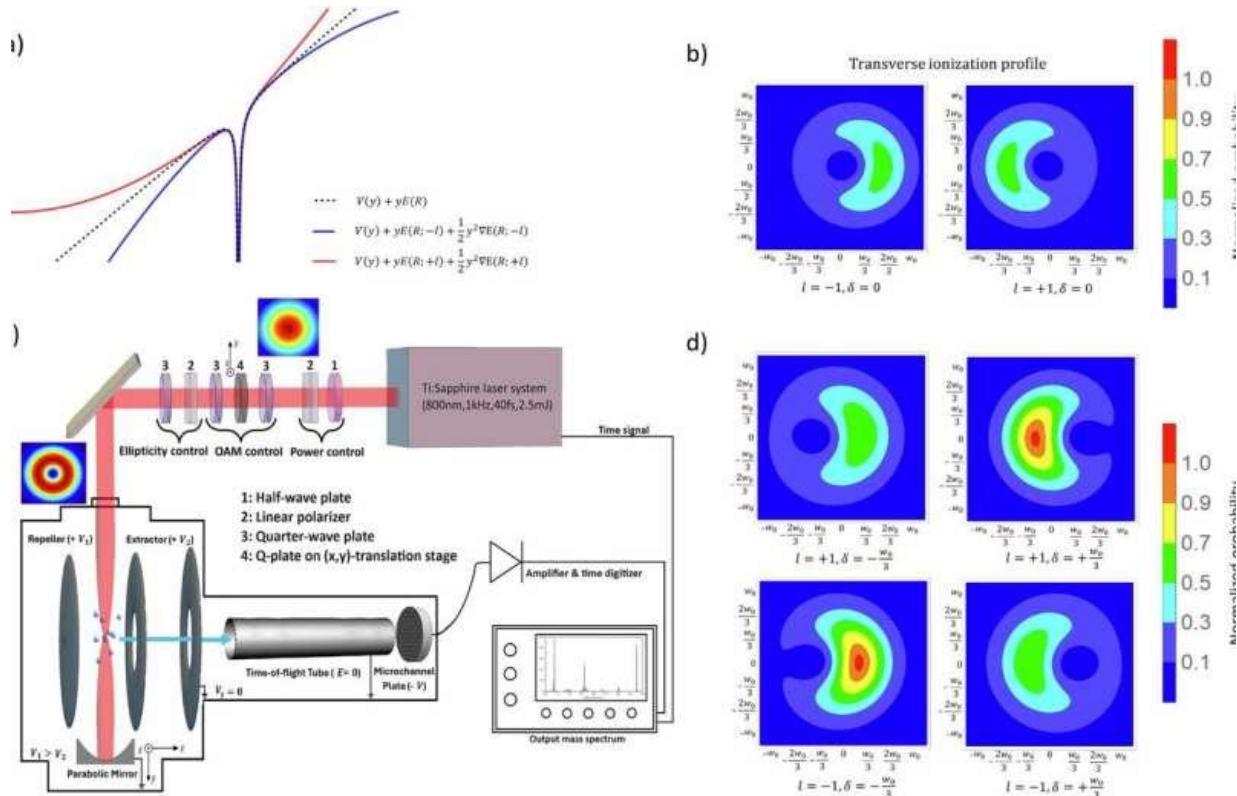
Journal information: [Nature Materials](#)

Provided by [Max Planck Institute of Microstructure Physics](#)

MARCH 14, 2025

Physicists use optical vortex beams to control atom ionization

by Bernard Rizk, [University of Ottawa](#)



OAM-dependent ionization in atoms. Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-025-57618-8

A team of researchers from the University of Ottawa has made significant strides in understanding the ionization of atoms and molecules, a fundamental process in physics that has implications for various fields including X-ray generation and plasma physics.

The research, titled "Orbital angular momentum control of strong-field ionization in atoms and molecules," is [published](#) in *Nature Communications*.

Think about atoms—the building blocks of everything around us. Sometimes, they lose their electrons and become charged particles (that's ionization). It happens in lightning, in plasma TVs, and even in the [northern lights](#). Until now, scientists thought they could only control this process in limited ways.

Led by Ravi Bhardwaj, Full Professor at uOttawa's Department of Physics, and Ph.D. student Jean-Luc Begin, in collaboration with Professors Ebrahim Karimi, Paul Corkum and

Thomas Brabec, the research introduces innovative methods to control ionization using specially structured [light beams](#).

Ionization is crucial in strong field physics and attosecond science, where it describes how electrons escape from their atomic bonds. Traditionally, it was understood that this process could not be manipulated beyond certain limits. However, this new study challenges that notion.

"We have demonstrated that by using optical vortex beams—light beams that carry [angular momentum](#)—we can precisely control how an electron is ejected from an atom," explains Professor Bhardwaj. "This discovery opens up new possibilities for enhancing technology in areas such as imaging and particle acceleration."

The research took place over two years at uOttawa's Advanced Research Complex. The team found that the handedness and properties of the optical vortex beams significantly affect ionization rates. By adjusting the position of a "null intensity region" within the beam, they achieved selective ionization, introducing a novel concept called optical dichroism.

This work builds upon foundational theories in the field and has the potential to revolutionize how scientists approach ionization. This isn't just for physics textbooks—it could lead to better [medical imaging](#), faster computers, and more efficient ways to study materials. It's especially promising for [quantum computing](#), where controlling individual particles is crucial.

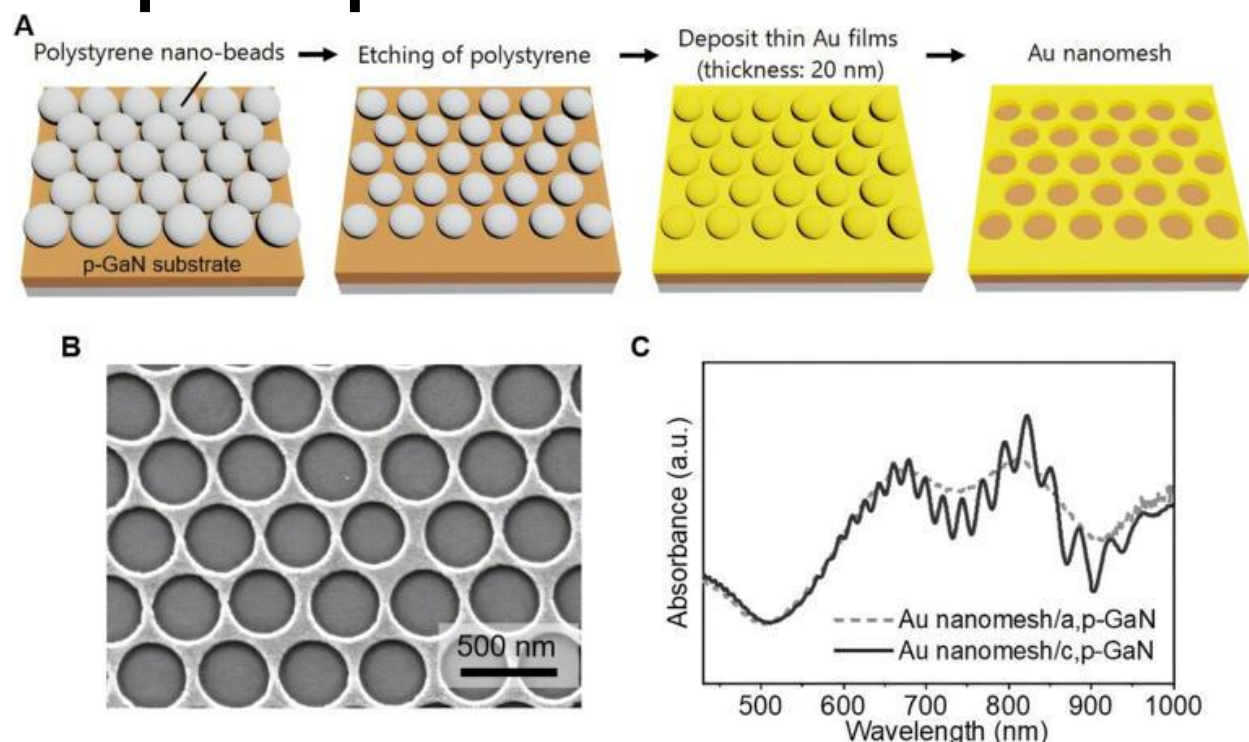
Professor Bhardwaj says, "Changing the way we think about how electrons are ejected has been challenging, but our research proves that using advanced laser technologies can lead to new discoveries that impact both science and technology."

More information: Jean-Luc Bégin et al, Orbital angular momentum control of strong-field ionization in atoms and molecules, *Nature Communications* (2025). DOI: [10.1038/s41467-025-57618-8](https://doi.org/10.1038/s41467-025-57618-8)

Journal information: [Nature Communications](#)

Provided by [University of Ottawa](#)

Advancing light-to-electricity energy conversion: New method extends lifespan of plasmonic hot holes



(A) Fabrication process of Au nanomesh, (B) Microscopic image of Au nanomesh, (C) Optical absorption spectrum of Au nanomesh-p-type GaN substrate. Credit: Science Advances (2025). DOI: 10.1126/sciadv.adu0086

When light interacts with metallic nanostructures, it instantaneously generates plasmonic hot carriers, which serve as key intermediates for converting optical energy into high-value energy sources such as electricity and chemical energy. Among these, hot holes play a crucial role in enhancing photoelectrochemical reactions. However, they thermally dissipate within picoseconds (trillionths of a second), making practical applications challenging.

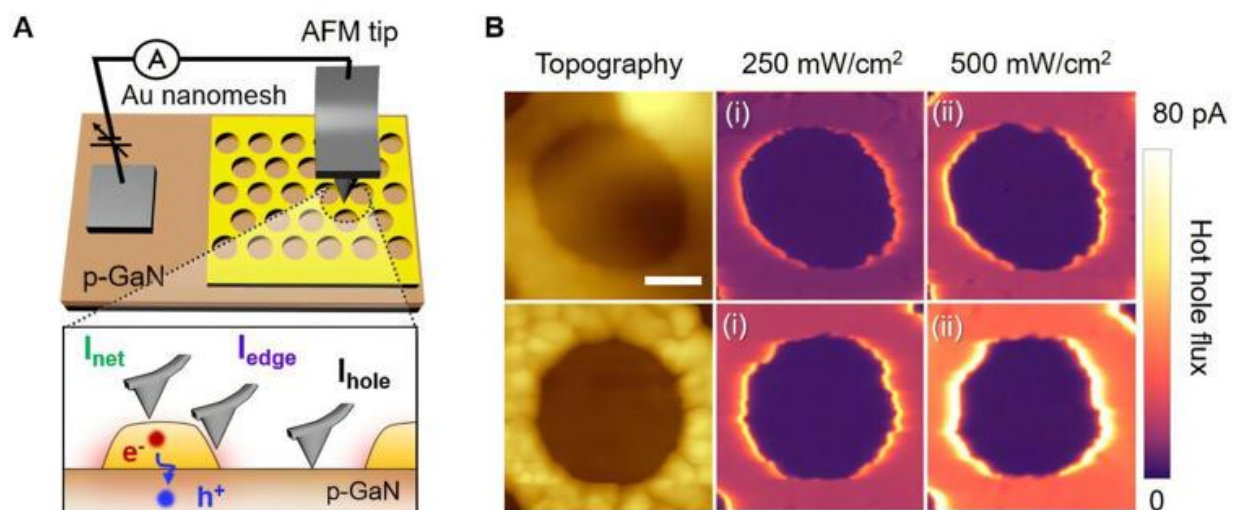
Now, a Korean research team has successfully developed a method for sustaining hot holes longer and amplifying their flow, accelerating the commercialization of next-generation, high-efficiency, light-to-energy conversion technologies.

The research team, led by Distinguished Professor Jeong Young Park from the Department of Chemistry at KAIST, in collaboration with Professor Moonsang Lee from the Department of Materials Science and Engineering at Inha University, has

successfully amplified the flow of hot holes and mapped local current distribution in real time, thereby elucidating the mechanism of photocurrent enhancement. The work is [published](#) in *Science Advances*.

The team designed a nanodiode structure by placing a metallic nanomesh on a specialized semiconductor substrate (p-type gallium nitride) to facilitate hot hole extraction at the surface. As a result, in gallium nitride substrates aligned with the hot hole extraction direction, the flow of hot holes was amplified by approximately two times compared to substrates aligned in other directions.

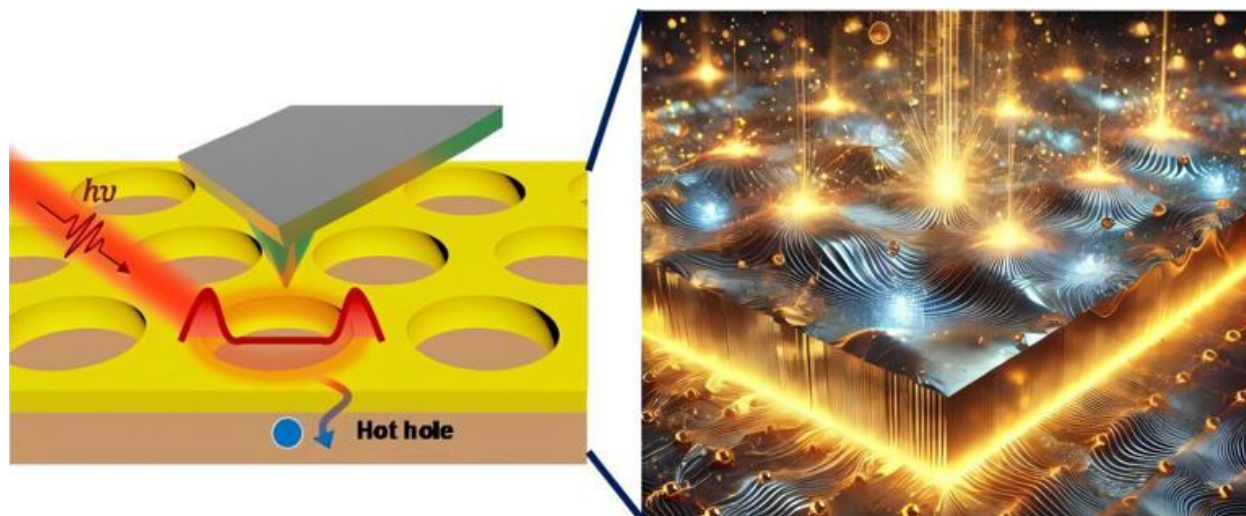
To fabricate the Au nanomesh, a polystyrene nano-bead monolayer assembly was first placed on a gallium nitride (p-GaN) substrate, and then the polystyrene nano-beads were etched to form a nanomesh template. Then, a 20 nm thick gold nano-film was deposited, and the etched polystyrene nano-beads were removed to realize the gold nano-mesh structure on the GaN substrate. The fabricated Au nanomesh exhibited strong light absorption in the visible range due to the plasmonic resonance effect.



(A) Schematic diagram of real-time hot-hole flux observation via atomic force microscopy. (B) Real-time images (left column) of the Au nanomesh on non-polarized gallium nitride (GaN) (upper row) and polarized GaN (lower row) substrates, and mapping of hot-hole flux detected in real time (middle and right columns). Credit: *Science Advances* (2025). DOI: 10.1126/sciadv.adu0086

Furthermore, using a photoconductive atomic force microscopy (pc-AFM)-based photocurrent mapping system, the researchers analyzed the flow of hot holes in real time at the nanometer scale (one hundred-thousandth the thickness of a human hair). They observed that hot hole activation was strongest at "hot spots,"

where light was locally concentrated on the gold nanomesh. However, by modifying the growth direction of the gallium nitride substrate, hot hole activation extended beyond the hot spots to other areas as well.



Conceptual diagram of controlling hot-hole using Au nanomesh. Credit: Science Advances (2025). DOI: 10.1126/sciadv.adu0086

Through this research, the team discovered an efficient method for converting light into electrical and chemical energy. This breakthrough is expected to significantly advance next-generation solar cells, photocatalysts, and hydrogen production technologies.

Professor Park stated, "For the first time, we have successfully controlled the flow of hot holes using a nanodiode technique. This innovation holds great potential for various optoelectronic devices and photocatalytic applications. For example, it could lead to groundbreaking advancements in solar energy conversion technologies, such as solar cells and hydrogen production.

"Additionally, the real-time analysis technology we developed can be applied to the development of ultra-miniaturized optoelectronic devices, including optical sensors and nanoscale semiconductor components."

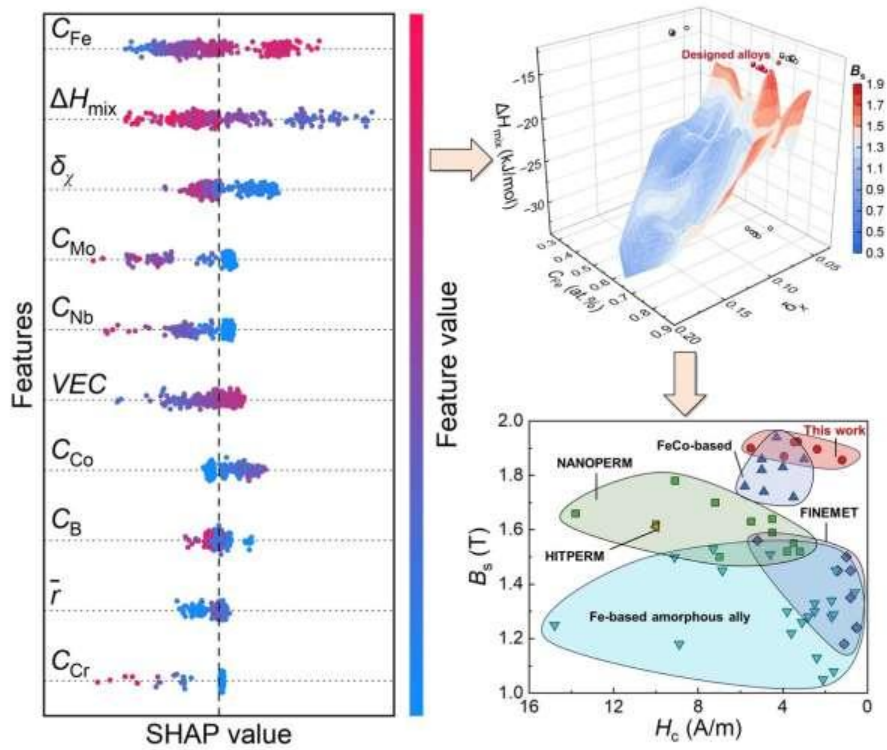
More information: Hyunhwa Lee et al, Reconfiguring hot-hole flux via polarity modulation of p-GaN in plasmonic Schottky architectures, *Science Advances* (2025). DOI: [10.1126/sciadv.adu0086](https://doi.org/10.1126/sciadv.adu0086)

Provided by The Korea Advanced Institute of Science and Technology (KAIST)

MARCH 19, 2025

AI helps design Fe-based amorphous alloys for efficient high-power electronics

by Li Yali, [Chinese Academy of Sciences](#)



Fe-

based amorphous alloys with high saturated magnetization developed via artificial intelligence. Credit: NIMTE

Researchers from the Ningbo Institute of Materials Technology and Engineering of the Chinese Academy of Sciences have leveraged artificial intelligence (AI) to design a novel series of Fe-based amorphous alloys. These materials exhibit both ultra-high saturation magnetization (B_s) and ultra-low coercivity (H_c), offering the potential to improve the energy efficiency and performance of high-frequency, high-power electronic devices. The findings are [published](#) in *Advanced Functional Materials*.

As electronics operate at higher frequencies in the MHz and GHz ranges, traditional soft magnetic materials such as silicon steel face significant limitations due to high core losses. This leads to reduced efficiency, excessive heat, and risks of thermal runaway, especially in high-power applications such as 5G communications and electric vehicles.

Fe-based amorphous alloys offer a promising alternative with low coercivity and minimal core losses, but their low saturation magnetization hinders their use in high-power-density devices.

To address these challenges, the research team employed machine learning models to predict and optimize the saturation magnetization of Fe-based amorphous alloys. Among the models tested, the XGBoost algorithm demonstrated superior performance, achieving an R^2 coefficient above 0.85 and a root-mean-square error below 0.12 T, indicating high predictive accuracy.

Feature analysis revealed that [iron content](#) (above 75 atomic percent), mixing enthalpy (between -18.7 and -14 kJ/mol), and electronegativity difference (below 0.07) are critical factors in achieving high B_s while maintaining glass-forming ability.

Building on these insights, the researchers introduced cobalt to exploit the Fe-Co exchange coupling effect, designing a series of Fe-based amorphous alloys, including Fe-Co-Ni-Si-B and Fe-Co-Ni-B-P-C. Following [magnetic field](#) annealing, these alloys achieved B_s values exceeding 1.85 T, with some reaching up to 1.92 T, and H_c as low as 1.2 A/m. These properties surpass those of conventional silicon steel, positioning the new alloys as promising candidates for high-performance applications.

The advanced Fe-based amorphous alloys hold significant promise for use in smaller, lighter magnetic components within electronic systems. Their enhanced performance could drive innovations in next-generation technologies requiring high power density and minimal thermal waste.

More information: Shiyu Yang et al, Designing Fe-Based Amorphous Alloys With both Ultra-High Magnetization and Ultra-Low Coercivity Through Artificial Intelligence, *Advanced Functional Materials* (2025). DOI: [10.1002/adfm.202425588](https://doi.org/10.1002/adfm.202425588)

Journal information: [Advanced Functional Materials](#)

Provided by [Chinese Academy of Sciences](#)

MARCH 19, 2025

Latest dark energy survey data suggest possible variations in dark energy over time

by Josie Fenske, [National Science Foundation](#)



The U.S. National Science Foundation Víctor M. Blanco 4-meter Telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile, a Program of NSF NOIRLab. The Blanco is home to the 570-megapixel Department of Energy-fabricated Dark Energy Camera (DECam) conducting DES. Credit: CTIO/NOIRLab/NSF/AURA/P. Horálek (Institute of Physics in Opava)

A new study using the Dark Energy Survey (DES) final datasets suggests potential inconsistencies in the standard cosmological model, known as Λ CDM. If confirmed, these findings could fundamentally alter our understanding of the universe.

DES was conducted using the 570-megapixel Department of Energy-fabricated Dark Energy Camera (DECam), mounted on the U.S. National Science Foundation Víctor M. Blanco 4-meter Telescope at Cerro Tololo Inter-American Observatory in Chile, a Program of NSF NOIRLab.

The Λ CDM (Lambda-CDM) model has been the foundation of modern cosmology for some time now, successfully describing large-scale structures in the universe. It proposes that

95% of the cosmos is composed of [dark matter](#) (25%) and dark energy (70%)—mysterious substances whose nature remains unknown. Only 5% of the universe consists of ordinary matter.

Dark energy, represented by the [cosmological constant](#) (Λ), is thought to drive the accelerating expansion of the universe, maintaining a constant energy density over time. However, new results from the Dark Energy Survey (DES), presented in a [paper](#) appearing on the *arXiv* preprint server and in talks at the American Physical Society's Global Physics Summit in Anaheim, California, hint at a deviation from this assumption, suggesting that dark energy might evolve over time. These findings align with previous studies, reinforcing their significance.

The DES is an [international collaboration](#) comprising more than 400 scientists from over 25 institutions, led by the U.S. Department of Energy's Fermi National Accelerator Laboratory. The DES was conducted using the 570-megapixel Department of Energy-fabricated Dark Energy Camera (DECam), mounted on the U.S. National Science Foundation (NSF) Víctor M. Blanco 4-meter Telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile, a Program of NSF NOIRLab.

By taking data on 758 nights across six years, DES scientists mapped an area almost one-eighth of the entire sky. The project employs multiple observational techniques, including supernova measurements, galaxy clustering analysis, and weak gravitational lensing, to study dark energy.

Two key DES measurements—Baryon Acoustic Oscillations (BAO) and distance measurements of exploding stars (Type Ia supernovae)—track the universe's expansion history. BAO refers to a standard cosmic ruler formed by sound waves in the early universe, with peaks spanning approximately 500 million light-years. Astronomers can measure these peaks across several periods of cosmic history to see how dark energy has stretched the scale over time.

Santiago Avila from the Centre for Energy, Environmental and Technological Research (CIEMAT) in Spain, who was responsible for the BAO analysis in DES, says, "By analyzing 16 million galaxies, DES found that the measured BAO scale is actually 4% smaller than predicted by Λ CDM."

Type Ia supernovae serve as "standard candles," meaning they have a known intrinsic brightness. Therefore, their apparent brightness, combined with information about their host galaxies, allows scientists to make precise distance calculations. In 2024, DES published the most extensive and detailed supernova dataset to date, providing highly accurate measurements of cosmic distances. These new findings from the combined supernovae and BAO data independently confirm the anomalies seen in the 2024 supernova data.

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By integrating DES measurements with cosmic microwave background data, researchers inferred the properties of dark energy—and the results suggest a time-evolving nature. If validated, this would imply that dark energy, the cosmological constant, is not constant after all, but a dynamic phenomenon requiring a new theoretical framework.

"This result is intriguing because it hints at physics beyond the standard model of cosmology," says Juan Mena-Fernández of the Subatomic Physics and Cosmology Laboratory in Grenoble, France. "If further data support these findings, we may be on the brink of a scientific revolution."



The Dark Energy Camera (DECam), fabricated by the Department of Energy (DOE), is mounted on the Víctor M. Blanco 4-meter Telescope at the Cerro Tololo Inter-American Observatory (CTIO) in north-central Chile. Telescope construction started in 1969 with the casting of the primary mirror. The assembly at the Cerro Tololo mountaintop was finished in 1974. Upon completion of construction it was the 3rd largest telescope in the world, behind the 200-inch Hale telescope at Palomar Observatory in California and the BTA-6 in southern Russia, and was the largest in the Southern Hemisphere (a title that it held for 22 years). It was later named in 1995 in honor of Víctor M. Blanco, Puerto Rican astronomer and former director of CTIO. Credit: DOE/FNAL/DECam/R.

Hahn/CTIO/NOIRLab/NSF/AURA

Although the current results are not yet definitive, upcoming analyses incorporating additional DES probes—such as galaxy clustering and weak lensing—could strengthen the evidence. Similar trends have emerged from other major cosmological projects, including the Dark Energy Spectroscopic Instrument (DESI), raising anticipation within the scientific community.

"These results represent years of collaborative effort to extract cosmological insights from DES data," says Jessie Muir of the University of Cincinnati. "There is still much to learn, and it will be exciting to see how our understanding evolves as new measurements become available."

The final DES analysis, expected later this year, will incorporate additional cosmological probes to cross-check findings and refine constraints on dark energy. The scientific community eagerly awaits these results, as they could pave the way for a paradigm shift in cosmology.

More information: DES Collaboration, Dark Energy Survey: implications for cosmological expansion models from the final DES Baryon Acoustic Oscillation and Supernova data, *arXiv* (2025). DOI: [10.48550/arxiv.2503.06712](https://doi.org/10.48550/arxiv.2503.06712)

Journal information: [arXiv](#)

Provided by [National Science Foundation](#)

How warp drives don't break relativity



Somehow, we all know how a warp drive works. You're in your spaceship and you need to get to another star. So you press a button or flip a switch or pull a lever and your ship just goes fast. Like really fast. Faster than the speed of light. Fast enough that you can get to your next destination by the end of the next commercial break.

Warp drives are staples of science fiction. And in 1994, they became a part of science fact. That's when Mexican physicist Miguel Alcubierre, who was inspired by Star Trek, decided to see if it was possible to build a warp drive. Not like actually build one with wrenches and pipes, but to see if it was even possible to be allowed to build a warp drive given our current knowledge of physics.

Physics is just a mathematical exploration of the natural universe, and the natural universe appears to play by certain rules. Certain actions are allowed, and other actions are not allowed. And the actions that are allowed have to proceed in a certain orderly fashion. Physics tries to capture all of those rules and express them in mathematical form. So Alcubierre wondered: does our knowledge of how nature works permit a warp drive or not?

Now, of course, our knowledge of nature is constantly changing and being updated, but what matters is right now, at this very moment, with this snapshot of our state of knowledge, can we do it? And the answer surprised him. It was yes. It's not a firm resounding yes. It's more like a soft hesitant yes, but a yes is still a yes, which opens up some intriguing possibilities.

And at first glance, it seems like it should be a hard no. I mean, we are talking about faster than light travel and we all know that you can't travel faster than the speed of light. That's baked into special relativity. And it isn't just some speed limit posted on the highway. It's a real hard and fast rule of the universe.

Don't even try getting around it. We've been testing it for over a century, and it seems to be a result of the way that space and time weave into each other. It's not just the speed of light. It's the speed of causality. It's how the universe orders itself from past to future and how causes lead to effects.

So just going really fast isn't going to do the trick. But special relativity [isn't the end of the story](#). There's a broader, more general version of relativity, which is general relativity, and general relativity says that you can never exceed the speed of light locally. That means that you can never measure yourself going faster than

light, and nobody right next to you can ever see you whiz by going faster than light. If I look at the stuff that surrounds me, then by comparing myself to nearby objects I can never go faster than light.

But faraway things can get faster than light. This is how we are able to understand things like the expansion of the universe. Distant galaxies appear to recede away from us faster than light. In fact, any galaxy that's further away than roughly 13.8 billion light-years is going to be moving away from us faster than the speed of light. And that's no big deal.

Here we are in the Milky Way. We look around and say no, we're not going faster than the speed of light. In fact, we're barely moving at all.

Then hop over to one of those distant galaxies, and everyone living in that distant galaxy, they look around. Same thing. They're not moving around at all.

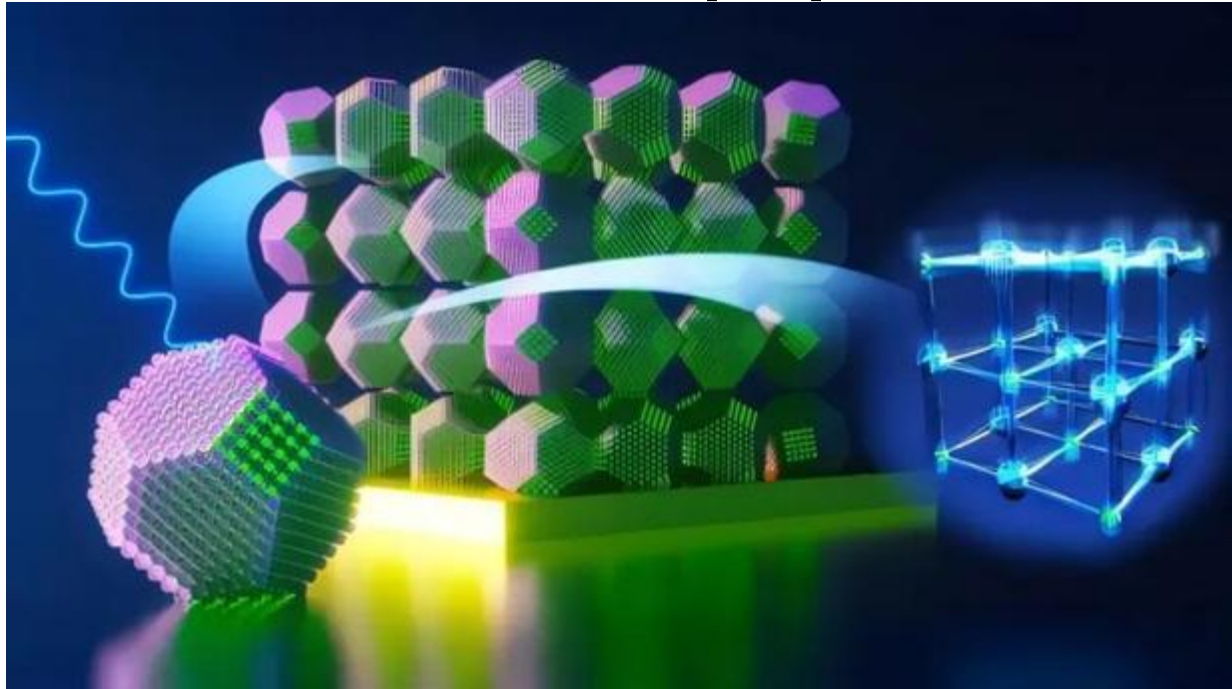
We're fine. We check our local environment, and we confirm we are not going faster than light. That far off galaxy checks its local environment and confirms that it's not going faster than light, and we're all good. But the space between us is expanding. And so even though neither of us is moving, we're still getting separated faster than the speed of light.

This doesn't break causality because that galaxy that's really far away and receding away from us faster than the speed of light is just too far away. We can never affect it. What this means is that galaxy is beyond our influence, that we're seeing the light that it emitted a long time ago, and we're never going to see the light that it is emitting right now. So causality is preserved even though distant galaxies are receding faster than light.

And warp drives exploit this same loophole—never locally going faster than light.

Provided by Universe Today

Light-induced symmetry changes in tiny crystals allow researchers to create materials with tailored properties



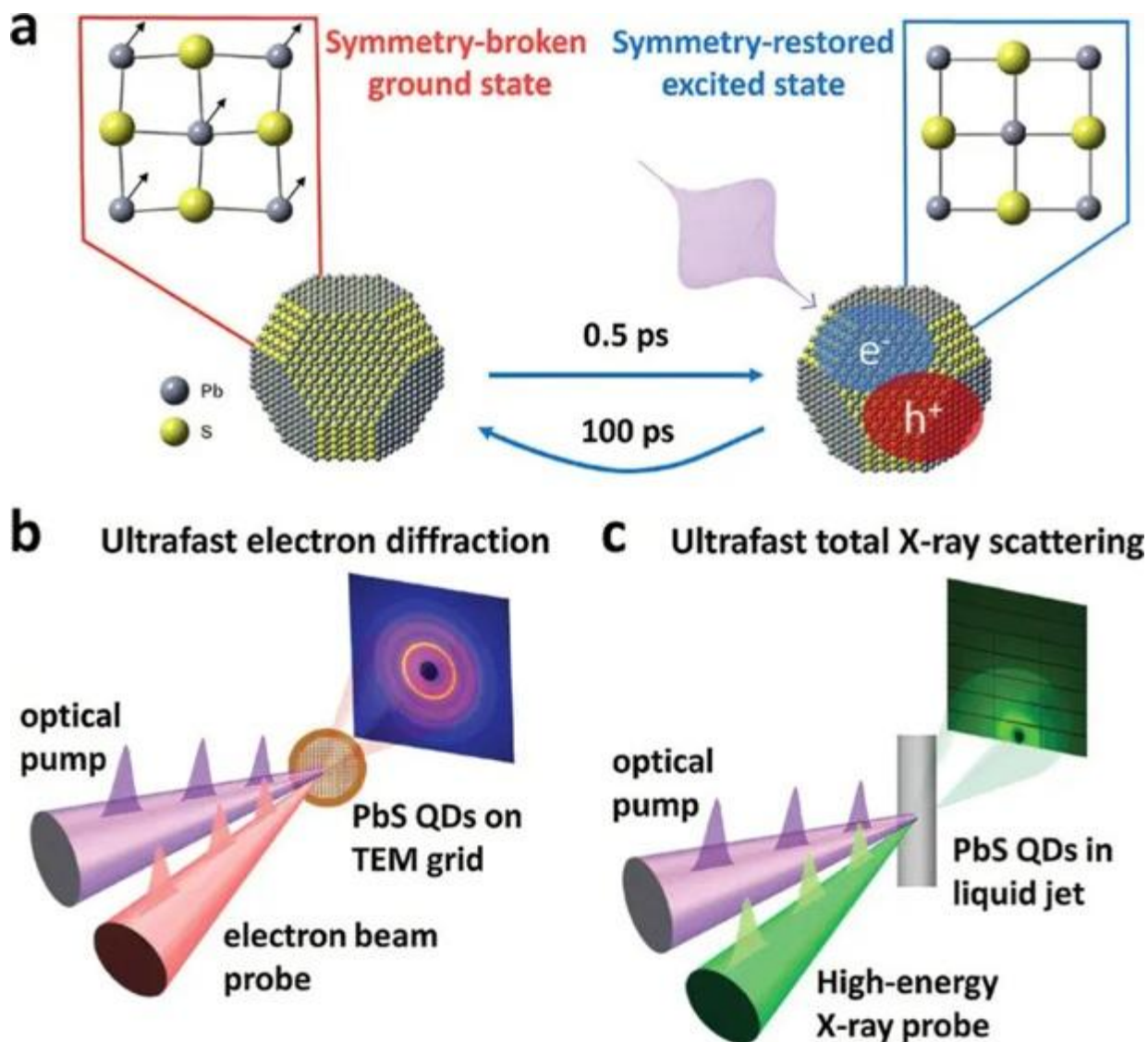
Artistic illustration of lead sulfide quantum dots as they undergo structural changes when exposed to light, with lead atoms temporarily shifting to a new position. Credit: Cottis Lab at Middlebury College.

Imagine building a Lego tower with perfectly aligned blocks. Each block represents an atom in a tiny crystal, known as a quantum dot. Just like bumping the tower can shift the blocks and change its structure, external forces can shift the atoms in a quantum dot, breaking its symmetry and affecting its properties.

Scientists have learned that they can intentionally cause symmetry breaking—or symmetry restoration—in quantum dots to create new materials with unique properties. In a recent study, researchers at the U.S. Department of Energy's (DOE) Argonne National Laboratory have discovered how to use light to change the arrangement of atoms in these minuscule structures.

Quantum dots made of semiconductor materials, such as lead sulfide, are known for their unique optical and electronic properties due to their tiny size, giving them the potential to revolutionize fields such as electronics and medical imaging. By harnessing the ability to control symmetry in these quantum dots,

scientists can tailor the materials to have specific light and electricity-related properties. This research opens up new possibilities for designing materials that can perform tasks previously thought impossible, offering a pathway to innovative technologies.



Symmetry control in photoexcited lead sulfide quantum dots (QDs). Credit: Advanced Materials (2024). DOI: 10.1002/adma.202414196

Typically, lead sulfide is expected to form a cubic crystal structure, characterized by high symmetry similar to that of table salt. In this structure, lead and sulfur atoms should arrange themselves in a very ordered lattice, much like alternating red and blue Lego blocks.

However, previous data has suggested that the lead atoms were not precisely where they were expected to be. Instead, they were slightly off-center, leading to a structure with less symmetry.

"When symmetries change, it can change the properties of a material, and it's almost like a brand-new material," Argonne physicist Richard Schaller explained. "There's a lot of interest in the scientific community to find ways to create states of matter that can't be produced under normal conditions."

The team used advanced laser and X-ray techniques to study how the structure of lead sulfide quantum dots changed when exposed to light. At DOE's SLAC National Accelerator Laboratory, they used a tool called Megaelectronvolt Ultrafast Electron Diffraction (MeV-UED) to observe the behavior of these quantum dots in incredibly short timeframes, down to a trillionth of a second.

Meanwhile, at the Advanced Photon Source (APS), a DOE Office of Science user facility at Argonne, they conducted ultrafast total X-ray scattering experiments using Beamline 11-ID-D to study temporary structural changes at timescales down to a billionth of a second. These X-ray measurements benefited from the recent APS upgrade, which delivers high-energy X-ray beams that are up to 500 times brighter than before.

Additionally, at the Center for Nanoscale Materials, another DOE Office of Science user facility at Argonne, the team performed fast—again, less than a trillionth of a second—optical absorption measurements to understand how the electronic processes change when the symmetry changes. These state-of-the-art facilities at Argonne and SLAC played a crucial role in helping researchers learn more about controlling symmetry and the optical properties of the quantum dots on very fast timescales.

Using these techniques, the researchers observed that when quantum dots were exposed to short bursts of light, the symmetry of the crystal structure changed from a disordered state to a more organized one.

"When quantum dots absorb a light pulse, the excited electrons cause the material to shift to a more symmetrical arrangement, where the lead atoms move back to a centered position," said Burak Guzelturk, a physicist at the APS.

The return of symmetry directly affected the electronic properties of the quantum dots. The team noticed a decrease in the bandgap energy, which is the difference in energy that electrons need to jump from one state to another within a semiconductor material. This change can influence how well the crystals conduct electricity and respond to external forces, such as electric fields.

Furthermore, the researchers also investigated how the size of the quantum dots and their surface chemistry influence the temporary changes in symmetry. By adjusting these factors, they could control the symmetry shifts and fine-tune the optical and electronic properties of the quantum dots.

"We often assume the crystal structure doesn't really change, but these new experiments show that the structure isn't always static when light is absorbed," said Schaller.

This study's findings are important for nanoscience and technology. Being able to change the symmetry of quantum dots using just light pulses lets scientists create materials with specific properties and functions. Just as Lego bricks can be transformed into endless structures, researchers are learning how to "build" quantum dots with the properties they want, paving the way for new technological advancements.

The results of this research were published in [Advanced Materials](#).

More information: Burak Guzelturk et al, Ultrafast Symmetry Control in Photoexcited Quantum Dots, *Advanced Materials* (2024). DOI: [10.1002/adma.202414196](https://doi.org/10.1002/adma.202414196)

Provided by Argonne National Laboratory

MARCH 26, 2025

Theoretical physicists completely determine the statistics of quantum entanglement

by Institute of Theoretical Physics, Saclay



When two observers measure an entangled state, the frequencies of their observed results manifest the strength of quantum theory. Extreme values governing these statistics have now been successfully identified. Credit: Jean-Daniel Bancal

For the first time, theoretical physicists from the Institute of Theoretical Physics (IPhT) in Paris-Saclay have completely determined the statistics that can be generated by a system using quantum entanglement. This achievement paves the way for exhaustive test procedures for quantum devices.

The study is [published](#) in the journal *Nature Physics*.

After the advent of transistors, lasers and [atomic clocks](#), the entanglement of quantum objects—as varied as photons, electrons and superconducting circuits—is at the heart of a second quantum revolution, with [quantum communication](#) and quantum computing in sight.

What's involved? Two objects prepared together in a quantum state—two horizontally or vertically polarized photons, for example—retain the memory of their common origin, even if they are moved far apart from each other. When the quantum state of the two entangled

objects is measured—their polarization, in the proposed example—a distinct correlation is observed between the measurement results.

Measurement obeying quantum statistics

What does this correlation depend on? First, the degree of entanglement between the two objects may vary, depending on the nature of the source of the entangled quantum objects—in the example, horizontally polarized photons may be produced more frequently than vertically polarized ones. Then, a choice of measurement must be made—such as selecting a direction in which to measure the polarization—which may impact its result.

In order to generate meaningful quantum correlations, it is indeed essential that each object may be measured using a minimum of two distinct measurements, each offering at least two potential outcomes.

In the simplest experiment revealing the extent of quantum entanglement, five parameters can thus affect the measurement statistics: the degree of entanglement between the objects and the two directions in which both apparatuses perform their measurements. Generally speaking, however, quantum physics allows for intricate systems with numerous degrees of freedom, leading to a wide variety of correlations.

Extracting knowledge from a black box

Quantum correlations have remarkable characteristics, notably their ability to pass a Bell test. When this happens, the results of a quantum experiment are "non-local" in the sense that they cannot be explained in terms of local hidden variable models, which capture our intuitive understanding of correlations. The [experimental demonstration](#) of this striking property was celebrated by the physics Nobel prize awarded in 2022 to Alain Aspect, John F. Clauser and Anton Zeilinger. But quantum correlations have more than one trick up their sleeve.

It turns out that physical attributes can often be estimated directly from the statistics obtained upon measurement of an entangled [quantum state](#). For instance, observed correlations can certify that the observed measurement results are random. Importantly, this conclusion is attainable from the measurement results alone, without any assumption on the behavior of the [quantum devices](#) at hand, considered as "black-boxes." Ultimately, some quantum statistics have the property of fully identifying the physical model describing the entangled objects.

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Unveiling the extent of quantum correlations

This stunning property, referred to as "self-testing," plays a crucial role in device-independent quantum information protocols. Because these protocols do not rely on any assumption regarding the proper functioning of the source and measurement apparatuses, they offer unparalleled reliability. So far, several [self-testing](#) results have been obtained. For example, it is known that all qubit states can be self-tested, although all possible self-tests are not known yet. Indeed, only self-tests corresponding to maximally entangled states of two qubits have been fully characterized.

IPhT [theoretical physicists](#) Victor Barizien and Jean-Daniel Bancal have now demonstrated that it is also possible to describe exactly and completely the statistics obtained when measuring partially entangled objects.

"The idea, which is cute but hard to explain, was to describe the statistics from partially entangled states using what we understand of maximally entangled ones. We found a mathematical transformation that allows for a fruitful physical interpretation," state the researchers.

In turn, identifying all correlations that can self-test partially entangled two-qubit states provided a complete description of the quantum statistics.

Considerable scope, both fundamental and applied

Having a complete knowledge of the quantum statistics achievable when entanglement is involved has wide consequences. On one hand, it identifies limits of quantum theory itself. In doing so, it bounds the extent of experimental results one can expect to observe provided that nature abides by the rules of quantum physics. On the other hand, it offers exceptionally effective test procedures, applicable to all types of entangled objects and measurements, and therefore to many different types of systems.

In particular, the security of devices using [quantum entanglement](#) can be enhanced by tests based on the results of observations made at each instant, rather than on the physical properties of the apparatuses, which are likely to evolve over time. More generally, the way is open to new protocols for quantum testing, communications, cryptography and computation.

More information: Victor Barizien et al, Quantum statistics in the minimal Bell scenario, *Nature Physics* (2025). DOI: [10.1038/s41567-025-02782-3](https://doi.org/10.1038/s41567-025-02782-3).

On *arXiv*: arxiv.org/abs/2406.09350

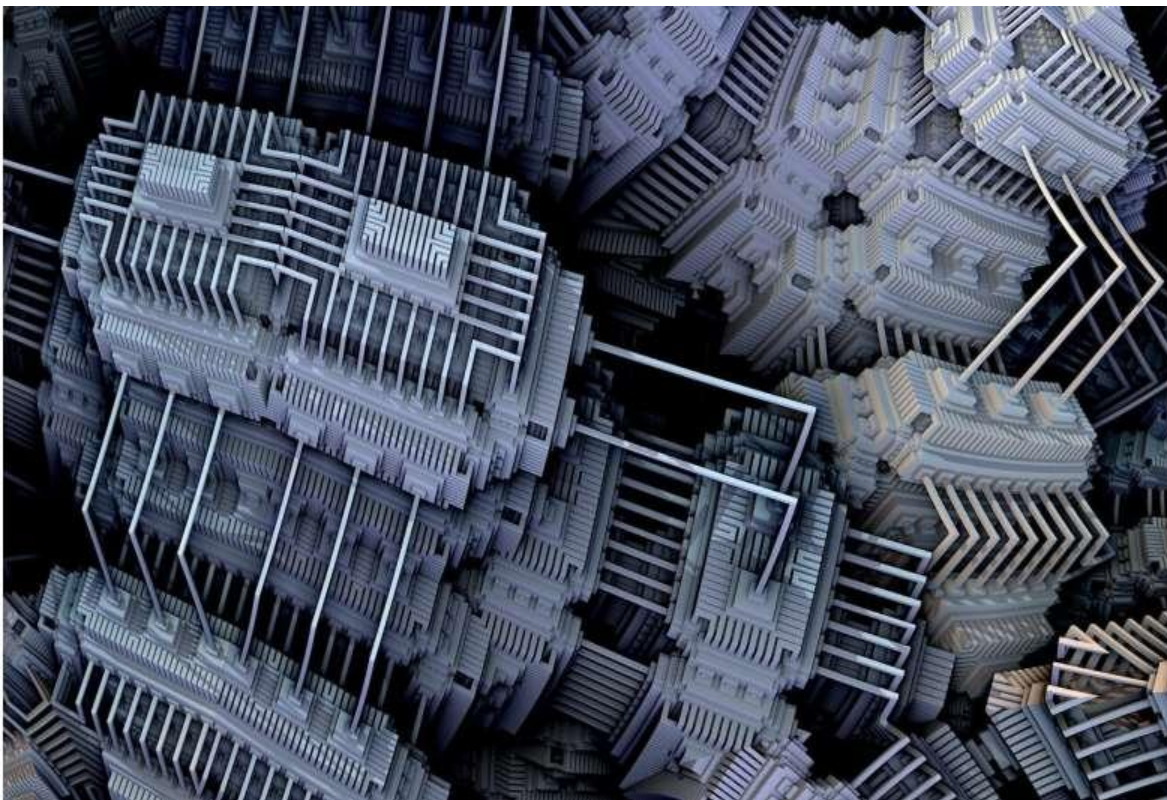
Journal information: [Nature Physics](#) , [arXiv](#)

Provided by Institute of Theoretical Physics, Saclay

MARCH 28, 2025

Physicist revisits the computational limits of life and Schrödinger's essential question in the era of quantum computing

by Howard University



Credit: Pixabay/CC0 Public Domain

More than 80 years ago, Erwin Schrödinger, a theoretical physicist steeped in the philosophy of Schopenhauer and the Upanishads, delivered a series of public lectures at Trinity College, Dublin, which eventually came to be published in 1944 under the title "What is Life?"

Now, in the 2025 International Year of Quantum Science and Technology, Philip Kurian, a [theoretical physicist](#) and founding director of the Quantum Biology Laboratory (QBL) at Howard University in Washington, D.C., has used the laws of quantum mechanics, which Schrödinger postulated, and the [QBL's discovery of cytoskeletal filaments exhibiting quantum optical features](#), to set a drastically revised upper bound on the computational capacity of carbon-based life in the entire history of Earth.

Published in [Science Advances](#), Kurian's latest work conjectures a relationship between this information-processing limit and that of all matter in the observable universe.

"This work connects the dots among the great pillars of twentieth century physics—thermodynamics, relativity, and quantum mechanics—for a major paradigm shift across the biological sciences, investigating the feasibility and implications of quantum information processing in wetware at ambient temperatures," said Kurian.

"Physicists and cosmologists should wrestle with these findings, especially as they consider the origins of life on Earth and elsewhere in the habitable universe, evolving in concert with the electromagnetic field."

Quantum mechanics and superradiance

The effects of quantum mechanics—the laws of physics that many scientists think apply at only small scales—are sensitive to disturbances. This is why quantum computers must be held at temperatures colder than outer space, and only small objects, such as atoms and molecules, typically display quantum properties.

By quantum standards, biological systems are quite hostile environments: they're warm and chaotic, and even their fundamental components—such as cells—are considered large.

But Kurian's group last year discovered a distinctly quantum effect in protein polymers in aqueous solution, which survives these challenging conditions at the micron scale, and may also [present a way](#) for the brain to protect itself from degenerative diseases like Alzheimer's and related dementias. Their results have suggested new applications and platforms for quantum computing researchers, and they represent a new way of thinking about the relationship between life and quantum mechanics.

In his single-author *Science Advances* paper, Kurian considered a mere trifecta of overarching assumptions: standard [quantum mechanics](#), the relativistic speed limit set by light, and a matter-dominated universe at critical mass-energy density.

"Combined with these rather innocuous premises, the remarkable experimental confirmation of single-photon superradiance in a ubiquitous biological architecture at thermal equilibrium opens up many new lines of inquiry across quantum optics, quantum information theory, condensed matter physics, cosmology, and biophysics," said Professor Marco Pettini of Aix-Marseille University and the CNRS Center for Theoretical Physics (France), who was not associated with the work.

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Quantum information processing, beyond biochemical signaling

The key molecule enabling these remarkable properties is tryptophan, an amino acid found in many proteins that absorbs ultraviolet light and re-emits it at a longer wavelength. Large networks of tryptophan form in microtubules, amyloid fibrils, transmembrane receptors, viral capsids, cilia, centrioles, neurons, and other cellular complexes.

The QBL's confirmation of quantum superradiance in cytoskeletal filaments has the profound consequence that all [eukaryotic organisms](#) can use these quantum signals to process information.

To break down food, cells undergoing aerobic respiration use oxygen and generate free radicals, which can emit damaging, high-energy UV light particles. Tryptophan can absorb this ultraviolet light and re-emit it at a lower energy. And, as the QBL study found, very large tryptophan networks can do this even more efficiently and robustly because of their powerful quantum effects.

The standard model for biochemical signaling involves ions moving across cells or membranes, generating spikes in an electrochemical process that takes a few milliseconds for each signal. But neuroscience and other biological researchers have only recently become aware that this isn't the whole story.

Superradiance in these cytoskeletal filaments happens in about a picosecond—a millionth of a microsecond. Their tryptophan networks could be functioning as quantum fiber optics that allow eukaryotic cells to process information billions of times faster than chemical processes alone would allow.

"The implications of Kurian's insights are staggering," said Professor Majed Chergui of the École Polytechnique Fédérale de Lausanne (Switzerland) and Elettra-Sincrotrone Trieste (Italy), who supported the 2024 experimental study.

"Quantum biology—in particular our observations of superradiant signatures from standard protein spectroscopy methods, guided by his theory—has the potential to open new vistas for understanding the evolution of living systems, in light of photophysics."

Aneural life and planetary computing capacity

By thinking of biological information processing primarily at the level of the neuron, many scientists overlook the fact that aneural organisms—including bacteria, fungi, and plants, which form the bulk of Earth's biomass—perform sophisticated computations. And as these organisms have been on our planet for much longer than animals, they constitute the vast majority of Earth's carbon-based computation.

"There are signatures in the interstellar media and on interplanetary asteroids of similar quantum emitters, which may be precursors to eukaryotic life's computational advantage," said Dante Lauretta, professor of planetary science and cosmochemistry at the University of Arizona and director of the Arizona Astrobiology Center, who was not associated with the work.

"Kurian's predictions provide quantitative bounds, beyond the colloquial Drake equation, on how superradiant living systems enhance planetary computing capacity. The remarkable properties of this signaling and information-processing modality could be a game-changer in the study of habitable exoplanets."

Performance comparisons with quantum computers

This latest analysis has likewise drawn the attention of researchers in quantum computing, because the survival of fragile quantum effects in a "noisy" environment is of great interest to those who want to make quantum information technology more resilient. Kurian has had conversations with several quantum computing researchers who were surprised to find such connections in the [biological sciences](#).

"These new performance comparisons will be of interest to the large community of researchers in open quantum systems and quantum technology," said Professor Nicolò Defenu of the Federal Institute of Technology (ETH) Zurich in Switzerland, a quantum researcher who was not associated with the work. "It's really intriguing to see a vital and growing connection between quantum technology and living systems."

In the *Science Advances* article, Kurian explains and revisits foundational quantum properties and thermodynamic considerations from a long line of physicists who made clear the essential link between physics and information.

With his group's discovery of UV-excited qubits in biological fibers, almost all life on Earth has the physical capacity to compute with controllable quantum degrees of freedom, allowing storage and manipulation of quantum information with error correction cycles far outpacing the latest lattice-based surface codes.

"And all this in a warm soup! The quantum computing world should take serious notice," Kurian said.

The work also piqued the attention of quantum physicist Seth Lloyd, a professor of mechanical engineering at MIT and a pioneer in the study of quantum computing and the computational capacity of the universe.

"I applaud Dr. Kurian's bold and imaginative efforts to apply the fundamental physics of computation to the total amount of information processing performed by living systems over the course of life on Earth. It's good to be reminded that the computation performed by living systems is vastly more powerful than that performed by artificial ones," Lloyd said.

"In the era of artificial intelligences and quantum computers, it is important to remember that physical laws restrict all their behaviors," Kurian said.

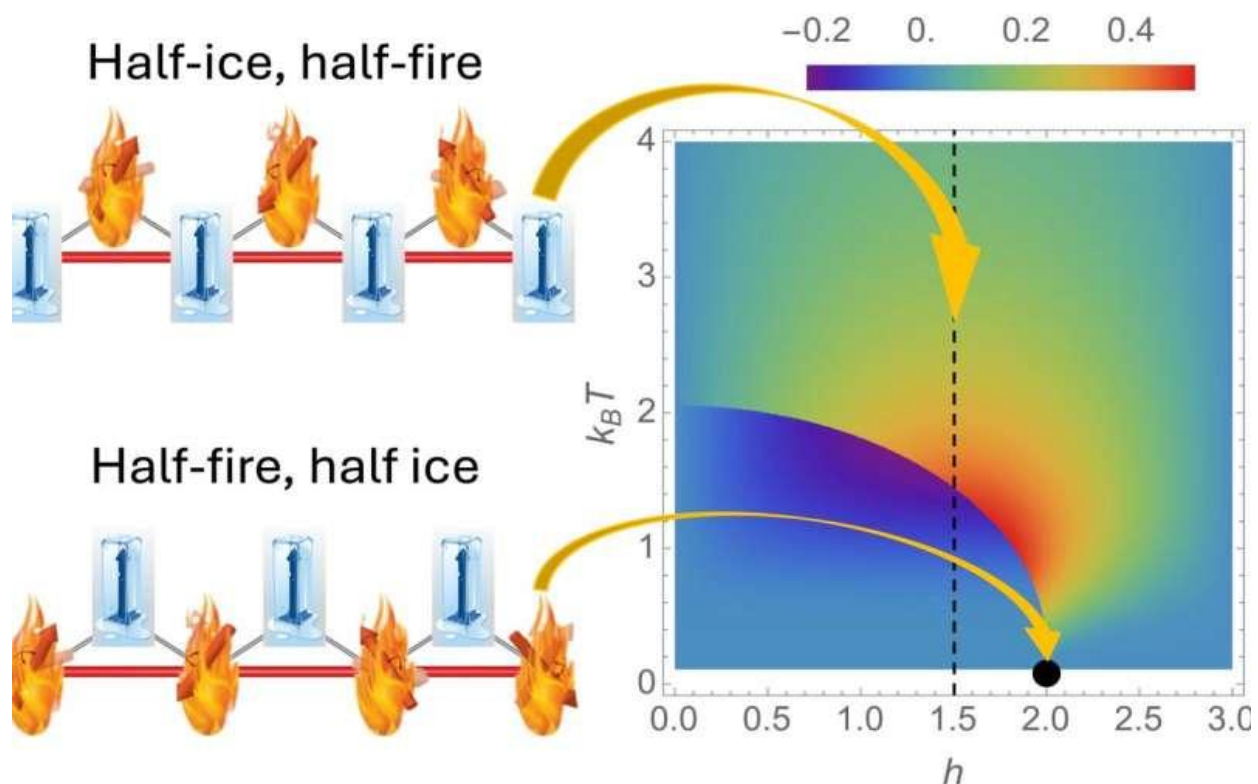
"And yet, though these stringent physical limits also apply to life's ability to track, observe, know, and simulate parts of the universe, we can still explore and make sense of the brilliant order within it, as the cosmic story unfolds. It's awe-inspiring that we get to play such a role."

More information: Philip Kurian, Computational Capacity of Life in Relation to the Universe, *Science Advances* (2025). DOI: [10.1126/sciadv.adt4623](https://doi.org/10.1126/sciadv.adt4623). www.science.org/doi/10.1126/sciadv.adt4623
Journal information: *Science Advances*
Provided by Howard University

MARCH 25, 2025

'Half ice, half fire': Physicists discover new phase of matter in a magnetic material

by Laura Mgrdichian-West, [Brookhaven National Laboratory](#)



This image shows a graphical interpretation of the "half-ice, half-fire" and "half-fire, half-ice" states (left). The plot (right) shows the magnetic entropy change in the magnetic field (h) versus temperature (T) plane. The black dot at zero temperature indicates where the half-

fire, half-ice state appears. The dashed line indicates where the half-ice, half-fire state hides. Credit: Brookhaven National Laboratory

Two scientists at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory have discovered a new phase of matter while studying a model system of a magnetic material.

The phase is a never-before-seen pattern of electron spins—the tiny "up" and "down" magnetic moments carried by every electron. It consists of a combination of highly ordered "cold" spins and highly disordered "hot" spins, and it has thus been dubbed "half ice, half fire." The researchers discovered the new phase while studying a one-dimensional model of a type of magnetic material called a ferrimagnet.

"Half ice, half fire" is notable not only because it has never been observed before, but also because it is able to drive extremely sharp switching between phases in the material at a reasonable, finite temperature. This phenomenon could one day result in applications in the energy and information technology industries.

The researchers, physicists Weiguo Yin and Alexei Tsvelik, describe their work in the Dec. 31, 2024, edition of the journal [Physical Review Letters](#).

"Finding new states with exotic physical properties—and being able to understand and control the transitions between those states—are central problems in the fields of condensed matter physics and materials science," said Yin. "Solving those problems could lead to great advances in technologies like [quantum computing](#) and spintronics."

Tsvelik added, "We suggest that our findings may open a new door to understanding and controlling phases and phase transitions in certain materials."

First came fire and ice

The "half-ice, half-fire" phase is the twin state of the "half-fire, half-ice" phase discovered by Yin, Tsvelik, and Christopher Roth, their 2015 undergraduate summer intern who is now a postdoc at the Flatiron Institute. They describe the discovery in a paper published in early 2024.

But the full story goes back to 2012, when Yin and Tsvelik were part of a multi-institutional collaboration, led by Brookhaven physicist John Hill, that was studying $\text{Sr}_3\text{CuIrO}_6$, a magnetic compound of strontium, copper, iridium, and oxygen. This research led to two papers, an experiment-driven study in 2012 and a theory-driven study in 2013, both published in *PRL*.

Yin and Tsvelik continued to look into the phase behaviors of $\text{Sr}_3\text{CuIrO}_6$ and, in 2016, found the "half-fire, half-ice" phase. In this state, which is induced by a critical external magnetic field, the "hot" spins on the copper sites are fully disordered on the atomic lattice and have smaller magnetic moments, while the "cold" spins on the iridium sites are fully ordered and have larger [magnetic moments](#). That work was [published](#) in *Physical Review B*.

"But despite our extensive research, we still didn't know how this state could be utilized, especially because it has been well known for one century that the one-dimensional Ising model, an established mathematical model of ferromagnetism that produces the half-fire, half-ice state, does not host a finite-temperature phase transition," said Tsvelik. "We were missing pieces of the puzzle."

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A hint to the missing pieces was recently identified by Yin. In two publications for systems with and without an [external magnetic field](#), respectively, he demonstrated that the aforementioned forbidden phase transition can be approached by ultranarrow phase crossover at fixed finite temperature.

In this current work, Yin and Tsvelik have discovered that "half fire, half ice" has an opposite, hidden state in which the hot and cold spins switch positions. That is, the hot spins become cold, and the cold spins become hot, which led them to name the phase "half ice, half fire."

The model reveals that switching between phases takes place over an ultranarrow temperature range, and Yin and Tsvelik have already suggested possible ways that this could be used in future applications. For example, ultrasharp phase switching with a giant magnetic entropy change—offered by "half fire, half ice"—could be useful for refrigeration technologies. The phenomenon could also be used as the foundation for a new type of quantum information storage technology in which phases act as bits.

"Next, we are going to explore the fire-ice phenomenon in systems with quantum spins and with additional lattice, charge, and orbital degrees of freedom," said Yin. "The door to new possibilities is now wide open."

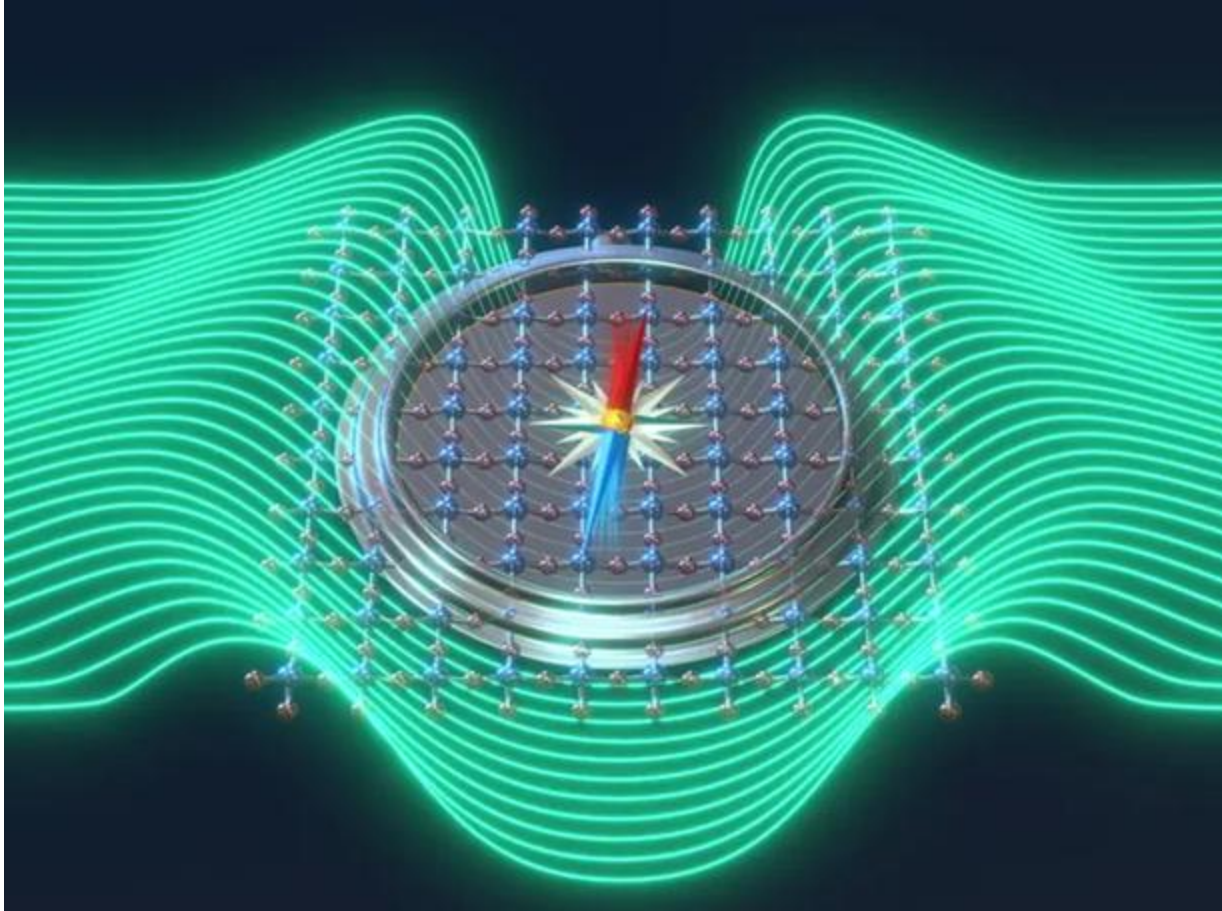
More information: Weiguo Yin et al, Phase Switch Driven by the Hidden Half-Ice, Half-Fire State in a Ferrimagnet, *Physical Review Letters* (2024). DOI:

[10.1103/PhysRevLett.133.266701](https://doi.org/10.1103/PhysRevLett.133.266701). On *arXiv*: arxiv.org/html/2401.00948v2

Journal information: [Physical Review B](#) , [Physical Review Letters](#) , [arXiv](#)

Provided by [Brookhaven National Laboratory](#)

A new wave in ultrafast magnetic control



Ultrafast disruption of superconductivity in a $\text{YBa}_2\text{Cu}_3\text{O}_7$ thin film triggers an abrupt magnetic field quench, setting off dynamics in a neighboring spin system. Credit: Giovanni de Vecchi, Joerg M. Harms / MPSD

Researchers at the Max Planck Institute for the Structure and Dynamics of Matter (MPSD) have developed an innovative method to study ultrafast magnetism in materials. They have shown the generation and application of magnetic field steps, in which a magnetic field is turned on in a matter of picoseconds.

The work has been [published](#) in *Nature Photonics*.

Magnetic fields are fundamental to controlling the magnetization of materials. Under static or slowly varying conditions, a material's magnetization aligns with the external field like a compass needle. However, entirely new magnetization dynamics emerge when magnetic fields change on ultrafast timescales—faster than the material's response time.

These rapid transients are of great interest for fundamental research into non-equilibrium states of matter and for potential applications in next-generation magnetic memory, where faster writing speeds are critical.

To address this challenge, the research team designed a novel superconducting device capable of producing ultrafast, unipolar magnetic field steps—sudden magnetic changes with picosecond-scale rise and super-nanosecond decay times.

"Our goal is to create a universal, ultrafast stimulus that can switch any magnetic sample between stable magnetic states," says lead author Giovanni De Vecchi.

"This breakthrough could drive advances in both fundamental science and technology."

Harnessing superconductors for ultrafast magnetic steps

The team, led by Andrea Cavalleri, achieved this feat by rapidly quenching supercurrents in a superconducting $\text{YBa}_2\text{Cu}_3\text{O}_7$ thin disk exposed to an external magnetic field. Supercurrents naturally form to expel magnetic fields from superconductors.

"By abruptly disrupting these currents using ultrashort laser pulses, we could generate ultrafast magnetic field steps with rise times of approximately one picosecond—one trillionth of a second," says fellow co-author Gregor Jotzu.

"Devising a method to track these magnetic transients in real-time was a major challenge," explains co-author Michele Buzzi. The researchers placed a spectator crystal near the superconducting sample to achieve this. The crystal's optical properties change in response to the local magnetic field.

This effect allows the team to track the magnetic field evolution by analyzing the polarization rotation of a femtosecond laser pulse.

"With this approach, we achieved sub-picosecond resolution and unprecedented sensitivity," adds co-author Sebastian Fava.

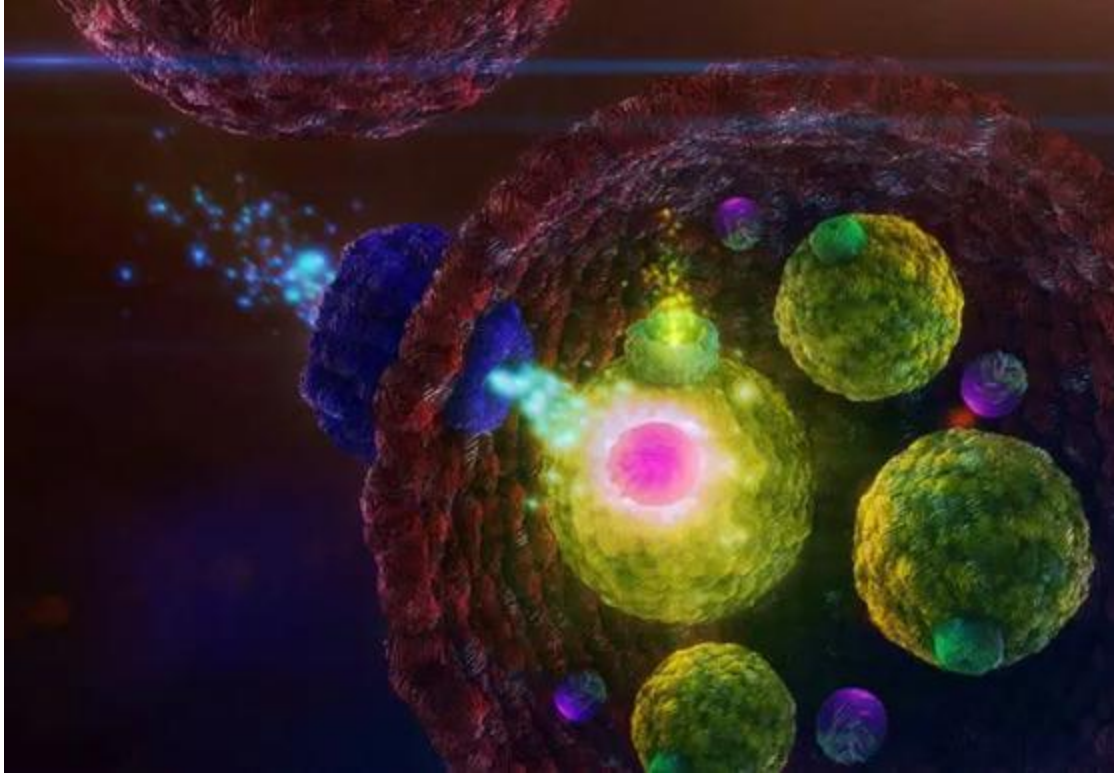
While the current magnetic steps do not yet achieve complete magnetization switching, the researchers believe optimizing the device geometry could enhance the amplitude and speed of the magnetic field transients.

"With suitable improvements, we envision applications ranging from phase transition control to complete switching of magnetic order parameters," says Cavalleri.

More information: G De Vecchi et al, Generation of ultrafast magnetic steps for coherent control, *Nature Photonics* (2025). DOI: [10.1038/s41566-025-01651-y](https://doi.org/10.1038/s41566-025-01651-y). www.nature.com/articles/s41566-025-01651-y

Provided by Max Planck Society

Scientists create synthetic cells that shape-shift in response to light



Using light-sensitive enzymes, scientists now precisely control cell movements, opening new possibilities in synthetic biology and advanced medical treatments. (CREDIT: CC BY-SA 4.0)© The Brighter Side of News

Cells constantly shift and transform, triggering the complex choreography that shapes living organisms. Whether dividing into new cells or sculpting an embryo, these tiny movements rely on chemical signals coordinating precise mechanical reactions. Recently, scientists harnessed these movements using beams of light to control cellular behavior, taking a big step toward creating [programmable synthetic cells](#).

Every living thing—from bacteria to humans—depends on cells dynamically changing shape. These tiny shape shifts allow cells to divide, move, and build tissues, forming complete organisms.

Behind each transformation is an intricate system of chemical signals interacting with tiny muscle-like fibers inside the cell. This powerful combination, called chemo-mechanical signaling, drives critical biological processes, including wound healing and [embryo development](#).

However, scientists face challenges in fully understanding these processes because they involve complex chemical interactions. To study these reactions accurately, researchers need precise control over how and when the cell receives these chemical signals. That's why scientists have turned to a powerful new tool: light.

Controlling Cells with Light

A team of researchers led by physicist Nikta Fakhri has now used optogenetics—a method of controlling biological processes with light—to manipulate how cells move and reshape themselves. Specifically, they studied [egg cells](#) from starfish, organisms frequently used as models for cell growth and development research. Starfish eggs exhibit a unique phenomenon known as surface contraction waves, a form of cellular motion crucial during the egg's early division process.

Normally, these waves are triggered by proteins called Rho and enzymes known as GEF, which together activate muscle-like contractions in the cell's outer layer. When GEF stimulates Rho, the protein moves from the cell's interior and binds to its surface membrane. This binding causes tiny fibers within the membrane to contract, changing the cell's shape.

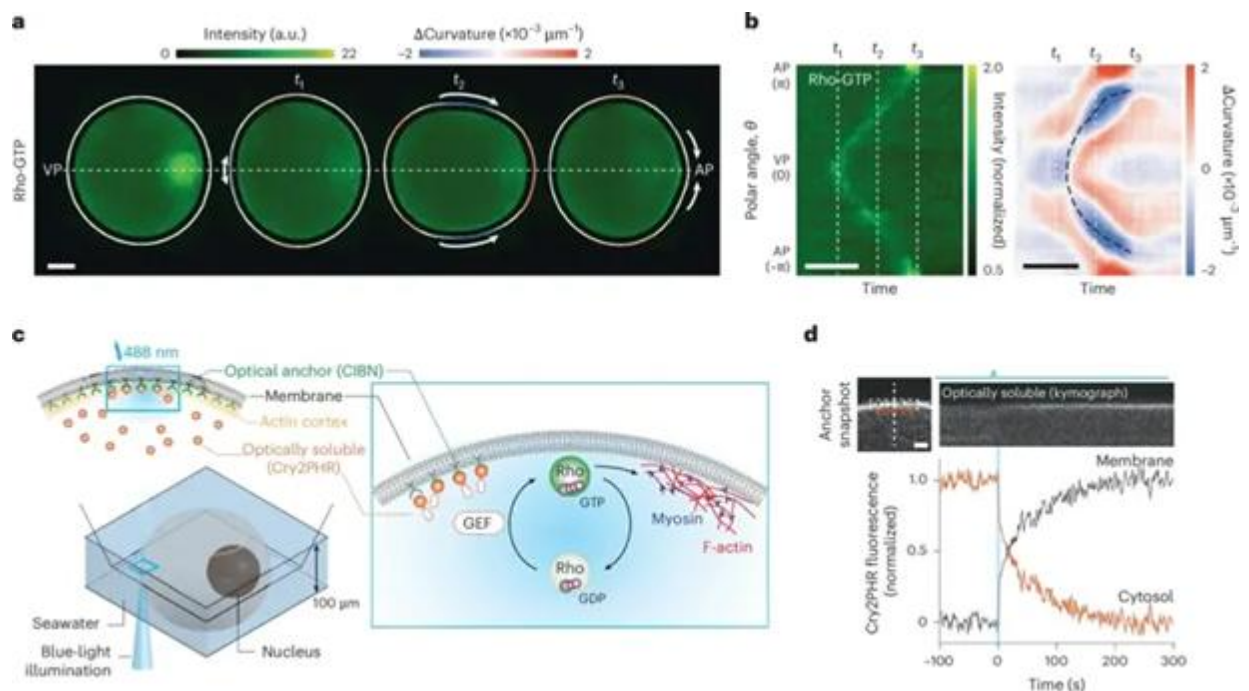
Researchers engineered a new type of GEF enzyme sensitive to light, giving them precise control over this cellular machinery. They extracted genetic instructions ([mRNA](#)) for the modified enzyme and injected these instructions into starfish egg cells. The cells began producing the new enzyme themselves, effectively becoming responsive to light signals.

Directing Cell Movements with Precision

Under a microscope, scientists then aimed tiny beams of light onto specific regions of these cells. As they did this, the light-sensitive GEF activated Rho proteins exactly where the light shone. Immediately, the activated [Rho proteins](#) triggered contractions in the cell surface, causing predictable and precise shape changes.

The researchers were able to induce small, local pinches or larger, sweeping waves of contraction. Remarkably, by carefully placing beams of light around the cells, they even reshaped their outlines entirely—transforming normally round cells into distinctly square shapes. Such precision highlights the potential of optogenetics in guiding complex cellular movements.

"We realized this Rho-GEF circuitry is an excitable system, where a small, well-timed stimulus can trigger a large, all-or-nothing response," said Nikta Fakhri, associate professor of physics at MIT and senior author of the study. "So we can either illuminate the whole cell or just a tiny place on the cell, recruiting enough enzyme so the system kickstarts contractions on its own."



Optogenetic GEF assay enables real-time control of cellular geometry in prophase-arrested starfish oocytes. (CREDIT: Nature Physics)© The Brighter Side of News

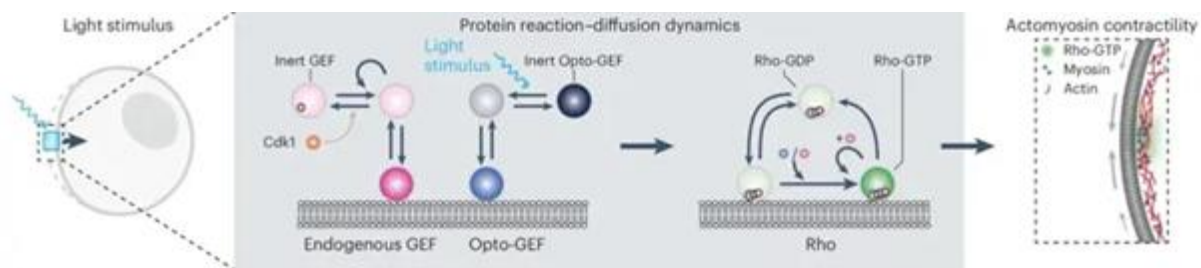
Understanding and Predicting Cell Behavior

The team didn't stop at manipulating the cells. They developed a mathematical model to predict how the cells would respond based on the pattern of light applied. This model accounts for chemical signals and how the cell's geometry affects its movements. Through this framework, scientists can now predict the

range of possible shapes and behaviors a cell might exhibit, based purely on how it's stimulated.

This new model clarifies a fundamental aspect of cell biology: the 'excitability' of cells, which dictates their readiness to respond dramatically to minor signals. According to Fakhri, understanding this excitability can provide crucial insights into biological processes such as [wound healing](#) and embryo formation, where cell movements must be precisely timed and coordinated.

The broader implications of this research are significant. By mastering how cells move in response to chemical signals—now controlled precisely by light—scientists envision developing synthetic cells that perform specific medical functions. These could include therapeutic cells designed to contract when exposed to light, aiding in wound closure, or carrier cells programmed to deliver drugs exactly where and when needed inside the body.



A chemo-mechanical model quantitatively captures the dynamic cell geometry in response to optogenetic stimuli. (CREDIT: Nature Physics)© The Brighter Side of News

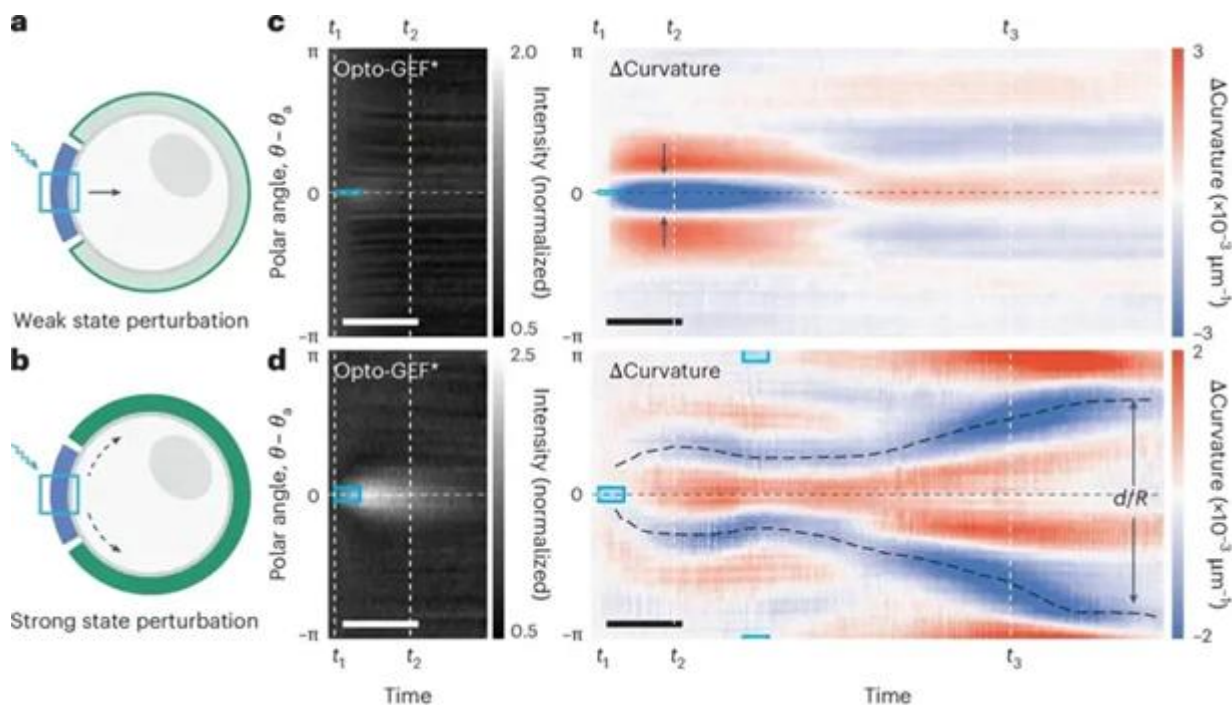
"By revealing how a light-activated switch can reshape cells in real time, we're uncovering basic design principles for how living systems self-organize and evolve shape," said Fakhri. "The power of these tools is that they're guiding us to decode all these processes of growth and development, helping us understand how nature does it."

The Role of Starfish: Nature's Model for Symmetry

Starfish offer a uniquely useful model for studying cell growth and shape. These creatures begin life as symmetrical cells but develop complex symmetry patterns as they mature—from bilateral symmetry as larvae to five-fold symmetry as

adults. Understanding the chemical signals guiding these symmetry changes provides essential clues about how [living organisms](#) organize themselves.

The researchers used starfish egg cells because these cells clearly demonstrate chemo-mechanical waves during division. These waves emerge due to peaks in the Rho protein, driven by the enzyme GEF. By choosing starfish cells, the researchers effectively showcased the potential to control and harness these fundamental biological processes in a simpler, observable system.



Bridging Biology and Technology

Advances in optogenetics bridge biology with technology, offering powerful tools to control life processes. Fakhri's group's achievement demonstrates that precise manipulation of cell behavior using light isn't just theoretically interesting—it is now practical and achievable. By controlling the cell's chemical circuitry with simple beams of light, scientists have created a groundbreaking way to influence how life physically develops.

The next steps include using this approach to create synthetic cells capable of complex, life-like movements. Future applications may revolutionize biotechnology, medicine, and [materials science](#), inspiring innovations in artificial

tissues, advanced wound healing therapies, and highly targeted drug delivery systems.

In uncovering the hidden choreography of cells, these researchers illuminate a pathway toward building programmable, life-like cells. Such advances hold promise not just in understanding biology but in applying that knowledge to enhance human health and technology, reshaping the boundaries between natural life and synthetic innovation.

The research findings were published in the journal [Nature Physics](#).

Light Moves Faster Than Ever in New Chip Device

Harnessing the power of special light-based technologies has long promised stable and efficient ways to control how light moves through devices. But one major limitation has been the need for slow and careful changes to maintain something called "adiabaticity" - a condition where light moves through a system without jumping unpredictably between different energy levels. A recent study offers an important advancement by identifying the shortest possible time these changes can happen, opening the door to smaller and faster optical devices.

Professor Tao Li and Dr. Wange Song, from Nanjing University have developed a method to reach this shortest limit - known as the adiabatic infimum, the minimum time or length needed to preserve stability in a system - using specially designed light-guiding structures made from lithium niobate, a crystal material often used in high-performance optics. Their work is published in the peer-reviewed journal Nature Communications.

The research centers on a process known as topological pumping, a way of transferring light or other particles from one location to another in a system by carefully adjusting conditions over time. What makes this process special is its topological nature - meaning it relies on the overall structure of the system rather than its specific details, which helps it remain stable even when imperfections are

present. Normally, this transfer requires slow adjustments to keep the system adiabatic, but the team discovered a way to speed up the process by optimizing the path that controls how the system evolves.

To make this work, Professor Li and Dr. Song focused on the shape of what's called a modulation loop, the path along which key system properties are varied to guide the light. Central to their approach was minimizing the Berry connection, a mathematical concept that describes how the quantum state of light shifts as it moves through the system. This connection determines how likely the light is to jump into unwanted states. By finding a way to reduce it along the path, the researchers made it possible for the system to evolve faster while still staying stable.

The team tested this using two versions of their design, both based on the Rice-Mele model, a simplified framework often used to study systems with two alternating parts, like a chain of optical waveguides. One design followed the traditional loop, while the other used their optimized version, referred to as the INFI loop - short for "infimum" - representing the most efficient route. In the standard setup, the light only moved cleanly when the device was relatively long. In contrast, the INFI loop achieved the same result over a much shorter distance. "We approach the adiabatic infimum by minimizing the effective Berry connection along the loop," Professor Li said, highlighting how this smarter route avoided problematic areas in the system's configuration.

These results weren't just theoretical. The researchers built the devices on chips using thin layers of lithium niobate, known as a thin-film lithium niobate-on-insulator platform, which is a technology that combines good optical properties with the ability to make compact devices. They injected light into the waveguide structures - tiny paths that guide light along specific routes - and observed how it moved. In the traditional design, the light failed to stay on track unless the path was long enough. But in the new design, the light followed its intended route over a much shorter length, confirming the success of the approach.

"The adiabatic infimum accelerates the topological pumps from the constraints of slow evolution and facilitates the design of compact topological devices" Dr. Song added. In other words, this method lifts the restrictions caused by slow processes and enables much smaller devices with the same performance. This is

especially important for lithium niobate platforms, which typically need more space because the material bends light less strongly than others like silicon.

The findings also provide new understanding of how light can be controlled in systems that are stable against imperfections. By rethinking how paths are shaped in the system's configuration space - the abstract landscape that represents all possible settings - the team has shown that light can be pumped faster without losing reliability. This has broad potential in areas such as quantum computing, where light needs to move precisely and quickly, or in telecommunications and sensing technologies that require compact, reliable optical circuits.

Professor Li and Dr. Song's study has not only improved the performance of these devices, but also offered new insights into the physics behind them. By reaching the adiabatic infimum, they've shown how careful design can push the limits of speed and efficiency in light-based systems - a step forward in developing the next generation of optical technologies.

Journal Reference

Wu S., Song W., Sun J., Li J., Lin Z., Liu X., Zhu S., Li T. "Approaching the adiabatic infimum of topological pumps on thin-film lithium niobate waveguides." *Nature Communications*, 2024. DOI: <https://doi.org/10.1038/s41467-024-54065-9>

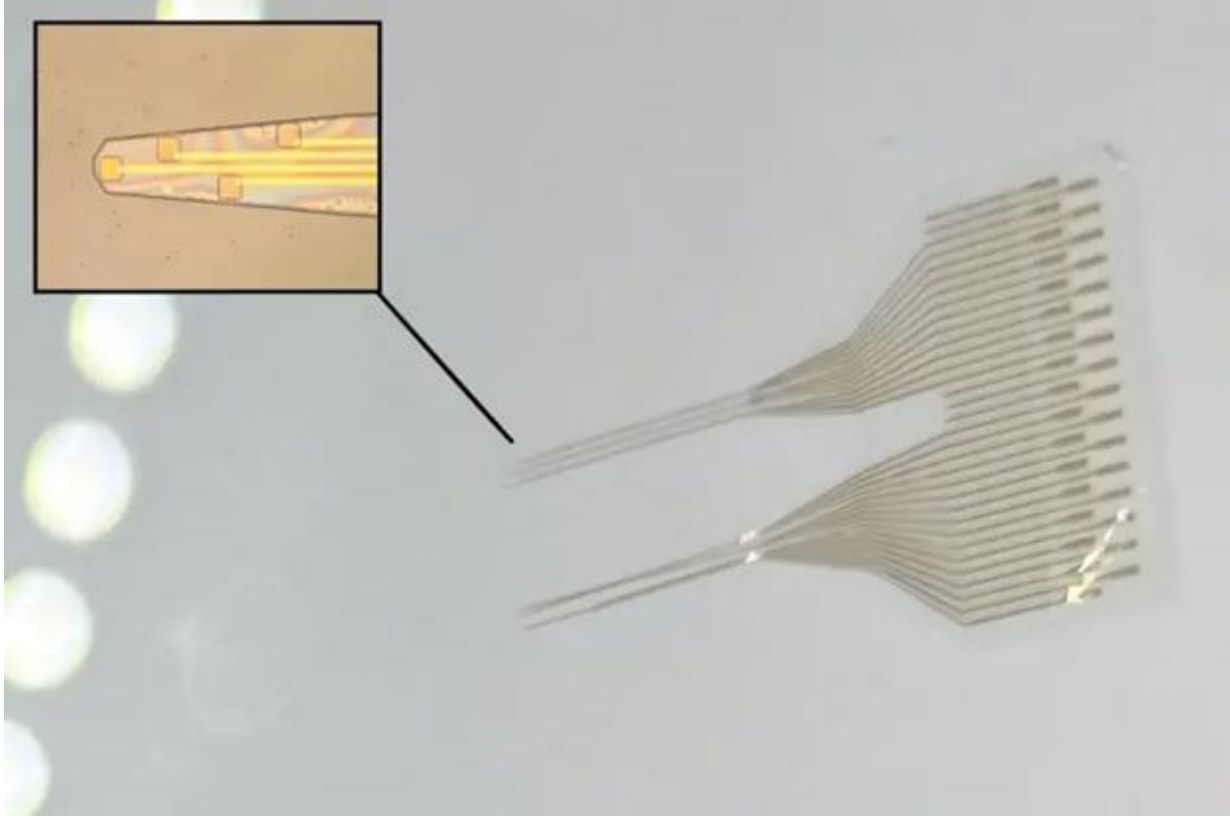
About the Authors

Tao Li is a professor at Nanjing University. He received the National Science Fund for Distinguished Young Scholars and the Excellent Young Scientists Fund. He has also received the "Wang Kuancheng" Education Fund from Hong Kong and has been selected as a leading talent in science and technology innovation by the Ministry of Science and Technology, as well as being part of the first cohort of Nanjing University's "Dengfeng Project B." He has been recognized five times for significant advancements in the field of optics in China. Professor Li has delivered over 50 invited talks at international conferences and has published more than 130 papers in journals such as *Nature* and its sub-journals, *Phys. Rev. Lett.*, and *Light Sci. Appl.*, with his work being cited over 12,000 times. Currently, he serves

as a youth editorial board member for the Chinese Laser Press and an editorial board member for several other journals and publications, including Science Bulletin and ADI. He is also a council member of the Metamaterials Division of the Chinese Materials Research Society, the Jiangsu Physical Society, and the Jiangsu Optical Society.

Wange Song is an associate researcher at Nanjing University and a visiting scholar at the University of Hong Kong. He obtained his Bachelor's degree in Materials Physics from Nanjing University in 2016 and his Ph.D. in Optical Engineering from the same university in 2021. He has been awarded the Wang Daheng Optics Award, the Jiangsu Province Young Optical Science and Technology Award, and has been selected as a Yuxiu Young Scholar at Nanjing University. Song's research primarily focuses on micro-nano optics, and in recent years, he has made significant contributions in the fields of topological optics and non-Hermitian optical field manipulation. To date, he has published over 30 papers in international academic journals such as PRL (6 papers), Nat. Commun., and Sci. Adv. His research has been featured in Editor's Suggestions and cover articles, and has been highlighted by Physics, PhysOrg and SPIE. He also serves as a youth editorial board member and guest editor for several academic journals.

Chance discovery improves stability of bioelectronic material used in medical implants, computing and biosensors



Implantable electrocorticography device made using the heat treatment method. Credit: Margaux Forner

A chance discovery led a team of scientists from Rice University, University of Cambridge and Stanford University to streamline the production of a material widely used in medical research and computing applications.

For more than two decades, scientists working with a composite material known as PEDOT:PSS, used a chemical crosslinker to make the conductive polymer stable in water. While experimenting with ways to precisely [pattern the material](#) for applications in biomedical optics, Siddharth Doshi, a doctoral student at Stanford collaborating with Rice materials scientist Scott Keene, skipped adding the crosslinker and used a higher temperature while prepping the material. To his surprise, the resulting sample turned out to be stable on its own—no crosslinker needed.



Rice University logo patterned into PEDOT:PSS using a femtosecond laser. Credit: Siddharth Doshi

"It was more of a serendipitous discovery because Siddharth was trying out processes very different to the standard recipe, but the samples still turned out fine," Keene said. "We were like, 'Wait! Really?' This prompted us to look into why and how this worked."

What Keene and his team found was that heating PEDOT:PSS beyond the usual threshold not only makes it stable without the need for any crosslinker, but it also creates higher-quality devices. This method, described in a [recent study](#) published in *Advanced Materials*, could make the manufacture of bioelectronic devices easier and more reliable with potential applications in neural implants, biosensors and next-generation computing systems.

PEDOT:PSS is a blend of two polymers: one that conducts electronic charge and does not dissolve in water and another that conducts ionic charge and is water-soluble. Because it conducts both types of charges, PEDOT:PSS bridges the gap between living tissue and technology.

"It allows you to essentially talk the language of the brain," said Keene, who researches advanced materials for smaller, high-resolution electrodes capable of both recording and stimulating neural activity with precision.

The human nervous system relies on ions—charged particles like sodium and potassium—to transmit signals, while electronic devices work with electrons. A material that can handle both is crucial for neural implants and other bioelectronic devices that need to translate biological activity into readable data and send signals without damaging sensitive tissue.

By eliminating the crosslinker, the research findings not only streamline the PEDOT:PSS fabrication process but also improve its performance. The new method produces a material with three times higher electrical conductivity and more consistent stability between batches—key advantages for medical applications.

The crosslinker worked by chemically bonding the two types of polymer strands in PEDOT:PSS together, creating an interconnected mesh. However, it still left some of the water-soluble strands exposed—a likely cause for the stability issues. Moreover, the crosslinker introduced variability and potential toxicity in the material.

In contrast, the higher heat stabilizes PEDOT:PSS by causing a phase change in the material. When heated beyond a certain temperature, the water-insoluble polymer reorganizes internally, pushing the water-soluble components to the surface, where they can be washed away. What remains is a thinner, purer and more stable conducting film.

"This method pretty much simplifies a lot of these problems that people have working with PEDOT:PSS," Keene said. "It also essentially eliminates a potentially toxic chemical."

Margaux Forner, a doctoral student at Cambridge who is a first author on the paper along with Doshi, said that heat-treated bioelectronic devices such as transistors, spinal cord stimulators and electrocorticography arrays—implanted grids or strips of neuroelectrodes used to record brain activity—were easier to fabricate, more reliable and equally high performing to those fabricated using the crosslinker.

"The devices made from heat-treated PEDOT:PSS proved to be robust in chronic in vivo experiments, maintaining stability for over 20 days post implantation," Forner said. "Notably, the film maintained excellent electrical performance when stretched, highlighting its potential for resilient bioelectronic devices both inside and outside the body."

The finding may help explain why previous efforts to use PEDOT:PSS in long-term neural implants, including those by Neuralink, ran into stability issues. By making PEDOT:PSS more reliable, this discovery could help advance neurotechnology, including implants to restore movement after spinal cord injuries and interfaces that link the brain to external devices.

Beyond simplifying fabrication, the team found a way to pattern PEDOT:PSS into microscopic 3D structures—a breakthrough that could further improve bioelectronic devices. Using a high-precision femtosecond laser, the researchers can selectively heat sections of the material, creating custom textures that enhance how cells interact with the devices.

"We are really excited about the ability to 3D-print the polymers at the microscale," Doshi said. "This has been a major goal for the community as writing this functional material in 3D could let you interface with the 3D world of biology. Typically, this is done by combining PEDOT:PSS with different photosensitive binders or resins; however, these additions affect the properties of the material or are challenging to scale down to micron-length scales."

In past research, Keene explored patterning grooves onto electrodes, finding that cells preferentially adhere to grooves on the same order as their length scale. In other words, "a 20 micron cell likes to grab on to 20 micron-sized textures," he said.

This technique could be used to design neural interfaces that encourage better integration with surrounding tissue, improving signal quality and longevity.

Keene had also previously researched PEDOT:PSS in the context of neuromorphic memory devices used to accelerate artificial intelligence algorithms. Neuromorphic memory is a type of artificial memory that mimics how the brain retains information.

"It basically emulates the synaptic plasticity of your brain," Keene said. "We can modify the connection between two terminals by controlling how conductive this material is; this is very similar to how your brain learns by strengthening or weakening synaptic connections between individual neurons."

By unseating a long-standing assumption, the research not only made PEDOT:PSS easier to work with but also more powerful—a shift that could accelerate the development of safer, more effective neural implants and bioelectronic systems.

More information: Siddharth Doshi et al, Thermal Processing Creates Water-Stable PEDOT:PSS Films for Bioelectronics, *Advanced Materials* (2025). DOI: [10.1002/adma.202415827](https://doi.org/10.1002/adma.202415827)

Provided by Rice University

Listening to quantum atoms talk together thanks to acoustics



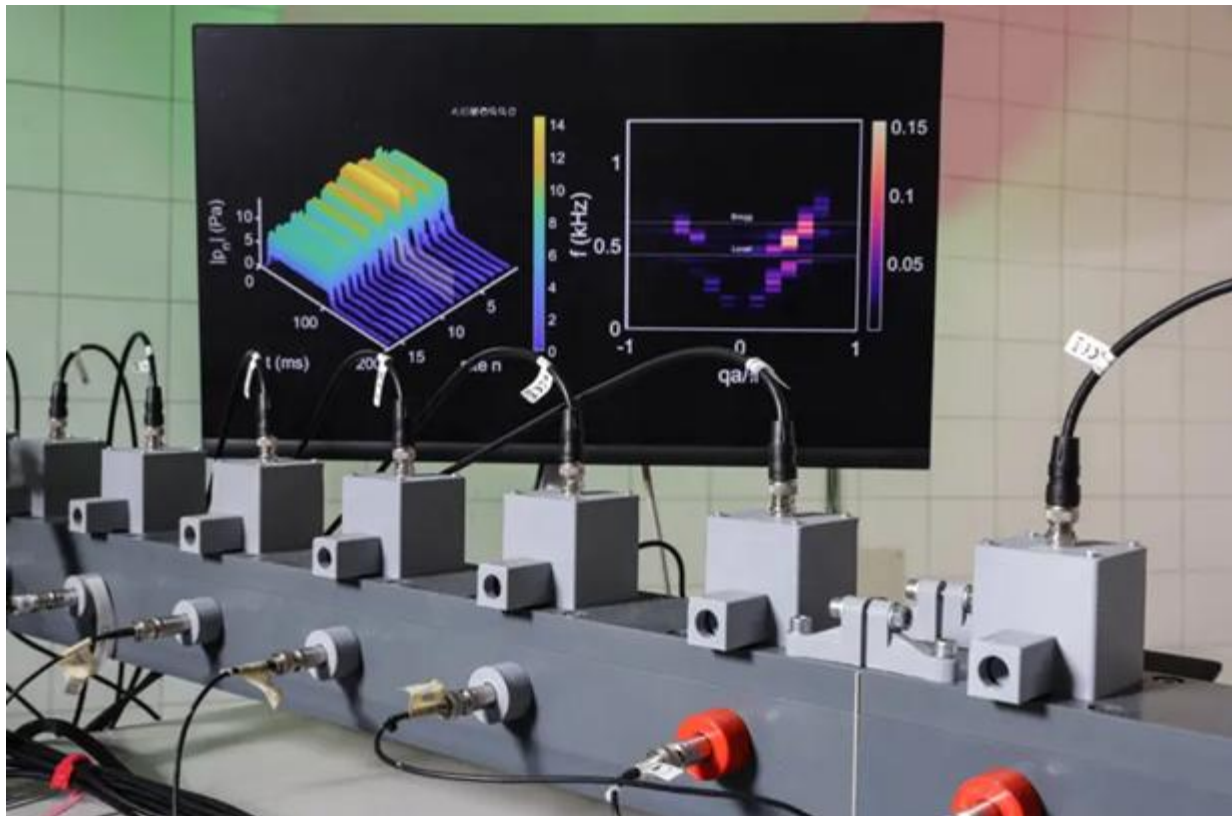
(From left to right): Mathieu Padlewski, Romain Fleury and Hervé Lissek standing with their metamaterial. More photos available in the press kit. Credit: Alain Herzog / EPFL

What happens when a quantum physicist is frustrated by the limitations of quantum mechanics when trying to study densely packed atoms? At EPFL, you get a metamaterial, an engineered material that exhibits exotic properties.

That frustrated physicist is Ph.D. student Mathieu Padlewski. In collaboration with Hervé Lissek and Romain Fleury at EPFL's Laboratory of Wave Engineering, Padlewski has built a novel acoustic system for exploring condensed matter and their macroscopic properties, all the while circumventing the extremely sensitive nature that is inherent to quantum phenomena. Moreover, the acoustic system can be tweaked to study properties that go beyond solid-state physics. The results are [published](#) in *Physical Review B*.

EPFL metamaterial. More photos available in the press kit. Credit: Alain Herzog / EPFL

"We've essentially built a playground inspired by quantum mechanics that can be adjusted to study various systems. Our metamaterial consists of highly tunable active elements, allowing us to synthesize phenomena that extend beyond the realm of nature," says Padlewski. "Potential applications include manipulating waves and guiding energy for telecommunications, and the setup may one day provide clues for harvesting energy from waves for instance."



Schrödinger's cat, the quantum conundrum

In quantum mechanics, the cat is both dead and alive inside of the box until you interfere with the system by measuring it, which is done in this case by opening the box. From a purely quantum perspective, the cat is in a superposition of two probable states: a probable state of being dead and a probable state of being alive, until you open the box only to observe if the cat is actually dead or alive.

A cat cannot be both dead and alive at the same time, and that's the essence of the Schrödinger cat, a thought experiment devised by Erwin Schrödinger in 1935 that illustrates the complexities of quantum concepts when imagined beyond the quantum scale, like the scale of a cat.

The sensitive nature of quantum physics that makes observation of solid states so difficult comes from the act of measuring the system, which forces the quantum system into a state, instead of allowing the system to exist—uninterrupted—in a superposition of probability states. That said, physicists know how to probe the electronic states indirectly and infer their corresponding properties.

Modeling quantum phenomena with sound waves

But there is another phenomenon for which Schrödinger's cat makes perfect sense in the macroscopic world, and it's one that we can interact with: sound.

If we take the sound of one's voice for instance, we know that the reason why someone's voice is unique and rich is because we hear the whole spectrum of frequencies. The frequency spectrum is characteristic for a given voice, but it also explains why the piano has its unique timbre, or why the trumpet sounds differently from the trombone.

In principle, we can simultaneously hear the fundamental frequency, aka the fundamental state, plus all of the higher frequencies known as the harmonics. Borrowing language from quantum physics, we are actually hearing a superposition of many states at once. Or by analogy with Schrödinger's cat, the cat is both dead and alive, and we can hear it.

"Quantum probability waves are waves after all—why not model them with sound?" says Padlewski. "Probing the electronic states of a solid state, directly without perturbation, would be like having a blind person tread through a busy street without a cane. But in acoustics, we can probe waves directly, in phase and in amplitude without destroying the state—which is nice."

Engineering an acoustic metamaterial

The acoustic metamaterial built at EPFL consists of a line of "acoustic atoms," essentially 16 small cubes connected to one another with openings to allow for the placement of multiple speakers or microphones. Speakers generate sound waves that are to propagate through the line of acoustic atoms in a controlled way, microphones measure sound waves for feedback control. The cubes can be viewed as building blocks for building more complex systems that go beyond a simple line.

"When you see the cochlea, the ear's organ responsible for hearing, it resembles our active acoustic metamaterial in its structure and functionality," says Lissek. "The cochlea consists of a perfect line of cells that amplify different frequencies."

Our metamaterial could potentially be tuned to function the same way and study hearing problems like tinnitus."

Towards a quantum-inspired analog computing

Padlewski is also keen to use the metamaterial building blocks to investigate ways to build one of the first acoustic analog computers capable of generating non-separable states. Inspired by the work of Pierre Deymier of Arizona University, this computer would essentially be an acoustic equivalent of a quantum computer. It would allow for the direct observation of superposed states without interfering with the system, because acoustic waves are not as fragile as quantum ones.

"An acoustic quantum analog computer would be more like a crystal lattice—a periodic array of cells just as atoms are arranged in crystals," adds Padlewski. "The acoustic approach to quantum computation has the potential to offer an alternate way of processing vast amounts of information simultaneously."

More information: Mathieu Padlewski et al. Observation of amplitude-driven nonreciprocity for energy guiding, *Physical Review B* (2025). DOI: [10.1103/PhysRevB.111.125156](https://doi.org/10.1103/PhysRevB.111.125156), [journals.aps.org/prb/abstract/ ... /PhysRevB.111.125156](https://journals.aps.org/prb/abstract/10.1103/PhysRevB.111.125156). On *arXiv*: arxiv.org/html/2409.20032v2

Provided by Ecole Polytechnique Federale de Lausanne

New Phase Of Matter In Magnets Is Like “Half Ice, Half Fire”



The half ice, half fire state doesn't look quite as cool (or as hot!) as this. - Image credit: glavbooh/Shutterstock.com© IFL Science

Less than a decade ago, researchers found a peculiar phase of matter where the electrons of a particular compound would behave in two very distinct phases. Some had spins that were very well organized, while others were a complete mess. They called this the “half fire, half ice” state. Now, researchers have found that under some extremely specific conditions, the opposite state forms.

The curious material in which they made this discovery is called $\text{Sr}_3\text{CuIrO}_6$, a magnetic compound of strontium, copper, iridium, and oxygen. In 2016, when studying this material, Alexei Tsvelik and Weiguo Yin from the Brookhaven National Laboratory uncovered a peculiar phase of matter over a certain temperature and under the influence of an external magnetic field.

Electrons have a property called spin, which is akin to the angular momentum, like that of a spinning top. They can point in specific directions or in random ones, but in this state – the “half fire, half ice” – the sites where copper atoms are have spins that are all disordered, while on the iridium sites, the spins are fully ordered.

The team has now discovered that, at a very specific point, the state goes from fire and ice to ice and fire. The copper sites become "frozen", while the iridium sites become "hot" with randomly pointing spins. In particular, the switch between the two states is very sharp, and the team thinks that this could have some exciting applications.

"Finding new states with exotic physical properties — and being able to understand and control the transitions between those states — are central problems in the fields of condensed matter physics and materials science," Yin said in a [statement](#). "Solving those problems could lead to great advances in technologies like quantum computing and spintronics."

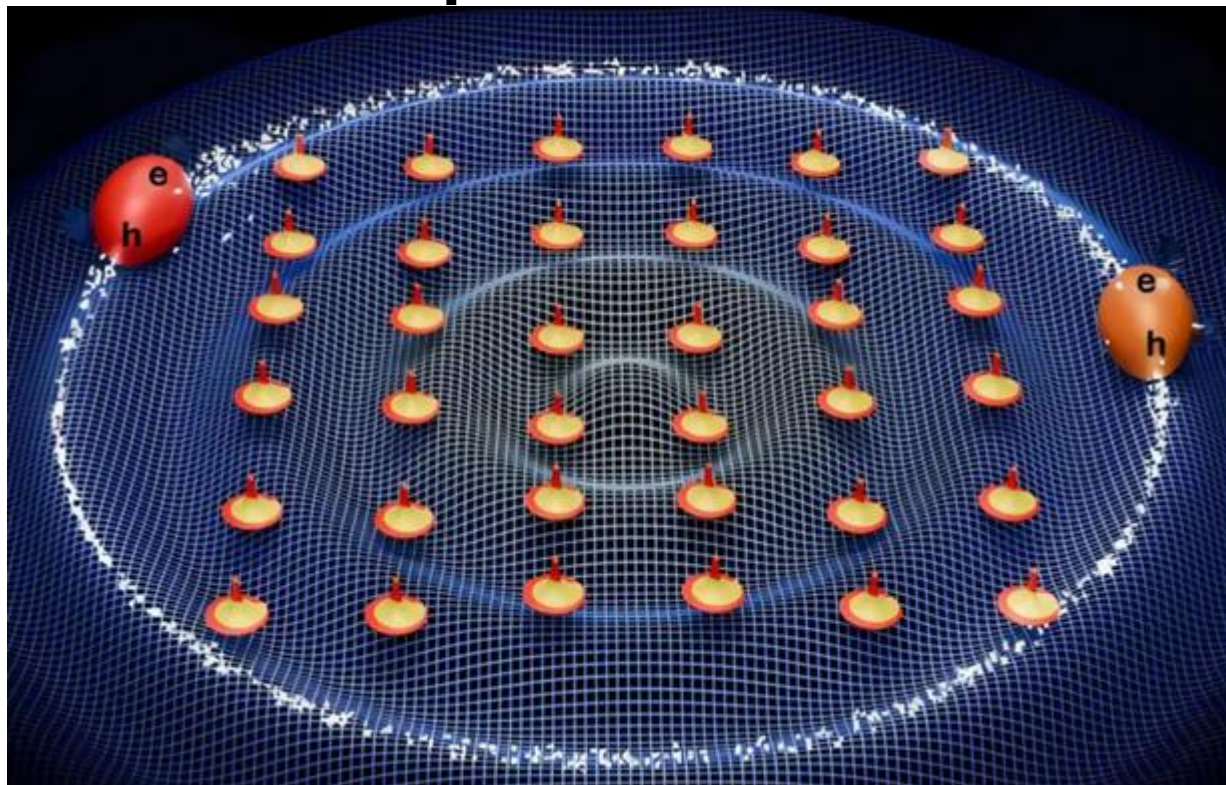
"We suggest that our findings may open a new door to understanding and controlling phases and phase transitions in certain materials," added Tsvelik.

The team believes that intriguing applications could be made in advanced refrigeration technologies, but the sharpness of the phase change could also be used in [quantum](#) information technology – for example, as a form of storage. Instead of 0s and 1s, you might have fire/ice or ice/fire.

"Next, we are going to explore the fire-ice phenomenon in systems with quantum spins and with additional lattice, charge, and orbital degrees of freedom," said Yin. "The door to new possibilities is now wide open."

The study is published in the journal [Physical Review Letters](#).

Physicists uncover electronic interactions mediated via spin waves



Rendition of the discovery where the excitons (e-h pairs) interact via ripples in the magnetic structure akin to an array of spinning tops generating a wave that affects each other and couples the excitons. Credit: Visakh Menon

Research by physicists at The City College of New York is being credited for a novel discovery regarding the interaction of electronic excitations via spin waves. The finding by the Laboratory for Nano and Micro Photonics (LaNMP) team headed by physicist Vinod Menon could open the door to future technologies and advanced applications such as optical modulators, all-optical logic gates, and quantum transducers. The [work](#) is reported in the journal *Nature Materials*.

The researchers showed the emergence of interaction between electronic excitations (excitons—electron hole pairs) mediated via spin waves in atomically thin (2D) magnets. They demonstrated that the excitons can interact indirectly through magnons (spin waves), which are like ripples or waves in the 2D material's magnetic structure.

"Think of magnons as tiny flip-flops of atomic magnets inside the crystal. One exciton changes the local magnetism, and that change then influences another

exciton nearby. It's like two floating objects pulling toward each other by disturbing water waves around them," said Menon.

To demonstrate this, the Menon group utilized a [magnetic semiconductor](#), CrSBr, which the group had previously shown to host strong light-matter interaction.

Post-doctoral fellows Biswajit Datta and Pratap Chandra Adak led the research along with graduate students Sichao Yu and Agneya Dharmapalan in collaboration with the groups at the CUNY Advanced Science Research Center, University of Chemistry and Technology—Prague, RPTU—Kaiserslautern, Germany and NREL, U.S.

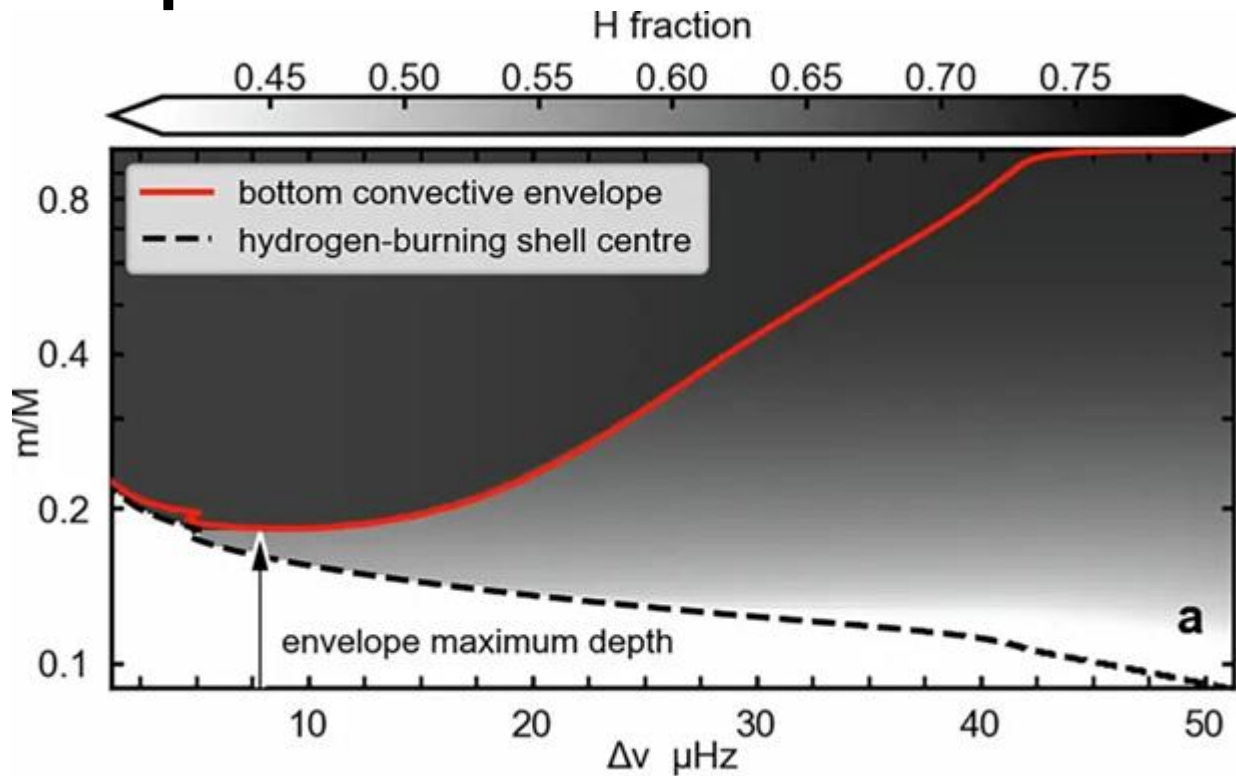
"What is especially exciting about this discovery is that the interaction between excitons can be controlled externally using a magnetic field, thanks to the tunable magnetism of 2D materials. That means we can effectively switch the interaction on or off, which is hard to do with other types of interactions," said Datta.

"One particularly exciting application enabled by this discovery is in the development of quantum transducers—devices that convert quantum signals from one frequency to another, such as from microwave to optical. These are key components for building quantum computers and enabling the quantum internet." said Adak, another lead author of this work.

More information: Biswajit Datta et al, Magnon-mediated exciton–exciton interaction in a van der Waals antiferromagnet, *Nature Materials* (2025). DOI: [10.1038/s41563-025-02183-0](https://doi.org/10.1038/s41563-025-02183-0)

Provided by The City University of New York

Astronomers listened to the 'music' of flickering stars—and discovered an unexpected feature



Hydrogen and helium fractions and the bottom of the convective envelope. Credit: Nature (2025). DOI: 10.1038/s41586-025-08760-2

The "music" of starquakes—enormous vibrations caused by bursting bubbles of gas that ripple throughout the bodies of many stars—can reveal far more information about the stars' histories and inner workings than scientists thought.

In [new research published in *Nature*](#), we analyzed the frequency signatures of starquakes across a broad range of giant stars in the M67 star cluster, almost 3,000 light years from Earth.

Using observations from the Kepler space telescope's K2 mission, we had a rare opportunity to track the evolution of stars during most of their journey through the giant phase of the stellar life cycle.

In doing so, we discovered that these stars get stuck "playing the same part of their tune" once their turbulent outer layer reaches a sensitive region deep inside.

This discovery reveals a new way to understand the history of stars—and of the entire galaxy.

The sound of starquakes

Starquakes happen in most stars (like our sun) that have a bubbling outer layer, like a pot of boiling water. Bubbles of hot gas rise and burst at the surface, sending ripples through the entire star that cause it to vibrate in particular ways.

We can detect these vibrations, which occur at specific "resonant frequencies," by looking for subtle variations in the brightness of the star. By studying the frequencies of each star in a group called a cluster, we can tune into the cluster's unique "song."

Our study challenges previous assumptions about resonant frequencies in giant stars, revealing they offer deeper insights into stellar interiors than previously thought. Moreover, our study has opened new ways to decipher the history of our galaxy.

The melody of a stellar cluster

Astronomers have long sought to understand how stars like our sun evolve over time.

One of the best ways to do this is by studying clusters—groups of stars that formed together and share the same age and composition. A cluster called M67 has attracted a lot of attention because it contains many stars with a similar chemical makeup to the sun.

Just as earthquakes help us study the Earth's interior, starquakes reveal what lies beneath a star's surface. Each star "sings" a melody, with frequencies determined by its internal structure and physical properties.

Larger stars produce deeper, slower vibrations, while smaller stars vibrate at higher pitches. And no star plays just one note—each one resonates with a full spectrum of sound from its interior.

A surprising signature

Among the key frequency signatures is the so-called small spacing—a group of resonant frequencies quite close together. In younger stars, such as the sun, this signature can provide clues about how much hydrogen the star still has left to burn in its core.

In red giants, the situation is different. These older stars have used up all the hydrogen in their cores, which are now inert.

However, hydrogen fusion continues in a shell surrounding the core. It was long assumed that the small spacings in such stars offered little new information.

A stalled note

When we measured the small spacings of stars in M67, we were surprised to see they revealed changes in the star's internal fusion regions.

As the hydrogen-burning shell thickened, the spacings increased. When the shell moved inward, they shrank.

Then we found something else unexpected: at a certain stage, the small spacings stalled. It was like a record skipping on a note.

We discovered that this stalling appears during a specific stage in the life of a giant star—when its outer envelope, the "boiling" layer that transports heat, grows so deep that it makes up about 80% of the star's mass. At this point the inner boundary of the envelope reaches into a highly sensitive region of the star.

This boundary is extremely turbulent, and the speed of sound shifts steeply across it—and that steep change affects how sound waves travel through the star. We also found that the stalling frequency is distinctively determined by the star's mass and chemical composition.

This gives us a new way to identify stars in this phase and estimate their ages with improved precision.

The history of the galaxy

Stars are like fossil records. They carry the imprint of the environments in which they formed, and studying them lets us piece together the story of our galaxy.

The Milky Way has grown by merging with smaller galaxies, forming stars at different times in different regions. Better age estimates across the galaxy help us reconstruct this history in greater detail.

Clusters like M67 also provide a glimpse into the future of our own sun, offering insight into the changes it will experience over billions of years.

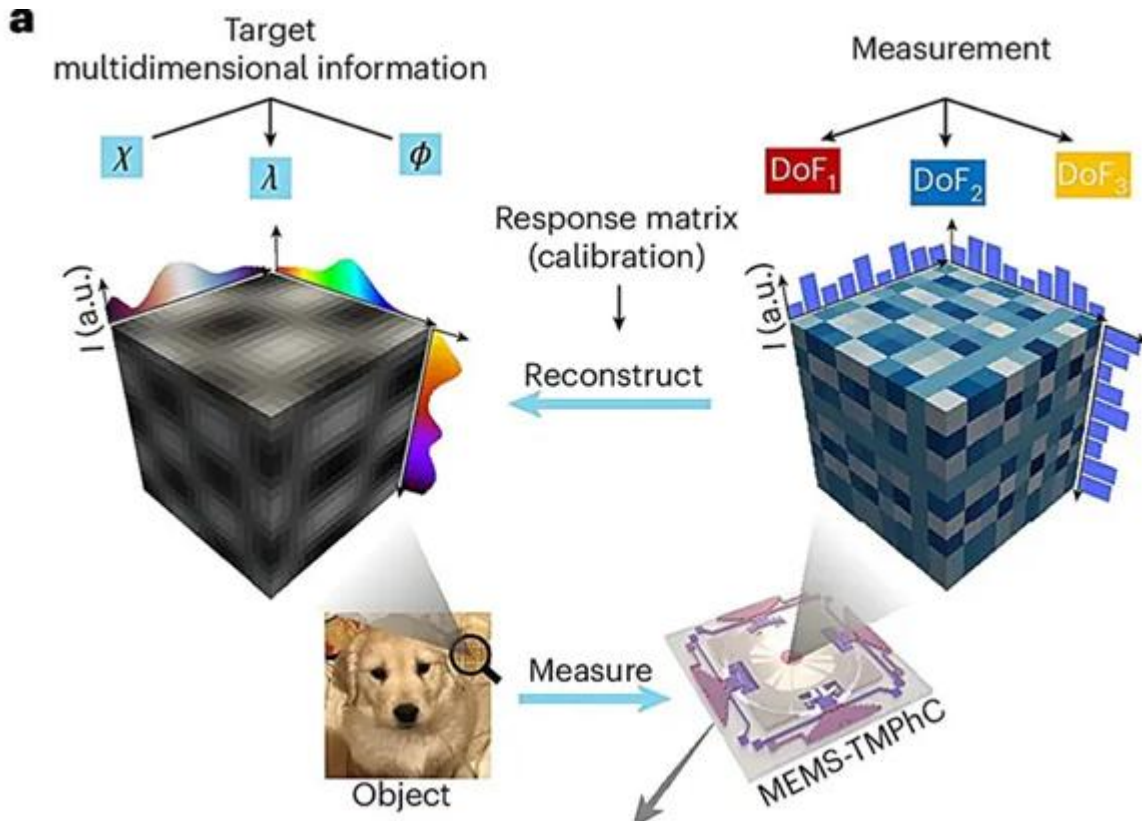
This discovery gives us a new tool—and a new reason to revisit data we already have. With years of seismic observations from across the Milky Way, we can now return to those stars and "listen" again, this time knowing what to listen for.

More information: Claudia Reyes, Acoustic modes in M67 cluster stars trace deepening convective envelopes, *Nature* (2025). DOI: [10.1038/s41586-025-08760-2](https://doi.org/10.1038/s41586-025-08760-2). www.nature.com/articles/s41586-025-08760-2

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Provided by The Conversation

Twisted crystals open door to smaller, more powerful sensors for optical devices



Computational reconstruction of multidimensional information. Credit: Nature Photonics (2025).
<https://doi.org/10.1038/s41566-025-01650-z>

Twisted moiré photonic crystals—an advanced type of optical metamaterial—have shown enormous potential in the race to engineer smaller, more capable and more powerful optical systems. How do they work?

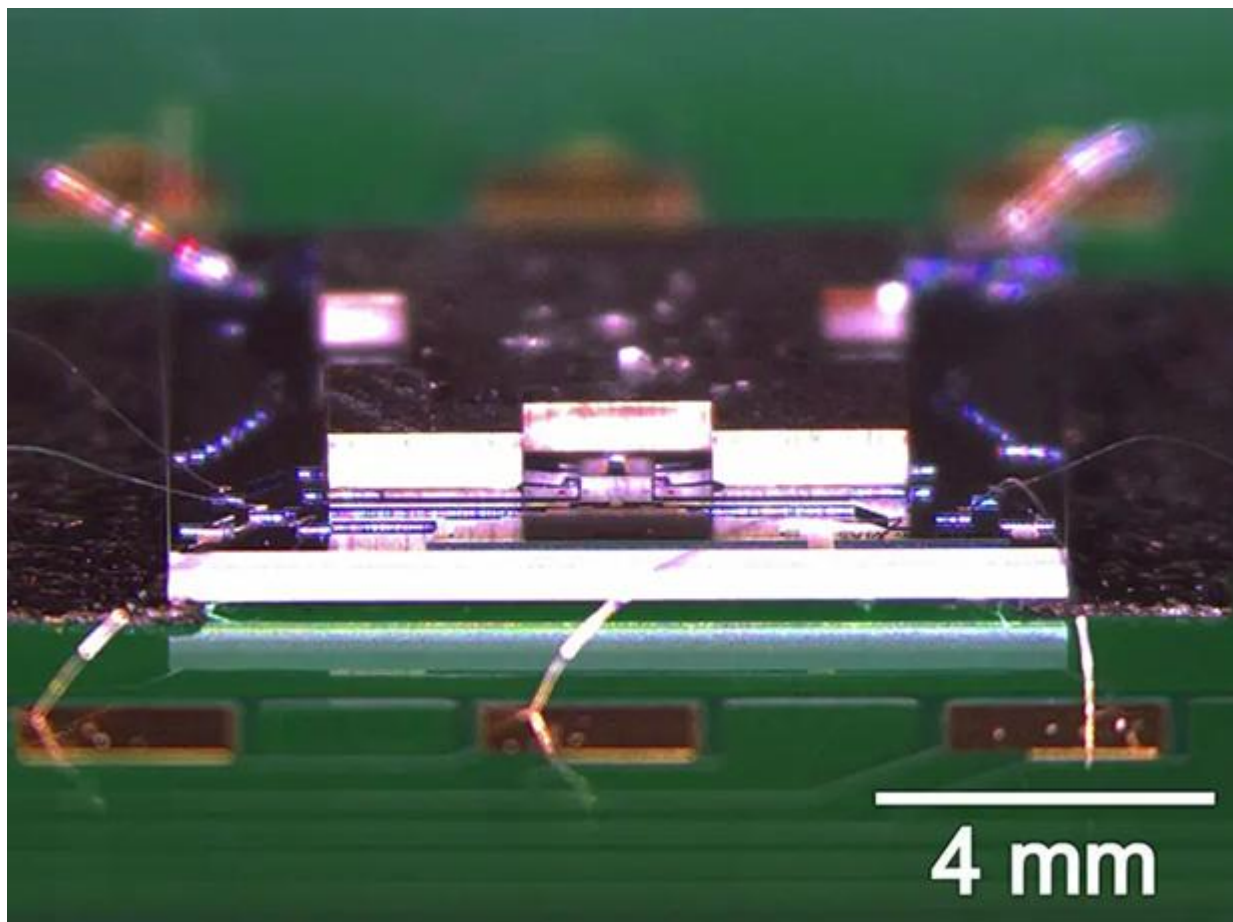
Imagine you have two pieces of fabric with regular patterns, like stripes or checkers. When you lay the two pieces of fabric directly on top of each other, you can see each pattern clearly. But if you slightly shift one piece of fabric or twist it, new patterns that weren't in either of the original fabrics emerge.

In twisted moiré photonic crystals, how the layers twist and overlap can change how the material interacts with light. By changing the twist angle and the spacing between layers, these materials can be fine-tuned to control and manipulate

different aspects of light simultaneously—meaning the multiple optical components typically needed to simultaneously measure light's phase, polarization, and wavelength could be replaced with one device.

However, researchers have been unable to integrate twisted moiré photonic crystals into devices that can actively control the twist and distance between layers in real time, severely limiting their application.

Now, researchers from the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS), in collaboration with Stanford University and the University of California—Berkeley, have developed an on-chip twisted moiré photonic crystal sensor that uses MEMS technology to control the gap and angle between the crystal layers in real time. The sensor can detect and collect detailed polarization and wavelength information simultaneously.



The sideview of the packaged MEMS-TMPhC device wire bonded to printed circuit board. Credit: Nature Photonics (2025). <https://doi.org/10.1038/s41566-025-01650-z>

The research is [published](#) in *Nature Photonics*. The sample fabrication was performed at Harvard University Center for Nanoscale Systems.

"Twisted moiré photonic crystals are promising for engineering smaller, more powerful optical systems because they offer highly tunable optical properties, precise light control, compact and scalable design, and broad application potential across various advanced photonic technologies," said Eric Mazur, the Balkanski Professor of Physics and Applied Physics at SEAS and senior author of the paper.

"Our research demonstrates how powerful these materials can be when we have precise control and establishes a scalable path towards creating comprehensive flat-optics devices suitable for versatile light manipulation and information processing tasks," said Haoning Tang, a postdoctoral fellow at SEAS and first author of the study.

In the Harvard device, the layers of photonic crystals sit on vertical and rotary actuators, connected to an electrode. The whole device is only a few millimeters in scale and can be fabricated using CMOS-compatible processes, meaning it can be mass-fabricated using standard foundry nanofabrication processes.

The researchers demonstrated that by using the actuators to change the distance and rotational position of the layers of photonic crystals, they could perform simultaneous hyperspectral and hyperpolarimetric imaging—meaning every pixel captured by the sensor contained information from across the electromagnetic spectrum and detailed information about the polarization state. It is the first device with active tuning to demonstrate such detailed information about multiple properties of light.

"These devices could be used for a range of applications including quantum computing, data communications, satellites or medical scans, where getting a clear image and detailed information about light and color is really important," said Tang.

In the future, these devices would be made with even more complex tuning capabilities, including actuators with even more degrees of freedom.

More information: Tang, H. et al, An adaptive moiré sensor for spectro-polarimetric hyperimaging, *Nature Photonics* (2025). doi.org/10.1038/s41566-025-01650-z. www.nature.com/articles/s41566-025-01650-z

Provided by Harvard John A. Paulson School of Engineering and Applied Sciences

What's the shape of the universe?

Mathematicians use topology to study its shape and everything in it



When you look at your surrounding environment, it might seem like you're living on a flat plane. After all, this is why you can navigate a new city using a map: a flat piece of paper that represents all the places around you. This is likely why some people in the past believed the Earth to be flat. But most people now know that is far from the truth.

You live on the surface of a giant sphere, like a beach ball the size of the Earth with a few bumps added. The surface of the sphere and the plane are two

possible 2D spaces, meaning you can walk in two directions: north and south or east and west.

What other possible spaces might you be living on? That is, what other spaces around you are 2D? For example, the surface of a giant doughnut is another 2D space.

Through a field called geometric topology, [mathematicians like me](#) study all possible spaces in all dimensions. Whether trying to design [secure sensor networks](#), [mine data](#) or use [origami to deploy satellites](#), the underlying language and ideas are likely to be that of topology.

The shape of the universe

When you look around the universe you live in, it looks like a 3D space, just like the surface of the Earth looks like a 2D space. However, just like the Earth, if you were to look at the universe as a whole, it could be a more complicated space, like a giant 3D version of the 2D beach ball surface or something even more exotic than that.

While you don't need topology to determine that you are living on something like a giant beach ball, knowing all the possible 2D spaces can be useful. Over a century ago, mathematicians figured out [all the possible 2D spaces](#) and many of their properties.

In the past several decades, mathematicians have learned a lot about all of the possible 3D spaces. While we do not have a complete understanding like we do for 2D spaces, we do [know a lot](#). With this knowledge, physicists and astronomers can try to determine what [3D space people actually live in](#).

While the answer is not completely known, there are many [intriguing and surprising possibilities](#). The options become even more complicated if you consider time as a dimension.

To see how this might work, note that to describe the location of something in space—say a comet—you need four numbers: three to describe its position and one to describe the time it is in that position. These four numbers are what make up a 4D space.

Topology in higher dimensions

At this point, it may seem like there is no reason to consider spaces that have dimensions larger than four, since that is the highest imaginable dimension that might describe our universe. But a branch of physics called [string theory](#) suggests that the universe has many more dimensions than four.

There are also practical applications of thinking about higher-dimensional spaces, such as [robot motion planning](#). Suppose you are trying to understand the motion of three robots moving around a factory floor in a warehouse. You can put a grid on the floor and describe the position of each robot by their x and y coordinates on the grid. Since each of the three robots requires two coordinates, you will need six numbers to describe all of the possible positions of the robots. You can interpret the possible positions of the robots as a 6D space.

As the number of robots increases, the dimension of the space increases. Factoring in other useful information, such as the locations of obstacles, makes the space even more complicated. In order to study this problem, you need to study high-dimensional spaces.

There are countless other scientific problems where high-dimensional spaces appear, from modeling the [motion of planets and spacecraft](#) to trying to understand the ["shape" of large datasets](#).

Tied up in knots

Another type of problem topologists study is how one space can sit inside another.

For example, if you hold a knotted loop of string, then we have a 1D space (the loop of string) inside a 3D space (your room). Such loops are called mathematical knots.

The [study of knots](#) first grew out of physics but has become a central area of topology. They are essential to how scientists understand [3D and 4D spaces](#) and have a delightful and subtle structure that researchers are [still trying to understand](#).

In addition, knots have many applications, ranging from [string theory](#) in physics to [DNA recombination](#) in biology to [chirality](#) in chemistry.

What shape do you live on?

Geometric topology is a beautiful and complex subject, and there are still countless exciting questions to answer about spaces.

For example, the [smooth 4D Poincaré conjecture](#) asks what the "simplest" closed 4D space is, and the [slice-ribbon conjecture](#) aims to understand how knots in 3D spaces relate to surfaces in 4D spaces.

Topology is currently useful in science and engineering. Unraveling more mysteries of spaces in all dimensions will be invaluable to understanding the world in which we live and solving real-world problems.

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Provided by The Conversation

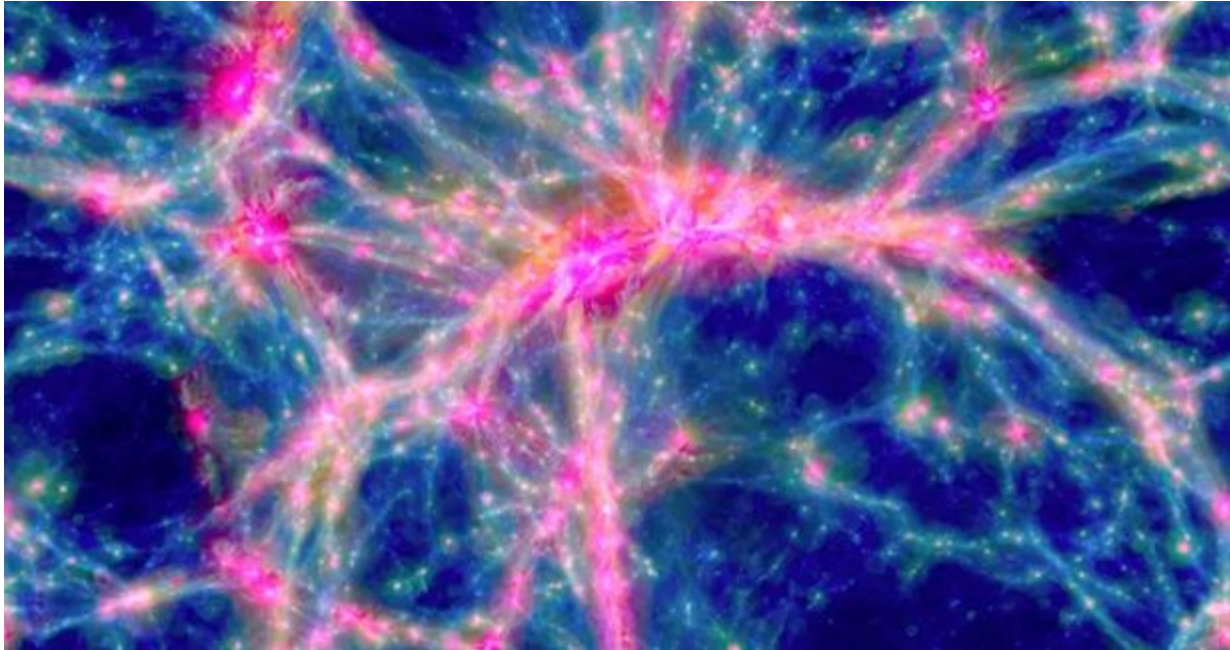
Unknown physics may help dark energy act as 'antigravity' throughout the universe

Dark energy could have an accomplice that helps it slow the growth of large cosmic structures, such as vast superclusters made up of clusters of galaxies.

A new analysis of astronomical data suggests [unknown physics](#) is at work assisting [dark energy](#) in acting almost as "antigravity," undoing the work of [gravity](#), which clumps together matter to build vast structures.

The [large-scale structure of the universe](#) refers to vast, interconnected patterns of galaxies, galaxy clusters, and superclusters organized into filaments, voids, and walls that comprise the "[cosmic web](#)."

Gravity has shaped this structure over billions of years. The team found that it is forming more slowly today compared to the rate at which it formed in the 13.8 billion-year-old universe's distant past.



A visualization of the cosmic web from the Evolution and Assembly of Galaxies and their Environments (EAGLE) Project (Image credit: EAGLE Project)

Researchers discovered these hints at new physics using data from the Baryon Oscillation Spectroscopic Survey (BOSS).

BOSS maps the spatial distribution of luminous red galaxies (LRGs) and [black hole-powered quasars](#) to detect variations in matter in the early universe, or "baryon acoustic oscillations," which are "frozen into" a cosmic fossil called the [Cosmic Microwave Background](#) (CMB).

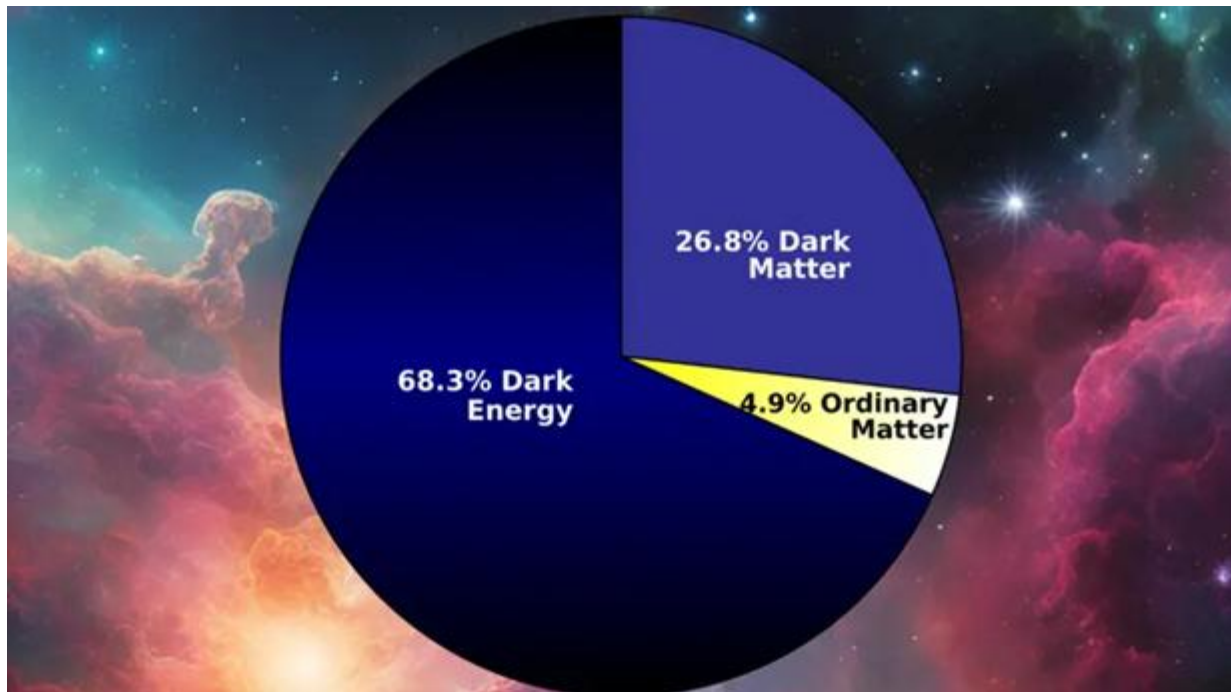
"We found that structure formation in the late universe, as probed by galaxies in the BOSS survey, seems to be suppressed relative to expectations," team leader and Princeton University researcher Shi-Fan (Stephen) Chen told Space.com. "In fact, our results suggest that the suppression is quite independent of dark energy."

Why dark energy may not be acting alone

Dark energy is the placeholder name for whatever is accelerating the expansion of the universe. [Discovered by two independent teams of astronomers in 1998](#),

dark energy is thought to account for around 70% of the cosmos's total matter-energy budget.

The current "best explanation" for dark energy is the "cosmological constant" represented by the Greek letter lambda (Λ) in the so-called standard model of cosmology, also known as the [Lambda Cold Dark Matter \(\$\Lambda\$ CDM\) model](#).



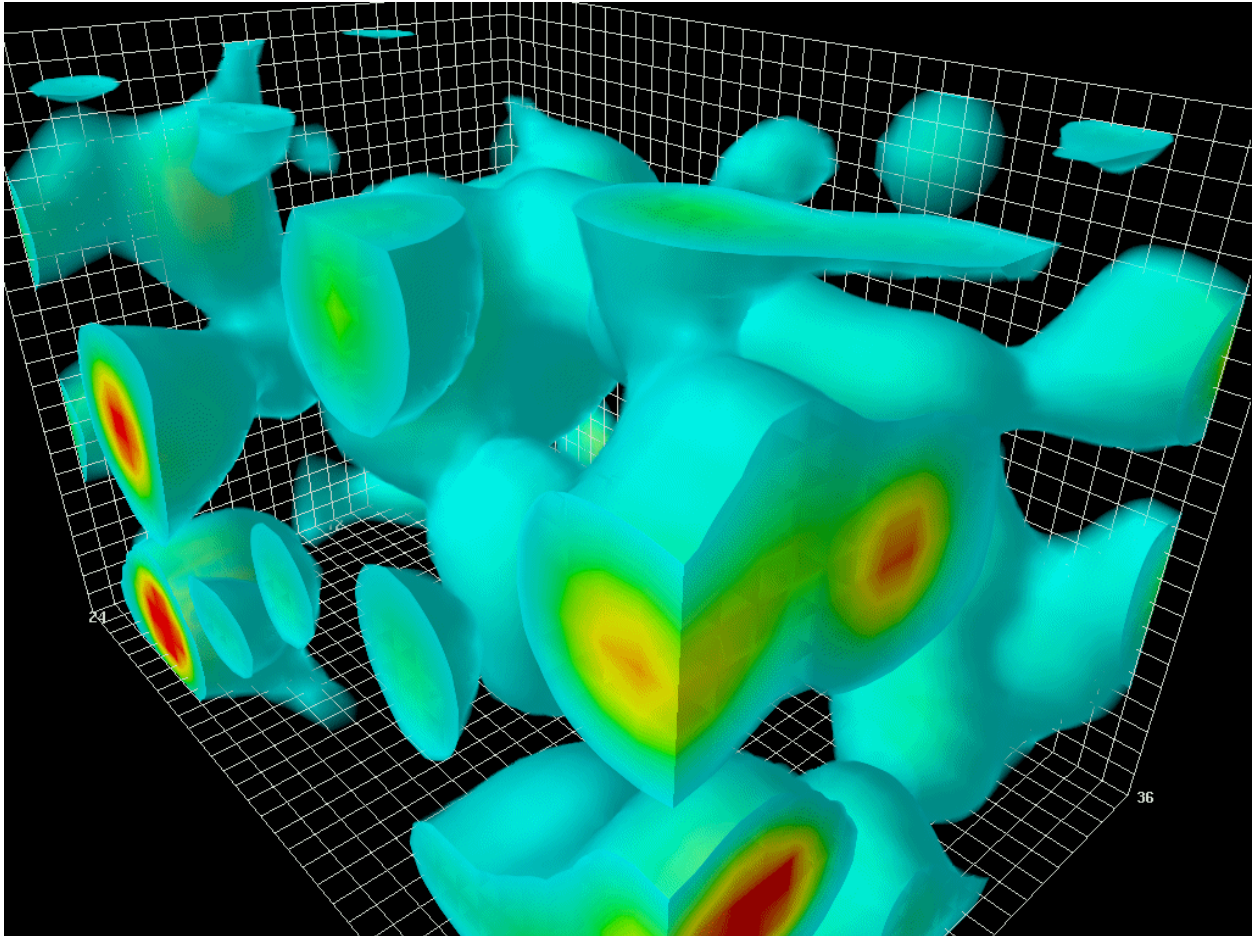
A pie chart showing the universe's matter-energy budget (Image credit: Robert Lea (created with Canva))

The cosmological constant represents "vacuum energy," or the energy of empty space. This may sound very strange as it is connected to pairs of matter and antimatter particles popping in and out of existence. If a matter and antimatter particle pair is created with equal and opposite energy within a limited space, then the total energy of that space is still zero.

This is akin to the universe's overdraft facility, but rather than lending money, it lends energy. Just like a bank, however, the universe demands this energy to be paid back, which virtual particles do by [annihilating each other](#).

This means that "empty space" can't ever really be guaranteed to be empty.

As crazy as the idea of matter appearing from nothing sounds, we've verified it experimentally. The Casimir effect, observed in labs across the globe, is a very famous example of virtual particles and the [quantum fluctuations](#) that create them and thus vacuum energy.



An animation shows how empty space is never really empty with virtual particles popping in and out of existence (Image credit: Derek Leinweber)

Here's the kicker: if dark energy is the cosmological constant, it should be exactly that, *constant*. So in the Λ CDM, even though dark energy causes a change in the rate at which the universe expands, the cosmological constant shouldn't change.

Recently, however, anomalies in [results from the Dark Energy Spectroscopic Instrument \(DESI\)](#) caused a stir with cosmologists when they indicated that dark energy is changing over time. Thus, this changing or "dynamical dark energy" is contrary to Λ CDM.

"Recent results from DESI suggest that dark energy may not be a cosmological constant, but rather might evolve over time— we were curious to see if this tension with Λ CDM could be tied to the suppression of structure," Chen said.

If anything, checking DESI findings with data from BOSS has left the team with a larger mystery on their hands.

Dark energy and cosmological constant

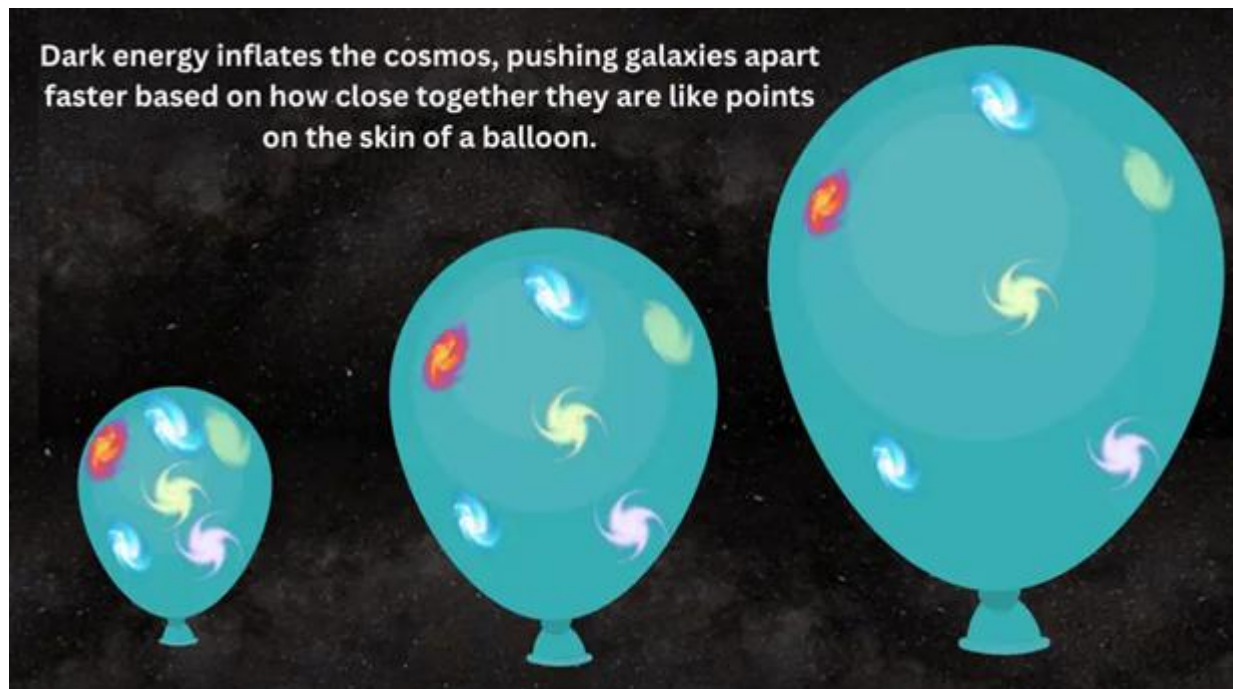
Whatever dark energy is, be it the cosmological constant or something else, the expansion of spacetime works on extremely large scales, so you won't see your coffee cup stretching away from you, and dark energy won't make your journey to work longer each morning (there is another excuse out of the window, sorry).

However, we *can* see distant galaxies moving away from us at ever-accelerating speeds. We can also see their effects in the BAO fluctuations frozen into the CMB because this fossil light from an event just after [the Big Bang](#) is almost evenly spread across the entire universe.

As such, it should come as no surprise that dark energy, as a force pushing apart galaxies, plays a role in stopping large-scale structures like [galaxy clusters](#) and [superclusters](#) from forming.

What is remarkable about the results obtained by Chen and colleagues is that they show that large-scale structures are even less common today than predicted by both the Λ CDM model of cosmology *and* when dark energy is allowed to vary. That implies something else, something new, is also at play, the identity of which is unknown.

"Many different theoretical explanations have been given for why the measured amplitude of cosmic structure at late times seems to come in slightly below expectations," Chen said. "At present, there are no conclusive answers."



The expansion of the universe due to dark energy with galaxies expanding like points on the skin of an inflating balloon (Image credit: Robert Lea (created with Canva))

However, there is one clue regarding the suppression of large-scale cosmic structures. This suppression seems to have kicked in around the same time dark energy came to dominate the universe.

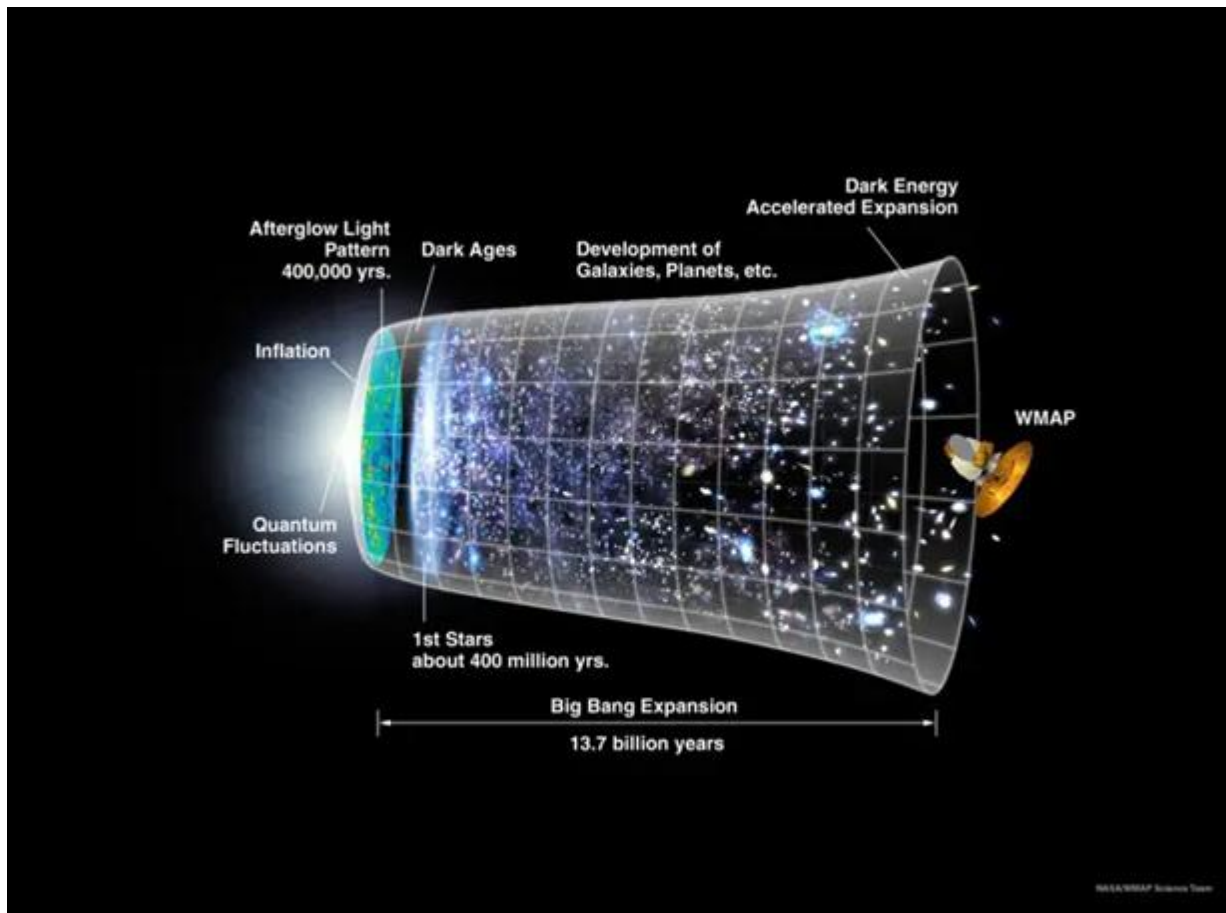
When matter ruled the cosmos

Dark energy may rule the universe now. But this wasn't always the way. Immediately after the Big Bang, the universe was dominated by radiation, driving its rapid inflation.

Around 70,000 years after the Big Bang, the universe had cooled enough to allow gravity to overwhelm radiation pressure. This slowed the initial [Big Bang-driven expansion](#), bringing it to a near stop, and the first aggregates of matter, stars and galaxies were allowed to form.

At around 9 to 10 billion years after the Big Bang, or about 5 to 4 billion years ago, something strange began to happen. The universe started to expand again. Not only that, but this expansion began accelerating, and it is still accelerating today.

This is the beginning of the dark energy-dominated epoch; the problem is that no one knows how the [switch from matter to dark energy domination](#) happened.



This graphic shows a timeline of the universe based on the Big Bang theory and inflation models. (Image credit: NASA/WMAP)

"The BOSS data probes the universe when dark energy is beginning to kick in, and we think that this suppression cannot have occurred much earlier than that," Chen said.

So while dark energy seems linked to this suppression, this mysterious force still can't solely explain why the formation of large cosmic structures is slowed in the modern universe.

"When combining probes of the peculiar velocities of these galaxies, known as redshift-space distortions, and their cross correlation with the weak lensing of the CMB, we find that the probability of our results occurring due to random chance is 1 in 300,000," Chen said. "That suggests either that there's some unknown physics at work or that there's some unknown systematic error in the BOSS data."

The researcher added that with better data on the horizon, including the first public data on galaxy clustering from DESI released last week, the team will re-apply their methods, compare their results with their current findings, and detect any statistically significant differences.

"I think there are more questions than answers at this point," Chen said. "This research certainly enforces the idea that different cosmological datasets are beginning to be in tension when interpreted within the standard Λ CDM model of cosmology."

The team's research was published in the journal [Physical Review Letters](#).

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The study links differences in alpha- and beta-frequency oscillations with brain-wide variation in the balance between excitatory neurons—those that boost activity by firing and passing signals to other neurons—and inhibitory neurons—those that regulate activity by telling other neurons not to fire. The researchers validated the personalized models by showing they could reproduce global individual alpha and beta patterns and forecast future brain-wide activity accurately, verifying the explanatory power of their framework.

"This new technique provides a powerful tool for exploring the mechanisms underlying individual brain dynamics based on noninvasive measurements of brain activity," Ching said. "This will allow us to advance high-level neuroscience, create precision brain models for individuals that can forecast future brain activity and use that knowledge to inform personalized medical interventions."

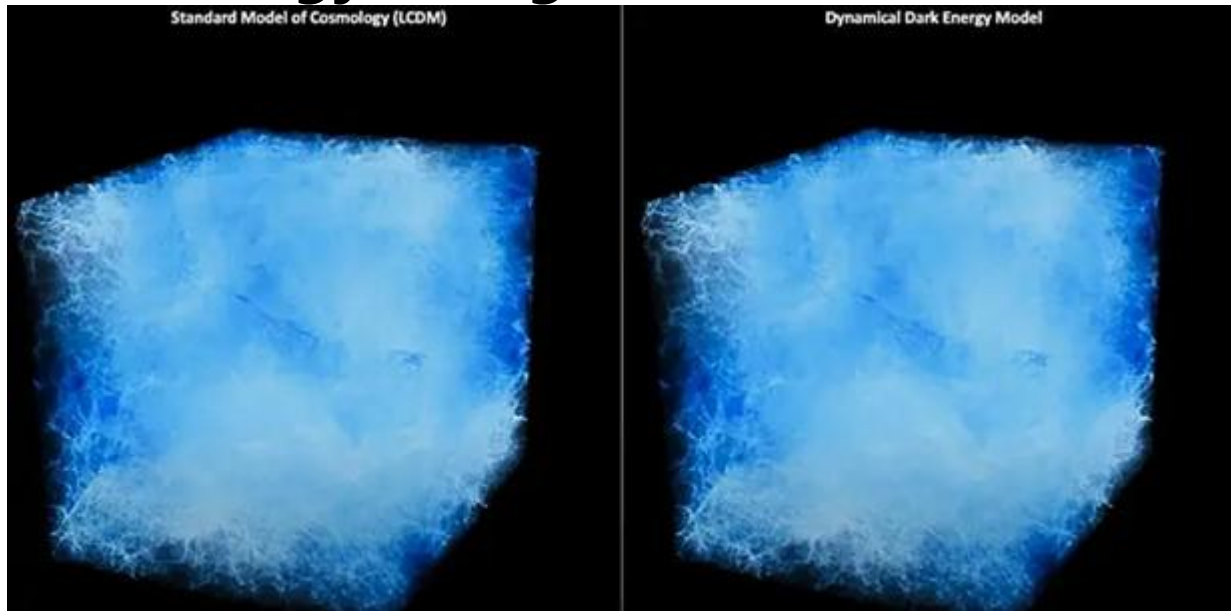
"Ongoing collaboration, expansion and refinement of our model will be a key part of the next steps of this project," Braver added. "Our innovative approach has the potential to provide new insights into how individual variation in brain dynamics results in differences in cognitive functioning. We hope this framework may also eventually inform new ways of enhancing cognitive functioning, such as with neurostimulation."

More information: Matthew F. Singh et al, Precision data-driven modeling of cortical dynamics reveals person-specific mechanisms underpinning brain

electrophysiology, *Proceedings of the National Academy of Sciences* (2025). DOI: [10.1073/pnas.2409577121](https://doi.org/10.1073/pnas.2409577121)

Provided by Washington University in St. Louis

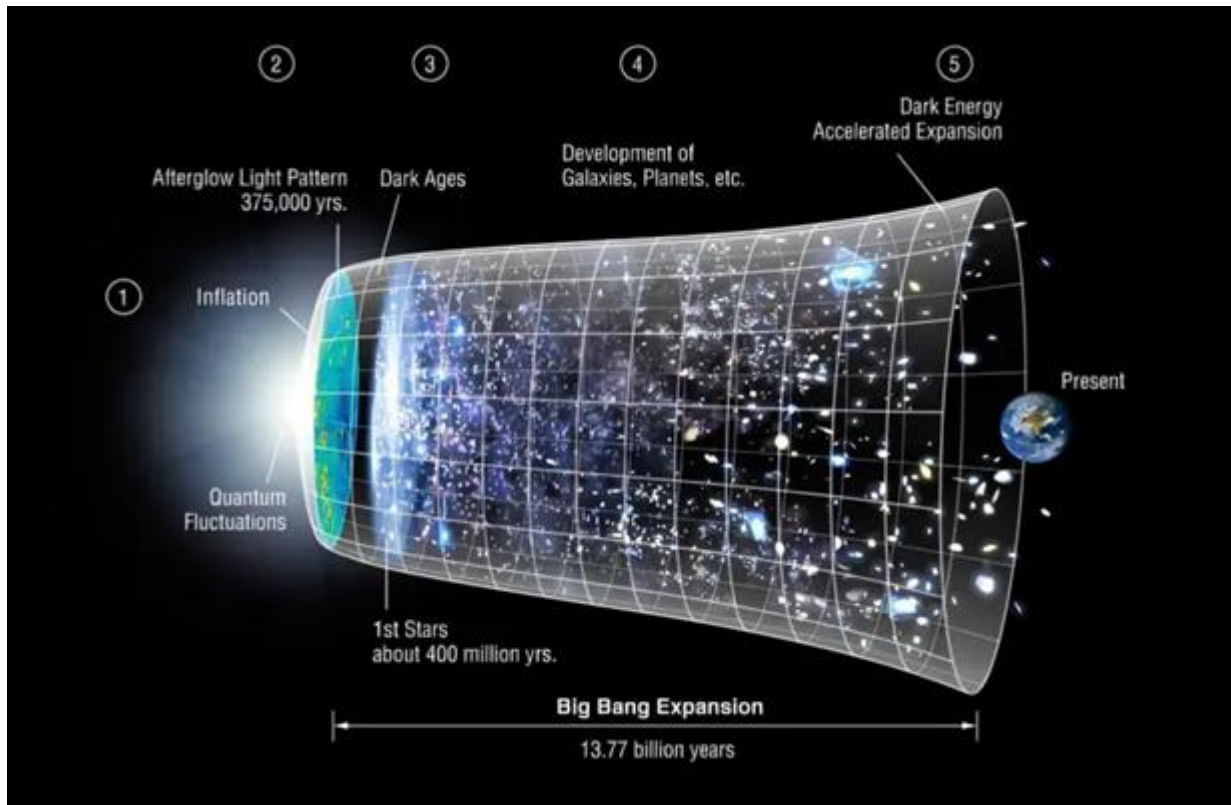
A simulated universe works better when dark energy changes over time



Supercomputer simulations tested the Standard Cosmological Model against a Dynamical Dark Energy Model to see which one better matched new DESI data. Credit: ALCF Visualization and Data Analytics Team and the HACC Collaboration

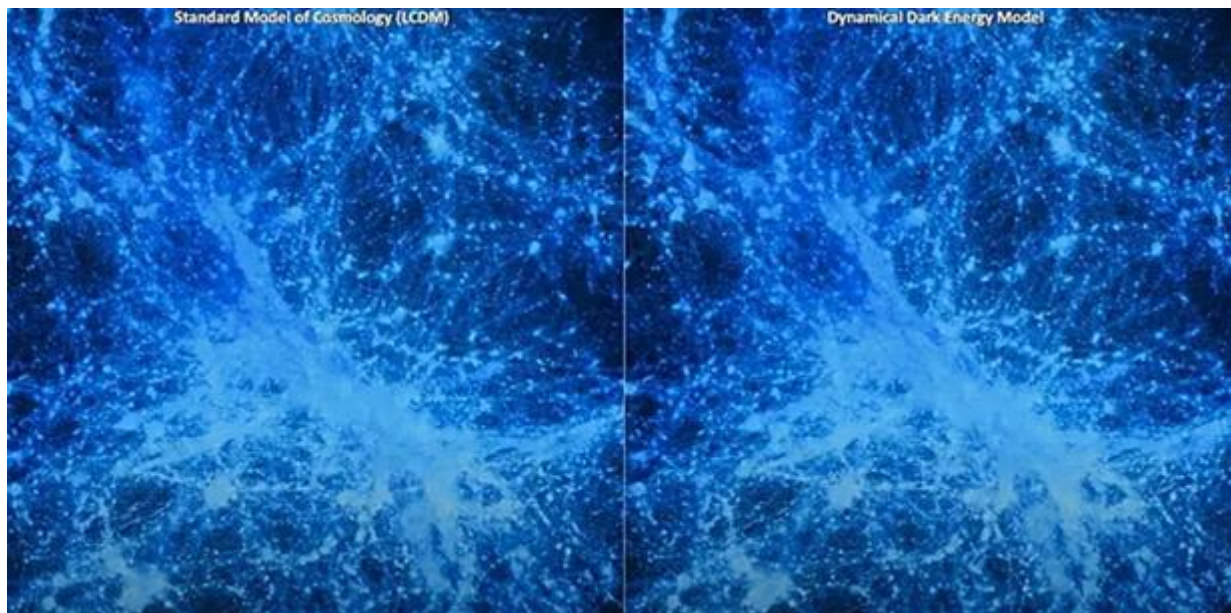
Dark energy is a mystery so daunting that it stretches and strains our most robust theories. The universe is expanding, driven by the unknown force that we've named Dark Energy. Dark Energy is also accelerating the rate of expansion. If scientists could figure out why, it would open up a whole new avenue of understanding.

The drive to understand dark energy is so powerful that a special instrument designed just to understand it has been created: DESI, the Dark Energy Spectroscopic Instrument. DESI's main survey began in 2021 and relies on baryon acoustic oscillations (BAO) to create a map of how matter is distributed in the universe. The survey covers an enormous volume of the universe in extreme detail.



This graphic shows some of the theorized stages in the universe according to the Standard Model of Cosmology.
Credit: NASA/ LAMBDA Archive / WMAP Science Team

Our understanding that the universe is expanding dates back to the early 20th century when astronomers noticed that the light from some distant objects was shifted toward the red end of the spectrum. This is called redshift, and researchers concluded that it was because the objects were moving away from Earth.



The Discovery simulations simulate two large-scale regions of the universe with different parameters. The standard model of cosmology is on the left, and the dynamical dark energy model is on the right. There are subtle differences between the two, which aren't apparent on a large scale but become clearer on a small scale. Credit: ALCF Visualization and Data Analytics Team and the HACC Collaboration

A breakthrough came when Edwin Hubble figured out that the farther an object was from Earth, the faster it was moving away. It dawned on us that we're living in a dynamic universe rather than a static one.

Cosmologists thought that gravity was slowing the rate of expansion. However, in 1998, astronomers discovered that it was actually accelerating. The cosmological constant explains this acceleration and is basically an energy density that seems to be an inherent part of the universe. The Hubble constant is intertwined with this, and it's the rate of expansion of the universe.

Put simply, the Hubble constant is how fast the universe is currently expanding, while the cosmological constant is a factor that affects that speed. Efforts to measure these constants have yielded different answers. Clearly, we have a mystery on our hands.

"The cosmological constant is essentially just an extra term in the equation that everyone has been using for years," said Andrew Hearin, a physicist at the U.S. Department of Energy's (DOE) Argonne National Laboratory, which is a DESI member institution. "We don't know why it takes on the particular value that it does, but it's a very mundane explanation for this unexpected cosmic acceleration."

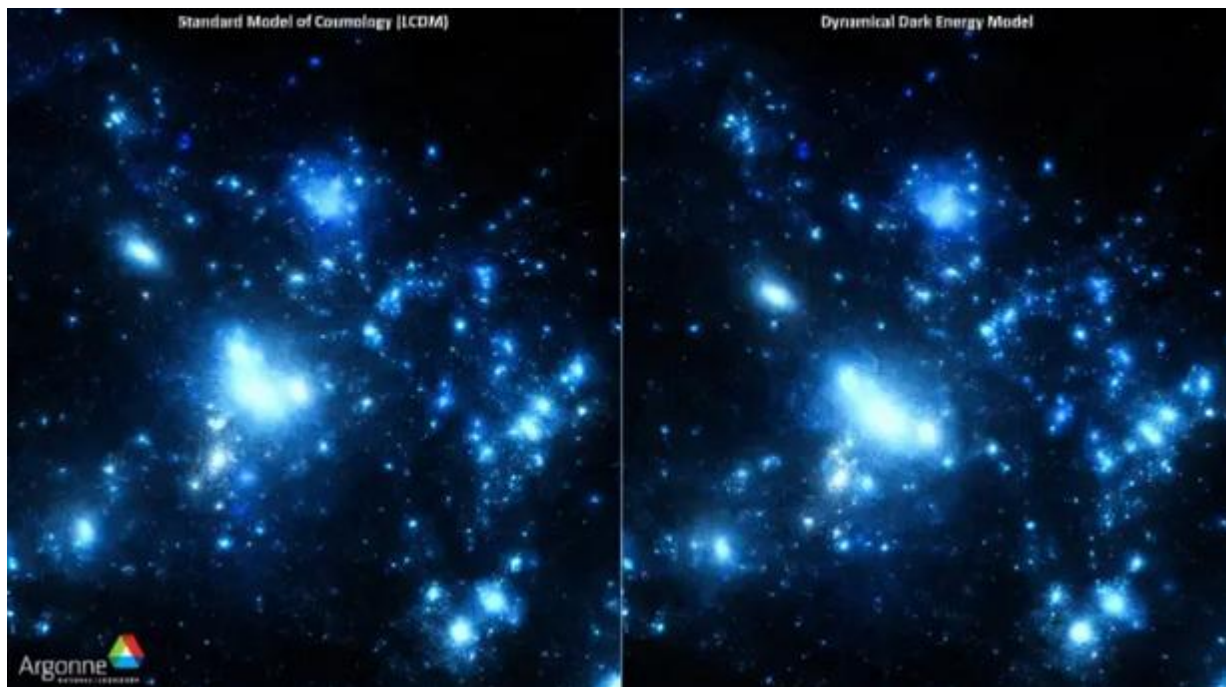
DESI's first year of data tracked the expansion of the universe over 11 billion years. This initial data largely agreed with our Standard Model of Cosmology, called Lambda CDM. However, there were some small discrepancies suggesting that dark energy was changing over time. If it is changing, it's a direct challenge for the cosmological constant.

This might seem disappointing on the surface. One of our most foundational understandings of the universe is being challenged by powerful observations. However, the reverse is true: it generated excitement.

"If the DESI result holds up, it means that a cosmological constant is not the origin of cosmic acceleration. It's much more exciting," said Hearin. "It would mean that space is pervaded by a dynamically evolving fluid with negative gravity, which has never been observed in any tabletop experiment on Earth."

To make headway, Hearin and his colleagues turned to supercomputer simulations. They used the Aurora exascale supercomputer at the Argonne Leadership Computing Facility to run large-scale simulations of the universe. These simulations allow researchers to test DESI's data.

Hearin and his fellow researchers presented the results of their simulations in a new paper titled "Illuminating the Physics of Dark Energy with the Discovery Simulations." The paper has been submitted to the *Open Journal of Astrophysics* and is [available](#) on the *arXiv* preprint server. The lead author is Gillian Beltz-Mohrmann, a postdoctoral fellow in the Cosmological Physics and Advanced Computing Group at Argonne National Laboratory.



These panels visually compare a small region in the simulations. On the left is the standard model of cosmology, and on the right is the dynamical dark energy model based on DESI's first year of data. The differences are subtle but still clearly visible at the substructure level. Credit: ALCF Visualization and Data Analytics Team and the HACC Collaboration

"When this result came out last year, we got really, really excited," said Katrin Heitmann, a cosmologist and deputy director of Argonne's High Energy Physics division. "Our team got together to discuss what we could do to help the community look into this from the simulation side. Simulations play a crucial role in disentangling fundamental physics from systematics in the observations or in the data analysis."

One of the challenges in observing the universe is determining if what we're seeing is a true representation of reality or if it contains distortions of our own making, like observational biases or problems in processing observational data. Powerful supercomputer simulations are a way scientists can test their observations in depth.

"Since we can't create a mini-universe to conduct experiments, we can test theories by using really big computers like Aurora to simulate the growth of structure in the universe over time," said Gillian Beltz-Mohrmann, a postdoctoral research fellow at Argonne.

The researchers conducted two separate simulations called the Discovery simulations. Both had the same initial conditions, but in one, dark energy was constant, and in the other, it changed over time. Simulations can't prove outright that we're right or wrong, but they're an important next step.

"The Discovery simulations are a pair of boxes with identical initial conditions; the only difference between the two simulations is cosmology," the authors write in their paper. "The first box uses a Lambda CDM cosmology, while the second box contains a dark energy equation of state w , which evolves in time." The values of cosmological parameters are based on DESI's year one results.

"The idea is that you create a model universe under one set of assumptions, and then you compare your model universe to the real universe. If the agreement is very good, it gives you some confidence that your assumptions are correct," Hearin said. "But if you have some gross discrepancy, then it tells you that your assumptions don't align with the real universe and don't represent the truth."

This is only possible because of massive increases in computing power. What would once take weeks and weeks to simulate now takes only days with the Aurora supercomputer. "These simulations serve as a demonstration of a unique new capability to run high-resolution simulations of cosmological volume in ~ 2 days, allowing for close-to-real-time investigations of new cosmological results," the researchers explain in their paper.

"Using Aurora's immense processing power to rapidly run large-scale simulations at sufficiently high resolution, we can respond much faster to new insights from cosmological observations," said Argonne computational scientist Adrian Pope. "These simulations would have taken weeks of compute time on our earlier supercomputers, but each simulation took just two days on Aurora."

"This pair of simulations really illustrates our ability to take a result that's hot off the presses from a collaboration like DESI, immediately run a simulation based on those results and then see what it looks like," Beltz-Mohrmann said.

There are only small discrepancies between the two simulations, but they're there, and they're important.

"If looking at these two simulations gives us an idea of the type of measurement we should make to help us narrow in on a cosmological model, then we can go

back to the real DESI data and make that same measurement and see what it tells us," Beltz-Mohrmann said. Observations and simulations are in a feedback loop together.

The simulations showed that our understanding of the dark matter halo mass function might be in error. The halo mass function is part of understanding how dark matter is distributed in the universe. "At all redshifts and for all masses, the halo mass function is suppressed in the Λ CDM simulation compared to the w_0wa CDM simulation," the authors write. The w_0wa CDM simulation is based on DESI's data showing fluctuating dark energy.

The simulations also showed a difference in the rate at which dark matter halos accrete mass. At low redshifts, w_0wa CDM halos accrete mass slightly faster than halos in the Λ CDM simulations. At greater redshifts, the difference shrinks.

The simulations also produced different star-formation rates (SFRs). "Among low mass halos, the largest differences in star formation rates between the two cosmologies appear at high redshift ($z > 1$), where the star formation rate of w_0wa CDM galaxies is $\sim 2\%$ lower than the star formation rate of Λ CDM galaxies," the authors write in their paper. Among intermediate and high-mass halos, the difference grows.

The results support the dynamic dark energy model, where dark energy changes over time. However, the authors caution that these results are not conclusive yet.

"It should be noted that because the Discovery simulations contain differences in all of their cosmological parameters, we are not isolating the effect of evolving dark energy but rather examining the differences in these two simulations based on their overall cosmologies," the authors explain in their paper.

More information: Gillian D. Beltz-Mohrmann et al, Illuminating the Physics of Dark Energy with the Discovery Simulations, *arXiv* (2025). DOI: [10.48550/arxiv.2503.05947](https://doi.org/10.48550/arxiv.2503.05947)

Provided by Universe Today

Space itself may have created galaxies



According to new research, the earliest seeds of structures may have been laid down by gravitational waves sloshing around in the infant universe.

Cosmologists strongly suspect that the extremely early universe underwent a period of exceptionally rapid expansion. Known as inflation, this event expanded the universe by a factor of at least 10^{60} in less than a second. Powering this event was a new ingredient in the cosmos known as the inflaton, a strange quantum field that ramped up, drove inflation, and then faded away.

Inflation didn't just make the universe big. It also laid down the seeds of the first structures. It did so by taking the quantum foam, the subatomic fluctuations in spacetime itself, and expanding that along with everything else. Slowly, over time, those fluctuations grew, and hundreds of millions of years later they became the first stars and galaxies, ultimately leading to the largest structure in the universe, the cosmic web.

But mysteries remain. We do not know the identity of the inflaton, or what powered it, or why it turned off when it did. And we have no conclusive evidence that inflation actually happened.

So researchers are always looking for alternatives, especially ones that don't invoke some new and mysterious ingredient. In [a recent paper](#) posted to the *arXiv* preprint server, a team of astrophysicists describe a model where inflation happens, leading to the large-scale structure of the universe, all without an inflaton.

The model described by the researchers is set in the backdrop of an expanding universe that is accelerating in its expansion, just like the modern-day universe is. In that expanding universe, the quantum foam releases gravitational waves. Those ripples in space spread outwards, colliding with each other and amplifying themselves.

Gravitational waves usually can't create structures on their own, but the researchers found that in certain special cases the gravitational waves can amplify each other in just the right way. When that happens, the imprints they make in space are nearly the same at a wide variety of length scales.

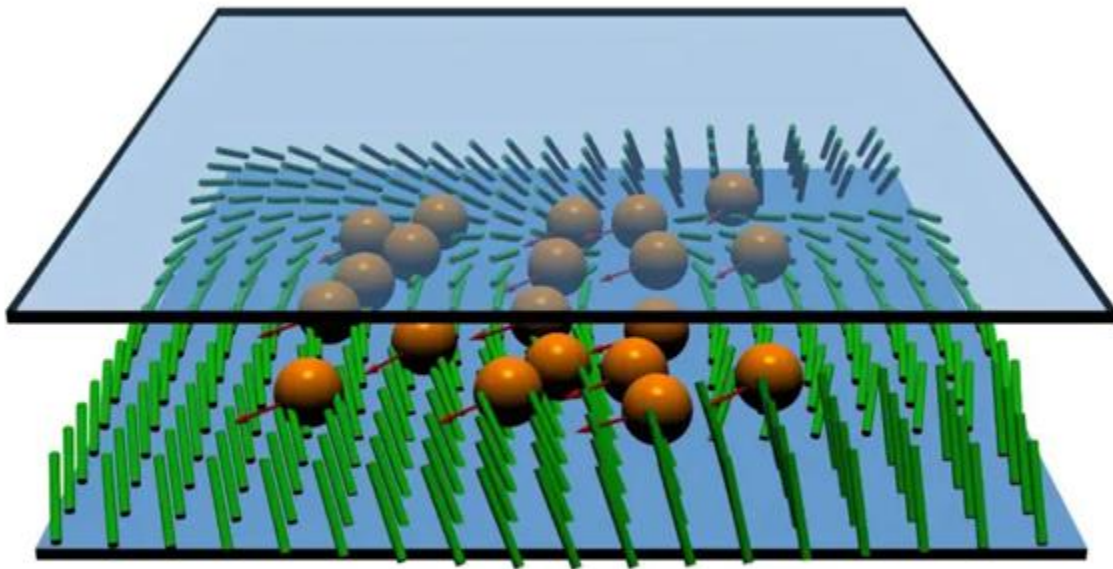
This is precisely what cosmologists observe in the cosmic microwave background, the leftover light from the early universe. This radiation contains a faint impression of the echoes of inflation, and it shows that whatever set the seeds of structure, it had to have that kind of pattern.

There are slight differences between the kinds of structures generated in this inflation-without-inflaton scenario and traditional inflation. In this first paper, the researchers did not yet calculate how strong those differences are, but an important next step is to explore the observational consequences of this model and see if it's worth investigating further.

More information: Daniele Bertacca et al, Inflation without an Inflaton, *arXiv* (2024). [DOI: 10.48550/arxiv.2412.14265](https://doi.org/10.48550/arxiv.2412.14265)

Provided by Universe Today

Scientists uncover how microswimmers move faster in groups, paving way for tiny drug-delivering robots



An artistic impression of microswimmers (orange spheres) moving through a confined liquid crystal environment. The green rods represent the aligned molecular structure of the liquid crystal, which helps guide and influence the swimmers' motion. Credit: Loughborough University

Scientists have revealed how tiny swimming organisms—such as bacteria—are able to move faster when traveling as a group—and the research could accelerate the development of microscopic robots that deliver drugs to specific regions of the body.

The work, conducted by researchers from Loughborough University and the Indian Institute of Science, shows that when "microswimmers" move together through enclosed environments, they change the properties of the fluid around

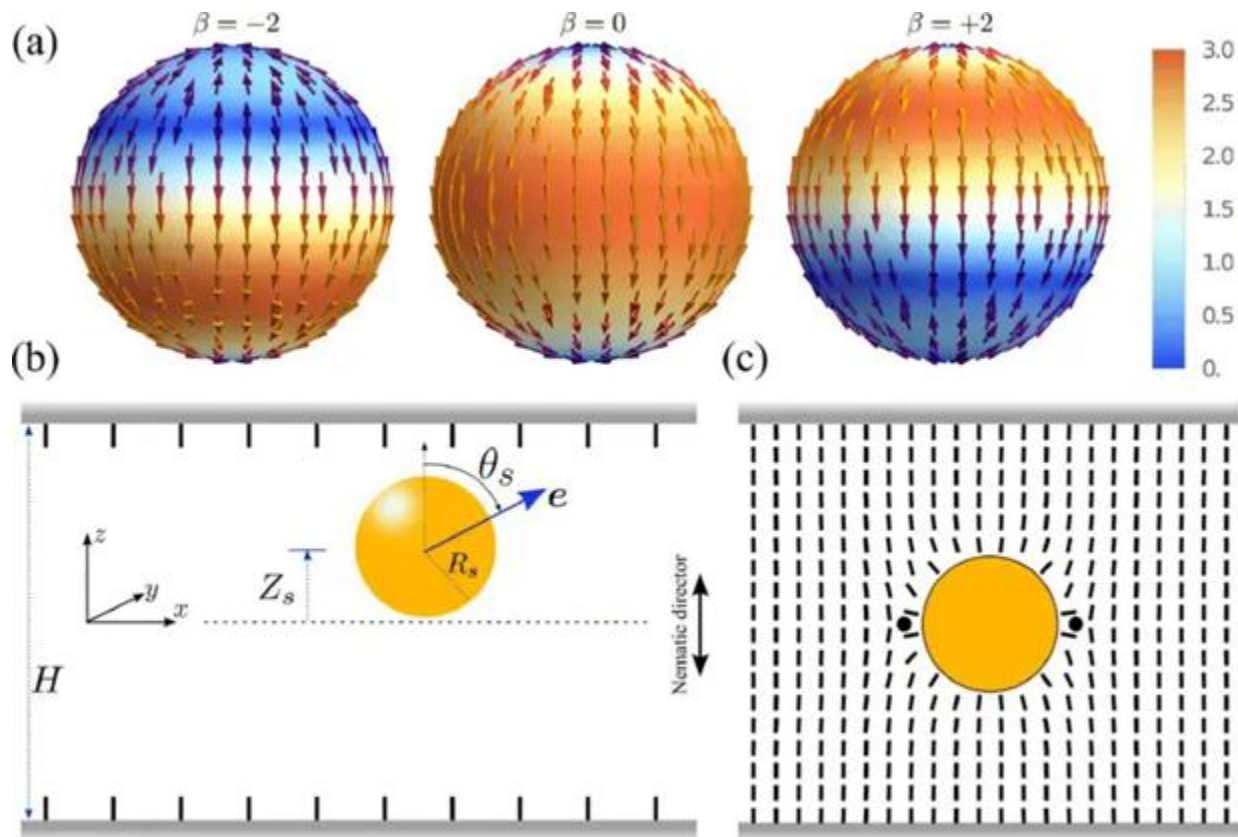
them, reducing resistance and increasing their speed compared to swimming alone.

The findings could be key to designing artificial microswimmers—tiny, controllable, swimming robots—that could be used for a variety of medical applications, such as IVF, parasite treatment, and targeted medical drug delivery that replaces traditional, less precise interventions.

"Imagine if we could create artificial microswimmers that can be injected into the bloodstream and controlled from the outside. We could navigate them to specific areas of the body, for example, cancer cells, and have them deliver drugs only to these areas," says Dr. Marco Mazza, the study's senior author.

"To do this, we first need to understand how naturally occurring microswimmers navigate different fluid environments and our study has made significant progress in this area."

The research, [published](#) in *Physical Review Letters*, focuses on a theoretical model for Paramecium—tiny single-celled organisms that live in water and propel themselves by beating hair-like structures called cilia. Their movement is similar to that of sperm and other microswimmers, which also use appendages to generate motion and navigate fluid environments.



(a) Schematics of the squirmer's surface velocity, whose direction is represented with arrows and magnitude with background color (see color bar), for representative pusher ($\beta = -2$), neutral ($\beta = 0$), and puller ($\beta = 2$). (b) Schematic representation of our system consisting of a single squirmer suspended in a stationary nematic liquid crystal bounded by two parallel walls. Geometric and dynamical quantities are indicated. The bulk director field is oriented along the z axis due to strong homeotropic anchoring on both the walls. (c) Nematic director field around the squirmer with the Saturn ring defect [55] resulting from the homeotropic anchoring on the squirmer's surface. Credit: Physical Review Letters (2025). DOI: 10.1103/PhysRevLett.134.128302

Using computer simulations and theoretical models, the researchers analyzed how an individual microswimmer and groups of up to 10 move through a confined liquid crystal environment—a unique type of fluid that flows like a liquid but has molecules that line-up in an ordered way. These structured fluids naturally occur in nature and biological systems, including cell membranes and tissues.

The key findings are:

- Microswimmers moving in groups create flow fields—movements in the surrounding liquid—that help them swim more efficiently by reducing resistance and enhancing propulsion.

- As more swimmers join, their average speed increases, allowing them to move faster than they could alone.
- Liquid crystal environments help guide and direct microswimmers, influencing their movement.
- There are two types of microswimmers—"pushers" and "pullers." Pushers benefit from collective movement, while pullers hinder each other, showing the effect depends on swimmer type.

The next step is to expand the research, moving from small-scale simulations to those that replicate how hundreds of microswimmers move through different enclosed liquid environments.

The scientists also hope to collaborate with experimental researchers working with *Paramecium* and other types of microswimmers to compare real-world behavior with their theoretical models. This will provide deeper insights into collective swimming dynamics, which could inform the design of artificial microswimmers.

Professor Tony Croft, one of the study authors and Emeritus Professor of Mathematics Education at Loughborough University, hopes the impact of this research will be felt beyond the academic realm.

"This work has the power to ignite curiosity in young minds, inspiring new generations of learners to explore the fascinating intersection of mathematics, physics and biology," he said.

"Too often, students perceive mathematics as dry and irrelevant; our work challenges that notion, revealing its deep connections to the real world and its potential to unlock exciting new discoveries."

Lead author Dr. Shubhadeep Mandal, of the Indian Institute of Science, said, "This research examines how key properties of complex fluids, such as anisotropy and elasticity, affect the motion of swimming entities like motile cells and synthetic microrobots. Viscous anisotropy and elasticity are indeed present in biological environments such as mucus, saliva, and the cell cytoskeleton. The research demonstrates how one could design swimmer traits to control their motion in these complex fluids."

Tom Mason, a Ph.D. student at Loughborough University and one of the study's co-lead authors, said, "Our research on nematic microswimmers in confined environments advances our understanding of active matter in complex fluids, with implications for both fundamental physics and real-world applications. By exploring the interplay between swimmer dynamics, confinement, and nematic elasticity, we provide insights into how microscale swimmers navigate structured environments—relevant to microfluidics, biomedical engineering, and soft matter physics.

"We have identified distinct swimmer behaviors—wall hovering, oscillation, and central migration—that offer a framework for controlling microscale motion in liquid crystalline media. These findings have potential applications in targeted drug delivery, micro-robotics, and synthetic biological systems. Through theoretical modeling and computational simulations, our work lays the foundation for advancing autonomous microscale technologies and understanding complex fluid-structure interactions."

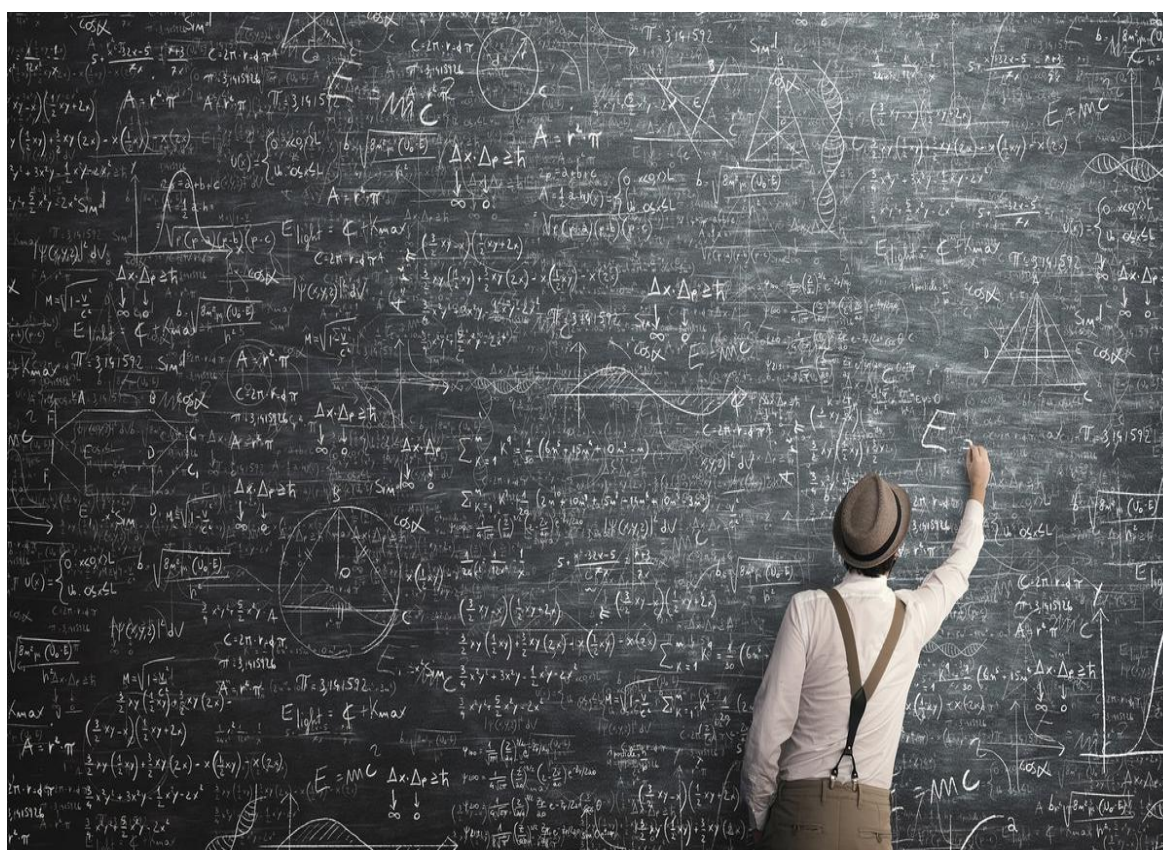
More information: Shubhadeep Mandal et al, Cooperativity of Confined Nematic Microswimmers: From One to Many, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.128302](https://doi.org/10.1103/PhysRevLett.134.128302)

Provided by Loughborough University

380-year-old Descartes circle problem finally solved with help from physics

Researchers explained that spinors, commonly used in quantum mechanics, played a key role in cracking the ancient puzzle.

Apr 04, 2025



Man solving math problem.

The world of geometry just witnessed a pivotal breakthrough.

Mathematicians at Monash University have cracked a centuries-old puzzle dating back to the 17th century, extending Descartes' Circle Theorem into a bold new territory.

Using advanced mathematical tools inspired by physics, the team has derived a general equation for any number of tangent circles, offering fresh insights into an equation originally proposed by mathematician René Descartes.

Descartes' theorem, a cornerstone of geometry, defines the relationship between four mutually tangent circles.

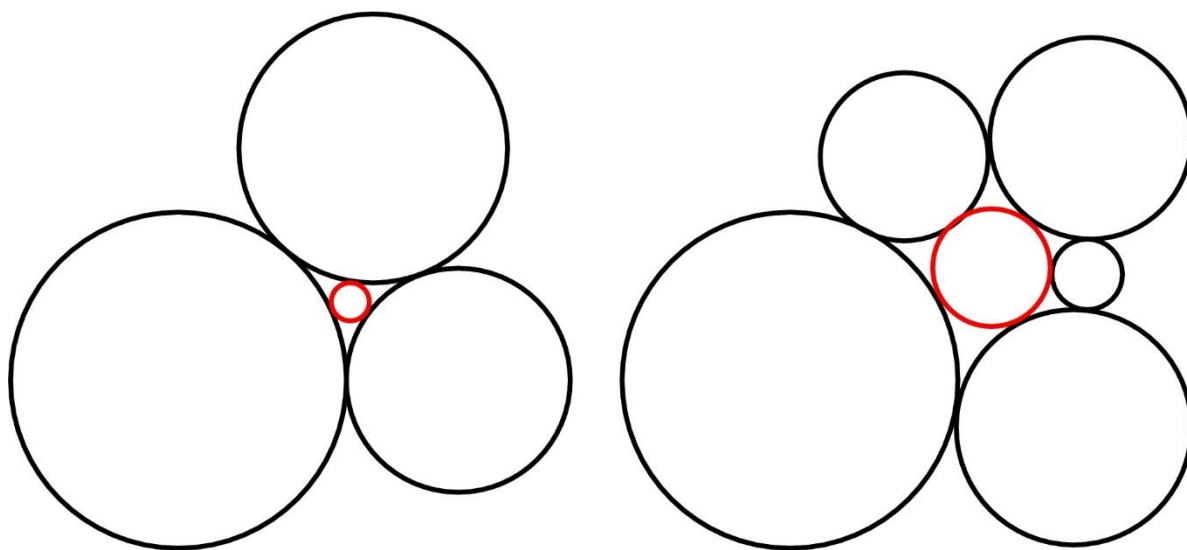
But for centuries, generalizing the equation to more than four circles had eluded mathematicians—until now.

Associate Professor Daniel Mathews from Monash University's School of Mathematics, along with PhD candidate Orion Zymaris, has identified the equation that governs “n-flowers”—the complex geometric patterns formed by larger configurations of tangent circles.

In circle packing theory, flowers serve as a fundamental building block.

It is well established that once the curvatures of the outer circles (petals) in an n-flower are known, the curvature of the central circle can be precisely determined.

The researchers based their study on modern mathematical techniques involving spinors—mathematical entities that also appear in quantum mechanics and relativity.



3-flower (Left) 5-flower (Right) – *Journal of Geometry and Physics*

From Descartes to spinors

“Descartes posed a problem to Princess Elisabeth of the Palatinate in 1643, assuming he could solve it. After all, he had just invented Cartesian coordinates! But he couldn't, and when he revised the problem to a practically solvable one, this has become known as the classic Descartes Circle Theorem,” Mathews said in a [release](#).

The equation was first proposed by Yamaji Nushizumi in 1751 and has been independently rediscovered multiple times—by Jakob Steiner in 1826, William

Beecroft in 1842, and Frederick Soddy in 1936, who famously rephrased it in the form of a poem.

“Others have generalised the result in other ways, but this is the first extension of the result to give an explicit equation relating the radii of an arbitrary number of circles in the plane.”

Zymaris, whose PhD research led to the breakthrough, highlighted the unexpected connections to other fields of mathematics and physics.

“Our approach used advanced geometric tools inspired by physics, which was surprising,” he said.

He explained that spinors, commonly used in quantum mechanics, played a key role in their approach.

“We used a version of spinors developed by Nobel prize-winner Roger Penrose, and Wolfgang Rindler, which they applied to the theory of relativity.”

“It turns out that the same mathematical structures that describe quantum spin and relativity also help us understand circle packings.”

A 380-year-old question finds answers

The work not only marks a significant step forward in pure [mathematics](#) but also showcases the growing strength of the topology group at Monash University, which now includes nine PhD students—five of them women.

“This discovery is an exciting example of how classical problems can inspire new mathematics centuries later,” Mathews said.

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- Mathematicians solve 380-year-old problem inspired by Descartes

Mathematicians solve 380-year-old problem inspired by Descartes

10 March 2025

A long-standing geometric mystery dating back to the 17th century has finally been solved by Monash University mathematicians, shedding new light on an equation first written by philosopher and mathematician René Descartes.



Associate Professor Daniel Mathews

The discovery, published in the [*Journal of Geometry and Physics*](#), extends the famous Descartes Circle Theorem, which describes the relationship between four mutually tangent circles. Despite centuries of mathematical progress, a general equation for larger configurations of circles remained elusive—until now.

Associate Professor Daniel Mathews, a mathematician at Monash University School of Mathematics, and PhD candidate Orion Zymaris have found the equation that governs these larger patterns of tangent circles, known as “n-flowers.”

Their proof, which draws on modern mathematical techniques involving spinors—objects that also play a role in quantum mechanics and relativity—solves a problem that has remained open for more than 380 years.

“Descartes posed a problem to Princess Elisabeth of the Palatinate in 1643, assuming he could solve it. After all, he had just invented Cartesian coordinates! But he couldn’t, and when he revised the problem to a practically solvable one, this has become known as the classic Descartes Circle Theorem,” said Associate Professor Mathews. “Others have generalised the result in other ways, but this is the first extension of the result to give an explicit equation relating the radii of an arbitrary number of circles in the plane.”

Zymaris, whose PhD research led to the breakthrough, highlighted the unexpected connections to other fields of mathematics and physics.

“Our approach used advanced geometric tools inspired by physics, which was surprising,” he said. “Spinors are widely used in physics, especially in quantum mechanics. We used a version of spinors developed by Nobel prize-winner Roger Penrose, and Wolfgang Rindler, which they applied to the theory of relativity.”

“It turns out that the same mathematical structures that describe quantum spin and relativity also help us understand circle packings.”

The work not only advances pure mathematics but also highlights the growing strength of the topology group at Monash University, which now includes nine PhD students—five of whom are women.

“This discovery is an exciting example of how classical problems can inspire new mathematics centuries later,” said Associate Professor Mathews. “It’s incredible to think that a question Descartes struggled with in the 1600s still has new answers waiting to be found.”

Further information

Silvia Dropulich

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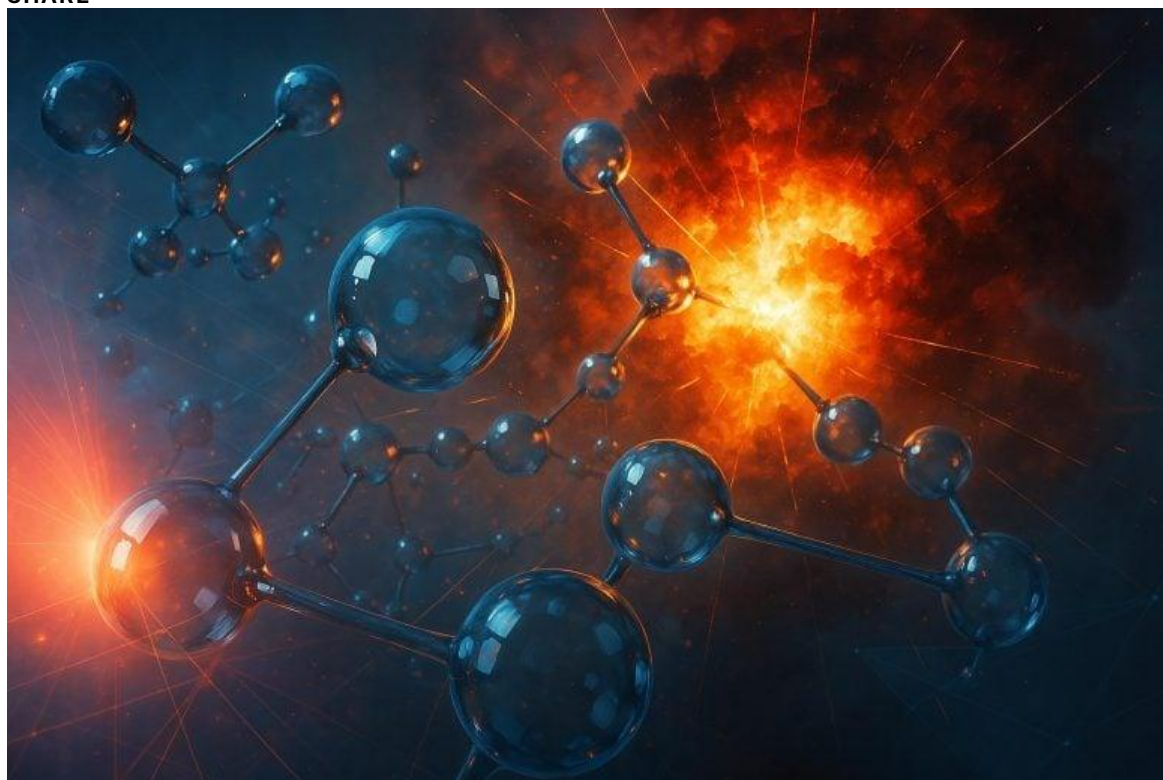
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Rivaling TNT: Scientists Discover Bizarre “Magic Molecules” With Explosive Potential

BY SKOLKOVO INSTITUTE OF SCIENCE AND TECHNOLOGY APRIL 5, 2025 [NO COMMENTS](#) 5 MINS READ

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Skoltech researchers have identified over 220 carbon-oxygen compounds, many previously unknown, with some showing explosive energy close to that of TNT, despite lacking nitrogen. Their findings on oxocarbons open up new possibilities for space exploration, advanced batteries, and energetic materials, challenging conventional chemistry and expanding the understanding of molecular diversity. (Artist's concept.)

Credit: SciTechDaily.com

Skoltech scientists discovered over 200 carbon-oxygen compounds with high energy potential, some rivaling TNT, offering new insights into non-nitrogen-based explosives and applications in energy, space, and chemical research.

Skoltech researchers have conducted a theoretical study exploring a wide range of molecules formed by oxygen and carbon atoms—beyond the well-known carbon dioxide and carbon monoxide. These oxygen-carbon compounds are of significant interest across

multiple fields, including space exploration, battery development, biochemistry, and even the design of industrial explosives and rocket propellants.

Published in *Materials Today Energy* and supported by a Russian Science Foundation [grant](#), the study identifies dozens of previously unknown molecules, some of which possess more than 75% of the explosive energy of TNT.

These compounds fall under the category of high-energy-density materials, substances capable of releasing large amounts of chemical energy per unit mass. Such materials are critical for advancing propellants and explosives that outperform conventional nitrogen-based compounds like TNT and ammonium perchlorate. Remarkably, the Skoltech team discovered a new class of explosive chemistry entirely free of nitrogen while studying a family of compounds called oxocarbons, or carbon oxides.

The Role of Carbon Monoxide and Stability

“The reason why many high-energy-density materials are based on nitrogen chemistry is this. In the course of chemical reactions, nitrogen atoms seek to form the remarkably stable molecule N_2 . As the atoms adopt this energetically favorable configuration, vast amounts of energy are released,” said Skoltech MSc student Elizaveta Vaneeva from the Materials Science program, the lead author of the study.

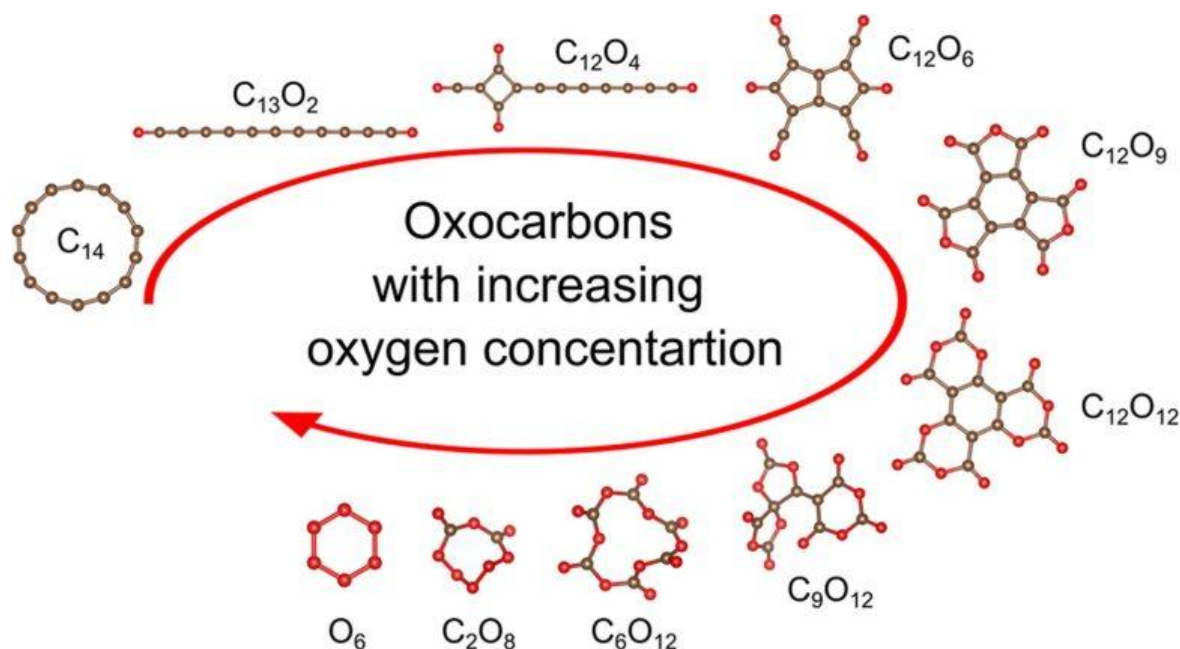


Image. Graphical abstract of the Skoltech study showing some of the possible carbon oxides in the range probed by the researchers: no more than 16 oxygen atoms, possibly zero atoms of either element. Credit: Elizaveta Vaneeva et al./Materials Today Energy

“So there was this idea that since the bond energy in the carbon monoxide molecule CO is even somewhat greater, one could find a compound that decomposes into carbon

monoxide plus something else, and that process would release even more energy,” she went on. “As it turned out, some carbon oxides that we studied release up to 81% as much energy as TNT when they decompose into products that include carbon dioxide, not carbon monoxide.”

The team’s analysis uncovered an entire “molecular zoo” numbering some 224 oxocarbons, of which only 78 had been reported in earlier papers and still fewer had been investigated at that level of detail. Among them the scientists identified 32 compounds with explosive potential and some prospect of synthesis. These include C_4O_8 and C_4O_9 and the newly discovered C_6O_{12} and C_6O_{13} , all of which release 75% or more of the energy of TNT, with the molecule C_4O_9 packing the biggest punch at 81% the equivalent of TNT.

The Surprising Richness of Molecular Chemistry

The principal investigator of the study, Distinguished Professor Artem R. Oganov, who heads the Material Discovery Laboratory at Skoltech, commented on the fundamental significance of the work: “This molecular chemistry is unusual. You see, it is commonly held that molecules are understood better than crystals. But what we see is just the opposite. The variability of chemical compositions of crystals is very limited. Molecules, on the contrary, show great diversity. Still, even among molecules not every composition conceivable on paper will actually form in nature, and we have explained why and predicted a number of those that will likely be found.”

The explanation draws on the concept of “magicity,” which is itself an extension of the notion of magic numbers from nuclear physics to the level of molecules. Rather than evaluate the absolute energy contained in the bonds that hold any given molecule together to assess its stability, the researchers compared the energy of a molecule to that of molecules with the closest possible compositions, i.e., with one extra or one missing oxygen or carbon atom. Any compound that proves energetically more favorable than the neighboring configurations is deemed a “magic” molecule, suggesting its relative stability and high likelihood of formation.

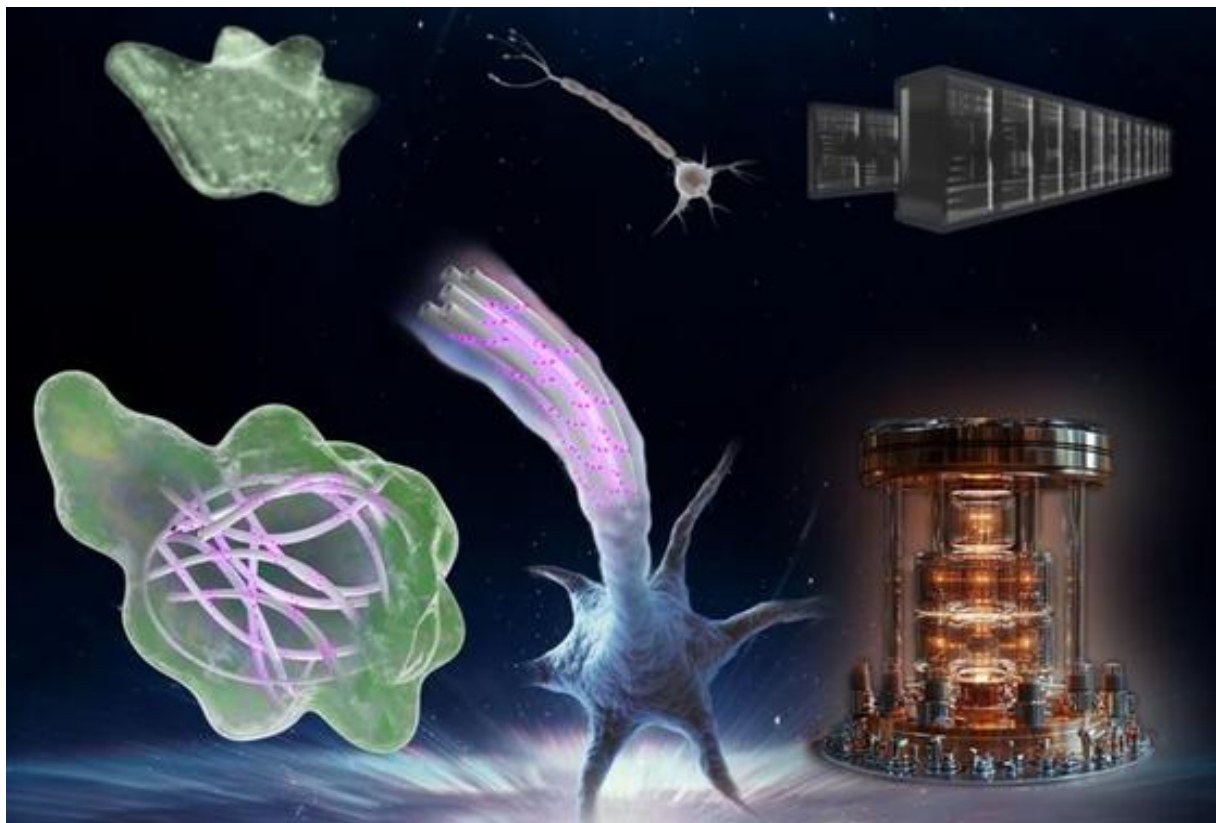
Oxocarbons are promising for many applications including advanced energetics, electrode materials for lithium-ion batteries, atmospheric chemistry, and biochemical studies. They are important for the study of combustion products of common hydrocarbon fuels such as kerosene, ethanol, and dimethyl ether. Oxocarbons are also expected to exist in the interstellar medium and in planets, making them a target of astrophysical research. That said, compounds of carbon and oxygen remain insufficiently studied, with the bulk of the data available for several textbook molecules, primarily for carbon dioxide and carbon monoxide. The Skoltech study is a step to remedy that. Reference: “Exploring the diversity of molecular carbon oxides, and their potential as high energy density materials” by Elizaveta E. Vaneeva, Sergey V. Lepeshkin, Dmitry V. Rybkovskiy and Artem R. Oganov, 6 February 2025, *Materials Today Energy*.

[DOI: 10.1016/j.mtener.2025.101821](https://doi.org/10.1016/j.mtener.2025.101821)

All biological systems may be leveraging quantum information processing

Howard University researcher says recent discovery of amino acids producing UV-excited qubits could mean computing capacity of life is far greater than previously thought.

From Howard University 02/04/25 (first released 28/03/25)



Credit: Quantum Biology Laboratory, Philip Kurian.

More than 80 years ago, Erwin Schrödinger, a theoretical physicist steeped in the philosophy of Schopenhauer and the Upanishads, delivered a series of public lectures at Trinity College, Dublin, which eventually came to be published in 1944 under the title *What is Life?*

Now, in the 2025 International Year of Quantum Science and Technology, Philip Kurian, a theoretical physicist and founding director of the Quantum Biology Laboratory (QBL) at Howard University in Washington, D.C., has used the laws of quantum mechanics, which Schrödinger postulated, and the QBL's discovery of cytoskeletal filaments exhibiting quantum optical features, to set a drastically revised upper bound on the computational capacity of carbon-based life in the entire history of Earth.

Published in *Science Advances*, Kurian's latest work conjectures a relationship between this information-processing limit and that of all matter in the observable universe.

"This work connects the dots among the great pillars of twentieth century physics—thermodynamics, relativity, and quantum mechanics—for a major paradigm shift across the biological sciences, investigating the feasibility and implications of quantum information processing in wetware at ambient temperatures," said Kurian.

"Physicists and cosmologists should wrestle with these findings, especially as they consider the origins of life on Earth and elsewhere in the habitable universe, evolving in concert with the electromagnetic field."

QUANTUM MECHANICS AND SUPERRADIANCE

The effects of quantum mechanics—the laws of physics that many scientists think apply at only small scales—are sensitive to disturbances.

This is why quantum computers must be held at temperatures colder than outer space, and only small objects, such as atoms and molecules, typically display quantum properties.

By quantum standards, biological systems are quite hostile environments: they're warm and chaotic, and even their fundamental components—such as cells—are considered large.

But Kurian's group last year discovered a distinctly quantum effect in protein polymers in aqueous solution, which survives these challenging conditions at the micron scale, and may also present a way for the brain to protect itself from degenerative diseases like Alzheimer's and related dementias.

Their results have suggested new applications and platforms for quantum computing researchers, and they represent a new way of thinking about the relationship between life and quantum mechanics.

In his single-author Science Advances paper, Kurian considered a mere trifecta of overarching assumptions: standard quantum mechanics, the relativistic speed limit set by light, and a matter-dominated universe at critical mass-energy density.

“Combined with these rather innocuous premises, the remarkable experimental confirmation of single-photon superradiance in a ubiquitous biological architecture at thermal equilibrium opens up many new lines of inquiry across quantum optics, quantum information theory, condensed matter physics, cosmology, and biophysics,” said Professor Marco Pettini of Aix-Marseille University and the CNRS Center for Theoretical Physics (France), who was not associated with the work.

QUANTUM INFORMATION PROCESSING, BEYOND BIOCHEMICAL SIGNALING

The key molecule enabling these remarkable properties is tryptophan, an amino acid found in many proteins that absorbs ultraviolet light and re-emits it at a longer wavelength.

Large networks of tryptophan form in microtubules, amyloid fibrils, transmembrane receptors, viral capsids, cilia, centrioles, neurons, and other cellular complexes.

The QBL’s confirmation of quantum superradiance in cytoskeletal filaments has the profound consequence that all eukaryotic organisms can use these quantum signals to process information.

To break down food, cells undergoing aerobic respiration use oxygen and generate free radicals, which can emit damaging, high-energy UV light particles.

Tryptophan can absorb this ultraviolet light and re-emit it at a lower energy.

And, as the QBL study found, very large tryptophan networks can do this even more efficiently and robustly because of their powerful quantum effects.

The standard model for biochemical signaling involves ions moving across cells or membranes, generating spikes in an electrochemical process that takes a few milliseconds for each signal.

But neuroscience and other biological researchers have only recently become aware that this isn't the whole story.

Superradiance in these cytoskeletal filaments happens in about a picosecond—a millionth of a microsecond.

Their tryptophan networks could be functioning as quantum fiber optics that allow eukaryotic cells to process information billions of times faster than chemical processes alone would allow.

"The implications of Kurian's insights are staggering," said Professor Majed Chergui of the École Polytechnique Fédérale de Lausanne (Switzerland) and Elettra-Sincrotrone Trieste (Italy), who supported the 2024 experimental study.

"Quantum biology—in particular our observations of superradiant signatures from standard protein spectroscopy methods, guided by his theory—has the potential to open new vistas for understanding the evolution of living systems, in light of photophysics."

ANEURAL LIFE AND PLANETARY COMPUTING CAPACITY

By thinking of biological information processing primarily at the level of the neuron, many scientists overlook the fact that aneural organisms—including bacteria, fungi, and plants, which form the bulk of Earth's biomass—perform sophisticated computations.

And as these organisms have been on our planet for much longer than animals, they constitute the vast majority of Earth's carbon-based computation.

"There are signatures in the interstellar media and on interplanetary asteroids of similar quantum emitters, which may be precursors to eukaryotic life's computational advantage," said Dante Lauretta, professor of planetary science and cosmochemistry at the University of Arizona and director of the Arizona Astrobiology Center, who was not associated with the work.

“Kurian’s predictions provide quantitative bounds, beyond the colloquial Drake equation, on how superradiant living systems enhance planetary computing capacity.

The remarkable properties of this signaling and information-processing modality could be a game-changer in the study of habitable exoplanets.”

PERFORMANCE COMPARISONS WITH QUANTUM COMPUTERS

This latest analysis has likewise drawn the attention of researchers in quantum computing, because the survival of fragile quantum effects in a “noisy” environment is of great interest to those who want to make quantum information technology more resilient.

Kurian has had conversations with several quantum computing researchers who were surprised to find such connections in the biological sciences.

“These new performance comparisons will be of interest to the large community of researchers in open quantum systems and quantum technology,” said Professor Nicolò Defenu of the Federal Institute of Technology (ETH) Zurich in Switzerland, a quantum researcher who was not associated with the work.

“It’s really intriguing to see a vital and growing connection between quantum technology and living systems.”

In the Science Advances article, Kurian explains and revisits foundational quantum properties and thermodynamic considerations, from a long line of physicists who made clear the essential link between physics and information.

With his group’s discovery of UV-excited qubits in biological fibers, almost all life on Earth has the physical capacity to compute with controllable quantum degrees of freedom, allowing storage and manipulation of quantum information with error correction cycles far outpacing the latest lattice-based surface codes.

“And all this in a warm soup!”

“The quantum computing world should take serious notice,” Kurian said.

The work also piqued the attention of quantum physicist Seth Lloyd, a professor of mechanical engineering at MIT and a pioneer in the study of quantum computing and the computational capacity of the universe.

"I applaud Dr. Kurian's bold and imaginative efforts to apply the fundamental physics of computation to the total amount of information processing performed by living systems over the course of life on Earth."

"It's good to be reminded that the computation performed by living systems is vastly more powerful than that performed by artificial ones," Lloyd said.

"In the era of artificial intelligences and quantum computers, it is important to remember that physical laws restrict all their behaviors," Kurian said.

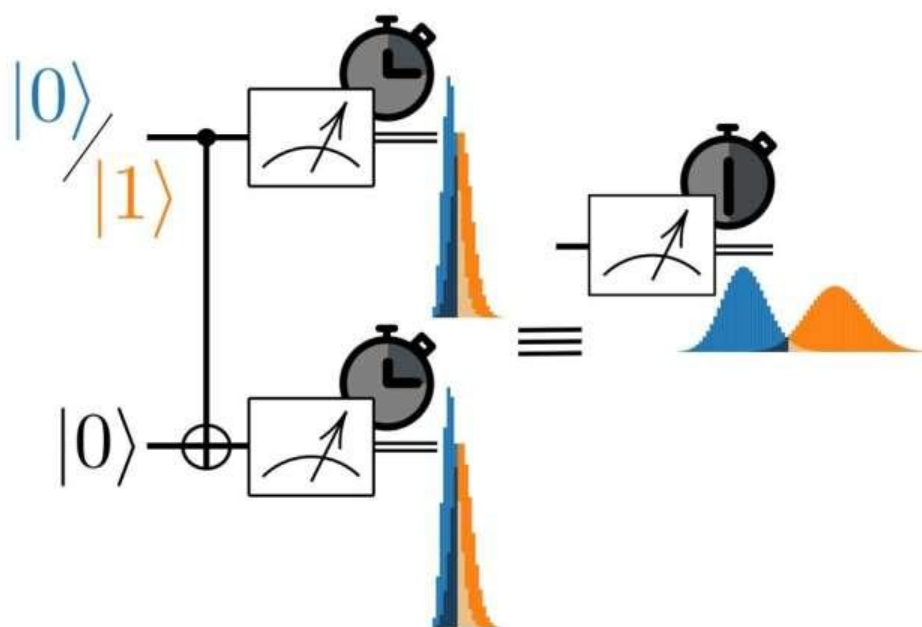
"And yet, though these stringent physical limits also apply to life's ability to track, observe, know, and simulate parts of the universe, we can still explore and make sense of the brilliant order within it, as the cosmic story unfolds.

"It's awe-inspiring that we get to play such a role."

MARCH 29, 2025

Scientists develop method to speed up quantum measurements using space-time trade-off

by Tejasri Gururaj , Phys.org



A quantum circuit showing a fast measurement outcome for two qubits is the same as a slow measurement outcome for one qubit. Credit: Chris Corlett

In an attempt to speed up quantum measurements, a new *Physical Review Letters* [study proposes](#) a space-time trade-off scheme that could be highly beneficial for quantum computing applications.

Quantum computing has several challenges, including error rates, qubit stability, and scalability beyond a few qubits. However, one of the lesser-known challenges [quantum computing](#) faces is the fidelity and speed of [quantum measurements](#).

The researchers of the study address this challenge by using additional or ancillary qubits to significantly reduce measurement time while maintaining or improving the quality of measurements.

Led by Christopher Corlett, Professor Noah Linden, and Dr. Paul Skrzypczyk from the University of Bristol, the work was a collaborative effort, including members from the University of Oxford, University of Strathclyde, and Sorbonne Université.

Phys.org spoke to Corlett, Professor Linden, and Dr. Skrzypczyk about their work.

"The measurement process in quantum mechanics is one of its most important and fascinating features. It is also vital for future quantum technologies," explained Corlett.

"Accurate and fast quantum measurements are crucial for the development of emerging quantum technologies. Recent seminal results in quantum error correction demonstrate the need for fast and accurate measurements in order to facilitate error decoding, without which [fault tolerance](#) would be impossible," added Dr. Skrzypczyk.

The measurement challenge

There are infinitely many measurements that can be performed on a qubit. A particularly important one is probing whether it is one of two natural states: 0 or 1. To perform this measurement accurately typically involves probing the qubit for a long time.

These longer measurements typically yield higher accuracy but introduce significant overhead and delay, particularly problematic for mid-circuit measurements required in [quantum error correction](#). Additionally, longer measurements introduce noise and decoherence that can accumulate during this time.

The researchers explain this with an analogy.

"Imagine you're shown a picture of two glasses of water, one glass with 100 ml and the other with 90 ml, and you have to determine, by sight, which glass has more water.

"If you're only shown the picture for one second you might struggle to tell which glass is more full. However, if you're shown the picture for two seconds, you can be more confident about which glass is more full," explained Corlett.

The researchers used an ancillary qubit to amplify the amount of information the measurement can gather about the qubit state in a fixed amount of time.

It is like doubling the volume of each glass; a difference of 20 ml would be easier to observe than a difference of 10 ml. It gives more confidence in the answer. If this process is continued and the amount of information continuously increases, the time taken to answer reduces.

"Continuing with the analogy, adding a second auxiliary qubit would triple the volumes to 300 ml and 270 ml, which you would be able to distinguish, with confidence, in 0.66 seconds. In this way, you can achieve a linear increase in readout speed with the number of qubits," explained Professor Corlett.

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Trading time for space

The researchers' scheme builds on previous protocols that use repetition codes for error correction. This method entangles the target qubit (on which measurement is to be conducted) with ancillary qubits.

More specifically, the target qubit is entangled with $N-1$ ancillary qubits. The information from the target qubit is then copied to all the ancillary qubits using so-called CNOT gates.

Here is where the innovation lies. Instead of measuring the target qubit for time t , all N qubits (target and ancillary) are measured simultaneously for t/N time. All the measurements are then added for a combined result, which gives the same statistical confidence as a longer single measurement.

The space (the number of qubits used) is being traded for time. The measurement of a single [qubit](#) for five seconds is the same as measuring five qubits simultaneously for one second.

"Remarkably, this allows the quality of a measurement to be maintained, or enhanced, even as it is sped up. The scheme is widely applicable to a broad range of leading quantum hardware platforms, including cold atoms, trapped ions, and superconducting qubits," said Corlett.

Robust against noise

The researchers investigated their scheme first in ideal conditions with no noise and then with realistic noise models. They found that the ideal case showed a perfectly linear speedup with the number of qubits.

The noise models also showed significant speedup and sometimes had better than linear improvement. The researchers showed that their approach can achieve higher maximum measurement quality than previously possible.

"Making sure our scheme is robust to this noise is incredibly important as it ensures it is useful for real-world implementation where noise is unavoidable," said Professor Linden.

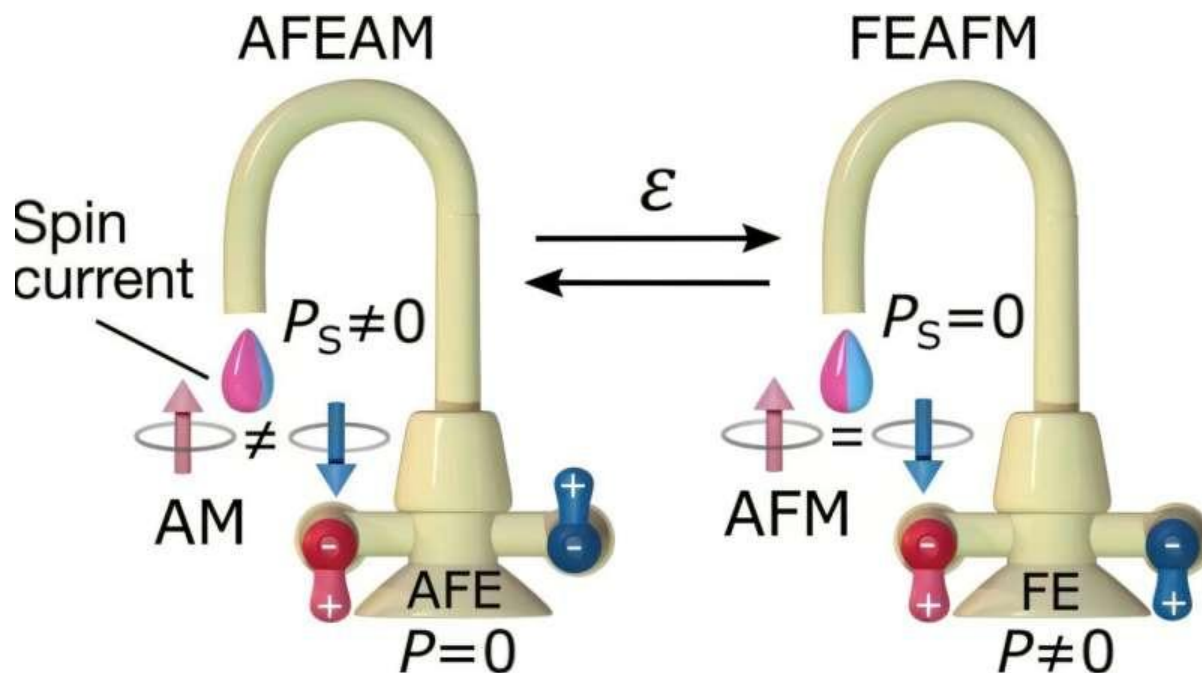
The researchers are eager to see the experimental implementation of their scheme and are working to develop it in more detail for specific systems like superconducting qubits.

More information: Christopher Corlett et al, Speeding Up Quantum Measurement Using Space-Time Trade-Off, *Physical Review Letters* (2025). [DOI: 10.1103/PhysRevLett.134.080801](#).

Journal information: [Physical Review Letters](#)

Researchers propose a simple magnetic switch using altermagnets

by David Appell , Phys.org



Schematic of the Zhou et al magnet switch. Acronyms are as in the body of the text.

FEAFM: ferroelectric antiferromagnet. Red and blue arrows indicate spins. ϵ is an applied, switchable electric field. P is electric polarization. P_s is spin polarization. Credit: Tong Zhou, Eastern Institute of Technology, Ningbo and American Physical Society

Controlling magnetism in a device is not easy; unusually large magnetic fields or lots of electricity are needed, which are bulky, slow, expensive and/or waste energy. But that looks soon to change, thanks to the recent discovery of altermagnets. Now scientists are putting forth ideas for efficient switches to manage magnetism in devices.

Magnetism has traditionally come in two varieties: ferromagnetism and antiferromagnetism, based on the alignment (or not) of [magnetic moments](#) in a material. Early last year, physicists announced [experimental evidence](#) for a third variety of magnetism: altermagnetism, a different combination of spins and crystal symmetries. Researchers are now learning how to tune altermagnets, bringing science closer towards practical applications.

We're all familiar with ferromagnetism (FM), like a refrigerator magnet or compass needle, where magnetic moments in atoms lined up in parallel in a crystal. A second class was added [about a hundred years ago](#) called antiferromagnetism (AFM), where magnetic moments in a crystal align regularly in alternate directions on differing sublattices, so the crystal has no net magnetization, but usually does at low temperatures.

Altermagnets (AM) are a sort of mixture of the two: the [crystalline material](#) is ordered where the magnetic moments alternate, resulting in no net magnetization. But the spins don't simply cancel out, as in antiferromagnetism. Instead, the crystal's symmetry creates an electronic band structure with strong spins that flip in direction the deeper one probes through the material's energy bands.

Altermagnets have some properties similar to ferromagnets, but new properties as well, having no net magnetism but with strong spin-dependent effects. This makes altermagnets potentially quite useful for spintronics applications—devices where electron spin is used to carry information, akin to how electron charge carries information in electronics.

Altermagnets have been of great interest since their discovery, and new theoretical advances have shown how to create a switch for them, an important step towards applications in spintronics. The research, led by Tong Zhou of the Eastern Institute of Technology, Ningbo in China, is [published](#) in *Physical Review Letters*.

"We've created a material that lets you control magnetism as easily as turning the handle on your faucet," said Zhou. "Imagine having two knobs: when they're set opposite each other, you get a special magnetic current; when they're turned the same way, it turns off. It's that simple."

Altermagnets show electronic band levels that are divided between spin-up and spin-down bands. This splitting can be used to polarize an electric current, as one spin state will flow more easily through the material than the other. This implies more rapid spintronics applications are possible that operate with greater efficiency than current spintronics devices.

What's still needed is a way to alter the spin properties of an altermagnet.

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Researchers are now advocating using electric fields to do this switching. For this, electric fields have an advantage, since they're more amenable to controlling magnetic devices than are magnetic fields—easier to manipulate and implement. They would also be much faster, potentially in the sub-nanosecond range, and use less energy.

A proposal published by Zhou's group can be called an "antiferroelectric altermagnet" (AFEAM). Similarly to an antiferromagnet, an antiferroelectric (AFE) material consists of atomic structures whose electric dipoles are aligned in opposite directions.

The group hypothesized a material where the electric dipoles are coupled to magnetic spins such that the population of spin-up sublattices is linked to the spin-down sublattices through rotational symmetry. Such a material would have both antiferroelectric and altermagnetic properties.

A small applied electric field causes the electric dipoles to line up in the same direction, transforming the material into a ferroelectric (FE) crystal. In a ferroelectric state (again, dipoles aligned) it would no longer be an altermagnet but would be an antiferromagnet (magnetic moments not aligned). Then it would not polarize an electronic current. The electric field toggles the spin polarization on or off.

"Controlling magnetism means future gadgets like memory storage and computers could become much faster, use less energy, and last longer on battery power," Zhou said.

Another group and a lone researcher have also proposed technologies that also use electric fields for magnetic switching.

A group led by Qihang Liu of the Southern University of Science and Technology in Shenzhen, China, and researcher Libor Šmejkal of the Max Planck Institute for the Physics of Complex Systems in Germany also propose a ferroelectric switchable altermagnet, where an applied electric field interacts with deformation modes of the crystal to control the sign of the altermagnet's spin splitting.

For [Liu and colleagues](#), the deformation is the [Jahn-Teller distortion](#), an alternating contraction and elongation of specific bonds. For Šmejkal's [proposal](#), the deformation comes from rotations of sublattice units within the material that, when activated electrically, reverse the ferroelectric polarization of the system, a phenomenon called the altermagnetoelectric effect.

"It's rare to bring two big ideas—antiferroelectricity and altermagnetism—together into one material and have them work in harmony. That's what makes this discovery so special," said Zhou.

"Honestly, it feels like we've uncovered a hidden switch inside materials—one that lets us toggle spin behavior without ever touching the magnetic structure. That's a game-changer."

More information: Xunkai Duan et al, Antiferroelectric Altermagnets: Antiferroelectricity Alters Magnets, *Physical Review Letters* (2025). [DOI: 10.1103/PhysRevLett.134.106801](https://doi.org/10.1103/PhysRevLett.134.106801). On *arXiv*: [DOI: 10.48550/arxiv.2410.06071](https://doi.org/10.48550/arxiv.2410.06071)

Journal information: [Physical Review Letters](#) , [arXiv](#)

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MARCH 29, 2025

Quantum entanglement reveals strange metals' unique electron behavior at critical point

by [Rice University](#)

Qimiao Si is the Harry C. and Olga K. Wiess Professor of Physics and Astronomy at Rice. Credit: Jeff Fitlow/Rice University.

Scientists have long sought to unravel the mysteries of strange metals—materials that defy conventional rules of electricity and magnetism. Now, a team of physicists at Rice University has made a breakthrough in this area using a tool from quantum information science. Their study, published recently in [Nature Communications](#), reveals that electrons in strange metals become more entangled at a crucial tipping point, shedding new light on the behavior of these enigmatic materials. The discovery could pave the way for advances in superconductors with the potential to transform energy use in the future.

Unlike conventional metals such as copper or gold that have well-understood electrical properties, strange metals behave in much more complex ways, making their inner workings beyond the realm of textbook description. Led by Qimiao Si, the Harry C. and Olga K. Wiess Professor of Physics and Astronomy, the research team turned to quantum Fisher information (QFI), a concept from quantum metrology used to measure how electron interactions evolve under extreme conditions, to find answers. Their research shows that electron entanglement, a fundamental quantum phenomenon, peaks at a quantum [critical point](#): the transition between two states of matter.

"Our findings reveal that strange metals exhibit a unique entanglement pattern, which offers a new lens to understand their exotic behavior," Si said. "By leveraging quantum information theory, we are uncovering deep quantum correlations that were previously inaccessible."

A new way to study strange metals

In most metals, electrons move in an orderly fashion, following well-established laws of physics. Strange metals, however, break these rules, showing unusual resistance to electricity and behaving in unusual ways at very low temperatures. To explore this puzzle, the researchers focused on a theoretical model called the Kondo lattice, which describes how magnetic moments interact with surrounding electrons.

At a critical transition point, these interactions become so intense that the fundamental building blocks of electrical behavior, known as quasiparticles, vanish. Using QFI, the researchers tracked the origin of this quasiparticle loss to how electron spins become entangled, finding that entanglement reaches its peak precisely at this quantum critical point.

This novel approach applies QFI, primarily used in quantum information and precision measurements, to the study of metals.

"By integrating [quantum information science](#) with condensed matter physics, we are pivoting in a new direction in materials research," Si said.

Possible path to more efficient energy

The researchers' theoretical calculations unexpectedly matched real-world [experimental data](#), specifically aligning with results from inelastic neutron scattering, a technique used to probe materials at the atomic level. This connection reinforces the idea that quantum entanglement plays a fundamental role in the behavior of strange metals.

Understanding [strange metals](#) is more than just an academic challenge; it could have significant technological benefits. These materials share a close connection with high-temperature superconductors, which have the potential to transmit electricity without energy loss. Unlocking their properties could revolutionize power grids, making energy transmission more efficient.

The study also demonstrates how quantum information tools can be applied to other exotic materials. Strange metals could play a role in future quantum technologies, where enhanced entanglement is a valuable resource. The research provides a new framework for characterizing these complex materials by showing when entanglement peaks.

The research team included Rice's Yuan Fang, Yiming Wang, Mounica Mahankali and Lei Chen along with Haoyu Hu of the Donostia International Physics Center and Silke Paschen of the Vienna University of Technology.

More information: Yuan Fang et al, Amplified multipartite entanglement witnessed in a quantum critical metal, *Nature Communications* (2025). [DOI: 10.1038/s41467-025-57778-7](https://doi.org/10.1038/s41467-025-57778-7)

Journal information: [Nature Communications](#)

Provided by [Rice University](#)

MARCH 31, 2025

Dark matter could make planets spin faster

by Evan Gough, [Universe Today](#)



The content of the Universe is widely thought to consist of three types of substance: normal matter, dark matter and dark energy. Some dark matter can find its way inside planets, where it can interact with baryonic matter, producing heat and making the planet rotate more quickly. Credit: ESA

Dark matter is a confounding concept that teeters on the leading edges of cosmology and physics. We don't know what it is or how exactly it fits into our understanding of the universe. We only know that its unseen mass is a critical part of the cosmos.

Astronomers know [dark matter](#) exists. They can tell by the way galaxies rotate, by exploiting [gravitational lensing](#), and by analyzing fluctuations in the Cosmic Microwave Background. But new research suggests that there might be another way to detect its presence.

The research is "[Dark Matter \(S\)pins the Planet](#)," and it's available on the *arXiv* preprint server. Haihao Shi, from the Xinjiang Astronomical Observatory at the Chinese Academy of Sciences, is the lead author. The co-authors are all from Chinese research institutions.

"Dark matter(DM) constitutes approximately 85% of the universe's matter content, as evidenced by a multitude of astrophysical and cosmological observations. Despite its pervasive presence, the fundamental nature and composition of [dark matter particles](#) remain elusive, pointing to new physics beyond the Standard Model and general relativity," the authors write, capturing the issue neatly.

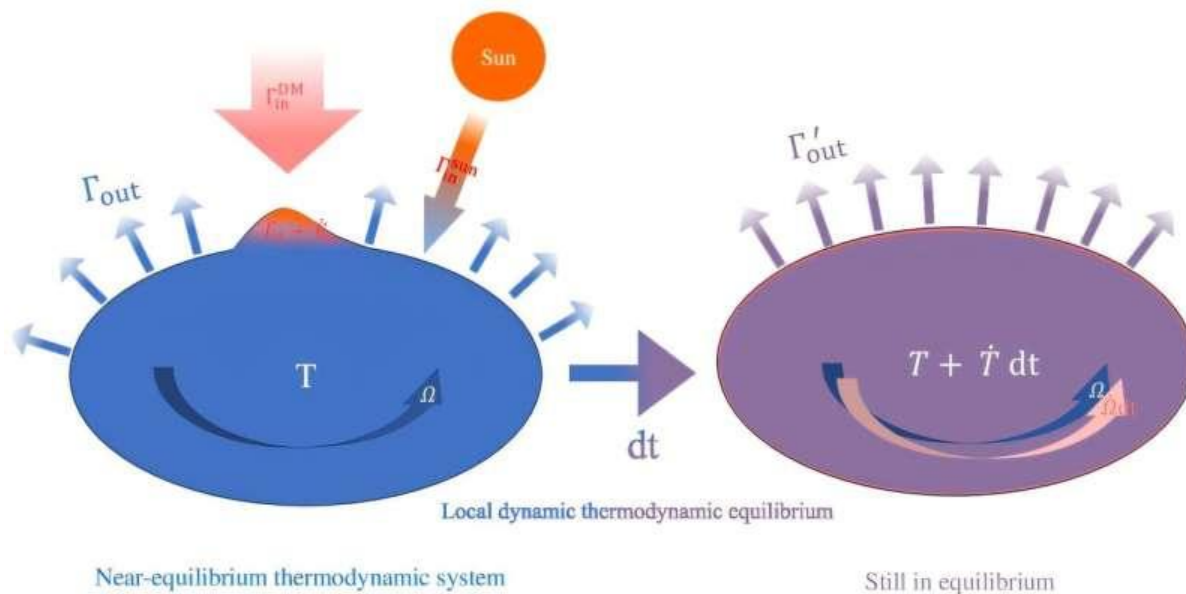
The research rests on [previous research](#) suggesting that DM can find its way into the interior of planets, a phenomenon called dark matter planetary capture. The idea is that the gravitational pull of planets can attract dark matter particles. The physics behind it are complex, but scientists are working on it, including trying to estimate its density inside planets. Scientists expect the density to be very low, making it difficult to detect.

There are a variety of explanations for what DM could be. It could be [primordial black holes](#), it could be axions, or it could be weakly interacting massive particles (WIMPs). There are other candidates as well. But this research tries to constrain DM's properties on a planetary scale rather than on a microscopic or cosmic scale.

"Planets serve as long-term probes of dark matter effects, having interacted with the surrounding dark matter halo for billions of years," the authors write. "These interactions may lead to cumulative, observable consequences, such as changes in planetary temperature, rotational dynamics, and atmospheric properties."

The basic idea behind dark matter capture is that DM interacts with planetary matter and deposits energy into the planet. While dark matter and [baryonic matter](#) don't interact or collide in the normal sense, they can interact due to factors like quantum tunneling. These interactions lead to changes in a planet's rotation and temperature, accelerating one and raising the other. Scientists can observe these changes, and the authors have developed a new approach to detecting them.

Though the physics themselves are fascinating on their own, planetary dark matter could affect habitability. "Furthermore, dark matter effects at planetary scales could influence planetary habitability by altering thermal conditions, potentially affecting the stability of liquid water and atmospheric evolution," the paper states.



The left and right figures respectively represent the planetary system before and after experiencing perturbation T' due to dark matter and sun's heating. Since the perturbation is minimal, we consider the process under local dynamic thermodynamic equilibrium. The perturbations follow $E' \rightarrow 1 + E' \rightarrow T' + \Omega'$, where the planetary temperature evolves as $T \rightarrow T + T' \otimes d \otimes t$, and the planetary angular velocity changes as $\Omega \rightarrow \Omega + \Omega' \otimes d \otimes t$. Credit: *arXiv* (2025). DOI: 10.48550/arxiv.2503.17206

When dark matter particles enter planets, they are subject to scattering, capture, and annihilation. When they scatter—or collide—they impart kinetic energy into the planetary particles, which manifests as heat. The same happens when they're annihilated. The temperature increase is due to how much dark matter enters the planet, and the energy that's input can also accelerate the planet's rotation period.

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In their work, the researchers simulated dark matter planetary capture in 15 confirmed exoplanets, including ones like 55 Cancri d (Lipperhey) and Epsilon Eridani b, both of particular interest to scientists. They also applied their model to Jupiter and Earth.

"Our theory suggests that the energy provided by dark matter heating is not entirely converted into temperature but is distributed according to the planet's intrinsic properties, such as mass and radius, as well as its current state, including temperature and angular velocity," the authors write.

Earth is not immune to dark matter capture, according to the research.

The authors write that "... our predictions suggest that the combined energy input from dark matter and the sun will lead to a surface atmospheric temperature increase of approximately 0.015 K over 100 years and 0.15 K over 1000 years."

Dark matter heating can also increase a planet's rotational velocity, though that's more difficult to differentiate from other influences. Things like tidal effects and earthquakes can also affect rotational velocity. "For Earth, we predict that the heating of dark matter will accelerate its rotation period on the order of seconds per hundred years," they write.

Earth's rotation period will decrease by about 12 seconds in 100 years. In 1,000 years, that's 120 seconds. These are large numbers, and the authors say we should be able to detect these effects with ground-based measurement methods.

The authors claim that as we understand these effects more clearly, they could help us understand exoplanet habitability.

"In the future, as humanity searches for a second home in the universe, the impact of dark matter on planetary rotation proposed in this work may serve as a reference for assessing planetary habitability," they conclude.

More information: Haihao Shi et al, Dark Matter (S)pins the Planet, *arXiv* (2025). [DOI: 10.48550/arxiv.2503.17206](https://doi.org/10.48550/arxiv.2503.17206)

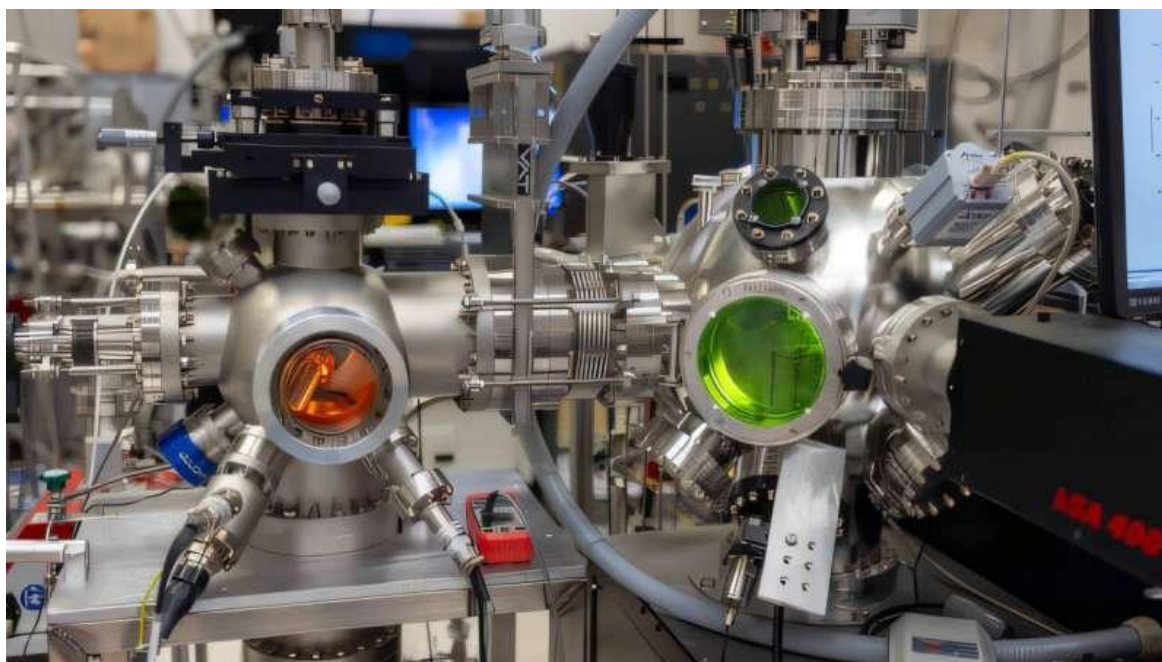
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Scientists merge two 'impossible' materials into new artificial structure

by Kitta MacPherson, [Rutgers University](#)



By building a unique, advanced machine, scientists have created a structure with quantum qualities. The green window (right) is the main growth chamber where synthesis of the quantum "sandwiches" occurs. Within the amber window (left) are advanced characterization tools that uncover chemical and electronic properties of the grown quantum thin films without exposing them to air. Credit: Jeff Arban

An international team led by Rutgers University-New Brunswick researchers has merged two lab-synthesized materials into a synthetic quantum structure once thought impossible to exist and produced an exotic structure expected to provide insights that could lead to new materials at the core of quantum computing.

The work, [described](#) in a cover story in the journal *Nano Letters*, explains how four years of continuous experimentation led to a novel method to design and build a unique, tiny sandwich composed of distinct atomic layers.

One slice of the microscopic structure is made of dysprosium titanate, an inorganic compound used in nuclear reactors to trap [radioactive materials](#) and contain elusive magnetic monopole particles, while the other is composed of pyrochlore iridate, a new magnetic semimetal mainly used in today's experimental research due to its distinctive electronic, topological and magnetic properties.

Individually, both materials are often considered "impossible" materials due to their unique properties that challenge conventional understanding of quantum physics.

The construction of the exotic sandwich structure sets the stage for scientific explorations in what is referred to as the interface, the area where the materials meet, in the atomic scale.

"This work provides a new way to design entirely new artificial two-dimensional quantum materials, with the potential to push [quantum technologies](#) and provide deeper insight into their fundamental properties in ways that were previously impossible," said Jak Chakhalian,

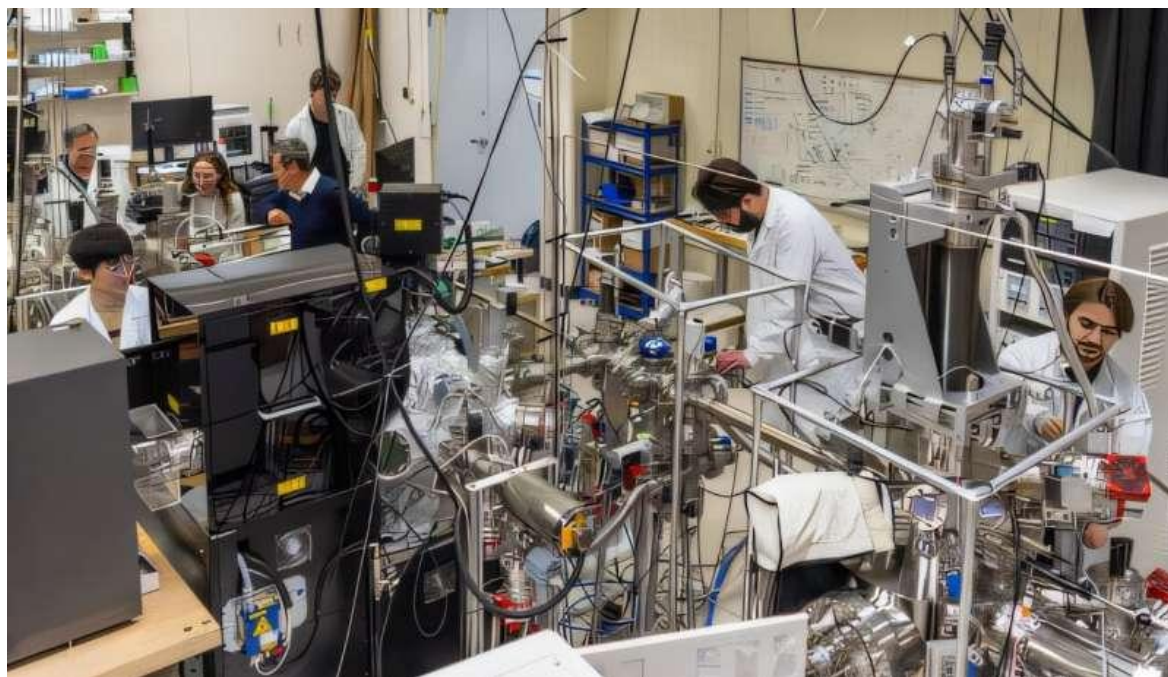
the Claud Lovelace Endowed Professor of Experimental Physics in the Department of Physics and Astronomy at the Rutgers School of Arts and Sciences and a principal investigator the study.

Chakhalian and his team are exploring a realm that follows the laws of quantum theory, a branch of physics that describes the behavior of matter and energy at the atomic and subatomic level. Central to quantum mechanics is the concept of wave-particle duality, where [quantum objects](#) can possess both wave-like and particle-like properties—a foundational principle behind technologies such as lasers, magnetic resonance imaging (MRI) and transistors.

Chakhalian highly praised the efforts of three Rutgers students who made major contributions to the research: Michael Terilli and Tsung-Chi Wu, both doctoral students, and Dorothy Doughty, who graduated in 2024 and worked on the study as an undergraduate. In addition, Mikhail Kareev, who is a materials scientist working with Chakhalian, made a main contribution to the new synthesis method, as well as Fangdi Wen, a doctoral student who recently graduated from the Department of Physics and Astronomy.

Chakhalian said that creating the unique quantum sandwich was so technically challenging that the team had to build a new device to accomplish the feat.

The instrument, called Q-DiP, short for quantum phenomena discovery platform, was completed in 2023. Q-DiP incorporates an infrared laser heater with another laser which enables the construction of materials on an atomic level, layer by layer. The combination allows the scientists to explore the most intricate quantum properties of materials down to ultra cold temperatures near absolute zero.



Members of the Chakhalian Lab conduct an experiment using Q-DiP, short for quantum

discovery platform. The probe is unique in the U.S. and represents a breakthrough as an instrumental advance. Credit: Jeff Arban

"To the best of our knowledge, this probe is unique in the U.S. and represents a breakthrough as an instrumental advance," Chakhalian said.

The half of the experimental sandwich that is dysprosium titanate, also known as [spin ice](#), possesses special qualities. Tiny magnets inside, called spins, are arranged in a way that looks exactly like the pattern of water ice. The unique structure of the tiny magnets in spin ice allows them to emerge as special particles called magnetic monopoles.

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A magnetic monopole is a particle that acts like a magnet, but with only one pole—either north or south, but not both. This object, predicted in 1931 by the Nobel prize winner Paul Dirac, does not exist in free form in the universe and yet inside spin ice it emerges as a result of the quantum mechanical interactions within the material.

On the other side of the sandwich, the semimetal pyrochlore iridate is also considered exotic because it contains tiny relativistic particles called Weyl fermions. Again, surprisingly, though predicted by Hermann Weyl in 1929, these exotic particles, discovered in 2015 in crystals, move like light and can spin in different ways—left-handed or right-handed.

Their [electronic properties](#) are very strong and resist certain types of disturbances or impurities, making them very stable when operated as a part of electronic devices. As a result, pyrochlore iridate can conduct electricity very well, respond in unusual ways to magnetic fields and show special effects when exposed to electromagnetic fields.

Chakhalian said the combined properties of the new material created makes it a promising candidate for use in advanced technologies, including quantum computing and especially for the next-generation quantum sensors.

"This study is a big step forward in material synthesis and could significantly impact the way we create quantum sensors and advances spintronic devices," he said.

Quantum computing employs the principles of quantum mechanics to process information. Quantum computers use quantum bits or qubits that exist in multiple states simultaneously due to a quantum physical principle called superposition. This allows for complex computations to be performed much more efficiently than by classical computers.

The specific electronic and [magnetic properties](#) of the material developed by the researchers can help in creating very unusual and yet stable quantum states, which are essential for quantum computing.

When quantum technology becomes practical, it will significantly impact ordinary life by revolutionizing drug discovery and medical research, markedly improving operations, predictability and cost savings in finance, logistics and manufacturing. It is also expected to

To improve the properties of PDMS-based materials, they have been combined with inorganic fillers such as nanoparticles or nanosheets. Generally, the introduction of nanosheets into polymers leads to the formation of a layered structure that exhibits superior thermal, mechanical, and gas barrier properties. Furthermore, an improved crack-healing ability of oriented films has been reported. This improvement is attributed to polymer diffusion concentrated in the in-plane direction.

Researchers at Waseda University, Japan, have made significant progress in enhancing self-healing siloxane materials by developing a more efficient method for fabricating multilayered [films](#). In a study published 6 January 2025, in the journal [Chemical Communications](#), a team led by Professor Atsushi Shimojima, with Research Associate Yoshiaki Miyamoto and Assistant Professor Takamichi Matsuno, fabricated a composite film comprising highly cross-linked organosiloxane (silsesquioxane) and grafted PDMS layers using a self-assembly process.

"Replacing traditional materials with our self-healing material, which is less susceptible to deterioration and has high hardness, would be in high demand for maintenance-free and durable applications," says Miyamoto, the lead author of the study.

The researchers began by depositing a solution containing 1,2-bis(triethoxysilyl)ethane, Pluronic P123 (a PEO–PPO–PEO triblock copolymer, where PEO stands for poly([ethylene oxide](#)) and PPO stands for poly(propylene oxide)), and a PEO–PDMS–PEO block copolymer onto a silicon or glass substrate using spin-coating or drop-casting techniques. This process formed a thin film with a lamellar (layered) structure.

The film was then calcinated in air at 170 °C for 4 hours, resulting in the removal of the PEO and PPO blocks. This process left behind a multilayered structure composed of silsesquioxane and PDMS layers.

To impart self-healing properties to the film, Si–O[−] groups were introduced. These groups promote rearrangement and reconnection of the siloxane (Si–O–Si) networks. To achieve this, the film was immersed in a solution of tetrahydrofuran, water, and potassium hydroxide (KOH). In this process, hydroxide ions (OH[−]) from KOH removed protons (H⁺) from silanol (Si–OH) groups, converting them into Si–O[−] ions. The final film could repair micrometer-scale cracks when heated to 80 °C at 40% relative humidity for 24 hours.

The film showed superior properties compared to conventional PDMS-based materials. The cross-linked organosiloxane layers provided greater rigidity and served as a barrier against the volatilization of cyclic siloxanes, addressing the limitations of traditional PDMS materials. While conventional self-healing PDMS elastomers have a hardness of 49 MPa, the final self-healing film exhibited a hardness of 1.50 GPa.

"This innovative multilayered design allows our material to be both harder and more heat-resistant than existing self-healing siloxane-based materials, paving the way for more durable and reliable applications," says Miyamoto.

With its high hardness and [self-healing](#) properties, this material is well-suited for protective coatings, flexible electronics, and other applications that require long-lasting performance.

More information: Yoshiaki Miyamoto et al, Multilayered organosiloxane films with self-healing ability converted from block copolymer nanocomposites, *Chemical Communications* (2025). [DOI: 10.1039/D4CC05804F](https://doi.org/10.1039/D4CC05804F)

Journal information: [Chemical Communications](#)

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