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Discovery in quantum materials could make electronics 1,000 times faster

by Kate Rix, [Northeastern University](#) edited by [Lisa Lock](#), reviewed by [Robert Egan](#)

Alberto De la Torre used controlled heating and cooling to make a quantum material switch between a conductive state and an insulating state. Credit: Matthew Modoono/Northeastern University

Researchers at Northeastern University have discovered how to change the electronic state of matter on demand, a breakthrough that could make electronics 1,000 times faster and more efficient.

By switching from insulating to conducting and vice versa, the discovery creates the potential to replace silicon components in electronics with exponentially smaller and faster quantum materials.

"Processors work in gigahertz right now," said Alberto de la Torre, assistant professor of physics and lead author of the research. "The speed of change that this would enable would allow you to go to terahertz."

Via controlled heating and cooling, a technique they call "thermal quenching," researchers are able to make a quantum material switch between a metal conductive state and an insulating state. These states can be reversed instantly using the same technique.

Published in the journal *Nature Physics*, the [research findings](#) represent a breakthrough for [materials scientists](#) and the future of electronics: instant control over whether a material conducts or insulates electricity.

The effect is like a transistor switching electronic signals. And just as transistors allowed computers to become smaller—from the huge machines the size of rooms to the phone in your pocket—control over quantum materials has the potential to transform electronics, says Gregory Fiete, a professor of physics at Northeastern who worked with de la Torre to interpret the findings.

"Everyone who has ever used a computer encounters a point where they wish something would load faster," says Fiete. "There's nothing faster than light, and we're using light to control [material properties](#) at essentially the fastest possible speed that's allowed by physics."

By shining light on a quantum material called 1T-TaS₂ at close to room temperature, researchers achieved a "hidden metallic state" that had so far only been stable at cryogenically cold temperatures. Now researchers have created that conductive metallic state at more practical temperatures, says de la Torre. The material maintains its programmed state for months—something that has never been accomplished before.

"One of the grand challenges is, how do you control material properties at will?" says Fiete. "What we're shooting for is the highest level of control over material properties. We want it to do something very fast, with a very certain outcome, because that's the sort of thing that can be then exploited in a device."

So far, electronic devices have needed both conductive and insulating materials, plus a well-engineered interface between the two. This discovery makes it possible to use just one material that can be controlled with light to conduct and then insulate.

"We eliminate one of the engineering challenges by putting it all into one material," Fiete says. "And we replace the interface with light within a wider range of temperatures."

The research expands upon previous work that used ultra-fast laser pulses to temporarily change the way materials conduct electricity. But those changes only lasted tiny fractions of a second and usually at extremely cold temperatures.

Stable conductivity switching at higher temperatures is a significant advance for [quantum mechanics](#), Fiete says, and for the long game of supplementing or replacing silicon-based technology. Semiconductors, he says, are so dense with logic components that engineers are now stacking them in three dimensions. But this approach has limitations, he said, which make tiny [quantum materials](#) more important for electronics design.

"We're at a point where in order to get amazing enhancements in information storage or the speed of operation, we need a new paradigm," Fiete says. "Quantum computing is one route for handling this and another is to innovate in materials. That's what this work is really about."

More information: Alberto de la Torre et al, Dynamic phase transition in 1T-TaS₂ via a thermal quench, *Nature Physics* (2025). DOI: [10.1038/s41567-025-02938-1](https://doi.org/10.1038/s41567-025-02938-1). On *arXiv*: DOI: [10.48550/arxiv.2407.07953](https://arxiv.org/abs/10.48550/arxiv.2407.07953)

Journal information: [Nature Physics](#) , [arXiv](#)
Provided by [Northeastern University](#)

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New superheavy isotope reveals complex relationship between quantum effects and fission

by [Tejasri Gururaj](#), Phys.org edited by [Sadie Harley](#), reviewed by [Robert Egan](#)

Electronic configuration of seaborgium (Sg). Credit: Ahazard.sciencewriter/Wikimedia Commons.

[commons.wikimedia.org/wiki/File:106_seaborgium_\(Sg\)_enhanced_Bohr_model.png](https://commons.wikimedia.org/wiki/File:106_seaborgium_(Sg)_enhanced_Bohr_model.png).

In a study [published](#) in *Physical Review Letters*, scientists at GSI Helmholtzzentrum für Schwerionenforschung have discovered a new superheavy isotope, ^{257}Sg (seaborgium), whose properties are providing new insights into nuclear stability and fission in the heaviest elements.

Superheavy elements exist in a delicate balance between the attractive nuclear force that holds protons and neutrons together and the repulsive electromagnetic force that pushes positively charged protons apart.

Without quantum shell effects, analogous to electron shells in atoms, these massive nuclei would split apart in less than a trillionth of a second.

Phys.org spoke to co-authors Dr. Pavol Mosat and Dr. J. Khuyagbaatar from GSI Helmholtzzentrum für Schwerionenforschung, Germany, about their work.

The study reveals our incomplete understanding of how the most extreme atomic nuclei behave, with the findings suggesting that the [quantum effects](#) that keep superheavy nuclei from instantly disintegrating might operate differently than previously believed.

Investigating nuclear stability

The international research team used GSI's gas-filled recoil separator TASCA to create ^{257}Sg through fusion reactions between chromium-52 and lead-206 nuclei.

They found that the new isotope lives for 12.6 milliseconds, longer than its even-even neighbor ^{258}Sg , and decays through both [spontaneous fission](#) and alpha-particle emission.

The alpha decay pathway proved particularly revealing. When ^{257}Sg emits an alpha particle, it transforms into ^{253}Rf (rutherfordium), which then undergoes fission after just 11 microseconds.

This observation supports recent findings that have questioned the traditional understanding of how angular momentum affects fission. While higher K quantum numbers were expected to provide stronger fission hindrance, emerging data suggests this relationship may be more complex than previously believed.

"We studied ^{257}Sg and ^{253}Rf isotopes and found that, in general, K-quantum numbers do indeed hinder fission," said Mosat. "However, the absolute value of hindrances is still unknown."

First K-isomer in seaborgium

Perhaps even more significant was the team's discovery of the first K-isomeric state in a seaborgium isotope. K-isomers are special nuclear configurations with high angular momentum that resist fission far more effectively than ordinary nuclear states.

In ^{259}Sg , the researchers detected a conversion electron signal appearing 40 microseconds after nuclear formation, strong evidence for a K-isomeric state that could be stable against the fission hundreds of times longer than the ground state.

"K isomeric states have already been observed in superheavy nuclei such as $^{252-257}\text{Rf}$, and ^{270}Ds ," noted Khuyagbaatar. "We observed K-isomer exclusively in nuclei with 106 protons, i.e., in Sg isotopes for the first time."

This finding fills a crucial gap in scientists' understanding of [superheavy elements](#) and could have profound implications for future element discovery efforts.

Implications for the 'island of stability'

The discovery comes at a critical time in superheavy element research.

Scientists have long searched for the theoretical "island of stability," a region where certain superheavy nuclei might exist for extended periods due to favorable shell effects. However, the new findings suggest this landscape may be more complex than anticipated.

"It may happen that the superheavy nucleus, for instance, an isotope of a not-yet-discovered element, may live less than 1 μs [microsecond]," explained Khuyagbaatar.

"If so, then the discovery of element 120 will likely face separation and detection challenges. However, if a K-isomeric state exists in this nucleus, it could live longer, as we recently demonstrated with ^{252}Rf ."

The researchers estimate that the still-undiscovered ^{256}Sg could have a dramatically shorter half-life than theoretical predictions suggest, potentially dropping from the predicted 6 microseconds to just one nanosecond.

Such a significant deviation in stability would represent an important new insight in nuclear physics.

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Technical challenges and future work

The experimental achievement required overcoming significant technical challenges. Working with nuclei that exist for mere milliseconds demanded extraordinarily fast detection systems and precise timing.

"In the case of short-lived nuclei, it is very important to have a relatively short-length separator and, more crucially, to have fast digital electronics that can disentangle radioactive decay signals down to about 100 ns," explained Khuyagbaatar.

The team developed specialized digital electronics at GSI that have proven crucial for multiple superheavy element discoveries.

The team's next goal is synthesizing ^{256}Sg to test whether the predicted dramatic decrease in stability actually occurs.

"Indeed, we will try to explore further cases of long-lived K-isomeric states in superheavy nuclei," said Mosat. "Concerning the current topic, our next plan will be to try to synthesize the next unknown ^{256}Sg ."

JULY 3, 2025

Quantum equivalent of thermodynamics' second law discovered for entanglement manipulation

by [University of Warsaw](#) edited by [Gaby Clark](#), reviewed by [Robert Egan](#)

Illustration of an entanglement battery. The battery allows reversible interconversion between any two entangled states. Credit: American Physical Society

Just over 200 years after French engineer and physicist Sadi Carnot formulated the second law of thermodynamics, an international team of researchers has unveiled an analogous law for the quantum world. This second law of entanglement manipulation proves that, just like heat or energy in an idealized thermodynamics regime, entanglement can be reversibly manipulated, a statement which until now had been heavily contested.

The new [research](#)—released on July 2, 2025 in *Physical Review Letters*—deepens understanding of entanglement's basic properties and provides critical fundamental insight into how to efficiently manipulate entanglement and other [quantum phenomena](#) in practice.

Entanglement is arguably the central feature of quantum mechanics. If two microscopic particles are said to be entangled, then if someone measures a quantum property of one of the particles and then repeats the measurement on its entangled partner, they will always find that the pair is correlated, even when the two particles are separated by vast distances. Therefore, knowing the state of one particle automatically provides information about the other.

Entanglement was introduced about 90 years ago as proof of the absurdity of quantum theory if treated as a complete description of nature. Yet it is not regarded as absurd today.

After exhaustive proofs of entanglement's authenticity in the real world, it is now the key resource in quantum information theory, allowing quantum teleportation and quantum cryptography, and offering significant advantages in quantum computing, communication and precision measurements.

Though entanglement still appears counterintuitive to our lived experience of the world, researchers have discovered striking parallels with something much more familiar: thermodynamics. In fact, many similarities have emerged between the theories of quantum entanglement and thermodynamics. For example, "entanglement entropy" is a characteristic of idealized, noiseless quantum systems that mimics the role of thermodynamical entropy.

However, an equivalent to the second law of thermodynamics—which dictates that processes tend towards increasing disorder (the aforementioned entropy) and that perfect reversibility is an attainable though rare and highly efficient ideal—has remained stubbornly out of reach. Here, reversibility does not refer to time symmetry but the ability of an external agent to manipulate the system into a different state and then manipulate it back to its [initial state](#) without any loss.

"Finding a second law analogous to the [second law of thermodynamics](#) has been an open problem in quantum information science," says study co-author Tulja Varun Kondra. "Solving this has been our primary motivation."

Much work towards addressing this problem has focused on a scenario in which two distant parties (often called Alice and Bob) want to exchange quantum information, but are restricted to acting locally on their quantum systems and communicating classically, by say, phone or the internet. This limitation to local operations and classical communication (LOCC) simplifies the situation, meaning whatever Alice and Bob do, they cannot affect the intrinsically nonlocal properties of entanglement between their quantum systems.

"It is known that under LOCC operations in this scenario, entanglement is irreversible," explains senior author of the study, Alexander Streltsov. "So the question is, can we somehow go beyond LOCC in a meaningful way, and recover reversibility?" The team's answer is 'yes,' as long as Alice and Bob share an additional entangled system: an entanglement [battery](#).

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Just as an ordinary battery stores energy which can be used to inject or store work in the context of thermodynamics, an entanglement battery injects and stores entanglement. The battery can be used in the state transformation process and the state of the battery itself can be changed to perform operations. There is only one rule: whatever Alice and Bob do, they must not decrease the level of entanglement within the battery.

And just as a regular battery allows tasks to be performed that would be impossible without one, so too does an entanglement battery. By assisting standard LOCC operations with their hypothetical entanglement battery, the team demonstrated that any mixed-state entanglement transformation can be made perfectly reversible.

This achievement is a significant contribution to the debate around whether entanglement manipulation is generally reversible. But a more important outcome of this work is that the researchers have shown that the methods they have developed are applicable beyond mixed-state entanglement transformation, allowing them to leverage the entanglement battery to verify reversibility in various scenarios. Proving that entanglement manipulations across all quantum states are reversible is expected to lead to a family of second laws for entanglement manipulation.

The entanglement battery may even find uses outside entanglement theory. For example, the same principles apply to systems involving more than two entangled particles, paving the way for understanding and manipulating complex quantum networks and perhaps developing future, highly efficient quantum technologies.

In addition, generalizing the concept of an entanglement battery to a resource battery—an additional quantum system that participates in the transformation process without reducing the resource in question—could allow the systematic demonstration of reversibility across quantum physics based on a minimal set of assumptions.

"We can have a battery that is supposed to preserve coherence or free energy, and then we can formulate a reversible framework in this setting where, instead of [entanglement](#), we reversibly manipulate that particular resource of our system," says Streltsov. "Though many of these other principles of reversibility have already been confirmed via other approaches, our technique offers a unified proof framework based on well-established physical principles."

More information: Ray Ganardi et al, Second Law of Entanglement Manipulation with an Entanglement Battery, *Physical Review Letters* (2025). DOI: [10.1103/kl56-p2vb](https://doi.org/10.1103/kl56-p2vb).

On *arXiv*: DOI: [10.48550/arxiv.2405.10599](https://doi.org/10.48550/arxiv.2405.10599)

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

Provided by [University of Warsaw](#)

JULY 7, 2025

An approach to realize heralded photon storage in a Rydberg superatom

by [Ingrid Fadelli](#), Phys.org edited by [Sadie Harley](#), reviewed by [Robert Egan](#)

Image illustrating entangling two quantum nodes via heralded storage. Credit: An et al. Quantum technologies, systems that operate leveraging quantum mechanical effects, have the potential to outperform classical technologies in some specific tasks. Over the past decades, some researchers have also been trying to realize quantum networks, systems comprised of multiple connected quantum devices.

So far, [photons](#) have been the most widely used particles for carrying [quantum information](#) across different devices in quantum networks. The main reasons for this are that photons can travel at remarkable speeds, while weakly interacting with their surrounding environment, which helps to preserve the quantum states they are carrying.

To successfully employ photons in quantum networks, however, physicists and engineers need to be able to confirm that they are stored successfully without destroying them.

Heralded storage is a promising technique to achieve this, as it entails the storage of photons accompanied by the production of a signal (i.e., 'herald') that confirms that their storage was successful.

Researchers at the University of Science and Technology recently demonstrated the heralded storage of photons in a Rydberg superatom (i.e., a cloud of atoms that behave as an individual quantum system under certain conditions).

Using newly proposed experimental methods, which were outlined in a paper published in [Physical Review Letters](#), they were able to successfully demonstrate the heralded storage of photons without relying on traditional high-finesse optical cavities, as done in earlier works.

"Prior to this work, [we introduced a technique we called photon compensation in a Rydberg superatom](#), which we used to demonstrate the generation of atom-photon entanglement, and [multiphoton entanglement](#)," Xiao-Hui Bao, co-senior author of the paper, told Phys.org.

"In subsequent discussions, we explored new potential applications of this technique, leading to the idea of heralded storage."

Bao and his colleagues have been trying to identify more promising techniques and experimental platforms for the realization of large-scale quantum networks for years. Their

recent study was aimed at realizing the heralded storage of photons in Rydberg superatoms, quantum systems that they often employed in their earlier experiments.

"In our initial proposal for demonstrating heralded storage, we planned to use two Rydberg superatom setups, with the input photonic qubit encoded in the spatial degree of freedom," explained Bao.

"While this scheme appeared straightforward, its implementation demanded extensive experimental resources and introduced considerable complexity."

Bao and his colleagues found that demonstrating heralded storage using two Rydberg superatoms was more challenging than they had originally anticipated, thus they devised a new and simpler approach.

The scheme they employed relies on a single superatom and entails the encoding of individual qubits in the time-bin degree of freedom (i.e., in the time in which a photon arrives, as opposed to its location or its polarization).

"Heralded storage has traditionally been considered a capability unique to cavity-QED systems," said Bao. "However, our scheme and experimental results demonstrate that a Rydberg [superatom](#) can perform this task effectively as well."

This work introduces a new promising and viable scheme for realizing entanglement between two remote superatoms via the heralded storage of photons. In the future, their proposed methods could contribute to the advancement and up-scaling of quantum networks.

"As an application, our current experiment demonstrates the generation of two-node entanglement via heralded storage, eliminating the need for an intermediate node," added Bao. "In the near future, we plan to incorporate this technique into a metropolitan-scale quantum [network](#)."

Written for you by our author [Ingrid Fadelli](#), edited by [Sadie Harley](#), and fact-checked and reviewed by [Robert Egan](#)—this article is the result of careful human work. We rely on readers like you to keep independent science journalism alive. If this reporting matters to you, please consider a [donation](#) (especially monthly). You'll get an **ad-free** account as a thank-you.

More information: Zi-Ye An et al, Entangling Two Rydberg Superatoms via Heralded Storage, *Physical Review Letters* (2025). DOI: [10.1103/cmpn-jfqr](https://doi.org/10.1103/cmpn-jfqr). On *arXiv*: DOI: [10.48550/arxiv.2504.05021](https://arxiv.org/abs/10.48550/arxiv.2504.05021)

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JULY 7, 2025

[The GIST](#)

Light and heavy electrons cooperate in magic-angle superconductors

by Clea Simon, Harvard Gazette edited by [Lisa Lock](#), reviewed by [Robert Egan](#)

The left plot shows the particular quantity the microscope measures as a function of electron density (x axis) and magnetic field (y axis). In the right zoomed-in panel, some diagonal lines are visible in the upper portion of the plot, but they disappear about halfway down. This indicates that the light electrons are present at low magnetic field. Credit:

Adapted from *Nature Physics* (2025). DOI: 10.1038/s41567-025-02956-z

Electrons play many roles in solid materials. When they are weakly bound and able to travel—i.e., mobile—they can enable electrical conduction. When they are bound, or "heavy," they can act as insulators. However, in certain solid materials, this behavior can be markedly different, raising questions about how these different types of electrons interact.

In a study just [published](#) in *Nature Physics*, researchers working with Professor of Physics and Applied Physics Amir Yacoby at Harvard examined the interplay between both types of electrons in this material, shedding new [light](#) on how they may help form novel quantum states.

"Before our work, people could only ask 'What is the overall ground state?'" said Andrew T. Pierce, one of the paper's lead authors. Pierce, currently a fellow at Cornell University, was a graduate student in Yacoby's lab when they began to study this question. What wasn't clear was the true nature of these different states and how the separate light and heavy electrons joined forces to form them.

Additionally, because of the more obvious role of heavy electrons to drive insulators, light electrons have often been dismissed as "doing nothing" or "being spectators," said Yonglong Xie, one of the paper's lead authors. A former Harvard Quantum Initiative Prize postdoctoral fellow in Yacoby's lab, Xie, now an assistant professor at Rice University, noted that the effect of these light electrons on the overall system was hard to detect.

The interplay between electrons with different masses is believed to drive intricate quantum phenomena. In the novel material known as magic-angle twisted trilayer graphene (MATTG), where three layers of graphene are stacked together with the middle sheet rotated slightly, electrons with small and large masses coexist. This material supports a plethora of exotic quantum phenomena, including superconductivity (i.e., electrical conduction without heating), thereby providing a new setting to address this question.

To understand what was going on in these cases, the researchers used a specialized form of microscopy, known as scanning single-electron transistor (scanning SET), pioneered by Yacoby, to examine tiny "puddles" in the MATTG where electrons are trapped when the MATTG enters an insulating state. The scanning SET indicated that while the heavy electrons enable insulating states, the light electrons remain mobile, suggesting that they should participate in forming the novel states, including superconductivity.

"The heavy electrons form an insulator among themselves, creating the illusion of an overall insulating state, but in reality the light electrons remain free," clarified Pierce. "This raises the possibility that the light electrons can mediate interactions between heavy electrons."

This surprising finding underscores how complex the interplay between light and heavy electrons in MATTG can be, the researchers said. They suggested that exploring further methods of "tuning" the ratio of heavy and light electrons in two-dimensional materials will lead to exciting new discoveries.

"The problem of coexisting light and heavy [electrons](#) in solids is a long-standing one, and we hope our scheme for disentangling their roles gives a new approach to these intriguing materials," said Pierce.

More information: Andrew T. Pierce et al, Tunable interplay between light and heavy electrons in twisted trilayer graphene, *Nature Physics* (2025). DOI: [10.1038/s41567-025-02956-z](https://doi.org/10.1038/s41567-025-02956-z)

Journal information: [Nature Physics](#)

Provided by Harvard Gazette

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Individual defects in superconducting quantum circuits imaged for the first time

by [National Physical Laboratory](#) edited by [Lisa Lock](#), reviewed by [Robert Egan](#)

Experimental setup for imaging TLS defects. Credit: *Science Advances* (2025). DOI: [10.1126/sciadv.adt8586](https://doi.org/10.1126/sciadv.adt8586)

Individual defects in superconducting quantum circuits have been imaged for the first time, thanks to research by scientists at the National Physical Laboratory (NPL) in collaboration with Chalmers University of Technology and Royal Holloway University of London.

In a paper [published](#) in *Science Advances*, scientists at NPL achieved a pivotal step in understanding tiny material defects known as two-level system (TLS) defects in superconducting quantum circuits for the first time.

The significant advancement makes it possible to locate, image and eventually mitigate these defects and can lead to stable and reliable quantum computers capable of revolutionizing the different fields of cybersecurity, optimization, drug discovery, and clean energy.

A major challenge for quantum computers is decoherence of the fragile quantum states. Decoherence happens when [quantum information](#) stored in the computer leaks out and is irretrievably lost. For quantum processors built using superconducting circuits—one of the most promising platforms used by several industry leaders—the primary source of decoherence is these TLS defects residing in the circuits.

While researchers have known about these defects for over five decades, it has never been possible to locate individual defects and study how each of them contributes to decoherence in a live quantum circuit.

Now, scientists at NPL have built a new instrument capable of locating and studying individual TLS defects for the first time. The instrument combines advanced microscopy techniques with live quantum circuits and operates in a light-tight, dark chamber cooled to just above absolute zero to minimize thermal fluctuations.

The scientists believe that this new tool will help them study these defects to first chemically identify and eventually get rid of them, paving the path for building reliable and stable quantum computers ready to outperform classical computers.

Dr. Riju Banerjee, a senior scientist at NPL and one of the lead authors of the paper said, "For years people have believed that TLS defects perturb quantum circuits. It is remarkable to finally be able to visualize the fluctuations and [decoherence](#) each TLS defect causes as it interacts with the circuit.

"The first data that we have taken using our new instrument looks as if there's an actual noisy liquid sloshing around the circuit, and individual defects appear as rings, just like ripples from raindrops on a pond."

"We now have a new tool with which we can learn so much more about these nasty defects that plague quantum circuits. It can now help us to find ways to get rid of these [defects](#) in the future," said Dr. Sebastian de Graaf, principal scientist at NPL.

More information: Marius Hegedüs et al, In situ scanning gate imaging of individual quantum two-level system defects in live superconducting circuits, *Science Advances* (2025). DOI: [10.1126/sciadv.adt8586](https://doi.org/10.1126/sciadv.adt8586)

Journal information: [Science Advances](#)
Provided by [National Physical Laboratory](#)

JULY 7, 2025

Physicists reveal how a lone spinon emerges in quantum magnetic models

by [University of Warsaw](#) edited by [Gaby Clark](#), reviewed by [Robert Egan](#)

Today, magnets play a key role in many technologies—from computer memory and speakers to electric motors and medical diagnostics. They have also become a common travel souvenir. Credit: Marek Wohlfeld Copy University of Warsaw

Researchers from the Faculty of Physics at the University of Warsaw and the University of British Columbia have described how a so-called lone spinon—an exotic quantum excitation that is a single unpaired spin—can arise in magnetic models. The discovery deepens our understanding of the nature of magnetism and could have implications for the development of future technologies such as quantum computers and new magnetic materials. The work is [published](#) in *Physical Review Letters*.

Magnetism has been known to humanity since ancient times, when naturally magnetized magnetite was discovered. This finding soon found highly practical applications. The first compasses were created in the [11th century](#) in China, and began to be used for navigation.

Today, magnets play an important role in many technologies that surround us, from computer memory and speakers to [electric motors](#) and medical diagnostics. Interestingly, alongside photography, magnets have also become a common souvenir of travel, occupying a prominent place in our homes.

Despite its widespread use, the nature of magnetism remained incompletely understood for a long time. The situation became further complicated when Niels Bohr and Hendrika Johanna van Leeuwen showed that magnetism could not be explained within the framework of classical physics. It was not until the development of quantum mechanics in the 1920s that it was understood that the magnetic properties of matter are primarily due to interactions between the spins of electrons. Spin, along with mass and electric charge, is one of the fundamental properties of elementary particles.

In 1931, Hans Bethe proposed a mathematically elegant solution to one of the fundamental quantum models of magnetism—the so-called one-dimensional Heisenberg model. Less than half a century later, in 1981, Ludwig Faddeev and Leon Takhtajan realized that the solutions to this model exhibited a surprising phenomenon: as if an indivisible electron "splits" into two more fundamental particles. The spin of the electron is $1/2$ (in units of Planck's constant \hbar) and can be oriented in any direction in space.

In the standard situation, an excitation involves the reversal of the spin of one electron, resulting in a change in the spin of the whole system by 1. However, from Faddeev and

Takhtajan's theory, it follows that the fundamental excitations in a magnet change the total spin of the system by $1/2$. These exotically behaving excitations were named spinons.

Since then, many experiments have confirmed their existence. However, it was long believed that spinons could only form in pairs—and indeed, they had always been observed in this form—which made the phenomenon seem somewhat less "exotic."

A lone spinon

In the paper just published in *Physical Review Letters*, a team of scientists from the Faculty of Physics at the University of Warsaw and the University of British Columbia has shown how such a singular excitation can be created as a single spinon. Such a spinon can be created in a very simple way: it is enough to add one extra spin to the ground state of the one-dimensional Heisenberg model (a theoretical description of a number of interacting spins).

The researchers also discovered that the same effect can be obtained if, instead of the [ground state](#), a very simplified model of the so-called valence-bond solid (VBS) is used, in which the spins are paired in a very ordered way. A spinon in this model can be understood as a single unpaired spin that "travels" through a network of such paired spins.

Importantly, this theoretical prediction was recently successfully confirmed experimentally in the paper by Zhao and team in "Spin excitations in nanographene-based antiferromagnetic spin- $1/2$ Heisenberg chains," [published in March](#) in *Nature Materials*.

Spinons and their significance for future technologies

This is an important step toward a better understanding of the quantum properties of magnetics and could open the way to discovering new features of them. Of particular importance, spinons are the result of strong interactions between electrons and quantum phenomena such as [quantum entanglement](#).

Similar mechanisms play a key role in phenomena as fundamental as [high-temperature superconductivity](#) or the fractional Hall effect in two-dimensional quantum liquids. Quantum entanglement is also the foundation of quantum computers and quantum computing as a whole.

"Our research not only deepens our knowledge of magnets, but can also have far-reaching consequences in other areas of physics and technology," concludes Prof Krzysztof Wohlfeld of the Faculty of Physics at the University of Warsaw.

More information: Teresa Kulka et al, Nature of Spinons in 1D Spin Chains, *Physical Review Letters* (2025). DOI: [10.1103/stvg-lg9h](https://doi.org/10.1103/stvg-lg9h). On *arXiv*: DOI: [10.48550/arxiv.2303.02276](https://doi.org/10.48550/arxiv.2303.02276)

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

Provided by [University of Warsaw](#)

JULY 10, 2025

Quantum battery model achieves theoretical speed limit, demonstrates genuine advantage

by [Ingrid Fadelli](#), Phys.org edited by [Gaby Clark](#), reviewed by [Robert Egan](#)

Credit: Created using ChatGPT.

Over the past few years, researchers have developed various quantum technologies, alternatives to classical devices that operate by leveraging the principles of quantum mechanics. These technologies have the potential to outperform their classical counterparts in specific settings or scenarios.

Among the many quantum technologies proposed and devised so far are quantum batteries, energy storage devices that could theoretically store energy more efficiently than classical batteries, while also charging more rapidly. Despite their predicted potential, most quantum battery solutions proposed to date have not yet proven to exhibit a genuine quantum advantage, or in other words, to perform better than their classical counterparts.

Researchers at PSL Research University and the University of Pisa recently introduced a new deceptively simple quantum battery model that could exhibit a genuine quantum advantage over a classical analog battery. The new model, outlined in a paper [published](#) in *Physical Review Letters*, was found to successfully reach the so-called quantum speed limit, the [maximum speed](#) that a quantum system could theoretically achieve.

"Quantum batteries are microscopic devices that can exhibit quantum advantages over their classical counterparts in energy-related tasks," Vittoria Stanzione and Gian Marcello Andolina, co-authors of the paper, told Phys.org. "This research area originated from quantum information theory, which predicts that quantum resources—such as entanglement—can dramatically enhance the charging power of quantum systems.

"In recent years, some of the authors of the present work proposed a model displaying such a quantum advantage: the Sachdev–Ye–Kitaev (SYK) model. However, this model is highly complex, both experimentally—due to its many-body interactions—and theoretically, as it is analytically challenging."

Earlier works demonstrating a quantum advantage of batteries based on the SYK model only did so using [numerical simulations](#), without performing any further analyses. Building on their earlier efforts, Stanzione, Andolina and their colleagues tried to identify the simplest

possible quantum battery model that could display a quantum advantage in terms of charging power.

"Our model consists of two coupled harmonic oscillators: one acts as the 'charger,' and the other serves as the 'battery,'" explained Stanzione and Andolina. "The key ingredient enabling the quantum advantage is an anharmonic interaction between the two oscillators during the charging process. This anharmonic coupling allows the system to access non-classical, entangled states that effectively create a 'shortcut' in Hilbert space, enabling faster energy transfer than in classical dynamics."

To rigorously certify their model's quantum advantage, the researchers compared it to a suitable classical battery model, while also implementing a formal bound that was outlined by Maciej Lewenstein and other researchers at the Institute of Photonic Sciences (ICFO) in Barcelona. Overall, their findings suggest that their quantum battery model does outperform its classical counterpart.

"To the best of our knowledge, this work provides the first rigorous certification of a genuine quantum advantage in a solvable model," said Stanzione and Andolina. "Furthermore, the proposed setup can be realized with current experimental technologies."

Discover the latest in science, tech, and space with over **100,000 subscribers** who rely on Phys.org for daily insights. Sign up for our [free newsletter](#) and get updates on breakthroughs, innovations, and research that matter—**daily or weekly**. So far, the researchers' model is merely theoretical, and much work still needs to be done before it can be realized experimentally. In their paper, the team briefly explores the possibility of realizing their proposed battery model using superconducting circuits, which are [electrical circuits](#) made of materials that exhibit a resistance of zero at low temperatures.

"We now plan to collaborate with experimental groups in the future to pursue a proof-of-principle realization," added Stanzione and Andolina. "At the same time, the development of a fully functional quantum [battery](#)—integrated with other [quantum technologies](#)—remains a distant goal. We hope that our work will stimulate further research on this exciting topic, fostering progress on both the theoretical and experimental fronts."

Written for you by our author [Ingrid Fadelli](#), edited by [Gaby Clark](#), and fact-checked and reviewed by [Robert Egan](#)—this article is the result of careful human work. We rely on readers like you to keep independent science journalism alive. If this reporting matters to you, please consider a [donation](#) (especially monthly). You'll get an **ad-free** account as a thank-you.

More information: Gian Marcello Andolina et al, Genuine Quantum Advantage in Anharmonic Bosonic Quantum Batteries, *Physical Review Letters* (2025). DOI: [10.1103/kzvn-dj7v](https://doi.org/10.1103/kzvn-dj7v). On *arXiv*: arxiv.org/abs/2409.08627

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

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JULY 10, 2025

Tunable laser light: Ring design could be used in telecom, medicine and more

by Anne J. Manning, [Harvard John A. Paulson School of Engineering and Applied Sciences](#)

edited by [Sadie Harley](#), reviewed by [Robert Egan](#)

Artist's illustration of the new tunable ring laser. Credit: Joshua Mornhinweg
Researchers at the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) and Technical University of Vienna (TU Wien) have invented a new type of tunable semiconductor laser that combines the best attributes of today's most advanced laser products, demonstrating smooth, reliable, wide-range wavelength tuning in a simple, chip-sized design.

Tunable lasers, or lasers whose light output wavelengths can be changed and controlled, are integral to many technologies, from high-speed telecommunications to medical diagnostics to safety inspections of gas pipelines.

Yet laser technology faces many trade-offs—for example, lasers that emit across a wide range of wavelengths, or colors, sacrifice the accuracy of each color. But lasers that can precisely tune to many colors get complicated and expensive because they commonly require moving parts.

The new Harvard device could one day replace many types of tunable lasers in a smaller, more cost-effective package.

The research is published in [Optica](#) and was co-led by Federico Capasso, the Robert L. Wallace Professor of Applied Physics and Vinton Hayes Senior Research Fellow in Electrical Engineering at SEAS, and Professor Benedikt Schwarz at TU Wien, with whom Capasso's group has maintained a longstanding research partnership.

The researchers initially demonstrated a laser that emits light in the mid-infrared wavelength range because that's where quantum cascade lasers, upon which their architecture is based, typically emit.

"The versatility of this new platform means that similar lasers can be fabricated at more commercially relevant wavelengths, such as for telecommunications applications, for medical diagnostics, or for any laser that emits in the visible spectrum of light," said Capasso, who co-invented the [quantum cascade laser in 1994](#).

The new laser consists of multiple tiny ring-shaped lasers, each a slightly different size, and all connected to the same waveguide. Each ring emits light of a different wavelength, and by adjusting electric current input, the laser can smoothly tune between different wavelengths.

The clever and compact design ensures the laser emits only one [wavelength](#) at a time, remains stable even in harsh environments, and can be easily scaled. The rings function either one at a time or all together to make a stronger beam.

"By adjusting the size of the ring, we can effectively target any line we want, and any lasing frequency we want," said co-lead author Theodore Letsou, an MIT graduate student and research fellow in Capasso's lab at Harvard.

"All the light from every single laser gets coupled through the same waveguide and is formed into the same beam. This is quite powerful, because we can extend the tuning range of typical semiconductor lasers, and we can target individual wavelengths using a different ring radius."

"What's really nice about our laser is the simplicity of fabrication," added co-lead author Johannes Fuchsberger, a graduate student at TU Wien, where the team fabricated the devices using the cleanroom facilities permanently provided by the school's Center for Micro and Nanostructures. "We have no mechanically movable parts and an easy fabrication scheme that results in a small footprint."

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The laser's unique architecture also guards against common problems like optical feedback, or when some [laser light](#) gets reflected backward into the source and can cause destabilization. Since the new laser's rings emit unidirectionally, either clockwise or counterclockwise, there's no chance of back-reflection.

The new ring laser could possibly replace current technologies for different types of tunable semiconductor lasers that each have strengths and drawbacks depending on the application. For example, distributed feedback lasers make smooth and accurate beams and are therefore used in telecommunications fiber to send optical signals long distances, but their tuning range is narrow.

External cavity lasers, on the other hand, have broader tuning ranges but more complex designs and moving parts, which makes their laser lines tend to skip around.

These are commonly used in gas sensors that test for leaks in pipelines, because they can detect gases like methane and carbon dioxide which absorb light at distinct wavelengths.

The paper was co-authored by Dmitry Kazakov and Rolf Szedlak. The team has worked in collaboration with the Harvard Office of Technology Development and the TU Wien Patent and License Management Office to protect the underlying intellectual property, with the goal of commercializing this idea in the future.

More information: Johannes Fuchsberger et al, Continuously and widely tunable semiconductor ring lasers, *Optica* (2025). DOI: [10.1364/OPTICA.559884](https://doi.org/10.1364/OPTICA.559884)

Journal information: [Optica](#)

Provided by [Harvard John A. Paulson School of Engineering and Applied Sciences](#)

JULY 10, 2025

The Milky Way could be teeming with more satellite galaxies than previously thought

by [Royal Astronomical Society](#) edited by [Lisa Lock](#), reviewed by [Robert Egan](#)

Credit: The Aquarius simulation, the Virgo Consortium/Dr Mark Lovell

The Milky Way could have many more satellite galaxies than scientists have previously been able to predict or observe, according to new research. Cosmologists at Durham University used a new technique combining the highest-resolution supercomputer simulations that exist, alongside novel mathematical modeling, to predict the existence of missing "orphan" galaxies.

Their findings suggest that there should be 80 or perhaps up to 100 more satellite galaxies surrounding our home galaxy, orbiting at close distances.

If these galaxies are seen by telescopes, then it could provide strong support for the Lambda Cold Dark Matter (LCDM) theory, which explains the large-scale structure of the universe and how galaxies form.

This ongoing [research](#) is being presented on Friday 11 July at the Royal Astronomical Society's National Astronomy Meeting ([NAM 2025](#)) at Durham University.

The research is based on the LCDM model where ordinary matter in the form of atoms represents only 5% of the universe's total content, 25% is [cold dark matter](#) (CDM), and the remaining 70% is [dark energy](#).

In this model, galaxies form in the center of gigantic clumps of [dark matter](#) called halos. Most galaxies in the universe are low-mass dwarf galaxies, the majority of which are satellites orbiting around a more massive galaxy, such as our Milky Way.

The existence of these enigmatic objects has long posed challenges to LCDM—otherwise known as the standard model of cosmology. According to LCDM theory, many more Milky Way companion galaxies should exist than cosmological simulations have so far produced, or astronomers have been able to see.

The new research shows that the Milky Way's missing satellites are extremely faint galaxies stripped almost entirely of their parent dark matter halos by the gravity of the Milky Way's halo. These so-called "orphan" galaxies are lost in most simulations, but should have survived in the real universe.

Using their new technique, the Durham researchers were able to track the abundance, distribution, and properties of these Milky Way orphan galaxies—showing that many more Milky Way satellites should exist and be observable today. It is hoped that new advances in telescopes and instruments like the Rubin Observatory LSST camera (which recently saw its first light), will give astronomers the ability to detect these very faint objects, bringing them into our view for the first time.

Lead researcher Dr. Isabel Santos-Santos, in the Institute for Computational Cosmology, Department of Physics, Durham University, said, "We know the Milky Way has some 60 confirmed companion satellite galaxies, but we think there should be dozens more of these faint galaxies orbiting around the Milky Way at close distances.

"If our predictions are right, it adds more weight to the Lambda Cold Dark Matter theory of the formation and evolution of structure in the universe.

"Observational astronomers are using our predictions as a benchmark with which to compare the new data they are obtaining.

"One day soon we may be able to see these 'missing' galaxies, which would be hugely exciting and could tell us more about how the universe came to be as we see it today."

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The concept of LCDM is the cornerstone of our understanding of the universe. It has led to the Standard Model of Cosmology and is the most widely accepted model for describing the universe's evolution and structure on large scales.

The model has passed multiple tests but has recently been challenged by puzzling observational data on dwarf galaxies.

The Durham researchers say that even the best existing cosmological simulations (which include gas and star formation, in addition to dark matter) do not have the resolution needed to study galaxies as faint as those astronomers are starting to discover close to the Milky Way.

These simulations also lack the precision required to follow the evolution of the small [dark matter halos](#) that host the dwarf galaxies as they orbit around the Milky Way over billions of years.

This leads to the artificial disruption of some halos, leaving galaxies "orphaned." Although the simulations lose the halos of "orphan" galaxies, such galaxies should survive in the real universe.

The Durham researchers combined cosmological supercomputer simulations with analytical models to overcome these numerical issues.

This included the Aquarius simulation, produced by the Virgo Consortium. Aquarius is the highest resolution simulation of a Milky Way dark matter halo ever created and is used to understand the fine-scale structure predicted around the Milky Way.

It also included the GALFORM model, a cutting-edge code developed at Durham over the past two decades which follows the detailed physical processes that are responsible for the formation and evolution of galaxies.

Their results showed that halos of dark matter, which may host a satellite galaxy, have been orbiting around the central Milky Way halo for most of the age of the universe, leading to the stripping of their dark matter and stellar mass, and rendering them extremely small and faint.

As a result, the research predicts that the total number of satellite galaxies—of any brightness—likely to exist around the Milky Way is around 80 or potentially up to 100 more than currently known.

The research puts particular emphasis on the approximately 30 newly discovered tiny Milky Way satellite candidates that are extremely faint and small.

Scientists are unclear if these are dwarf galaxies embedded in a dark matter halo, or globular clusters, collections of self-gravitating stars.

The Durham researchers argue that these objects could be a subset of the faint population of [satellite galaxies](#) they predict should exist.

Co-researcher Professor Carlos Frenk, of the Institute for Computational Cosmology, Department of Physics, Durham University said, "If the population of very faint satellites that we are predicting is discovered with new data, it would be a remarkable success of the LCDM theory of galaxy formation.

"It would also provide a clear illustration of the power of physics and mathematics. Using the laws of physics, solved using a large supercomputer, and mathematical modeling we can make precise predictions that astronomers, equipped with new, powerful telescopes, can test. It doesn't get much better than this."

More information: The contribution of "orphan" galaxies to the ultrafaint population of MW satellites. [conference.astro.dur.ac.uk/eve ... 7/contributions/515/](https://conference.astro.dur.ac.uk/eve.../7/contributions/515/)
Provided by [Royal Astronomical Society](#)

JULY 15, 2025

The 100-year journey from quantum science to quantum technology

by Harry Quiney, [University of Melbourne](#) edited by [Lisa Lock](#), reviewed by [Andrew Zinin](#)

Credit: CC0 Public Domain

You may not have realized it yet, but the United Nations has declared 2025 the [International Year of Quantum Science and Technology](#).

However, it really is something to celebrate, not least because the electronic device that you are using to read this article depends on some of the advanced applications of quantum phenomena.

This year was chosen because 2025 marks the centenary of the publication of the first articles on [quantum mechanics](#), also known as [quantum physics](#).

These [research papers](#) identified the scientific principles that describe the motion and [interaction of subatomic particles](#) like photons and electrons—the particles that make up everything we currently understand about matter.

A century later, technologies based on quantum mechanics are everywhere.

Devices like mobile phones depend on advanced applications of the [theory of quantum electrodynamics](#), which describes the interactions between matter and electromagnetic radiation at the level of individual atoms.

The illusion of simplicity and certainty

To the end-user, [electronic devices](#) represent a pinnacle of modern technology.

Your [mobile phone](#) is a machine that seems to be able to do almost anything and everything, with apparently infallible certainty.

It employs technology that you need no [physical access](#) to, other than a button to turn it on and off, a touchscreen, speaker and microphone to interact with it and a socket to charge the battery.

This illusion of simplicity evaporates when it comes to understanding how these devices work at the atomic scale.

The word "uncertainty" has a precise technical meaning in quantum mechanics that presents both a challenge and an opportunity in the development of new technologies.

The familiar certainties of our everyday experience—like the expected actions from a touchscreen—emerge from the collective behaviors of quantum mechanical complexity and uncertainty.

At the heart of quantum mechanics is the [uncertainty principle](#).

There are some fundamental quantities, like the position and momentum of a particle, which we cannot simultaneously measure precisely.

If we know the precise location of an electron, for example, we can know nothing about its momentum. Conversely, if we know precisely its momentum, we cannot make any definite statement about where it is.

The [uncertainty principle](#) puts limits on the precision of simultaneous measurements of some physical quantities.

No experimental strategies, no matter how devious or ingenious, can get around this fundamental rule of nature.

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Uncertainty is not an obstacle to progress

Certainty is replaced in quantum mechanics by probability.

We can only talk about the probabilities that measurements of properties like position and momentum will be obtained at any given time.

Everything that we can know about a quantum mechanical system is contained within a mathematical object called [a wavefunction](#), which is used to calculate these probabilities, using some well-defined rules.

We are now very good at obtaining these wavefunctions and using the rules of quantum mechanics to predict the outcomes of physical measurements.

Quantum electrodynamics, for example, has been tested against experiments to an accuracy of better than one part in 1,000,000,000,000.

It's the most accurate physical theory that we have yet devised.

But there are two distinct schools of thought among physicists and philosophers about the role of quantum mechanics as a scientific theory.

There are those who view quantum mechanics as a purely mathematical process for predicting and interpreting physical measurements.

Then there are others who insist that it should reveal the very nature of physical reality.

The second group argues that the continuing lack of consensus about the interpretation of quantum mechanics shows us it's an incomplete physical theory—despite its unfailing predictive power.

The next 100 years

One of the most surprising consequences of its mathematical structure suggests that quantum systems can be used to construct new types of information technology.

The theoretical power of these so-called [quantum computers](#) far exceeds the abilities of today's most powerful supercomputers.

When this idea was first circulated forty years ago, it seemed fanciful that the formidable technical challenges of manipulating and measuring quantum systems could be overcome in the design of a working quantum computer.

Today, the School of Physics at the University of Melbourne supervises graduate students designing computational algorithms that are executed on the first generation of functional quantum computers in a thriving collaboration with IBM.

Our researchers are also tackling [experimental research](#) on the design of the next generation of quantum computing hardware and devices that utilize quantum mechanics to sense tiny electromagnetic fields.

Like many projects in physics, challenges eventually give way to progress.

Sometimes this progress takes decades and involves large, collaborative, interdisciplinary and international teams of researchers.

The School of Physics at Melbourne once housed [CSIRAC](#), Australia's first digital computer.

Seventy years later, we remain at the forefront of computational physics, leading research on the potential applications of quantum computers.

This may make possible the development of new pharmaceuticals and the discovery of high-temperature superconducting materials using first-principles computational implementations of quantum mechanics.

The [search for dark matter](#) promises to expand our understanding of the subatomic particles in the universe.

It may even lead, perhaps, to the formulation of the elusive "[theory of everything](#)" that fully reconciles the theories of quantum mechanics and general relativity.

That we have made such progress in the first century of quantum mechanics is surely worth celebrating.

Provided by [University of Melbourne](#)

Swiss physicists detect traces of a potential fifth force of nature



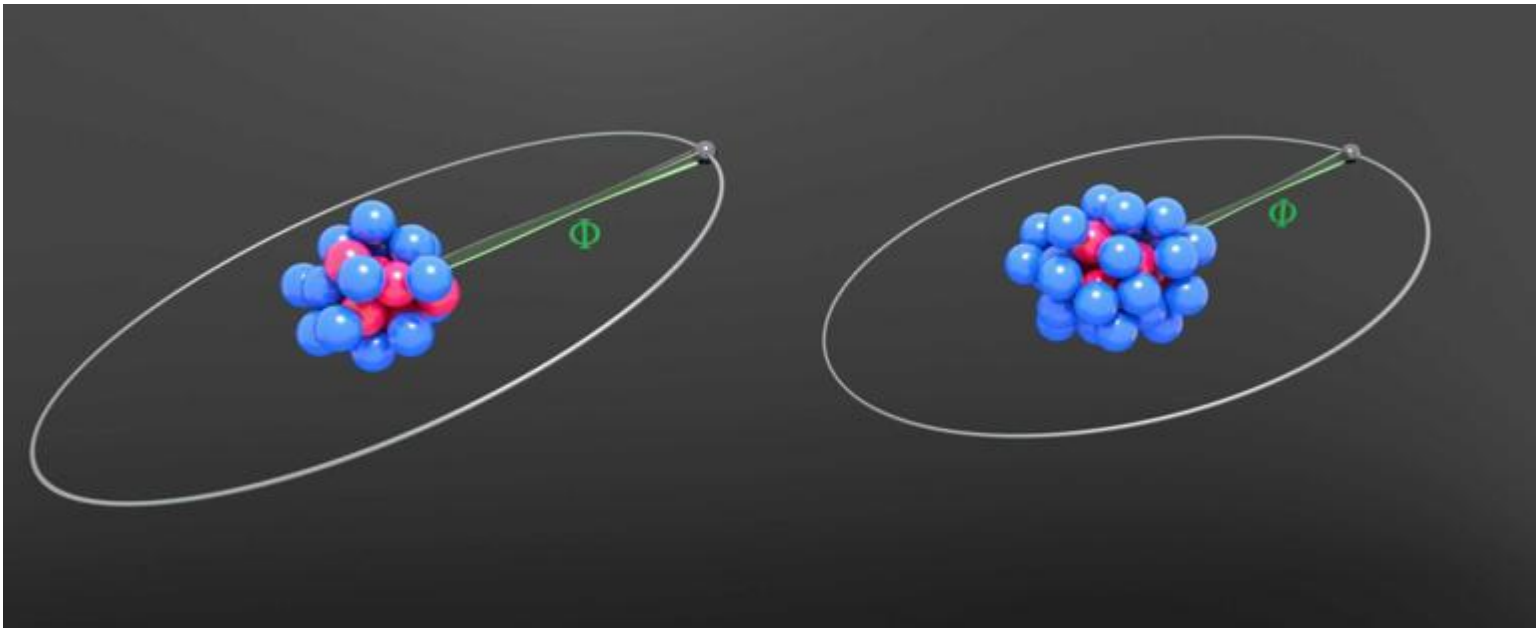
Luca Huber, doctoral student at ETH Zurich, aligns a laser light for an experiment with calcium isotopes. (CREDIT: Gabriele Giuli / ETH Zurich)© The Brighter Side of News

Physicists in Switzerland are turning to a new method in the search for nature's possible fifth force—one that might explain some of the universe's greatest mysteries. Their work centers on [atomic spectroscopy](#), a technique that allows them to measure tiny shifts in the energy levels of atoms with incredible precision. These subtle changes could point to an undiscovered particle responsible for a new force acting between electrons and neutrons.

The research, led by a team at [ETH Zurich](#), aims to find evidence of a force beyond the four known ones: gravity, electromagnetism, and the strong and weak nuclear forces. While past searches have relied heavily on particle accelerators like the Large Hadron Collider, this team is exploring a more delicate route. By examining how electrons behave in calcium isotopes, they hope to find the fingerprints of something new—a clue that might extend the boundaries of modern physics.

Searching Beyond the Standard Model

The [Standard Model of particle physics](#) has helped scientists map out the structure of matter and the forces that govern it. But even with its success, the model cannot explain everything. One of the biggest gaps is dark matter, the mysterious substance that makes up most of the universe's mass.



Depiction of a hypothetical force between neutron (blue) and electron (gray), mediated by the force-carrying particle ϕ (green). It could be detected by measurements on isotopes – types of the same atom that have the same number of protons (red) in the nucleus, but a different number of neutrons. (CREDIT: PTB)© The Brighter Side of News

Though invisible, dark matter reveals itself through the way galaxies rotate and how gravity behaves on large scales. Physicists suspect that dark matter may require a new theory—possibly involving a fifth fundamental force.

Diana Prado Lopes Aude Craik, a physics professor at ETH Zurich, has long studied this possibility. “The Standard Model is currently the best explanation of the universe,” she said. “But we know it cannot explain everything.” She and her team think an unknown force might connect the neutrons in an [atom’s nucleus](#) to the electrons orbiting around it. This hypothetical interaction could be carried by a new particle, much like how photons carry the electromagnetic force.

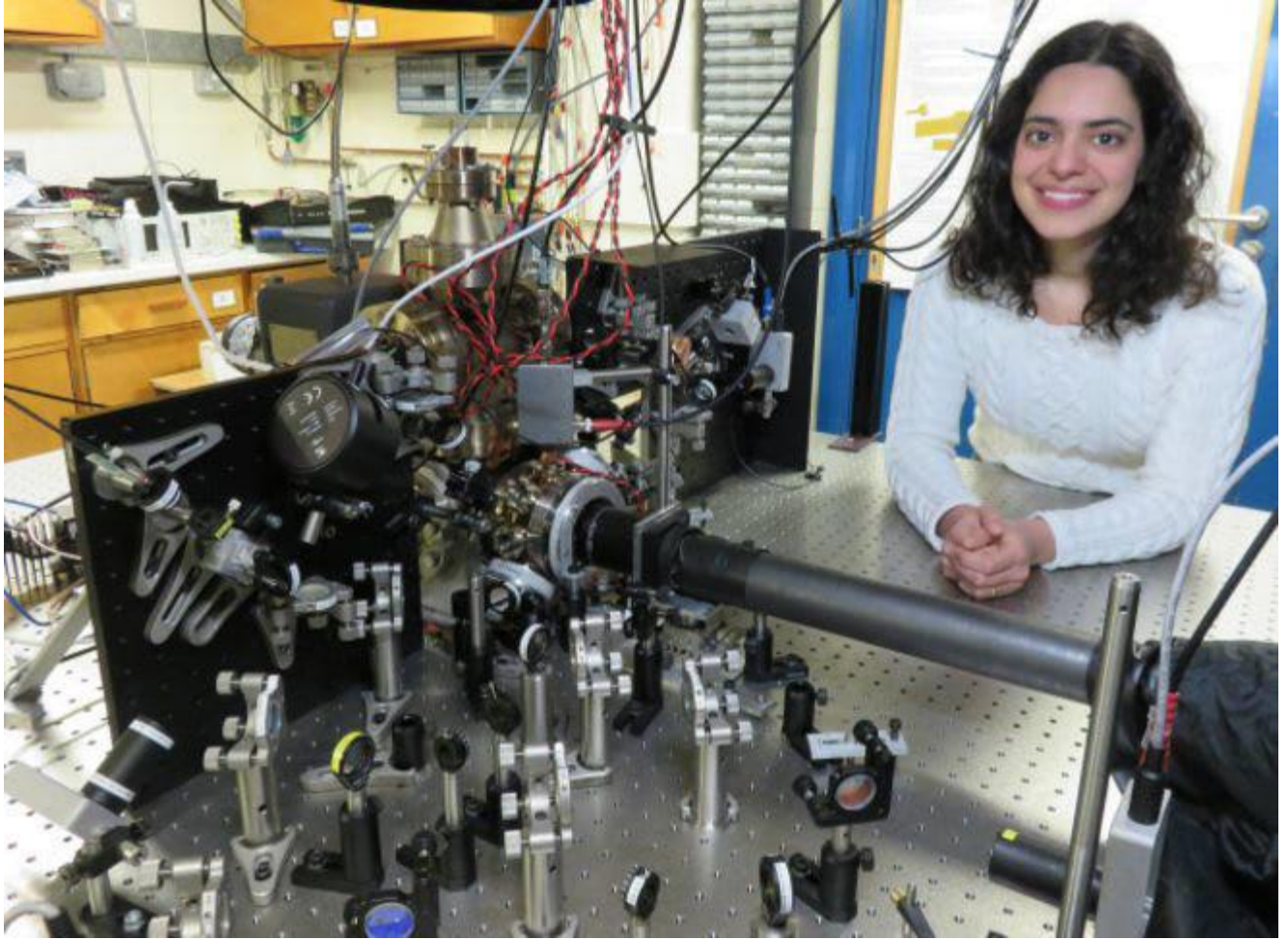
Instead of smashing particles together at high speeds, Craik’s team is using atomic physics to look for tiny clues that might suggest this new force exists. “As atomic physicists, we can measure the atom with extremely high precision,” she said. Their approach involves comparing different versions of the same atom, known as isotopes, and measuring the way their energy levels shift.

Probing Calcium Atoms for Clues

Isotopes are atoms with the same number of protons and electrons, but different numbers of neutrons. These slight differences in mass can affect how electrons experience forces within the atom. If a new force exists, it could slightly alter the energy levels of electrons in atoms with more or fewer neutrons.

To explore this, the team studied five stable isotopes of [calcium](#). Each atom had 20 protons, but their neutron counts ranged from 20 to 28. The scientists used a precision instrument called an ion trap, where electromagnetic fields hold a single charged atom in place. Then, they excited the atom with lasers and recorded the light it emitted during changes in energy levels.

They achieved a remarkable level of precision—measuring shifts as small as 100 millihertz, which is 100 times more precise than past measurements. One key to their success was trapping two isotopes at once, allowing for side-by-side comparisons while reducing noise that could interfere with the results.



Prof. Dr. Diana Prado Lopes Aude Craik, assistant professor in the physics department of ETH Zurich. (CREDIT: ETH Zurich)© The Brighter Side of News

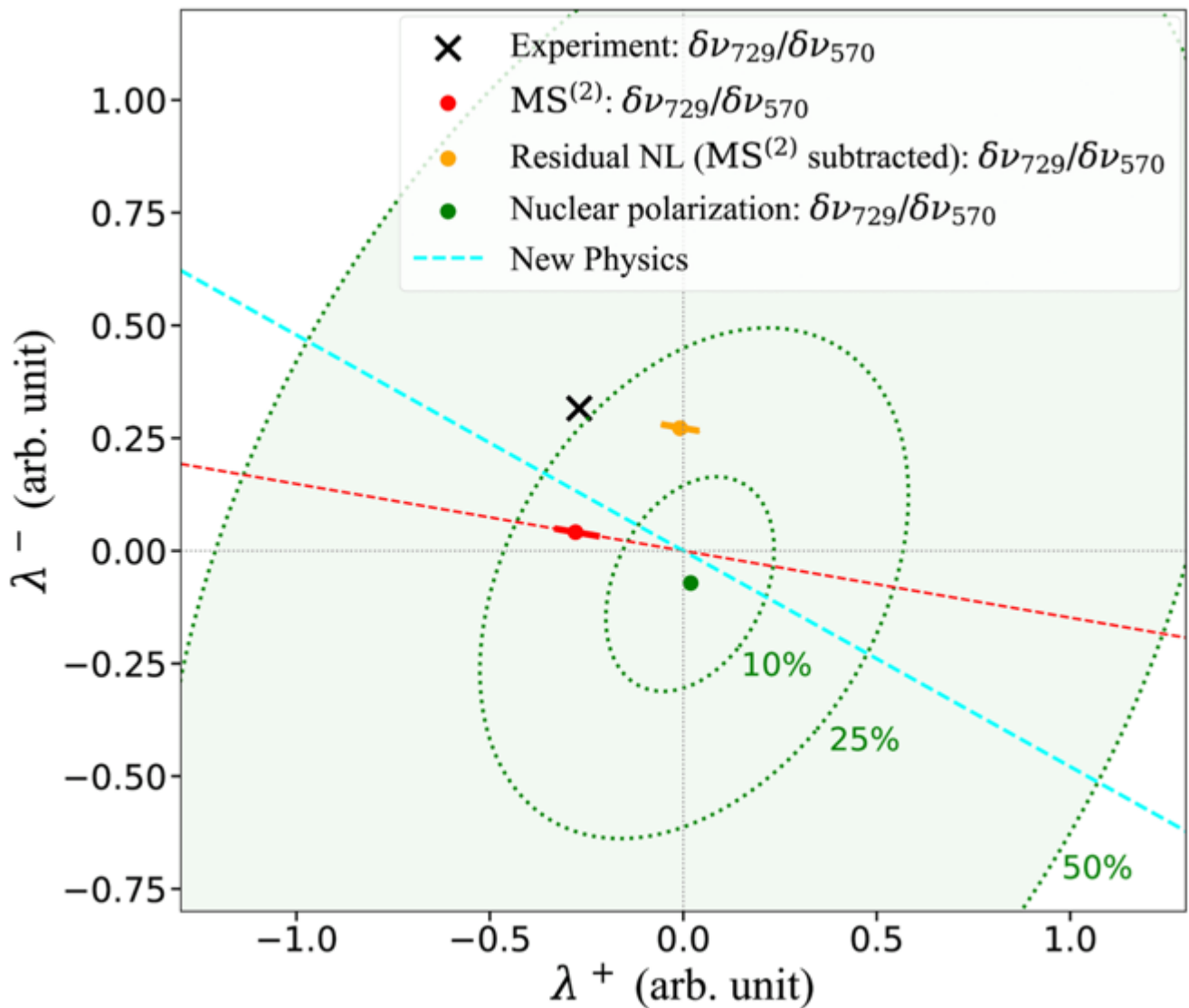
Testing Limits with International Help

Despite this high accuracy, the team wanted to rule out other known effects that might cause similar energy shifts. Collaborators in Germany and Australia joined the effort. A group at the [Physikalisch-Technische Bundesanstalt](#) in Braunschweig tested the same calcium isotopes in a more highly charged state. Meanwhile, another team at the [Max Planck Institute for Nuclear Physics](#) in Heidelberg measured the ratios of nuclear masses between the isotopes with unmatched accuracy.

After analyzing all the data, the results showed something unexpected. The small differences in energy levels couldn't be fully explained by known nuclear effects alone. One potential explanation was nuclear polarization—a rare and poorly

understood behavior where the nucleus slightly deforms due to interactions with [electrons](#). The calculations suggested that this effect might be large enough to account for the data, although it could still fit within the current Standard Model.

“We can’t say that we’ve discovered new physics here,” Craik admitted. “However, we know how strong the new force can be at most because we would have seen it otherwise in our measurements, even with the uncertainties.”



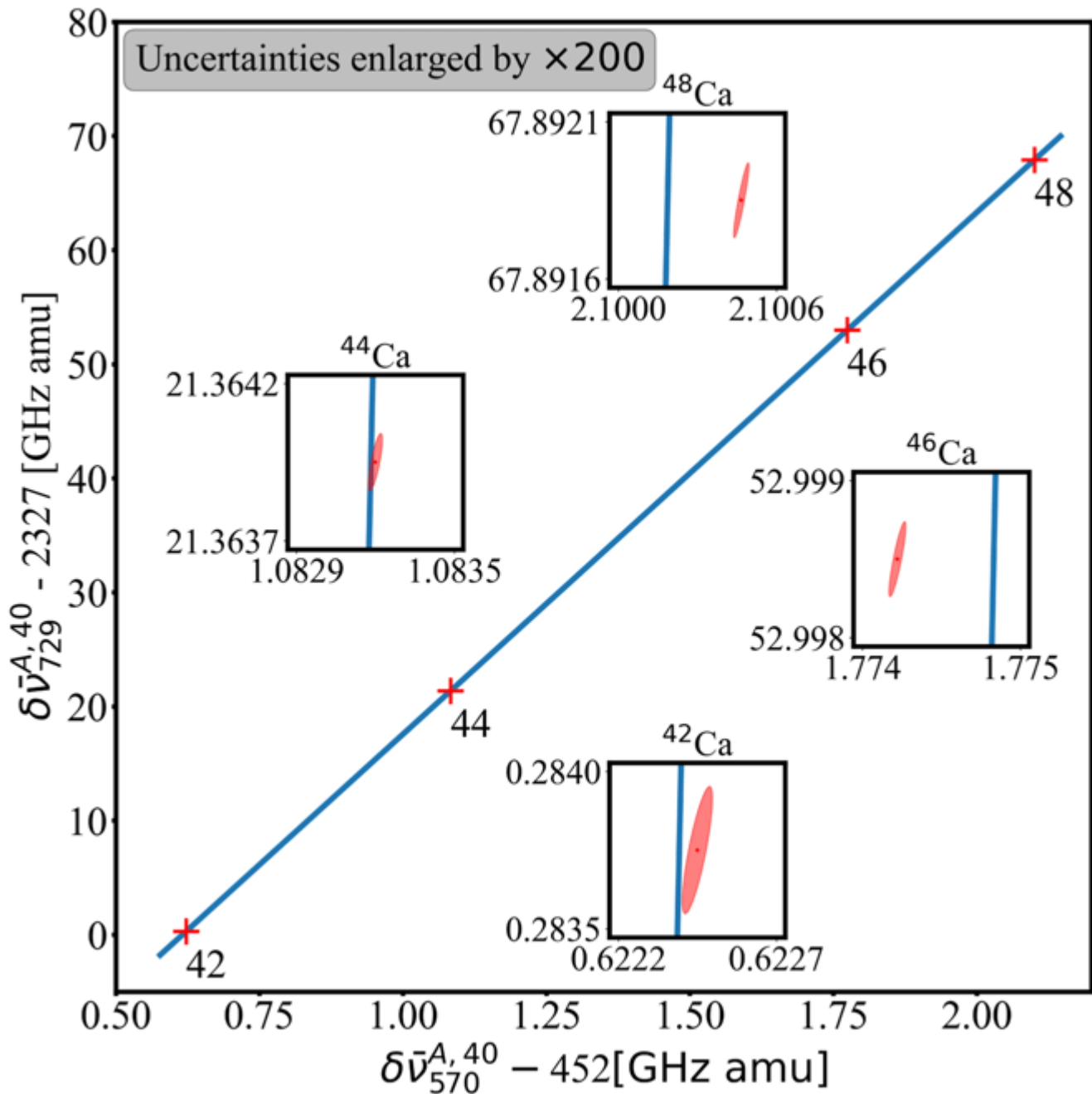
Decomposition plot comparing the measured NL (black cross, uncertainty not visible at this scale) with predictions of different NL sources. (CREDIT: Physical Review Letters)© The Brighter Side of News

Still, the researchers used the data to place new limits on the possible mass and electric charge of a hypothetical particle that might carry this fifth force. These boundaries help refine the search and point future studies in a more focused direction.

What Comes Next

The team's work isn't finished. They are currently measuring a third energy transition in the calcium isotopes. With even greater precision, this new data will help them build a three-dimensional version of what's called the King plot. This tool helps physicists visualize how [energy levels in isotopes](#) shift and whether those shifts follow known laws—or hint at something new.

“We hope that this will help us overcome the theoretical challenges,” said Craik, “and make further progress in the search for this new force.”



A nonlinearity with a significance of $\sim 103\sigma$ appears in the King plot displaying the modified isotope shifts of the transitions. (CREDIT: Physical Review Letters)© The Brighter Side of News

Their research, titled “*Nonlinear Calcium King Plot Constrains New Bosons and Nuclear Properties*”, was published in [Physical Review Letters](#). It marks a major

milestone in the growing field of high-precision atomic spectroscopy as a tool for exploring the unknown.

This effort to detect a fifth force using careful measurements, rather than massive machines, offers a fresh way to explore the universe's hidden structure. It could someday help explain dark matter, challenge current physics theories, and lead to discoveries that reshape our understanding of the cosmos.

Note: The article above provided above by [The Brighter Side of News](#).

JULY 21, 2025

Quantum internet moves closer as researchers teleport light-based information

by [Ingrid Fadelli](#), Phys.org edited by [Gaby Clark](#), reviewed by [Andrew Zinin](#)

Quantum teleportation is a fascinating process that involves transferring a particle's quantum state to another distant location, without moving or detecting the particle itself. This process could be central to the realization of a so-called "quantum internet," a version of the internet that enables the safe and instant transmission of quantum information between devices within the same network.

Quantum teleportation is far from a recent idea, as it was experimentally realized several times in the past. Nonetheless, most previous demonstrations utilized frequency conversion rather than natively operating in the telecom band.

Researchers at Nanjing University recently demonstrated the teleportation of a telecom-wavelength photonic qubit (i.e., a [quantum bit](#) encoded in light at the same wavelengths supporting current communications) to a telecom quantum memory. Their paper, published in [Physical Review Letters](#), could open new possibilities for the realization of scalable quantum networks and thus potentially a quantum internet.

"Quantum teleportation is always a fascinating protocol in quantum communication for its ability to transfer quantum states without ever revealing," Xiao-Song Ma, senior author of the paper, told Phys.org. "To extend the state transmission distance further, the incorporation of quantum memory into a quantum teleportation system is of critical importance."

The main objective of the recent study by Ma and his colleagues was to successfully integrate a telecom solid-state quantum memory into a quantum teleportation system, which

would enable the storage of transmitted [quantum information](#). The main role of this memory would be to spread and store entangled particles across a quantum network (i.e., entanglement distribution).

Quantum networks rely on quantum repeaters, devices that can break the distances across which information is transmitted into shorter and more manageable sections, known as elementary links. When placed at the end of these sections, quantum memories could store quantum information for the time necessary for entanglement to be established across entire segments of networks, which could in turn enable its transmission across longer distances.

"We employed five systems to accomplish the experiment," explained Ma. "These include an Input state preparation; an EPR-source to generate entangled photon pairs from an integrated photonic chip, a Bell-state measurement and a quantum memory based on erbium ion ensembles. We also employed a frequency distribution and fine-tuning module based on an F-P cavity and PDH technique."

This recent work by Ma and his colleagues shows that quantum information could be transferred across a network using devices and optical wavelengths that are compatible with those currently employed in communications. The team's demonstration of quantum teleportation could inform the advancement of quantum networks, potentially contributing to the future realization of a reliable quantum internet.

"Our study demonstrated the [quantum teleportation](#) from telecom photons to a solid-state quantum memory based on erbium ions for the first time," added Ma. "Our entire system uses components compatible with existing fiber networks perfectly. This telecom-compatible platform for generating, storing and processing quantum states of light establishes a highly promising approach to large-scale quantum networks."

As part of their next studies, the researchers plan to focus on improving the performance of the erbium ion-based solid-state [memory](#) employed in their experiments. More specifically, they would like to extend its storage times and improve the efficiency with which it stores quantum information.

Written for you by our author [Ingrid Fadelli](#), edited by [Gaby Clark](#), and fact-checked and reviewed by [Andrew Zinin](#)—this article is the result of careful human work. We rely on readers like you to keep independent science journalism alive. If this reporting matters to you, please consider a [donation](#) (especially monthly). You'll get an **ad-free** account as a thank-you.

More information: Yu-Yang An et al, Quantum Teleportation from Telecom Photons to Erbium-Ion Ensembles, *Physical Review Letters* (2025). DOI: [10.1103/3wh8-2gh1](#).

Journal information: [Physical Review Letters](#)

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JULY 23, 2025

The most complete view of the human genome yet sets new standard for use in precision medicine

by [Jackson Laboratory](#) edited by [Stephanie Baum](#), reviewed by [Andrew Zinin](#)

An international team of scientists has decoded some of the most stubborn, overlooked regions of the human genome using complete sequences from 65 individuals across diverse ancestries.

The study, [published](#) in *Nature* and co-led by The Jackson Laboratory (JAX), reveals how hidden DNA variations influence everything from digestion and [immune response](#) to muscle control—and could explain why certain diseases strike some populations harder than others.

This milestone builds on two foundational studies that reshaped the field of genomics. In 2022, researchers achieved the first-ever complete sequence of a single human genome, filling in major gaps left by the original Human Genome Project.

In 2023, scientists released a draft pangenome constructed from 47 individuals—a critical step toward representing global genetic diversity. The new study significantly expands on both efforts, closing 92% of the remaining data gaps and mapping genomic variation across ancestries with a breadth and resolution never before achieved.

"For too long, our genetic references have excluded much of the world's population," said Christine Beck, a geneticist at JAX and the University of Connecticut Health Center who co-led the work.

"This work captures essential variation that helps explain why disease risk isn't the same for everyone. Our genomes are not static, and neither is our understanding of them."

By decoding DNA segments once thought too complex or variable to analyze, the study sets a new gold standard for [genome sequencing](#) and propels the field toward a more complete and inclusive vision of human biology. The findings clear a critical path for advancing precision medicine and ensuring that future discoveries benefit all populations—not just those historically overrepresented in research.

Hiding within our DNA

Scientists decode DNA by reading the order of its building blocks, called nucleotides, which act like letters in an instruction manual to direct all body functions.

Current technologies can read most of that text but often miss or misread long, complex, and highly repetitive segments that span millions of letters that influence how genes work. These long stretches are called [structural variants](#), and they can increase disease risk, protect the body, or offer no apparent effect at all.

Structural variants mainly arise when cells replicate and repair DNA, especially in sections with extremely long and repetitive sequences prone to errors.

Unlike many other types of genetic variation, there are different types of structural variants, and they can span large regions of DNA. These structural variants include deletions, duplications, insertions, inversions, and translocations of genome segments. More complex variations, where large DNA chunks rearrange and fuse in unpredictable ways, were a primary focus of the new study.

Complex rearrangements of genomes can also drive evolutionary changes that shape our biology, like how the human brain became larger and more sophisticated over time. But mapping these changes contiguously is remarkably difficult because they scramble the genome in ways that defy decoding—like trying to make sense of pages from a book that's been torn up, rearranged, and reassembled without seeing the original version.

"It's only been in the last three years that technology finally got to the point where we can sequence complete genomes," said Charles Lee, the Robert Alvine Family Endowed Chair and a JAX geneticist, who in 2004 discovered the widespread presence of structural DNA variation in people's genomes.

"Now, we've captured probably 95% or more of all these structural variants in each genome sequenced and analyzed. Having done this for not five, not 10, not 20—but 65 genomes—is an incredible feat."

Discover how hidden complexities of the human genome are revealed by scientists from The Jackson Laboratory. Technological advancements are now allowing us to assemble continuous genomes with unprecedented clarity. This breakthrough also enables scientists to identify and resolve complex rearrangements within the genome. In this JAX in Motion, learn how this new level of discovery could revolutionize health care and our understanding of human health. Credit: The Jackson Laboratory

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Turning on the light

Until now, geneticists could only chart the "easiest" of structural variations in our DNA, leaving in the dark not only the most tangled, repetitive regions, but also their connection to rare genetic diseases. The new research has now broken that logjam, untangling 1,852 previously intractable complex structural variants and sharing an open-source playbook that any scientists sequencing genomes to this level can use in their laboratories.

Resolving these previously "hidden" regions across a wide range of ancestries turns areas that were once genetic blind spots into valuable sources of insight.

The work completely resolved the Y chromosome from 30 male genomes, shedding light on a chromosome that has been particularly challenging to resolve due to its highly repetitive sequences, and which JAX scientists [fully sequenced](#) from telomere to telomere.

In addition, the team fully resolved an intricate region of human genomes associated with the immune system called the Major Histocompatibility Complex, which is linked to cancer, autoimmune syndromes, and more than 100 other diseases.

The work also provides full sequences for the notoriously repetitive SMN1 and SMN2 regions, the target of life-saving antisense therapies for spinal muscular atrophy, as well as a gene called NBPF8 involved in developmental and neurogenetic disease.

The amylase gene cluster, which helps humans digest starchy foods according to a [JAX study](#), was also fully sequenced.

The study additionally mapped transposable DNA elements in unprecedented detail, cataloging 12,919 of these mobile element insertions across the 65 individuals. These elements, which can "jump" around the genome and change how genes work, accounted for almost 10% of all structural variants.

In 1983, Barbara McClintock, a Hartford, Conn. native, received the Nobel Prize in Physiology and Medicine for her discovery of similar "jumping genes," also known as transposable elements, in corn.

Some of these jumping genes in this study were even found in centromeres—regions of the chromosome that are essential for cell division and extremely difficult to sequence due to their repetitive DNA. Overall, the work accurately resolved and validated 1,246 human centromeres, shedding light on the extreme variability at their cores.

"With our health, anything that deals with susceptibility to diseases is a combination of what genes we have and the environment we're interacting with," Lee said.

"If you don't have your complete genetic information, how are you going to get a complete picture of your health and your susceptibility to disease?"

The work was made possible by genome sequencing techniques that combine highly accurate medium-length DNA reads with longer, lower-accuracy ones. The interpretation of variation in the genomes was driven by software from JAX that accurately catalogs variants between two human sequences. This software has now pushed forward to identifying structural variation within the most complex regions of human DNA.

"Just because we have a long, complete sequence doesn't mean we actually know what's in it. It's like having a really good book, but there are still some pages we can't read, and these tools are finally allowing us to interpret those missing parts of the genome," said Peter

Audano, a JAX computational biologist in the Beck lab who developed and implemented the variant-finding software.

"Now we can say, "Here's a mutation, it starts here, ends there, and this is what it looks like." That's a huge step forward. Now, scientists studying autism, rare diseases, and cancers will have the tools to see everything we've been missing for decades."

This work was conducted in collaboration with more than 20 institutions, including the University of Washington, the European Molecular Biology Laboratory, Heinrich Heine University, University of Pennsylvania, Clemson University, Yale University and the University of Colorado, under the auspices of the Human Genome Structural Variation Consortium.

More information: Tobias Marschall, Complex genetic variation in nearly complete human genomes, *Nature* (2025). DOI: [10.1038/s41586-025-09140-6](https://doi.org/10.1038/s41586-025-09140-6). www.nature.com/articles/s41586-025-09140-6

Journal information: [Nature](#)

Provided by [Jackson Laboratory](#)

Scientists used an AI program to discover new laws of physics, and it worked!

Unlike typical AI research, where a model predicts outcomes or cleans up data, researchers at Emory University in Atlanta did something unusual. They trained a neural network to discover new physics.

The team achieved this unique feat by feeding their AI system experimental data from a mysterious state of matter called dusty plasma, a hot, electrically charged gas filled with tiny dust particles. The scientists then watched as the AI revealed surprisingly accurate descriptions of strange forces that were never fully understood before.

The development shows that AI can be used to uncover previously unknown laws that govern how particles interact in a chaotic system. Plus, it corrects long-held assumptions in plasma physics and opens the door to studying complex, many-particle systems ranging from living cells to industrial materials in entirely new ways.

"We showed that we can use AI to discover new physics. Our AI method is not a black box: we understand how and why it works. The framework it provides is also universal. It could potentially be applied to other many-body systems to

open new routes to discovery,” Justin Burton, one of the study authors and a professor at Emory, [said](#).

How did the AI learn to create laws?

The researchers combined real-world experiments with a [carefully designed AI model](#). They began by studying dusty plasma. This state of matter is found across the universe, from Saturn’s rings and the moon’s surface to wildfire smoke on Earth.

However, despite its cosmic presence, the exact forces acting between the particles in dusty plasma have remained poorly understood. That’s because the system behaves in a non-reciprocal way, which means that the force one particle applies on another isn’t necessarily matched in return.

Understanding such interactions using traditional physics has proven incredibly difficult. So to tackle this problem, the scientists built a sophisticated 3D imaging system to observe how plastic dust particles moved inside a chamber [filled with plasma](#). They used a laser sheet and high-speed camera to capture thousands of tiny particle movements in three dimensions over time.

These detailed trajectories were then used to train a custom neural network. Unlike most AI models that need huge datasets, the Emory team’s network was trained on a small but rich dataset and was engineered with built-in physical rules, like accounting for gravity, drag, and particle-to-particle forces.

“When you’re probing something new, you don’t have a lot of data to train AI. That meant we would have to design a neural network that could be trained with a small amount of data and still learn something new,” said Ilya Nemenman, senior study author and a professor at the university.

The neural network broke down the particle motion into three components: velocity effects (like drag), environmental forces (such as gravity), and inter-particle forces. This allowed the [AI to learn complex behaviors](#) while obeying basic physics principles.

As a result, it discovered precise descriptions of the non-reciprocal forces with over 99% accuracy. One surprising insight was that when one particle leads, it pulls the trailing one toward it, but the trailing one pushes the leader away. This

kind of asymmetric interaction had been suspected but never clearly modeled before.

Neural network also rectified past assumptions

The [AI corrected some faulty](#) assumptions that shaped plasma theory for years. “What’s even more interesting is that we show that some common theoretical assumptions about these forces are not quite accurate. We’re able to correct these inaccuracies because we can now see what’s occurring in such exquisite detail,” Nemenman added.

For instance, one such assumption was that a particle’s electric charge increases exactly with its size—turns out, it doesn’t. Instead, the relationship depends on the surrounding plasma’s density and temperature.

Another mistaken idea was that the force between particles always decreases exponentially with distance, regardless of their size. The [AI](#) revealed that this drop-off also depends on how big the particles are, an insight previously overlooked.

The best part is, this AI model ran on something as modest as a desktop computer. It produced a universal framework that can now be applied to all sorts of many-particle systems, from paint mixtures to migrating cells in living organisms. This research also demonstrates that AI can go far beyond crunching numbers. It can actually help scientists discover the hidden rules that govern nature.

“For all the talk about how AI is revolutionizing science, there are very few examples where something fundamentally new has been found directly by an AI system,” Nemenman said. Hopefully, this work will encourage scientists to explore many other ways in which AI can benefit science and society.

The [study](#) is published in the journal *PNAS*.

The shape of the universe revealed through algebraic geometry

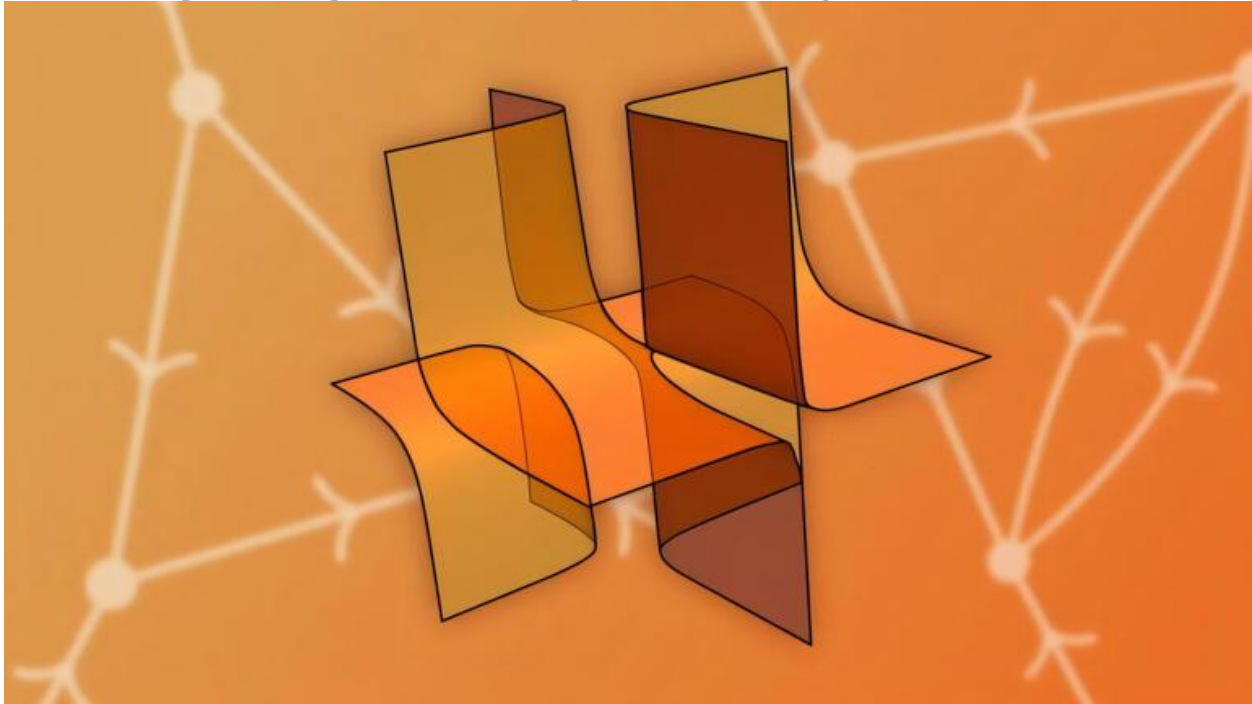


Illustration of a set of real zeros of a graph polynomial (middle) and two Feynman diagrams (Collage). Credit: Max-Planck-Institut für Mathematik in den Naturwissenschaften

How can the behavior of elementary particles and the structure of the entire universe be described using the same mathematical concepts? This question is at the heart of recent work by the mathematicians Claudia Fevola from Inria Saclay and Anna-Laura Sattelberger from the Max Planck Institute for Mathematics in the Sciences, recently [published](#) in the *Notices of the American Mathematical Society*.

Mathematics and physics share a close, reciprocal relationship. Mathematics offers the language and tools to describe physical phenomena, while physics drives the development of new mathematical ideas. This interplay remains vital in areas such as quantum field theory and cosmology, where advanced mathematical structures and physical theory evolve together.

In their article, the authors explore how algebraic structures and geometric shapes can help us understand phenomena ranging from particle collisions, such as happen, for instance, in particle accelerators, to the large-scale architecture of the cosmos. Their research is centered around algebraic geometry. Their recent

undertakings also connect to a field called positive geometry—an interdisciplinary and novel subject in mathematics driven by new ideas in particle physics and cosmology.

This field was inspired by the geometrical concept of positive geometry, which expands the standard Feynman diagram approach in particle physics by representing interactions as volumes of high-dimensional geometric objects, such as the amplituhedron, as introduced by the theoretical physicists Nima Arkani-Hamed and Jaroslav Trnka in 2013. It carries a rich combinatorial structure and offers an alternative, potentially simpler way to compute scattering amplitudes, from which one can derive probabilities of scattering events.

This approach has far-reaching implications that go beyond particle physics. In cosmology, scientists are using the faint light of the cosmic microwave background and the distribution of galaxies to infer what shaped the early universe. Similar mathematical tools are now being applied. For instance, cosmological polytopes, which are themselves positive geometries, can represent correlations in the universe's first light and help reconstruct the physical laws that governed the birth of the cosmos.

A geometry for the universe

The article highlights that positive geometry is not a niche mathematical curiosity but a potential unifying language for forming branches of theoretical physics. These geometric frameworks naturally encode the transfer of information between physical systems, for example, by mapping concrete, sensory-based concepts to abstract structures, a process that mirrors how humans metaphorically understand the world.

The mathematics behind this is sophisticated and spans multiple disciplines. The authors draw on algebraic geometry, which defines shapes and spaces through solutions to systems of polynomial equations, algebraic analysis, which studies differential equations through mathematical objects called D-modules, and combinatorics, which describes the arrangements and interactions within these structures.

The formal objects under consideration, such as Feynman integrals, generalized Euler integrals, or canonical forms of positive geometries, are not merely

mathematical abstractions. They correspond to observable phenomena in high-energy physics and cosmology, enabling precision computations of particle behavior and cosmic structures alike.

Bridging scales with mathematics

The study presents an approach with broad applicability and scalability. Scattering processes are often illustrated using Feynman diagrams. Feynman's approach in the study of scattering amplitudes boils down to the study of intricate integrals associated to such diagrams. Algebraic geometry provides a range of tools for systematically investigating these integrals.

The graph polynomial of a Feynman diagram is defined in terms of the spanning trees and forests of the underlying graph. The associated Feynman integral can be expressed as a Mellin transform of a power of this graph polynomial, interpreted as a function of its coefficients. These coefficients, however, are constrained by the underlying physical conditions. Feynman integrals are therefore closely connected to generalized Euler integrals, specifically through restrictions to the relevant geometric subspaces.

One way to study these holonomic functions is via the linear differential equations they satisfy, which are D-module inverse images of hypergeometric D-modules. Constructing these differential equations explicitly, however, remains challenging. In theoretical cosmology, correlation functions in toy models also take the form of such integrals, with integrands arising from hyperplane arrangements.

The complement of the algebraic variety defined by the graph polynomial in an algebraic torus is a very affine variety, and the Feynman integral can be viewed as the pairing of a twisted cycle and cocycle of this variety. Its geometric and (co-)homological properties reflect physical concepts such as the number of master integrals. These master integrals form a basis for the space of integrals when the kinematic parameters vary, and the size of this basis is, at least generically, equal to the signed topological Euler characteristic of the variety.

A field in motion

Fevola and Sattelberger's work reflects a growing international effort. It brings together mathematics, particle physics, and cosmology, focusing on precisely these connections between algebra, geometry, and theoretical physics.

"Positive geometry is still a young field, but it has the potential to significantly influence fundamental research in both physics and mathematics," the authors emphasize. "It is now up to the scientific community to work out the details of these emerging mathematical objects and theories and to validate them. Encouragingly, several successful collaborations have already laid important groundwork."

The recent developments are not only advancing our understanding of the physical world but also pushing the boundaries of mathematics itself. Positive geometry is more than a tool. It is a language. One that might unify our understanding of nature at all scales.

More information: Claudia Fevola et al, Algebraic and Positive Geometry of the Universe: From Particles to Galaxies, *Notices of the American Mathematical Society* (2025). DOI: [10.1090/noti3220](https://doi.org/10.1090/noti3220). [www.ams.org/journals/notices/2 ...](http://www.ams.org/journals/notices/2...)
[.html?adat=September](http://www.ams.org/journals/notices/2...)

Provided by Max Planck Society

AUGUST 13, 2025

The shape of the universe revealed through algebraic geometry

by Jana Gregor, [Max Planck Society](#)

edited by [Gaby Clark](#), reviewed by [Robert Egan](#)

Illustration of a set of real zeros of a graph polynomial (middle) and two Feynman diagrams (Collage). Credit: Max-Planck-Institut für Mathematik in den Naturwissenschaften
How can the behavior of elementary particles and the structure of the entire universe be described using the same mathematical concepts? This question is at the heart of recent

work by the mathematicians Claudia Fevola from Inria Saclay and Anna-Laura Sattelberger from the Max Planck Institute for Mathematics in the Sciences, recently [published](#) in the *Notices of the American Mathematical Society*.

Mathematics and physics share a close, reciprocal relationship. Mathematics offers the language and tools to describe physical phenomena, while physics drives the development of new mathematical ideas. This interplay remains vital in areas such as [quantum field theory](#) and cosmology, where advanced mathematical structures and physical theory evolve together.

In their article, the authors explore how algebraic structures and geometric shapes can help us understand phenomena ranging from particle collisions, such as happen, for instance, in particle accelerators to the large-scale architecture of the cosmos. Their research is centered around [algebraic geometry](#). Their recent undertakings also connect to a field called positive geometry—an interdisciplinary and novel subject in mathematics driven by new ideas in [particle physics](#) and cosmology.

This field was inspired by the geometrical concept of positive geometry, which expands the standard Feynman diagram approach in particle physics by representing interactions as volumes of high-dimensional geometric objects, such as the amplituhedron, as introduced by the theoretical physicists Nima Arkani-Hamed and Jaroslav Trnka in 2013. It carries a rich combinatorial structure and offers an alternative, potentially simpler way to compute scattering amplitudes, from which one can derive probabilities of scattering events.

This approach has far-reaching implications that go beyond particle physics. In cosmology, scientists are using the faint light of the cosmic microwave background and the distribution of galaxies to infer what shaped the early universe. Similar mathematical tools are now being applied. For instance, cosmological polytopes, which are themselves positive geometries, can represent correlations in the universe's first light and help reconstruct the physical laws that governed the birth of the cosmos.

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The formal objects under consideration, such as Feynman integrals, generalized Euler integrals, or canonical forms of positive geometries, are not merely mathematical

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"Positive geometry is still a young field, but it has the potential to significantly influence fundamental research in both physics and mathematics," the authors emphasize. "It is now up to the scientific community to work out the details of these emerging mathematical objects and theories and to validate them. Encouragingly, several successful collaborations have already laid important groundwork."

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AUGUST 10, 2025

Using geometry and physics to explain feature learning in deep neural networks

by [Ingrid Fadelli](#), Phys.org [Editors' note](#)

A handmade folding ruler analogy, which the team found could be used to model DNN training in different regimes. Credit: Shi, Pan & Dokmanic.
Deep neural networks (DNNs), the machine learning algorithms underpinning the functioning of large language models (LLMs) and other artificial intelligence (AI) models, learn to make accurate predictions by analyzing large amounts of data. These networks are structured in layers, each of which transforms input data into 'features' that guide the analysis of the next layer.

The process through which DNNs learn features has been the topic of numerous research studies and is ultimately the key to these models' good performance on a variety of tasks. Recently, some computer scientists have started exploring the possibility of modeling feature learning in DNNs using frameworks and approaches rooted in physics.

Researchers at the University of Basel and the University of Science and Technology of China discovered a [phase diagram](#), a graph resembling those used in thermodynamics to delineate liquid, gaseous and solid phases of water, that represents how DNNs learn features under various conditions. Their paper, [published](#) in *Physical Review Letters*, models a DNN as a spring-block chain, a simple mechanical system that is often used to study interactions between linear (spring) and nonlinear (friction) forces.

"Cheng and I were at a workshop where there was an inspiring talk on 'a law of data separation,'" Ivan Dokmanić, the researcher who led the study, told Phys.org. "The layers of a deep neural network (but also of [biological neural networks](#) such as the human visual cortex) process inputs by progressively distilling and simplifying them.

"The deeper you are in the network, the more regular, more geometric these representations become, which means that representations of different classes of objects (e.g., representations of cats and dogs) become more separate and easier to distinguish. There's a way to measure this separation.

"The talk showed that in well-trained neural nets it often happens that these data separation 'summary statistics' behave in a simple way, even for very complicated [deep neural networks](#) trained on complicated data: each layer improves separation by the same amount."

The team found that the 'law of data separation' held true in networks with commonly used 'hyperparameters,' such as learning rate and noise, but not for different hyperparameter choices. They realized that understanding why this happens could shed light on how DNNs

learn good features across models. They thus set out to find a suitable theoretical description of these intriguing findings.

"At the same time, we were involved in some projects in geophysics where people use spring-block models as phenomenological models of fault and earthquake dynamics," said Dokmanić. "The data separation phenomenology reminded us of that. We thought about many other analogies. For instance, Cheng thought that equal data separation is a bit like a retractable coat hanger; I thought it's a bit like a folding ruler.

"We spent that winter holiday exchanging pictures and videos of various 'layer-structured' household items and tools, including these coat hangers, folding rulers, etc. I remember discussing whether a certain stretch trivet is a good model for a famous deep neural net called a ResNet."

After identifying various potential theoretical models and layered [physical systems](#) that could be used to study how DNNs learn features, the researchers ultimately decided to focus on spring block models. These models have already proved valuable for studying a wide range of real-world phenomena, including earthquakes and the deformation of materials.

Figure representing the team's spring-block theory of feature learning in deep neural networks. Credit: Shi, Pan & Dokmanic.

"We showed that the behavior of this data separation is eerily similar to the behavior of blocks connected by springs which are sliding on a rough surface (but also to the behavior of other mechanical systems, such as folding rulers)," explained Dokmanić.

"How much a layer simplifies the data corresponds to how much a spring extends. Nonlinearity in the network corresponds to how much friction there is between the blocks and the surface. In both systems we can add noise."

When looking at the two systems in the context of the law of data separation, Dokmanić and his colleagues found that the behavior of DNNs was similar to that of spring-block chains. A DNN responds to the training loss (i.e., request to explain observed data) by separating data layer by layer. Similarly, a spring-block chain responds to a pulling force by separating the blocks layer by layer.

"The more nonlinearity there is, the more discrepancy there is between the outer (deep) and inner (shallow) layers: the deep layers learn / separate more; same for springs," said Dokmanić.

"However, if we add training noise or start shaking / vibrating the spring-block system, then blocks will spend some time 'in the air,' without experiencing friction, and this will allow the springs to equalize the separation a bit. It's actually similar to 'acoustic lubrication' in process engineering, as well as to certain stick-slip phenomena in geophysics."

This recent study introduces a new theoretical approach to study DNNs and how they learn features over time. In the future, this approach could help to deepen the present

understanding of deep learning algorithms and the processes through which they learn to reliably tackle specific tasks.

"Most existing results treat simplified networks that are missing key aspects of real deep nets used in practice—either depth or nonlinearity or something else," explained Dokmanić.

"These works study a single impact factor on a stylized model, but the success of deep nets is predicated on an accumulation of factors (depth, nonlinearity, noise, learning rate, normalization, ...). In contrast, we took a top-down approach which is phenomenological, not first-principles, but we obtain a general theory, an understanding of the interplay of all these things."

The spring-block theory employed by the researchers was so far found to be both simple and effective for understanding the ability of DNNs to generalize across different scenarios. In their paper, Dokmanić and his colleagues successfully used it to compute the data separation curves of DNNs during training and found that the shape of these curves is indicative of the performance of the trained network on unseen data.

Amusing videos of folding ruler experiments and DNN training in different regimes.
Credit: *Physical Review Letters* (2025). DOI: 10.1103/ys4n-2tj3

"Since we also understand how to change the shape of the data separation curve in either direction by varying noise and nonlinearity, this gives us a (potentially) powerful tool to speed up training of very large nets," said Dokmanić.

"Most people have strong intuitions about springs and blocks but not about deep neural nets. Our theory says that we can make interesting, useful, true statements about deep nets by leveraging our intuition about a simple mechanical system. That's great because neural nets have billions of parameters, but our spring block system only has a handful."

The theoretical model employed by this team of researchers could soon be used by both theorists and computer scientists to further investigate the underpinnings of deep learning-based algorithms. As part of their next studies, Dokmanić and his colleagues hope to also use their theoretical approach to explore feature learning from a microscopic standpoint.

"We're close to having a first-principles explanation for the spring-block phenomenology (or perhaps the folding ruler phenomenology) in deep, nonlinear networks give or take a few approximations," explained Dokmanić.

"The other direction we are pursuing is to really double down on how to operationalize this to improve deep net training, especially for very large transformer-based networks like large language models. Having a proxy for generalization that is cheap to compute at training time, and an understanding of how to steer training to improve generalization, is a sort of a holy grail, an alternative route to the currently very popular scaling laws."

By understanding how the training of DNNs can be carefully engineered to improve their ability to generalize across other tasks, the researchers could also devise a diagnostic tool for large neural networks. For instance, this tool might help to identify areas that need to be improved to boost a model's performance, similarly to how stress maps are used in

structural mechanics to identify regions of concentrated stress that could compromise the safety of structures.

"By analyzing the internal load distribution in a neural net, we can find layers / regions that are overloaded which may indicate overfitting and hurt generalization, or layers that are barely used, indicating redundancy," added Dokmanić.

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More information: Cheng Shi et al, Spring-Block Theory of Feature Learning in Deep Neural Networks, *Physical Review Letters* (2025). DOI: [10.1103/ys4n-2tj3](#).

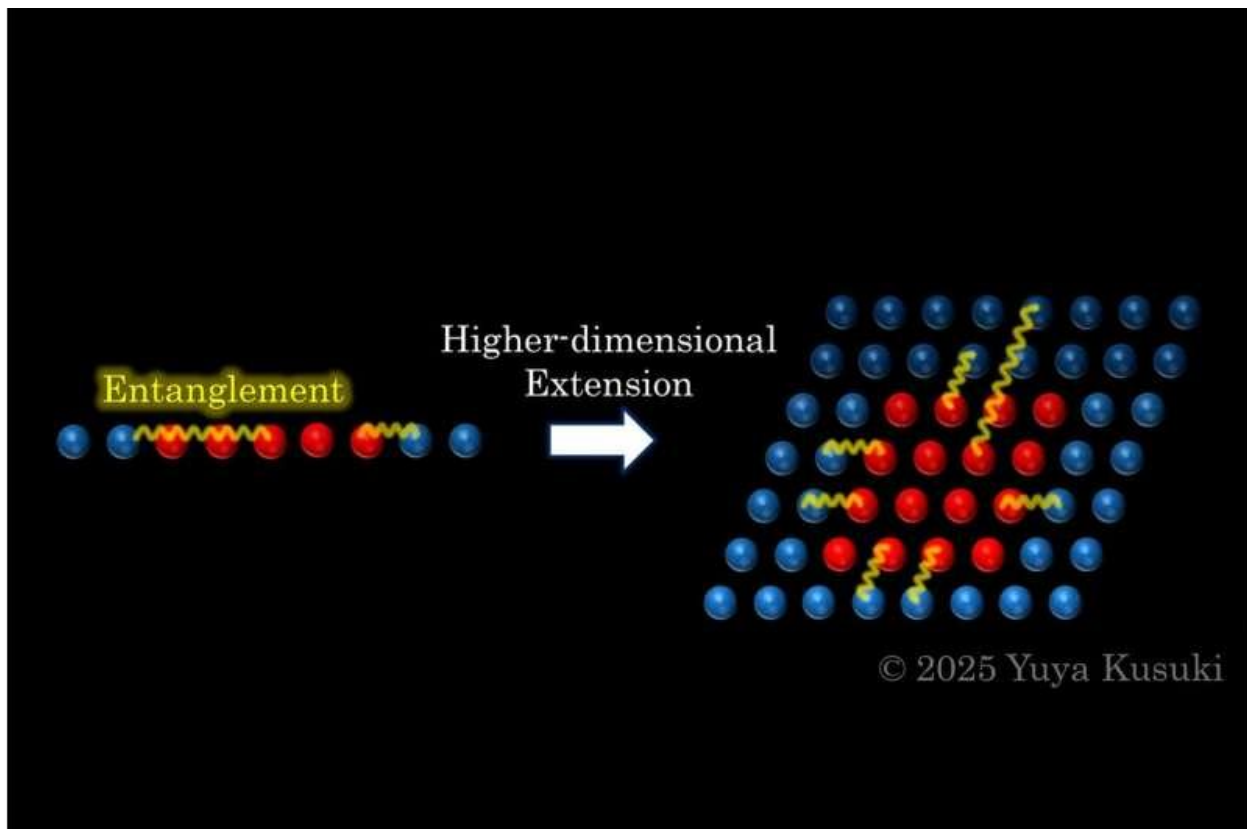
Journal information: [Physical Review Letters](#)

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AUGUST 6, 2025

Researchers discover universal rules of quantum entanglement across all dimensions

By [The Kavli Foundation](#) edited by [Sadie Harley](#), reviewed by [Robert Egan](#)



Quantum entanglement in 1+1 and 2+1 dimensions. Credit: Yuya Kusuki

A team of theoretical researchers used thermal effective theory to demonstrate that quantum entanglement follows universal rules across all dimensions. Their study was [published](#) online in *Physical Review Letters*.

"This study is the first example of applying thermal effective theory to quantum information. The results of this study demonstrate the usefulness of this approach, and we hope to further develop this approach to gain a deeper understanding of quantum [entanglement](#) structures," said lead author and Kyushu University Institute for Advanced Study Associate Professor Yuya Kusuki.

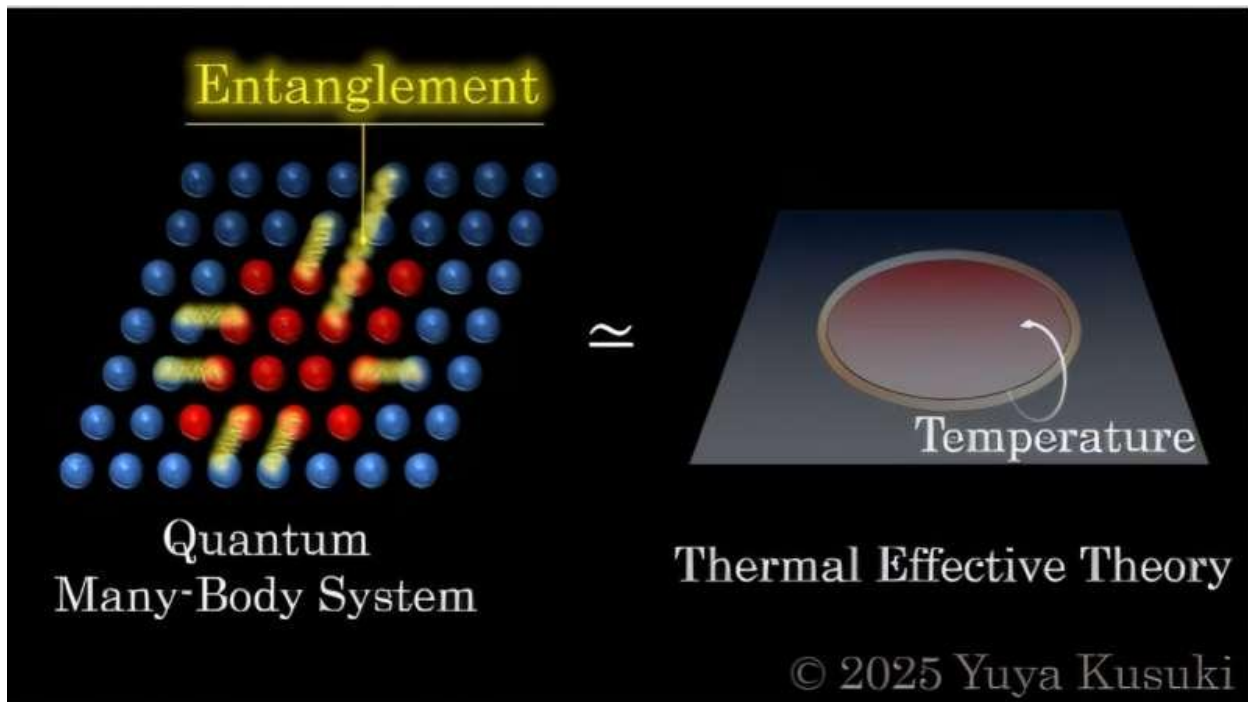
In [classical physics](#), two particles that are far apart behave independently. However, in [quantum physics](#), two particles can exhibit strong correlations regardless of the distance between them. This quantum correlation is known as quantum entanglement.

Quantum entanglement is a fundamental phenomenon underlying quantum technologies such as quantum computation and quantum communication, and understanding its structure is important both theoretically and practically.

One of the key measures used to quantify quantum entanglement is the Rényi entropy. Rényi entropy quantifies the complexity of quantum states and the distribution of information, and plays a crucial role in the classification of quantum states and in assessing the feasibility of simulating quantum many-body systems.

Moreover, Rényi entropy serves as a powerful tool in theoretical investigations of the black hole information loss problem, and frequently appears in the context of quantum gravity.

But uncovering the structure of quantum entanglement is a challenge for both [theoretical physics](#) and quantum information theory. However, most studies to date have been limited to (1+1)-dimensional systems, or 1 spatial dimension plus time dimension. In higher dimensions, analyzing the structure of quantum entanglement becomes significantly more difficult.



Looking a quantum entanglement in a quantum many-body system using thermal effective theory, which uncovers universal features of quantum entanglement. Credit: Yuya Kusuki
A research group led by Kusuki, the University of Tokyo Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) and the California Institute of Technology (Caltech) Professor Hirosi Ooguri, and Caltech researcher Sridip Pal, has shown the

universal features of quantum entanglement structures in higher dimensions by applying theoretical techniques developed in the field of particle physics to quantum information theory.

The research team focused on the thermal effective theory, which has recently led to major advances in the analysis of higher-dimensional theories in particle physics. This is a theoretical framework designed to extract universal behavior from [complex systems](#), based on the idea that observable quantities can often be characterized by only a small number of parameters.

By introducing this framework into quantum information theory, the team analyzed the behavior of Rényi entropy in higher-dimensional quantum systems.

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Rényi entropy is characterized by a parameter known as the replica number. The team demonstrated that, in the regime of small replica number, the behavior of the Rényi entropy is universally governed by only a few parameters, such as the Casimir energy, a key physical quantity within the theory.

Furthermore, by leveraging this result, the team clarified the behavior of the entanglement spectrum in the region where its eigenvalues are large. They also investigated how universal behavior changes depending on the method used to evaluate the Rényi entropy.

These findings hold not only in (1+1) dimensions, but in arbitrary spacetime dimensions, marking a significant step forward in the understanding of quantum entanglement structures in higher dimensions.

The next step for the researchers is to further generalize and refine this framework. This work represents the first demonstration that thermal effective theory can be effectively applied to the study of quantum entanglement structures in higher dimensions, and there remains ample room to further develop this approach.

By improving the thermal effective theory with quantum information applications in mind, researchers could gain a deeper understanding of [quantum entanglement](#) structures in higher-dimensional systems.

On the applied side, the theoretical insights gained from this research may lead to improvements in numerical simulation methods for higher-dimensional quantum systems, propose new principles for classifying quantum many-body states, and contribute to a [quantum-information-theoretic](#) understanding of quantum gravity. These developments hold promise for broad and impactful future applications.

More information: Yuya Kusuki et al, Universality of Rényi Entropy in Conformal Field Theory, *Physical Review Letters* (2025). DOI: [10.1103/fsg7-bs7q](https://doi.org/10.1103/fsg7-bs7q)

Journal information: [Physical Review Letters](#)

A new perspective on how cosmological correlations change based on kinematic parameters

Time without Time

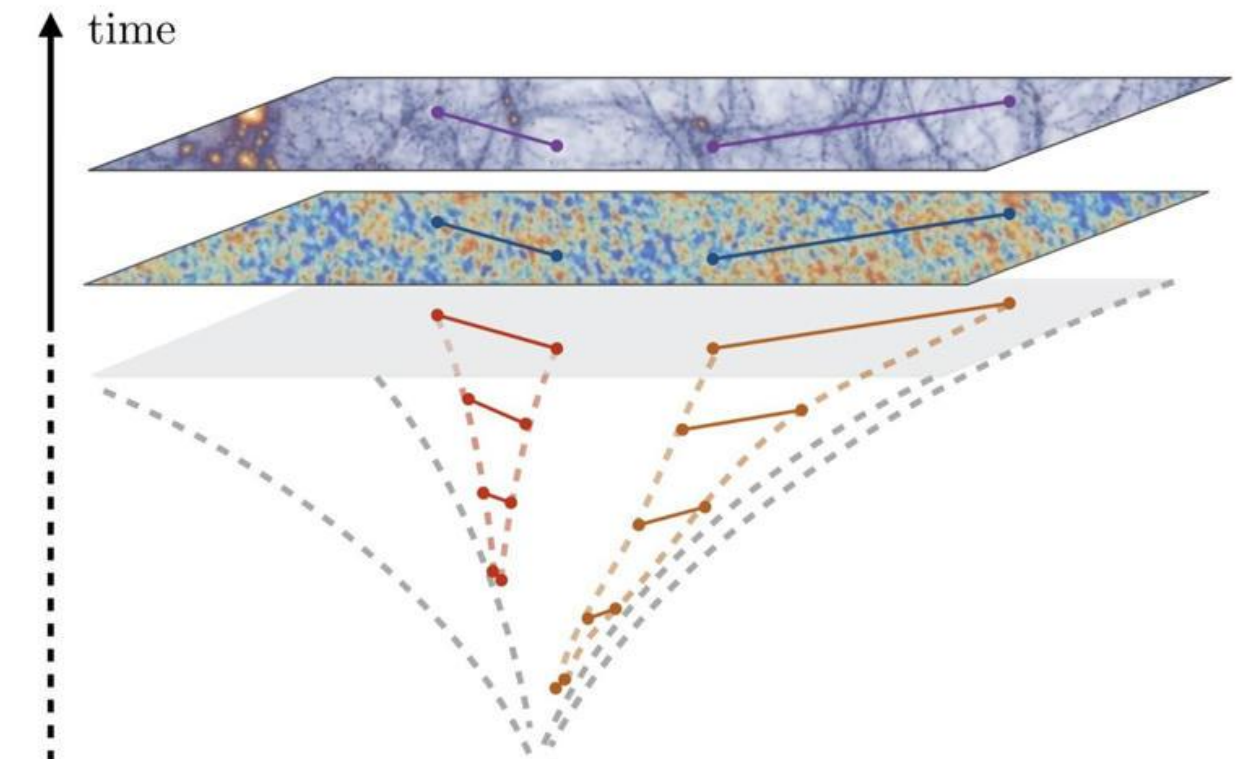


Figure illustrating the main idea behind the study. Specifically, it provides a 'timeless' view of early universe cosmology. The team filled in the timeline of the universe before the grey surface with this idea of correlations being stretched more or less during an earlier phase of the universe. Credit: Created by Guilherme Leite Pimentel, using snapshots of the CMB taken by the Planck satellite (ESA). The upper panel is from the Millennium simulation (hosted in the Max Planck Institute for Astrophysics).

To study the origin and evolution of the universe, physicists rely on theories that describe the statistical relationships between different events or fields in spacetime, broadly referred to as cosmological correlations. Kinematic parameters are essentially the data that specify a cosmological correlation—the positions of particles, or the wavenumbers of cosmological fluctuations.

Changes in cosmological correlations influenced by variations in kinematic parameters can be described using so-called differential equations. These are a type of mathematical equation that connects a function (i.e., a relationship between an input and an output) to its rate of change. In physics, these equations are used extensively as they are well-suited for capturing the universe's highly dynamic nature.

Researchers at Princeton's Institute for Advanced Study, the Leung Center for Cosmology and Particle Astrophysics in Taipei, Caltech's Walter Burke Institute for Theoretical Physics, the University of Chicago, and the Scuola Normale Superiore in Pisa recently introduced a new perspective to approach equations describing how cosmological correlations are affected by smooth changes in kinematic parameters.

Their paper, [published](#) in *Physical Review Letters*, introduces a framework, called "kinematic flow," that could help to derive these differential equations from basic combinatorial rules (i.e., principles to determine the number of ways in which a number of objects in a set can be arranged or selected).

"We started working on this paper around September 2020," Guilherme Leite Pimentel, one of the authors of the paper, told Phys.org. "Our motivation was to understand why this mathematical structure—differential equations in kinematic space—kept appearing in cosmology.

"Was it because of symmetry? Some simpler reason? There was suspicion that we were trading time evolution for spatial separation—the idea is that looking at a snapshot of the early universe at long distances probed the earliest phases of the universe—and we wanted to make that precise."

Over the past decades, equations in kinematic space have proved to be useful for predicting what might have happened in the early days of the universe, more so than approaches that entail delineating a possible timeline and evolving it. As particle physicists also used similar approaches, Pimentel and his colleagues tried to apply some of the constructs they relied on to the cosmology problem central to their study.

"The story told in the paper came about when the number of equations started to become very large," said Pimentel. "To keep track of what's going on, we decided to draw pictures of the terms in the equations, rather than write

formulas. Staring at these pictures eventually made it clear that there was a pattern. The pictures had a 'life of their own' and we could predict the equations by a simple set of rules that involved cutting and coloring the pictures."

In their theoretical analyses, the researchers first considered the kinematic space of a given correlator (i.e., tool measuring the strength of a relationship between two quantities). Subsequently, they applied a set of rules to this correlator.

The idea has a few parts: first, we consider the kinematic space of a given correlator. Then, we applied a set of rules to it: "We sliced it, drew tubes (or, alternatively, triangulated it) and then applied some seemingly esoteric recipe of growing these tubes, merging them, absorbing etc.," explained Pimentel.

"If you buy these rules, then you can predict all terms that appear in a mathematically consistent family of equations. The solutions to these equations—which depended only on spatial separations, or the kinematics of the correlators—are time integrals. In that sense, time emerges. The appearance of this structure hints that there are other ways of organizing these calculations, without invoking explicit time evolution."

This recent work by Pimentel and his colleagues introduces a simpler approach to understanding and describing complex cosmological correlations. Their proposed framework is aligned with other themes rooted in quantum gravity, such as the use of boundary observables and the emergence of spacetime. It could potentially contribute to a timeless description of cosmology.

"We introduced a new array of techniques to compute early universe cosmological correlators, borrowing from other areas of theoretical physics," said Pimentel.

"We expect many of the techniques to be widely applicable, beyond the toy models we described in the letter. The usage of techniques from other fields triggered the interest of mathematicians and particle physicists, who are looking for ways to bring their expertise and contribute. These connections hint that there is probably more knowledge that can be leveraged across these fields."

This team's recent paper could soon inspire further theoretical studies building on the framework they introduced. Meanwhile, Pimentel and his colleagues are seeking further examples in which their described concept of kinematic flow

could appear and more sophisticated models could be considered in additional research.

"In our next studies, we could also apply these techniques to models which are closer to what we expect the early universe to look like," said Pimentel.

"Another frontier for future research will be to push beyond the leading term—meaning, going from trees to loops—where many new theoretical and mathematical challenges appear. I've also been deeply involved in finding a new description of spinning particles in cosmology, where we are seeing glimpses of new mathematical structures that also previously appeared in particle physics."

More information: Nima Arkani-Hamed et al, Kinematic Flow and the Emergence of Time, *Physical Review Letters* (2025). DOI: [10.1103/dsjm-tckw](https://doi.org/10.1103/dsjm-tckw).

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