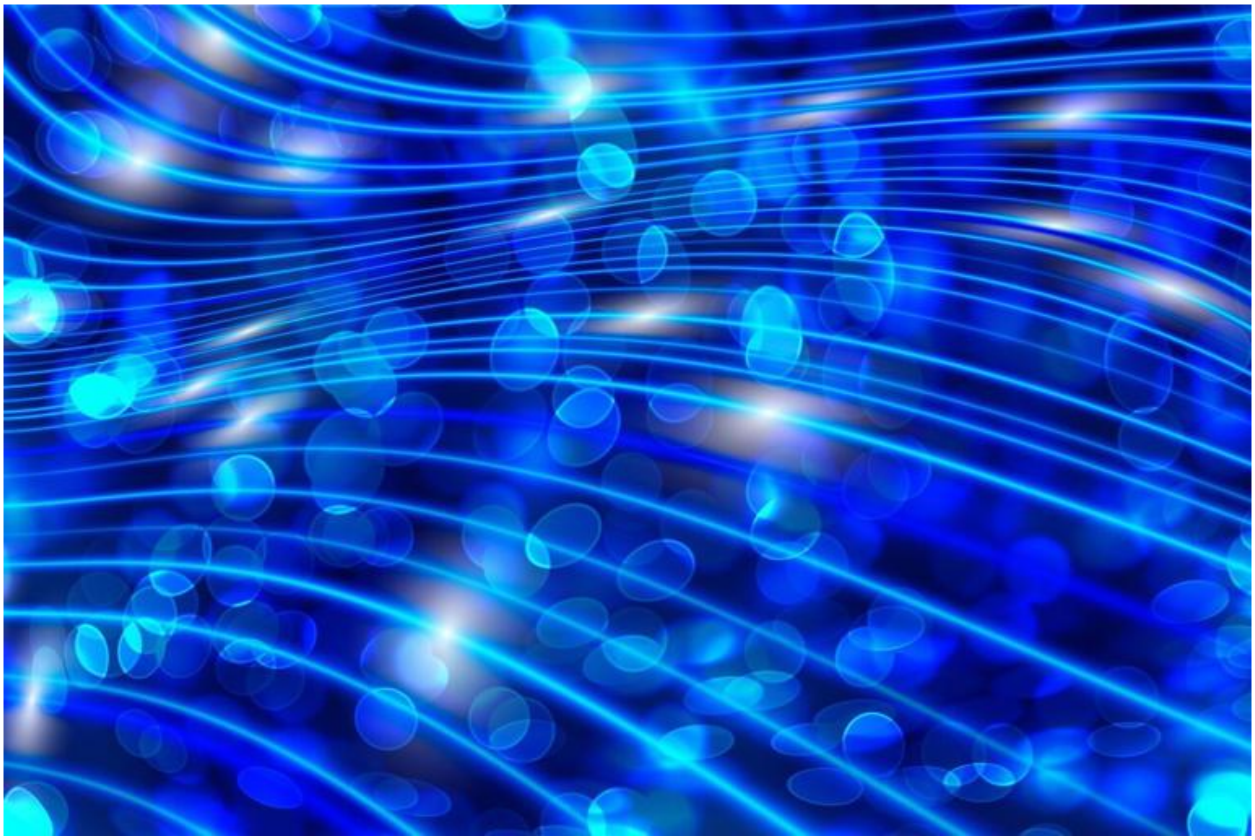
QUANTUM TECH VOL 3

Physicists discover new state of quantum matter



Professor Luis Jauregui of the UC Irvine Department of Physics & Astronomy described how the new material he and his lab developed only exists in their labs. Credit: Steve Zylius / UC Irvine

Researchers at the University of California, Irvine have discovered a new state of quantum matter. The state exists within a material that the team reports could lead to a new era of self-charging computers and ones capable of withstanding the challenges of deep space travel.

"It's a new phase of matter, similar to how water can exist as liquid, ice or vapor," said Luis A. Jauregui, professor of physics & astronomy at UC Irvine and corresponding author of the new paper in *Physical Review Letters*.

"It's only been theoretically predicted—no one has ever measured it until now."

This new phase is like a liquid composed of electrons and their counterparts, known as "holes," spontaneously pairing and forming exotic states known as excitons. Unusually, the electrons and holes spin together in the same direction.

"It's its own new thing," Jauregui said. "If we could hold it in our hands, it would glow a bright, high-frequency light."

The phase exists in a material developed at UC Irvine by Jinyu Liu, a postdoctoral researcher in Jauregui's lab and the first author of the paper. Jauregui and his team measured the phase using high magnetic fields at the Los Alamos National Laboratory (LANL) in New Mexico.

The key to creating the new quantum matter was in applying a high-intensity magnetic field of up to 70 Teslas to the material (by comparison, the magnetic field from a strong fridge magnet is around 0.1 Teslas), which the team calls hafnium pentatelluride.

Jauregui explained that, as his team applied the magnetic field, the "material's ability to carry electricity suddenly drops, showing that it has transformed into this exotic state," he said. "This discovery is important because it may allow signals to be carried by spin rather than electrical charge, offering a new path toward energy-efficient technologies like spin-based electronics or quantum devices."

Unlike conventional materials used in electronics, this new quantum matter isn't affected by any form of radiation, which makes it an ideal candidate for space travel.

"It could be useful for space missions," Jauregui said. "If you want computers in space that are going to last, this is one way to make that happen."

Companies like SpaceX are planning human-piloted space flights to Mars, and to do that effectively, you need computers that can withstand prolonged periods of exposure to radiation.

"We don't know yet what possibilities will open as a result," Jauregui said.

The material was synthesized, characterized and made into measurable devices at UC Irvine by Jinyu Liu with assistance from graduate students Robert Welser and Timothy McSorley, and undergraduate researcher Triet Ho.

Theoretical modeling and interpretation were provided by Shizeng Lin, Varsha Subramanyan, and Avadh Saxena at LANL.

High-magnetic-field experiments were conducted with the support of Laurel Winter and Michael T. Pettes at LANL and David Graf at the National High Magnetic Field Laboratory in Florida.

More information: Jinyu Liu et al, Possible Spin-Triplet Excitonic Insulator in the Ultraquantum Limit of HfTe5, *Physical Review Letters* (2025). DOI: 10.1103/bj2n-4k2w

Provided by University of California, Irvine

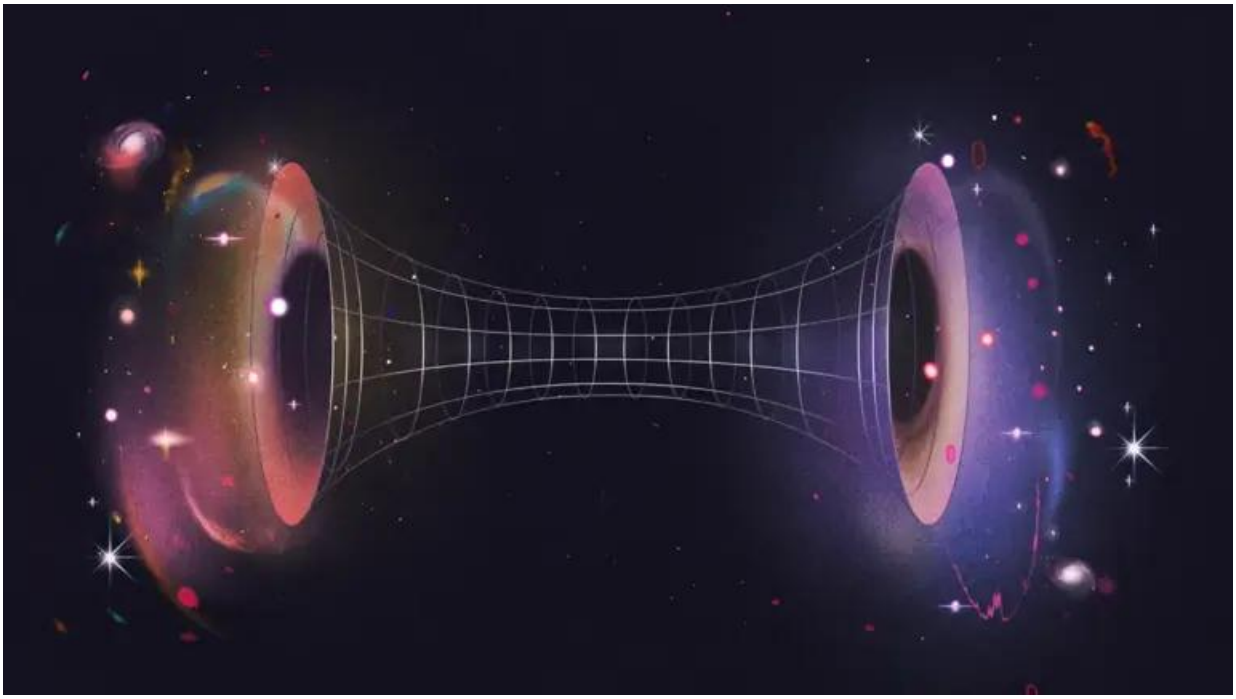
Quantum networks could unlock the secrets of time and gravity

For decades, quantum physics and general relativity have stood as two powerful but separate theories. Quantum physics explains the behavior of tiny particles like atoms and photons. General relativity, on the other hand, describes how gravity shapes the universe through the bending of space and time.

Both have been confirmed through countless experiments, yet how they work together still remains a mystery. Now, thanks to advances in quantum networking, researchers are finally able to test how these two giants of science interact.

Quantum networking is a fast-growing technology that could lead to a global quantum internet. This would allow ultra-secure communication and link quantum computers across the planet. But beyond its practical uses, scientists are now realizing that quantum networks can do much more. They may help answer deep questions about how the universe works at its most basic level.

A team of physicists — Igor Pikovski from Stevens Institute of Technology, Jacob Covey from the University of Illinois at Urbana-Champaign, and Johannes Borregaard at Harvard University — have taken a major step in that direction. In their new study, published in PRX Quantum, they describe how quantum networks can be used to probe curved spacetime, the very fabric of the universe according to Einstein.



Quantum networks and curved spacetime come together as scientists test how entangled atomic clocks respond to shifting time flows caused by gravity. (CREDIT: CC BY-SA 4.0)© The Brighter Side of News

Superpositions Meet Spacetime

At the heart of this idea is the quantum principle of superposition. In the quantum world, particles don't just exist in one state or another — they can exist in many states at once. A particle can spin in two directions at the same time, or a bit of quantum information — a qubit — can be both a 0 and a 1.

Quantum computers use this principle to perform powerful calculations, and quantum networks can spread these qubits across distances. But when those distances cross areas of curved space-time, strange things happen.

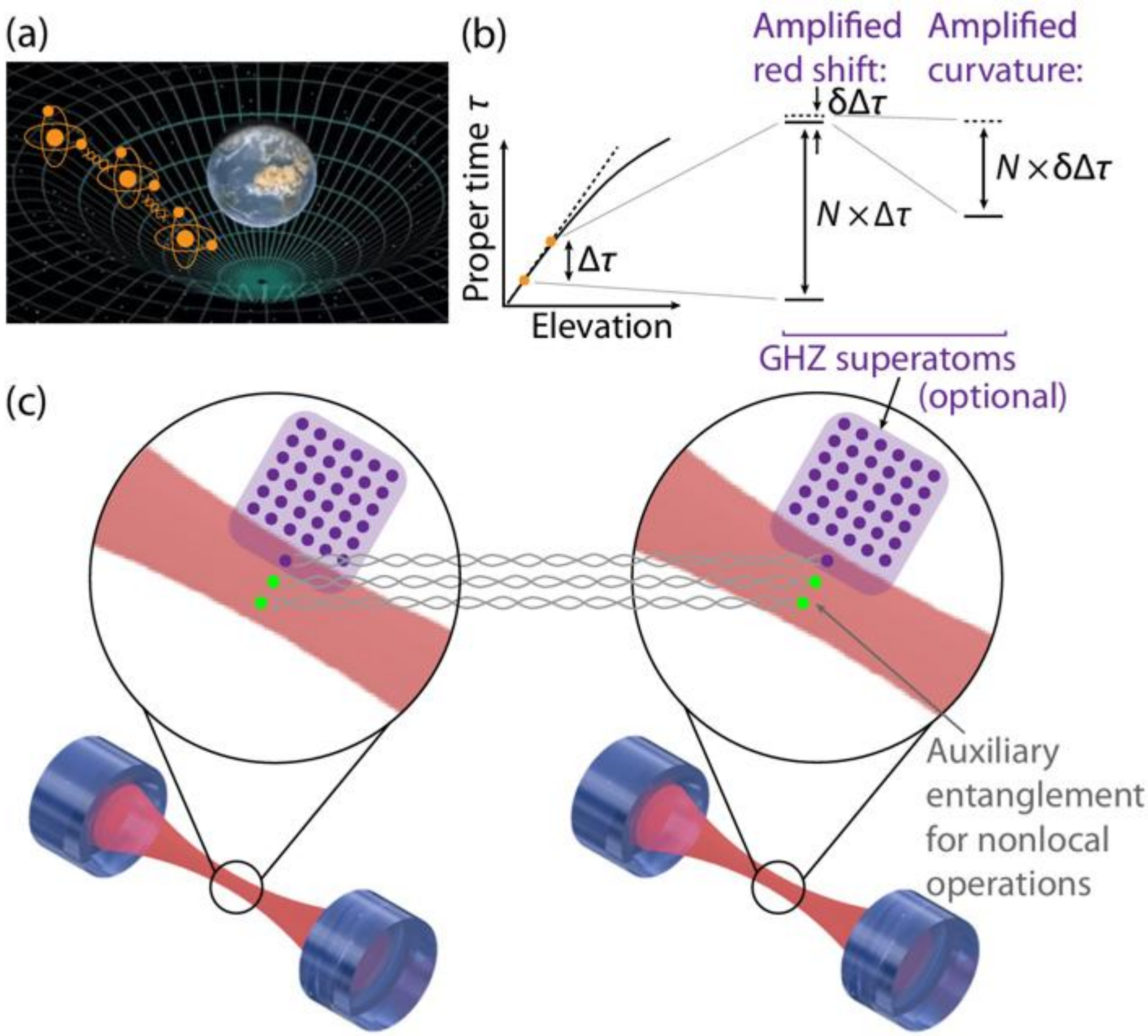
According to general relativity, gravity is not a force that pulls objects, but a bending of space and time caused by massive objects like planets. This bending changes how time flows. Near a massive object like Earth, time slows down — a phenomenon that's been measured with extreme accuracy. It was even featured in the film Interstellar, where a planet's strong gravity made minutes stretch into hours. What happens when a quantum system in superposition experiences this change in time? That's the question Pikovski and his colleagues set out to explore.

In a prior paper, Pikovski and Borregaard proposed that superpositions of atomic clocks in a quantum network would experience multiple time flows at once. Because of gravity, the flow of time isn't the same everywhere.

If you place two entangled clocks at different heights above Earth's surface, one will tick slightly faster than the other. When these clocks are in a quantum superposition, they effectively "tick" at multiple rates at once. This is something that could never be tested before. But now, with the power of quantum networking, such a test has become possible.

Building the Experiment

To take their theory from paper to practice, the team joined forces with Covey's lab. Together, they developed a protocol that allows these quantum clocks to be connected through a network and share quantum information. The method uses entangled W-states, which are special states where multiple qubits are all linked together. When one qubit is changed, the others respond instantly, no matter the distance between them.



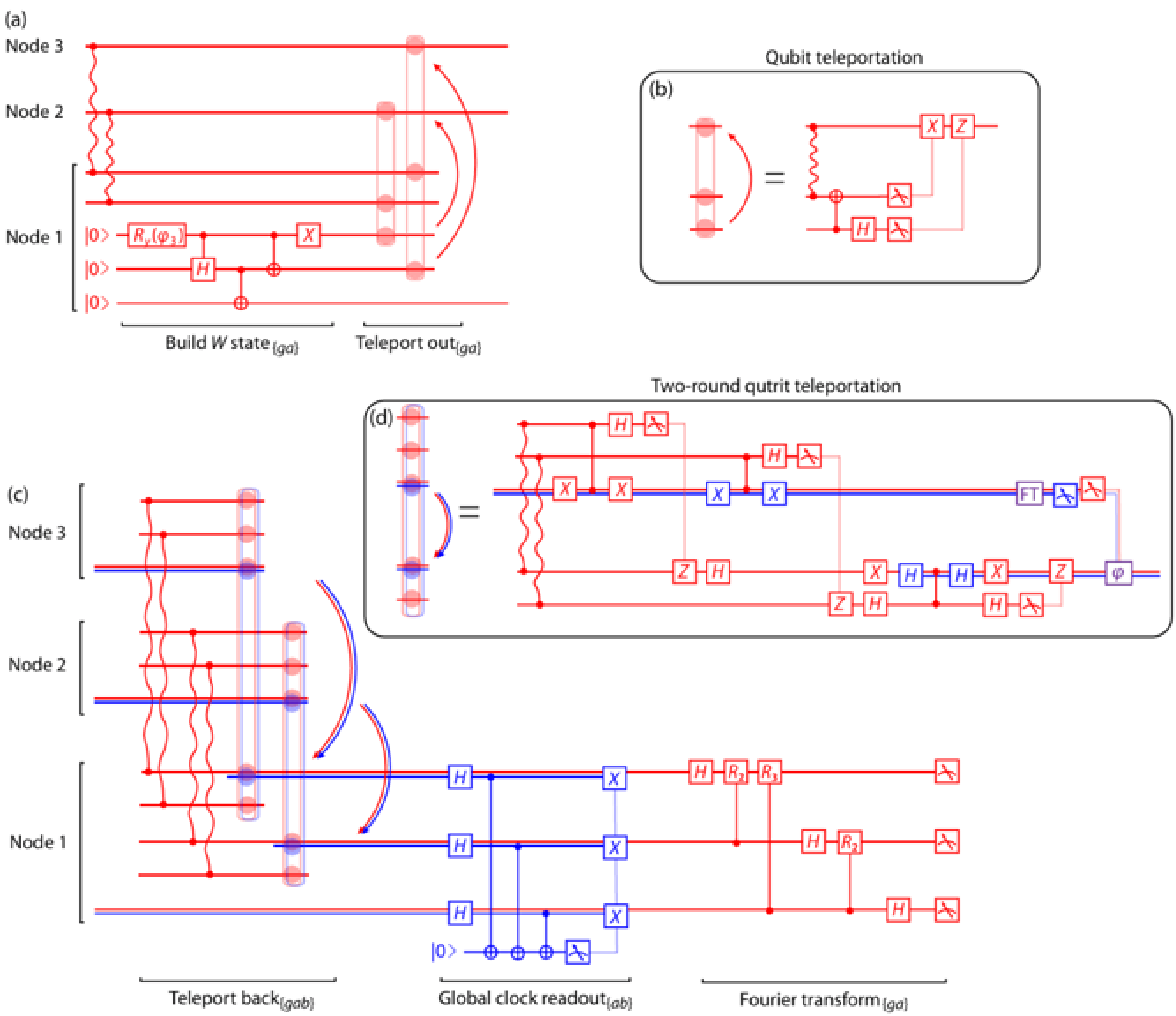
Probing curved spacetime with entangled clocks. (CREDIT: PRX Quantum)© The Brighter Side of News

The researchers also used a technique called quantum teleportation, where the quantum state of a particle can be transferred to another without moving the particle itself. This, combined with Bell pairs — pairs of qubits that are as entangled as physically possible — creates a powerful platform for testing fundamental physics.

By setting up this type of network with atomic clocks located at different gravitational heights, the team showed that they could detect subtle changes in time caused by Earth's gravity — while the clocks remained entangled in a quantum state. The interference patterns that form when these clocks interact show the effects of curved spacetime on quantum information.

“We assume that quantum theory holds everywhere — but we really don’t know if this is true,” Pikovski says. “It might be that gravity changes how quantum mechanics works. In fact, some theories suggest such modifications, and quantum technology will be able to test that.”

What’s important here is that the experiment doesn’t just test the known laws of physics. It tests the unknown. It pushes the edge of what’s possible, bringing science closer to uniting the quantum world with the cosmic one.



Creating, distributing, and detecting W states. (CREDIT: PRX Quantum)© The Brighter Side of News

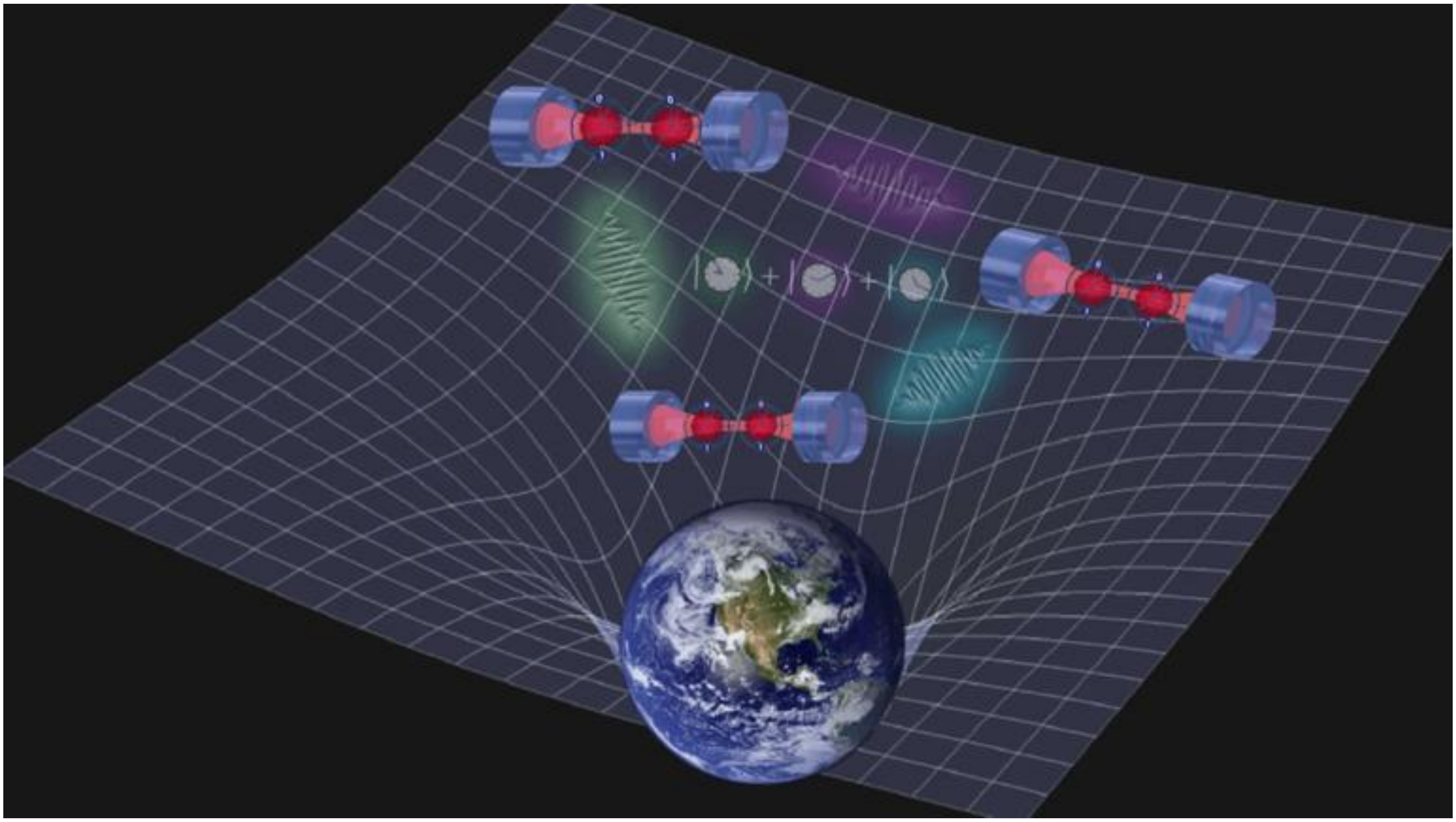
A New Frontier in Physics

This work suggests that quantum networks aren't just useful for communication or building quantum computers. They can also act as sensitive tools for exploring deep questions in physics — the kinds of questions that can't be answered with classical tools. Traditional sensors or clocks would never be able to probe time differences at the quantum level. But when quantum superpositions and entanglement are used, entirely new effects can be measured.

"The interplay between quantum theory and gravity is one of the most challenging problems in physics today, but also fascinating," says Pikovski. "Quantum networks will help us test this interplay for the first time in actual experiments." By combining modern quantum capabilities with Einstein's view of the universe, researchers have opened the door to a whole new class of experiments. And these aren't just thought experiments — they're doable now, with today's technology.

Looking Ahead

This discovery marks a turning point. Quantum networking, once seen mainly as a way to send secret messages or link distant computers, now promises something much bigger. It may help solve one of the oldest puzzles in science: how gravity and quantum mechanics fit together.



A network of quantum-entangled clocks spread across vast distances could reveal how quantum mechanics interacts with the curvature of space-time predicted by Einstein's general relativity—or expose where our current understanding of physics begins to fail. (CREDIT: Igor Pikovski)© The Brighter Side of News

While a full theory of quantum gravity — one that fully unites quantum physics with general relativity — still doesn't exist, results like these move the needle forward. They show that it's no longer just theory. With the right tools, scientists can begin to test and measure the strange ways that space, time, and quantum states affect one another.

The journey to a global quantum internet continues, and with it comes the chance to uncover new truths about the universe. The work by Pikovski, Covey, and Borregaard doesn't just offer a glimpse into the future of technology. It offers a new lens through which to view the very nature of time, space, and reality itself.

New unified gravity theory could finally bridge Einstein and quantum physics

Researchers have proposed a new way to bring gravity into the same mathematical language as the other forces of nature. JOSHUA SHAVIT

Published May 7, 2025

Physicists may finally unify gravity with quantum physics, solving one of science's biggest challenges. (CREDIT: NanoGrav)

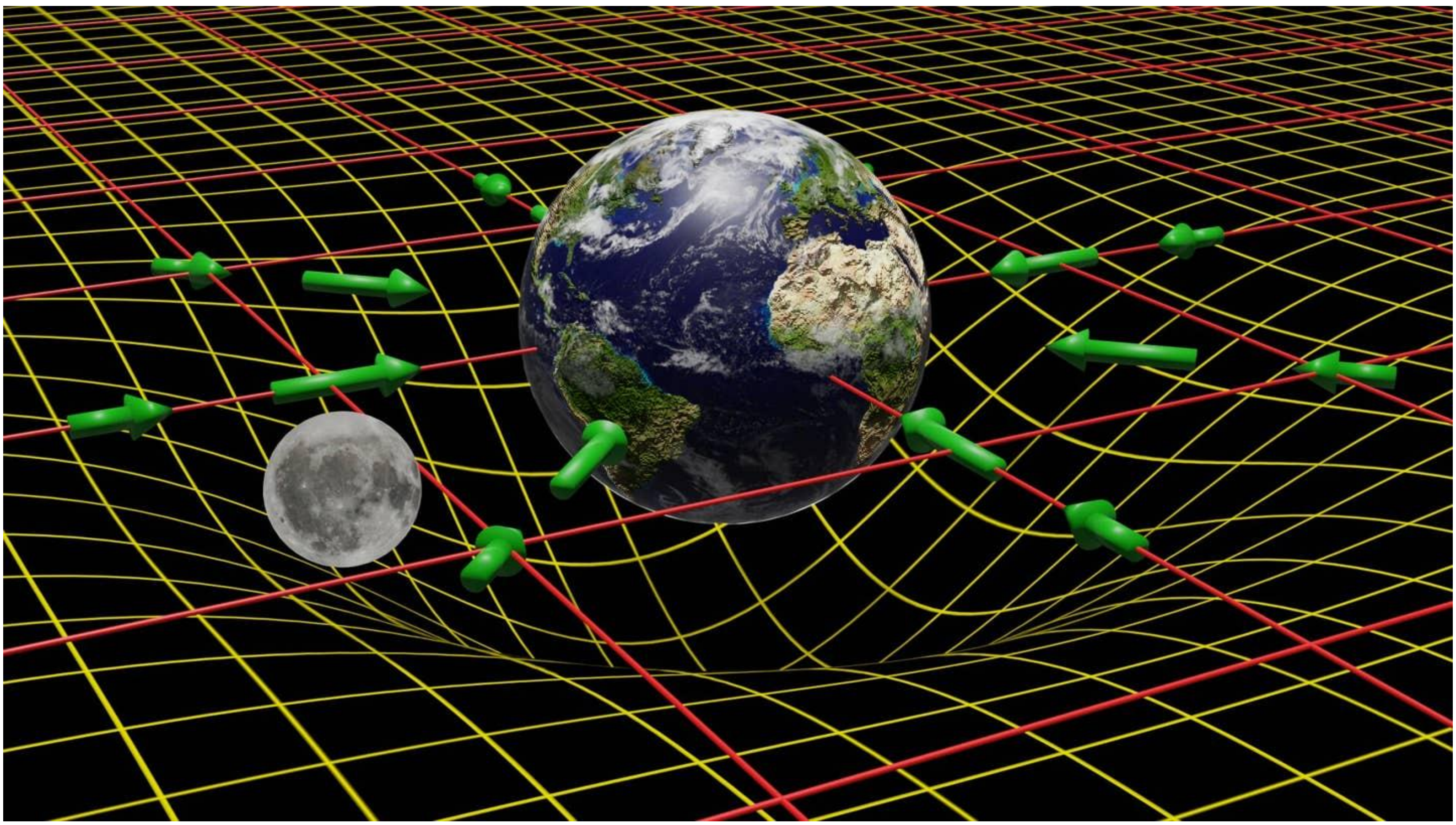
In a bold step toward solving one of science's most puzzling problems, researchers have proposed a new way to bring gravity into the same mathematical language as the other forces of nature. While the electromagnetic, weak, and strong forces are described by the Standard Model of particle physics, gravity remains an outlier—resisting efforts to be fully explained by quantum theory.

Now, two physicists from Aalto University in Finland—Mikko Partanen and Jukka Tulkki—have developed a fresh theory that could finally unite gravity with the Standard Model.

Their work, recently published in Reports on Progress in Physics, suggests that gravity, like the other forces, can be described by a gauge theory. This insight opens the door to what physicists call a "Theory of Everything."

Why Gravity Resists Unification

The Standard Model is built on a framework called quantum field theory. This theory merges classical field theory, quantum mechanics, and special relativity. It explains how particles interact through gauge fields—mathematical constructs that ensure the symmetries of nature's laws are preserved. These symmetries, which are compact and finite-dimensional, govern everything from light to atomic nuclei.



The gravity quantum field is calculated in flat spacetime. The curved classical metric is calculated using the expectation value of the gravity quantum field. (CREDIT: Aalto University)

Gravity, on the other hand, is described by general relativity, which sees space-time as curved by the presence of mass and energy. The symmetries in general relativity are infinite-dimensional and tied to the fabric of space itself.

This clash between internal symmetries of quantum fields and the external symmetries of space-time has made gravity very difficult to fit into the quantum framework.

As a result, alternative theories have emerged—string theory, loop quantum gravity, asymptotic safety, and others—all aiming to fill this gap. Still, none have offered a

complete, renormalizable quantum theory of gravity that aligns with the Standard Model.
The main obstacle has been renormalizability: the ability to remove infinities from quantum equations using a finite number of corrections. This step is crucial for making reliable predictions, especially at high energies, like those near black holes or the Big Bang.

Codemakers race to secure the internet as quantum threat looms

With quantum computing on the horizon, cryptographers are working to secure digital communications against a new generation of potential threats.

How do you outsmart a computer that could soon eclipse anything we have ever built? That is the challenge facing researchers who are working to build up our defenses against the coming age of quantum computing.

The idea is simple, yet serious. Third parties can intercept and store encrypted data now, and wait until more powerful decryption tools, such as quantum computers, are available in the future. Once they have those tools, they can go back and decrypt the stored data, which may still be sensitive or valuable.

That is where cryptographers come in. They study, design and test new methods for protecting data. Their role will take on added importance in the context of quantum computing.

According to Curty, upgrading the digital infrastructure that protects communications could take five to seven years, making early preparation and improvements in cryptography essential.

Evolving tools for evolving technology

Codes are not new. Julius Caesar used a simple alphabet-based cipher to conceal military information. Over time, these simple systems have evolved into the complex cryptographic methods we rely on today, protecting everything from online payments to personal health records.

"Protecting company secrets from foreign digital spying will become even more relevant in future," said Curty. "And concerns about personal privacy have become more prominent, especially following recent whistleblower revelations about mass surveillance."

JULY 30, 2025

D-Wave Quantum Announces Strategic Development Initiative for Advanced Cryogenic Packaging

New initiative aims to improve packaging capabilities, equipment and processes in order to accelerate both gate model and annealing quantum processor development

PALO ALTO, Calif. – July 30, 2025 – D-Wave Quantum Inc. (NYSE: QBTS) ("D-Wave"), a leader in quantum computing systems, software, and services, today announced a new strategic development initiative focused on advanced cryogenic packaging. Designed to advance and scale both gate model and annealing quantum processor development, the initiative builds on D-Wave's technology leadership in superconducting cryogenic packaging and will expand the company's multichip packaging capabilities, equipment, and processes. By bolstering its manufacturing efforts with state-of-the-art technology, D-Wave aims to accelerate its cross-platform technology development efforts while maintaining and expanding fundamental components of its supply chain.

As part of this initiative, D-Wave is leveraging deep expertise and processes at the NASA Jet Propulsion Laboratory ("JPL"), a research and development lab federally funded by NASA and managed by Caltech. Harnessing JPL's superconducting bump-bond process, D-Wave has demonstrated end-to-end superconducting interconnect between chips, work that D-Wave expects will serve as an important foundation for scaling both D-Wave’s annealing architectures and its fluxonium-based gate-model architectures. D-Wave believes that superconducting bump bonds will be key to the scalable control of fluxonium and to interconnectivity in multichip quantum processor architectures. D-Wave is also acquiring equipment and developing processes with a goal to increase circuit densities in its pioneering superconducting printed-circuit-board (“PCB”) manufacturing, required for both scaling to larger processors and supporting analog-digital quantum computing technology.

“Scaling both annealing and gate-model quantum computers requires high performance packaging,” said Dr. Trevor Lanting, chief development officer at D-Wave. “We believe this strategic initiative will allow us to further extend our leadership position in quantum systems technology development and support our exciting and aggressive product roadmap on the path to 100,000 qubits.”

Packaging quantum processors involves unique and demanding requirements, including: compatibility with ultra-low temperature operation, extremely low magnetic fields, and fully superconducting interconnects with no interruptions in superconductivity all the way from on-chip circuitry through to external control wiring. D-Wave's differentiated solution encompasses cryogenic compatible mechanical and electromagnetic design, regularly achieves lower qubit temperatures than most in the industry, and supports coherence times that meet the requirements for error-corrected gate-model quantum computing technology.

About D-Wave Quantum Inc.

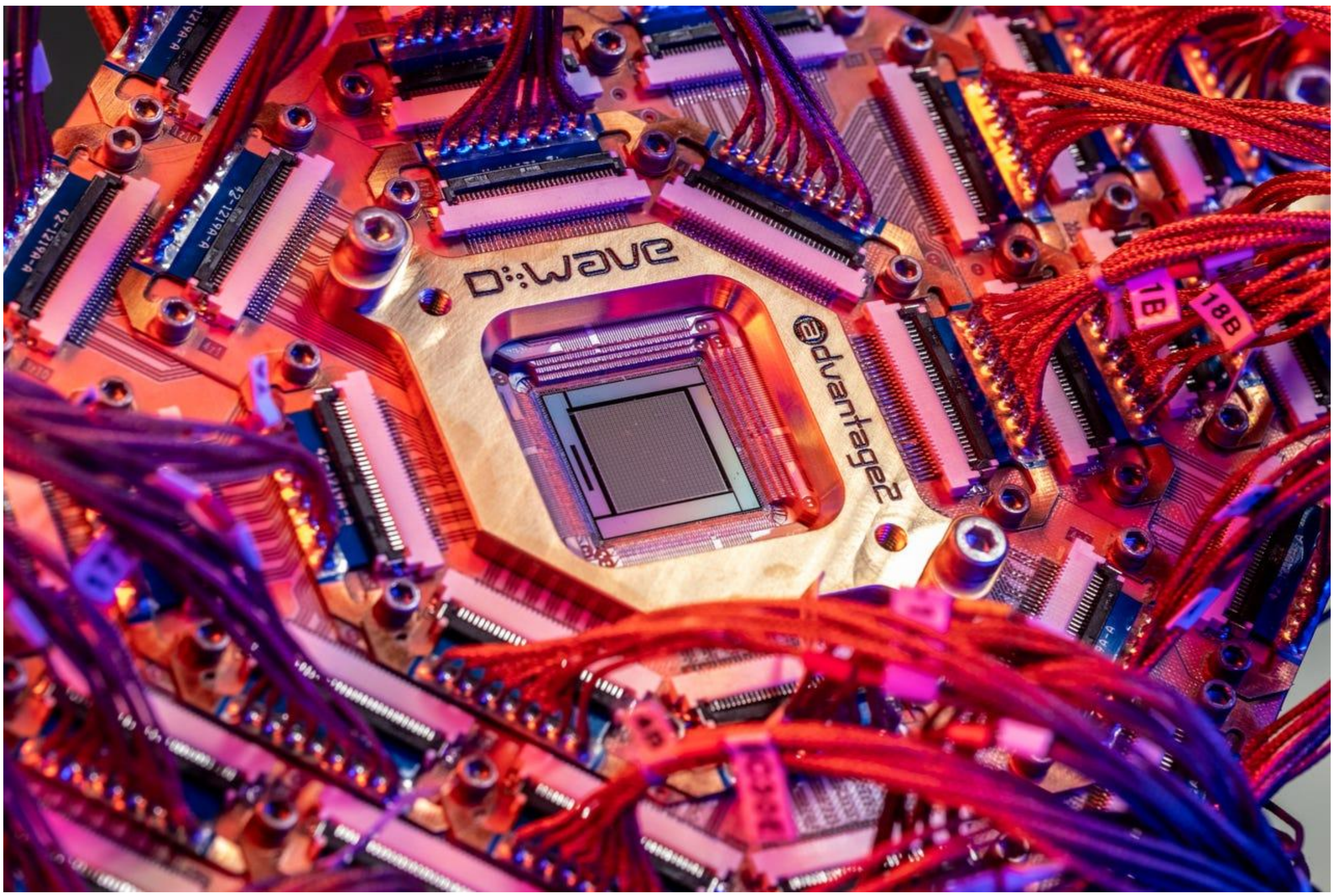
D-Wave is a leader in the development and delivery of quantum computing systems, software, and services. We are the world's first commercial supplier of quantum computers, and the only company building both annealing and gate-model quantum computers. Our mission is to help customers realize the value of quantum, today. Our quantum computers — the world's largest — feature QPUs with sub-second response times and can be deployed on-premises or accessed through our quantum cloud service, which offers 99.9% availability and uptime. More than 100 organizations trust D-Wave with their toughest computational challenges. With over 200 million problems submitted to our quantum systems to date, our customers apply our technology to address use cases spanning optimization, artificial intelligence, research and more. Learn more about realizing the value of quantum computing today and how we're shaping the quantum-driven industrial and societal advancements of tomorrow: www.dwavequantum.com.

D-Wave Partners with NASA JPL to Scale Quantum Computing

Strategic initiative aims to advance cryogenic packaging technology to support scaling quantum processors to 100,000 qubits

Berenice Baker, Editor, Enter Quantum, co-editor AI Business, Informa TechTarget

July 30, 2025



D-WAVE QUANTUM

D-Wave Quantum has launched a strategic development initiative focused on advanced cryogenic packaging to scale its quantum processors. The company is collaborating with NASA's Jet Propulsion

Laboratory to overcome manufacturing challenges that have been limiting quantum computing power.

This technological advancement is part of D-Wave's aggressive plan to scale quantum processors to 100,000 qubits, significantly beyond current capabilities of just thousands. The initiative builds on D-Wave's technology expertise in superconducting cryogenic packaging and will expand the company's multichip packaging capabilities, equipment and processes.

"Scaling both annealing and gate-model quantum computers requires high-performance packaging," said D-Wave chief development officer Trevor Lanting.

"We believe this strategic initiative will allow us to further extend our leadership position in quantum systems technology development and support our exciting and aggressive product roadmap on the path to 100,000 qubits."

Quantum processor packaging presents several demanding requirements, including compatibility with ultra-low temperature operation, tolerance for extremely low magnetic fields and fully superconducting interconnects without interruptions from on-chip circuitry through external control wiring.

Related: IonQ, Oak Ridge Lab Advance Quantum Grid Optimization

D-Wave's approach includes cryogenic-compatible mechanical and electromagnetic design, which achieves lower qubit temperatures than industry standards and supports coherence times that meet requirements for error-corrected gate-model quantum computing.

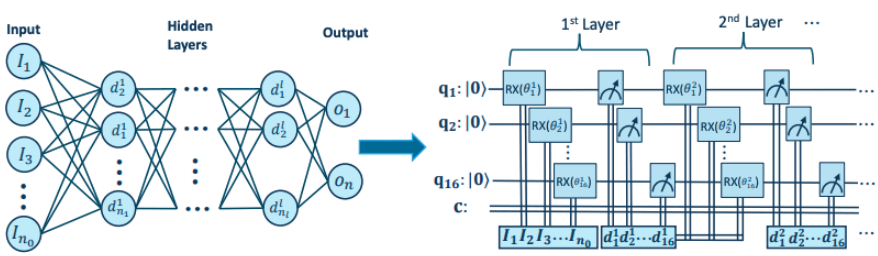
As part of this initiative, D-Wave is leveraging JPL's superconducting bump-bond process, which D-Wave has successfully employed to demonstrate end-to-end superconducting interconnect between chips.

The bump-bond process creates microscopic conductive connections between semiconductor components, allowing signals to pass between chips while maintaining superconductivity at extremely low temperatures. The company believes these superconducting bump bonds will be key to the scalable control of fluxonium and to interconnectivity in multichip quantum processor architectures.

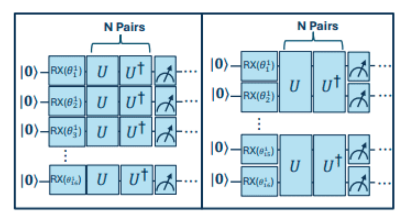
D-Wave is also acquiring equipment and developing processes to increase circuit densities in its superconducting printed-circuit-board manufacturing, which is necessary for both scaling to larger processors and supporting analog-digital quantum computing technology.

Quantum Neural Network Improves Image Classification with Controlled Measurement Uncertainty

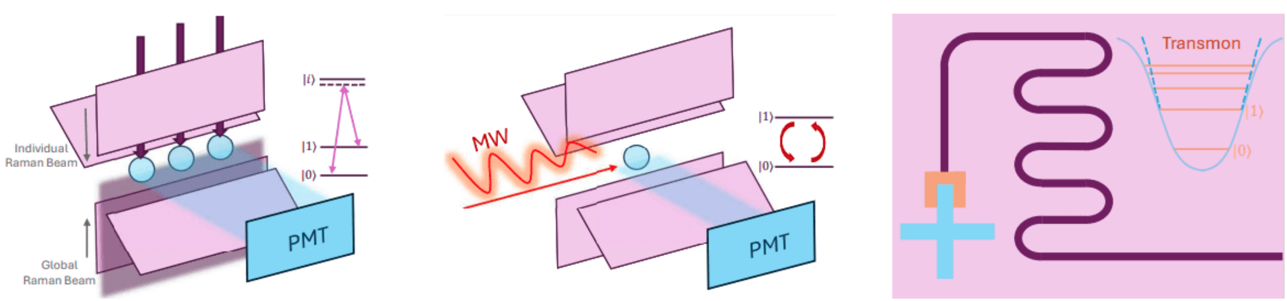
July 30, 2025BY QUANTUM NEWS



(a) Mapping from classical NN to BQNN.



(b) BQNN circuit injecting U and $U^\dagger$ pairs with single- (left) and two-qubit (right) gates.



Quantum neural networks represent a potentially transformative approach to machine learning, and a team led by Djamil Lakhdar-Hamina, Xingxin Liu, and Richard Barney at the Joint Quantum Institute and University of Maryland are pioneering their development on real quantum hardware. Researchers are now demonstrating a tunable quantum neural network capable of classifying images, a task typically handled by conventional computers, using both trapped-ion and superconducting quantum processors. This work is significant because it moves beyond theoretical proposals, directly comparing quantum and classical performance on physical devices and identifying scenarios where the quantum network excels, even in the presence of noise. By carefully controlling the degree of quantum behaviour within the network, the team reveals that these systems can correctly classify images that challenge classical algorithms, suggesting a pathway towards quantum advantage in machine learning applications.

The network's feedforward process involves rotations applied to qubits, where the angles of these rotations depend on the results of measurements in the previous layer. Training is initially performed using classical simulations, but the network's performance is ultimately evaluated on actual quantum hardware. A crucial aspect of this work is the control of the connection between classical and quantum computation, managed by an adjustable parameter that introduces varying degrees of quantum uncertainty.

Natural Quantization Mimics Spin Glass Dynamics

This research presents a novel approach to neural networks by incorporating principles from quantum physics, drawing parallels between the training dynamics of classical networks and the behavior of physical systems, particularly spin glasses. The authors propose that the training process can be understood as a search for a low-energy state within a complex energy landscape, and that quantization emerges naturally from this underlying physics, differing from many other quantum machine learning approaches. This connection between stochastic neurons in classical networks and the inherent noise in quantum systems justifies using quantum mechanics as a natural model for the training process. The proposed framework envisions hybrid networks where classical and quantum components work together, potentially exhibiting measurement-induced phase transitions leading to novel computational capabilities. The research could pave the way for new quantum machine learning algorithms that are more efficient and powerful than classical algorithms, and could lead to advances in artificial intelligence by providing a more natural and efficient way to represent and process information. The connection between neural networks and spin glasses could also lead to new insights into the behavior of complex materials.

Quantum Neural Network Classifies MNIST Images

Researchers have successfully implemented a quantum neural network capable of classifying images from the widely used MNIST dataset. This network, designed to bridge classical and quantum computation, achieves improved performance when incorporating a controlled degree of quantum uncertainty, demonstrating a potential advantage over purely classical approaches. The network functions by processing information through layers of qubits, where rotations applied to these qubits depend on the outcomes of measurements in the preceding layer. Training is initially performed using classical simulations, but the crucial step involves running the network on actual quantum hardware, utilizing both trapped-ion and superconducting quantum computers.

Introducing quantum uncertainty enhances the network's ability to correctly classify images, particularly those that challenge classical neural networks. Interestingly, the quantum network demonstrates a unique sensitivity to physical noise, and moderate levels can actually *improve* classification accuracy, especially for difficult images. This suggests the network leverages fluctuations caused by noise to navigate the complex landscape of possible solutions, effectively escaping local minima that trap classical networks. Researchers quantified this effect by deliberately adding noise gates to the circuits, observing a predictable decline in performance as noise levels increased, providing a new metric for characterizing hardware quality.

The team observed that the quantum network correctly classified images that consistently failed to be recognized by its classical counterpart, suggesting a distinct ability to extract subtle features or patterns within the images. Furthermore, the network's performance in the presence of noise indicates a robustness not typically seen in classical systems, hinting at a pathway toward building more resilient and reliable machine learning algorithms. This work represents a significant step toward realizing the potential of near-term quantum computers for practical machine learning applications, and opens exciting avenues for exploring the interplay between quantum mechanics and artificial intelligence.

Quantum Neural Networks Classify Handwritten Digits

This work demonstrates the successful implementation of a quantum neural network capable of classifying handwritten digits from the MNIST dataset using both trapped-ion and IBM quantum computers. The researchers observed that introducing quantum uncertainty into the network can improve performance, particularly when classifying images that challenge purely classical networks. While the network successfully classifies images, the observed performance gains are currently modest and limited by the scale of available quantum hardware. Future research will focus on scaling up these networks to explore the possibility of achieving a definitive quantum advantage, and on mitigating the effects of noise to improve the reliability of quantum classification. The team also intends to investigate the potential of this approach with more complex datasets and network architectures.

👉 **More information**
🗞 *Benchmarking a Tunable Quantum Neural Network on Trapped-Ion and Superconducting Hardware*

Quantum HyperSpace Project Could Secure $Billions in Transatlantic Data

July 15, 2025BY QUANTUM NEWS

Scientists are attempting to establish a secure, unhackable communication system across the Atlantic, building on over a century of wireless transmission advancements. The €15 million HyperSpace project, co-funded by the EU and Canada, unites researchers from seven institutions to overcome the limitations of fibre-optic quantum communication by utilising satellite-based transmission. Scheduled for completion this September, the initiative aims to demonstrate the feasibility of intercontinental quantum key distribution, potentially underpinning a future global quantum internet and secure data network.

Quantum Communication's Transatlantic Ambition

The HyperSpace project represents a renewed ambition to establish transatlantic communication, albeit predicated on fundamentally different principles than those employed by Marconi. Rather than relying on radio waves, the initiative seeks to create a system of quantum secure communication, leveraging the principles of quantum mechanics to guarantee the inviolability of transmitted data. While a fully functional transatlantic link remains a considerable undertaking, the project aims to resolve the key scientific and technological challenges obstructing such a breakthrough.

At the core of this endeavour lies quantum entanglement, a phenomenon whereby two or more particles become linked in such a way that they share the same fate, irrespective of the distance separating them. This interconnectedness allows for the generation of encryption keys at a distance, offering a level of security unattainable through conventional cryptographic methods. Any attempt to intercept a quantum signal inevitably disrupts the entanglement, immediately alerting communicating parties to the intrusion and rendering the communication unusable to an eavesdropper.

Current quantum communication systems predominantly utilise fibre optic cables, but their range is limited by signal attenuation, typically extending to only a few hundred kilometres. To overcome this limitation, HyperSpace is investigating the feasibility of space-based transmission, exploring methods to relay quantum signals between satellites and ground stations. This approach promises to extend the reach of secure communication to intercontinental distances.

Furthermore, the HyperSpace consortium is exploring high-dimensional entanglement, a technique designed to increase the information-carrying capacity of individual photons. Unlike standard entanglement, which transmits one bit of information at a time, high-dimensional entanglement allows for the simultaneous transmission of multiple bits, potentially increasing data transfer rates and bolstering the system's resilience against interference and hacking attempts.

The project's immediate focus is the development of a proof-of-concept system utilising shorter terrestrial free-space optical links, with the ultimate goal of establishing a secure quantum communication link between Europe and Canada. Success in this endeavour would not only demonstrate the viability of intercontinental quantum networks but also provide a blueprint for a future global system capable of supporting secure data sharing, precise navigation, and advanced computing applications.

The initiative benefits from a strong foundation in European quantum optics and photonic integration, crucial for scaling quantum communication technologies beyond laboratory settings and into operational spaceborne networks. Co-funded by the European Union's Horizon Europe programme and Canada's Natural Sciences and Engineering Research Council, the consortium brings together leading research institutions from across Europe and Canada, including Fraunhofer IOF, CEA-Leti, TU Wien, the Universities of Padua and Pavia, the Institut National de la Recherche Scientifique, the University of Toronto, and the University of Waterloo.

The Principles of Quantum Entanglement

The principle of quantum entanglement, central to HyperSpace, arises from the peculiar rules governing quantum mechanics. Unlike classical physics, where properties of an object are definite, quantum particles exist in a superposition of states until measured. Entanglement occurs when two or more particles become correlated in such a way that their fates are intertwined. Measuring a property of one particle instantaneously determines the corresponding property of the other, regardless of the distance separating them – a phenomenon Einstein famously termed "spooky action at a distance". This correlation is not due to any physical signal passing between the particles, but rather a fundamental property of their shared quantum state.

This interconnectedness is exploited in quantum secure communication by utilising the entangled particles to generate shared, random encryption keys. These keys are not transmitted directly, but are instead established through the measurement of the entangled particles. Any attempt by an eavesdropper to intercept or measure the particles disrupts the entanglement, altering the quantum state and immediately alerting the communicating parties to the intrusion. This inherent security is a critical distinction from conventional cryptography, which relies on the computational difficulty of mathematical problems and is therefore vulnerable to advances in computing power, including quantum computers.

The HyperSpace team is further investigating high-dimensional entanglement to enhance the efficiency and robustness of the system. Standard entanglement typically encodes information onto a single property of a photon, effectively transmitting one bit of information at a time. High-dimensional entanglement, however, leverages multiple degrees of freedom within the photon – such as its polarisation or orbital angular momentum – to encode multiple qubits simultaneously. This increases the information-carrying capacity of each photon, potentially boosting data transfer rates and improving resilience against noise and interference, ultimately strengthening the foundations of quantum secure communication.

Overcoming Distance Limitations

The limitations of terrestrial fibre optic networks necessitate the exploration of alternative transmission methods. HyperSpace is therefore focused on establishing quantum communication links via satellite relays, a complex undertaking requiring precise pointing and tracking of optical signals across vast distances. Maintaining the delicate quantum state of photons during transmission through the atmosphere and space presents significant technical challenges, including atmospheric turbulence, signal scattering, and photon loss.

The project is investigating advanced adaptive optics and error correction protocols to mitigate these effects and ensure reliable data transmission.

Beyond simply extending the range of quantum communication, the HyperSpace consortium is actively researching techniques to increase the data throughput of these links. Standard quantum key distribution (QKD) protocols, while secure, often suffer from relatively low key generation rates. High-dimensional entanglement offers a pathway to overcome this bottleneck. By encoding multiple qubits onto a single photon – utilising properties beyond simple polarisation – the information-carrying capacity can be substantially increased. This not only accelerates key generation but also enhances the system's resilience against both interference and deliberate attacks, bolstering the integrity of quantum secure communication.

Successful implementation of space-based quantum communication will require not only technological advancements but also the development of standardised protocols and infrastructure. Establishing a globally interoperable quantum network will necessitate agreement on key distribution methods, data formats, and security standards. The HyperSpace project, by fostering collaboration between leading research institutions in Europe and Canada, aims to contribute to the development of these essential standards, paving the way for a future where quantum secure communication is readily accessible and widely deployed.

Enhancing Capacity with High-Dimensional Entanglement

The exploration of high-dimensional entanglement represents a significant advancement in enhancing the capacity of quantum communication systems. While standard entanglement schemes encode information onto a single quantum property – effectively transmitting one bit per photon – high-dimensional entanglement leverages multiple degrees of freedom within the photon itself. These degrees of freedom include, but are not limited to, polarisation, orbital angular momentum, and time-bin encoding. By exploiting these additional dimensions, each photon can carry multiple qubits simultaneously, substantially increasing the information-carrying capacity and potential data transfer rates. This approach moves beyond the limitations of single-bit transmission, offering a pathway to more efficient and scalable quantum secure communication.

Beyond simply increasing throughput, high-dimensional entanglement also offers inherent advantages in terms of robustness. Encoding information across multiple degrees of freedom diversifies the potential attack vectors. An eavesdropper attempting to intercept the quantum signal would need to simultaneously monitor and disrupt multiple, independent quantum states, significantly increasing the complexity and detectability of the attack. Furthermore, the increased dimensionality provides greater resilience against noise and interference, as errors in one dimension are less likely to corrupt the entire message. This enhanced robustness is crucial for establishing reliable quantum secure communication links, particularly over long distances and through challenging atmospheric conditions.

The implementation of high-dimensional entanglement is not without its challenges. Maintaining the coherence of multiple quantum states simultaneously requires precise control and measurement techniques. Furthermore, the detection and decoding of high-dimensional quantum states often necessitate sophisticated optical setups and signal processing algorithms. The HyperSpace consortium is actively developing and refining these technologies, focusing on integrated photonic circuits and advanced quantum detectors. These advancements are essential for translating the theoretical benefits of high-dimensional entanglement into practical, deployable quantum communication systems, ultimately bolstering the security and efficiency of future networks.

A Collaborative European-Canadian Initiative

The initiative benefits from a strong foundation in European quantum optics and photonic integration, crucial for scaling quantum communication technologies beyond laboratory settings and into operational spaceborne networks. Co-funded by the European Union's Horizon Europe programme and Canada's Natural Sciences and Engineering Research Council, the consortium brings together leading research institutions from across Europe and Canada, including Fraunhofer IOF, CEA-Leti, TU Wien, the Universities of Padua and Pavia, the Institut National de la Recherche Scientifique, the University of Toronto, and the University of Waterloo.

The HyperSpace consortium, concluding in September this year, comprises Fraunhofer IOF, CEA-Leti, TU Wien, the Universities of Padua and Pavia, and, from Canada, the Institut National de la Recherche Scientifique, the University of Toronto, and the University of Waterloo. This collaborative structure is intended to leverage complementary expertise in quantum optics, photonic integration, satellite communication, and free-space optical links, accelerating the development of essential technologies for intercontinental quantum secure communication.

Europe has established a strong lead in quantum optics and photonic integration, crucial for scaling quantum communications from laboratory experiments to spaceborne networks. This expertise is particularly relevant to the development of compact, efficient, and robust quantum transmitters and receivers, essential for deployment on satellites and ground stations. The Canadian contribution focuses on advanced free-space optical communication techniques and satellite mission design, complementing the European strengths in quantum photonics.

The consortium's collaborative approach extends beyond technological development to include the standardisation of protocols and infrastructure. Establishing a globally interoperable quantum network will necessitate agreement on key distribution methods, data formats, and security standards. The HyperSpace project, by fostering collaboration between leading research institutions in Europe and Canada, aims to contribute to the development of these essential standards, paving the way for a future where quantum secure communication is readily accessible and widely deployed.

World-first: Scientists unlock quantum state in objects at room temperature

Researchers at the University of Wien (TU Wien) in collaboration with those at ETH Zurich have unlocked quantum states in glass spheres, sized smaller than a grain of sand, without having to resort to ultra-low temperatures.

This record-breaking achievement has pushed the boundaries of quantum physics, making it easier to study quantum properties in ways that were considered impossible before.

Quantum physics is a relatively newer field of science that attempts to explain the world around us through the study of matter and energy at atomic and submatomic scales.

While we are still beginning to scratch surface of this field, applications in areas such as sensing, computation, simulation as well as cryptography are already being developed.

As the field expands, researchers are also keen to know the limits of quantum physics. So far, studies have focused on understanding properties such as entanglement or superposition at subatomic levels.

However, researchers at ETH Zurich and TU Wein wondered if objects larger than atoms and molecules also displayed quantum properties.

Oscillations in quantum states

In the everyday world, we look at oscillations as big movements. For instance, the pendulum of a clock can oscillate at various angles and varying speeds. But as we zoom into microscopic levels, oscillations take a different form. Microscopic particles wobble at all times.

“This oscillation depends on the energy and on how the particle is influenced by its environment and its temperature,” explained Carlos Gonzalez-Ballestero from the Institute of Theoretical Physics at TU Wien, who led the work.

“In the quantum world, however, things are different: if you look at oscillations with very low energy, you find that there are very specific’ oscillation quanta'”.

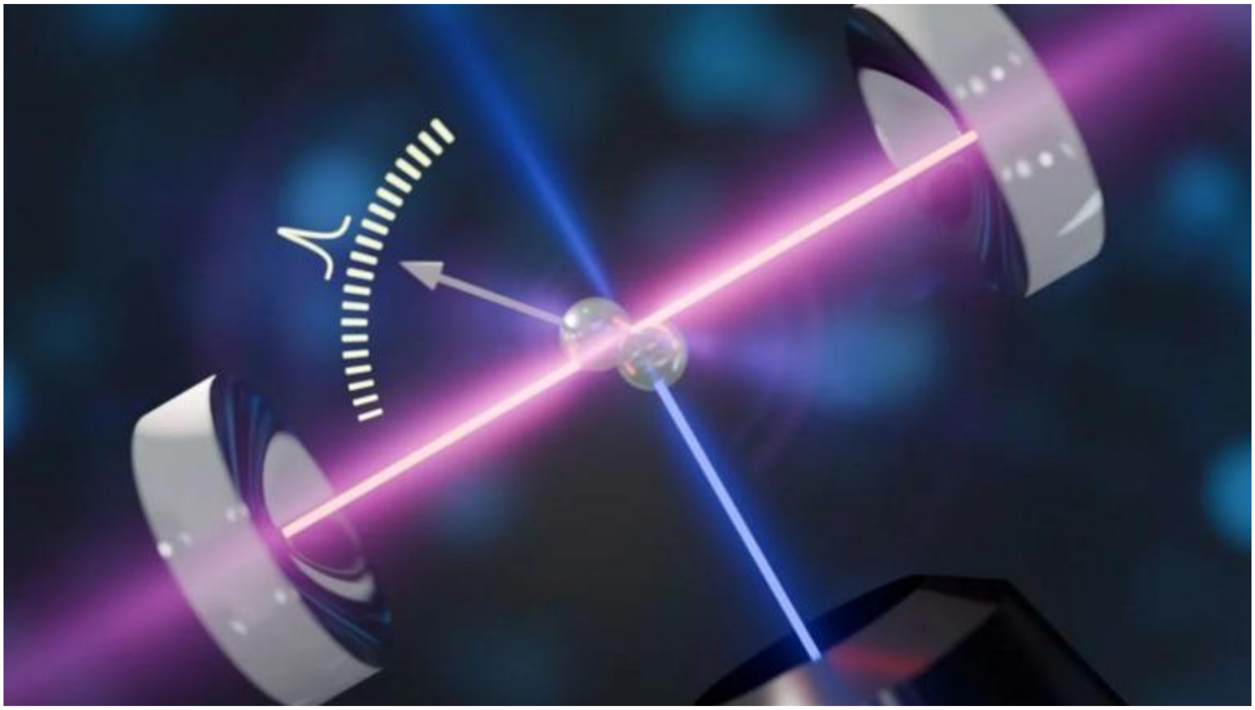
The minimum vibration amplitude is known as the ground state, with excited states existing sequentially with an increase in vibration and energy levels. While there are no intermediate states, a particle can exist in a combination of different vibration states.

To identify the quantum states of a particle, scientists need to isolate it from perturbations arising from its surroundings. This is why quantum experiments are carried out at extremely low temperatures close to absolute zero.

Quantum state at room temperature

The research collaboration worked on a technique to a nanoparticle to its quantum state even when it was not near an ultracooled state. The nanoparticle used in the experiments was not perfectly round but slightly elliptical.

“When you hold such a particle in an electromagnetic field, it starts to rotate around an equilibrium orientation, much like the needle of a compass,” added Gonzalez-Ballestero in a press release.



Graphic representation of the system of lasers and mirrors used by scientists in their experiments. Image credit: Lorenzo Dania (ETHZ)

To study the quantum properties of this vibration, the research team used lasers and mirror systems that could perform the dual role of supplying or even extracting energy from it.

"By adjusting the mirrors in a suitable way, you can ensure that energy is extracted with a high probability and only added with a low probability. The energy of the rotational movement thus decreases until we approach the quantum ground state,' Gonzalez-Ballestero further explained.

The researchers succeeded in bringing the nanoparticle's rotation to a state resembling the ground state. Interestingly, this was achieved when the particle was several hundred degrees hot, instead of being ultracooled.

"You have to consider different degrees of freedom separately," said Gonzalez-Ballestero, explaining their achievement. "This allows the energy of the rotational movement to be reduced very effectively without having to reduce the internal thermal energy of the nanoparticle at the same time. Amazingly, the rotation can freeze, so to speak, even though the particle itself has a very high temperature."

The achievement allows particles to be studied in significantly 'purer' quantum states without requiring ultracold temperatures.

The research findings were published in the journal *Nature Physics*.

High-purity quantum optomechanics at room temperature

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Abstract

Exploiting quantum effects in a mechanical oscillator, such as back-action-evading measurements or squeezing of the mechanical degrees of freedom, requires the oscillator to be prepared in a high-purity quantum state. The largest state purities in optomechanics to date have been achieved with costly cryogenic cooling combined with coupling to electromagnetic resonators driven with a coherent radiation field. Here we use coherent scattering into a Fabry–Pérot cavity to cool the megahertz-frequency librational mode of an optically levitated silica nanoparticle from room temperature to its quantum ground state. We use sideband thermometry to infer a phonon population of 0.04 quanta under optimal conditions, corresponding to a state purity of 92%. The purity reached by our room-temperature experiment exceeds the performance offered by mechanically clamped oscillators in a cryogenic environment, establishing a platform for high-purity quantum optomechanics at room temperature.

Main

The prospect of observing and exploiting quantum states of massive systems has been driving the field of optomechanics[1]. Mechanical motion controlled by optical or microwave fields offers opportunities to develop quantum-enhanced sensing schemes[2,3,4] and transduction technologies[5], test quantum mechanics at unprecedented mass and length scales[6,7], and gain insights into the role of the gravitational field in the evolution of quantum states[8,9]. Crucial to these applications is the suppression of thermal noise, which calls for operation in a cryogenic environment. Although highly effective, the cost and technical complexity of cryogenic cooling severely limit further proliferation of optomechanical technologies. The promise of room-temperature quantum optomechanics has, therefore, spurred the development of experimental platforms operating without the need for cryogenic cooling[10].

The necessity to suppress thermal noise is rooted in the requirement of any quantum protocol to initialize the oscillator in a quantum mechanically pure state[11,12]. For a thermal state with mean occupation number *n*, the purity is defined by (ref. [13]). For sufficiently large mechanical frequencies, such as gigahertz mechanical modes of nanobeams[14] or bulk acoustic-wave resonators[15], state purification can be achieved by thermalization to a cryogenic bath sufficiently cold to render the oscillator in its ground state of motion. For megahertz or even lower mechanical frequencies, high-purity state preparation requires a combination of cryogenic cooling with other techniques such as cavity sideband cooling[16,17,18] or measurement-based feedback cooling[19,20]. With such combined cooling schemes, megahertz electromechanical oscillators have been prepared with a phonon occupation of 0.07 (88% state purity)[16] and gigahertz optomechanical systems have been brought to a purity of 85% (ref. [21]).
The key to circumventing the need for cryogenic cooling is to suppress the coupling of the mechanics to its thermal environment. In this vein, two approaches have been followed. The first is based on complete mechanical decoupling of the oscillator from its environment by optical levitation in vacuo[22]. Cooling the centre-of-mass motion of an optically levitated nanoparticle in room-temperature experiments has been reported using both measurement-based feedback[23] and laser-sideband cooling[24], reaching a phonon population of 0.6, corresponding to a state purity of 47% (ref. [23]). The second approach focuses on careful design of the strain and phononic dispersion of the mechanical tether[25,26]. In a tour de force of mechanical and optical engineering, recent efforts have enabled quantum optomechanics at room temperature with a clamped system, reaching a purity of 34% (ref. [27]).

Despite these efforts, no room-temperature optomechanical platform can, at present, rival the state purities achieved with the aid of cryogenics.

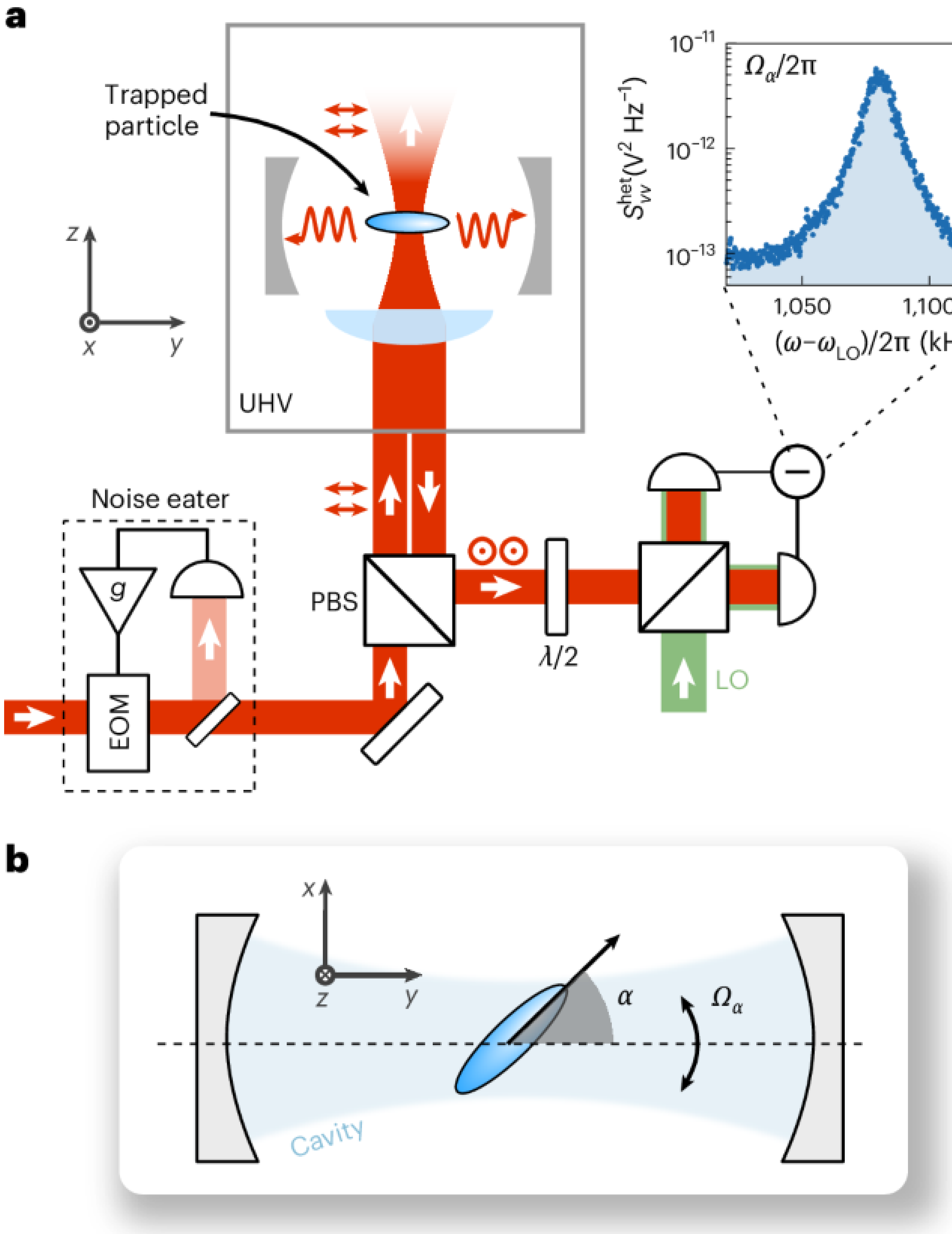
Here we report cooling of a megahertz librational mode of an optically levitated nanoparticle to a phonon population of n = 0.04 in a room-temperature experiment, corresponding to a state purity . Cooling is realized by coupling the nanoparticle to a high-finesse optical cavity in a coherent-scattering configuration[28]. To reach such high purity, we operate our libration-cavity system deep in the sideband-resolved regime, we actively suppress laser phase noise, and we choose the polarization state of the tweezer to maximize the optomechanical coupling rate. Regarding quantum mechanical purity, our results place levitated oscillators in room-temperature experiments ahead of the most performant opto- and electromechanical systems, even those aided by cryogenics and gigahertz mechanical mode frequencies.

Experimental set-up

The nanomechanical oscillator investigated in this work is the harmonic angular motion of an optically levitated anisotropic particle[29]. The axis of largest polarizability of an anisotropic scatterer in a linearly polarized field aligns with the polarization direction of the field[30]. Small deviations from this alignment result in harmonic angular motion, termed 'libration'[31].
Figure 1a shows a sketch of the experimental set-up. More details are given in the Supplementary Information. We use an optical tweezer (power of ~1.2 W, numerical aperture NA = 0.75 and wavelength λ = 1,550 nm) to trap single anisotropic nanoparticles inside a vacuum chamber at a pressure of 5×10^{-9} mbar and at room temperature. The tweezer beam propagates along the z direction and is linearly polarized along the y axis, resulting in centre-of-mass frequencies $(\Omega_x, \Omega_y, \Omega_z)/(2\pi)$ = (250, 220, 80) kHz. We trap anisotropic nanoparticles, which are clusters of a few silica nanospheres. The nanospheres have a nominal diameter of 120 nm. The measured centre-of-mass gas damping rates (Supplementary Information) indicate that each nanoparticle has its long axis aligned to the tweezer polarization[29] and that its shape is not cylindrically symmetric[32]. We detect the orientation of the nanoparticle by interfering backscattered light from the tweezer with a local oscillator shifted by $\omega_{LO}/(2\pi)$ = 2.73 MHz in a balanced heterodyne scheme, where ω_{LO} is the frequency of the local oscillator. The optical tweezer is positioned in the waist

of a high-finesse optical cavity whose axis points along the *y* direction, that is, it is oriented perpendicularly to the tweezer axis and along the polarization direction of the tweezers. Light scattered by the nanoparticle populates the fundamental transverse electromagnetic (TEM_{00}) mode of the cavity, resulting in optomechanical coupling through coherent scattering (Supplementary Information). The cavity mode has a linewidth $\kappa/(2\pi)$ = 330 kHz and a resonance frequency $\omega_c = \omega_{tw} + \Delta$, detuned by Δ from the tweezer frequency ω_{tw}. The nanoparticle position y_{eq} along the cavity standing wave is tunable with the nanopositioner holding the trapping lens. Finally, our system contains a noise eater that allows us to controllably suppress laser phase noise[33].

Fig. 1: Sketch of the experimental set-up.


a
Trapped
particle
UHV
z
x
y
$\Omega_\alpha/2\pi$
10^{-11}
10^{-12}
10^{-13}
$S_{vv}^{het}(V^2\ Hz^{-1})$
1,050
1,100
$(\omega-\omega_{LO})/2\pi$ (kHz)
Noise eater
g
EOM
PBS
$\lambda/2$
LO
b
x
z
y
α
Ω_α
Cavity

a, An anisotropic silica nanoparticle (schematically illustrated as an ellipsoid) is trapped by an optical tweezer in an ultrahigh vacuum. The tweezer light is linearly polarized along the *y* axis by a polarizing beam splitter. The long axis of the nanoparticle aligns parallel to the tweezer polarization and undergoes angular harmonic oscillations, termed librations, at a frequency $\Omega_\alpha/(2\pi)$ in the *x*–*y* plane. This libration motion is coupled to a high-finesse optical cavity. The high-NA lens forming the optical trap is mounted on a nanopositioner (not shown) such that the particle equilibrium position can be varied across the cavity intensity profile. The *x*-polarized light backscattered from the nanoparticle is collected by the trapping lens and mixed with a local oscillator of frequency ω_{LO} in a balanced heterodyne detector. This detector provides a measurement of the libration motion unaltered by the cavity transfer function. Inset: power spectral density acquired at 6 mbar from this backward detector. The librational mode of the particle peaks at $\Omega_\alpha/(2\pi)$ = 1.08 MHz. Laser phase noise in the tweezer beam is suppressed by a noise eater composed of a phase-noise detector and an electro-optic modulator. The suppression level is varied with a gain *g*. **b**, Illustration of the libration mode. The tweezer polarization is aligned to the cavity axis (*y*). The libration angle α denotes the deviation of the long axis of the particle from the polarization direction of the tweezer field in the *x*–*y* plane. EOM, electro-optic modulator; LO, local oscillator; PBS, polarizing beam splitter; UHV, ultrahigh vacuum.

The anisotropic particle shape results in three distinct moments of inertia (Supplementary Information), giving rise to three non-degenerate libration modes associated with the orientation angles γ, β and α[34,35], with corresponding frequencies $(\Omega_\gamma, \Omega_\beta, \Omega_\alpha)/(2\pi)$ = (0.15, 0.7, 1.08) MHz. Recent experiments have cooled several libration and centre-of-mass modes simultaneously, either by feedback control[30,32,35] or by cavity-cooling through coherent scattering[34]. Here we optimize our experimental settings to enhance single-mode cooling of the α libration mode.

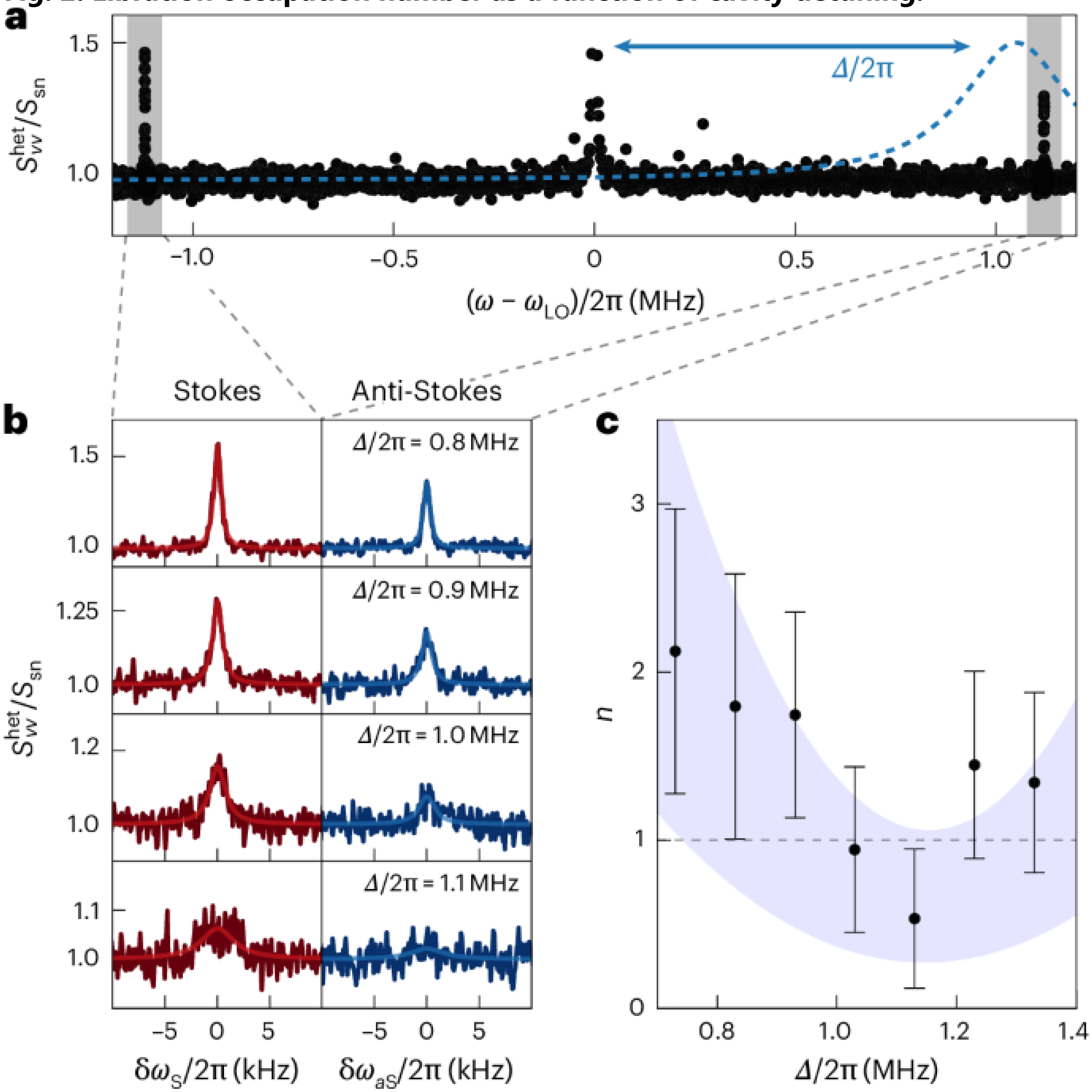
The high-frequency α mode corresponds to angular oscillations in the tweezer focal plane (*x*–*y* plane in Fig. 1b)[32]. The inset of Fig. 1a shows a high-pressure (6 mbar) spectrum of the heterodyne signal. We associate the Lorentzian peak with the motion of the α mode. In this work, we focus on cavity-cooling this mode for two reasons. First, the α mode lies deep in the sideband-resolved regime ($\Omega_\alpha \gg \kappa$), which is a required condition to reach the ground state through cavity-cooling[36]. Second, optimal cooling of the α mode is achieved on polarizing the tweezer along the y axis (Fig. 1b)[28,37]. Moreover, this configuration directs the dipole radiation pattern of light elastically scattered by a nanoparticle outside the cavity, thus minimizing the heating effects of laser phase noise[38]. As the particle orientation oscillates in the x–y plane, light from the tweezer is inelastically scattered into the cavity mode at the Stokes and anti-Stokes frequencies $\omega_{tw} \pm \Omega_\alpha$. For a cavity detuning $\Delta \approx \Omega_\alpha$, the anti-Stokes scattering is enhanced, promoting energy transfer from the mechanics to the light field and resulting in cavity-cooling of the librational motion.

In the following, we detail how we maximize the state purity of our levitated librator. To do this, we first benchmark our thermometry scheme. Then, we optimize the cavity detuning for best cooling performance. Finally, we optimize the particle position in the cavity mode in the presence of phase-noise suppression.

Sideband thermometry and cavity detuning scan

The free-space heterodyne detector gives us access to both Stokes and anti-Stokes sidebands of the α librational mode. We confirm cavity-cooling through Raman sideband thermometry[20,23]. Figure 2a shows a heterodyne spectrum of the libration motion (black dots, normalized to the shot-noise level) obtained for cavity detuning $\Delta/(2\pi) = 0.8$ MHz. The plot shows the Stokes (left) and anti-Stokes (right) libration peaks, highlighted by the shaded grey bands. The area a_S (a_{aS}) below the Stokes (anti-Stokes) sideband is associated with light-scattering events that increase (decrease) the librational energy. An asymmetry between the two sidebands arises as the angular motion of the particle is cooled close to its ground state. We can deduce the libration occupation number n from the ratio of the sidebands $a_{aS}/a_S = n/(n + 1)$ (ref. 39). We stress that, unlike schemes detecting the cavity output spectrum[18,24,40], our free-space detection does not rely on prior knowledge of the cavity detuning and it is insensitive to sideband artefacts from classical laser phase noise, which may corrupt the occupation estimation[41,42]. Furthermore, in the Supplementary Information we rule out the detector transfer function as a possible source of sideband asymmetry.

Fig. 2: Libration occupation number as a function of cavity detuning.



a, Heterodyne libration spectrum measured with the free-space backward detector (black), superposed with the cavity lineshape (blue dashed line). The detuning Δ is the difference between the tweezer frequency and the cavity resonance frequency. Highlighted in grey are the Stokes and anti-Stokes librational sidebands. For $\Delta \approx \Omega_\alpha$, with $\Omega_\alpha/(2\pi)$ = 1.08 MHz being the librational frequency, the cavity enhances the anti-Stokes scattering, leading to resolved-sideband cooling. **b**, Stokes (left) and anti-Stokes (right) heterodyne spectra normalized to the shot-noise level S_{sn} with fitted Lorentzian lines for Δ increasing from top to bottom as indicated in the plot. $\delta\omega_S$ and $\delta\omega_{aS}$ denote the frequency differences from the Stokes and anti-Stokes peak centres, respectively. **c**, Occupation number n obtained from sideband thermometry as a function of Δ. It reaches a minimum of $n = 0.5(3)$ at $\Delta/(2\pi) = 1.13$ MHz. Occupation values are extracted from Lorentzian fits to the heterodyne spectra. Error bars correspond to one standard deviation of the fitted asymmetries around the calculated occupation numbers. The dashed line marks the $n = 1$ threshold. The shaded area corresponds to a theoretical estimation of n based on libration-cavity coupling, laser phase noise, radiation-torque shot noise and their uncertainties (Supplementary Information).

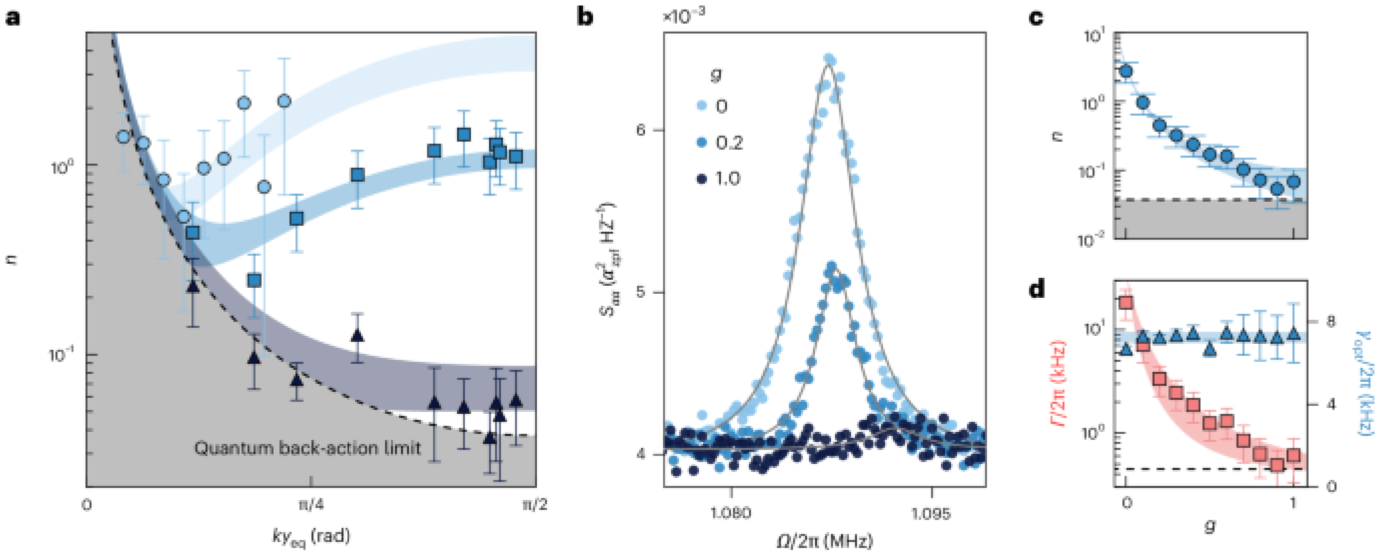
By using sideband thermometry, we measure the libration occupation number as a function of the cavity detuning. For this measurement, the particle is positioned at $ky_{eq} \approx 0.1\pi$ in the cavity standing wave, where k is the wavenumber, and we define the position along the cavity axis such that $y_{eq} = 0$ coincides with the intracavity intensity minimum. Figure 2b shows heterodyne spectra normalized to the detection shot-noise level S_{sn} centred around the Stokes (left column) and anti-Stokes (right column) libration peaks and for increasing values of the cavity detuning Δ (top to bottom). To facilitate comparison, the spectra have been shifted along the frequency axis to compensate for the optical spring effect and to align the Stokes and anti-Stokes peaks (Supplementary Information). As the detuning approaches the optimal value $\Delta \approx \Omega_\alpha \approx 2\pi \times 1.1$ MHz, the linewidth increases and the peak height decreases due to cavity-cooling. From a Lorentzian fit (lines in Fig. 2b) to each lineshape, we extract the occupation number n.

In Fig. 2c we plot the measured occupation number n including the standard deviation of the fits as a function of the cavity detuning Δ. We obtain the minimum occupation $n = 0.5(3)$ for $\Delta = 2\pi \times 1.1$ MHz. To put this result into perspective, we compare n to the back-action limit for the phonon population in a coherent-scattering configuration, which is given by . The first term arises due to the interaction of the oscillator with the cavity mode, and the second term is the phonon population due to scattering into free space[43]. An estimate of the back-action limit using our cavity parameters yields , rendering the result in Fig. 2c far from the optimal. To identify our limitation, we show as the blue area in Fig. 2c the theoretical estimate based on our system parameters, including the libration-cavity coupling rate, laser phase noise of the tweezer beam, and radiation-torque shot noise, that is, measurement back-action on a rotor[44]. Our model indicates that the final occupation number in this experiment is limited by laser phase noise in the tweezer beam, a limitation that has plagued previous optomechanics experiments[38,45]. Phase noise is detrimental whenever elastically scattered light at the tweezer frequency populates the cavity, as it turns phase fluctuations into amplitude fluctuations leading to further heating. Elastic scattering into the cavity mode can arise from small experimental imperfections, such as a misalignment between the tweezer polarization and the cavity axis, or a small ellipticity of the tweezer polarization.

Position dependence of cooling performance

To corroborate our understanding, we study the dependence of the cooling performance as a function of particle position in the cavity. Although heating due to laser phase noise is position dependent[24,38], radiation-torque shot noise and heating from gas collisions[44] do not depend on position. The blue circles in Fig. 3a show the occupation n measured for different positions y_{eq} along the standing wave of the cavity field, whose periodicity is set by the wavenumber k. This experiment is done at optimal cavity detuning $\Delta \approx \Omega_\alpha$. We observe that the occupation reaches a minimum value of $n = 0.5$ for $ky_{eq} \approx 0.1\pi$. This is the position where the data in Fig. 2c has been acquired. The initially decreasing trend of n with position y_{eq} is due to the increasing cooling rate when moving away from the intensity minimum of the cavity mode. However, as the particle is placed further away from the node, the cavity photon population builds up and so does heating due to phase noise. This behaviour is quantitatively captured by our model (light-blue area behind the blue circles in Fig. 3a; see Supplementary Information for details), supporting the hypothesis that our cooling performance is limited by phase noise.

Fig. 3: Dependence of cavity-cooling on particle position in the standing wave and phase noise.



a, Occupation number n measured for different particle positions y_{eq} along the cavity standing wave and for different levels of phase-noise cancellation g as indicated. The cavity intensity minimum coincides with the position $y_{eq} = 0$ (cavity node), and the maximum occurs for $ky_{eq} = \pi/2$ (cavity anti-node). Occupation values are extracted from Lorentzian fits to calibrated homodyne spectra. The error bars derive from the standard deviation in the Lorentzian fits and from the statistical error on the calibration method. The coloured areas are fits to our model including phase noise, cavity coupling and radiation-torque shot noise (Supplementary Information). The black dashed line corresponds to the quantum back-action limit reachable in the absence of phase noise. **b**, Homodyne spectra $S_{\alpha\alpha}$ of the libration degree of freedom for different cancellation gains and with the particle at the anti-node. Data are expressed in units of the zero-point angular displacement α_{zpf}. Grey solid lines are Lorentzian fits. **c**, Occupation number n as a function of phase-noise cancellation g for a particle in the cavity anti-node at optimal detuning. Occupation values are obtained from a fit to calibrated spectra, and error bars derive from the standard deviation in the fit and statistical errors from the calibration. The blue area represents the theoretical prediction, and the black dashed line is the quantum back-action limit. **d**, Total heating rate $\Gamma = n\gamma_{opt}$ (red) and optical cooling rate γ_{opt} (blue) as a function of g, extracted from the same dataset underlying **c**. The cooling rates γ_{opt} were extracted from Lorentzian fits to the homodyne spectra, and their error bars represent one standard deviation of the fitted parameter. The error bars of Γ were obtained by propagating the errors of n and γ_{opt}. The coloured areas following the data points are theoretical predictions based on our model. The black dashed line is the heating rate due to radiation-torque shot noise extracted from the fits in **a**.

Phase-noise reduction

To combat phase noise in our experiment, we implement a phase-noise eater based on an imbalanced Mach–Zehnder interferometer for noise detection and feedback to the laser through an electro-optic phase modulator[33]. The feedback gain g determines the phase-noise suppression, which we characterize in Supplementary Information. The remaining experiments described in this Article are carried out with a different nanoparticle, which has the same libration frequency Ω_α as that used for all experiments presented thus far (Supplementary Information). Furthermore, we implement a quasi-homodyne libration detection scheme[32] (Supplementary Information) cross-calibrated by sideband thermometry to boost detection efficiency so that we can resolve small occupation numbers.

Figure 3a shows as blue squares the occupation n obtained with phase-noise cancellation gain $g = 0.2$. The occupation reaches a minimum value of $n = 0.25$ at a position $ky_{eq} \approx 0.2\pi$, closer to the cavity anti-node with respect to the situation without phase-noise cancellation. For gain $g = 1$, shown as black triangles in Fig. 3a, the occupation monotonically decreases and reaches its minimum near the cavity anti-node ($ky_{eq} \approx \pi/2$). This is the behaviour expected in the absence of phase noise, where the optimum position of the particle for libration cooling is at the anti-node of the cavity field[28]. The lowest measured occupation is $n = 0.04(1)$ quanta, corresponding to a ground-state purity of 92%. The blue and grey areas in Fig. 3a are simultaneous theoretical fits to both data-sets taken with phase-noise cancellation. From these fits, we extract the shot-noise heating rate $\Gamma_{BA}/(2\pi) = 0.5(1)$ kHz. This is the heating rate due to free-space measurement back-action, that is, it arises from scattering of the tweezer beam outside the cavity mode. We use this value to calculate the back-action-limited occupation that can be provided by our system, shown as the dashed black line in Fig. 3a. The proximity of the shot-noise limit to the data taken at cancellation gain $g = 1$ (black triangles) indicates that at this level of laser phase noise (; Supplementary Information) the measured occupations are predominantly limited by quantum back-action. Figure 3b is a direct comparison between spectra obtained with and without the noise eater. For these measurements, the particle was positioned at the anti-node, with the same feedback gains used in Fig. 3a. The spectra were calibrated with sideband thermometry and are expressed in units of α_{zpf}, the zero-point angular displacement (Supplementary Information). We observe how the area below the libration peak shrinks as the gain increases, whereas the noise floor of the detection remains unaltered. This observation shows that phase noise affects the librational energy, without altering the free-space detection. Finally, we study the behaviour of our system as a function of cancellation gain g in some more detail. To do this, we set the detuning to its optimum value $\Delta = \Omega_\alpha$ and place the particle in the anti-node of the cavity field. Figure 3c shows the measured libration occupation n as a function of cancellation gain g. At $g = 0$, despite otherwise optimal cooling conditions, excess phase noise leads to occupations above unity ($n > 1$). As g increases, the occupation decreases following our phase-noise model (blue area) and approaches the quantum back-action limit (black dashed line).

Figure 3d shows the rates that determine the occupation of our levitated librator under cavity-cooling as a function of the cancellation gain g. First, we determine the optomechanical cooling rate γ_{opt} as the width of the Lorentzian fit to the libration peak, shown as light-blue triangles in Fig. 3d. We observe that γ_{opt} does not depend on the cancellation gain g, as expected. Second, we extract the total heating rate Γ of the libration as $\Gamma = \gamma_{opt} n$ (ref. 24) and show it as red squares in Fig. 3d. The total heating rate decreases with cancellation gain g and approaches its fundamental limit Γ_{BA} (black dashed line). In the Supplementary Information, we present an independent measurement of the phase-noise heating rate performed by turning off the phase-noise cancellation and observing the population of the librator (Supplementary Information).

Conclusions

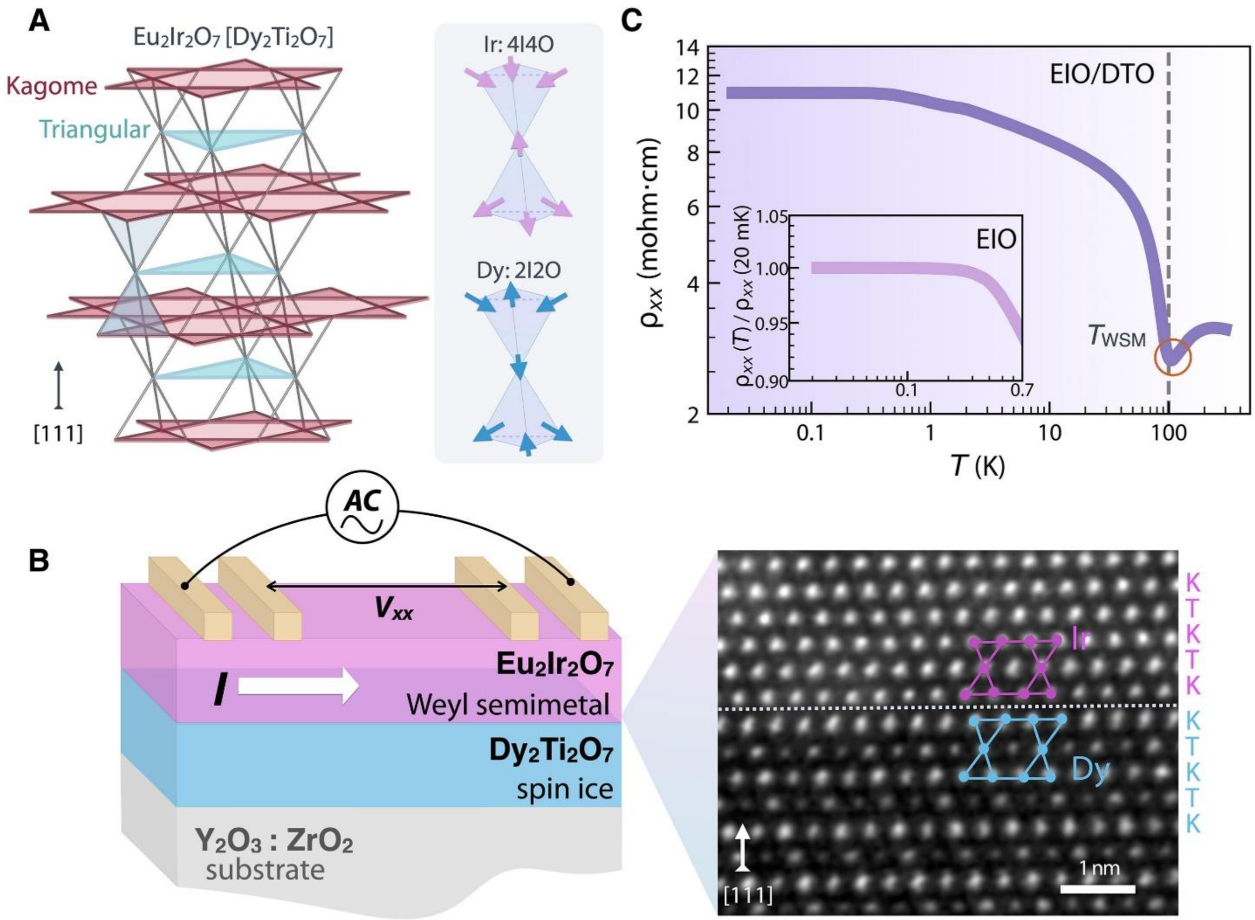
In conclusion, we have cooled a megahertz-frequency librational mode of an anisotropic levitated nanoparticle to the quantum ground state. Cooling was provided by coupling the photons inelastically scattered by the particle to a high-finesse cavity in the resolved-sideband regime. We have used Raman sideband thermometry to determine the phonon occupation of the levitated librator. Starting at room temperature, we have achieved a minimum occupation of 0.04(1) quanta, corresponding to a state purity of 92%. A crucial technical step to reach this high purity was to minimize the impact of heating due to laser phase noise. Active phase-noise cancellation in the tweezer beam by up to ~20 dB put our system into a regime where the phonon occupation is a result of the balance between cavity-cooling and heating by radiation-torque shot noise, that is, measurement back-action. Furthermore, compared to systems cooling the centre-of-mass motion in levitation, our levitated librator operates deeper in the resolved-sideband regime due to its higher resonance frequency[40].

The high purity achieved in our experiment places levitated librators on the forefront of experimental test beds for room-temperature quantum optomechanics experiments[27]. Furthermore, the purity of our system exceeds even that reached with gigahertz-frequency oscillators when laser-cooled in a cryogenic environment[21]. A central element setting our system apart from the canonical clamped optomechanics approach is the coherent-scattering configuration[24]. Although this configuration suffers from further back-action due to coupling of the mechanics not only to a single cavity mode but also to free space, it keeps the field strengths in the optical resonator low, circumventing excess back-action associated with thermal loading of the mirrors[27].

In the context of multi-mode ground-state cooling of levitated systems, extending the phase-noise suppression demonstrated here to other librational and centre-of-mass modes will facilitate cavity-based six-dimensional cooling[34] (Supplementary Information). The high-purity librational ground state could serve as a stepping stone towards preparing non-classical states of motion[31]. An interesting first step would be to squeeze the high-purity librational state by modulating the confining potential[46], in a free fall experiment[47] or by exploiting unstable dynamics provided by the cavity[48]. Looking further, rotational motion exhibits genuine quantum effects with no counterparts in centre-of-mass dynamics. Examples include orientational quantum revivals[47] and quantum-persistent tennis-racket flips[49]. Finally, the megahertz motional frequency demonstrated here may open up the possibility to resonantly couple levitated nanoparticles to other well-controlled quantum systems, such as trapped atomic ions[50], and to exploit qubit nonlinearities to engineer non-classical states of motion[51].

New quantum state of matter found at interface of exotic materials JULY 31, 2025

by Kitta MacPherson, Rutgers University edited by Lisa Lock, reviewed by Andrew Zinin



Crystal structure and temperature dependence of resistivity of EIO/DTO. Credit: *Science Advances* (2025). DOI: 10.1126/sciadv.adr6202

Scientists have discovered a new way that matter can exist—one that is different from the usual states of solid, liquid, gas or plasma—at the interface of two exotic materials made into a sandwich.

The new quantum state, called quantum liquid crystal, appears to follow its own rules and offers characteristics that could pave the way for advanced technological applications, the scientists said.

In an article published in the journal *Science Advances*, a Rutgers-led team of researchers described an experiment that focused on the interaction between a conducting material called the Weyl semimetal and an insulating magnetic material known as spin ice when both are subjected to an extremely high magnetic field. Both materials individually are known for their unique and complex properties.

"Although each material has been extensively studied, their interaction at this boundary has remained entirely unexplored," said Tsung-Chi Wu, who earned his doctoral degree in June from the Rutgers graduate program in physics and astronomy and is the first author of the study. "We observed new quantum phases that emerge only when these two materials interact. This creates a new quantum topological state of matter at high magnetic fields, which was previously unknown."

The team discovered that at the interface of these two materials, the electronic properties of the Weyl semimetal are influenced by the magnetic properties of the spin ice. This interaction leads to a very rare phenomenon called "electronic anisotropy" where the material conducts electricity differently in different directions. Within a circle of 360 degrees, the conductivity is lowest at six specific directions, they found. Surprisingly, when the magnetic field is increased, the electrons suddenly start flowing in two opposite directions.

This discovery is consistent with a characteristic seen in the quantum phenomenon known as rotational symmetry breaking and indicates the occurrence of a new quantum phase at high magnetic fields.

The findings are significant because they reveal new ways in which the properties of materials can be controlled and manipulated, Wu said. By understanding how electrons move in these special materials, scientists could potentially design new generations of ultra-sensitive quantum sensors of magnetic fields that work best in extreme conditions—such as in space or inside powerful machines.

Weyl semimetals are materials that allow electricity to flow in unusual ways with very high speed and zero energy loss because of special relativistic quasi-particles called Weyl fermions. Spin ice, on the other hand, are magnetic materials where the magnetic moments (tiny magnetic fields within the material) are arranged in a way that resembles the positions of hydrogen atoms in ice. When these two materials are combined, they create a heterostructure, composed of atomic layers of dissimilar materials.

Scientists have found that new states of matter appear under extreme conditions, including very low temperatures, high pressures or high magnetic fields, and behave in strange and fascinating ways. Experiments such as the Rutgers-led one may lead to a new, fundamental understanding of matter beyond the naturally occurring four states of matter, according to Wu.

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"This is just the beginning," Wu said. "There are multiple possibilities for exploring new quantum materials and their interactions when combined into a heterostructure. We hope our work will also inspire the physics community to explore these exciting new frontiers."

Physicists led by Jak Chakhalian (left) and including Tsung-Chi Wu (right) and Michael Terilli (center) are studying new quantum phenomena that could pave the way for advanced technologies. Credit: Jeff Arban
The research was conducted using a combination of experimental techniques, led by the principal investigator for the project, Jak Chakhalian, the Claud Lovelace Endowed Professor of Experimental Physics in the Department of Physics and Astronomy and a co-author of the study. The work was theoretically supported by Jedediah Pixley, an associate professor in the Department of Physics and Astronomy, also a co-author of the study.

"The experiment-theory collaboration is what really makes the work possible," Wu said. "It took us more than two years to understand the experimental results. The credit goes to the state-of-the-art theoretical modeling and calculations done by the Pixley group, particularly Jed Pixley and Yueqing Chang, a postdoctoral researcher. We are continuing our collaboration to push the frontier of the field as a Rutgers team."

Most of the experiments were conducted at the National High Magnetic Field Laboratory (MagLab) in Tallahassee, Fla., which provided the unique conditions to study these materials at ultra-low temperatures and high magnetic fields.

"We had to initiate the collaboration and travel to the MagLab multiple times to perform these experiments, each time refining ideas and methods," Wu said. "The ultra-low temperatures and high magnetic fields were crucial for observing these new phenomena."

The research builds on previous Rutgers-led research published earlier this year by Chakhalian, Mikhail Kareev, Wu and other physicists. The report described how four years of continuous experimentation led to a novel method to design and build a unique, tiny, atoms-thick structure composed of a Weyl semimetal and spin ice. The quantum heterostructure was so difficult to create, the scientists developed a machine to make it: the Q-DiP, short for quantum phenomena discovery platform.

"In that paper, we described how we made the heterostructure," said Chakhalian. "The new *Science Advances* paper is about what it can do."

More information: Tsung-Chi Wu et al, Electronic anisotropy and rotational symmetry breaking at a Weyl semimetal/spin ice interface, *Science Advances* (2025). DOI: 10.1126/sciadv.adr6202
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Oxford Scientists Successfully Test Technology That Used Quantum Teleportation To Make Quantum Supercomputers Possible

Quantum computing is getting a lot of attention these days, and many people are excited about the fact that once it is fully operational, it will allow the solving of calculations much faster. So fast that computations that would today take decades could be done in just hours or days.

While a lot of work still needs to be done to get standard quantum computing out into the mainstream, researchers at the University of Oxford are already working on the next major advancement. Quantum supercomputers.

Quantum supercomputers would work by combining many quantum processors together to amplify their power. To make this even more impressive, the researchers are using something called quantum teleportation in order to make it possible for systems that are not built together to operate as one.

For this test, they linked two quantum processors together. They were only 6.5 feet apart, but the concept could work at much greater distances. They used a method called photonic network interface, which was analyzed and explained in a paper they published in the journal Nature.

In addition to making extraordinarily fast computers, a quantum supercomputer would also be far more secure than traditional options, which will be important in the future when everyone has a quantum computer.

The team was led by Dougal Main, who is an Oxford University Physics graduate student. He explained how this works in a statement, saying:

“In our study, we use quantum teleportation to *create* interactions between these distant systems. By carefully tailoring these interactions, we can perform logical quantum gates — the fundamental operations of quantum computing — between qubits housed in separate quantum computers.” He went on, “This breakthrough enables us to effectively 'wire together' distinct quantum processors into a single, fully connected quantum computer."

They hope that they will be able to use light rather than electrical systems to send and receive the data. This will help them to overcome various engineering challenges that exist due to the fact that it is hard to keep electrical signals in a stable quantum state. Main went on to say:

"By interconnecting the modules using photonic links, the system gains valuable flexibility, allowing modules to be upgraded or swapped out without disrupting the entire architecture."

The test performed for the study helps to prove that this is possible using today's technology. Most cutting-edge computer scientists understand that scaling up quantum computing will be very difficult and may require advancements in physics to be successful. So, using the concept of supercomputers shown in this study, engineers should be able to dramatically increase the speed and security of a system while using only technology that is available today.

This would likely serve as a bridge between the current limits of quantum computing and those that may be possible when (or if) new physics is discovered that would allow them to maintain stable quantum states more effectively.

New algorithm lets quantum computers fix their own 'noise' in real-time

Quantum researchers have created a new algorithm that can reduce noise in qubits while they are working, and it does this in real time. The method works for many different types of qubits, even when there are a lot of them.

Noise is a big problem in quantum computers. Qubits, the tiny building blocks of quantum processors, are extremely sensitive – small changes in their surroundings can cause errors.

Now, researchers from the Niels Bohr Institute, MIT, NTNU, and Leiden University have developed a way to control this noise more effectively.

Decoherence in quantum states

In quantum devices, noise disturbs the coherent state you aim to store, manipulate, or read. Such unwanted disturbances are referred to as decoherence.

Quantum devices can have extremely high precision and sensitivity, much higher than classical physics.

Quantum devices have many capabilities: highly increased precision in medical appliances, resulting in better diagnostics, quantum simulations of molecules or drugs, enhanced security in information technologies, and vastly improved computing speed.

Mitigating the challenge

Noise can come from tiny electrical or magnetic changes in the material around qubits.

There are a few ways to deal with it: improve the material, redesign the qubits to be less sensitive, or, as researchers have been doing for the past 10-15 years, develop methods to cancel out the noise and improve performance.

“You can measure the actual noise, and once we know the noise, we can correct the control-path to mitigate the decoherence,” said Dr. Fabrizio Berritta.

Researchers have introduced a new way to handle this challenge.

One of the toughest parts of cancelling noise is that it needs to be done almost instantly. Imagine your quantum device is sending readings to your computer.

When the data reaches your screen, the noise shifts, making your correction too late. In other words, you’re always one step behind.

Frequency Binary Search

A research team led by Fabrizio has created a new method called Frequency Binary Search.

They tested it using a Quantum Machines controller with a built-in Field Programmable Gate Array (FPGA). This controller can directly control and read the qubits while collecting experiment data.

Importantly, it can estimate the qubit's frequency immediately, without sending data back to a desktop computer, which would be too slow.

The algorithm records these changes in real time during the experiment because the environment around a qubit causes its frequency shift.

Observing perspectives

"Today, in quantum processing units in general, we calibrate these qubits by taking many measurements: thousands or even tens of thousands of measurements," said Fabrizio.

"With the frequency binary search, you can calibrate across all the qubits simultaneously with exponential precision with the number of measurements (in practice, less than 10). With the number of qubits going up, we should be able to find good use of our method," he added.

By tackling noise in real time, the new method brings quantum computers one step closer to reliable, large-scale use.